ALGAL REMAINS IN RECENT LAKE SEDIMENTS

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for the degree of Doctor of Philosophy

by

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ABSTRACT

The preservation of algal remains and their stratigraphy in recent lake sediments is examined in relation to documented fluctuations in the composition and abundance of the phytoplankton in the same lakes.

Identifiable remains of non-siliceous algae were commonly recovered, but the degree of preservation varied specifically and between lakes. Smaller species were under-represented owing to rapid decomposition and selective consumption by herbivores. Larger species were relatively better preserved, especially in the sediments of the more productive lakes where long annual periods of anoxia, or the presence of an algal mat, may inhibit bacterial decomposition.

The stratigraphy of many algal remains from one site, Rostherne Mere, accurately reflected the documented fluctuations in the phytoplankton. This correlation enabled the establishment of an 'algal chronology' which provided independent verification of radionuclide dating. Viable akinetes of blue-green algae were recovered from sediments up to 70 years old. Cores from the same site in the mere showed no significant qualitative differences although there were quantitative areal variations. Estimates of standing crop and the concentration of algal remains in either entrapped seston or the sediments were typically within the same order of magnitude. Evidence is presented to refute the suggestion that the mere has recently become enriched by gull excreta.

The diatom stratigraphy of two Cumbrian lakes - Grasmere and Elterwater - corresponded to recorded alterations in the phytoplankton, associated with recent changes in sewage treatment.

Sediments rich in algal remains are compared to similar deposits in other countries and the possibility that some fossil fuels originated from algal oozes is discussed.

FIGURES

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CHAPTER ONE

INTRODUCTION

CHAPTER ONE: INTRODUCTION

i) Preservation in Lake Sediments

Organic remains preserved in lake sediments are integral in many palaeolimnological studies. In conjunction with chemical and physical parameters, biological analysis of sediment cores can give a detailed insight into past events in both the lake and its drainage basin. A variety of preserved biological remains have been identified in different types of lake sediment, although only pollen grains and diatom frustules are commonly found and used to investigate changes in the flora. The most complete record is that for the flowering plants, since pollen grains are highly resistant to decomposition and physical damage. However palynology is chiefly concerned with long term changes in the terrestrial flora of the catchment, and not directly with events in the water body itself. The aquatic organisms respond to environmental change rapidly and annual changes are reflected in both species composition and abundance, moreover the dominant group of organisms may alter several times during the course of a single year. Unfortunately the autochthonous flora and fauna of many lakes are poorly represented in the sedimentary sequence, due to their delicate physical make-up and easily degradable chemical composition, and the remaining evidence is often fragmentary and inconclusive.

The degree of preservation amongst the algae is commonly such that only the siliceous remains are found. Of the freshwater animals only a small number are preserved, mainly as the chitin remains of numerous cladocera, the heads of chironomids, sponge spicules and the

shells of molluscs and ostracods. Other organic remains occasionally found in lacustrine sediments include fish vertebrae and scales (Pennington & Frost, 1961), plant tissue, fruits and seeds, and fungal hyphae (c.f. Birks, 1976).

ii) Algal remains in Lake Sediments

Many algae decompose quickly, either before or on reaching the bottom muds, and hence leave no record. It is common only to find the siliceous remains of the diatoms and Chrysophyceae below the superficial sediments. Even this record may not be present if either the silica undergoes dissolution or the frustules are subjected to physical turbulence resulting in the disintegration of delicate species, such as Rhizosolenia. Sufficient solution of silica to destroy the distinctive morphological features is uncommon in freshwater, but depends on factors such as pH and depth of water (c.f. Parker, Conway & Yaguchi, 1977). Chrysophyceae are represented by spines, scales and resting cysts. Identification of the scales depends on the delicate ornamentation (e.g. Takahashi, 1978). Chrysophyte cysts usually cannot be related to a genus or taxa but descriptions, such as by Nygaard (1956) can be used for comparison.

Diatom studies have been extensively used for research into the quaternary sediments (e.g. Pennington, 1943; Round, 1957; and Haworth 1976a) and in the study of seasonal and annual fluctuations. Tippett (1964) examined a varved sediment from Canada and found the abundance and species composition of diatom and Chrysophyceae cysts differed between the paired layers. Simola (1977) studied the microbanding of recent sediments and found seasonal fluctuations in the diatoms, while

Haworth (in prep.) has examined the incorporation of a distinctive diatom population into the sedimentary sequence.

Reports of non-siliceous algal groups found preserved in lake sediments have come mainly from outside the British Isles and notably from the USSR. Korde (e.g. 1960 and 1966) records a great number of algal remains in the highly organic muds and oozes (known as 'sapropels') from a series of Russian lakes. She has found a variety of algal taxa, including representatives of the Chlorophyceae, Cyanophyceae and Dinophyceae (see Table 1a). Some of the sapropels consist almost entirely of a single alga, and Korde is able to classify the sediments according to the dominant algal group, e.g. Phacotus gyttja. In the varved sediments of Lake Zürich, Nipkow (1927) recorded the remains of Phacotus, Ceratium and Dinobryon cysts and Staurastrum. Birks (1976) identified Pediastrum, Botryococcus, Tetraedron, Scenedesmus, Coelastrum, Tetradesmus and Gloeotrichia in samples from Wolf Creek, Minnesota. Species of Staurastrum and Pediastrum have been found in a 200 m-long core from Lake Biwa, Japan (e.g. Kadota, 1976) while the latter is often found on pollen preparations (e.g. Alhonen & Ristlluoma, 1973). Desmids are typically fairly resistant and may be found in some post-glacial deposits (e.g. Messikommer, 1938).

Although the cells often decompose, algal groups may sometimes be identified by analysis of the organic compounds remaining in the deposits (see review by Philp, Maxwell & Eglington, 1976). Chlorophyll degradation products have been correlated with past fertility (e.g. Gorham, 1960; Belcher & Fogg, 1964), but since the specific origin of these products is uncertain the interpretation of the results may be misleading. However Zullig (1961) related myxoxanthophyll to the abundance of blue-green algae, while oscillaxanthin is specific to the

Table 1a Non-siliceous algal remains recorded in lake sediments from the USSR

1. Chlorophyceae

Botryococcus	Phacotus
Coelastrum	Scenedesmus
Cosmarium	Staurastrum
Euastrum	Tetraedron
Pediastrum	

2. Cyanophyceae

Anabaena	Gloeothece
Aphanizomenon	Gloeotrichia
Aphanocapsa	Lyngbya
Aphanothece	Microcystis
Gloeocapsa	Phormidium

3. Dinophyceae

Ceratium	Peridinium

(from Korde, 1966)

genera Oscillatoria (Brown & Colman, 1963) and has been used to study past populations (Griffiths, 1978). Cranwell (1976) studied the breakdown of Ceratium hirundinella O.F. Muller and the subsequently formed organic compounds in the sediments.

iii) The preservation of algal sequence

This thesis examines the preservation of algal remains and their stratigraphy in recent lake sediments in relation to documented fluctuations in the composition and abundance of the phytoplankton in the same lakes.

Although there have been many algal taxa reported to have been preserved in the sediments of Russian lakes, few workers in the British Isles have sought non-siliceous remains. Instead botanists have chosen to digest the muds with chemicals (e.g. concentrated acids and hydrogen flouride) in order to clean and concentrate the material. In this study the examination of fresh sediment has preceded any digestion or separation techniques.

Historical records can be of palaeolimnological value in that they may enable the biostratigraphy of sediment cores to be qualitatively and quantitatively compared with past assemblages in the lake. Detailed algological records exist only for a small number of lakes in Britain and many of these are for sites within the English Lake District. Alterations in algal composition or abundance in the stratigraphy can be dated if sufficiently detailed, documentary evidence is available and the sedimentary record has remained both ordered and discrete. This 'algal chronology' may be compared with other techniques of dating recent sediments (e.g. radionuclides).

iv) Radionuclide dating of recent sediments

The dating of recent deposits in this study employs both caesium-137 and lead-210. Caesium-137 can establish the position of the 1963 horizon (and often that of 1954 as well) while lead-210 can date sediment deposited over the last 100 to 150 years.

Caesium-137 is a man-made radionuclide (half-life 30 years) produced by the detonation of a nuclear device. Significant levels of fallout in the atmosphere were first detected with the advent of nuclear weapons testing in 1954 and reached a peak in 1963 (Cambray et.al., 1971). Cs-137 deposited on a lake surface quickly becomes adsorbed by the suspended material in the water column and is deposited on the lake bottom. The Cs-137 is bound tightly onto the sediment material and there is very little diffusion of the Cs-137 atom (Tamura, 1964). Cs-137 falling onto the soil also becomes adsorbed on small-size particles and organic matter (Davis, 1963; Tamura, 1964) and subsequent movement from the point of deposition is by physical processes such as erosion (Rogowski & Tamura, 1970). The distribution pattern of Cs-137 within lake sediment cores has been shown to be a reliable method of dating (Pennington, Cambray & Fisher, 1973; Ritchie, McHenry & Gill, 1973). Comparison of deposition rates by Cs-137 with surveying techniques has shown the estimates to be within 10% of each other (Ritchie & McHenry, 1977). The method is not applicable if large scale mixing of the sediment occurs.

Lead-210 is a naturally occuring isotope with a half life of 22.26 years. There are two sources of Pb-210 in the sediments, (1) that from the deposition of Pb-210 into the water body which is known as the 'unsupported' fraction and (2) Pb-210 produced as a decay product of the naturally occuring radium-226, this is known as the 'supported'

fraction. The addition of supported and unsupported Pb-210 gives the 'total' lead.

The lead-210 technique has been successfully used in both freshwater (e.g. Pennington et al., 1976) and marine sediments (e.g. Koide, Soutar & Goldberg, 1972).

v) The sites

The sites chosen for this study represent a wide spread of lake and sediment types. There were two criteria used in the selection, firstly that a range of algal species and standing crops was represented and secondly that phytoplankton records existed for some of the sites, particularly if there had been a recent change in the composition or size of the assemblage.

Sites in the English Lake District were chosen primarily because Dr J.W.G. Lund has studied many of the lakes and a wealth of phytoplankton data (published and unpublished) was kindly made available for this study. The Lake District contains lakes of varying trophic status (see Macan, 1970) but contrasting sites were also sought in N.W. Scotland and in the lowland areas of Shropshire-Cheshire and Norfolk.

CHAPTER TWO

SEDIMENT CORES - METHODS

CHAPTER TWO: SEDIMENT CORES - METHODS

i) Introduction

The procedures have been carried out to achieve similar standards of accuracy and precision, both between and within cores. Departures from the methods described in this chapter will be found elsewhere.

ii) Corers

Three different types of corer were used during the study. All can sample the sediment-water interface without disruption, and differ only in the mode of operation and in the amount of material they collect.

The Mackereth one metre "minicorer" (Mackereth, 1969), a derivative of a 6 m model (Mackereth, 1958), is a pneumatically operated corer designed to take a 1 m-long core. Two models were used, one with a core tube of diameter 6.5 cm and the other of 5.5 cm. The clear Perspex tubing enables the operator to inspect the core before extrusion to confirm that the interface has been collected without disturbance.

The Jenkin surface mud sampler is outlined by Mortimer (1942) and fully described by Macan (1970). A core of between 8 and 15 cm (and diameter 7.0 cm) is usually taken with the sampler, depending on the weight of the corer and the type of sediment. The core tubes were modified by a series of 1 mm-wide holes at 1 cm intervals inserted in the lower 20 cm (Collins et al., 1973). These were sealed by water-proof adhesive tape during the operation of the sampler. The shutting of the lids may potentially disrupt the sediments by pushing the core up into the tube. However, disturbance of the flocculant interface is easily seen through the perspex tube and cores that appeared to have been disturbed were discarded.

The FBA Gilson corer (outlined in Macan, 1970) is a portable gravity corer. The core tube is 30 cm long and 5.3 cm in diameter. The length of sediment column sampled depends on the weight loaded onto the instrument. This corer was only used where its portability was an asset, e.g. some remote lochs in Northern Scotland.

iii) Extrusion and storage of cores

Where practicable the cores were extruded by the lake-side, although they were brought back to the laboratory if obtained from the immediate vicinity. Duplicate or spare cores, not extruded, were stored in the dark at $6 \pm 2^{o}C$.

The extraction of cores taken with the minicorer is by hydraulic pressure acting on a rubber piston which pushes the sediment column up the tube. This can be performed in a controlled manner such that samples of accurately known dimensions can be obtained. In most cases the cores were extruded into 1 cm thick slices, the upper 20 or 30 cm in contiguous sections and the remainder at intervals of 5 or 10 cm. The samples were then placed in plastic bags and tightly sealed by a rubber band or waterproof tape.

Before samples were extracted from the Jenkin corer, the tube was first drained of the overlying water by stripping the tape from the holes above the sediment interface. A 1 ml graduated syringe, fitted with a hypodermic needle, was then pushed through the tape and 0.5 ml of sediment extracted. Care was taken to ensure the needle was kept in the same vertical plane whilst an area described by a horizontal arc was sampled. The samples were placed in glass vials with tight-fitting lids.

The Gilson cores were extruded in a similar manner to that of the minicorer, except that the piston was mechanically moved by a

plunger and not by hydraulic pressure. The sections cannot be cut to the same precision as the minicorer. The top 5 or 10 cm were sliced into 1 cm-thick sections and placed in plastic bags which were tightly sealed.

All core samples were stored in the dark at 6 ± 2°C.

iv) Preparation, enumeration and identification

Examination of fresh sediment for algal remains was carried out on diluted material. The core sections stored in plastic bags were first mixed, by hand, and then sampled using a graduated 1 ml syringe without a needle. It was usual to extract 0.5 ml of fresh sediment and dilute with three equal parts of a 1:1 mixture of gycerol:distilled water. Further dilution was often necessary, depending on the concentration of organic and mineral particles. The gycerol ensures that the sub-samples do not dry out whilst they are being counted. The diluted samples were kept in air-tight vials and placed in a refrigerator (6 ± 2°C) until examined. The Jenkin core material was diluted in the same manner.

Slides from the sub-samples were made by taking 10 µl aliquots with an Eppendorf pipette and then carefully placing a 22 mm square cover slip over the drop. Most of the slides enumerated contained 20 µl of the dilution. To ensure an even coverage over the cover slip a drop of distilled water was added, sometimes containing a staining agent. Methylene blue was used to stain up mucilage while Indian ink and iodine were used to facilitate identification of particular species. The slides were counted on a Vickers Photoplan M41 at magnifications of x 100 and x 200, although the taxonomy was often performed at higher powers. In every case the whole slide was scanned.

Chemical digestions of the sediment were carried out to remove organic or mineral fractions, thus concentrating the algae under examination. A known volume of fresh sediment was obtained by sampling with a 1 ml graduated syringe without a needle. Organic matter was digested using a mixture of chromic acid and hydrogen peroxide (Barber, 1962). The digestion was left overnight and then the acid removed by repeated centrifuging, decanting and washing with distilled water. Samples of the cleaned material were re-suspended in distilled water to a known volume. This was sub-sampled with a 10 µl Eppendorf pipette and dried onto a cover slip. Permanent mounts were prepared with "Naphrax" diatom mountant (refractive index 1.74). The complete slide was enumerated at magnifications of x 400 and x 1000 under phase contrast.

Digestions were also carried out using 1N hydrochloric acid or 10% potassium hydroxide. The alkaline treatment destroys the silica component of the sediment whilst the acid digests some of the organic matter, leaving the resistant parts of some algae intact. These methods were used for only a small number of samples.

Taxonomy for the diatoms is based on Hustedt (1930; 1930-1966; and 1950), although reference was made to Cleve-Euler (1951-1955), Schmidt (1873-1959) and Patrick & Reimer (1966; 1975). Cysts of the Chrysophyceae were compared with those illustrated in Nygaard (1956). Blue-green algae were identified according to Komarek in Komarek & Ettl (1958), other works used included Starmach (1966) and Rippka et al. (1979). Belcher & Swale (1976), Bourrelly (1966; 1968; 1970) and West & Fritsch (1927) were also consulted. Extensive use was made of the Fritsch Collection of Algae Illustrations (housed at the Freshwater Biological Association).

v) Chemistry

Percentage water content was estimated by drying approximately 10 g of fresh sediment at 100 ± 5°C until constant weight was achieved. The samples were stored in a desiccator. Carbon, hydrogen and nitrogen were assessed with a Hewlett-Packard F & M Scientific 185 analyzer on duplicate samples.

vi) Radionuclide dating

The radionuclide dating was carried out by the Atomic Energy Research Establishment, Harwell.

Cs-137 dating was performed using the methods of sample preparation and analysis given in Pennington et al. (1973). Samples were dried and analysed by gamma-ray spectrometry (Salmon & Creevy, 1971) using germanium (lithium) detectors. Pb-210 analysis was carried out as described in Pennington et al. (1976). The total Pb-210 was determined by the activity of its alpha emitting daughter, polonium-210, whilst the supported fraction was determined by measurement of its radium-226 parent.

vii) X-radiography

X-radiography was performed at the North Western Forensic Science Laboratory, Chorley. A Scanray DOA 200 X-ray tube was run at 80 kV for 6 mA minutes with a SFD of 107 cm.

CHAPTER THREE

SEDIMENT CORES FROM HIGHLAND BRITAIN

A. ALGAL REMAINS IN THE SURFACE SEDIMENTS

B. DIATOM STRATIGRAPHY FROM GRASMERE AND ELTERWATER

CHAPTER THREE: SEDIMENT CORES FROM HIGHLAND BRITAIN

INTRODUCTION

This chapter is concerned with two aspects of the preservation of algae and the algal record in recent sediments. Firstly non-siliceous algal remains have been sought in highland lakes of differing trophic status and secondly the diatom stratigraphy, in two lakes, has been compared with documented changes in the phytoplankton.

A. ALGAL REMAINS

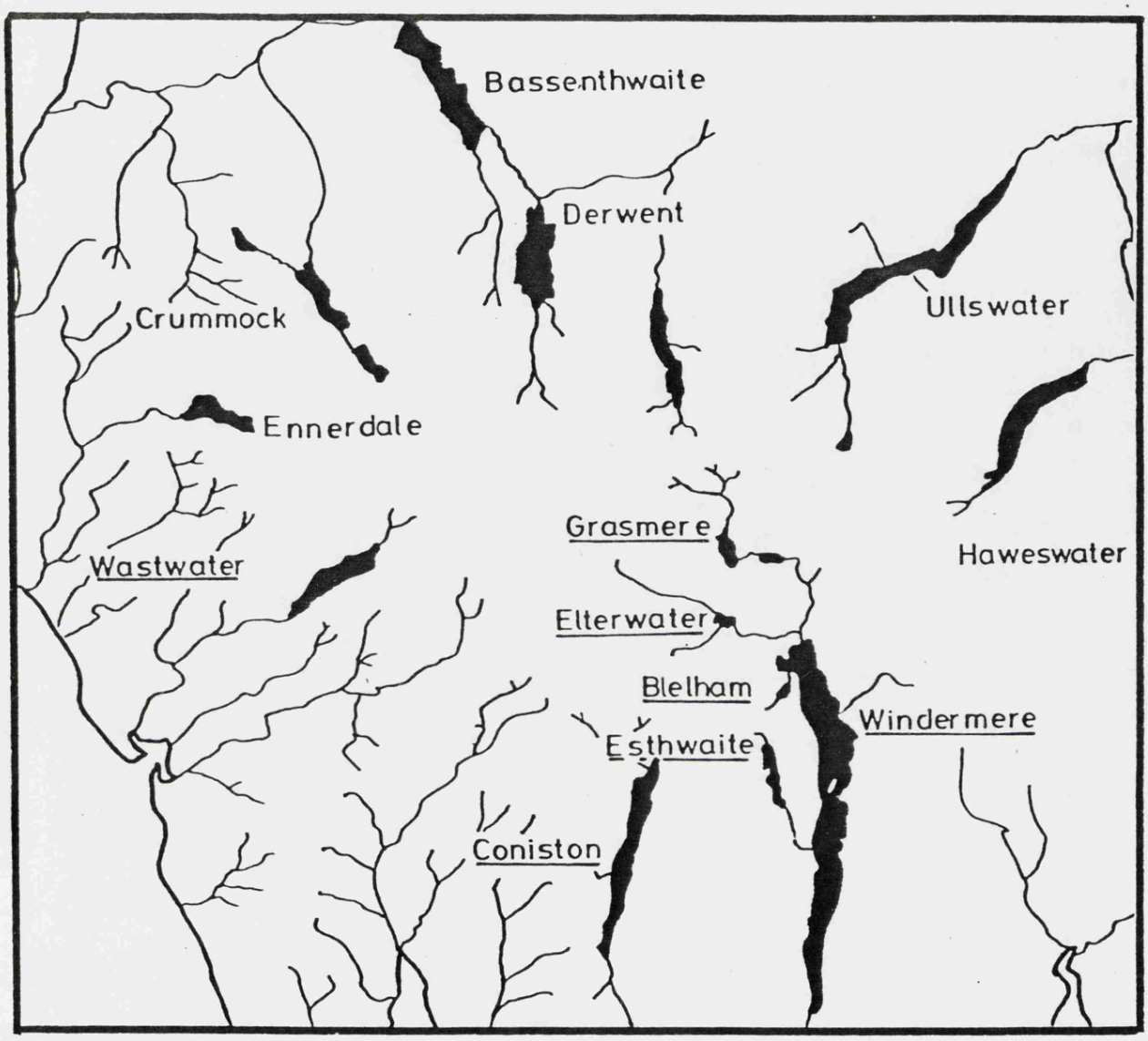
1. INTRODUCTION

The sites investigated illustrate a wide range of lake types within the highland regions of the English Lake District and north-west Scotland (figures 3.1 and 3.2).

The lakes of the English Lake District have been the subject of intensive biological studies (see Macan, 1970) and there is a wealth of algological data covering many years. The phytoplankton composition, and abundance, of the oligotrophic lakes, such as Wastwater, provides a contrast to the productive water bodies such as Esthwaite Water and Blelham Tarn. The Scottish lochs investigated vary from a marl lake to an acid brown-water site; they are a contrast to many of the richer Cumbrian sites in that they receive little sewage effluent.

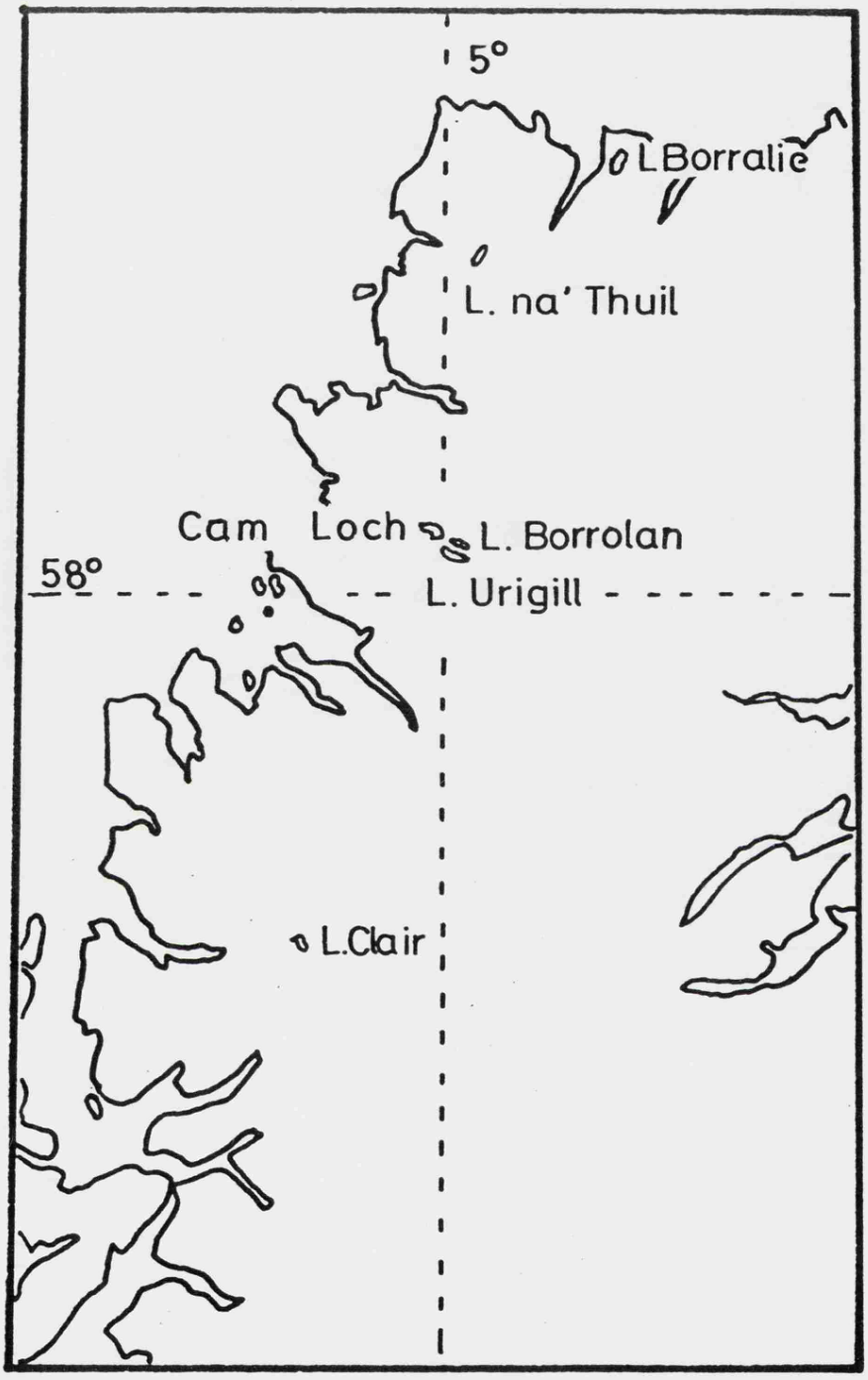
The physical characteristics of the sites are given in table 3a. The cores were usually taken from the deepest area of each lake and the surface sediments were examined for algal remains. All the deposits contained diatom frustules; only the non-siliceous remains are considered in this section.

figure 3.1



English lake district
site map

figure 3.2



site map – northern Scotland.

Table 3a Physical Characteristics

lake (national grid ref.)	area (km^2)	max depth (m)	alt. (m)	catch. area (km^2)	pop.
Esthwaite (SD360965)	1.0	15.5	65	17.1	1239
Blelham (NY365005)	0.1	15.1	45	2.9	1000
Grasmere (NY340063)	0.6	21.5	62	27.9	1550
Elterwater (NY335042)	0.1	7.0	57	-	-
Windermere S (SD383915)	6.7	42.0	39	-	1197
Coniston (SD300940)	4.9	56.0	50	60.7	290
Wastwater (NY165060)	2.9	78.6	61	48.5	17
Clair (NH002570)	0.5	28.3	92	-	5
Urigill (NC245100)	2.2	12.2	167	-	0
Borrolan (NC265105)	0.5	7.0	152	-	100
Cam (NC210135)	2.6	37.2	137	-	50
na'Thuill (NC244503)	0.3	19.0	40	-	0
Borrallie (NC382670)	0.3	13.0	15	-	0

lake area, maximum depth, altitude above sea level, area of catchment, population of catchment per km^2 of lake area.

SOURCES: Pennington (1978), Macan (1970), Gorham et al. (1974).

2. PHYTOPLANKTON

The phytoplankton descriptions for the English Lake District are based on the published and unpublished data of Dr J.W.G. Lund F.R.S. The algae described are those which have become common during the last few years.

The Scottish lochs have been less intensively studied and the sites chosen have no past plankton records. Collections were made on field excursions with a net or, less frequently, a 5 m tube (Lund & Talling, 1957).

i. English Lake District

The phytoplankton of the Cumbrian lakes can be characterised both by the frequency, or abundance, of particular algae and by the absence or rarity of others. Many of the species which are commonly thought of as 'typical' of oligotrophic waters can be found in eutrophic lakes. For example Esthwaite Water, a productive lake, has had abundant populations of desmids and Dinobryon in recent years. However the converse is not true in that oligotrophic lakes do not have large crops of dinoflagellates or blue-green algae.

Gorham et al. (1974) considered the algae of many Cumbrian waters, and demonstrated that the more productive lakes have both more blue-green and large algae and also more μ-algae which dominate oligotrophic waters (table 3b).

The phytoplankton composition of Esthwaite, Blelham, Grasmere, Windermere and Coniston shows many similarities and they differ only in the abundance of particular species. In general terms, Coniston may be considered as a 'dilute' Windermere which in turn is less rich than, say, Blelham. Ceratium hirundinella O.F. Müller is typical of these

Table 3b Average standing crops of algae in the English Lakes

(from Gorham, Lund, Sanger & Dean, 1974)

Lake	μ-algae cells ml^{-1}	"large"algae cells ml^{-1}	blue-green algae indiv. ml^{-1}	Approx. dry weight
Wastwater	650	3	0	23
Elterwater	-	144	5	490
Coniston	2650	238	0	790
Grasmere	-	280	1	910
Windermere (SB)	4746	799	24	2800
Blelham	4766	1110	8	3600
Esthwaite	2116	1849	114	6800

Data are means of samples taken 1949-1951, 1955-1956 and 1961-1963, by J.W.G. Lund.

"Large algae" - retained by 65 μ net but also includes the larger nannoplankters because they were large enough to be estimated at low magnification.

"u-algae" - usually taken to be the taxa not retained by a townet (see Hutchinson, 1967).

note: the phytoplankton composition and abundance of Grasmere has altered since 1963 (see Lund, 1979).

lakes; Esthwaite commonly has very large populations during the summer whereas Windermere has fewer individuals, although it may be still the dominant alga in the summer. Blue-green algae are more frequent in the richer lakes, typical examples being Microcystis aeruginosa (Kützing) emend. Elenkin, Anabaena flos-aquae (Lynbye) Brébisson, Aphanizomenon flos-aquae Ralfs. ex Born. et Flah. and species of Oscillatoria (particularly O. redekei Van Goor, O. bourrellyi Lund, and O. agardhii Gomont var isothix Skuja). The characteristic diatoms are Asterionella formosa Hassall, Tabellaria flocculosa var asterionelloides (Grun. in van Heurck) Knudson, Melosira italica (Ehr.) Kützing var. Subarctica Müller, Fragilaria crotonensis Kitton, Cyclotella pseudostelligera Hustedt and Stephanodiscus spp. Colonial green algae occur in all the lakes whereas Cryptomonads and Chrysochromulina parva Lackey are more frequent in the richer lakes. Species of Trachelmonas are common in Blelham Tarn and Esthwaite Water where it flourishes on the boundary between aerobic and anaerobic water provided that there is sufficient light (Lund - personal communication).

Wastwater is characterised by general poverty. Small algae make up the bulk of the sparse phytoplankton including small species of Peridinium sp, Koliella sp. Sphaerocystis sp, Rhizosolenia sp. and Kephyrion/Pseudokephyrion Pascher which are infrequent in the richer lakes. Desmids and the diatom Cyclotella comensis Grunow are also common in Wastwater.

Elterwater's phytoplankton is characterised by the abundance of small coccoid green algae, and sometimes by vast populations of Volvox globator L., Cryptomonas, Rhodomonas, Cyclotella pseudostelligera, Ankyra sp., Asterionella formosa and Synedra spp. and the absence, or rarity, of Ceratium, Melosira, Fragilaria crotonensis and blue-green algae.

ii. North-west Scotland

Loch Borralie is a calcareous lake with exceptionally clear waters (Spence, 1975). The sparse plankton (June 1978) consisted of Ceratium hirundinella with species of Ankistrodesmus, Oscillatoria and various desmids. Brook (1964) described the plankton of such calcareous lakes as: "...although typically eutrophic in its specific composition is quantitatively poor...".

Loch na'Thuill is a brown water lake draining the surrounding blanket bog (Spence, 1975). The poor phytoplankton is dominated by Chrysophyceae, especially species of Mallomonas. A net collection also contained Dinobryon and Ceratium hirundinella plus occasional colonies of Asterionella formosa and Anabaena flos-aquae.

Lochs Borrolan, Cam and Urigill are situated at the southern end of the outcrop of Durness limestone. The catchments are dominated by blanket bog although grassland and birchwoods occur on the limestone outcrops. Cam Loch has a more extensive mountainous catchment. The phytoplankton contains species not only common in acid lochs but also those more typical of more alkaline or nutrient rich conditions. The phytoplankton collections were dominated by Asterionella formosa while Anabaena flos-aquae was abundant in June when it was clearly visible in the water column and formed surface scums in slack water. Species of Dinobryon, Staurastrum and Ceratium hirundinella were also common.

Loch Clair supports a sparse phytoplankton. An August sample was dominated by diatoms, especially species of Fragilaria, with occasional individuals of Dinobryon sp., Ceratium hirundinella and species of Chlorophyceae (particularly desmids).

3. ALGAL REMAINS

A summary of the non-siliceous algal remains recorded in the recent sediments of the thirteen lakes examined (table 3c) shows that few algal genera were observed, and these mainly in the more productive lakes.

Individuals of Staurastrum were commonly recorded (10 lakes), especially near the surface (figure 3.3). This alga has also been frequently found by other workers (see Chapter 1) and is apparently fairly resistant to decomposition. Cosmarium also contains resistant species of desmid, common in peat cores, and a few individuals were found in Elterwater.

Ceratium hirundinella is a frequent member of the phytoplankton in the highland lakes. Cells of the alga were very rarely recorded; many apical horns were present in the surface floc of Esthwaite Water around October but these quickly disintegrated. The cysts, however, were found in the sediments, those in the topmost layers contained intracellular matter, but those at depth typically were empty except for an orange-brown residue (see Chapter 5 plate III), shown by stippling on figure 3.3. The empty cysts were assumed to have germinated, but recent work (D. Chapman - personal communication) has suggested that they may be the result of decay or parasitism (see Chapter 7). The cysts were only found in the productive lakes of Esthwaite, Blelham and Windermere although the alga was also recorded in the plankton of Lochs Urigill, Borrolan and Cam, plus Coniston.

Remains of blue-green algae were recovered from the sediments of the productive lakes, where they are common in the plankton. Colonies of Microcystis were recorded near the mud surface of Esthwaite and Blelham. The colonies appeared healthy and were assumed to be

Table 3c Summary of non-siliceous algal remains in lake sediments from highland Britain

Lake	Depth	Ceratium	Microcystis	Staurastrum	Anabaena	Trachelomonas	Scenedesmus	Pediastrum	Oscillatoria	Cosmarium	Volvox
Esthwaite	0–2 cm	●	●	●	●	●	●		●		
	3–12cm	●	●	●	●	●					
Blelham	0–2 cm	●	●	●		●		●			
	3–5 cm	●	●	●	●	●	●				
Windermere (S basin)	0–2 cm	●		●							
	3–5 cm	●									
Grasmere	0–2 cm			●							
	3–5 cm			●	●						
Elterwater (inner)	0–2 cm			●	●		●	●	●	●	●
	3–5 cm						●				
Coniston	0–3 cm										
Wastwater	0–3 cm										
Urigill	0–3 cm				●						
Cam	0–3 cm				●						
Borrolan	0–3 cm										
Borrallie	0–3 cm			●							
Clair	0–3 cm										
na'Thuill	0–3 cm										

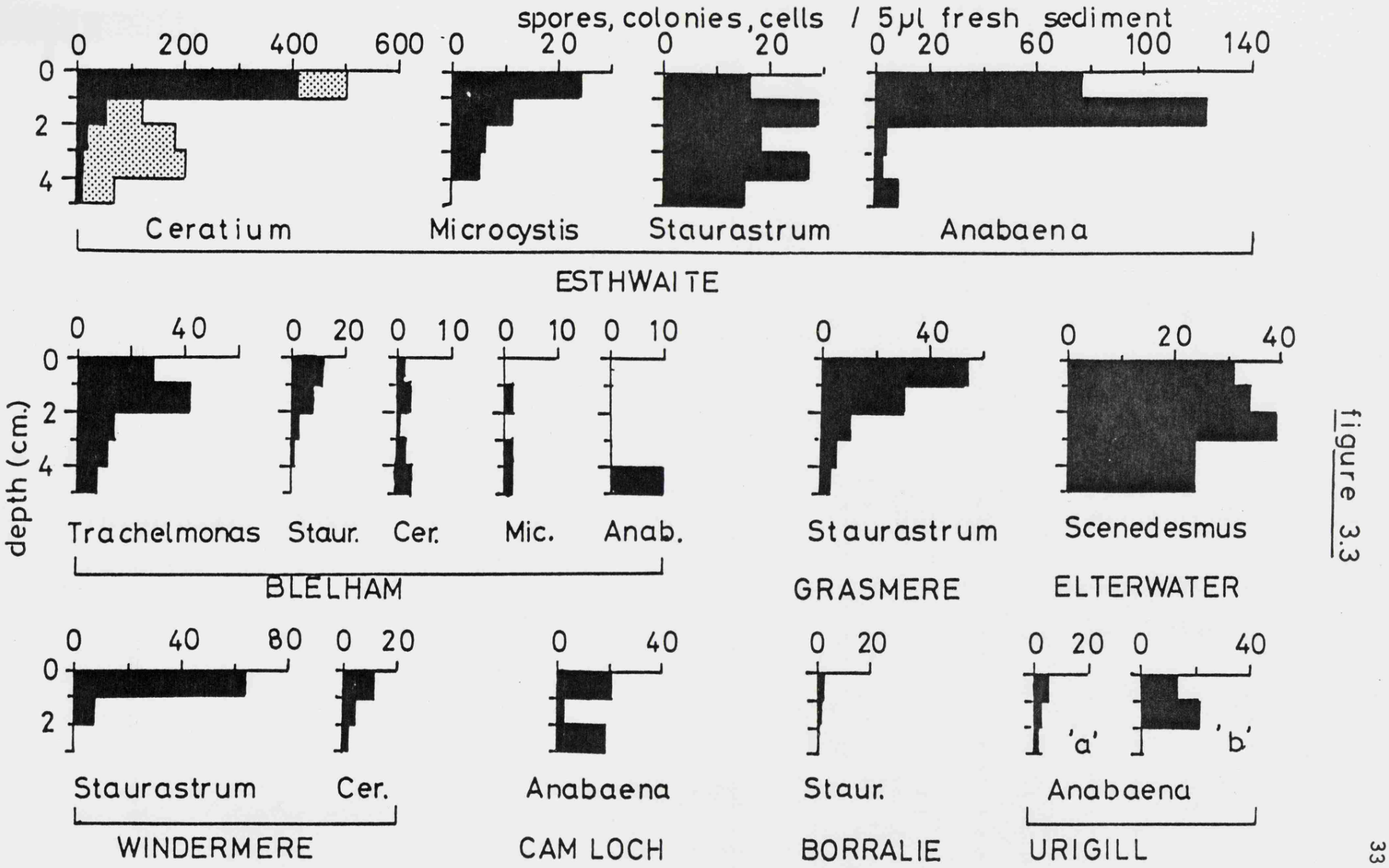

spores, colonies, cells / 5µl fresh sediment
0 200 400 600
0 20
0 20
0 20 60 100 140
0
2
4
Ceratium
Microcystis
Staurastrum
Anabaena
ESTHWAITE
depth (cm.)
0 40
0 20
0 10
0 10
0 10
Trachelmonas
Staur.
Cer.
Mic.
Anab.
BLELHAM
0 40
Staurastrum
GRASMERE
0 20 40
Scenedesmus
ELTERWATER
0 40 80
0 20
Staurastrum
Cer.
WINDERMERE
0 40
Anabaena
CAM LOCH
0 20
Staur.
BORRALIE
0 20
0 40
'a'
'b'
Anabaena
URIGILL

figure 3.3

part of the overwintering population (see Reynolds & Rogers, 1976). A few colonies were found at depth but these were paler and more diffuse. A small number of healthy filaments of Oscillatoria were also recorded, but only on the sediment surface. The akinetes of Anabaena were found in most of the productive lakes. The akinetes were assumed to be those of Anabaena flos-aquae since the alga is common in the plankton and the akinetes were commonly found in aggregates of about 10 to 20 individuals, although clumps of upto 50-70 were recorded. The aggregation of akinetes is common in those species of Anabaena which tend to form large tight colonies (e.g. A. flos-aquae and A. circinalis Rabenhorst ex Bornet et Flahault) rather than those which remain as single trichomes (e.g. A. spiroides Klebahn and A. solitaria Klebahn).

Trachelomonas spp. were recorded in the sediments of Esthwaite and, in particular, Blelham. Dr A.P. Bonny (personal communication) observed that pollen preparations of seston material from Blelham contained large numbers of Trachelomonas However treatment by 10% potassium hydroxide and glacial acetic acid failed to concentrate the alga from the surface sediments. It is possible that only live material is suitable for this treatment and that resistance is lost on death.

Pediastrum is another resistant alga commonly recorded on pollen slides. A few individuals were recorded from the sediments of Blelham and Elterwater. These two lakes, plus Esthwaite, also contained the occasional Scenedesmus colony in the topmost oozes. Volvox globator has, recently, been frequent in Elterwater (inner basin) and a single spore was identified in the sediments.

4. DISCUSSION

It is only the sediments of the more productive lakes that contain any quantity of non-siliceous algal remains. Most of the remains were recorded in the upper horizons of the cores and there are few instances of preservation at depth.

The phytoplankton of the sites in the English Lake District has not been constant, the composition and abundance have often reflected changes in nutrient input (e.g. Blelham Tarn - Lund, 1978). However the algal remains bear little relationship, qualitatively or quantitatively, to the phytoplankton recorded in recent years. For example, Ceratium hirundinella has been very abundant in Esthwaite during the past decade or so (Lund, 1979), but the cyst concentration in the sediments declines rapidly from the surface. The topmost 10 cm of the core represents circa 11 years (table 3d - Pennington, 1978) and so the lack of remains below 3 cm is interpreted as indicating the rapid decomposition of the cyst. Similarly the blue-green alga Microcystis aeruginosa reached a maximum in Blelham Tarn in 1973 but this was not found in the core.

The upper 2 cm, or so, of the sediments consists of recently deposited material. Algae found in these layers cannot be considered to be preserved if the remains have not been in the muds long enough for significant decomposition to have taken place. The loss of microscopic remains does not necessarily result in the loss of the algal record. For example no filaments of Oscillatoria agardhii var isothrix were recorded below the surface sediments in Esthwaite Water and past crops (see Lund, 1971) are assumed to have disintegrated. However the algal record can still be traced from the specific carotenoid, oscillaxanthin which is preserved in the sediments (Griffiths, 1978).

Table 3d Deposition rates, carbon content of the sediments and minimum oxygen saturation in the water

Lake	rate of sediment accumulation since 1963 mm yr^{-1}	mg C cm^{-2} yr^{-1}	min. oxygen saturation %
Esthwaite	0.9	19.9	0
Blelham	0.7	11.4	0
Grasmere	0.5	5.8	0
Elterwater (inner)	0.4	6.6	0
Windermere (south)	0.4	7.1	22
Coniston	-	-	-
Wastwater	0.2	2.7	90
Clair	0.1	3.3	55
Urigill	-	-	-
Borrolan	-	-	-
Cam	-	-	-
Borrallie	-	-	-
na'Thuill	-	-	-

source: Pennington (1978)

Algae which were observed in the surface sediments are:

i) algae which are highly resistant and have been used as indicators of past environments by other workers. e.g. Pediastrum and Staurastrum (see Chapter 1).

ii) algae which live or overwinter on, or near, the sediment surface. e.g. Oscillatoria, Microcystis and Trachlemonas.

or iii) the resting spores of specific algae. e.g. Ceratium and Anabaena.

The only exception to the above is Scenedesmus which was recorded in small numbers in the surface sediments of the productive lakes and in particular was common in Elterwater. However Scenedesmus can survive for a number of years in an anaerobic environment (Lund, personal communication). A few degraded, unidentified, Chlorophyceae were also recorded.

Pennington (1978) hypothesised that high productivity and seasonal hypolimnetic anoxia may lead to the survival of autochthonous organic matter into the permanent sediment. The breakdown (or 'mineralization') of organic matter in both the bottom deposits and the hypolimnion can lead to the deoxygenation of hypolimnetic waters. However this is not only a function of productivity but also of morphometry. Thus a lake with a small hypolimnion and low productivity can deoxygenate (e.g. Grasmere,prior to 1970, - Pearsall & Pennington, 1973) or a productive lake with a large hypolimnion can remain oxygenated (e.g. Windermere - Lund, 1979). In shallow lakes the establishment of a thermocline and concomitant hypolimnetic deoxygenation is often transient since wind mixing ensures oxygenation of the whole water body. Of the sites investigated, those which contain some algal remains (e.g. Esthwaite and Blelham) are also the lakes with the higher deposition rates, more organic sediments and seasonally deoxygenated hypolimnetic

waters (table 3d). However, although more non-siliceous algal remains are found in the superficial sediments of the productive lakes the bulk of the algae are apparently rapidly decomposed.

It is also possible that the algae commonly found in richer waters are more resistant to decomposition than those present in oligotrophic lakes. The phytoplankton of Wastwater is dominated by Chlorophyceae species which apparently are not preserved in the sediments of either oligotrophic or eutrophic waters (e.g. Elterwater). The probability of finding algal remains in the deposits of unproductive lakes is reduced due to their smaller standing crops. Consequently if an alga is not recorded in the sediments it cannot be assumed that it was absent from the phytoplankton. For example Wastwater contains the desmid Staurastrum which is frequently preserved, but not a single individual was recorded in the sediments. However the equally plankton-poor Loch Borrallie contained a number of Staurastrum cells in the topmost sediments.

In conclusion, from the sites studied there seems little evidence that the recent sediments of highland lakes preserve non-siliceous algal remains, and past assemblages are not recorded in the sedimentary record. A small number of remains were, however, observed in the surface deposits of the more productive lakes. The decomposition of, identifiable, algal remains appears to take about 2-4 years for some of the more resistant species while the remainder decay more rapidly. There is also the possibility that the rate of decomposition is lower in the more productive lakes because of the reduced oxygen in the sediments. Further discussion on decomposition may be found in Chapter 8.

B. GRASMERE AND ELTERWATER

The construction of sewage treatment plants for the villages of Grasmere and Elterwater in the early nineteen seventies resulted in an alteration in the quality of effluent reaching the lakes. Increased concentrations of nutrients, particularly phosphorus (see Hall et al, 1978), resulted in not only an alteration in the phytoplankton composition but also in its abundance(Lund, 1979). These changes have resulted in potential stratigraphic markers being incorporated into the sediments. This section studies the changes in the diatom assemblages from the recent sediments of Grasmere and Elterwater and compares them with the phytoplankton data.

1. GRASMERE

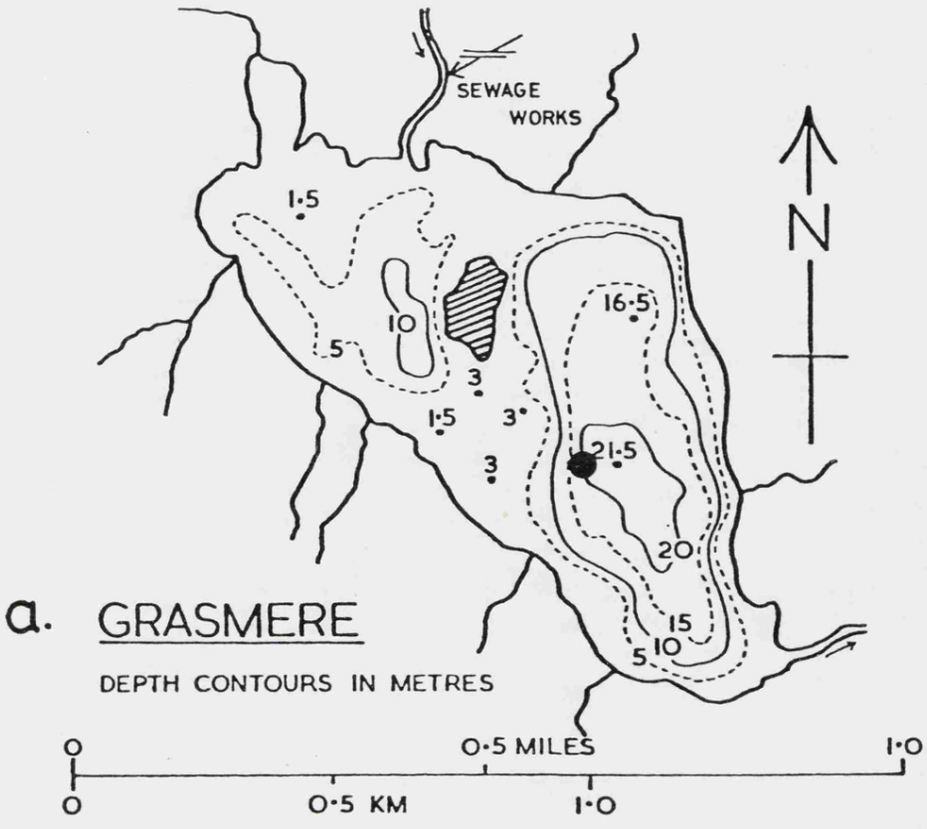
a. Site description

Grasmere is a small lake with a mountainous catchment. The lake has two basins, a large deep one and a small, shallower one (figure 3.4a). The lake has one main inflow, the River Rothay, which also drains the lake into Windermere, via Rydal Water.

Sewage effluent, from an activated sludge treatment plant, was first discharged into the main inflow in June 1971. Prior to this the lake may have been receiving a significant amount of enrichment from surface run-off and seepage from the cesspools and septic tanks around its shores (F.B.A. annual report, 1970) while some establishments discharged directly into the river (Elliott, 1977).

Before the construction of the sewage works the waters were taken to be of intermediate nutrient status (Smyly, 1968; Gorham et al.,

figure 3.4

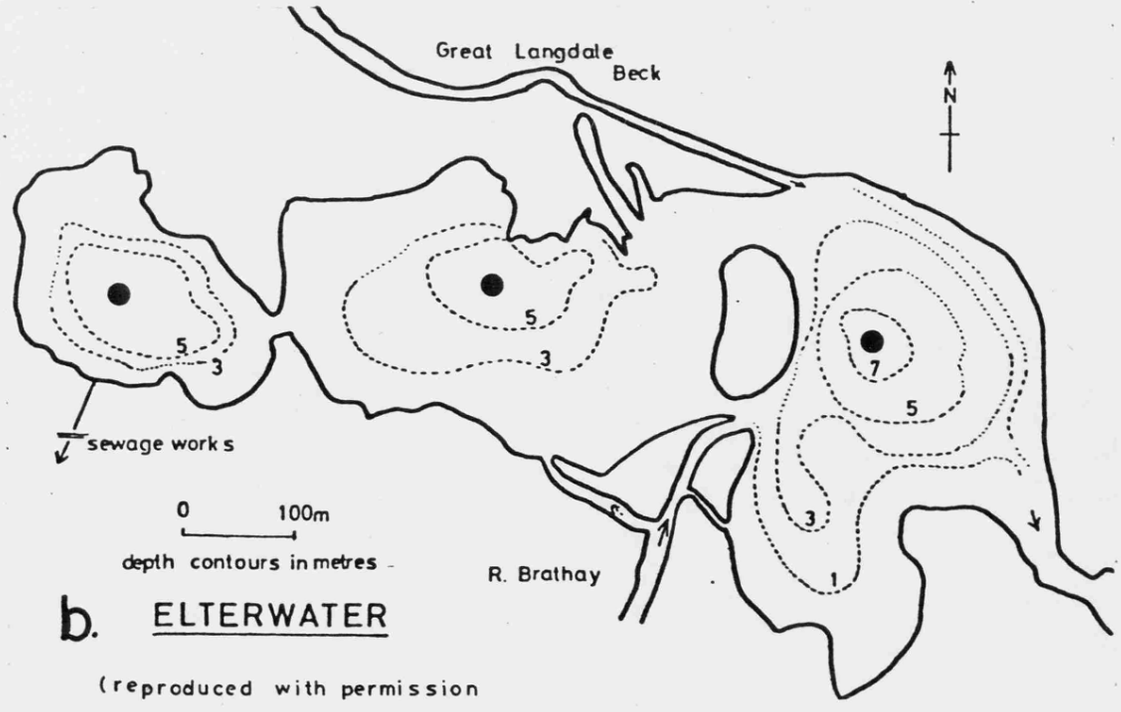


a. GRASMERE

DEPTH CONTOURS IN METRES

(from Ramsbottom 1976)

● - Coring site



b. ELTERWATER

(reproduced with permission of M. Mortimer)

1974) and the phytoplankton indicative of oligotrophic waters (Lund, 1979). The change to mains drainage and sewage treatment works has resulted in an increase in phosphorus concentration and an increase in the rate and extent of deoxygenation in the hypolimnion (Jones, 1972; Hall et al., 1978). The composition of both the phytoplankton and zooplankton populations have also altered (Lund, 1979; Elliott, 1977; Smyly, 1978).

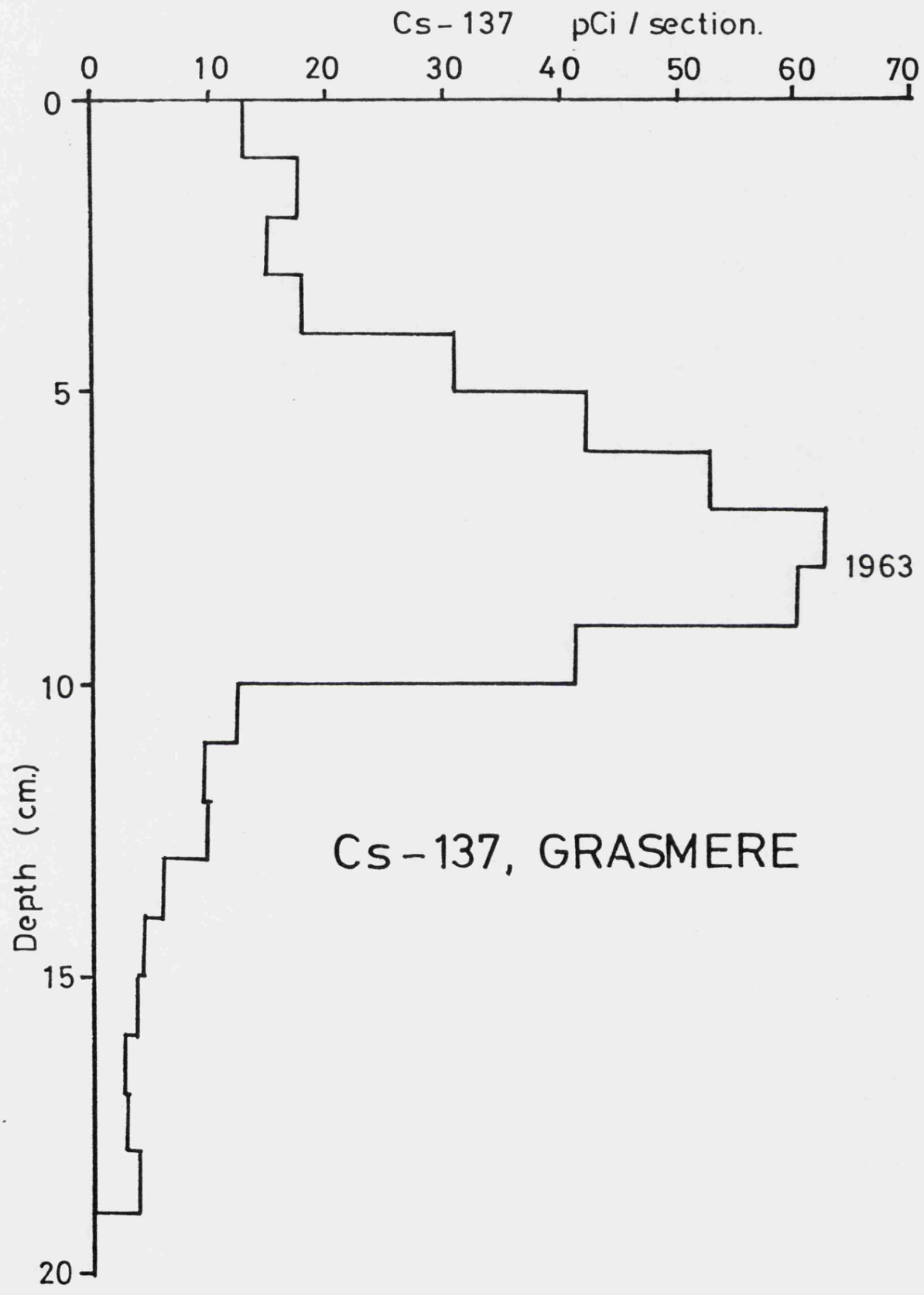
b. The Sediment

The core taken for this study was obtained in December 1977 from the deepest area of the lake, circa 20 m (figure 3.4a). The stratigraphy was marked by a transition, around 30 cm, from an upper dark brown/black watery ooze to a more compact lighter brown mud.

Round (1957) found the littoral sediments of Grasmere to be the most organic (38% by loss-on-ignition) in a series of Lake District sites. Organic chemical analyses are reported by Brooks et al. (1976) and Philp et al. (1976).

The core used in this study was the third core from Grasmere to be dated, and was consistant with its predecessors (Pennington, unpublished data). Caesium-137 dating was undertaken on the same core as the algal analyses (figure 3.5) and the results are expressed as concentrations per section, to be compatible with the fresh sediment counts. The profile is similar to that found in other Cumbrian lakes for Cs-137 deposition from atmospheric fallout (Pennington, Cambray & Fisher, 1973) and the distribution pattern shows a pronounced maximum between 7-9 cm, which is assumed to be the 1963 fallout peak. Mixing, either biological or physical, may be assumed to be insufficient to destroy stratification. The mean annual accumulation rate (1963-1977) is 0.5 - 0.9 cm yr^{-1}.

figure 3.5


Cs - 137 pCi / section.
0
10
20
30
40
50
60
70
0
5
10
15
20
Depth (cm.)
1963
Cs - 137, GRASMERE

c. Phytoplankton

The earliest collections, examined by West & West (1909), were net tows which were dominated by the Chrysophyceae, particularly Dinobryon cylindricum Imhof var. divergens (Imhof) Lemm. and Peridinium willei Huitfeldt-Kass, and the diatoms Asterionella formosa Hassall and Tabellaria fenestrata (Lyngbye) Kützing var asterionelloides Grunow in van Heurck. Also common were various blue-green algae and the dino-flagellate Ceratium hirundinella O.F. Müller.

Lund (1979) has studied the phytoplankton since 1949 and has recorded a change, in both abundance and composition of the phytoplankton associated with the introduction of treated sewage from the new plant in 1971. Collections made from 1949 to 1971 were dominated by species of Dinobryon and Uroglena americana Calkins (synonymous with Uroglenopsis americana Lemmermann) while nano-algae were numerous, especially the Chrysophyceae and Chlorophyceae, plus Cryptomonas and Rhodomonas. Small numbers of the centric diatoms Cyclotella comta (Ehrenburg) Kützing and Cyclotella comensis Grunow were recorded before 1971 (the latter also occured in 1972 and 1974).

Since 1971 blue-greens, diatoms and certain small algae have become more abundant, and some species noted for the first time (e.g. Cyclotella pseudostelligera Hustedt and Tabellaria flocculosa (Roth) Kützing var. asterionelloides (Grunow in van Heurck) Knudson. Most noticeable has been an increase in the populations of Asterionella formosa, from a yearly average, prior to 1969, of 6 cells ml^{-1} to one of 1053 cells ml^{-1} after 1971. A large population developed in 1969 (yearly mean 224 cells ml^{-1}) but Lund (1979) attributes this to the effect of the construction work on the mains sewerage, the soil and

dirty water adding nutrients to the water. Other species to become abundant after 1971 were Fragilaria crotonensis Kitton and Oscillatoria spp.

d. The siliceous remains

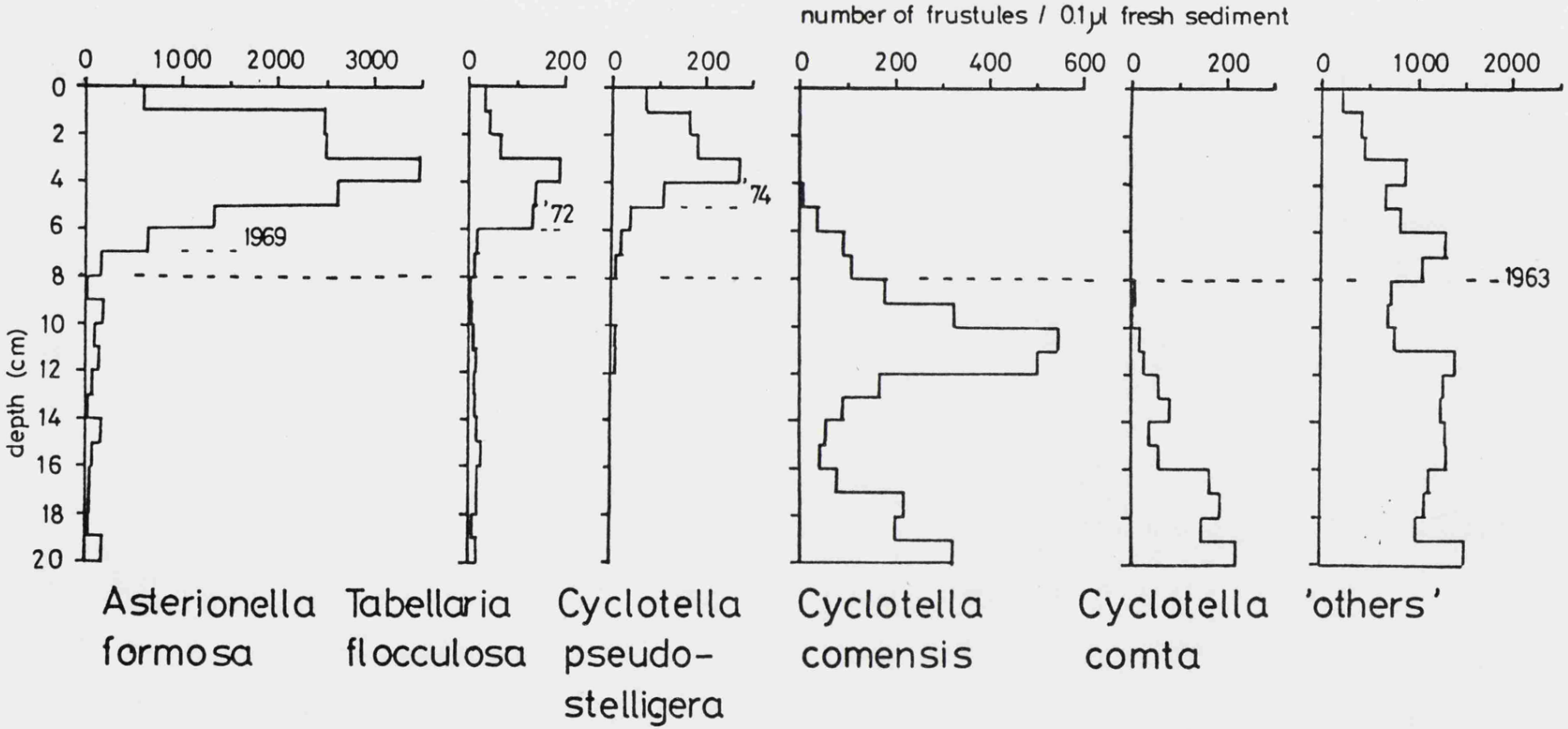
On the permanent mounts, diatoms and Chrysophyeae cysts were abundant. The planktonic diatoms were identified to species, whilst the attached and benthic taxa were counted as a single entity. It was not possible to identify the Chrysophyceae cysts to species, or even genus, but they were, subjectively, placed into three groups

CYST A - smooth walled, diameter typically ~ 15 μm with a short (< 2 um) collar

CYST B - smooth, typically circa 7 μm with short neck

CYST C - highly variable in both shape and size, although often large (> 15 μm), ornamented (often with large spines) and long necked.

The diatom assemblage of the topmost 10 cm reflects many features of the plankton records associated with the change in sewage treatment (figure 3.6). Increases in Asterionella formosa, Tabellaria flocculosa var. asterionelloides and Cyclotella pseudostelligera have occurred since 1969, enabling the topmost sediments to be dated by comparison with the phytoplankton records of J.W.G. Lund (1979 and unpublished). Thus Cyclotella pseudostelligera was recorded as abundant in 1974 (1074 cells ml^{-1}), although occurring in small numbers in 1973 and 1972, and this may be reflected in the 4-5 cm section of the core (figure 3.6). Similarly the rise of Tabellaria flocculosa var. asterionelloides in 1972 can be located above 6 cm in the core. The rise of Asterionella formosa begins circa 7 cm below the mud surface in the core (figure 3.7a). This



GRASMERE

figure 3.6

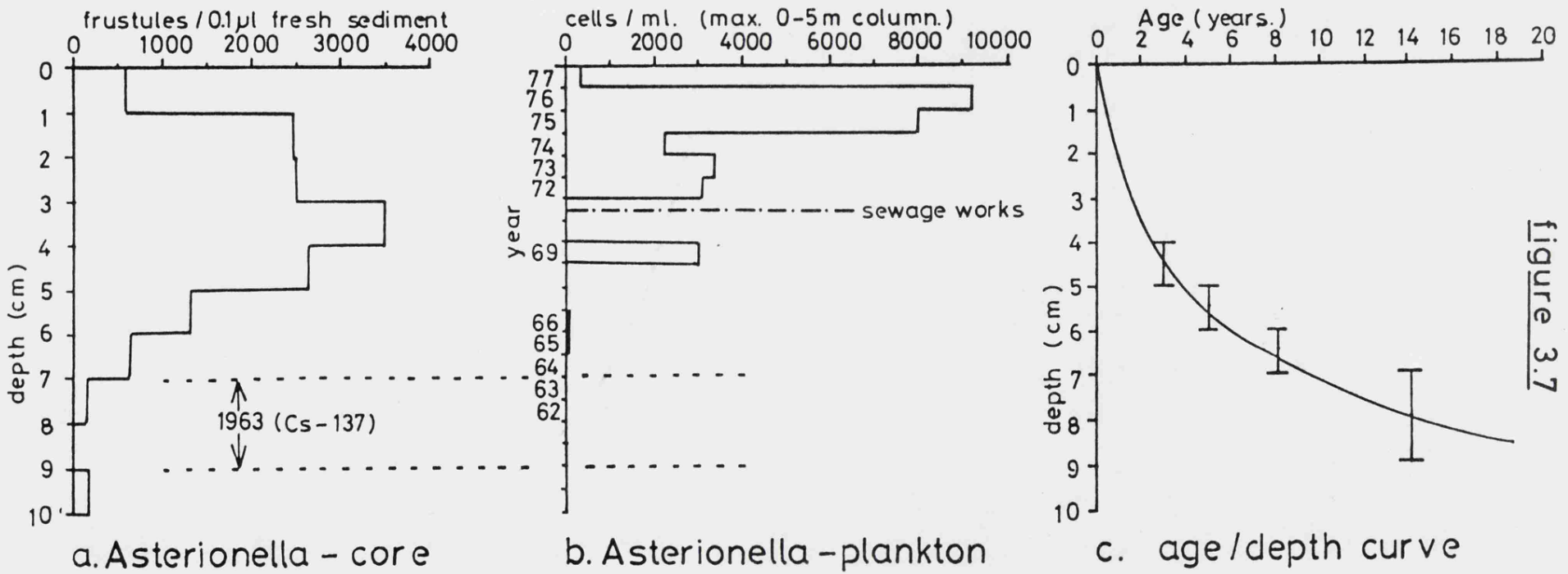


figure 3.7

GRASMERE

may be taken to represent 1969 when large populations of the alga became common in the lake (figure 3.7b).

If this 'algal chronology' is combined with the Cs-137 derived date the rate of sediment accumulation can be estimated since 1963 (figure 3.7c). The plot indicates that there has been an increased rate of deposition from the beginning of the 1970's. The mean annual increment between 1963 and 1969 is about 1.7 mm yr^{-1}, 1969-1972 3.3 mm yr^{-1}, 1972-1974 5.0 mm yr^{-1} and 1974-1977 16 mm yr^{-1}.

The diatom assemblage before the nineteen sixties is dominated by two Cyclotella species, C. comensis and C. comta (figure 3.8). Small numbers of Cyclotella kutzingiana Thwaites were common below 25 cm. It was difficult to differentiate this species from C. comensis due to morphological variation in both taxa which gave no clear demarcation between the two. Hence the totals have been summed, although valves recorded as C. kutzingiana are shown by stippling. The black/brown colour discontinuity is not associated with any change in the diatom assemblage (figure 3.8).

The profiles of the Chrysophyceae cysts (figures 3.9) reflect the decrease of the dominant Dinobryon and Uroglena species in Grasmere before 1971. The common taxa were D. divergens Imhof, D. bavaricum Imhof (synonymous with D. stipitatum Stein), D. sertularia Ehrenburg and Uroglena americana. Lund (unpub. data) also recorded, less frequently, D. suecicum Lemm. and D. crenulatum West & West. Details of these cysts were extracted from the Fritsch collection of Algal Illustrations (housed at the Freshwater Biological Association) but unfortunately it was not possible to relate the cysts found in the sediments to species recorded in the plankton. The size ranges quoted in the literature are very similar for the species concerned e.g.

Figure 3.8

Siliceous remains 0 - 50 cm, Grasmere

a) *Asterionella formosa*

b) *Tabellaria flocculosa* var. *asterionelloides*

c) *Cyclotella pseudostelligera*

d) *Cyclotella comensis* (*C. kutzginiana* shaded)

e) *Cyclotella comta*

f) other diatoms (predominantly non-planktonic)

g) total diatoms (dominant plankters shaded)

h) total Chrysophyceae cysts

i) stratigraphy

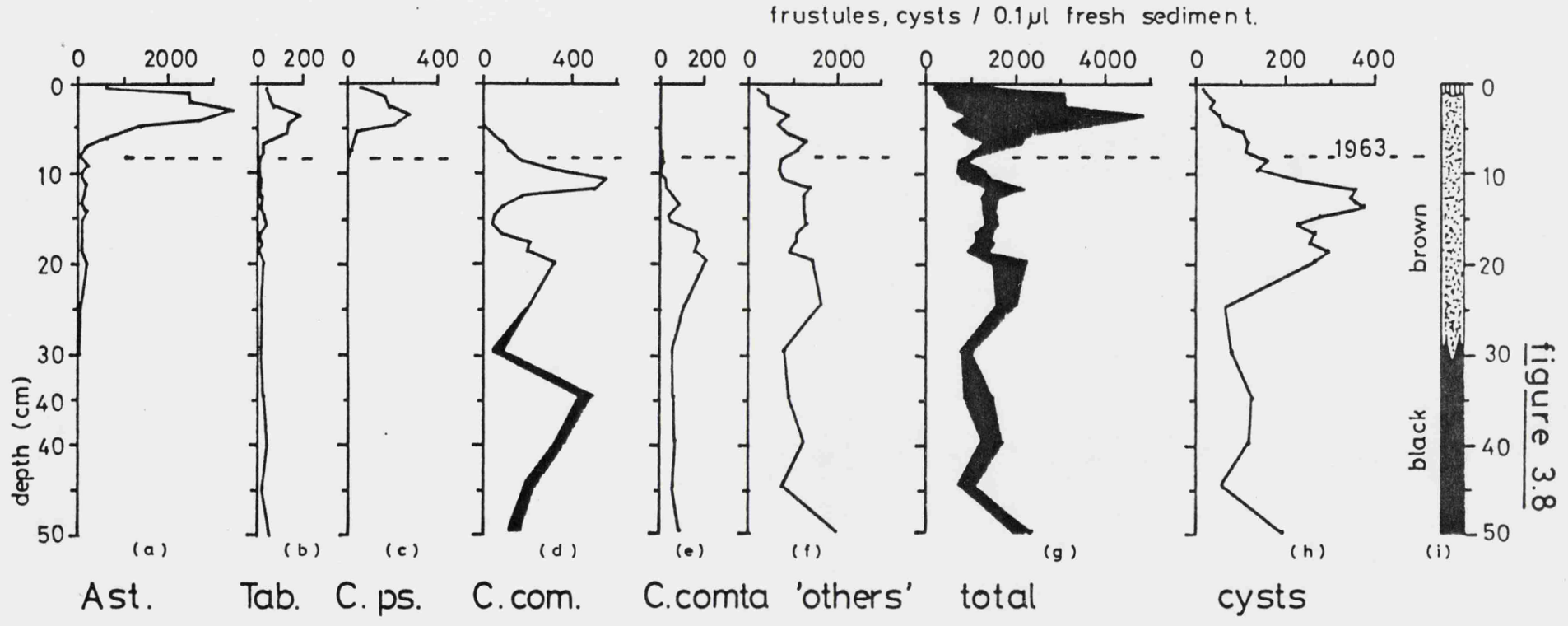
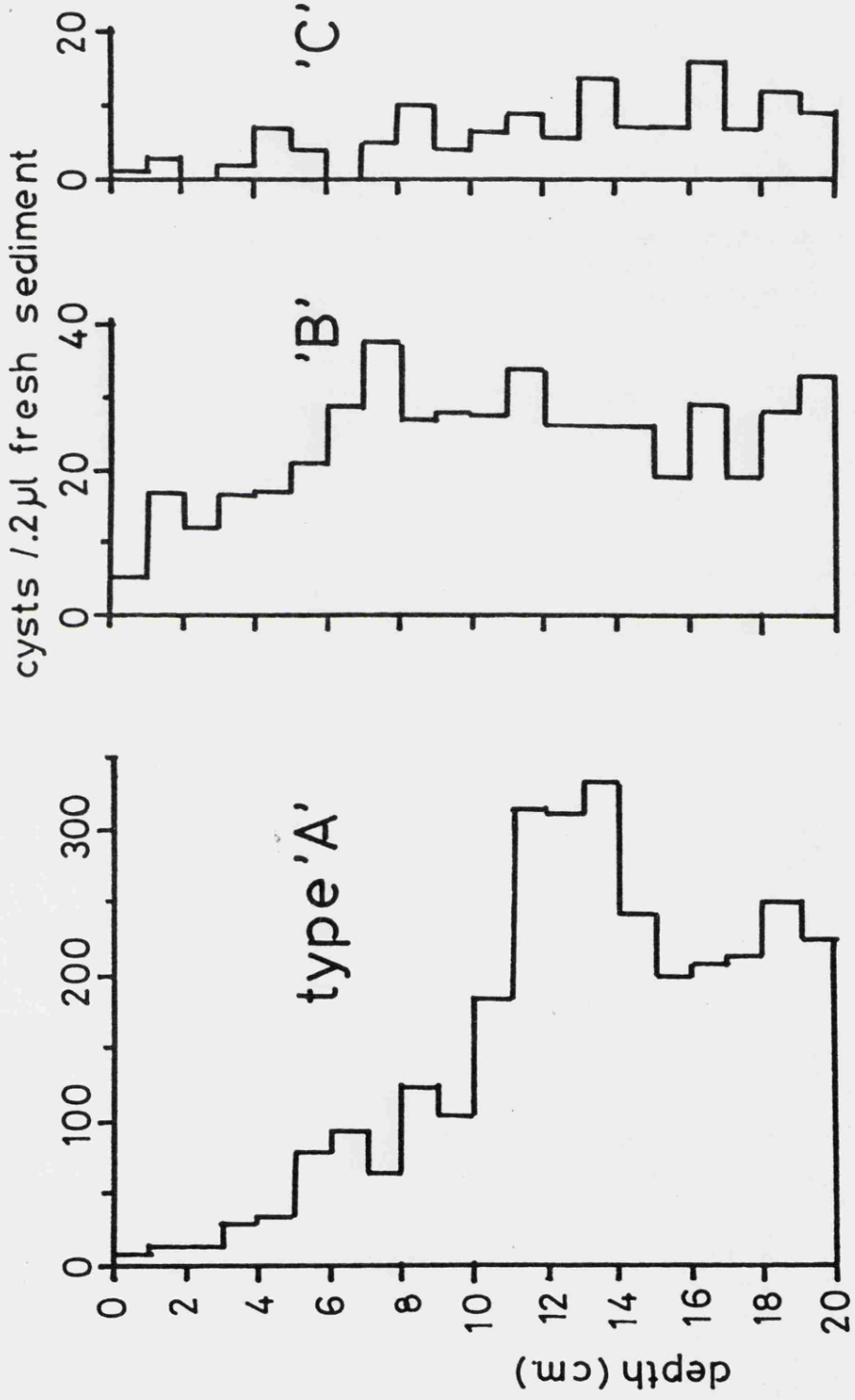


figure 3.8

GRASMERE

figure 3.9


GRASMERE - Chrysophyceae cysts
cysts /.2µl fresh sediment
depth (cm)
type 'A'
'B'
'C'
0
100
200
300
20
40
2
4
6
8
10
12
14
16
18

14–16 μm - D. sertularia, 10–11.4 μm - D. bavaricum, 11–13 μm - D. divergens and 10–17 μm - U. americana. All the cysts were shown as smooth, spherical and with small or no collars. Detailed analysis of the cysts found in the sediments may reveal finer differences which may be used to separate the species.

Sketches of Chrysophyceae cysts from the Grasmere and Elterwater sediments are given in figure 3.10. Examples of types A (no. 1), B (2 & 7), C (3, 4, 5, 6 & 8) are shown. The similarity between no. 2, from Grasmere, and no. 7, from Elterwater, suggests that the cyst may have originated from the same species.

2. ELTERWATER

a. Site description

Elterwater is situated on the silty valley floor of the River Brathay, although the catchment includes some of the highest fells in the Lake District. There are two main inflows (figure 3.4b), both of which flow into the outer basin. In times of flood the water level can rise 1.5 m in 12 hours and increase the lake area twofold (Cooper, 1966).

The lake is divided into three, almost separate, basins, joined by narrow channels. The inner basin is fed predominantly by back-up waters and one or two small streams and drains. In late 1973 a sewage treatment plant was constructed for the nearby village, replacing a septic tank system. The effluent from the sewage works is discharged into a small stream running into the inner basin.

CHRYSOPHYCEAE CYSTS: GRASMERE and ELTERWATER

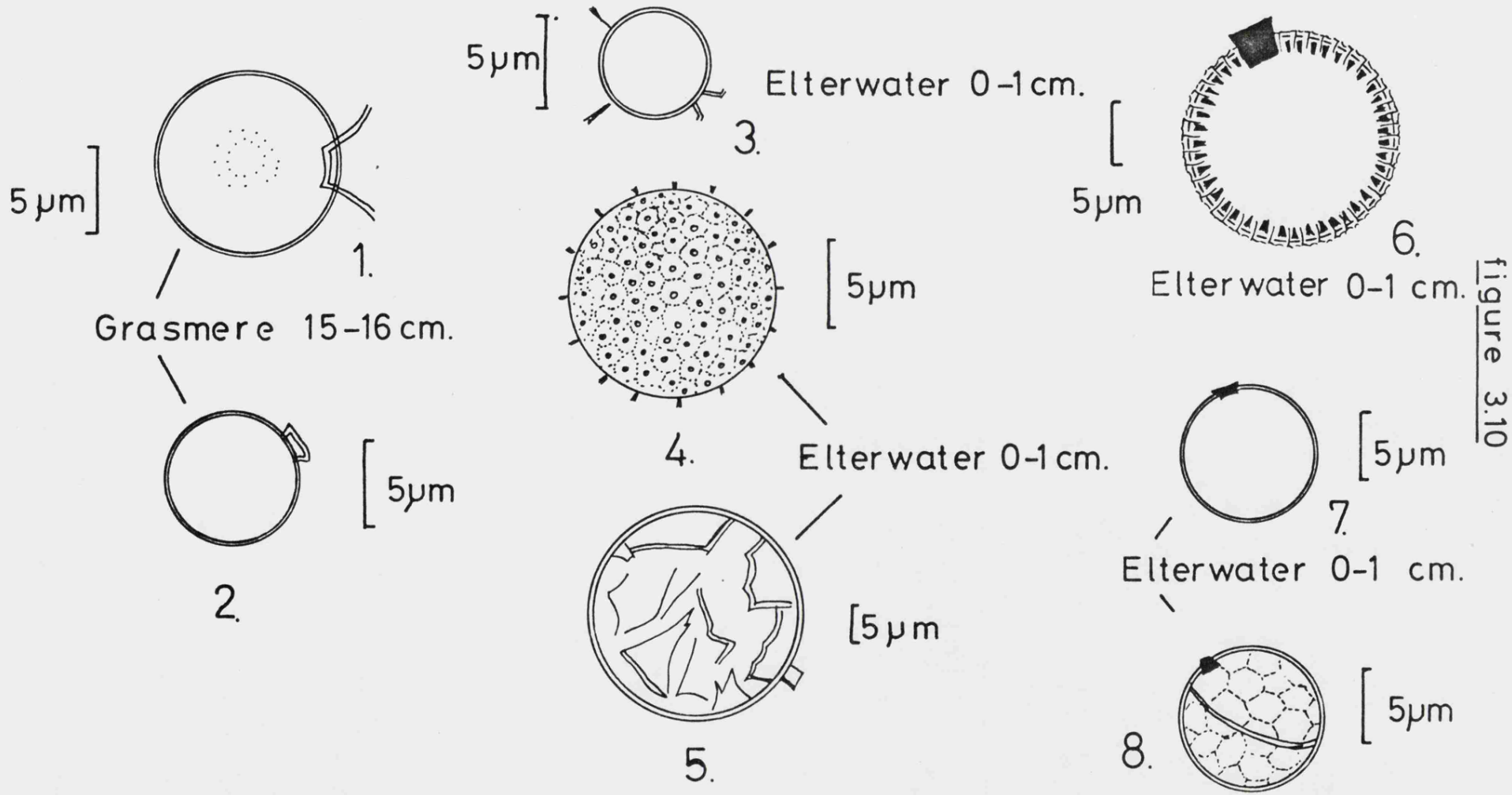


figure 3.10

Due to the lake's morphology, the increase in nutrients brought in by the sewage effluent has grossly affected the inner basin, which now acts as a sewage oxidation pond (Lund, 1979). The rapid throughput of water in the outer basin results in almost riverine conditions and considerable dilution of any effluent from the inner basin.

b. The Sediments

The deep water sediments of Elterwater were cored in February 1975, the cores used in this study were obtained at the same time as those analysed by Pennington (1978 and unpublished data). The core from the inner basin had a black to brown colour discontinuity at 30 cm but those from the middle and outer basins were mottled dark brown-black throughout.

Caesium-137 dating was performed on cores taken at the same time as the ones used for algal analyses. The core from the inner basin showed a peak in the 5-6 cm section and hence the mean annual increment of sediment accumulation (1963-1975) is 4-5 mm yr^{-1}. Material from the middle and outer basins did not show a structured profile, and the cores were assumed to show the absence of orderly accumulation of sediment (Pennington - personal communication) in these small basins fed by relatively large rivers.

c. The phytoplankton

The three basins of Elterwater range from the highly eutrophic inner basin to the nutrient poor outer basin. This is well illustrated by the chlorophyll *a* annual means for 1976 with values of 65 ug l^{-1}, 21 ug l^{-1} and 4 ug l^{-1} for the inner, middle and outer basins respectively (Lund, 1979).

The phytoplankton of the inner basin reflects the input of sewage effluent, in that the composition is similar to that found in sewage oxidation ponds (Lund, 1979). Small, nanoplanktonic, algae are often abundant, including the diatom Cyclotella pseudostelligera, coccoid greens and cryptomonads. Asterionella formosa is typically abundant. There is an absence of gas-vacuolate blue-green algal blooms which although common in enriched lakes are typically infrequent in sewage oxidation ponds. Few algae enter the outer basins, except in times of flood but are then highly diluted.

d. The Siliceous Remains

The core from the inner basin of Elterwater was dominated by non-planktonic diatoms, making up between 50% and 90% of the frustules (figure 3.11). Of the planktonic species Asterionella formosa, Tabellaria flocculosa var. asterionelloides, Synedra spp. and Melosira italica (Ehr.) Kützing were the most frequent. Of these only Asterionella shows a rise in abundance in the most recent sediments. The rise in the small centric Cyclotella pseudostelligera was not observed in the core since it did not appear in the plankton until after the core was taken, but it was present in surface samples taken in 1979.

The Cs-137 dating of another core placed 1963 within the 5-6 cm horizon, which gives a mean annual accumulation rate (1963 to 1975) of 4-5 mm yr^{-1}. The distribution pattern of Cs-137 can be areally variable (see Pennington et al., 1976) and so the use of 'replicate' cores may be questionable. However the peak of Asterionella formosa appears to have occurred circa 1972-1974 on the basis of the radionuclide dating, consistant with the construction of the sewage treatment works in 1973.

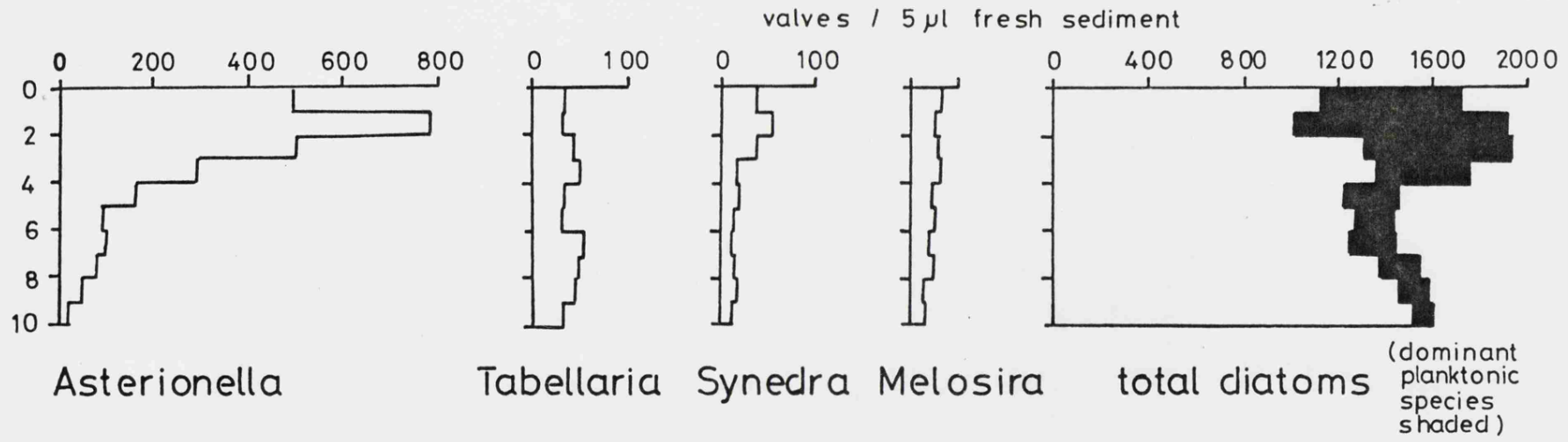


figure 3.11

ELTERWATER - inner basin

Frequency data for the inner basin (figure 3.12) from 50 cm to the surface shows Asterionella formosa as a very recent addition to the phytoplankton. Tabellaria flocculosa var. asterionelloides appears to have been the dominant planktonic diatom before 1960. The attached species make up the bulk of the 'non-planktonic' group, especially individuals from the genus Achnanthes. Three species are dominant, A. microcephala Kützing, A. minutissima Kützing and A. minutissima Kützing var. cryptocephala Grunow. There are few relative changes in the profiles and there is no evidence of any alteration in diatom composition across the colour discontinuity at 30 cm (figure 3.12).

The profiles for Asterionella formosa, Tabellaria flocculosa var. asterionelloides and Melosira italica for each of the three Elterwater basins (figure 3.13) reflect both the biological and physical factors affecting Elterwater. The lower number of frustules found in the outer basins results from a combination of lower productivity and increased flow, especially in times of flood. The spate flows also appear to disturb ordered sedimentation in the outer basin where the distinctive Asterionella stratigraphy was not found. Large debris, such as branches and cans, may be seen near the inflows and the core material from the outer basin contained twigs and leaves. The profiles from the inner and middle basins are similar, although fewer diatoms are present in the mid-basin core.

3. DISCUSSION

The diatoms from the sediments of Grasmere and Elterwater (inner basin) reflect the qualitative and quantitative changes in the plankton which resulted from the introduction of sewage effluent from treatment

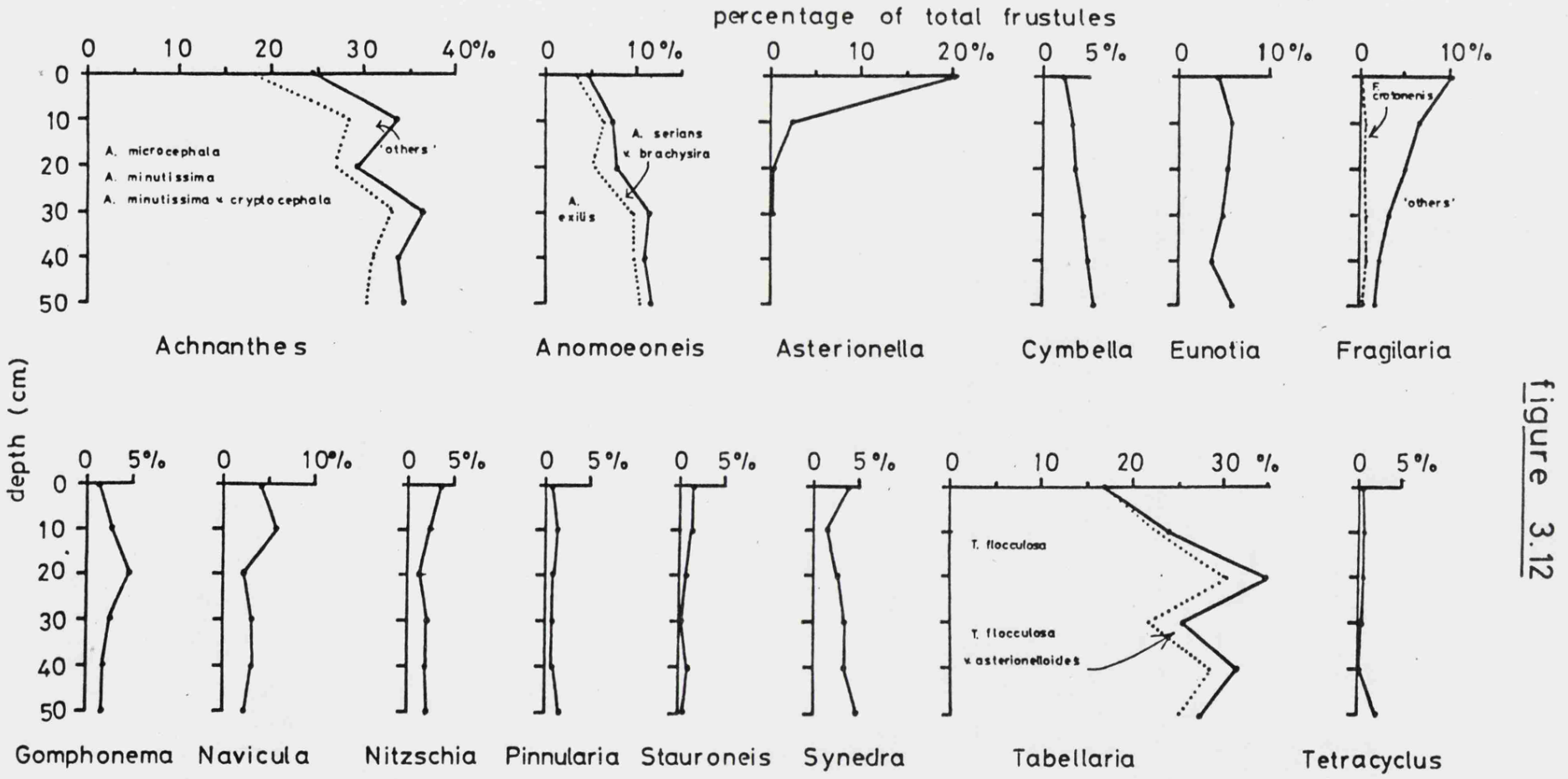
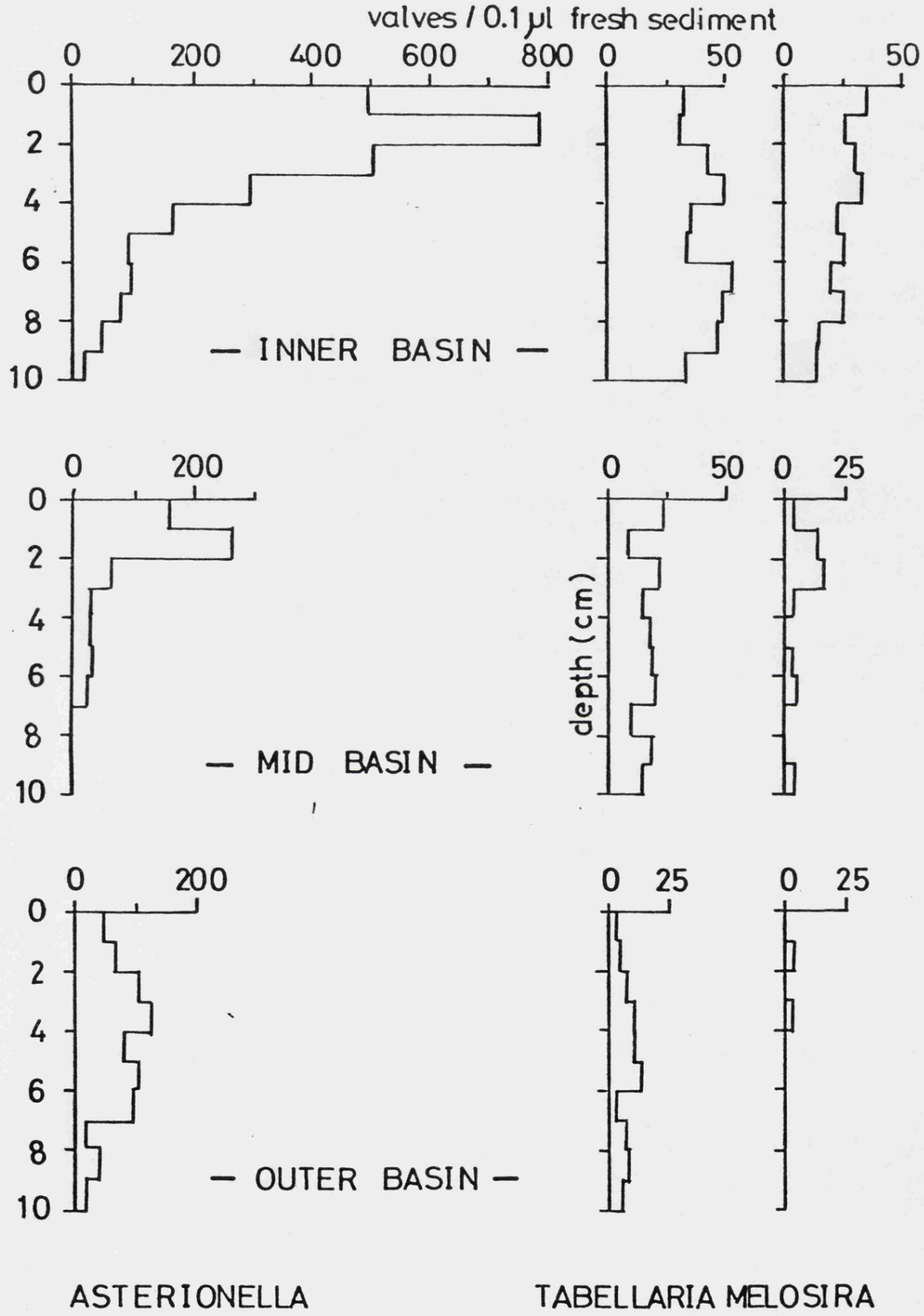


figure 3.12

ELTERWATER – inner basin.

figure 3.13



ELTERWATER

plants which replaced a septic tank system. The enrichment of some Cumbrian lakes by man has been the result of recent changes in population, washing materials, sewage treatment and farming practice (see also Lund, 1978). Increases in population have generally been associated with tourism. The installation of mains water to some villages has led to an increase in the volume of waste water. More water is used for washing, flush toilets and improved cleanliness in farm practices. The introduction of detergents and washing machines in the early 1960's resulted in an increase in phosphate in the waste.

The septic tank method of sewage disposal results in little addition of plant nutrients to the lake, provided that the tank has a good soakway and is not overloaded (Macan, 1970). Any overflow reaching the lake would be via the soil which would probably remove excess phosphorus (Jones, 1972). The introduction of sewage treatment plants has resulted in an alteration in the quality of effluent reaching water courses. The treatment of domestic wastes in a sewage works does little to strip out the plant nutrients, and the introduction of effluent into lakes such as Grasmere and Elterwater has led to an increase in productivity.

The provision of a sewage plant has, however, usually been in response to the septic tank system becoming overloaded and inefficient, thus leading to the pollution of nearby waters. For example the village of Hawkshead, at the head of Esthwaite Water, was served by septic tanks until 1973, when a sewage treatment plant was installed. The effect on the phosphate and nitrate concentrations was small, since prior to 1973 the grossly overloaded septic tanks near the inflow often overflowed and sewage solids entered the lake, providing nutrients (Lund, 1979).

The change in sewerage has increased the phosphate concentrations in Grasmere by an order of magnitude (circa 0.1 μg PO_4-P l^{-1} to 1.0 μg l^{-1}) but this is still low when compared to other productive lakes in the area (Lund, 1979). The introduction of treated effluent has changed not only the phytoplankton but also the zooplankton (Elliott, 1977; Smyly, 1978). The total mean number of rotifers and planktonic crustaceans have increased but the composition has altered due to the lower oxygen concentrations (Hall et al., 1978). The hypolimnetic and profundal crustacea have declined or modified their life-style in conjunction with the developing hypolimnetic oxygen deficit (Smyly, 1978). The rotifers which formerly dominated are those which attained their highest densities within a narrow range of oxygen concentrations and their decline may be partially correlated with the lower amounts of oxygen in all but the upper waters (Elliott, 1977).

The diatom assemblage recorded in the Grasmere sediments below 10 cm (i.e. before 1960), in particular Cyclotella comensis and Cyclotella kutzingiana, is typically found in the more oligotrophic water bodies of the English Lake District, such as Wastwater. Gorham et al. (1974) considered the phytoplankton crops recorded before 1963 and placed Grasmere in an intermediate group (see table 3b). West & West (1909) found the phytoplankton of Grasmere to be "almost exclusively dominated by Asterionella formosa and Tabellaria fenestrata var asterionelloides" (now T. flocculosa var. asterionelloides - Knudson (1952)) and did not record the species of Cyclotella which dominate the core material at depth. This apparent discrepancy may be due to the small Cyclotella spp. passing through the mesh in a plankton net, or the sampling may have been carried out during a period when no Cyclotella populations

were present, since collections were made only in June and September of 1903. The idea, proposed by West & West (1909) that Grasmere village was polluting the lake seems a little incongruous when the effects of the nineteen seventies are considered.

The introduction of treated sewage effluent into Grasmere is coincident with the increase in the mean annual increment of sediment accumulation. The rate of deposition between 1963 and 1969 is about 1.7 mm yr^{-1}, comparable with that of Ennerdale and Wastwater (c.f. table 3d), although the latter values are for the period represented between 1963 and the surface of the core. The mean rate, for Grasmere, between 1969 and 1977 is 7.8 - 10.0 mm yr^{-1} which is similar to the rates recorded in the productive Esthwaite Water and Blelham Tarn.

The approximate rate of dry sediment accumulation (supplied by R.S. Cambray, A.E.R.E., Harwell) suggests that the increase in the deposition rate is not solely a result of increasing water content near the interface (table 3e).

The increase in sediment accumulation post 1971 may be due either to the survival of undegraded autochthonous material or to the addition of solids originating from the sewage plant. Lund (1979) noted that construction work, in 1969, resulted in a quantity of soil entering the water causing an increase in turbidity. Jones, Downes & Talling (in press) observed that particulate matter from the sewage works, as well as much of the suspended load of the River Rothay, is deposited in the area surrounding the inflow, rather than in the deeper areas. The increase in deposition rate, therefore, is likely to be autochthonous input from the greater standing crops observed in recent years.

Table 3e Grasmere - dry sediment deposition

Depth (cm)	Period	Dry sediment accumulation ($mg\ cm^{-2}\ yr^{-1}$)
7 - 8	1963 - 1969	25.1
6 - 7	1969 - 1972	45.7
5 - 6	1972 - 1974	64.5
0 - 5	1974 - 1977	158.0

The validity of the Cs-137 dating and the 'algal chronology' must also be considered. Small centric diatoms (e.g. Cyclotella pseudostelligera) may pass through the surface flocculant layers of the mud surface (Haworth, 1976b). However large colonies of Asterionella formosa would be more likely to settle onto the interface; although there is the possibility that the colonies may disintegrate and individuals cells move downwards. The fairly discrete layering of the diatom stratigraphy (e.g. the absence of a pronounced 'tail' on the profiles of, say, Tabellaria and Cyclotella pseudostelligera - figure 3.6) suggests that physical, or indeed, biological disturbance is not sufficient to destroy ordered sedimentation.

The Cs-137 dating technique has proved useful for estimating sediment deposition rates (see reviews by Krishnaswani & Lal, 1978 and Ritchie & McHenry, 1977), and studies by Pennington et al. (1973). Ritchie et al. (1973) and Robbins & Edginton (1975) have shown that Cs-137 in the sediments is related to the annual input, of the radionuclide, to the watershed. Once adsorbed to the suspended or deposited sediment very little chemical exchange or movement of the Cs-137 atom occurs (Duursma & Bosch, 1970; Lomenick & Tamura, 1965). Any mixing of the sediment would redistribute the Cs-137 which would result in a more uniform profile in the column. The pronounced maxima found in Grasmere (this study) and other Cumbrian lakes (Pennington et al., 1973) suggests that physical and biological mixing is insufficient to destroy the stratigraphic distribution. Therefore the validity of the Cs-137 dating for the Grasmere core is accepted. However Pennington et al. (1976) found that the Cs-137 1963 peak at five sites in Blelham Tarn occurred at different depths, showing an areal variation in accumulation rates. Thus the estimated mean annual rate of sediment

accumulation is for the core studied and must be extrapolated for other sites within the lake with caution. Two earlier cores from the deepest area of Grasmere however, also had a mean rate of deposition of circa 5 mm yr^{-1} (Pennington, unpublished data).

The contrasting diatom profiles from the three basins of Elterwater demonstrate the importance of a quiet depositional environment for an ordered stratigraphy. Somewhat paradoxically Grasmere also has a mountainous catchment, and receives torrential flood waters, but the sediment stratigraphy is relatively undisturbed. However the deepest area is sheltered from the direct effects of the flood waters, the energy of which is dissipated by the shallow water surrounding the inflow and the main flow is around the west side of the island and not over the deepest area (Jones et al., in press). The high rainfall, and mountainous catchment, may affect the number of algae reaching the sediments of Grasmere. For example if a flood occurs at a time of abundant Asterionella then a significant number may be washed out of the lake.

Pennington (1943) showed that the transition from lower, brown coloured, sediment to black ooze in Windermere coincides with a rise in abundance of Asterionella formosa. Black-brown colour discontinuities have been recorded in the recent sediments of Blelham (Pennington et al., 1976), Grasmere and Elterwater. However this does not imply that either the sediment-colour changes are identical or caused by the same process. The increase of Asterionella in Grasmere and Elterwater is not associated with the colour change, in fact the diatom profiles do not significantly alter, quantitatively or qualitatively, across the colour discontinuity. The oligotrophic diatom assemblage in Grasmere (and the Chrysophyceae cysts) indicates that enrichment is not associated

with the colour change. However the abundance of Asterionella formosa in Grasmere, Elterwater and Windermere is related to increased nutrient concentrations caused by a change in human activity, notable increases in population and changes in sewage disposal, within the catchment. The Asterionella rise in Windermere is correlated with an increase in population when around 1850 the introduction of the railway opened up the area, and in particular the town of Windermere, to visitors. The change from septic tank to mains sewerage in the villages surrounding Grasmere and Elterwater has caused an alteration in the algae, and changes in the diatom flora are reflected in the sedimentary record.

CHAPTER FOUR

SEDIMENT CORES FROM THREE LOWLAND WATERS

CHAPTER FOUR: SEDIMENT CORES FROM THREE LOWLAND WATERS

1. INTRODUCTION

The lakes in lowland Britain are typically much richer in all the major ions than the non-calcareous Lake District waters. The lakes in highland Britain generally lie on much harder and less easily weathered substrate, and in areas with both large amounts of precipitation and high relief. Both factors favour the rapid transport of salts to the sea and low ionic concentrations in the lake waters (Gorham, 1957). Although there is not a direct association between total ionic concentration and standing crop (algae also require trace elements and vitamins etc.) there is a general correlation (Lund, 1957).

Four lowland sites have been investigated, one of which, Rostherne Mere, is discussed in the following chapter. Priest Pot is situated in the English Lake District but is a small, highly eutrophic pond with a very high algal productivity. The sediments, as with all those studied in this section, have a high autochthonous/allochthonous ratio.

Ellesmere Mere is one of the Shrophsire-Cheshire Meres, a group of about 50 small, fertile lakes typically occupying hollows in the thick deposits of glacial drift covering the Shropshire-Cheshire plain (see Reynolds & Sinker, 1976; Reynolds 1979a). The basins are predominately fed by nutrient-rich ground water, having only small or no inflows; the waters are usually alkaline and well-buffered. The phytoplankton composition of the meres is usually dominated by diatoms, dinoflagellates and blue-green algae. The sediments are characteristically black organic oozes and contain few mineral particles (Reynolds & Sinker, 1976).

The Norfolk Broads were formed around the fourteenth and fifteenth centuries when a rise in relative sea level flooded peat diggings on the alkaline peat deposits of the Norfolk river valleys (Ellis, 1965). Over the past few decades many of the broads have become enriched, commonly by sewage effluent and/or run-off of agricultural fertiliser, and extensive stands of submerged aquatic macrophytes have been replaced by dense phytoplankton populations (Mason & Bryant, 1975; Moss, 1977; Phillips et al., in press). Upton Broad, investigated in this study, still retains abundant submerged macrophytes and clear waters (Moss et al., in press).

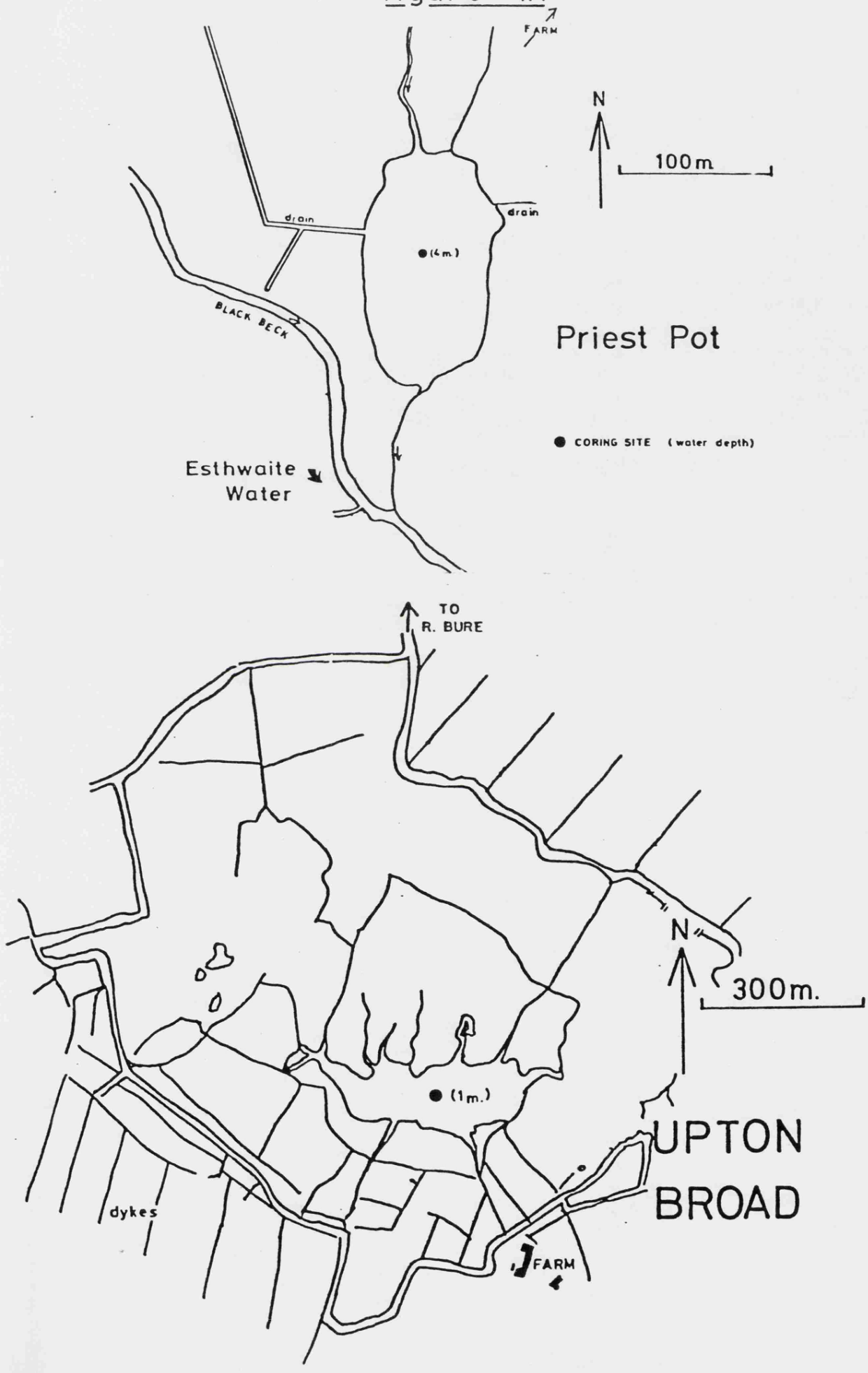
2. PRIEST POT

a. Site

Priest Pot (NGR SD 357977) is a small pond adjacent to Esthwaite Water (see figure 4.1a) with an area of 1×10^4 m^2 and a maximum depth of 4 m. It is fed by groundwater, field drains and two or three slow flowing ditches, one of which carries effluent from the nearby farm yard. The catchment is small, consisting of fertilised fields and a small area of rough grazing.

The pond is highly eutrophic due to the inflow of farm effluent and run off from the surrounding land, both of which are rich in nutrients, especially nitrogen and phosphorus. Details of surface water chemistry are given in Belcher, Swale & Heron (1966) and dissolved gases in Goulder (1971b).

figure 4.1


FARM
N
100m
drain
drain
(4m.)
BLACK BECK
Priest Pot
CORING SITE (water depth)
Esthwaite
Water
TO
R. BURE
N
300m.
(1m.)
UPTON
BROAD
dykes
FARM

b. The sediment

Goulder (1971a, 1971b, 1972a, 1972b) examined the sediments of Priest Pot in his study on the larger ciliated protozoa. He describes Jenkin cores as typically having a greenish-brown layer, 1-2 cm thick, overlying a more compact black mud. The organic content (by loss on ignition) was 50% at the surface.

The core for this study was taken at the F.B.A. buoy (in 4 m of water) in August 1978. The surface consisted of a green-grey floc which was overlying 5 cm of black, unconsolidated, ooze. From 5-20 cm the sediment was dark brown, between 20-70 cm brown and below 70 cm orange-brown in colour and more clayey in texture.

c. Phytoplankton

The periodicity of the phytoplankton (1974-1976) of Priest Pot has been examined by Dr. A.E. Irish (unpublished data) and the results are reproduced with his permission. Samples were taken with a one metre water sampler (Irish, 1979).

In 1975 the spring maximum was characterised by the diatom Cyclotella pseudostelligera and species of Cryptomonas. Asterionella formosa was also common in the plankton. During the summer large populations of algae belonging to the Chlorococcales and Volvocales occurred, notably Dictyosphaerium sp. (maximum 62600 cells ml^{-1}) and Diacanthos belenophorus Korshikov (51150 cells ml^{-1}). Scenedesmus spp. (at least seven different species are thought to occur, Irish - personal communication) are common during the summer (max. 0-1 m circa 17000 cells ml^{-1}) but larger populations can occur at depth. Summer maximum chlorophyll a levels (1974-1976) varied from 400 - 1300 $\mu g\ l^{-1}$ (cf. Esthwaite maximum < 400). Occasional observations in other years

have yielded similar results (Lund - personal communication). Water blooms of blue-green algae are very rare but large populations of Aphanothece can occur.

The morphology of Cyclotella pseudostelligera from Priest Pot has been examined by Belcher, Swale & Heron (1966).

d. Algal remains

i. non-siliceous remains

Small species of Chlorophyceae dominate the phytoplankton of Priest Pot but only species of Scenedesmus were recorded, in any number, from the sediments. The occasional Pediastrum colony was observed and a few small, unidentified, blue-green colonies.

The colonies of Scenedesmus which composed the surface green floc on the core (figure 4.2), contained cells with healthy-looking chloroplasts. With depth there was a sharp decline in abundance of cells and an increase in the relative numbers without contents and/or pigmentation (phase contrast facilitated counting these colonies).

The profile of the Scenedesmus remains is similar to those obtained for other non-siliceous remains from the highland lakes (Chapter 3) and suggests that large scale preservation does not occur.

ii. siliceous remains

The planktonic diatoms in the core (figure 4.3) were dominated by Cyclotella pseudostelligera, and to a lesser extent Asterionella formosa. Other species commonly recorded were Fragilaria crotonensis, Cyclotella meneghiniana Kützing, Tabellaria flocculosa var. asterionelloides (not on diagram) and various small Synedra species (included with the 'non-planktonic' diatoms). The number of attached and benthic taxa show a steady increase with depth.

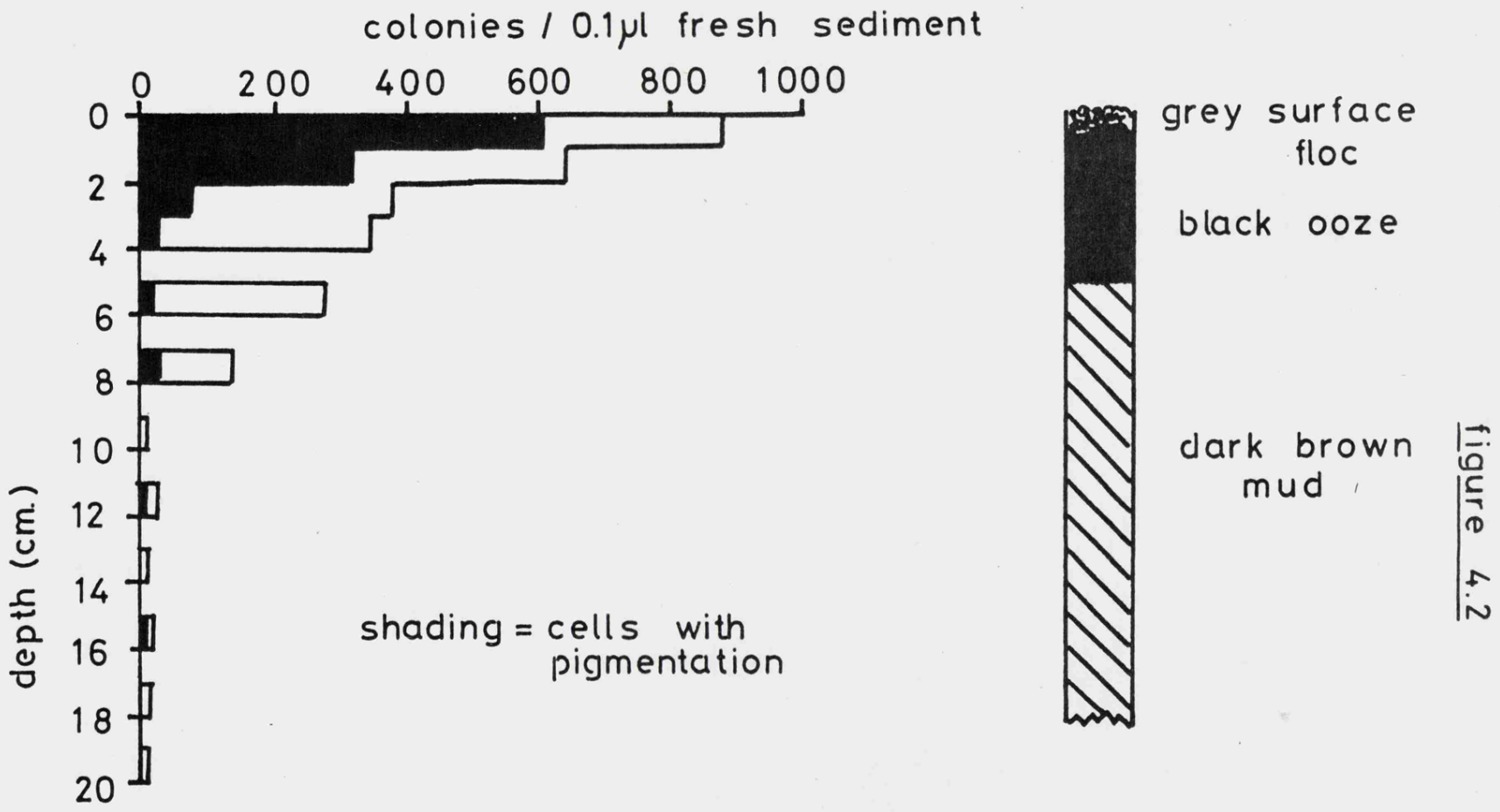


figure 4.2

PRIEST POT - Scenedesmus remains

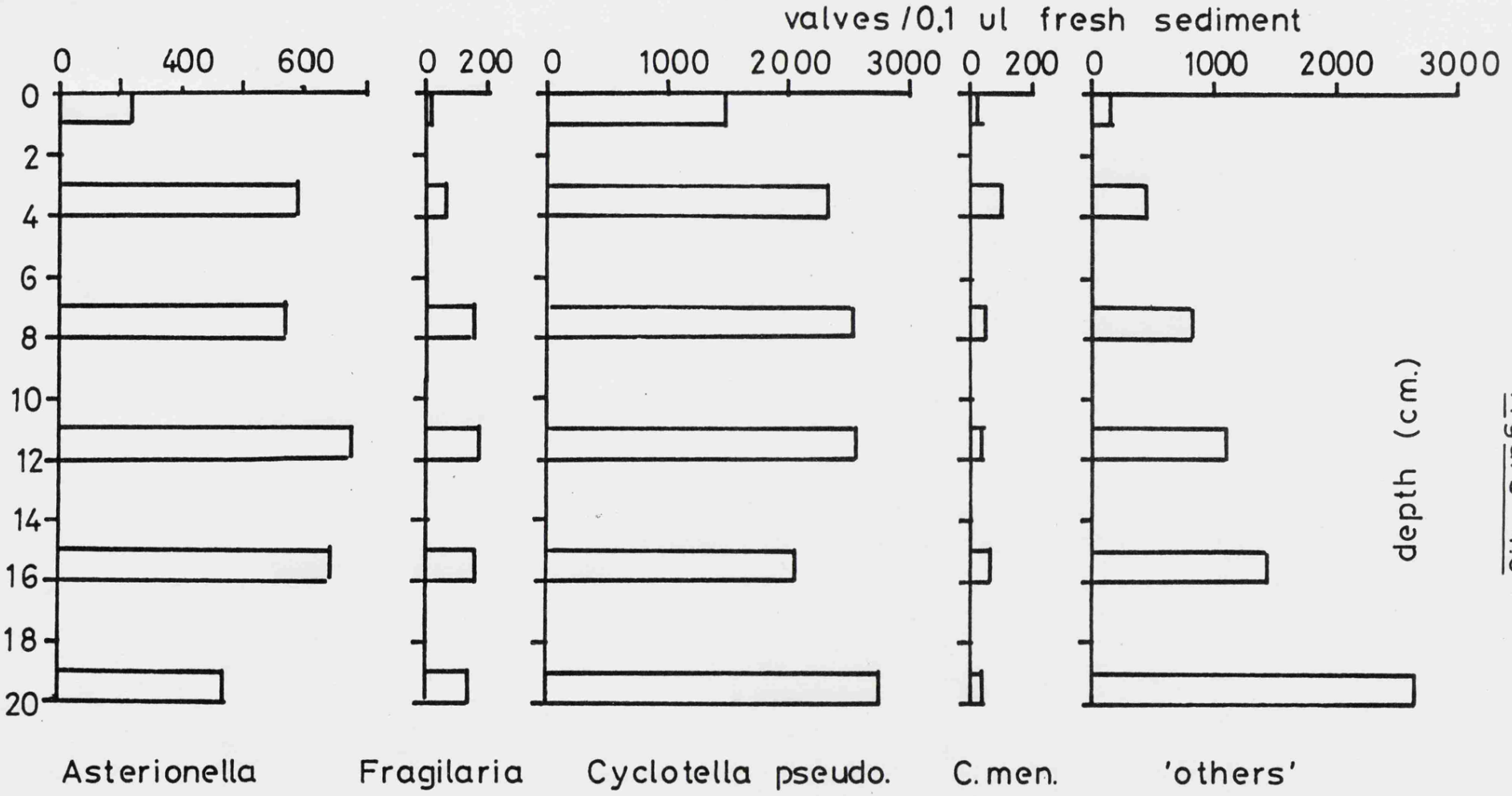


figure 4.3

PRIEST POT - diatoms.

The morphological variations found in Cyclotella pseudostelligera by Belcher et al. (1966) in the plankton were also observed in the core material. The planktonic diatoms do not show any stratigraphic discontinuities, although differences may be masked by the spacing of the sampling interval (4 cm).

It appears that the eutrophic conditions which now prevail in Priest Pot have been present over the period represented by the top 20 cm of the core. The time span cannot be estimated without some method of dating the sediments.

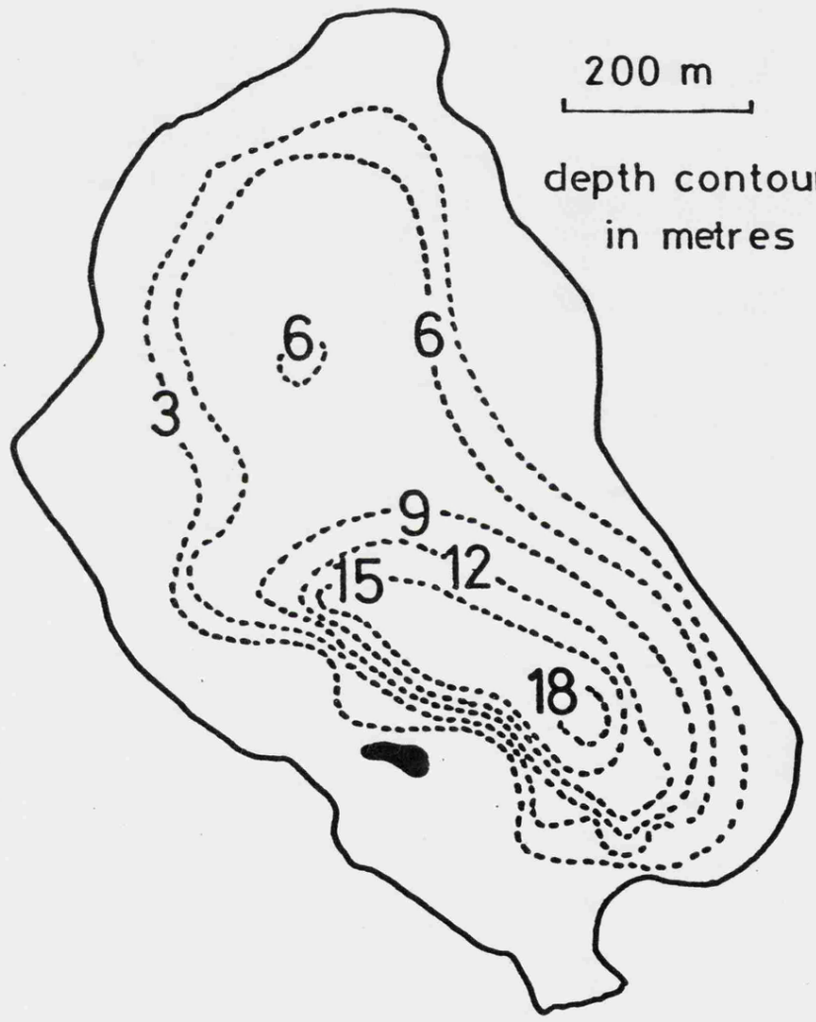
3. ELLESMERE MERE

a. Site

Ellesmere Mere (NGR SJ 406350) lies on boulder clay deposits and is one of a group of meres situated around the town of Ellesmere. The lake (figure 4.4) has an area of 0.47 km^2 and a maximum depth of 19.5 m. The surface inflows are small and the residence time of the waters is probably in the order of 2-3 years (Reynolds, 1979a). The catchment is partly agricultural land, mainly pastoral, and partly urban since part of the town of Ellesmere lies within the catchment. Mains sewerage takes the effluent from the town to a treatment works beyond the mere (Reynolds, 1973).

Ellesmere Mere is a calcareous lake, rich in phosphate and moderately so in nitrogen (Reynolds, 1973).

figure 4.4



Ellesmere Mere

(from Reynolds [in press] redrawn
from Wilson [1966])

b. The sediment

The cores were taken in May 1978 from the deepest area of the mere. There was little visual stratigraphy, the sediment was composed of dark brown muds overlain by a slightly darker ooze.

c. The phytoplankton

The phytoplankton periodicity of the mere was examined in 1967 and 1968 by Reynolds (1973). The lake is atypical of many meres (although very similar to Rostherne Mere - see following chapter) in that the plankton is sparse for the first four months of the year. The dominant diatoms are similar to those found in other meres, consisting predominantly of Asterionella formosa and Melosira granulata. From May until autumn the phytoplankton is dominated by blue-greens and dinoflagellates. Anabaena circinalis Rabenh., ex Born. et Flah. was abundant in both years and was succeeded by Microcystis aeruginosa. Subdominant in the autumn and summer were Microcystis wesenbergii Komárek, Ceratium hirundinella and various Chlorophyceae.

d. Algal remains

i. non-siliceous remains

The sediments of Ellesmere Mere contain many non-siliceous algae and their remains can be found throughout the core (figure 4.5). The most abundant remains are the resting spores of Ceratium, Anabaena and Aphanizomenon; colonies of Microcystis, Pediastrum and Coelastrum; and cells of Staurastrum.

Apart from the upper strata the Ceratium cysts observed in the sediments were devoid of contents except for a small orange-brown

Figure 4.5

Ellesmere Mere - algal remains

a. Ceratium hirundinella : cysts (shading = with contents)

b. Microcystis aeruginosa : colonies

c. Anabaena spp : akinetes

d. Staurastrum spp : cells

e. Pediastrum spp : colonies

f. Coelastrum sp : colonies

g. Stephanodiscus astraea : cells

h. Aphanizomenon flos-aquae : akinetes

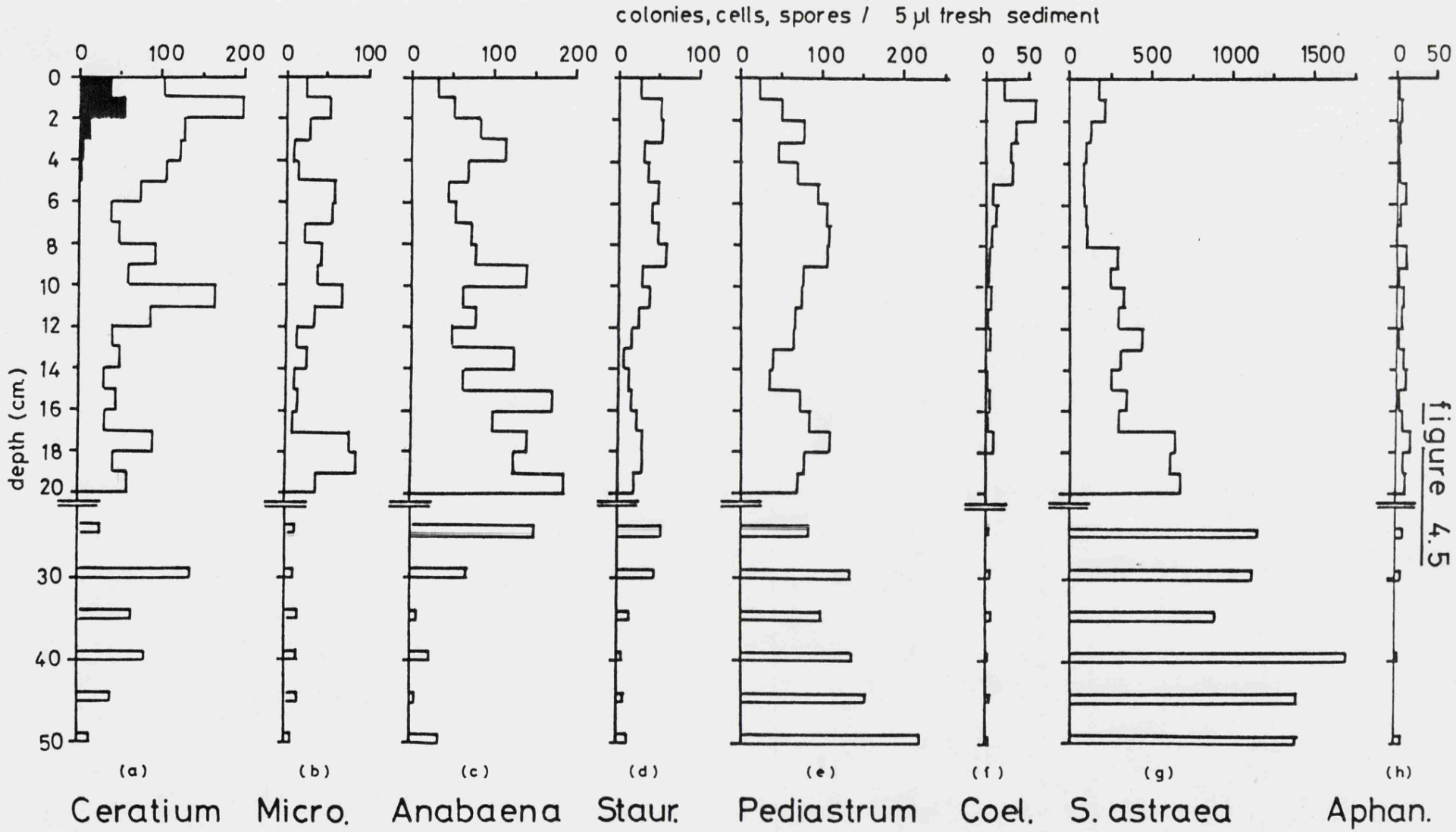


figure 4.5

ELLESMERE MERE - algal remains

intracellular residue, a common feature in preserved Ceratium cysts from other lakes.

Akinetes of Anabaena and Aphanizomenon were present throughout the core and occasionally contents, similar in appearance to those found in the plankton, were observed. The viability of blue-green akinetes, from Rostherne Mere, was tested (Chapter 6). The remains of Microcystis colonies were also found at all depths. Near the interface the colonies were dense and dark green but at depth the pigmentation faded and the mucilage contained fewer cells.

Large numbers of Pediastrum colonies, along with smaller amounts of Coelastrum, were recorded near the interface. The cell contents were intact in the upper strata but were absent at depth. The Coelastrum colonies showed a tendency to collapse, resulting in an array of shapes which hindered identification. The highly resistant cell walls of Pediastrum were present throughout the core but those of Coelastrum appear to be less resistant. A small number of Scenedesmus colonies were recorded in the topmost 4 cm.

Amongst the non-siliceous algae of Ellesmere Mere the taxa which form the abundant summer populations, Microcystis, Anabaena and Ceratium, are well represented in the sediments. The remains, unlike those found in the highland deposits, were not restricted to the flocculent surface layers. Therefore it appears that the sediments of Ellesmere Mere preserve certain algae, since these show little evidence of decomposition with depth. The absence of detailed records precludes any discussion on the discreteness of the stratigraphy or the validity of past algal assemblages.

ii. siliceous remains

The diatoms in the Ellesmere Mere sediments were dominated by Stephanodiscus hantzschii which typically comprised of over 75% of the total number of diatoms recorded (figure 4.6). Other common species were Asterionella formosa, Melosira granulata and Stephanodiscus astraea, with small numbers of Fragilaria crotonensis.

The cell morphology of Stephanodiscus hantzschii was found to be extremely variable, both in cell size and striae patterns. Two types were identified, type 'a' is the commonly illustrated form while 'b' may be mistaken for Stephanodiscus tenuis Hustedt (Dr. E.Y. Haworth - personal communication). Type 'b' has not been common in the plankton, occuring in only two periods during the time span represented by the core. Belcher, Swale & Heron (1966) showed that variation in cell morphology of Cyclotella pseudostelligera was correlated with alterations in silica concentrations and this may also be true for the different forms of S. hantzschii observed.

Stephanodiscus astraea was enumerated on fresh and digested material (compare figures 4.5 and 4.6). Qualitatively the profiles are extremely similar but quantitatively they show small differences. The anomalies may be due to a number of factors including:

a) the increased error involved in counting a smaller volume of material (and hence less individuals)
b) the destruction or loss of some frustules during digestion and mounting
c) the concealment of the cells by other particles on the fresh mounts.

The last error is most likely to be the most significant since diluting a thickly covered slide often gave a larger result. However the

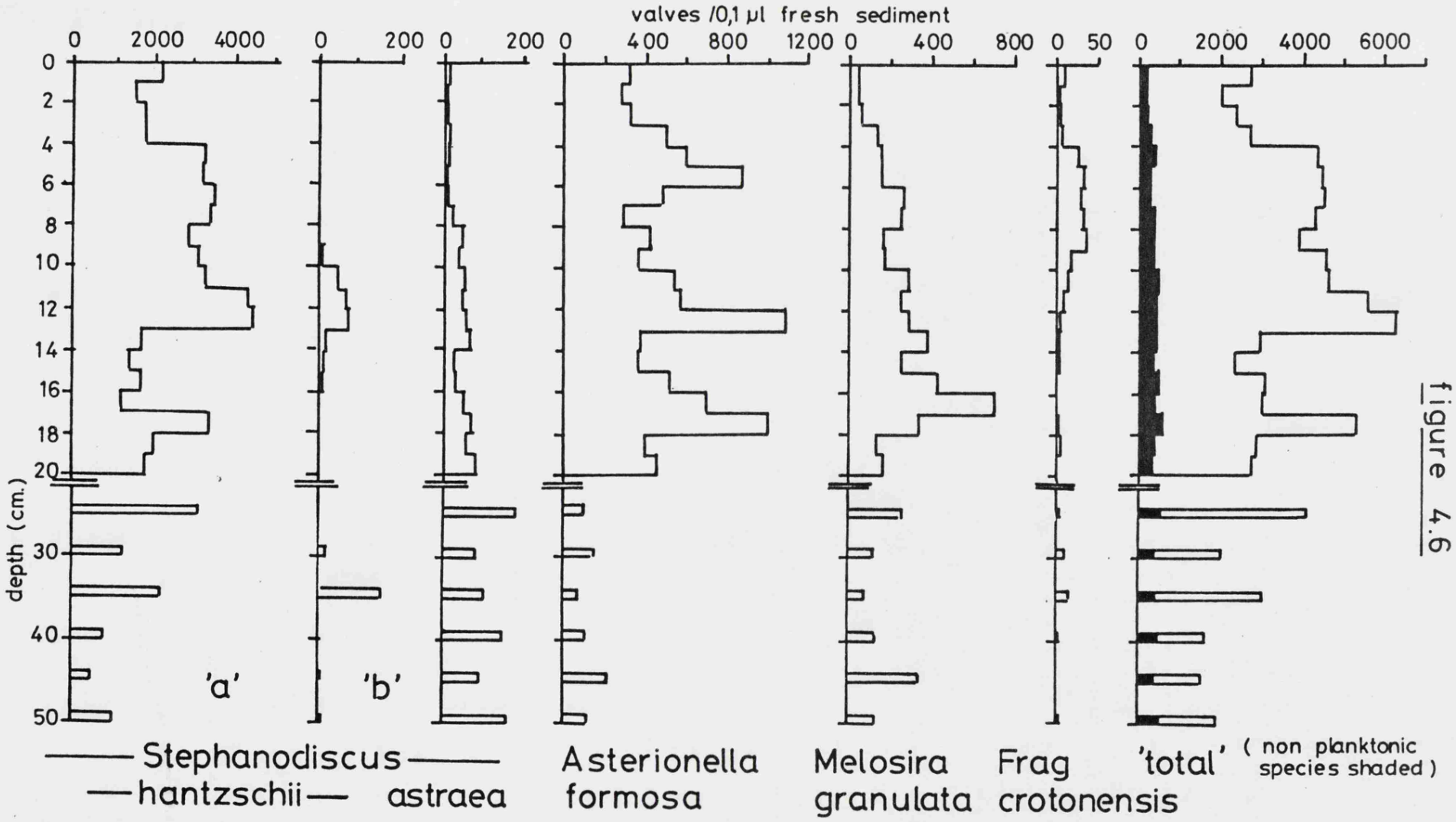


figure 4.6

ELLESMERE MERE - diatoms

sediment was diluted to give sufficient numbers of non-siliceous remains to count, which were typically less numerous.

When compared to the diatom assemblages of Grasmere and Elterwater the relative abundance of non-planktonic species in the sediments is very low. The counting of six dominant phytoplankters made up over 90% of the total number of diatom frustules found in the deep water sediments. If the upper and lower 25 cm of the core are compared there appears to be a recent increase in the numbers of Asterionella formosa and a decrease in Stephanodiscus astraea. The abundance of Melosira granulata and Stephanodiscus astraea appears to be more variable.

4. UPTON BROAD

a. Site

Upton Broad (NGR TG 389134) is a by-pass broad in the main valley of the River Bure, although it has no direct connection with the river (figure 4.1b). It lies about one mile from the Bure and is surrounded by drained grazing marsh. Unlike other broads there are no tidal fluctuations or other regular water movement.

The broad is small (0.5 km^2) and extremely shallow. Lambert & Jennings (1951) show a maximum of 1.7 m depth but in August 1978 a brief survey found only 1.0 m of water. The surface inflow is a slow-flowing dyke. It is situated in extensive alder woodland, which has developed over lacustrine muds, with a thin margin of reedswamp and fen (Jennings & Lambert, 1951; Lambert & Jennings, 1951; Lambert, 1951). Unlike many of the Norfolk Broads today, Upton typically contains abundant submerged macrophytes, predominantly Najas marina L.

A small mixed farm lies close to the southern edge of the broad. Effluent from the piggery may reach the inflowing waters (Moss et al., in press).

b. The sediments

Lambert & Jennings (1951) describe the sediments as a thick deposit of soft uncompacted organic and calcareous muds formed by the accumulation of aquatic plants and animals. They found the depth of material varied from 1.4 m to 0.8 m and was underlain by granular wood peat.

Moss et al. (in press) found the sediments had a high marl content which they attribute to calcite precipitation caused by the intense summer photosynthesis of the macrophyte beds (cf. Wetzel, 1966). Moss et al. examined the diatoms from a core dated by Lead-210. The dating revealed an increased rate of sediment accumulation in recent years. From circa 65 cm (circa 1400 $\pm$ 50 AD) to 24-25 cm (1935 $\pm$ 7) the average deposition rate was 0.7 mm yr^{-1} and since 1935 this has increased to circa 12 mm yr^{-1} in the 1970's.

Cores for this study were taken from the centre of the lake in August 1978 (1 m of water). The topmost 20 cm of the sediment column was bright green and overlaida light brown marl-like deposit. The bottom of the cores (below circa 70 cm) consisted of dark brown peat (Plate I). The peat was only cored on three out of five occasions showing that the depth of the lacustrine deposits varied. The brown lake sediment contained many mollusc shells and calcified particles. It was streaked with darker grey-brown bands. The green sediment was extremely flocculent and had a pungent, sulphide, smell. The surface muds contained small gas pockets and in shallower water bubbles were seen rising from the sediment.

PLATE I

One-metre core from Upton Broad, Norfolk

PLATE I

The sediment was composed of many small aggregates (up to 0.5 mm in diameter). These were predominantly of organic remains, in fact the number of mineral particles was very small. To separate the aggregates, which bound the algal remains together, the samples were placed in an MSE ultra sonicator (30 secs at 84W).

The bacterium Achromatium was abundant on the surface of the core. It is a genus typically found at the interface of anoxic-oxic environments in association with decaying organic material, often of algal origin, where hydrogen sulphide is present (Linton et al., 1971).

c. Phytoplankton

The plankton of Upton Broad appears to be very sparse, the bulk of the primary production seemingly undertaken by benthic algae, particularly blue-greens.

Samples taken in 1951 (July) and 1952 (September) were examined by Dr. J.W.G. Lund (unpublished data). Individuals of Cryptomonas, Rhodomonas, Pediastrum, Peridinium, Melosira, Synedra and Chroococcus were recorded.

Phillips, Eminson & Moss (in press, cited by Moss et al. in press) have recorded a heavy growth of filamentous algae, particularly Spirogyra sp., in recent years. The growth of filamentous algae is believed to be symptomatic of the early stages of sufficiently severe enrichment for macrophyte growth to be restricted.

A phytoplankton sample taken in August 1978 was very sparse, with a small number of Ceratium hirundinella, Chroococcus. and Staurastrum spp. in a sustained net tow.

d. Algal remains

i. non-siliceous remains

The sediments of Upton Broad are notable in that they contain a great number of non-siliceous remains but very few diatoms. The bulk of the ooze is composed of colonial blue-green algae with small numbers of Scenedesmus and Pediastrum colonies and species of desmids.

The blue-green algae which dominate the algal remains (figure 4.7) are benthic forms, i.e. pseudovacuoles are absent. The mucilage, which surrounds the cells, binds the sediment (authochthonous and allochthonous) into large gelatinous aggregates. The separation by ultra-sonic disintegration was effective for the blue-greens but may have fragmented delicate taxa.

Identification of the blue-green algae from the bottom of Upton Broad presents a number of problems. Firstly the phycological taxonomy of such forms is unclear and secondly there has been a recent proposal to place the nomenclature of the blue-green algae (or cyanobacteria) under the rules of the International Code of Nomenclature of Bacteria (Stanier et al., 1978). This thesis used the nomenclature of Komarek (Komárek & Ettl, 1958).

Two dominant taxa were present in Upton Broad. The first had oval cells of 4-5 um by 8-9 um in a clear, thick mucilage (Plate IIa) and was identified as Aphanothece elebans (Brébisson) Elenkin. The second taxa had smaller cells (circa 1.5 - 2.5 um x 3 - 5 um) in clear mucilage (Plate IIc) and was identified as Aphanothece elebans f. minor (Nygaard) Elenkin. Both algae had very close colonies of irregular area and both are benthic forms (Starmach, 1966).

The genus Aphanothece was proposed by Nageli (1849) for organisms like Synechococcus that develop as irregular aggregates in a mucilage.

Figure 4.7

Upton Broad - algal remains

a. Aphanothece elebans : colonies

b. Aphanothece elebans fo. minor : colonies

c. Scenedesmus spp : cells

d. unidentified Chlorophyceae : individuals

e. Pediastrum spp : colonies

f. Staurastrum spp : cells

g. Cosmarium sp : cells

h. sediment profile

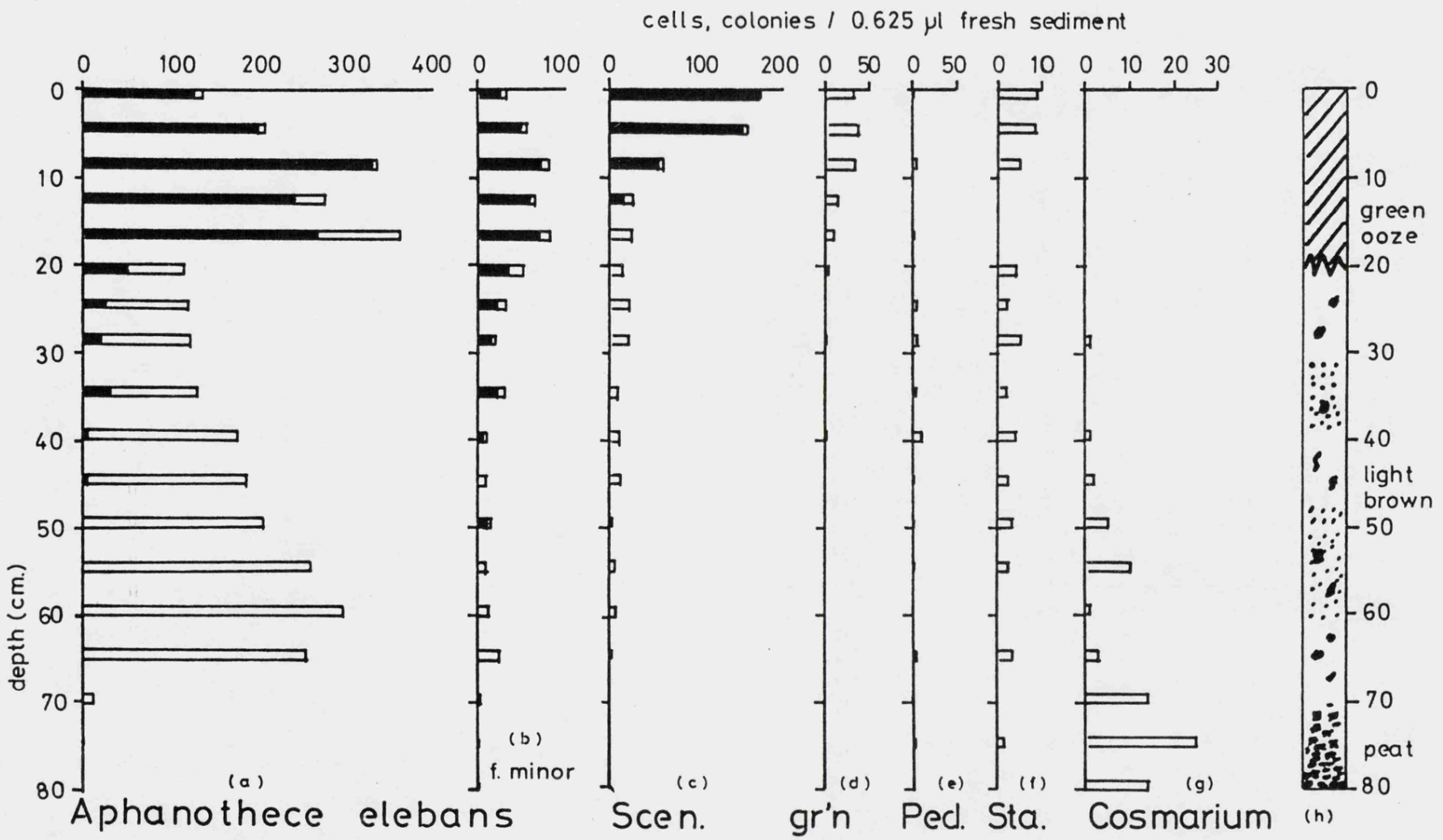


figure 4.7

UPTON BROAD - algal remains

Rippka et al. (1979) consider Aphanothece as part of the cyanbacteria genus Synechococcus. This is defined as unicellular; cells cylindrical to ovoid, single or forming colonial aggregates held together by additional outer cell wall layers; reproduction is by binary fission and division is in one plane; thylakoids are present and sheath absent.

Moss et al. (in press) attributed the green staining at the top of a core, from Upton Broad, to Aphanothece stagnina (Sprengel) A. Braun. Colonies were found both free living and in the faeces of chironomid larvae. The colonies of Aphanothece elebans from Upton closely resemble a photomicrograph from Bradley & Beard (1969) of Coccochloris elebans (Agardh) Drouet & Daily. Komárek regards Aphanothece and Coccochloris as synonymous.

The green colouration of the topmost 20 cm of sediment was derived from the pigmentation of the Aphanothece colonies. Below 20 cm the number of cells that had lost their pigmentation and/or contents increased, although retaining a pale yellow-green colouration (Plate II a and b). The very pale colonies of Aphanothece elebans f. minor were very difficult to count and were probably underestimated. The number of A. elebans was fairly constant throughout the core (figure 4.6) except for the peaty layers which contained few Cyanophyceae remains. A. elebans f. minor was not so abundant in the core and was mainly recorded towards the surface.

The profile for the Scenedesmus spp. is similar to that found in Priest Pot (figure 4.1). There is a rapid decrease in abundance from the topmost horizons, in which many of the cells retained their contents. Other small, unidentified, Chlorophyceae colonies were found near the surface while those of Pediastrum were present throughout the core (figure 4.7).

PLATE II

Aphanothece remains from Upton Broad

a. Aphanothece elebans
colony from core surface

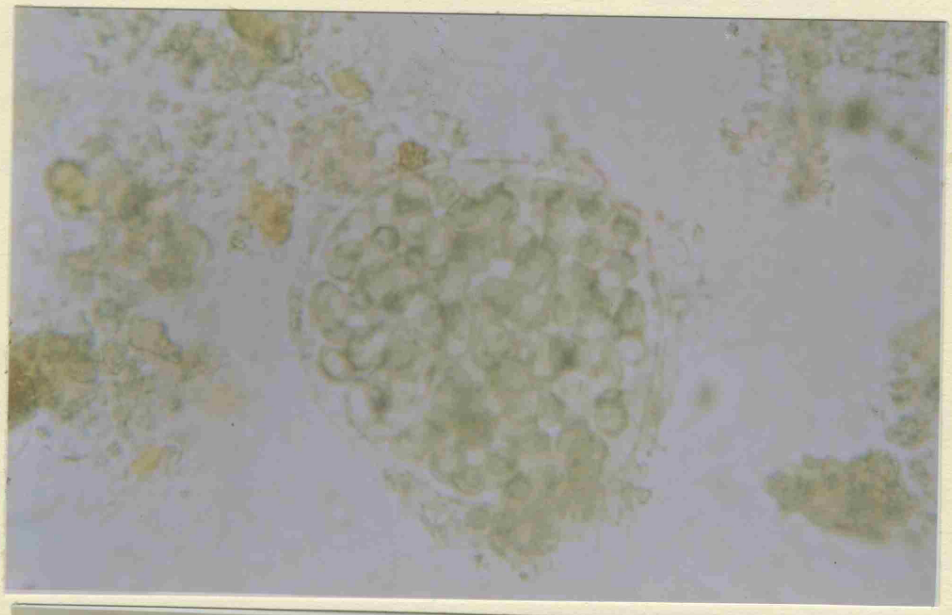
b. Aphanothece elebans
colony from 44-45 cm section (circa 1640 AD)

c. Aphanothece elebans f. minor
colony from surface section

magnification x 1600

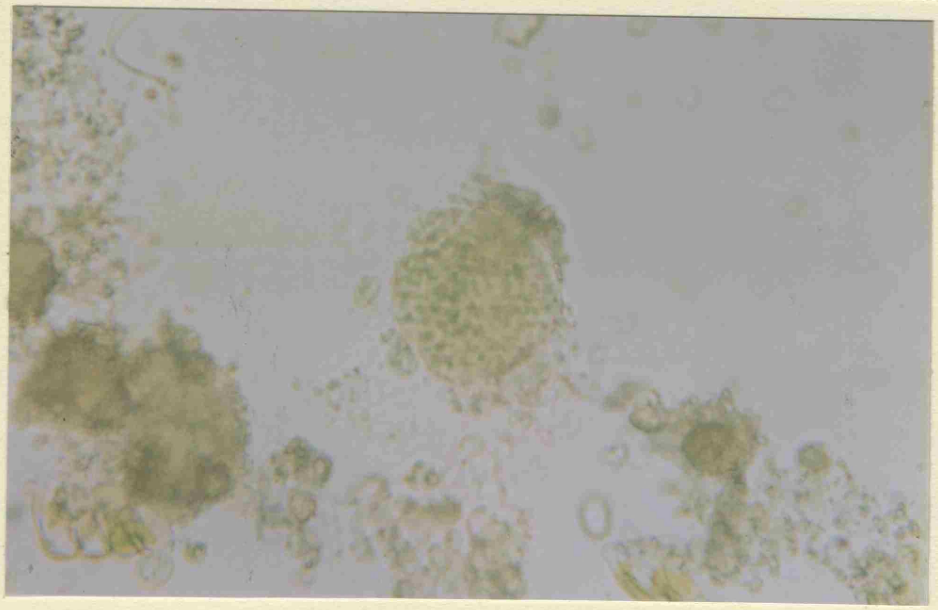
PLATE II

a



b

c



The dominant desmid genera in the core were Staurastrum and Cosmarium, the latter was more common in the lower sections of the core. The cells of Cosmarium were degraded which made identification difficult and the occasional individual of Micrasterias may have been included in the count.

ii. siliceous remains

Most of the diatom frustules in the core were recovered from the upper 40 cm and were dominated by the genus Fragilaria (figure 4.8). Over 95% of the total number of valves enumerated were of four species, F. brevistriata Grunow, F. construens (Ehrenburg) Grunow, F. pinnata Ehrenburg and F. elliptica Schumann. The core also contained the occasional fustules of Fragilaria vaucheriae (Kützing) Boye Peterson, Navicula spp. and Synedra arcus Kützing.

Moss et al. (in press) describe the diatom flora in the sediments of Upton Broad in more detail. They show that diatom concentrations were low during much of the lake's history but increased from about 1935 (circa 20 cm).

5. DISCUSSION

In contrast to the limited number of non-siliceous algal remains which are preserved in the sediments of the highland lakes, the deposits of Ellesmere Mere, Upton Broad, and Priest Pot contain a wealth of remains. Both Ellesmere Mere and Upton Broad show evidence of long term preservation of these algae.

In accord with Korde's findings (1960, 1966) algal preservation in the sediments appears to be selective, in that only specific remains

figure 4.8

UPTON BROAD – diatoms.

of certain taxa are recorded. For example, of the 24 genera (excluding the diatoms) found in the phytoplankton of Ellesmere Mere (Reynolds, 1973) only 7 were recorded in the sediments (table 4a). The small, unicellular algae are not preserved e.g. Chlorella, Rhodomonas, and Ankistrodesmus. Although some of the colonial blue-greens, such as Microcystis and Aphanothece, are preserved, the mucilage and/or cells of the colonial greens, such as Eudorina, do not appear to resist decomposition.

The phytoplankton of Priest Pot is dominated by Chlorophyceae and, apart from Scenedesmus, the lack of algal remains may be due not so much to unsuitable environmental conditions for preservation but more to the composition of the phytoplankton. The small green algae and cryptomonads are seemingly either consumed by grazing zooplankton or are rapidly decomposed in the water column and in the superficial sediments. The fact that large numbers of Scenedesmus colonies are found within the sediment column of Priest Pot to a depth of circa 8 cm, albeit with a steady decline from the surface and increasing loss of contents, suggests that decomposition rates within the muds are slow in Priest Pot and perhaps the more resistant algae could be preserved. It is notable that few individuals of Scenedesmus were recorded below circa 10 cm in the sediments of Upton Broad which contain a great number of preserved algae. However, it is not known whether the alga has always grown in Upton, or is a recent addition to the assemblage.

Goulder's work on the ciliated protozoa (1971a, 1971b, 1972a, 1972b) of Priest Pot gives an insight into an aspect of decomposition. The larger (> 150 μm) ciliates were found exclusively in the top centimetre of the sediments, with populations of up to 7700 individuals cm^{-2}. The common species in Priest Pot are Loxodes magnus Stokes and

Table 4a The Algae - Ellesmere Mere
(excluding the diatoms)

1. Myxophyceae
   - Anabaena → Akinetes preserved
   - Aphanizomenon → Akinetes preserved
   - Aphanocapsa
   - Coelosphaerium
   - Microcystis → Colonies preserved

2. Chrysophyceae
   - Chrysococcus

3. Chlorophyceae
   - Ankistrodesmus
   - Botryococcus
   - Chlorella
   - Closterium
   - Didymocystis
   - Elakatothrix
   - Eudorina
   - Pediastrum → Colonies preserved
   - Phacotus
   - Raphidonema
   - Scenedesmus → Colonies preserved (at surface only)
   - Staurastrum → Cells preserved
   - Tetraedron

4. Euglenophyceae
   - Trachelomonas

5. Dinophyceae
   - Ceratium → Cyst wall preserved
   - Peridinium

6. Crytophyceae
   - Cryptomonas
   - Rhodomonas

(from Reynolds (1973))

Loxodes striatus Penard but they become scarce in the sediments when saprobic conditions prevail in the hypolimnion (low in oxygen and high in potentially toxic substances such as sulphide, ammonia and carbon dioxide). A single Loxodes magnus is capable of digesting between 0.38 and 1.28 cells per hour and up to 76 Scenedesmus cells were found in a single organism. Goulder calculated that the population of L. magnus (estimates varied widely due to considerable variation from core to core) could graze 600-6170 cells cm^{-2} day^{-1}, which represented 0.003-0.68 % of the standing crop. Although Goulder states this is not a significant number, these estimates become 0.6-124.4 % when calculated for a period of 6 months (i.e. approximately when the waters are oxygenated) which may result in a substantial loss of Scenedesmus colonies, particularly when other ciliates, benthic rotifers and crustaceans are considered - all of which may also be feeding on Scenedesmus. Goulder does not state if the colonies are recognisable after egestion from the ciliates.

The lacustrine deposits, which overlie the peat of Upton Broad, represent over 500 years of sediment accumulation (Moss et al., in press). Therefore it is probable that the Aphanothece elebans colonies which are preserved near the peat boundary were deposited at the beginning of the fifteenth century. The colonies which retain their pigmentation are about 30-40 years old.

The desmids in the sediments of Upton Broad, although quantitatively unimportant, may give an insight into the past environment. Species of Staurastrum were found in most of the sections examined (except between 10 cm and 20 cm) but only two individuals were recorded in the peatier layers. These lower strata are dominated by species of Cosmarium which are often associated with boggy environments, although

some are cosmopolitan. The genus Staurastrum is common in the plankton of many lakes, particularly those with soft water. Therefore it can be hypothesised that the remains of the Cosmarium represents a period when bog was present, before the lake proper formed and Staurastrum became common. The decline in Cosmarium abundance may reflect the declining area of exposed peat as lake mud was deposited around the sites of the broad, over which there is now a fen-succession.

Despite the very shallow water the sediments of Upton Broad remain stratigraphically ordered (cf. Pb-210 dating). Undisturbed sediment cores have been taken from several shallow broads (Moss et al., in press). The presence of intact and uneroded diatom frustules throughout the core indicates that the rapid increase in valves towards the surface is not merely a silica dissolution curve.

Moss et al. (in press) attribute the recent (circa 1935) increase in fertility of Upton Broad, evidenced by increased diatom production and greater sedimentation, to the intensification of farming and land fertilisation in the post-war period. A further acceleration in the 1970's may be related to a nearby pig farm or even greater land fertilisation. Moss et al. suggested that the lack of diatoms, and the low diversity of the flora

> "..may reflect the 'extreme' chemical conditions of a highly calcareous lake in which trace elements and phosphate are readily precipitated out with carbonate particles".

They also mention that the dominant macrophyte, Najas marina, has a smooth texture which may not encourage epiphyte growth, and the phyto-plankton is comparatively sparse.

The superficial sediments of Upton Broad have previously been examined by Dr. W.H. Bradley (communications with J.W.G. Lund) and were found to be similar to the algal ooze of Mud Lake, Florida (Bradley & Beard, 1969). Mud Lake also resembles Upton Broad in that it is shallow (less than 0.85 m), fed by small sluggish streams and floored by 1.0 m of algal ooze which has been accumulating for circa 3000 years. The sediment is described as:

> "an extremely soft fluid accumulation of minute fecal pellets, produced predominantly by Chironomid larvae. The pellets themselves consist almost wholly of blue-green algae and their partially digested remains".

The benthic blue-greens (Aphanothece spp. are seemingly abundant in both lakes) overgrow the sediment particles, or faecal pellets, and cling together in gelatinous masses. Only the blue-green algae, or their empty cells, are preserved in Mud Lake, Bradley & Beard state:

> "Virtually all traces of the filamentous green algae are destroyed at, or above, the mud-water interface, despite the huge volumes produced during their seasonal blooms".

The dominant green alga in Mud Lake is Spirogyra triplicata (Collins) Transeau. In the past few years heavy growth of Spirogyra sp has been noted in Upton Broad (Phillips et al., in press).

The similarity between Upton Broad and Mud Lake suggests that the factors which promote the preservation of certain algae in the latter may be operating in Upton. Bradley & Beard (1969) hypothesise that decomposition is retarded by the inhibition of bacterial activity. Incubation of Mud Lake water only resulted in an extremely small number of bacterial colonies and a medium prepared using filtered water,

inhibited, or restricted, growth of bacteria isolated from the sediment pore water. The bacterial flora of Upton Broad is unknown, except for the abundance of *Achromatium* the sediment/water interface.

CHAPTER FIVE

SECIMENT CORES FROM ROSTHERNE MERE

CHAPTER FIVE: SEDIMENT CORES FROM ROSTHERNE MERE

1. INTRODUCTION

The algal remains contained within the sediments of Ellesmere Mere and Upton Broad suggest that lowland lakes offer a greater potential for finding preserved algae than the highland sites. However the lack of past phytoplankton data for Ellesmere and Upton precluded any discussion on the validity of the remains as indicators of past algal assemblages.

Rostherne Mere, Cheshire, has probably one of the longest phytoplankton records, excluding sites in the English Lake District, in this country. The first records date from the beginning of the century and since 1962 the lake has been monitored more or less regularly. In addition to a knowledge of the algae there is also a wealth of information relating to the flora, fauna and chemistry of the lake and its environs. Collectively these potentially provide one of the prime sites in Britain to study algal remains in recent lake sediments.

2. SITE DESCRIPTION

Rostherne Mere (national grid reference SJ 745843) is situated in a lowland farming area of Cheshire, to the south of Greater Manchester.

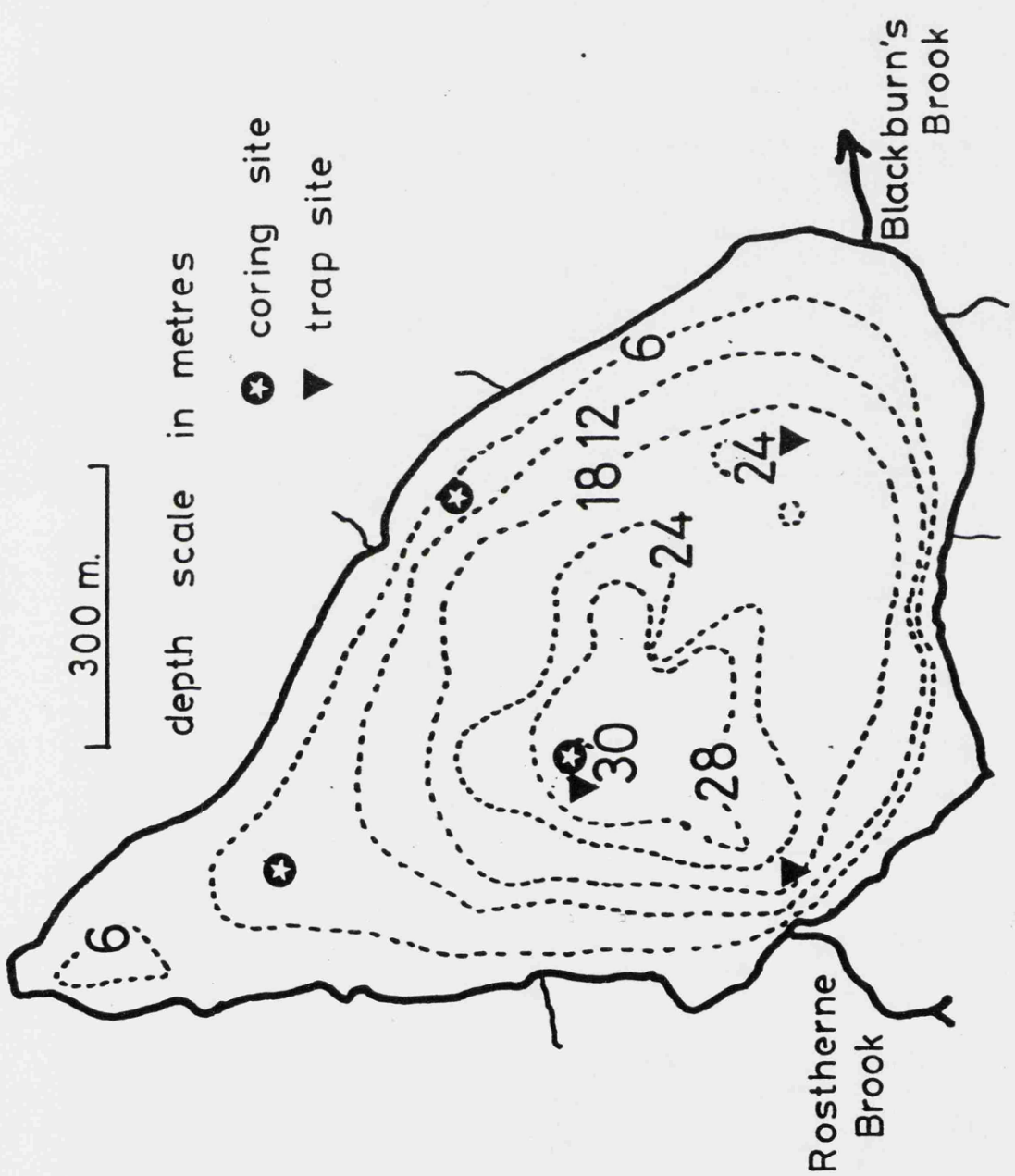
The lake lies in a depression formed in glacial drift (boulder clay and sand) which overlies Triassic marl and salt beds (Hains & Horton, 1969). The origin of the basin is uncertain and two explanations have been suggested. The mere may have formed as a result of subterranean solution of underlying salt beds or alternatively the basin

may be a kettle hole, formed by the melting of a stagnant ice block entombed in the drift. Unfortunately the lake neither coincides with the wedge of salt beds, nor do the drift deposits reach a thickness sufficient to contain the basin (Pritchard, 1961).

The basin (figure 5.1) is generally steep sloped except for the south-east corner where there are extensive shallows. It is the deepest, and one of the largest, of the meres group with an area of 0.4 65 km^2 and maximum depth of 30 m (mean depth 15 m). In common with the majority of the meres phreatic drainage is presumably an important component in the total input. The main surface inflow is Rostherne Brook which drains circa 8 km^2 of the 9 km^2 catchment and provides 80-90% of the total volume of surface inflow (Rogers, 1975). The brook passes through a small, highly rich lake, Mere Mere before reaching Rostherne. The outflow, Blackburns Brook, joins the River Birkin about 0.5 km from the lake and subsequently flows into the River Bollin and the Manchester Ship Canal. The gradient of Blackburns Brook is very gradual and after heavy rainfall the water backs up and occasionally the flow is reversed back into the mere (Pritchard, 1961). The retention time of the mere is of the order of two years (Harrison & Rogers, 1978).

The ionic composition of Rostherne Mere has been analysed by Tattersall & Coward (1914), Gorham (1957) and Grimshaw & Hudson (1970). The waters are rich in nitrogen and, in particular, phosphorus. The maximum concentrations of both nutrients have increased during the past twenty years (Reynolds, 1978). Grimshaw & Hudson (1970) discounted groundwater as a likely source of these elements and considered agricultural and urban runoff to be more significant. However the population of the catchment is small and Reynolds (1975) suggested that the groundwater inputs of Crose Mere were relatively rich in

figure 5.1


ROSTHERNE MERE.
depth scale in metres
300 m.
coring site
trap site
Blackburn's Brook
Rostherne Brook
6
12
18
24
28
30

nutrients. Another possible contributing source of nutrient input is the enrichment by bird faeces in the winter months (Brinkhurst & Walsh, 1967). A large gull roost, typically numbering up to 22 000 (Harrison & Rogers, 1978), is present on the mere from September to March. Leentvaar (1958, 1967) termed the enrichment of water bodies by bird droppings, 'guanotrophy'.

In 1961 the mere, and the surrounding land was declared a National Nature Reserve. It is managed primarily as an inland refuge for wildfowl.

3. THE SEDIMENTS

a. Introduction

The sediments of Rostherne Mere were described by Tattersall & Coward (1914) as a "fine oozy, black mud". This is generally true except for the northern end, where the deposits are peaty, and around the littoral areas which may be sandy.

Intensive organic geochemical analysis has been carried out on the bottom deposits of Rostherne Mere (c.f. Thompson & Eglinton, 1978). Discussion of the results is beyond the scope of this study but the organic composition of the sediments is indicative of high productivity and high autochthonous input.

A normal diverse benthic fauna was found by Brinkhurst & Walsh (1967) at depths less than 25 m. In the deepest area of the mere there was a 'lifeless' zone in which there was a complete absence of benthic organisms. This condition was attributed to the anoxia of the surface sediments throughout the year. They suggested that the de-oxygenation was caused by large quantities of bird droppings.

b. Deep water cores

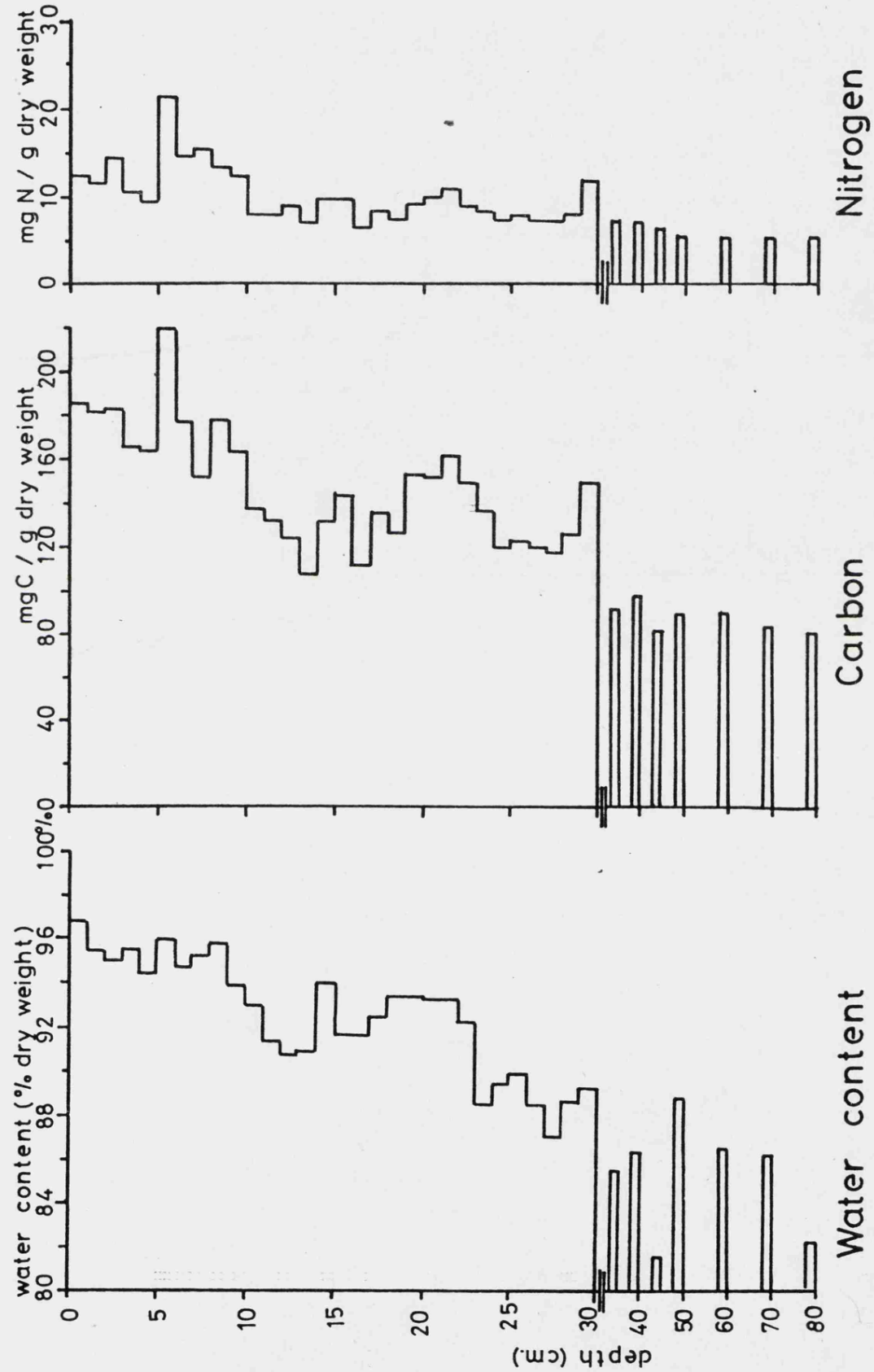
Sediment cores were collected from an area surrounding the permanent buoy in circa 30 m of water. Three cores (denoted A*, B* and C*) were examined for algal remains of which two, A* and B*, were Cs-137 dated and one, A*, Pb-210 dated. Diatoms were enumerated in core A* and dry weight, carbon and nitrogen were determined for core C*. Core A* was taken in March 1977 and B* and C* in August 1977.

The collection of cores with an undisturbed interface was difficult owing to the large amount of gas contained within the sediment column. The gas, which smelled strongly of sulphide, often destroyed the interface before the corer reached the surface. The release of the hydrostatic pressure (2 atmospheres) and the rise in temperature forced the gases to expand, coalesce and then bubble up through the tube. An attempt to allow the gas to expand laterally, via a series of small holes drilled into the side of the coring tube, was unsuccessful. Core A* was collected without any disruption of the interface but the results (see below) from other cores are similar and it appears that the gas moves around the sediment matrix and does not disturb the fine stratigraphy.

Cores from the deep water site had a distinctive, bright green, upper 2-3 cm coloured by blue-green algal colonies, predominately Microcystis. The remainder of the sediment was a black, reduced, ooze which was streaked by dark grey bands at circa 20 cm and 35 cm whilst below 70 cm the cores were very dark grey and more clayey.

The sediments of Rostherne Mere had a high water content throughout the upper 30 cm (figure 5.2). A syringe could be used to subsample this ooze while in cores from the Lake District the sediment below 5 cm was typically too compact to be handled in this way. As an approximate comparison, the water content of Blelham Tarn drops from about 93% to

figure 5.2


ROSTHERNE MERE
Water content
water content (% dry weight)
80
84
88
92
96
100%0
Carbon
mgC / g dry weight
40
80
120
160
200
Nitrogen
mg N / g dry weight
0
10
20
30
depth (cm.)
0
5
10
15
20
25
30
40
50
60
70
80

88% in the first 5 cm (Pennington et al., 1976) which compares with 96.8% to 94.4% for Rostherne.

The carbon content (figure 5.2) showed that the sediments are rich in organic matter. The mean values, since 1963, for the productive lakes of Esthwaite and Blelham are 12.7% and 16.4% respectively (Pennington, 1978) which are comparable with 15.7% for Rostherne. The oligotrophic Wastwater has a carbon content of circa 8.9%.

The nitrogen concentration (figure 5.2) of Rostherne Mere, since 1963, is 1.2%, comparable with Esthwaite (0.9%) and Blelham (1.7%) and greater than Wastwater (0.6%) (Pennington, 1978).

Gorham et al. (1974) found that the C:N ratio differed little between productive and unproductive lakes in the Lake District, and averaged 12. The mean C:N ratio for Rostherne (5-10 cm to be comparable with the data of Gorham et al.) was 11.76.

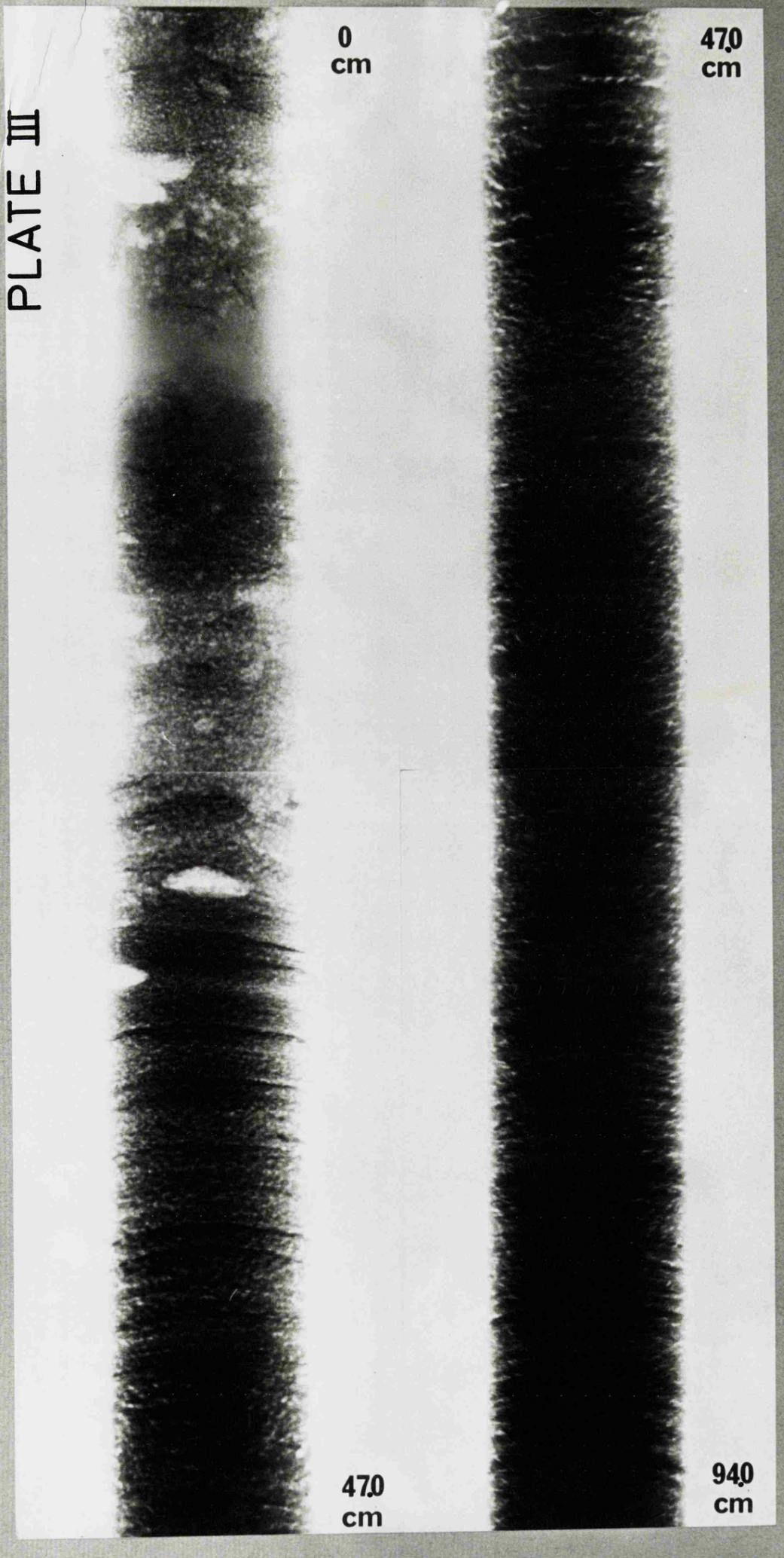
Sediment analysis of the topmost 10 cm of a Rostherne core by Mr. K. Chambers (personal communication) gave mean figures for the different size fractions of sand (> 64 μm) 5% dry weight, silt (> 2 μ, < 64 μ) 50% and clay (< 2 μ) 45%. The clay minerals, by X-ray diffraction, were illite and probably chlorite, both of which are also common in the Cumbrian lake sediments. Quartz was the dominant mineral, along with calcite, gypsum and feldspar.

X-radiography of a deep water core revealed a series of distinct black bands throughout the length of the column (Plate III). The bands are irregular and were not visible on the fresh sediment except in the upper 2 cm. The layers are assumed to be of calcite, which due to the X-ray absorption characteristics of calcite appear black on the plate. White "ash-like" layers were found in the sediment traps in September 1977 (see Chapter 7) which on inspection were granules of calcium carbonate. The core that was X-rayed had two similar bands

PLATE III

X-ray plate of a core from Rostherne Mere, Cheshire

PLATE III



in the upper section of the core. Unfortunately during transit the top 5 cm lifted from the body of the core and the layers appear distorted. The grey diffuse area at 9-13 cm is water which infilled when the top of the core broke away and the white areas inside the core tube are gas bubbles.

c. Shallow water cores

Sediment cores were taken in the shallower areas of Rostherne Mere to assess the effects of benthic organisms and oxygen in the sediments on the algal preservation and stratigraphy.

Two cores were taken, core Y* in June 1978 and core Z* in September 1978 from sites in about 8 m of water (figure 5.1). The steeply sloping west side, the peat in the north end and the sandy deposits to the south were avoided.

The cores bore little visual similarity to those from the deep water site. The top 2-4 cm was light brown, 4-20 cm black and the remainder dark brown. The mass of Cyanophyceae colonies which were a feature of the deep water cores were not visible in those from the shallower areas. The sediment column contained little gas and was more compact and sandy in texture.

4. RADIONUCLIDE DATING

a. Caesium-137

Similar results were obtained from the Cs-137 dating of cores A* and B* (figure 5.3). The maximum concentration in both cores was contained within the 16-17 cm section, and this is taken to represent

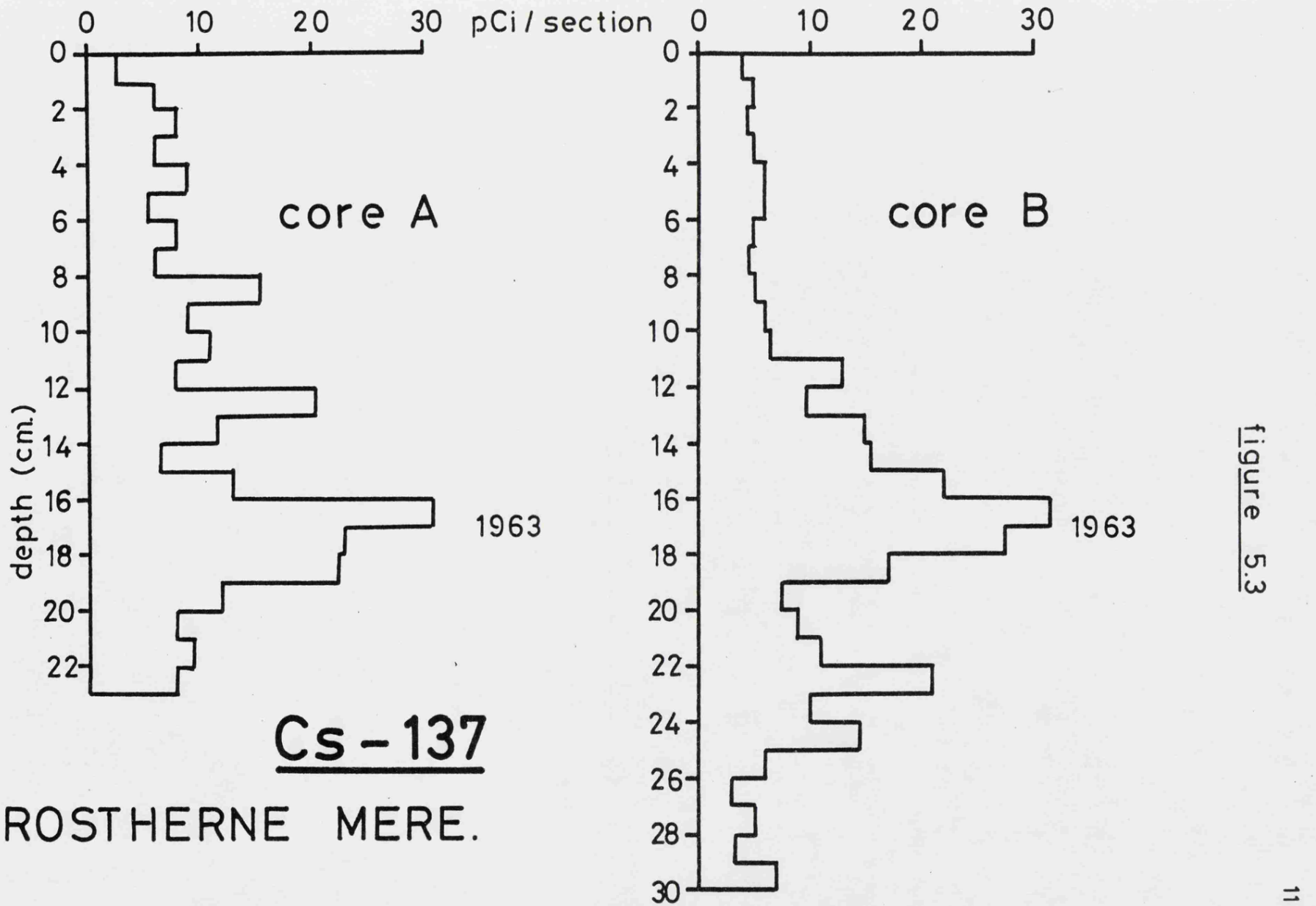

0 10 20 30 pCi / section
0 10 20 30
core A
core B
depth (cm.)
0 2 4 6 8 10 12 14 16 18 20 22
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
1963
1963
Cs - 137
ROSTHERNE MERE.

figure 5.3

the 1963 fallout peak. Thus the mean annual rate of sediment accumulation from 1963 to 1977 is about 1.22 cm yr^{-1}.

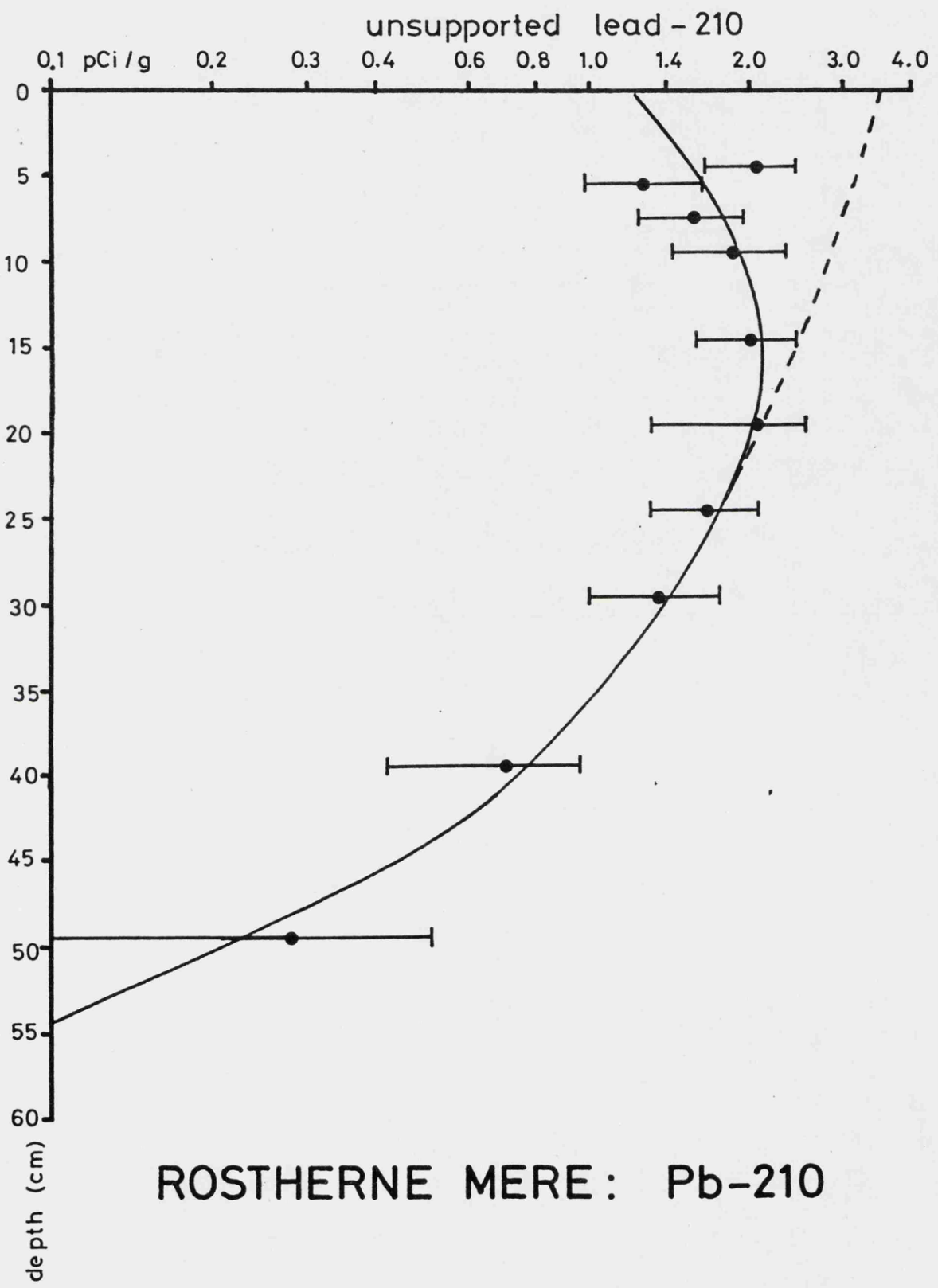
Cs-137 dating of an earlier core (Gaskell & Eglinton, 1976) gave an estimate of the annual deposition rate of 4-5 mm yr^{-1} (> 50% lower than the rate presented here). This apparent anomaly may be due to areal variation in Cs-137 concentrations (cf Pennington et al., 1973) or to the fact that Gaskell & Eglinton used a gravity corer which may have been unsuitable considering the highly flocculant surface sediments.

The profile from core A* is not smooth and although this may indicate some disturbance of the core no supporting evidence was found in the algal stratigraphy. The clay minerals of Rostherne are illite and chlorite and Tamura (1964) states that Cs-137 is very strongly retained on these (and less so on kaolinite and montmorillonite). If a section contained predominantly organic and sand particles it is possible that Cs-137 would not be retained due to a lack of suitable adsorbtion sites and hence be Cs-poor. Small peaks in a profile may represent inwash events of fine particles from the catchment. However the major peak in core A* is distinct and well correlated with core B*. The secondary peak on core B* at 22-23 cm may correspond to 1959 (R.S. Cambray, personal communication). Unfortunately analysis of core A* did not continue to this depth.

b. Lead-210

Pb-210 dating was carried out using material from core A*. The unsupported fraction (figure 5.4) increases towards the surface, until 20 cm when there is a marked inversion. Anomalously low Pb-210 concentrations in surface sediments are not uncommon but the inflection in the Rostherne core is far lower than found in other sites. Koide,

figure 5.4

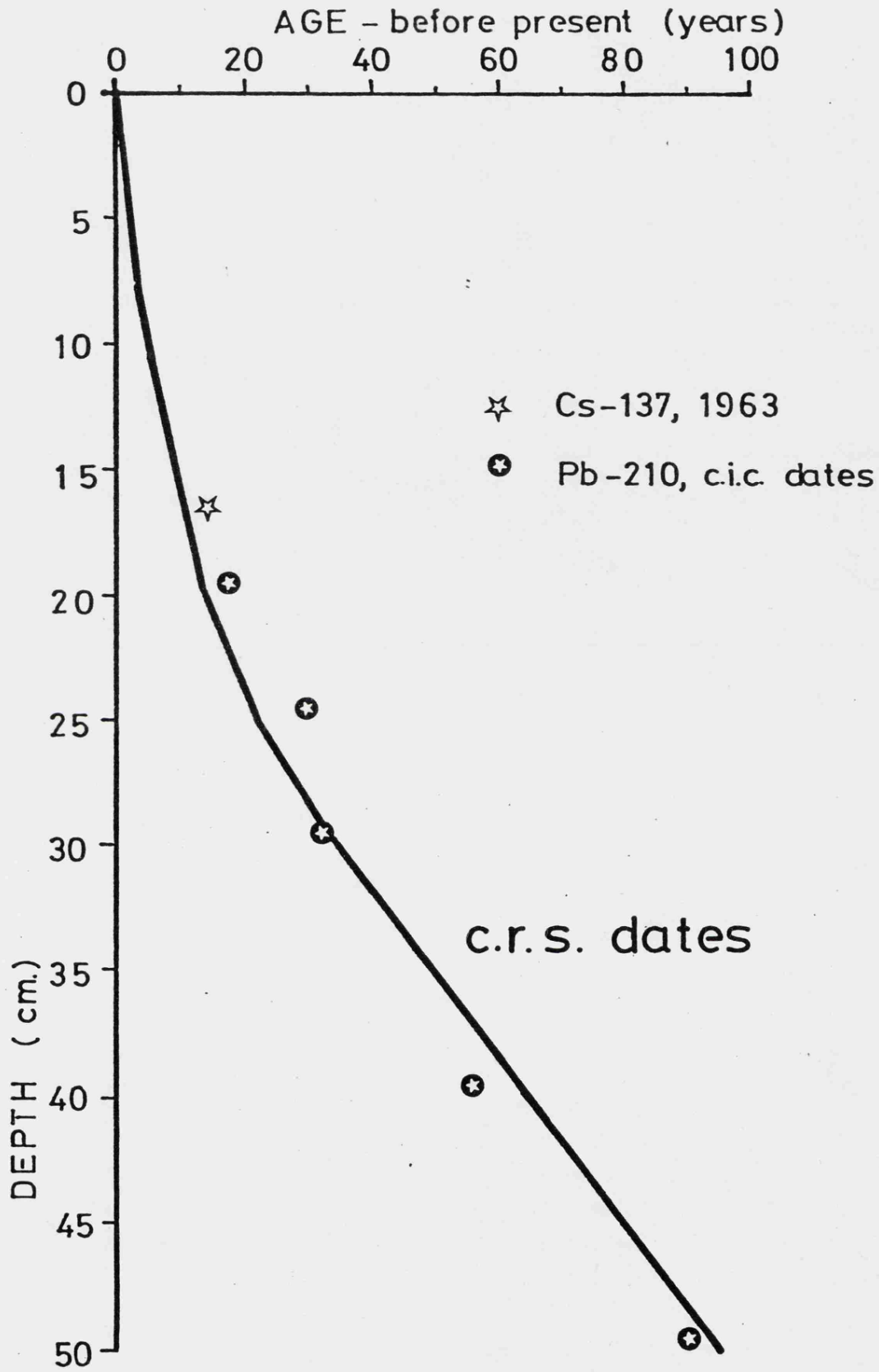

unsupported lead - 210
0.1 pCi / g
0.2
0.3
0.4
0.6
0.8
1.0
1.4
2.0
3.0
4.0
0
5
10
15
20
25
30
35
40
45
50
55
60
depth (cm)
ROSTHERNE MERE: Pb-210

Bruland & Goldberg (1973) discussed the possibility of diffusion in the surface layers to account for the depressed top point. This idea was discounted by Krishnaswany et al. (1973) who attributed lower concentrations to an increase in the rate of sedimentation. Mixing, either physical or biological, was postulated by Edgington & Robbins (1974) and Schubel & Hurschberg (1977) to be responsible. Biological mixing is unlikely in Rostherne Mere due to the lack of benthos in the deeper areas (Brinkhurst & Walsh, 1967).

Until recently Pb-210 dating assumed that there was a constant initial concentration (c.i.c.) of unsupported Pb-210 per unit dry weight in the sediment at each depth (Pennington et al., 1976; Robbins & Edgington, 1975). This assumes that there is an excess of lead available in the water and the uptake of the lead will be constant per unit weight of sediment. Therefore to calculate the age of a section by its unsupported Pb-210 content the concentration must decline linearly with depth. As the results from Rostherne Mere do not correspond with this demand the concentrations above 20 cm could not be used since they gave "negative" dates. Oldfield, Appleby & Batterbee (1978) proposed a different method of calculating the age of a section by Pb-210. They hypothesised that there is a limited amount of Pb-210 in the water, and hence an increase in the sediment accumulation rate would result in a 'dilution' of the lead per unit dry weight of sediment. This method, "constant rate of supply" (c.r.s.), allows calculation of age throughout the profiles irrespective of the rate of sediment accumulation. Appleby & Oldfield (1978) give a full exposition of the c.r.s. method and use it to provide a means of dating variations in accumulation rate resulting from human activity in the drainage basin.

The calculation of Pb-210 by the c.r.s. method results in a dating scheme for the top 50 cm of the core (figure 5.5). The c.i.c.

figure 5.5



ROSTHERNE MERE lead-210

dates (20-50 cm) and Cs-137 are in good agreement with the c.r.s. dates. The profile indicates a fairly uniform rate of sediment accrual of 5 mm yr^{-1} with an acceleration during the past 25 years.

5. PHYTOPLANKTON

The phytoplankton of Rostherne Mere is characteristic of many warm, eutrophic calcareous lakes. When compared to the richer lakes of Cumbria the mere contains fewer species, although they are far more abundant. The composition of the phytoplankton is characterised by a predominance of diatoms, dinoflagellates and blue-greens. In common with other meres the lake is subject to surface blooms during still summer weather. This is not a recent phenomenon as the "breaking of the meres" is part of local folklore (cf. Reynolds & Sinker, 1976). Unlike most Shropshire-Cheshire meres, but very similar to Ellesmere Mere, the phytoplankton for the first three months is very sparse (cf. Reynolds, 1979a).

Phytoplankton records for Rostherne Mere date from net collections made in 1912 (Pearsall, 1923), with further descriptions by Griffiths (1925) and Lind (1944). Since 1962 there has been frequent sampling (cf. Belcher & Storey, 1968; Reynolds, 1978) using a plastic hosepipe (Lund & Talling, 1957).

Pearsall (1923) found the dominant species to be Aphanizomenon flos-aquae and to a lesser extent Ceratium hirundinella. The common diatoms were Fragilaria crotonensis, Asterionella gracillima (Hantzsch) Heiberg (generally taken to be synonomous with Asterionella formosa), Coscinodiscus lacustris Grunow (possibly confused with Stephanodiscus astraea (Ehrenburg) Grunow. cf. Batterbee, 1976) and Fragilaria capucina

Desmazieres. Griffiths (1925) described a single sample taken in August 1922 which was dominated by Fragilaria crotonensis, Gomphosphaeria naegeliana (Unger) Lemmerman and Closterium aciculare var. subpronum W. and G.S. West. Also present were species of Staurastrum and Ceratium hirundinella but in common with the earlier collections very few colonies of Microcystis were observed.

The 1941-1943 samples (Lind, 1944) differed from those of Pearsall (1925) in that Coelosphaerium kutzingianum Nageli replaced Aphanizomenon as the dominant blue-green, Fragilaria crotonensis was inconspicuous and Stephanodiscus astraea was less common. However the late summer dominance was similar and Lind states: "Rostherne was remarkable for the abundance of Ceratium hirundinella".

Mrs. J. David (1964) examined net collections from 1962 and 1963. The spring diatoms were chiefly composed of Asterionella formosa, Fragilaria crotonensis and Fragilaria capucina. Asterionella was abundant in 1963 and the two Fragilaria species in 1962. The June maxima were of Aphanizomenon flos-aquae plus Coelosphaerium kutzingianum in 1962 and of Anabaena flos-aquae in 1963. The autumn of both years was dominated by blooms of Microcystis aeruginosa but in 1963 this was preceded by a large population of Ceratium hirundinella.

The summer and autumn samples for 1964, 1965 and 1966 were dominated by surface blooms of Microcystis aeruginosa (Belcher & Storey, 1968). These were preceded by large populations of Anabaena flos-aquae or Aphanizomenon flos-aquae. The dominant diatoms were Asterionella formosa (especially in 1965) and Stephanodiscus hantzschii with other frequent taxa being Melosira granulata, Fragilaria capucina and Fragilaria crotonensis.

Reynolds (1978) described the phytoplankton between 1967 and 1977 and found four out of the eight summers studied were dominated by Microcystis aeruginosa. In two of the remaining years (1971 and 1975) Ceratium hirundinella dominated while in 1967 both Ceratium and Microcystis were abundant and in 1968 neither thrived and the summer phytoplankton was dominated by Melosira granulata, Asterionella formosa and Anabaena spp. Yearly variations are seemingly commonplace in the phytoplankton with occasional maxima of the diatoms Cyclotella pseudostelligera (abundant in 1971), Melosira granulata (1968) and Stephanodiscus astraea (1973). These events, together with the Ceratium-Microcystis fluctuations, may provide many potential stratigraphic layers in the sediment column.

A synthesis of the phytoplankton data of Rostherne Mere is presented in table 5a. Additional or more detailed records are from the unpublished data of Mrs J.E. David and C.S. Reynolds and reproduced with their kind permission. It must be noted that the assessment of biomass was purely subjective and each alga was considered in isolation whenever possible.

6. ALGAL REMAINS

a. Deep water cores

The material from each of the deep water cores contains a wealth of non-siliceous algal remains. The relic assemblages resembled those from the Ellesmere Mere sediments but the remains were more numerous and well stratified in the sediment column. Most commonly recorded were remains of Ceratium, Microcystis, Staurastrum, Anabaena, Pediastrum and Aphanizomenon, while individuals of Coelastrum and

Table 5a Collected Phytoplankton Data 1912-1977

Year	19	12/13	22	41/43	62	63	64	65	66	67	68	71	72	73	74	75	77
Ceratium		A	C	A	p	A	C	C	p	C	p	A	C	p	p	A	p
Microcystis		p	p	p	A	A	A	A	A	C	p	p	A	A	A	p	A
Anabaena		p		p	p	A	C	C	C	C	A	C	p	A			c
Aphanizomenon		A		p	A	p	C	C	C	A	A	C		A			
Oscillatoria				p	p	p	p	p	p					p			
Coelosphaerium		p	A	C	A		p	p	p	p							
Staurastrum		C	C	p			C	C	C	p	p	p	p	p			p
Melosira granulata				p			C	C	C	p	A	C	C	p			p
Asterionella formosa		C	p	A	C	A	C	A	C	C	C	C	A	C			p
Cyclotella pseudostelligera						p	p	p	p	p	p	C	p	p			p
Fragilaria crotonensis		C	A	p	A	C	C	C	C	p	p	p	C	p			p
Fragilaria capucina		C		p	A	C	C	C	C	C	p	p	p	p			p
Stephanodiscus astraea		C		p		p	p	p	p	C	p	p	C	A			p
Stephanodiscus hantzschii						A	C	C	C	p	p	C	p	p			p

A - abundant

C - common

p - present

blanks - not recorded

Scenedesmus were occasionally observed. As with the remains in Ellesmere Mere the genera found in Rostherne Mere show many similarities to those recorded by Korde (1960, 1966) in the sapropel deposits of the U.S.S.R.

The cysts of Ceratium hirundinella were devoid of contents except for an orange-brown intracellular residue. Plate IV shows examples of such cysts, still recognisable by the distinctive horns. During the course of the study only two cells of Ceratium were observed to have been preserved in the muds (Plate V no. 6). The Microcystis colonies in the surface layers (0-2 cm) often appeared to be healthy (Plate VI no. 1). These tight, dark colonies gave the top of the cores the characteristic green spotted appearance. At depth the colonies became progressively paler and the cells more diffuse (Plate VI no. 2). Methylene blue, or negative stain, was used to identify these colonies (Plate VI no. 3).

Remains of the filamentous blue-greens, Anabaena and Aphanizomenon were restricted to the akinetes (Plate V nos. 3 and 4). Those of Anabaena were often found in clumps of up to 50-70 akinetes in one aggregate. Single akinetes of Anabaena were often difficult to differentiate from those of Aphanizomenon. The akinetes often contained intracellular contents, although not enumerated separately, and their viability was tested (see Chapter 6). Colonies of Pediastrum were common and counted in cores B* and C* along with small numbers of Coelastrum. Cells of Staurastrum were present throughout the core and the occasional Scenedesmus was recorded (cf. Plate V no. 5, colony from Blelham Tarn).

The diatoms of Rostherne's deep water sediments were dominated by planktonic species, particularly Stephanodiscus hantzschii,

PLATE IV

Ceratium remains

a + b. Cysts with contents, from surface sediments

c. Rostherne Mere
(core A*, section 25-26 cm)

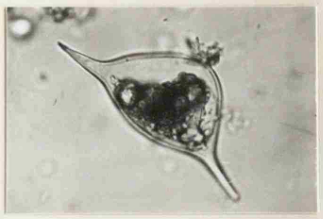
d. Esthwaite Water
empty cyst from culture experiment
(see Chapter 7)

e - h. Rostherne Mere
(core A*, sections 25-26 cm and 59-60 cm)

note: residue in the "empty" cysts except in (d)

magnification x 400

PLATE IV



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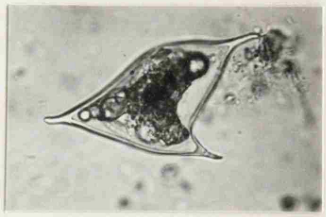

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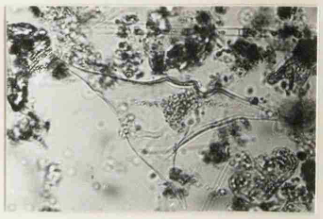

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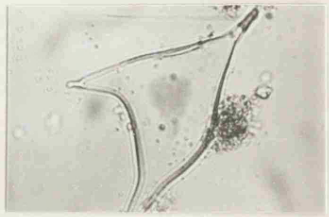

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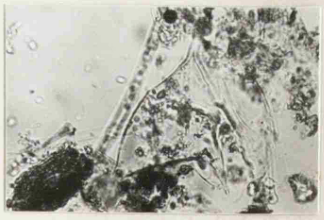

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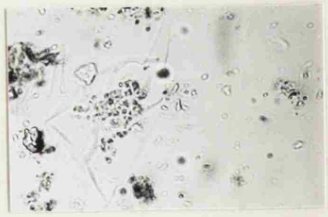

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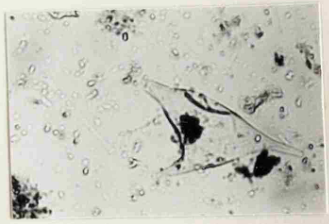

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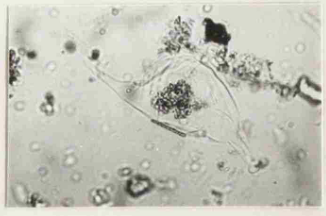


h

PLATE V

Algal remains

1. Microcystis x 100
   Rostherne Mere

2. Microcystis & Nitzschia palea x 100
   Rostherne Mere - plankton sample, September 1977

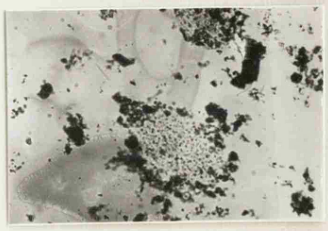
3. Anabaena akinetes x 200
   Rostherne Mere (core A*, section 27-28 cm)

4. Anabaena akinetes x 400
   Rostherne Mere (core A*, section 24-25 cm)

5. Scenedesmus x 600
   Blelham Tarn (section 4-5 cm)

6. Ceratium cell x 200
   Rostherne Mere (core A*, section 4-5 cm)

PLATE V



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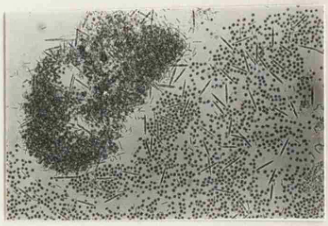

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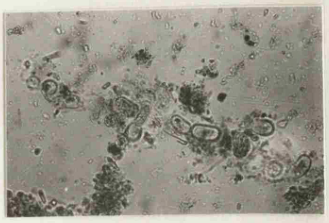

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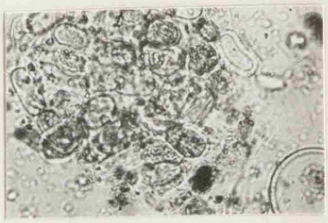

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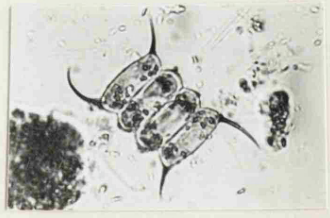

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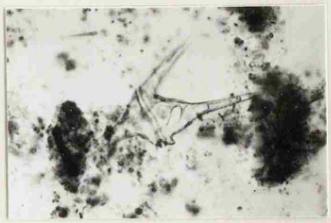


6

PLATE VI

Microcystis remains from the sediments of Rostherne Mere

1. Surface colony

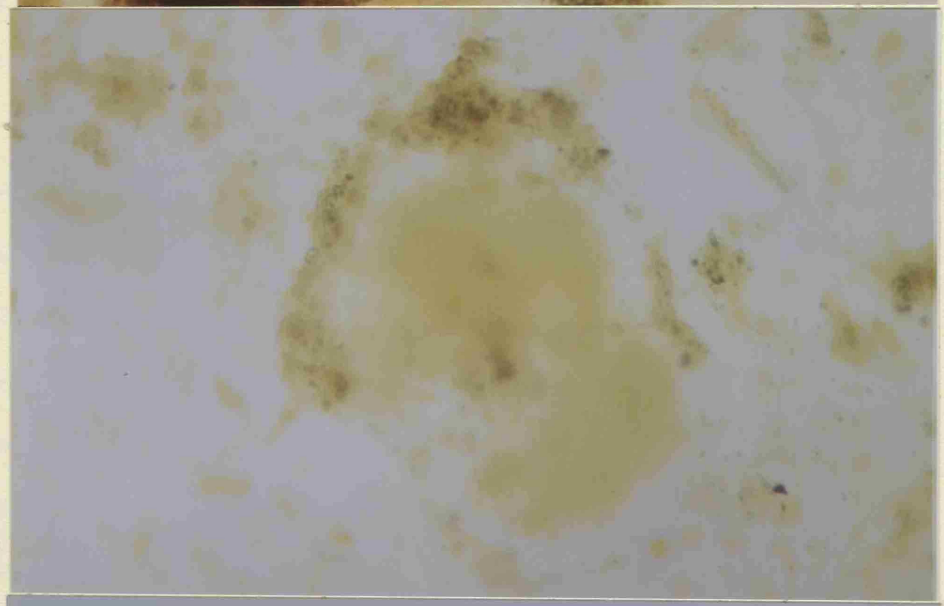
2. Colony from 4-5 cm section (circa 1974)

3. Colony from 16-17 cm section (circa 1964) stained with methylene blue

magnification x 400

PLATE VI

1



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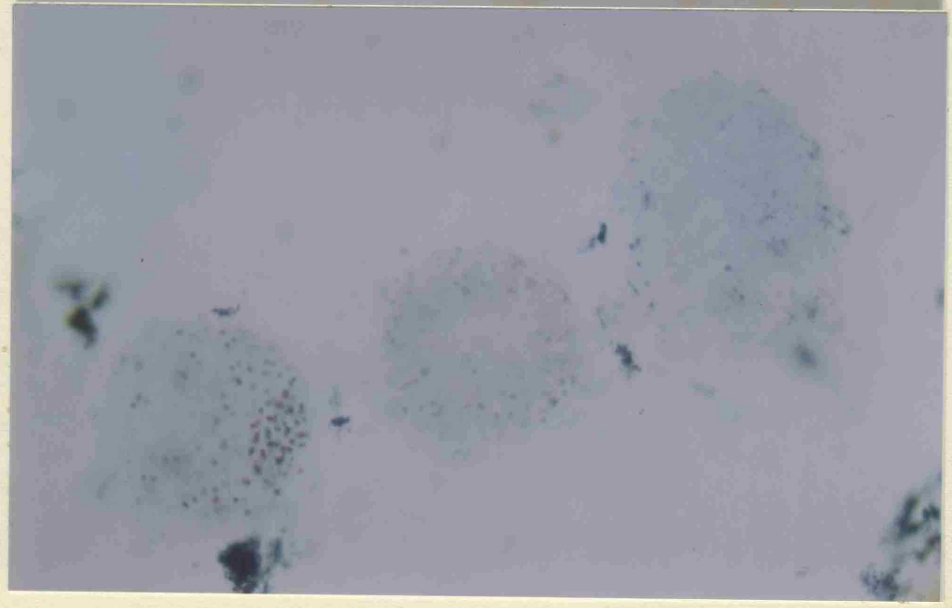


3

Asterionella formosa and Melosira granulata. Smaller numbers of Stephanodiscus astraea, Nitzschia palea and Cyclotella pseudostelligera were also present. Reynolds (1978) observed that in certain years the Microcystis colonies had considerable growths of Nitzschia on their periphery. Plate V no. 2 shows an example from a plankton sample taken in 1978. Ganf (1974) also recorded Nitzschia spp. embedded in the mucilage of Microcystis colonies from Lake George, Uganda.

The stratigraphy, considering the algal remains, of the three deep-water cores is very similar. However numerical differences between them may be greater than an order of magnitude. All the profiles are well structured and show little evidence of mixing (i.e. smoothing of the profiles). The availability of detailed algal records over the past 15 years enables specific horizons of a core to be dated by either the algal content of a section or a change in assemblage between sections.

Considering core A*, initially, the algal stratigraphy (figure 5.6) accurately reflects some aspects of the phytoplankton data and an 'algal chronology' can be established. The fluctuations in summer dominance during the period 1963-1977 between Microcystis and Ceratium are reproduced in the sediment column above 17 cm. The recent shift to increased Microcystis populations over the past two decades (Reynolds & Rogers, 1976) is found in the profile around 20 cm which dates circa 1958. Independently of the Cs-137 and Pb-210 methods, dates may be assigned to particular sections where "interludes" of Ceratium occur. Therefore the 2-3 cm slice can be taken to represent 1975 and similarly 1971 is reflected in the 8-9 cm section. It is not possible to date the remains of other non-siliceous algae because either the number of individuals was small (e.g. Staurastrum) or the

Figure 5.6

Rostherne Mere - algal remains, core A*

a. Ceratium hirundinella : cysts (shading = with contents)

b. Microcystis spp (predominantly M. aeruginosa)

c. Anabaena spp : akinetes

d. Aphanizomenon flos-aquae : akinetes

e. Staurastrum spp : cells

f. Stephanodiscus astraea : cells

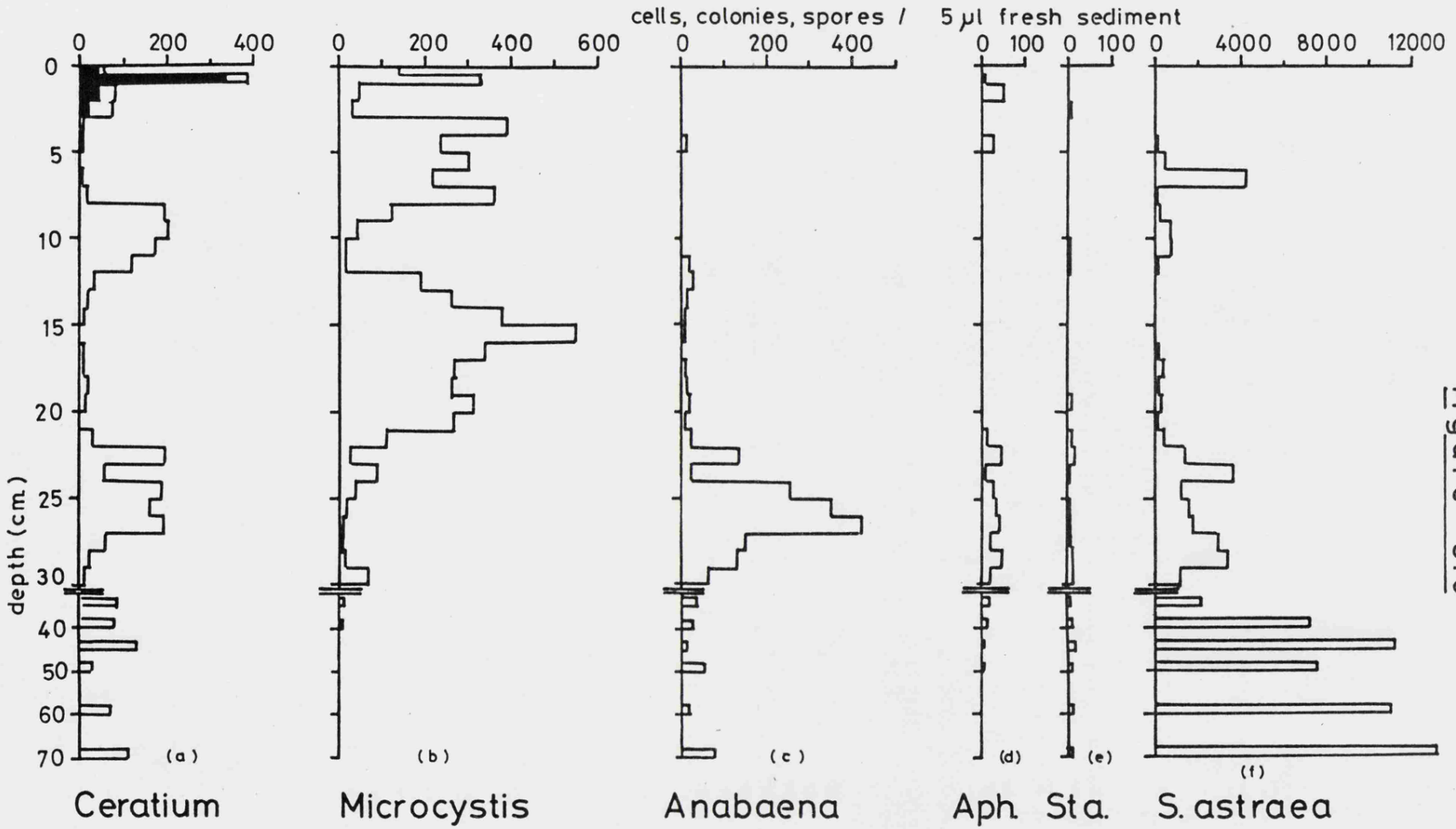


figure 5.6

ROSTHERNE MERE - algal remains

[core A]

bulk of the remains do not coincide with a period covered by the records (e.g. Anabaena). The more recent (post 1960) populations of Anabaena and Aphanizomenon are not reflected in the number of akinetes left in the sediments.

Stephanodiscus astraea was counted on both fresh and digested material. Although the pattern of the profiles is similar (figures 5.6 and 5.7) there are some numerical inconsistencies,especially at low concentrations. A similar result for the same alga was also found in Ellesmere Mere (see Chapter 4). The diatom was recorded by Pearsall (1923) and Lind (1944) and the core suggests that it was abundant around the turn of the century when compared to the present day. Reynolds (1978) quotes a typical figure of < 20 cells ml^{-1} but 1973 produced a relatively large population (maximum 110 cells ml^{-1}) and this is contained within the 6-7 cm slice of core A*. The limited occurrence of large populations of other diatoms (figure 5.7) enables this algal dating scheme to be extended. Therefore the maxima of Cyclotella pseudostelligera (8-9 cm) may be assigned to 1971 and that of Melosira granulata (11-12 cm) to 1968.

While the species which have had isolated maxima give discrete peaks within the sediment column those which have been regularly recorded leave an unclear record. Reynolds (1978) records a maximum of 7200 Asterionella cells ml^{-1} in May 1972 (typically about 1000 ml^{-1}) but it is not obvious on the profile. Similarly Stephanodiscus hantzschii was more numerous in 1971 than in other years studied by Reynolds but maxima in the profile do not correspond with the 1971 peak of Cyclotella pseudostelligera which is found in the 8-9 cm horizon.

Cores B* and C* showed very similar patterns of algal remains to core A* throughout their length (figures 5.8 and 5.9). The

Figure 5.7

Rostherne Mere - diatom stratigraphy, core A*

a. Asterionella formosa

b. Stephanodiscus astraea

c. Stephanodiscus hantzschii

d. Melosira granulata

e. Nitzschia palea

f. Cyclotella pseudostelligera

g. 'other' diatoms (predominantly non-planktonic)

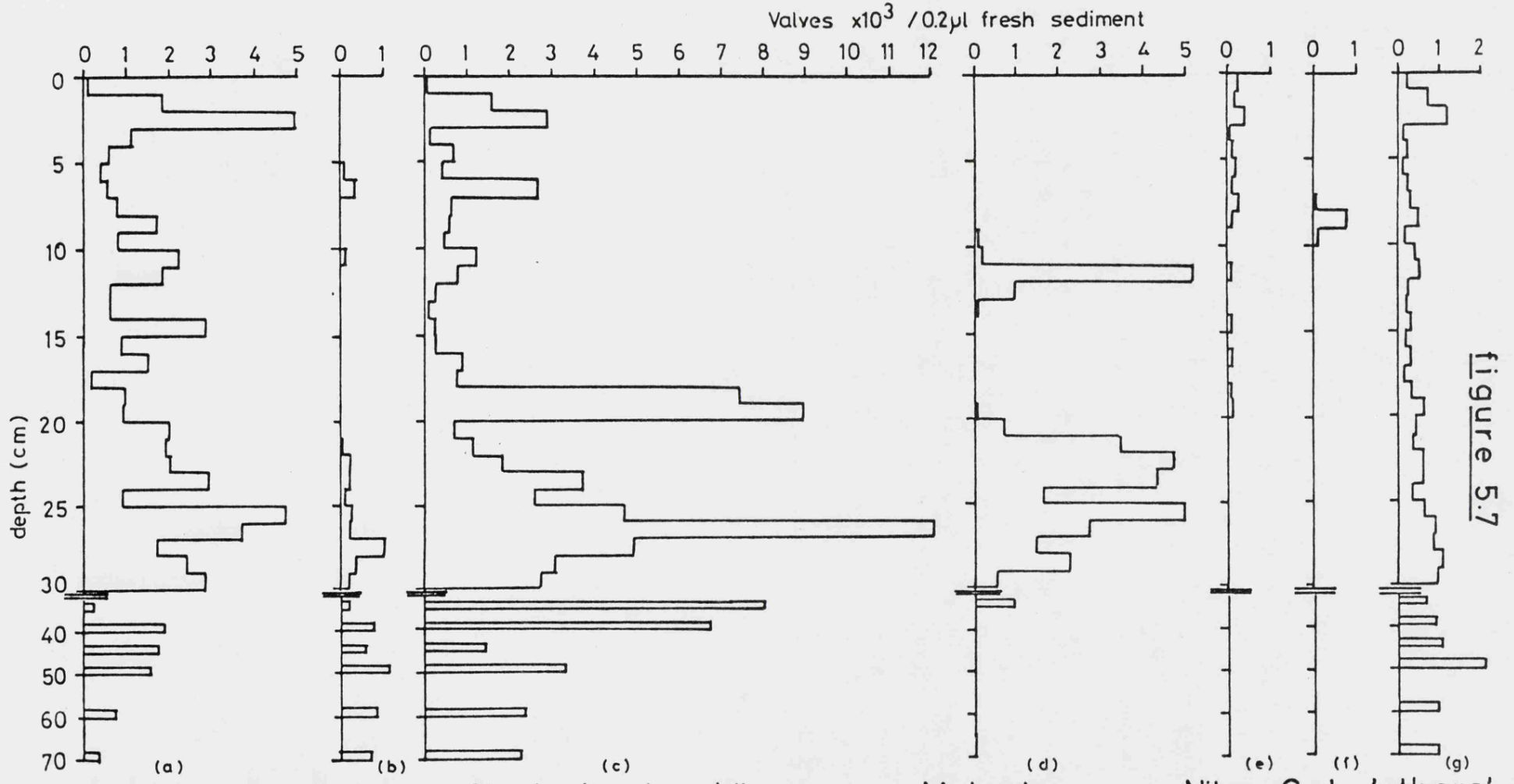


figure 5.7

ROSTHERNE MERE

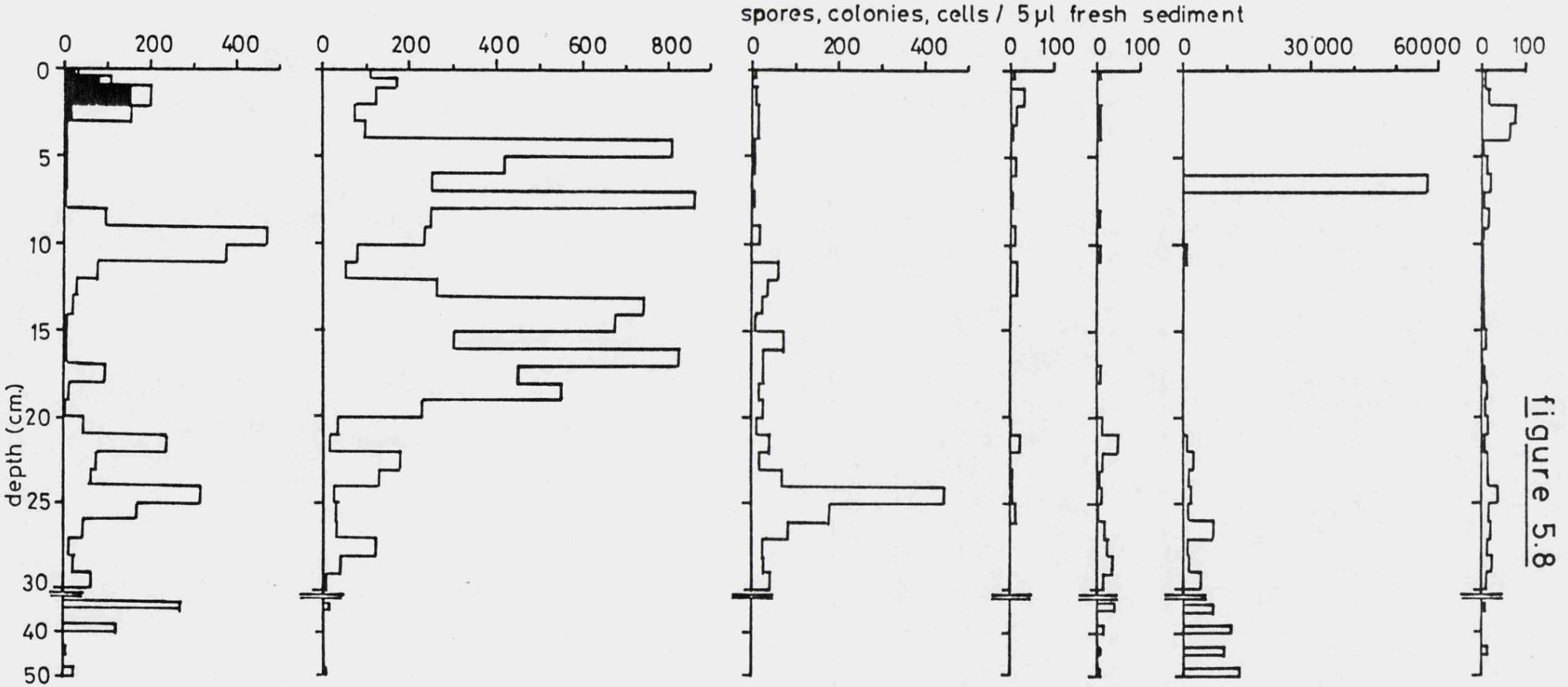


figure 5.8

ROSTHERNE MERE - algal remains

[core B]

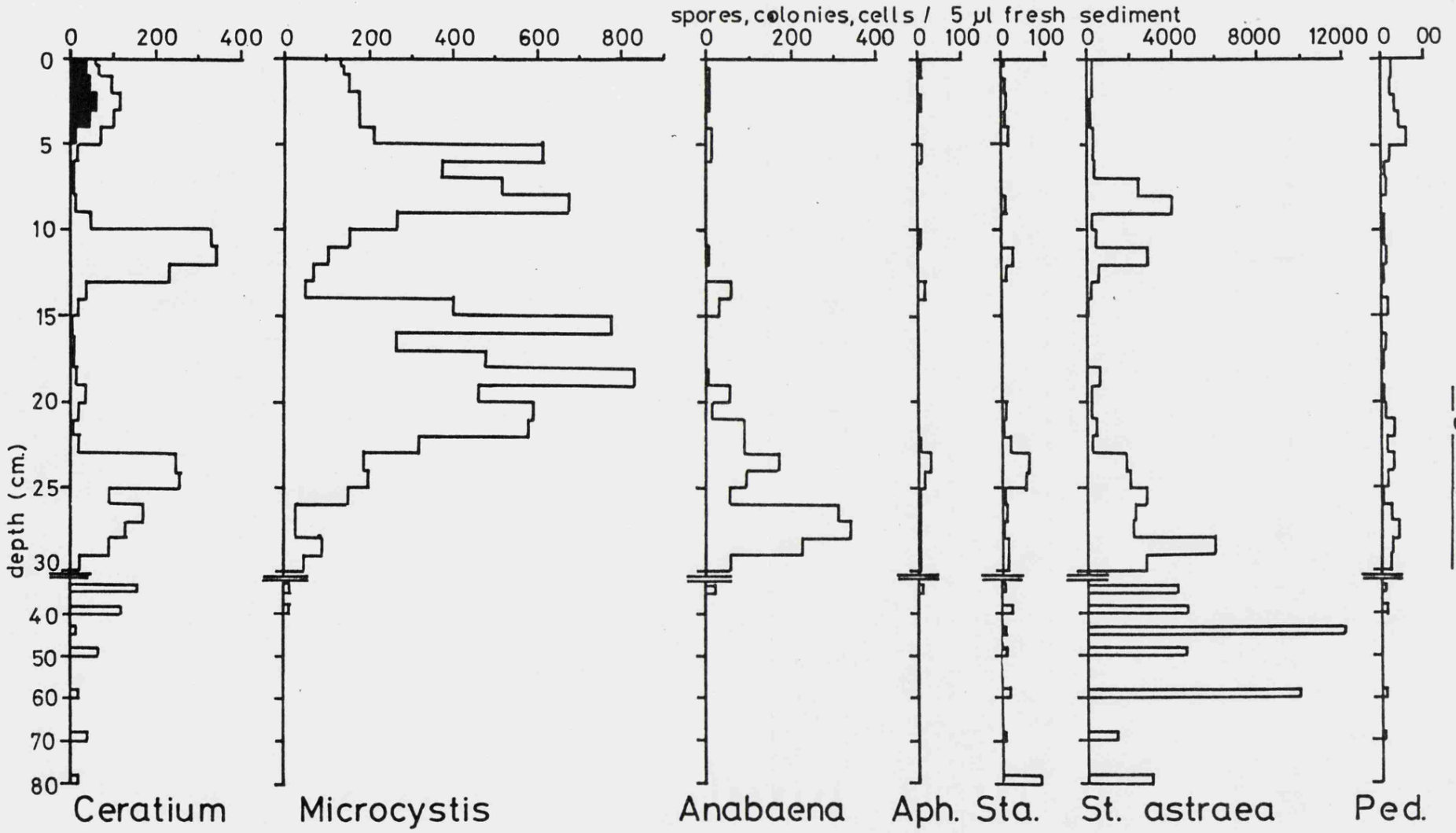


figure 5.9

ROSTHERNE MERE - algal remains.

[core C]

Ceratium peaks in the upper 20 cm are more pronounced than in core A* and 1975 and 1971 can be easily located. The dates for core B* correspond with those of A* but the top of core C* is slightly stretched, perhaps caused by the gas. Core B* shows a pronounced peak of Ceratium at 17-18 cm and this may represent the large 1963 population (David, 1964). A corresponding, but smaller, maxima may be found at 19-20 cm in core C* and circa 18 cm in A*. The dating of this level by the algal remains is consistent with the Cs-137 dating scheme (cf. Livingstone & Cambray, 1978).

The cores contained small numbers of Aphanizomenon and Staurastrum, although the latter was more numerous in the 79-80 cm slice from core C*. Large concentrations of Anabaena spores were present between 20-30 cm but, similar to core A*, the most recent phytoplankton populations are not represented. Pediastrum colonies were counted on cores B* and C*, although the occasional Coelastrum colony may also have been included. Remains of Pediastrum were found throughout the cores with a slight increase in the upper 5 cm which contained healthy-looking colonies.

The most striking difference between the three cores is the magnitude of the 1973 Stephanodiscus astraea peak. The maxima in cores A* and C* is around 4000 cells per 5 µl of fresh sediment while 57000 cells were recorded in core B*. At other depths the number of cells per unit volume is more comparable e.g. in the 45-50 cm section there are 10000-12000 cells in all three cores.

b. The shallow water cores

The sediment cores taken in shallower water (8 m) contained the same algal assemblage as the deep water cores. However the remains were far less numerous. This is true not only for those algae which

are rarely preserved (e.g. Microcystis) but also for the silica diatom frustules of Stephanodiscus astraea. During the summer of 1978 the filamentous blue-green Oscillatoria argardhii was abundant and many filaments were found in the surface layers of core Z* (taken in September), although no evidence of preservation can be given.

The profiles from the cores (figure 5.10) are not similar to those found in the deep water site (cf. figures 5.6, 5.8 and 5.9). The general pattern of the remains resembles those from the richer upland lakes (see Chapter 3).

The preservation of Microcystis is poor, especially in core Z* where very few colonies are found in the upper 6 cm and none below this. The abundance of Microcystis in core Y* is about an order of magnitude less than found in the deep water cores. The 1972-1977 period which was dominated by the blue-green alga is possibly represented by the remains found between 7-2 cm however the equally abundant years of 1960-1968 are not reflected in the core profile. Fewer remains and unstructured profiles were recorded for Aphanizomenon, Staurastrum, Pediastrum, Coelastrum and Scenedesmus. Core Z* was notable for the abundance of Anabaena akinetes, quantitatively comparable with the deep water cores.

The cells of Stephanodiscus astraea show similar maxima in the deep and shallow sites. The surface sections contain cells deposited between March 1977 (cf. core A*) and September 1978 (cf. core Z*) and offer another, potentially useful, stratigraphic marker. The 1973 peak is reflected in the shallow water sediments but the number of cells recorded (630 in Y* and 670 in Z* per 5 µl fresh sediment) were at least an order of magnitude lower than found in cores A*, B* (both circa 4000) or C* (57000).

Figure 5.10

Rostherne Mere - Shallow water cores

CORE Y*

a *Ceratium hirundinella* (cysts)
b *Microcystis* spp (colonies)
c *Anabaena* spp (akinetes)
d *Aphanizomenon flos-aquae* (akinetes)
e *Staurastrum* spp (cells)
f *Pediastrum* spp (colonies)
g *Coelastrum* sp (colonies)
h *Scenedesmus* spp (colonies)
i *Stephanodiscus astraea* (cells)

CORE Z*

a *Ceratium hirundinella* (cysts)
b *Microcystis* spp (colonies)
c *Anabaena* spp (akinetes)
d *Aphanizomenon flos-aquae* (akinetes)
e *Staurastrum* spp (cells)
f *Pediastrum* (colonies)
g *Coelastrum* (colonies)
h *Oscillatoria argardhii* (filaments)
i *Stephanodiscus astraea* (cells)

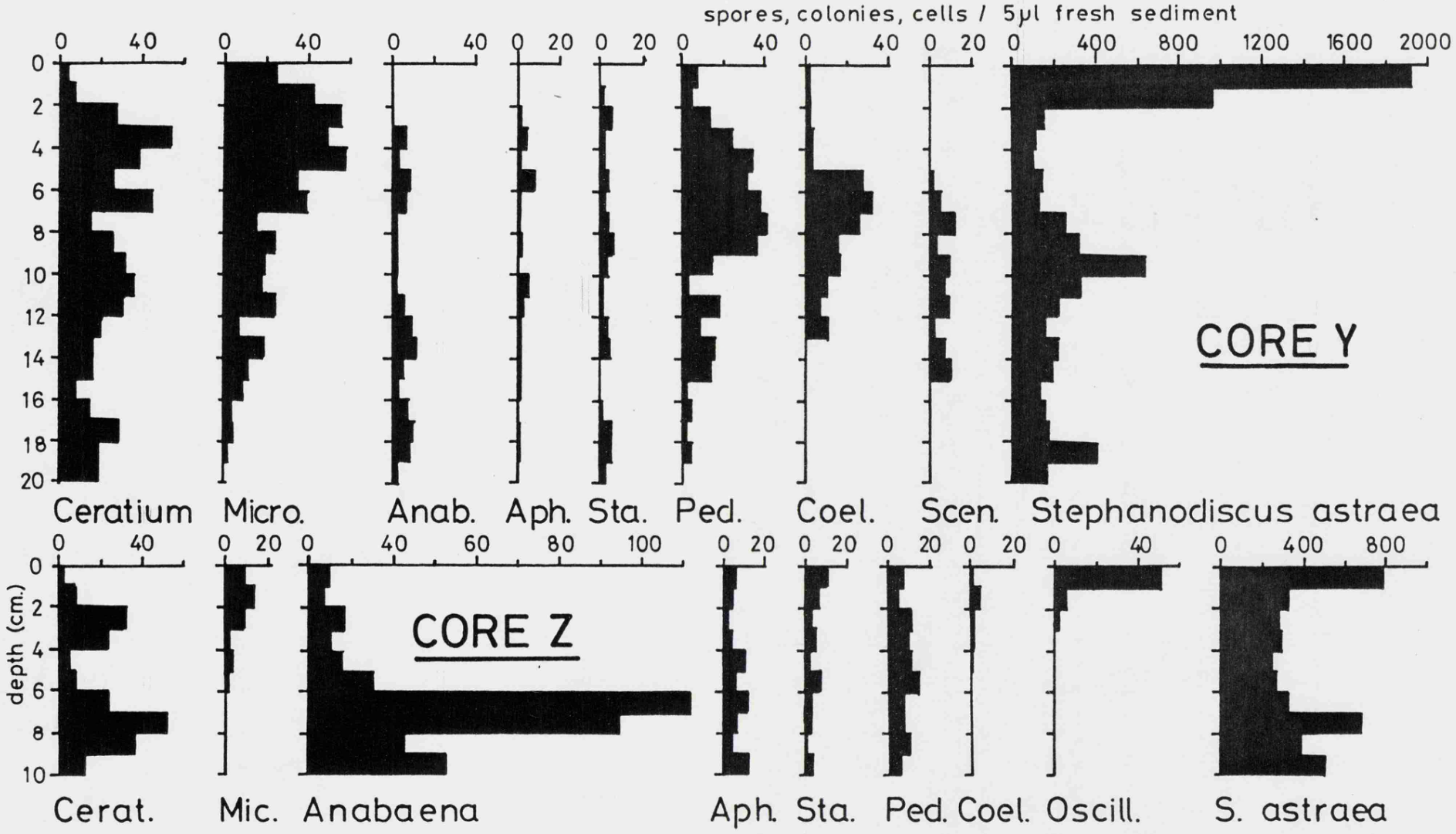


figure 5.10

ROSTHERNE MERE - SHALLOW WATER CORES

7. DISCUSSION

a. Algal remains and preservation

The numerous remains of non-siliceous algae found in Rostherne are similar to those observed in the sapropel deposits of the U.S.S.R. (Korde, 1960, 1966). 'Sapropel' is derived from the Greek for putrid mud and Challinor (1967) defines it as:

> "the unconsolidated product of the decomposition of aquatic plants and associated organisms under neutral or mildly alkaline conditions."

The algae are the main source of this organic sludge in aquatic environments (Challinor, 1967). The description appears highly suitable for both Rostherne Mere and Upton Broad (plus perhaps Ellesmere Mere). The highly reduced organic ooze of Rostherne Mere preserves some of the algae for many decades.

If numerous remains of an alga are found within the sediment core it may be assumed that it had been in the plankton. However the converse is not true, in that if remains are not found then that alga may still have been present in the lake. The species composition of algal remains in the sediments of Rostherne Mere is similar to that recorded in Ellesmere Mere. In both sites the resting spores of particular algae and the resistant cells or colonies of the larger species are preserved. There is a notable absence of the small unicellular genera such as Chlorella, Cryptomonas and Rhodomonas, which have been abundant in Rostherne Mere (Reynolds, 1978 and unpublished data).

The application of algal resting spores as indicators of past populations must be considered with some caution. In Rostherne Mere

the cysts of Ceratium, in the sediments, are seemingly related, in abundance, to plankton populations but the akinetes of the blue-greens Aphanizomenon and especially Anabaena do not reflect the vegetative population observed. The cores show that the Anabaena and Aphanizomenon populations pre-1960 (i.e. below 20 cm) produced many akinetes. Unfortunately no records are available for this section (1945-1960) and so it is not possible to correlate plankton populations with akinete concentration in the sediments. Both these algae have been common in the phytoplankton during the period 1963-1967 (see table 5a) but only a small number of akinetes are found in the corresponding sediments. These low concentrations may be attributed to:

i. Anabaena and Aphanizomenon can overwinter in the water column. Akinetes are not the only mechanism for perennation (Lund, 1965; see also Chapter 6).

ii. Akinetes may only be formed under adverse environmental conditions such as in surface blooms (Rother & Fay, 1977).

iii. Surface blooms can easily be blown to one section of the lake by prevailing winds and hence more akinetes may be deposited in littoral areas. Phytoplankton populations are also often not homogeneously distributed throughout the water column, leading to 'patchiness' (cf. Heaney, 1976).

iv. Akinetes can germinate within the water column, shortly after sporulation (Rother & Fay, 1977) and hence fewer whole specimens may reach the sediments after sedimenting through 30 m than, say, 3 m.

It is notable that the temporary nature of the akinetes, as suggested by Rother & Fay (1977) does not seemingly apply to all years when Anabaena was abundant ie. 1950-1960.

b. Sedimentation and Pb-210 dating

The Cs-137 dating method gives a mean annual rate of sediment accumulation (1963-1977) of *circa* 1.21 cm yr^{-1}. Average increments can also be computed for shorter time periods using the algal dating scheme. A rate of deposition of about 1.0 cm yr^{-1} is computed for the periods 1963-1968, 1968-1971 and 1971-1973. A rise to about 2.0 cm yr^{-1} took place after 1973.

The water content of the core does not display the typical rapid decline found in many sediments (c.f. Blelham Tarn, Pennington *et al.*, 1976). The *Microcystis* colonies hold a lot of water and there is a significant correlation (Spearman rank correlation coefficient, r_s = + 0.657, $p < 0.01$) between the alga and the water content over the top 30 cm of core C*. It could be argued that the correlation is not meaningful since *Microcystis* has only recently become abundant and water content typically increases towards the interface. However the profile of the *Microcystis* does not show an increase towards the upper layers, in fact the largest peaks are around 15 cm and 18 cm. Since the number of *Ceratium* cysts are negatively correlated with the water content (r_s = - 0.356, $p < 0.05$) it appears that the slices containing abundant *Microcystis* colonies contain more water. Therefore the annual increment laid down in a *Microcystis*-dominant year will be greater than during a *Ceratium* year. This fact was also substantiated by the trap data (see Chapter 7) when the volume of seston in 1977, which was *Microcystis* dominated was far greater than in 1978 which was *Oscillatoria* dominated.

The *Microcystis*, which contains a lot of water, is responsible for the increase in the rate of sediment accrual in the upper 20 cm of the core. It is this sudden, and irregular, rise in the rate of

sediment accumulation which renders the c.i.c. method of calculating the Pb-210 dates impractical (figure 5.11). The c.r.s. model of Pb-210 dating thus seems more accomodating to rapid accelerations in accumulation rates, although the two models are consistent below 20 cm where both suggest a uniform rate. The discrepancies between the Pb-210 and the algal dates are likely to be a function of the irregular fluctuations in sediment accrual caused by the 'interludes' of other algae apart from Microcystis (e.g. Ceratium). The c.r.s. method integrates between the points and hence is an average for that particular time period. It would be necessary to measure the Pb-210 concentrations in each contiguous slice to achieve the accuracy of the algal chronology. Therefore the c.r.s. model is applicable not only to variations in accumulation rate resulting from human activity, such as the installation of sewerage schemes, and catastrophic events such as volcanic ash layers (Oldfield et al., 1978) but also from changes in the autochthonous component of the sediment.

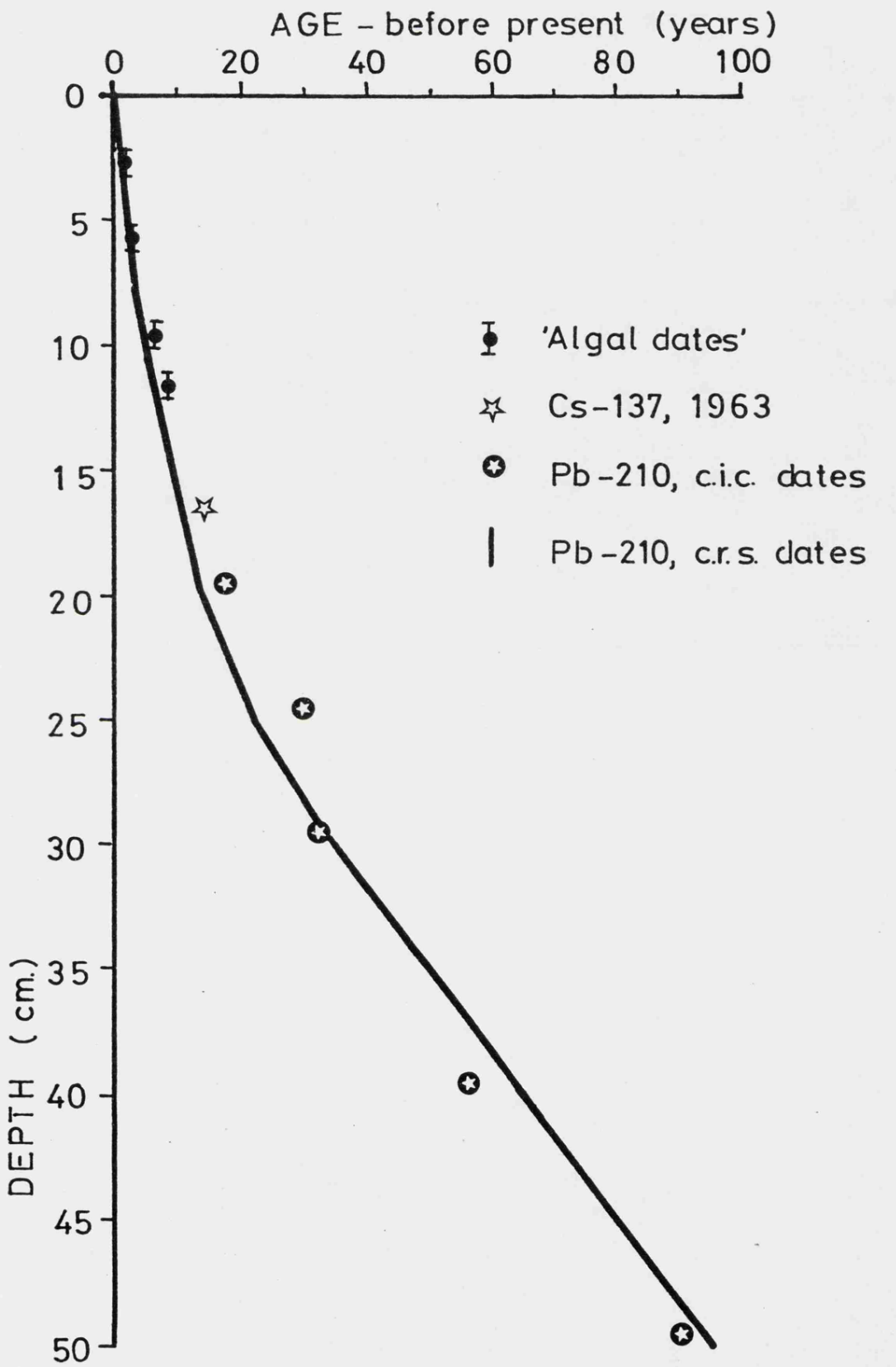
c. Calcite precipitation

The assimilation of carbon dioxide by photosynthesising plants consumes large quantities of CO_2 from the water. Since the exchange equilibrium of atmospheric CO_2 is a comparatively slow reaction, the concentration in surface waters during active photosynthesis may become depleted in eutrophic lakes within a very short time. This may result in saturation with respect to calcite and the induction of carbonate precipitation.

The condition for calcite precipitation is thermodynamically defined by:

$$Ca^{2+} + CO_3^{2-} = CaCO_3 \qquad (Ca^{2+})\,(CO_3^{2-}) = K_c$$

figure 5.11



ROSTHERNE MERE - dating scheme

Where K_c is the equilibrium constant, which at a given pressure (negligible <1000 m) is a function of temperature. (Ca^{2+}) and (CO_3^{2-}) are ionic activities of these ions at equilibrium and their product is termed the ionic activity product (I.A.P.) which may be derived from measurement of alkalinity plus pH or CO_2-acidity. The condition for saturation or supersaturation is

$$\text{I.A.P.} \geq K_c$$

Calcite deposits may result from carbonate precipitation induced by:

i. macrophytes; e.g. Wetzel (1960)

ii. physical factors, such as temperature; e.g. Brunskill (1969)

iii. phytoplankton; e.g. Megard (1968); Muller & Wagner (1978)

iv. a combination of the above; e.g. Kelts & Hsü (1978)

A useful comparison of the calcite bands found in Rostherne Mere can be made with the laminated sediments of Lake Zurich. Each annual varve comprises a dark, organic, layer and a light lamina rich in $CaCO_3$ (Nipkow, 1920). Yearly calcite precipitation in Lake Zürich is induced by phytoplankton and a rise in temperature (Kelts & Hsü, 1978). The calcite bands in Rostherne do not appear to be annual layers, but represent infrequent precipitation events. This probably occurs in summer during a period of quiet weather and when there is a large algal population. The algae will be concentrated within a small depth range (e.g. a surface bloom) and may induce saturation and hence carbonate precipitation. Inspection of the seston traps suggests that the Microcystis population in 1978 induced such an event.

Kelts & Hsü (1978) state on the basis of results from L. Zurich that the preservation of discrete calcite layers depends on :

i. the absence of bottom fauna

ii. lack of bottom currents

iii. little input of 'diluting' allochthonous material

iv. no excessive production of gas in the sediment

v. a stagnant, stratified water mass.

Rostherne Mere satisfies numbers i. and iii. of these conditions and there is probably a lack of bottom currents. It is not known how much of the gas found in the cores is released in situ. Lake Zürich is meromictic; however Rostherne does not have a density gradient near the bottom (Brinkhurst & Walsh, 1967) but the turbulence in the deeper area must be negligible, in order to preserve the discrete layering. Kelts & Hsü (1978) attribute the lack of benthos in the Zürich sediments to the anoxic and toxic conditions in the stagnant bottom water.

The value of X-radiography is evident in this study by showing the series of bands not visible and subsequently destroyed by sectioning the core. The calcite layers suggest that large algal crops have been present in Rostherne Mere for at least the past two hundred years and the profundal zone of the lake is a stable depositional environment.

d. 'Guanotrophy'

Brinkhurst & Walsh (1967) hypothesised that the persistence of de-oxygenated conditions in the deep-water sediments was caused by

"an abnormal quantity of faecal matter contributed to the lake by the exceptionally large populations of both resident and transient birds".

However Reynolds (1979b) considers that the increase in maximum nutrient concentrations observed in recent years (Gorham, 1957; Grimshaw & Hudson, 1970; Reynolds, 1979a) is largely attributable to enrichment by agricultural sources. He points out that similar changes, in both scale and timing, have occurred in nearby meres which do not have large

bird populations. This problem may be examined in the light of recent estimates of nutrient concentrations in gull droppings, the number of gulls in the Rostherne roost and the results from the sediment cores.

The winter gull roost on Rostherne Mere is typically dominated by the black-headed gull (Larus ridibundus) which may number 15000 birds. The roost was established around 1905 and over 1000 birds were observed in 1914 (Coward, 1914). Other gulls, notably the lesser black-backed gull (L. fuscus), the herring gull (L. argentatus) and the common gull (L. canus), also roost in the winter and the total may reach over 22000 gulls. Table 5b shows the increase in the roost over the past 70 years while Table 5c gives the 'typical' mean monthly roost numbers. These figures are approximate since most of the gulls enter the reserve at dusk and counting large numbers is difficult (T. Wall, personal communication). The totals in the table have been rounded up to avoid underestimation. The gulls feed outside the reserve and the herring gull, in particular, obtains most of its food by scavenging on the open rubbish tips around Manchester (Harrison & Rogers, 1978). The number of resident birds is relatively small (e.g. 4000 Mallard were recorded in the late 1950's) and often feed locally and thus bring little external nutrients to the waters. They may, however, be efficient at converting organic forms of phosphorus within the lake (invertebrates, macrophytes) to soluble inorganic phosphorus (Holden & Caines, 1974). From the monthly averages the total number of visits can be calculated and are expressed as 'gull nights' (Table 5c). Gould (1977) studied daily loads of faecal bacteria and nutrients from four species of captive gulls. The estimated 24 hour nutrient loads, for soluble-P were 92 mg for the herring gull, 47 mg for the lesser black-backed gull, 42 mg for the common gull and 30 mg for the black-

Table 5b Maximum Gull Numbers

	Black headed	Herring	Lesser black-backed	Common
1900	"uncommon"			
1910	start of roost			
1920	1000	irregular visitor	frequent	few
1930				
1940			117	
1950				
1960	5000	2000		100
1970	10000	10000	7000 7000	
1980	15000	6000	5000	2500 3000

From data extracted by Harrison & Rogers (1978)

Table 5c Rostherne Mere - Gull Roost Numbers

Month	Herring Gull	Common Gull	Lesser Black-backed Gulls	Black Headed Gull	Mean Daily No.	Monthly Sum
Aug	-	-	-	2000	2×10^3	60×10^3
Sep	200	200	1000	10000	12×10^3	360×10^3
Oct	300	200	1000	10000	12×10^3	360×10^3
Nov	2000	200	100	15000	18×10^3	540×10^3
Dec	6000	200	100	15000	22×10^3	660×10^3
Jan	6000	350	100	15000	22×10^3	660×10^3
Feb	6000	350	100	15000	22×10^3	660×10^3
Mar	1000	3000	200	1000	6×10^3	180×10^3
Apr	-	100	-	-	-	-
Total "Gull nights"	6.45×10^5	1.38×10^5	0.03×10^5	24.9×10^5	-	35×10^5

Source: Harrison & Rogers (1978)

headed gull. If the assumption is made that half of this is ejested during the roosting period then the yearly loading by the gull is circa 7.01×10^4 g sol-P yr^{-1}. The mere has an area of 4.87×10^5 m^2 and so the areal loading is circa 0.144 g sol-P m^{-2} yr^{-1}

A loading factor for the mere can be estimated using the PO_4-P values of Grimshaw & Hudson (1970). The mean of the depth profiles were taken to estimate a value for the water column and each sampling date (n = 27) averaged to obtain a mean figure of 1.7 g PO_4-P m^{-2} yr^{-1} (range 0.67 - 2.81). If the monthly values for 1966 are used, the remainder being irregular sampling dates in 1965 and 1967, the yearly average is 1.9 g PO_4-P m^{-2} yr^{-1}. These calculations assume that the residence time of the lake is 2 years (Harrison & Rogers, 1978). In comparison with this figure for Rostherne, Reynolds (1979b) gives a value of 0.5 - 1.3 g P m^{-2} yr^{-1} for Crose Mere which is less rich than Rostherne.

Therefore from these very approximate calculations it appears that the gull roost potentially only contributes about a tenth of the yearly input of phosphorus i.e. an order of magnitude less than the other inputs. Even if the number of gulls doubled or the estimate of phosphorus ejestion by the birds is too low the proportion would still be small. It may be noted that the sediments, as a phosphorus source, are not considered in the calculations. Although there may be regeneration of P in the bottom muds the net annual amount must be negligible otherwise there would be a cumulative annual increase of P in the water column. The water and the sediments will be in equilibrium with respect to P and although there will be a flux across the interface, including some guano-derived P, the basic conclusions will not be altered.

A similar calculation for nitrogen is not possible since Gould (1977) was unable to measure the oxidised forms of nitrogen and a true estimate of nitrogen in the water cannot be obtained. The summer values of NO_3-N in Rostherne Mere (Grimshaw & Hudson, 1970) are often negligible because the nitrogen has been taken up by the plankton. Reynolds (1973, 1976a)has proposed that nitrogen is likely to become limiting before phosphorus in Crose Mere.

The annual loading from the gulls of Kjeldahl-N (total nitrogen + NH_3) is 2.9 g m^{-2}. An estimate for the areal loading derived from the data of Grimshaw & Hudson is 6.6 g (NO_3-N + NH_4-N) m^{-2} yr^{-1}, which is very likely to be an underestimation and also is not comparable with the gull figure due to the different species of nitrogen considered in each case. Reynolds (personal communication) estimates that a Microcystis population of 250 x 10^6 cells l^{-1} would contain the equivalent of approximately 1.9 g N m^{-2}.

The increases in nitrogen and phosphorus observed in Rostherne Mere are similar to those found in other Shropshire-Cheshire waters over the past few decades (Reynolds, 1979a). Some of these meres do not have large bird populations and enrichment can be attributed to the increased use of agricultural fertilisers. The results of increased nutrient levels have been slight, the incidence of Microcystis as a summer dominant has increased although Ceratium is still common. Although the cores show that the periodicity of phytoplankton has been irregular, the nutrient rich species (e.g. the blue-greens and, in particular, dinoflagellates) have been common for many decades (cf. Reynolds & Sinker, 1976). Large scale enrichment by guano cannot be substantiated.

Gould (1977) also compared estimated daily loads of phosphorus from the gulls to daily human input (in crude sewage). The daily guano production, during January, in Rostherne Mere is equivalent to a population of 445 discharging untreated effluent into the mere. On an annual basis the gull population is equivalent to a human population of 171. The village of Rostherne has a population of circa 100 which discharges treated sewage effluent into the mere but the main inflows of phosphorus are probably groundwater and Rostherne Brook which drains a large proportion of the catchment and the rich Mere Mere. Grimshaw & Hudson (1970) found a concentration of 0.08 mg PO_4-P l^{-1} in Rostherne Brook.

Enrichment by bird droppings has been reported for Hickling Broad (Leah, Moss & Forrest, 1978) and several Dutch lakes (Leentvaar, 1967). These lakes are shallow and in the case of Hickling the number of gulls is larger (1×10^5 black-headed gulls) and thus the nutrient contribution by the birds may be more substantial. Leentvaar (1967) makes a "rough estimate" for annual ejestion of 50 g P-PO_4 $bird^{-1}$ yr^{-1} which is far higher than Gould's (1977) figures. However Leentvaar arrives at this figure indirectly, via a phosphate budget for one lake, and not by measurements of concentrations in the guano. Leentvaar's figure used on the Rostherne data results in a loading factor, by the gulls, of circa 4 g PO_4-P m^{-2} yr^{-1} which compares with the estimate used in this study of 0.14 g PO_4-P m^{-2} yr^{-1}. Rostherne displays few similarities with the Dutch lakes, Leentvaar states :

> "diatoms, blue-green algae and desmids are very scarce in guanotrophic environments".

Input of nutrients by birds has also been considered in Loch Leven (Holden & Caines, 1974). About 7000 geese typically roost around

L. Leven in winter and Holden & Caines calculate that they would contribute about 1.5 kg P day^{-1}. This is only a small contribution when compared to the quantity introduced by streams, sewage and industry.

Brinkhurst & Walsh (1967) suggested that the deoxygenation of the profundal zones was caused by the gull dropping and this resulted in the dearth of benthos. The corollary of this hypothesis is that before the start of the roost the sediments would have been oxygenated and contained a normal benthic fauna. The detailed stratigraphy and, in particular, the presence of calcite layers at depth present strong evidence that Rostherne Mere has not had a profundal benthos for at least two centuries. It is worth noting that Brinkhurst & Walsh also mention that the deep water sediments of Ellesmere Mere and Crose Mere also support a sparse benthic fauna. Tait-Bowman (1976 - cited in Reynolds, 1979a) studied chironomid larvae in Newton Mere, Crose Mere and Blake Mere and demonstrated the influence of hypolimnetic deoxygenation on distribution and abundance. Summer stagnation and low oxygen levels severely reduced the larval populations in the profundal zones in Crose Mere and, in particular, in Blake Mere. Both these lakes do not have a large bird roost and it may be proposed that the absence of bottom fauna in deep lakes is a result of the eutrophic conditions. Newton Mere has many chironomids at depth but the lake takes longer to deoxygenate and sulphide production is less marked than in Crose Mere and Blake Mere.

It is concluded that although gull excreta undoubtedly enriches the waters of Rostherne Mere the magnitude of this input is probably small. The calcite banding and biostratigraphy demonstrate that the lake has supported a rich phytoplankton for many years before the start of the roost and deoxygenation has always been a feature of the

Rostherne sediments and is not connected with enrichment by the gulls. Therefore to use the term "guanotrophic" for Rostherne Mere appears to be inaccurate.

e. Areal variability

Most palaeolimnological work, on any one lake, is carried out on a single core, usually because the time needed to process the material from one core precludes further coring and analyses. The three deep water and two shallow water cores from Rostherne Mere offer an opportunity to examine the areal variation of algal remains found within the sediments. This thesis is qualitative, rather than quantitative, in nature and a full statistical analysis of the errors involved in coring, sub-sampling and enumeration has not been attempted. However the results can be used to give some idea of the magnitude of variability between cores.

As shown, the three deep-water cores showed great variability in the quantitative estimates for particular algal remains, for example the 1973 Stephanodiscus astraea peak. The counts include both errors inherent in repetitive sub-sampling and areal variation on the lake bed. The counts were carried out on less than 0.02% of the total volume of each slice, the bulk of which was sent either for radionuclide dating or used for further analyses.

Five replicates of the final dilution were enumerated from a single section of core A* and agreement with the Poisson series tested by χ^2 (variance to mean ratio) (Elliott, 1977: p.41). Agreement with the Poisson series was accepted ($p > 0.05$) for the remains of Ceratium, Microcystis and Stephanodiscus. The hypothesis of randomness was not proved for Anabaena where the χ^2 value indicated that the

distribution was contagious, a result not unexpected considering the clumped nature of the akinetes. The maximum percentage variation from the mean was Ceratium 16%, Microcystis 23%, Anabaena 57% and Stephanodiscus 4%. The lack of material prevented replicate subsampling of each section but the errors involved depend on the lateral homogeneity of the section and the throughness of mixing. Separate dilutions of a single subsample from two sections of core B* showed the maximum variation, from the mean, between the counts was Ceratium 13%, Microcystis 11%, Anabaena 66% and Stephanodiscus 10%. Assuming complete mixing of the sections the variation associated with sub-sampling and counting appears to be < 50%, with the exception of Anabaena akinetes.

An idea of the between core variation may be gained by examination of the relative differences between the deep water cores. The comparison of characteristic peaks in the profile (table 5d.i) shows the variation from the mean depends on the species considered and maximum values range from 16% (Anabaena) to 163% (Stephanodiscus). The disadvantage of this method is that a discrete layer in the sediment column may be split between two, or more, sections during the slicing of a core. The 1973 Stephanodiscus astraea peak can be considered in isolation (table 5d.ii) but the variation is little changed. If the same computation is carried out on the Ceratium 'interlude' between 8-12 cm (10-13 cm in core C*) the variation is halved. Thus comparison of peak values may be affected by the extrusion and sectioning of the core. If the cumulative totals of the 0-30 cm sections are considered in the same manner (table 5d.iii) the variation from the mean is typically less than 30% (more for Stephanodiscus). This method, however makes the assumption that the time period covered by the selected section is the same for each core. Considering the close correlation between the derived chronologies this is justified for Rostherne Mere.

Table 5d Between Core Variation

i. peak values of selected maxima (1 cm sections)

alga	approx. depth of peak	Core A	Core B	Core C	Mean	Variation from mean
Ceratium	8 cm	119	477	342	339	40 - 41 %
Microcystis	4 cm	394	743	616	584	27 - 33 %
Anabaena	25 cm	420	446	338	401	11 - 16 %
Stephanodiscus	7 cm	4225	57792	4016	22011	82 -163 %

ii. totals for selected maxima

alga	peak	Core A	Core B	Core C	Mean	Variation from mean
Stephanodiscus	1973	4813	57792	6421	23009	79 -151 %
Ceratium	8-12 cm	677	1028	900	868	18 - 22 %

iii. cumulative totals 0 - 30 cm

alga	Core A	Core B	Core C	Mean	Variation from mean
Ceratium	2258	2749	2621	2543	8 - 11 %
Microcystis	5432	8188	9199	7606	21 - 29 %
Anabaena	1638	1272	1642	1517	8 - 16 %
Stephanodiscus	25899	86658	34366	48974	47 - 77 %

The effect of quantitative variation on the stratigraphic patterns was tested by rank correlation. Spearman's rank correlation coefficient, r_s, (see Elliott, 1977: p.121) tests whether the maxima and minima occur at similar depths within the profiles. The 1973 Stephanodiscus astraea peak provides a very obvious horizon at similar depths in all three deep-water cores, and hence was not tested. The profiles of Ceratium, Microcystis and Anabaena all show significant correlations ($p > 0.05$) between the cores (table 5e). Therefore although considerable quantitative variation may occur between cores the vertical profiles show little qualitative between core variation. The estimates of the mean annual rate of sediment accumulation derived from the three deep water cores are therefore very similar whilst estimates of areal density for a particular alga may show large differences.

The variation between the shallow water cores is of a similar order of magnitude to that found between the deep water cores but depends on the species considered (table 5f.i). It must be noted that cores Y* and Z* were not taken in the same area of the mere.

The shallow water cores generally contain fewer remains than the profundal cores, the notable exception being Anabaena (table 5f.ii). The profiles of cores Y* and B* are also dissimilar since correlation coefficients (r_s) were not significant for the four major algae (table 5f.iii). The profiles of Microcystis and Ceratium are similar, in shape, to those found in the Cumbrian lakes and it may be infered that there is greater decomposition in shallower, oxygenated, water. Explanations for the variability of Anabaena akinetes found at different sites have been put forward at the beginning of the discussion. It is possible that the surface bloom was blown to the north end of the lake and hence the akinetes are found at site Z* rather than Y* or in the deeper areas.

Table 5e Between-core Rank Correlation Coefficients

a) Ceratium

Cores	r_s	level of significance
AB	0.720	***
BC	0.371	*
AC	0.552	***

b) Microcystis

AB	0.639	***
BC	0.414	**
AC	0.623	***

c) Anabaena

AB	0.720	***
BC	0.588	***
AC	0.711	***

* $p > 0.05$

** $p > 0.01$

*** $p > 0.001$

Table 5f Variability - shallow water cores

i. cumulative totals (1-10 cm)

alga	Core Y	Core Z	Mean	Variation from mean
Ceratium	276	204	240	15 %
Microcystis	356	38	197	81 %
Anabaena	28	530	279	90 %
Stephanodiscus	4742	4085	4414	7 %

ii. comparison of shallow and deep water cores

alga	shallow cores mean (0-10 cm) n = 2	deep cores mean (0-10 cm) n = 3	shallow as % of deep
Ceratium	240	893	27 %
Microcystis	197	3023	7 %
Anabaena	297	42	707 %
Stephanodiscus	4414	24345	18 %

iii. correlation coefficients (r_s) cores Y* and B* (0-20 cm)

Ceratium	$r_s = 0.114$	not significant at 5 % level
Microcystis	$r_s = -0.364$	
Anabaena	$r_s = 0.388$	
Stephanodiscus	$r_s = 0.244$	

The difference in the number of Stephanodiscus astraea cells between deep and shallow water sites may be a product of water depth. During spring the waters are mixed and if the population is evenly distributed throughout the lake then fewer cells will sediment in the shallow area. As an approximation, the maximum number of cells recorded in 1973 was 110 ml^{-1} (Reynolds, 1978) which would result in 440 cells/ 5 µl fresh sediment in 8 m of water and 1650 cells in 30 m. These are in the same order of magnitude as the concentrations found in the cores, with the exception of B*.

Therefore the deep water cores show good reproducible stratigraphy but for specific algae the calculation of absolute deposition rates shows wide variation. The large amount of variability found between the three cores is partly due to procedural errors and partly to areal variation on the lake bed. The number of algae settling on to the sediments may be controlled by the plankton population above and 'patchiness' resulting in variations between areas on the lake bed. Small scale topography of the sediments may concentrate the remains into hollows. Resuspension of littoral material and subsequent deposition into the profundal zones would lead to a concentration of remains in the deep water cores. This process would be most effective at overturn when complete mixing occurs. Seston trapping in Rostherne Mere indicated that few 'out of season' algae sedimented and it was inferred that little material was resuspended from the littoral zones (see chapter 7).

The shallow water cores did not display a reproducible stratigraphy of non-diatomaceous remains, compared with each other or with the deep-water sites. The distinctive 1973 Stephanodiscus layer was, to some extent, found in the shallow water cores and at a similar depth

to the deep water cores. The indication that the rate of sediment accrual at both 8 m and 30 m water depth is similar was tested by seston trapping (see chapter 7). The fewer Microcystis colonies in shallow water would, however, result in a smaller annual increment.

Between-core variation has also been reported by Pennington et al. (1976) who found a lack of homogeneity with respect to Cs-137 concentrations at different sites in Blelham Tarn, leading to differences in estimated accumulation rates of up to 100%. Goulder (1972a) found 'considerable variation' between cores taken from the same area of Priest Pot when studied for ciliates and Scenedesmus cells.

f. Algal associations

The results of correlations carried out on core data must be interpreted with some caution. For example the colonies of Microcystis are so bulky that the chance of finding other algal remains in a Microcystis-dominated section is reduced. Each 1 cm thick section does not represent a similar time span and hence annual events cannot be compared.

The profiles of Ceratium and Microcystis, in the deep water cores are reciprocal. The Spearman rank correlation coefficient between the two algae are $r_s = -0.621$, $r_s = -0.613$ and $r_s = -0.719$, for cores A*, B* and C* respectively (sections 0-30 cm), all of which are significant ($P > 0.01$). From this it can only be said that the algae are rarely present together in the core. Reynolds (1978) illustrated the competitive interaction between Microcystis and Ceratium for seven years plankton data from Rostherne Mere. Although the correlation coefficient ($r = -0.602$) was not significant ($P > 0.05$) they were to some extent reciprocal. In the years studied by Reynolds

there was one year of co-dominance and one where neither flourished. The cores tentatively support the idea put forward by Reynolds (1978) that Ceratium may succeed if the earlier and potentially more rapid growth of Microcystis is inhibited for any reason.

It has already been discussed that Anabaena spp do not reflect the plankton data. The majority of the spores occur below the Microcystis layers and hence there is a significant negative correlation (r_s = -.532 $P > 0.001$, core A*). Without the knowledge of the plankton data (Table 5a) which shows Anabaena common in recent years there is a danger of misinterpreting the correlation.

The correlation coefficient between Microcystis and the total diatoms per section is also significant (r_s = -0.673 $P > 0.001$). This may reflect the dilution effect that the blue-green colonies have by increasing the annual increment of deposition. However the spring conditions, reflected by the diatoms, may have some bearing on the summer phytoplankton. The diatoms from the deep water cores are overwhelmingly planktonic (typically > 90%) and hence the total may be considered as the planktonic component. Box (1977) studied the growth of Microcystis, in Blelham Tarn, and suggested that the spring algal maximum, possibly that of the diatoms, alters the water so it becomes more favourable to the blue-green alga. The Rostherne cores suggest a reverse relationship, indicating that large spring diatom populations and small Microcystis populations may be related.

The causes of these associations, if not just a product of sedimentation, are obviously not supplied by the sediment cores. Further research is necessary on the living populations while the physical and chemical environment is monitored.

CHAPTER SIX

THE VIABILITY OF BLUE-GREEN AKINETES FROM THE SEDIMENTS OF ROSTHERNE MERE

CHAPTER SIX: THE VIABILITY OF BLUE-GREEN AKINETES FROM THE SEDIMENTS OF ROSTHERNE MERE

1. INTRODUCTION

Akinetes of Anabaena and Aphanizomenon with contents similar in appearance to those of live specimens were found below the surface layers in sediment cores taken from Rostherne Mere. Samples were taken from various levels in a dated core and placed in culture media in order to determine whether they were viable.

There are few recorded instances of this type of culture work, especially on akinetes of blue-green algae. The possibility of the benthos disturbing the sediment stratigraphy ('bioturbation') thereby mixing resting spores and live algae into older material cannot be excluded in many sites. However the deeper areas of Rostherne Mere are devoid of benthos (Brinkhurst & Walsh, 1967) and the sediments are discretely ordered. Therefore it is highly likely that the age of an akinete is the same as that of the sediment horizon in which it is embedded.

2. METHODS

All glassware (200 x 20 ml pyrex tubes and 5 x 100 ml flasks) was washed in a strong solution of tribasic sodium phosphate (Na_3PO_4), rinsed four times with tap water and twice with distilled water. The tubes and silicone sponge plugs (Hakuto International (U.K.) Ltd.) were heated at 110°C for 30 minutes.

Two experiments were performed, using material from the deep water core A*. Sediment volume was measured by a graduated syringe in the first experiment and by Eppendorf pipettes for the second. In experiment I material was taken from seven sections of the core (1-2 cm, 4-5 cm, 12-13 cm, 19-20 cm, 22-23 cm, 26-27 cm, 69-70 cm) and ten replicates, each containing 100 µl, were incubated along with ten controls. 10 ml of A.S.M. I culture media (Gorham et al., 1964) containing a small amount of actidione (a eukaryote inhibitor - Siegel & Sisler, 1964) was added to each tube. Tubes containing the media alone were used as controls. The second experiment was identical to the first except that a range of sediment volumes was taken from each section. Two tubes, each containing 10 µl, 50 µl, 100 µl, 500 µl or 1000 µl, were incubated from each section. As with the first experiment seven sections were investigated, the upper six from experiment I plus section 29-30 cm. Four flasks each containing circa 3 ml of material from 39-40 cm, 59-60 cm, or 69-70 cm and 50 ml of media were incubated with experiment II.

The tubes, including the controls, were incubated at 18°C and illuminated continuously from below by 4 x 40 W daylight lamps, giving a total of 3200 lux. They were examined, using a hand lens, or by eye, every second day. Aliquots were taken from the tubes for identification under a high-power microscope when new growth was observed and at the end of the experiments. Subsampling was carried out aseptically over a bunsen flame.

Experiment I was concluded after 25 days and experiment II after 45 days, although the tubes were moved to a north-facing window for a further 21 days.

3. RESULTS

The results of experiments I and II are given in figures 6.1 and 6.2. An alga was considered on a presence or absence basis and no quantitative estimate was attempted.

Vegetative filaments of Anabaena flos-aquae, Anabaena spiroides and Aphanizomenon flos-aquae plus the colonial Microcystis aeruginosa were observed in the cultures. Anabaena spiroides only germinated and grew in material from the 26-27 cm. Sections 1-2 cm, 22-23 cm, 26-27 cm and 29-30 cm also contained a non-gas vacuolate blue-green Aphanothece sp. It is not known whether the alga survived in the sediments as colonies or as single cells. Morphologically recognisable cells which might act as resting spores are unknown in this genus.

4. DISCUSSION

The viability of akinetes from species of Anabaena and Aphanizomenon has been shown to be long term. The deepest section containing viable Anabaena akinetes, which could be cultured, was 39-40 cm and 26-27 cm for Aphanizomenon. The sediment at these depths is approximately 69 and 28 years old (1908 and 1949) respectively. Germination, and subsequent growth, was not found at every depth sampled and was most prolific at the surface and in sections containing the highest concentration of akinetes (both with and without contents), figure 6.3. Sections 4-5 cm and 19-20 cm contained fewer viable akinetes which took longer to produce a 'planktonic' population.

Reynolds (1978) recorded four species of Anabaena in Rostherne Mere, Anabaena circinalis, Anabaena solitaria Kleb. f. planktonica

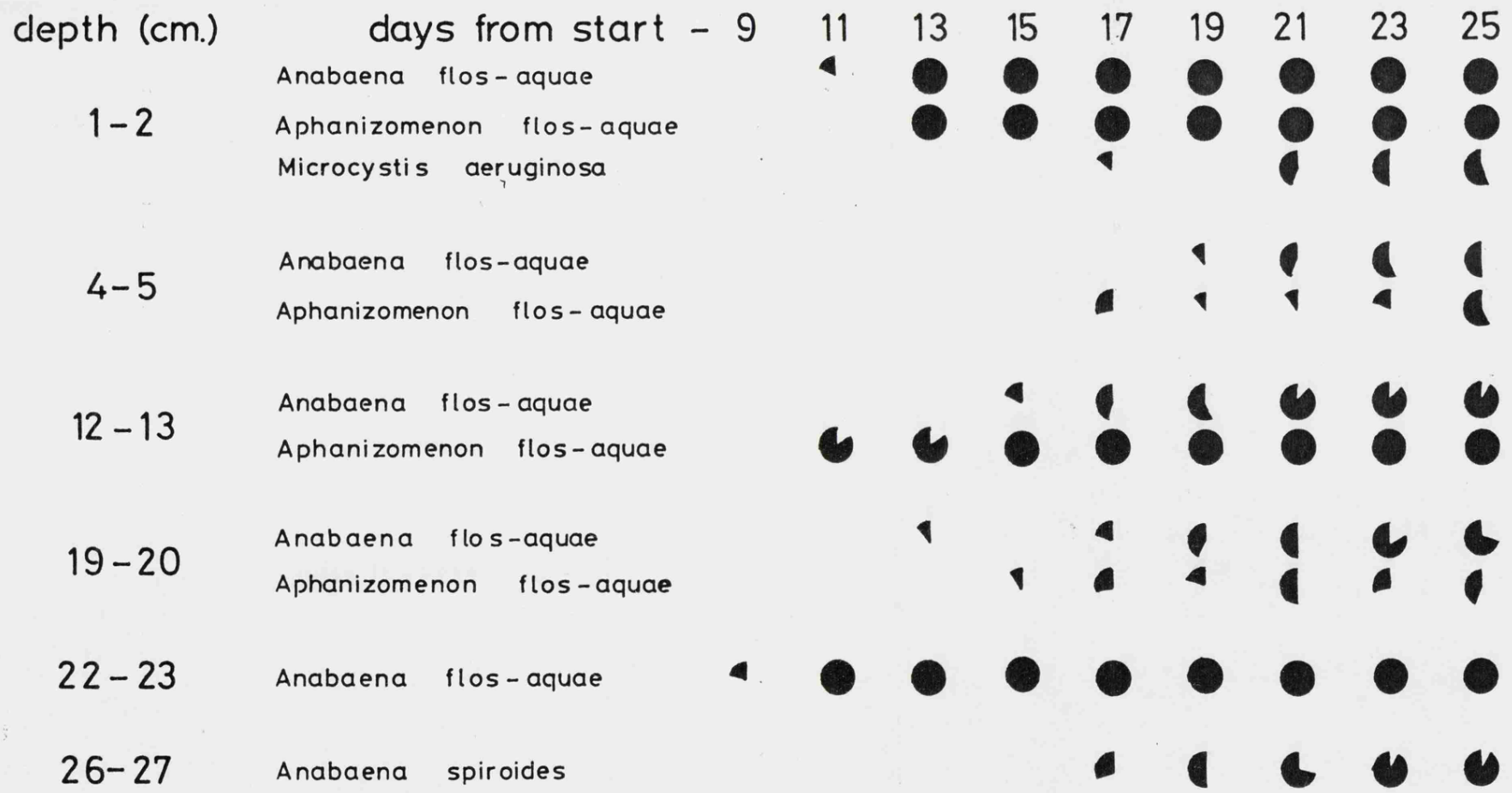


figure 6.1

EXPERIMENT I

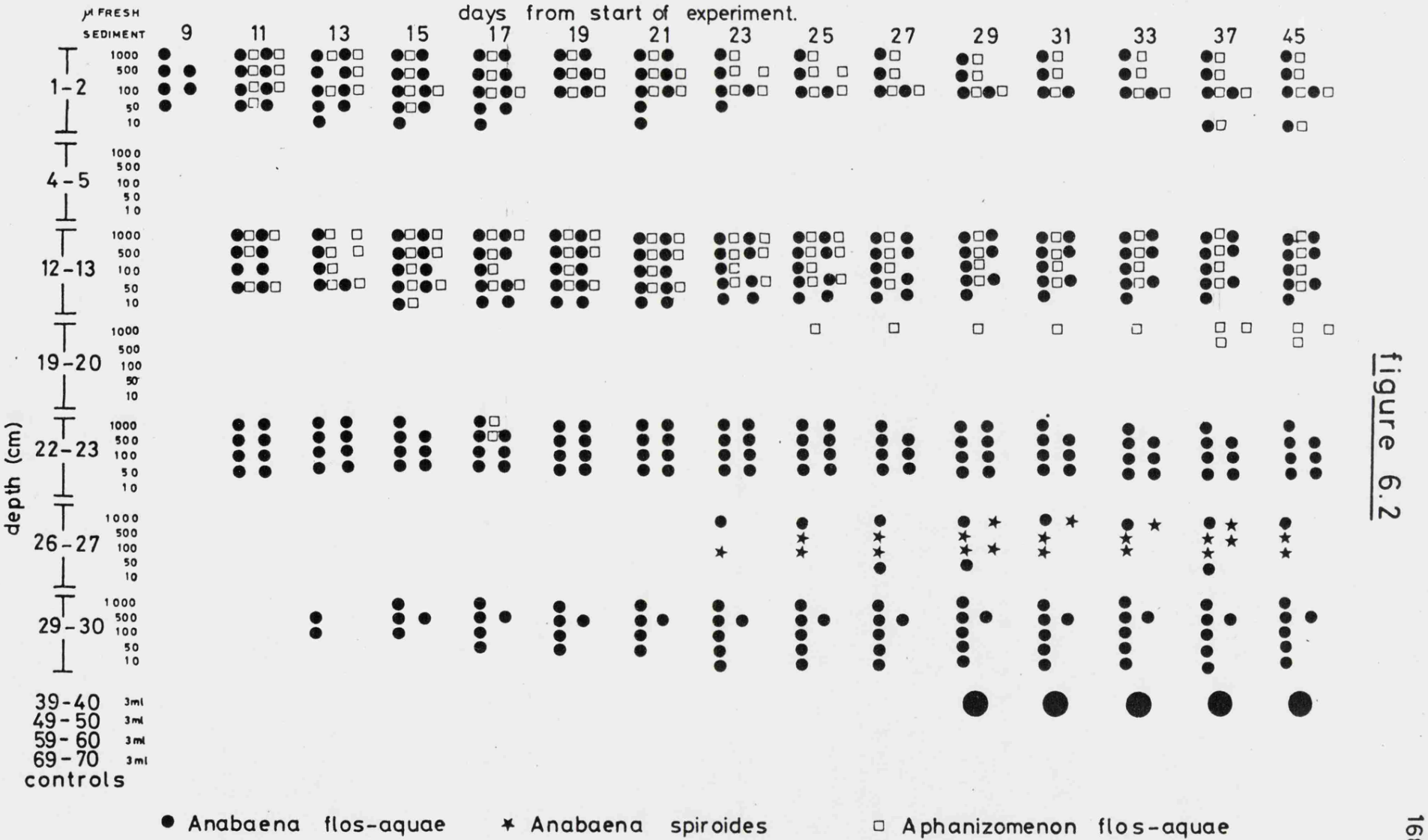

days from start of experiment.
9
11
13
15
17
19
21
23
25
27
29
31
33
37
45
depth (cm)
μ FRESH SEDIMENT
1000
500
100
50
10
1-2
4-5
12-13
19-20
22-23
26-27
29-30
39-40 3ml
49-50 3ml
59-60 3ml
69-70 3ml
controls
● Anabaena flos-aquae
★ Anabaena spiroides
□ Aphanizomenon flos-aquae

figure 6.2

figure 6.3

akinetes / 5 µl sed.
0 100 200 300 400
depth (cm.)
0 10 20 30 40 50 60
'positive' tube
I
II
1000 500 100 50 10
ANBAENA ★ spiroides ● flos-aquae
APHANIZOMENON flos-aquae
0 25 50

(Brunnth.) Komarek, Anabaena spiroides and Anabaena flos-aquae but only the latter two were observed in the cultures. Both Anabaena and Aphanizomenon have been a feature of the phytoplankton since the beginning of the century (cf. Table 5a).

In both experiments 9 days was the minimum period to lapse before noticable pseudo-vacuolate populations appeared, although for some sections it was longer. In some tubes growth was rapid, and dense populations formed; this was sometimes followed by an equally rapid death of the alga. Sporulation was observed in some of the more dense cultures, particularly in the older ones. The Anabaena spiroides was isolated by G. Jaworski and is now maintained in the F.B.A. culture collection (clone no. L301).

Records of algae cultured from sediment material are scarce. Nipkow (1927) found viable Ceratium hirundinella cysts from 5-6 year old varves in Lake Zürich. Nipkow (1950) also cultured the diatoms Melosira islandica O. Mull. var. helvetica O. Mull. and Stephanodiscus hantzschii from 5 and 10 year old material. Lund (1954) recorded live cells of Melosira italica var subarctica at 3-5 cm below the surface in cores taken from Esthwaite and Blelham. However he discussed the possibility of disturbance of the surface layers by the benthic fauna ('bioturbation'). This theme was expanded by Stockner & Lund (1970) who recorded invertebrates down to 65 cm. It is typically only the top circa 3 cm of the muds that contain sufficient benthos to disturb the stratigraphy to a significant degree (cf. Stockner & Lund, 1970). Live algae were found by Stockner & Lund down to 35 cm although the majority were cultured from the upper strata. They recorded mainly species of diatoms and most of the planktonic algae of the lakes were not found alive. Rostherne Mere, unlike Blelham Tarn, has a lack of benthos in the deepest waters (Brinkhurst & Walsh, 1967) and so

bioturbation is unlikely to be responsible for the mixing of akinetes down the core. The fine biostratigraphy and calcite banding of the core also precludes any physical disturbance.

In air dried soil, live algae have been found after many years (see Lund, 1967). Species of Cyanophyceae, in particular, are able to withstand rapid changes from very wet to very dry conditions. In arid areas, where soil algae depend on short, wet periods, prolonged saturation permits new communities to appear if the soil does not become anaerobic (Lund, 1967). Diatoms are not very resistant to desiccation but Nitzschia palea can remain alive in dry soil for 70-98 years (Bristol, 1919; Becquerel, 1942), although the cells may die when dried in air. Therefore it appears that anaerobic lake sediments and aerobic dry soil may maintain viable algal cells or resting spores but algae do not survive in anaerobic wet soil. It remains to be fully investigated if algae can survive for long periods in aerobic lake muds.

The traditional view on the function of blue-green akinetes has been that they provide an overwintering mechanism and a source of inoculum for the summer population. Rose (1934) and Wildman, Loescher & Winger (1975) recorded that akinetes of Aphanizomenon overwintered on the mud surface. However Rother & Fay (1977) studied sporulation of Anabaena and Aphanizomenon in two Shropshire Meres and concluded that the bulk of the akinetes produced germinate shortly after sporulation and the algae overwinter as vegetative filaments in the plankton. Rother & Fay found there was a considerable and rapid input of akinetes to the surface mud layers during the period immediately after a bloom but this was followed by an equally rapid decline. They considered this indicated rapid germination and up to 60% of the akinetes examined from plankton collections were empty, although few instances of germination

were observed. A small overwintering vegetative population was present in the plankton from both meres.

Reynolds (1971) found akinetes of Anabaena in the superficial sediments of Crose Mere during winter. Reynolds observed that these were lifted off the lake bed during turbulent conditions and germination was apparently triggered by external conditions whilst they were in suspension. However in 1973 Reynolds (1975) observed a different situation:

> "Mass germination of over wintering spores within the open water circulation of the lake evident in earlier seasons contributed little to the 1973 maximum which apparently originated from a small vegetative stock which had survived from the previous autumn."

Jones (1979) states that the growth of Aphanizomenon in Lough Neagh was derived from vegetative filaments rather than from germination of akinetes.

Rother & Fay (1977) see the function of akinetes in terms of the survival of algal populations during periods of environmental stress (e.g. surface blooms) rather than promoting survival over winter (but see Rother & Fay, 1979). Aphanizomenon and Anabaena do not produce akinetes each year, unlike genera such as Dinobryon and Ceratium which produce spores annually and appear to be essential for their continued existence (Lund, 1965). Thus the role of blue-green akinetes is uncertain and may differ under particular environmental conditions. However this study has shown that akinetes of both Anabaena and Aphanizomenon are not just short-lived, or indeed solely an overwintering mechanism, but may also ensure the long term survival of the alga in a particular lake.

The survival of akinetes in the deep sediments of Rostherne Mere may indicate that germination is retarded by the environmental conditions therein. The deep water muds are continuously deoxygenated, are under 2 atmospheres of pressure with low illumination and in non-turbulent flow. Rose (1934) found that light was not essential for the germination of Aphanizomenon akinetes but the water temperature had to be greater than 7°C. Reynolds (1971) noted that Anabaena circinalis appeared in Crose Mere when the surface temperature was greater than 6°C and Aphanizomenon flos-aquae at 9 to 11°C. Reynolds also took mud samples, containing akinetes, from Crose Mere in March and bottled them, allowed the mud to deoxygenate and kept them in the dark at 15°C. No germination was observed. A similar experiment performed with Ceratium hirundinella cysts in this study (Chapter 7) had the same result but a build-up of a toxic substance was hypothesised. If resuspension is a necessary criterion for germination (cf. Reynolds, 1972.) it is unlikely that akinetes will be lifted from the deeper areas of Rostherne Mere. However the littoral area of the mere is relatively small and akinetes, with intracellular deposits, were fairly numerous in the cores taken from 8 m of water. The tubes were not continually agitated and little material was kept in suspension, but germination still occurred. It is not possible to judge whether the akinetes failed to germinate in the sediments because of insufficient light, low temperatures, build up of toxic substances associated with the continuous deoxygenation, lack of resuspension or for other reasons, and this aspect requires further research.

It appears, from this study, that the function of the akinetes of Anabaena and Aphanizomenon is not limited to a single strategy. They do not require a maturation period (cf. Ceratium - Chapter 7)

and so may be a very short-term safeguard (cf. Rother & Fay, 1977). However they remain viable for longer periods of time and may be an overwintering mechanism or ensure longer term survival. Although the akinetes will be buried by subsequent sediment accumulation into a deoxygenated environment they may be uncovered by events such as slumping or the disturbance created by say, an eel or fish. Therefore the survival of sporulating blue-green algae is not dependent on favourable growth conditions each year.

CHAPTER SEVEN

THE INCORPORATION OF ALGAE INTO THE SEDIMENTS

A ESTHWAITE WATER

B ROSTHERNE MERE

CHAPTER SEVEN: THE INCORPORATION OF ALGAE INTO THE SEDIMENTS

INTRODUCTION

The superficial sediments and seston have been examined in order to gain some insight into the incorporation of algal remains into more stable sediment. Two approaches have been used; firstly the regular analysis of surface material and secondly the trapping of sedimenting seston in deep water.

In Esthwaite Water the fate of the annual layer of cysts from the dominant summer alga, Ceratium hirundinella, has been followed and the effect of cyst germination assessed. The relationship between the cyst density in the sediments, and the standing crop was also examined since there appeared to be a correlation between the cyst remains and the phytoplankton record in the sediments of Rostherne Mere (see Chapter 5).

Seasonal changes in the composition of algal remains in entrapped seston from Rostherne Mere were compared with qualitative and quantitative changes in the composition of the phytoplankton, and in the algal material at the sediment surface.

A. ESTHWAITE WATER

1. INTRODUCTION

a. Cyst formation

The cysts of Ceratium hirundinella are composed mainly of cellulose (see Wall & Evitt, 1975) and are similar to the general shape of the cell, but with shorter and stouter horns. The formation of the cyst takes place within the cell. The cyst wall forms around the intracellular contents which are withdrawn from the apical horns and cell wall. The cell fragments, and the cyst falls to the mud surface.

In Esthwaite Water the cysts of Ceratium are usually formed in the autumn, typically at the beginning of October (Heaney, 1976). It is not known what proportion of the planktonic population encysts. Huber & Nipkow (1922) found that Ceratium cysts from Lake Zürich required a resting period before being able to germinate. They also observed that the cysts were unable to resist protracted frost or drought but were unaffected by anoxia and pressures of up to 10 atmospheres. The hydrostatic pressure in Esthwaite, at the deepest point, is only 2 atmospheres and the surface sediments are anoxic from about June to October inclusive.

b. Cyst germination

On germination the cyst wall splits and a gymnodinium-like cell emerges. Subsequent development involves a gradual change from this "gymnoceratium" (Huber & Nipkow, 1922) through a stage where the cell shape (without horns) is formed, the "preceratium" stage, to the ultimate appearance of the theca and apical horns. The cell is capable of division a few hours after development is complete.

Huber & Nipkow found that temperature was an important factor in germination. The minimum temperature for germination was about 5°C but with temperatures below 7°C development demanded 4-5 weeks while at 23-26°C this was about 30 hours.

2. METHODS

Esthwaite Water (figure 7.1) was chosen as the site for the study as it has the advantages of accessibility, and extensive records of biological, chemical and physical parameters. Cell counts and temperature measurements are reproduced here with the permission of Dr. J.F. Talling F.R.S. and Dr S.I. Heaney (unpublished data). The samples were collected at the same time as the cores. The disadvantage of Esthwaite is the fact that the cysts are apparently not preserved in the sediments for more than a few years (see Chapter 3). Rostherne Mere which might have provided an excellent site did not produce an abundant Ceratium crop during the sampling period (1976-1978).

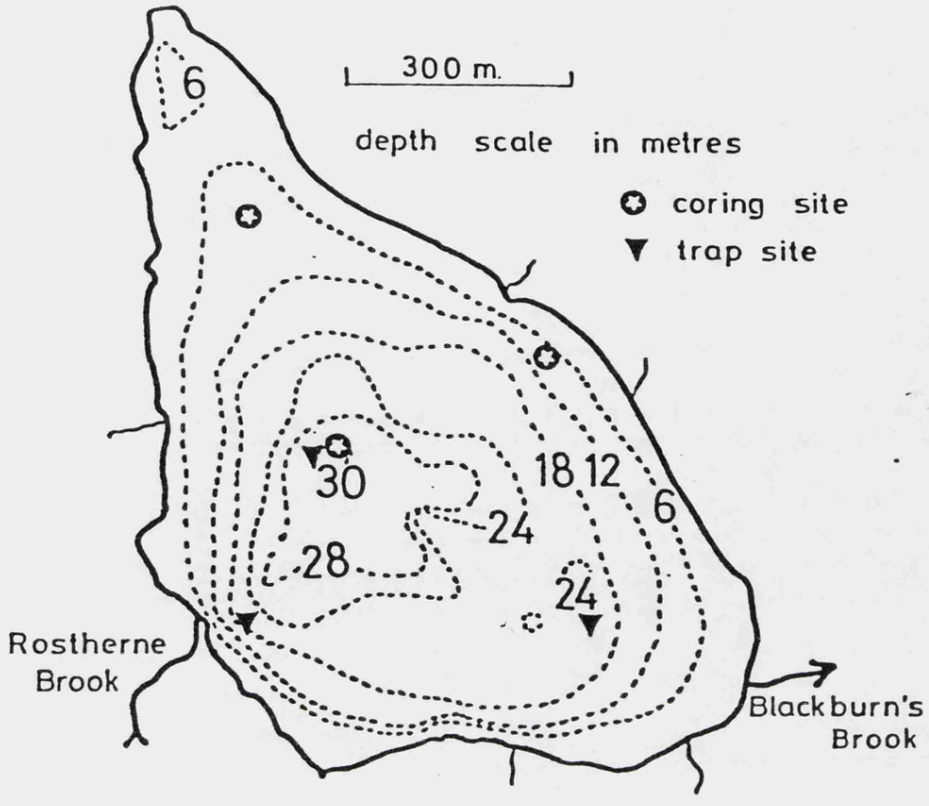
Jenkin cores were taken from the deepest area of the lake (figure 7.1) at weekly intervals from January 1977 to February 1978 and then monthly until November 1978. Some material was lost, during extrusion, in August and September 1977.

The cysts were counted in the top 3 cm of the cores until October 1977 and in the uppermost 5 cm thereafter. They were divided into two categories :

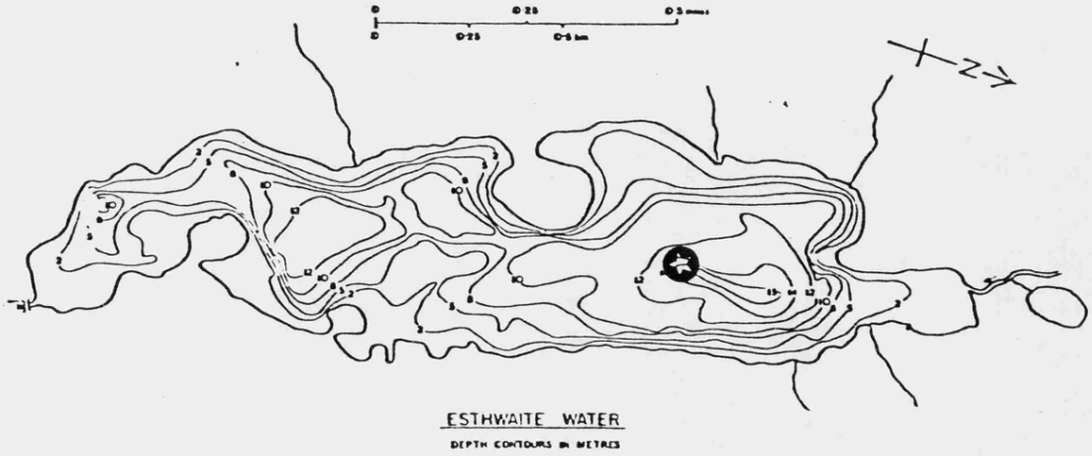
i) 'full' - cysts with contents, and possibly viable

ii) 'empty' - cysts without contents but often containing a small orange/brown residue

figure 7.1



ROSTHERNE MERE.



ESTHWAITE WATER

DEPTH CONTOURS IN METRES

3. RESULTS

a. Cores

The profiles from the surface layers of the 48 cores examined from Esthwaite Water show that most of the cysts of Ceratium hirundinella are contained within the topmost 3 cm of the sediment column (figure 7.2). Five cores were analysed to a depth of 12 cm, and 93% of the cysts (full and empty) were accounted for in the 0-3 cm strata. Large populations of Ceratium have been common in the lake for over a decade (Lund, 1979); and the lack of cysts at depth is, therefore, more likely to be a product of decomposition rather than a reflection of the phytoplankton. The mean rate of sediment accumulation in Esthwaite (post 1963) is circa 0.9 cm yr^{-1} (Pennington, 1978) and so the upper 5 cm of a core represents a period of approximately 4.5 years. The annual production of Ceratium cysts does not, however, lie in the top 0.9 cm of the cores but typically large numbers are found throughout the upper 2-3 cm (figure 7.2). The rate of sediment accumulation is a mean value from 1963 and hence factors such as compaction and diagenesis must be taken into account. It is likely that the flocculant upper 2 cm or so in Esthwaite represents an annual increment of deposition.

The cysts of Ceratium are thought to require a resting period before germinating (Huber & Nipkow, 1922) and since cells are extremely rare in the plankton during winter (C. Butterwick - personal communication) it may be inferred that the number of cysts on the lake bed should remain constant during this period. The number of cysts would, however, decrease if parasitism, decay or resuspension and washout were important factors. The quantitative differences between cores taken in the winter were large (e.g. figure 7.2 - November 1978) and it may be

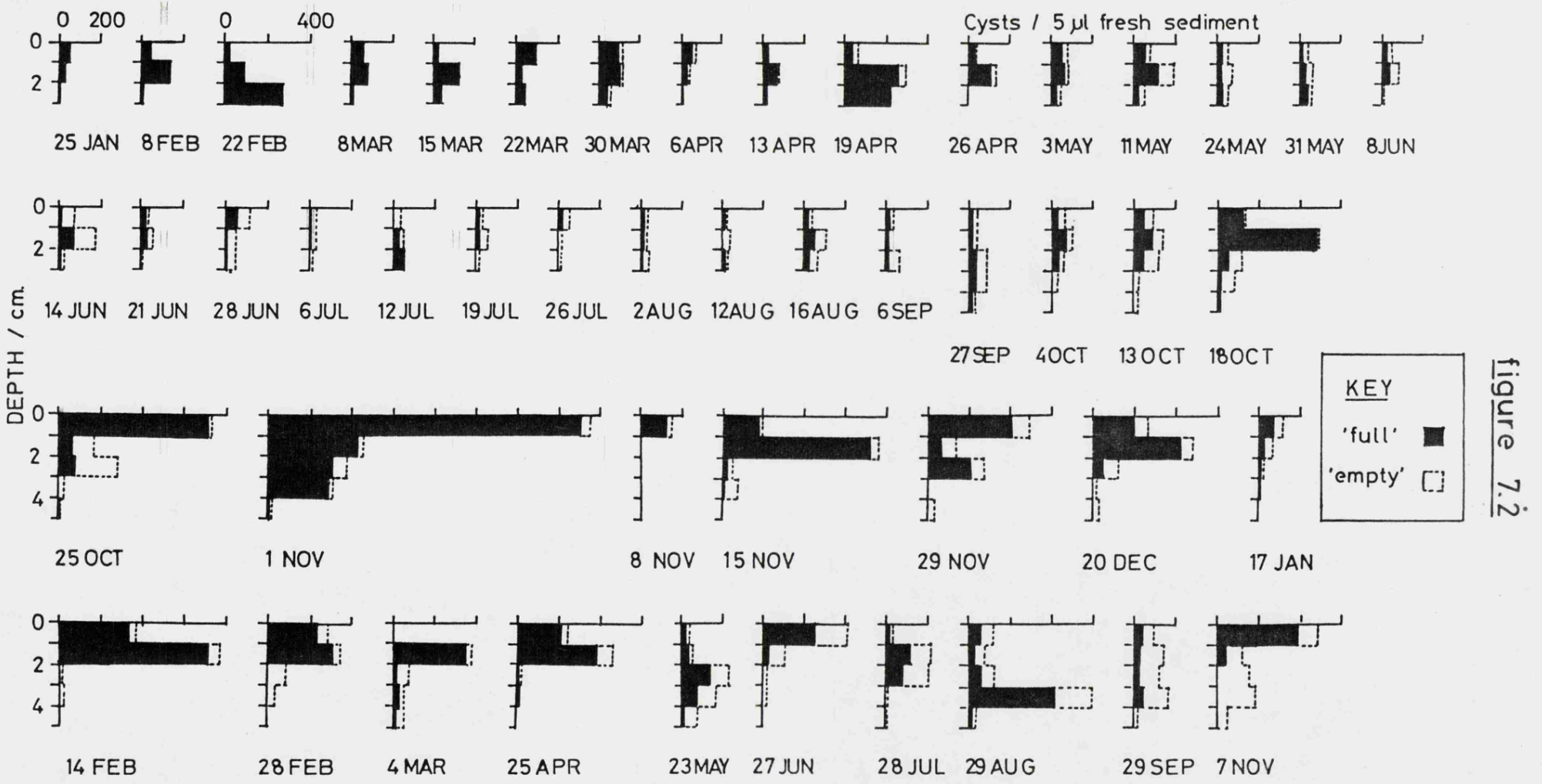


figure 7.2

ESTHWAITE - CERATIUM CYSTS – JANUARY 1977 - NOVEMBER 1978

suggested that areal variation, plus procedural errors, preclude any accurate estimate of cyst density (cf. Rostherne Mere).

If the cores from January-February 1977 and 1978 are compared the number of cysts is greater in the latter samples (figure 7.2). It may be inferred that more cysts sedimented in the autumn of 1977 than in 1976; however there is little supporting evidence from the plankton samples which contained similar numbers in both years (S.I. Heaney - unpublished data).

There is a decline in the number of full cysts during the summer (figure 7.2), a trend which is emphasised if the numbers contained within the topmost 3 cm are summed (figure 7.3). Conversely the relative number of empty cysts increases from about the end of February (figure 7.3). Not all the full, and perhaps viable, cysts germinate in any one year and it is possible that viable cysts may remain in the sediments for more than one year.

b. Germination experiments

i) experiment A

Fresh material from the cores was taken once a month, from October 1977, and attempts made to induce germination of the Ceratium cysts. The sediment was added to flasks of Chu 10 media (Chu, 1942) and placed in a cabinet at 18°C under continuous illumination (4000 lux). Cells of Ceratium were not observed in the cultures until mid-February 1978. This result is in agreement with the work of Huber & Nipkow (1922) who suggested that the cysts require a resting period before maturation.

figure 7.3

Ceratium cysts recovered from the sediments of Esthwaite Water

a. The total number of cysts (with and without contents) recovered from the 0-3 cm sections of Jenkin cores taken from January 1977 to November 1978.

b. The frequency of 'empty' cysts (expressed as a percentage of the total number recovered) in the 0-3 cm sections.

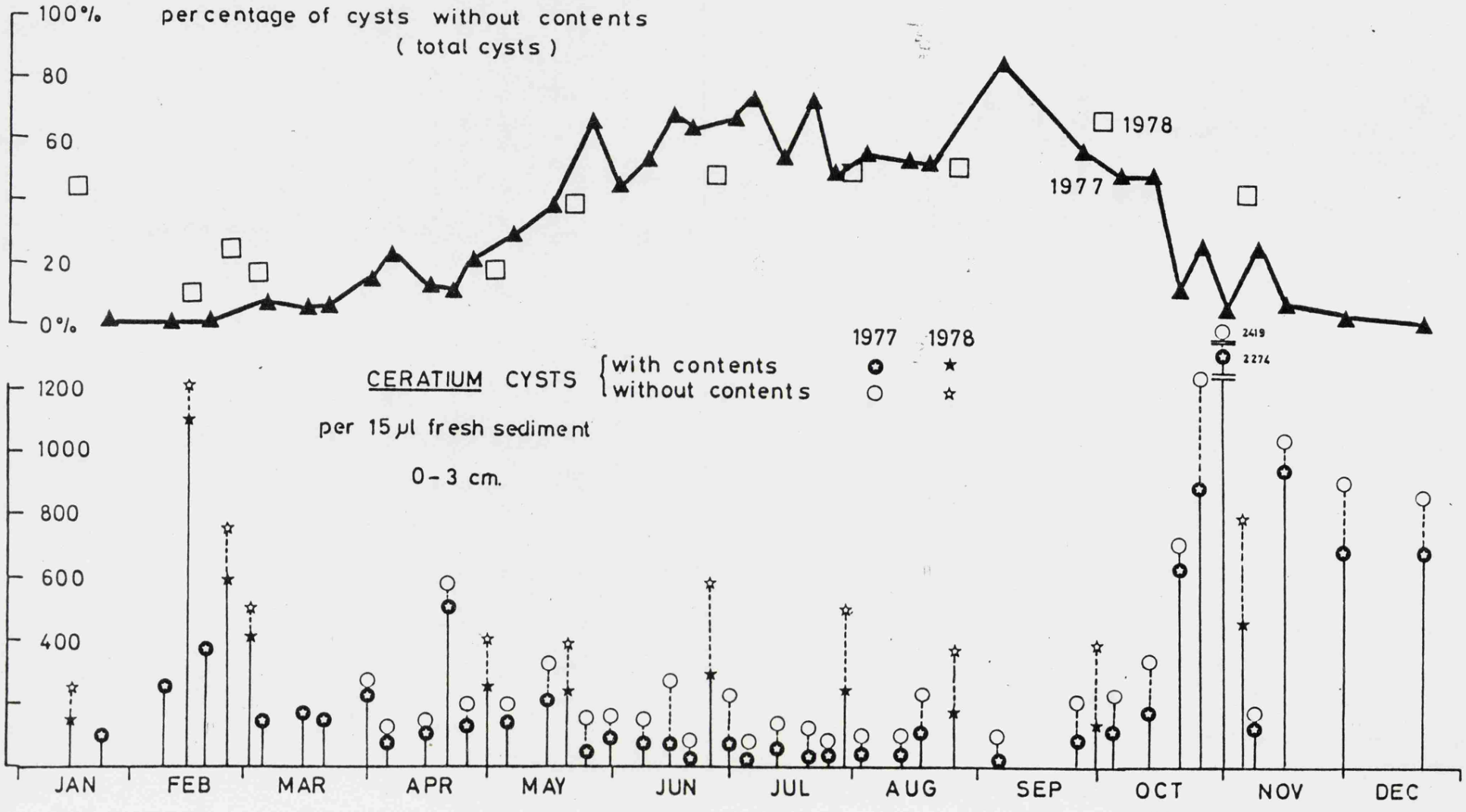


figure 7.3

ESTHWAITE

ii) experiment B

Cysts were collected from the plankton in September 1977 and a concentrate of cysts plus cells and other seston was placed in 24 flasks. Half of the flasks were sealed and left to go anaerobic whilst the remainder were plugged with cotton wool. The experiment was kept in the cold (circa 5°C) and dark. Every month two flasks (one 'anaerobic' and one 'aerobic') were removed and placed in the cabinet along with experiment A. Up to April 1978 no germination could be induced from either set of flasks. The water in both was discoloured and had a pungent smell. The failure to germinate may have been due to the build up of toxic conditions in the flasks. Unfortunately before any cysts were removed from the flasks and placed in fresh media the experiment was prematurely abandoned due to the breakdown of the refrigerator. It is worth noting that the anaerobic flasks, after 6 months, contained virtually no large living organisms and many apical horns of the Ceratium cells were still intact. The aerobic flasks contained many ciliates and other organisms and all the cells were fragmented and unrecognisable.

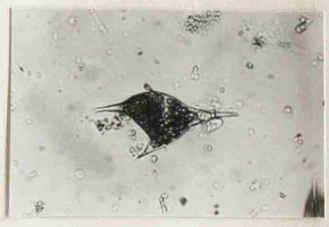
Germination of cysts from the sediment cores could be easily induced, from mid-February, by bringing them into the laboratory. The medium was not important since germination took place not only in Chu 10 but also in lake water, tap water or distilled water (although in the latter many cells failed to mature and were deformed). The majority of the cells were 4-horned. The presence or absence of light made no difference to the germination of mature cysts. Plate VII shows a time series for the growth of a 'gymoceratium' to a 'preceratium' in culture.

PLATE VII

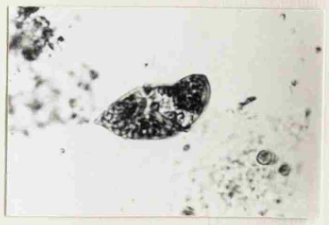
The development of a Ceratium hirundinella cell from Esthwaite Water : time series

magnification x 200

PLATE VII



cyst

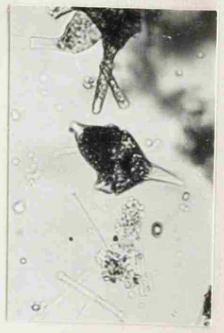


'gymnoceratium'

10,20 am

10,30

10,35



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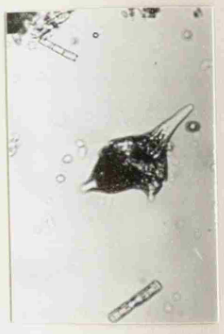

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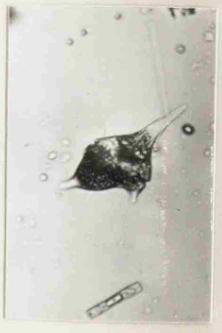

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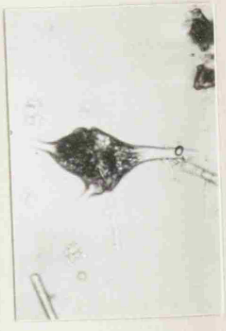

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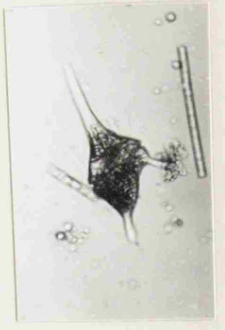

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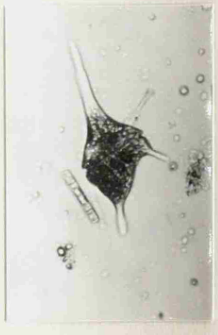

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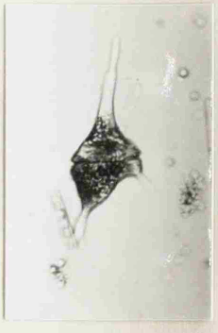

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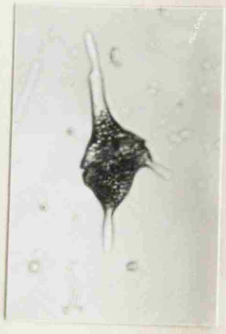

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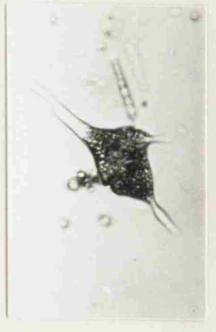


13,15

4. DISCUSSION

The encystment of a Ceratium population results in a potential stratigraphic layer being deposited onto the sediment surface. The crop of 'new' cysts, in the autumn, could be observed in the surface material of Esthwaite Water. However it was difficult to follow this crop's incorporation into the sediments because it was not possible to discern annual layers in the sediment. Not all of the cysts laid down in one year had germinated before the following year's planktonic population encysted. Those cysts which became empty did not remain in a layer below the 'new' (full) cysts, and apparently decomposed rapidly. The top 2-3 cm of the sediments in Esthwaite form the 'oxidised microzone', (Mortimer, 1942; Gorham, 1958) comprising the flocculent material which becomes oxygenated during the winter. In this zone the oxidation of organic matter can proceed before its incorporation into more mature sediment. Very few empty Ceratium cysts are preserved in the deeper, reduced sediment and it may be hypothesised that the cysts are decomposed in the oxidised microzone. In contrast, the sediments of Rostherne Mere are permanently anoxic and there is good preservation of Ceratium cysts (see also Chapter 8 for further discussion on decomposition).

Huber & Nipkow (1922) recorded viable Ceratium cysts in the sediments of Lake Zürich up to 5-6 years old. However the lack of full cysts in Esthwaite Water indicates that the cysts germinate or decay within a few years.

Cells of Ceratium hirundinella are not observed in the 0-5 m water column of Esthwaite during the winter months but the occasional 'shrivelled' individual is recorded in the spring (C. Butterwick - personal communication). Cysts are found in the plankton samples

throughout the winter, presumably resuspended from the littoral areas of the lake. The number of full cysts in the surface sediments starts to decrease at the end of February, and this is closely correlated with the appearance of cells in the 0-5 m sample at the beginning of March (figure 7.4). This suggests that the planktonic population may be derived from the cysts, rather than an overwintering population. There appears to be a rapid germination of cysts until the end of May as the population in the water also increases. From June the number of cells increases quickly (population doubling time during exponential growth is circa 6-7 days - Heaney, 1976) but recruitment from the sediment is seemingly unimportant. The relative number of empty to total cysts in the sediment decreases as encystment commences in the plankton during September.

When the surface sediment was placed in fresh water and brought into the laboratory virtually all the cysts germinated within five days. If temperature is the only mechanism responsible for initiating germination of the Ceratium cyst, then all viable, mature cysts would germinate at a critical temperature. This does not happen since full (and viable) cysts are present in the surface sediments over summer. Huber & Nipkow (1922) reckoned that the minimum temperature for germination was around 5°C. The bottom temperature of Esthwaite Water was about this figure in 1977 and 1978 when cells were first noted in the 0-5 m column (table 7a). However it must also be noted that this period also coincides with the time that the cysts reach maturity, i.e. no germination could be induced in culture before mid-February. The water temperature is much higher in the autumn and early winter when cells are not observed in the water column.

Typically between 56-96% of the empty cysts observed in the Esthwaite sediments contained a small orange-brown residue, similar to

Table 7a Esthwaite *Ceratium* - spring temperature data

Date	*Ceratium* (cells 100 ml^{-1})	Temperature (°C)	
	0-5 m column	surface	15 m
1977			
March 1	1	4.6	4.6
8	0	5.2	5.1
15	24	6.1	5.8
22	87	5.8	5.8
29	149	5.9	5.6
April 5	165	5.5	5.3
1978			
March 7	0	4.4	4.4
14	1	5.5	5.5
21	20	5.3	5.3
29	58	5.6	5.8
April 4	99	6.8	6.3

that present in cyst remains from Rostherne Mere and Ellesmere Mere. Cysts which were germinated in the laboratory experiments did not contain this residue, which is in accordance with the observations of Huber & Nipkow (1922). Therefore the empty cysts containing this residue may represent individuals which have decayed or been parasitised (D. Chapman - personal communication).

Around February-March the relative number of empty cysts increases which may reflect either an increase in the rate of cyst decomposition/parasitism or, more likely, a reflection of the number of viable cysts germinating as the planktonic community increases. Cysts which were totally devoid of contents were difficult to identify within the fresh sediment, and consequently may be underestimated, while the orange-brown residue enabled the cyst remains to be easily seen.

The non-germination of about 10% of the cysts may be a result of the build up of toxic conditions in either the superficial sediments or the overlying water. The number of cysts germinating appears to slow down around May-June (figure 7.4) while the onset of deoxygenation in 1977 occurred in mid-June (A. Wightman - personal communication). This may possibly explain why no germination could be induced from the flask experiments when both sets became foul smelling and discoloured. Reynolds (1971) also failed to germinate blue-green akinetes under anoxic conditions.

Therefore if cysts of Ceratium hirundinella are inhibited from germinating under anaerobic or saprobic conditions and subsequently decay, leaving an orange-brown residue and cyst wall, then the remains in the permanently deoxygenated sediments of Rostherne Mere may reflect the annual crop of cysts. Parasitism is unlikely to be significant in anoxic waters (Lund - personal communication). However the use of Ceratium cysts as indicators of past crops in Rostherne Mere makes the

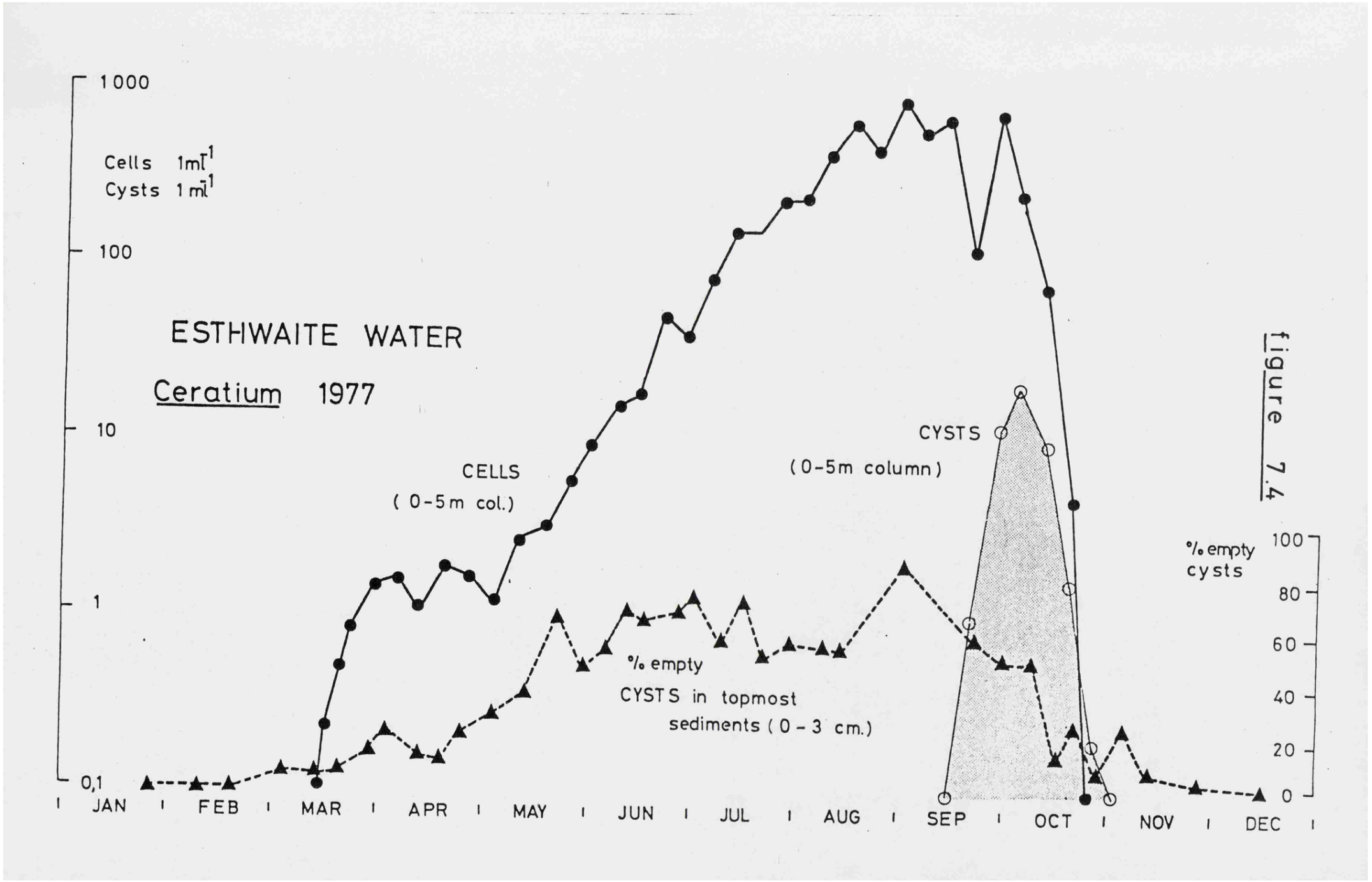

1000
Cells 1ml⁻¹
Cysts 1 ml⁻¹
100
ESTHWAITE WATER
Ceratium 1977
10
CELLS
(0-5m col.)
CYSTS
(0-5m column)
1
% empty
CYSTS in topmost
sediments (0 - 3 cm.)
0,1
% empty
cysts
100
80
60
40
20
0
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

figure 7.4

unqualified assumption that cyst abundance is correlated with cell density. For example Heaney (1976) noted that in 1971, there was a mass encystment of the Ceratium cells in Esthwaite, whereas in 1973 a large proportion of the vegetative cells underwent a sudden lysis at the end of September. However there appears to be an association in Rostherne (but not in Esthwaite) between years of abundance in the plankton and abundant remains in the sediments.

B. ROSTHERNE MERE

1. INTRODUCTION

The algal stratigraphy of the deep water cores in Rostherne Mere indicated that sedimentation was highly ordered and that algal remains were deposited in discrete layers on the sediment surface. Seston traps were placed in the lake to examine the accumulation of algal remains and to compare the seston with both the phytoplankton and the sediments.

a. Seston

Hutchinson (1967) defines seston as "the entire mass of suspended matter in a volume of free water". The seston consists of allochthonous and autochthonous particles present in the water column of a lake. Pennington (1974) comments, "since lake sediments originate from seston after microbial and chemical transformations seston is important both qualitatively and quantitatively in palaeolimnology".

b. Seston traps

There are many different designs of seston traps (cf. Pennington, 1974) and the design is crucial to any comparison involving the volume of seston caught (Tutin, 1955). There have been few comparative evaluations of trap performance, but studies have been carried out by Pennington (1974), Kirchner (1975) and Reynolds (1979c). However Reynolds states,

> "... the implicit assumption that what enters the trap, whatever the design, would otherwise have sedimented from that part of the water column has still not been tested adequately".

Traps in non-turbulent water layers have been shown to give good replication, but performance in the mixed layers is often significantly modified by turbulent flow around the trap (Pennington, 1974; Reynolds, 1979c).

c. Sediment - seston

Pennington (1974) compared the annual accumulation of sediment as measured by radionuclide, and palaeomagnetic, methods to the estimate derived from seston trapping. The two values were compatible for the deep water lakes of Windermere, Ennerdale Water and Wastwater but the seston traps in Esthwaite and Blelham, which are shallower, caught about twice the amount of material which was permanently incorporated into the sediments. This was interpreted as showing vigorous resuspension and recirculation of material on the lake bed and was a function of lake morphometry. Davis (1973) found that resuspension occurred during the whole year in a non-stratified lake but only during mixing events in a stratified lake. In the littoral zones Davis estimated that the

uppermost 6-12 mm of sediment could be disturbed by overturn mixing and even in deeper areas of the basin 1 mm may be disturbed. Seston traps can be used to demonstrate the movement of sediment from different areas of the lake bed to others and detect any sorting due to differential movement.

d. Phytoplankton - seston

Non-motile algae, such as diatoms, are dependent on turbulent water movements in order to remain in the water column, but motile or buoyant algae (e.g. dinoflagellates and cryptomonads or certain blue-green algae) are capable of controlling their vertical position within the limits imposed by turbulence. Thus, non-motile species have a constant tendency to sediment while motile and buoyant algae would only passively sink if the ability to regulate their vertical position was lost, for example by death of the cell.

Phytoplankton will ultimately sink to the lake bed unless it is:

(i) washed out of the system

(ii) consumed by grazing animals

(iii) decomposed or disintegrated whilst sinking

Comparison of the algal remains in the seston and phytoplankton records can show whether (ii) and (iii) are important. The small outflow of Rostherne Mere and long residence time of the waters means that wash out of the abundant phytoplankton crops must be neglibible.

All the phytoplankton results presented here are reproduced by kind permission of Dr C.S. Reynolds (unpublished data).

2. METHODS

The seston traps used were vertical-sided perspex cylinders, diameter 6.55 cm (Pennington, 1974 - p.217). These were used in pairs and attached to a rope between an anchor and a submerged float (Pennington, 1974 - p.220).

One set of three paired traps was situated in the centre of the mere in 30 m of water. The traps were placed 2 m, 12 m and 21 m above the mud surface. Two other sets, each with a pair of traps at both 2 m and 12 m above the mud surface, were also placed into the lake. One set was placed near the inflow (see figure 7.1), but not in direct line of flow, in 21 m of water and the other at the south end of the lake, near the outflow, in about 20 m of water. The top traps on each set were, therefore, positioned circa 8 - 9 m below the water surface and would remain below the epilimnion for most of the summer (see Grimshaw & Hudson, 1970). Pennington (1974) and Reynolds (1979c) have shown that seston traps sited in the epilimnion may give erroneous estimates of sedimentation owing to their performance in turbulent water.

The traps were emptied at approximately three monthly intervals. On collection the traps were gently lifted aboard a boat and then examined (by eye), emptied and cleaned before being returned to the lake. Material from the trap 'pairs' was amalgamated to provide sufficient material for analysis. Pennington (1974) found the replication of paired traps was satisfactory.

The wet volume of seston was measured after natural settling. The contents of the traps were emptied into suitable measuring cylinders and two drops of 40% formalin added to prevent further decomposition. The seston was left until constant volume was attained. In practice

no further settling was observed after circa 4 days. Supernatant water was removed with a pipette, the seston was then homogenised and aliquots removed by a graduated syringe (without needle).

Algal remains were enumerated on fresh seston (see Chapter 2) from each pair of traps. Diatoms were examined from only the bottom trap of the centre set.

Material from the centre-middle trap was lost during collection in December 1977 and estimates of areal density could not be calculated.

3. RESULTS

a. General observations

Over the period of study there was no significant difference in the amount of seston caught, or the dominant algal remains therein, between different traps ($p > 0.01$) for any given trapping period. Analysis of variance showed that spatial differences between traps had no appreciable effect on the trap behaviour (table 7b). Differences were, however, noted for algae such as Oscillatoria which are not preserved for any length of time.

Table 7b Analysis of Variance F-values

	between traps	between trapping periods
seston volume	0.19 *	28.32
Microcystis colonies	0.12 *	81.52
Stephanodiscus astraea	0.03 *	-
Melosira varians	0.11 *	-

* no significant difference ($p > 0.05$)

The bulk of the seston was caught in the latter part of 1977 (figure 7.5a) after an abundant population of Microcystis aeruginosa. As demonstrated in the deep-water cores the volume of this alga is such that large populations can produce a layer of sediment in excess of one centimetre thick. The depth of seston caught was over 3 cm thick.

The sets of traps raised at the end of September 1977 all contained a white 'ash-like' layer in the middle of the accumulated seston. The material contained many calcium carbonate granules, presumably precipitated by large surface blooms of Microcystis. This is consistent with the X-ray plates taken of the deep water cores (see Chapter 5).

Invertebrates were commonly observed in the traps but activity was typically greatest in the surface traps and decreased with depth. Hydra spp. were frequent and in January 1979 the bottom traps contained a large Cyclops sp. (Reynolds - personal communication).

b. Algal remains

The algal remains observed in the entrapped seston are similar, in composition, to those recorded in the sediment cores (table 7c). The attached and benthic diatoms, found in small numbers in both the seston and sediment, have been excluded from the table.

Microcystis aeruginosa colonies dominated the algal remains in the seston traps at the end of 1977 (figure 7.5b), a few individuals were also recovered in September 1978. Many of the colonies appeared healthy and some became buoyant in the sedimentation cylinders on return to the laboratory. Anabaena akinetes, both without and, more commonly, with contents were found in the traps covering the period June to September 1978 (figure 7.5c). These traps also contained the remains

figure 7.5

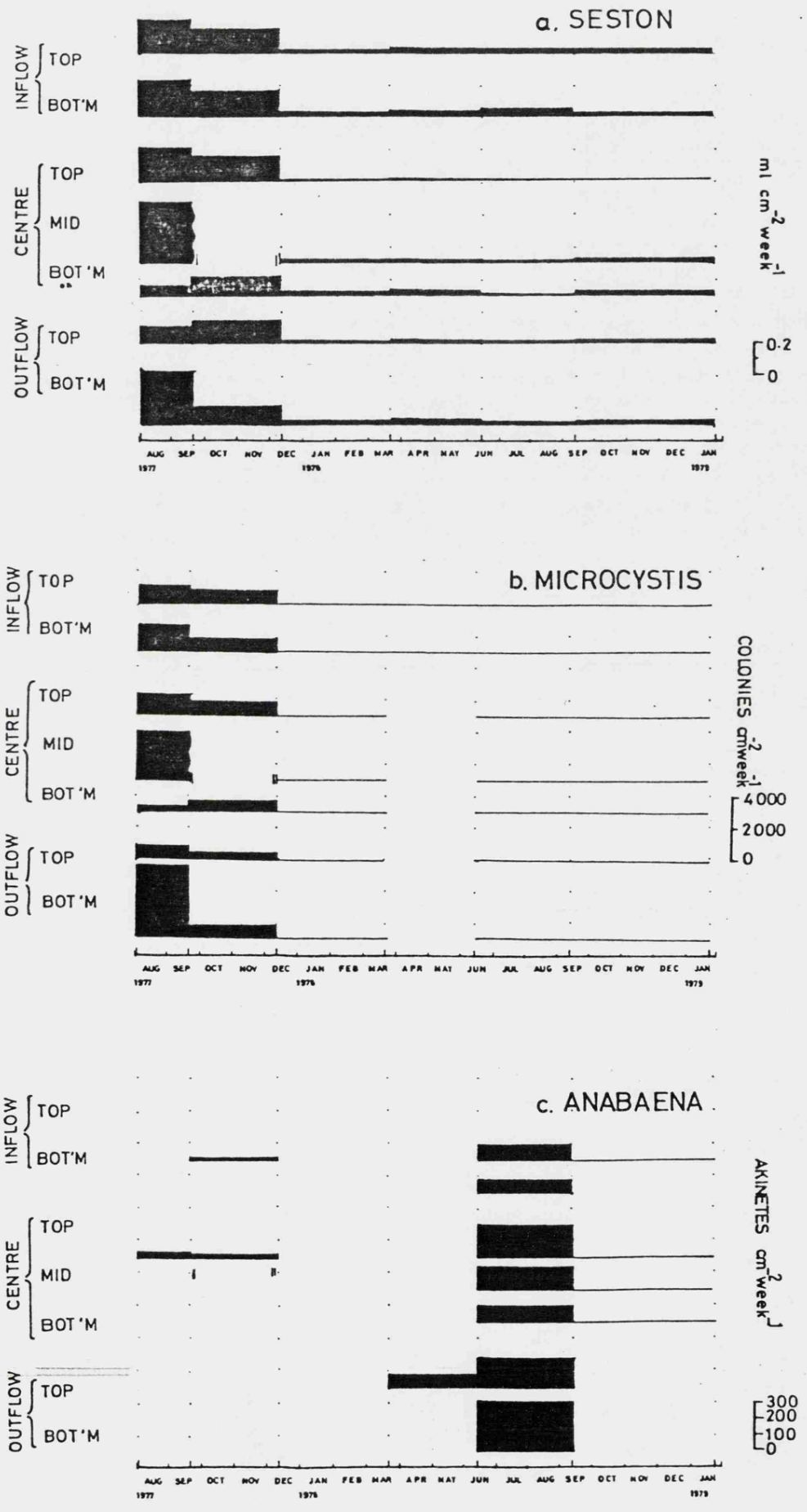

a. SESTON
INFLOW
TOP
BOT'M
CENTRE
TOP
MID
BOT'M
OUTFLOW
TOP
BOT'M
ml cm⁻² week⁻¹
0·2
0
AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC JAN
1977
1978
1979
b. MICROCYSTIS
INFLOW
TOP
BOT'M
CENTRE
TOP
MID
BOT'M
OUTFLOW
TOP
BOT'M
COLONIES cm⁻² week⁻¹
4000
2000
0
AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC JAN
1977
1978
1979
c. ANABAENA
INFLOW
TOP
BOT'M
CENTRE
TOP
MID
BOT'M
OUTFLOW
TOP
BOT'M
AKINETES cm⁻² week⁻¹
300
200
100
0
AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC JAN
1977
1978
1979

Table 7c Algal remains in the seston traps

Stephanodiscus astraea *	Fragilaria crotonensis *
Stephanodiscus hantzschii *	Fragilaria capucina *
Melosira arenaria *	Asterionella formosa *
Ceratium hirundinella *	Melosira varians *
Microcystis aeruginosa *	Anabaena spp. *
Aphanizomenon flos-aquae *	Oscillatoria agardhii *
Cosmarium sp.	Staurastrum spp. *
Scenedesmus *	Pediastrum *
Ankyra	

(* Recorded in sediment cores)

Table 7d Mean lengths of Oscillatoria filaments

Traps	inflow - bottom	54 µm	remainder contained too few filaments to obtain a figure, but an estimated length was circa 50 µm
	centre - middle	85 µm	
	centre - bottom	231 µm	

Phytoplankton	January	567 µm	June	224 µm
	February	810 µm	July	336 µm
	March	1030 µm	August	324 µm
	April	-	September	260 µm
	May	428 µm		

(Reynolds - unpublished data)

of Oscillatoria agardhii (figure 7.6a). Few healthy filaments were recovered, the majority were degraded and fragmented. The average filament length was estimated by measuring (where possible) 50 to 100 filaments greater than ~ 20 μm. The mean length generally increased with depth (table 7d).

A small number of Ceratium hirundinella cysts were trapped each year in the autumn (figure 7.6b). All the cysts had contents.

The green algae Pediastrum, Scenedesmus, Ankyra (?), Cosmarium and Staurastrum were recorded in the traps, albeit in small numbers. A few cells of Ankyra were present in the traps raised in January 1978. The cells appeared to have recently sedimented since the chloroplasts retained bright pigmentation. Pediastrum was recorded throughout the year and was frequent in the summer traps.

The large diatoms Stephanodiscus astraea and Melosira varians were enumerated on fresh material from all the traps. The remaining species were only assessed on diatom mounts from the centre-bottom traps. Melosira varians occurred predominantly in March - June 1978, although the inflow-bottom trap contained a comparable number from the September 1978 - January 1979 period (figure 7.6c). Stephanodiscus astraea was recovered from all the traps from both the above periods (figure 7.7a).

The bulk of the planktonic diatoms (> 90%) were trapped during the March - June period 1978 (figure 7.7b). The dominant species were Asterionella formosa (over half of the frustules recovered), Stephanodiscus hantzschii, Stephanodiscus astraea and Fragilaria crotonensis (figure 7.7c). The seston from the first part of the year also contained most of the 'non-plankton' species (e.g. Gomphonema, Cymbella, Cocconeis) except for Nitzschia spp which were particularly common at the end of

figure 7.6

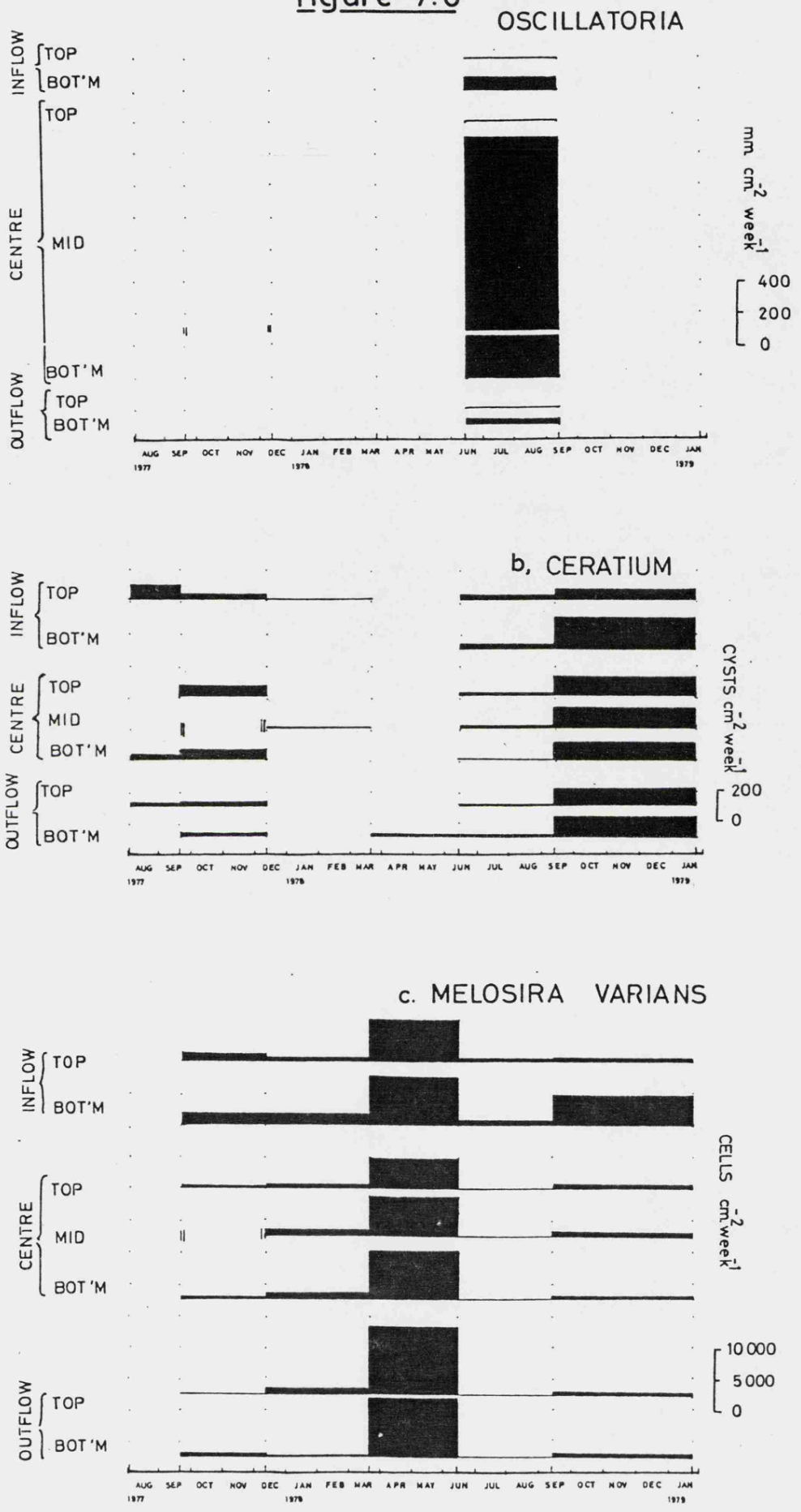
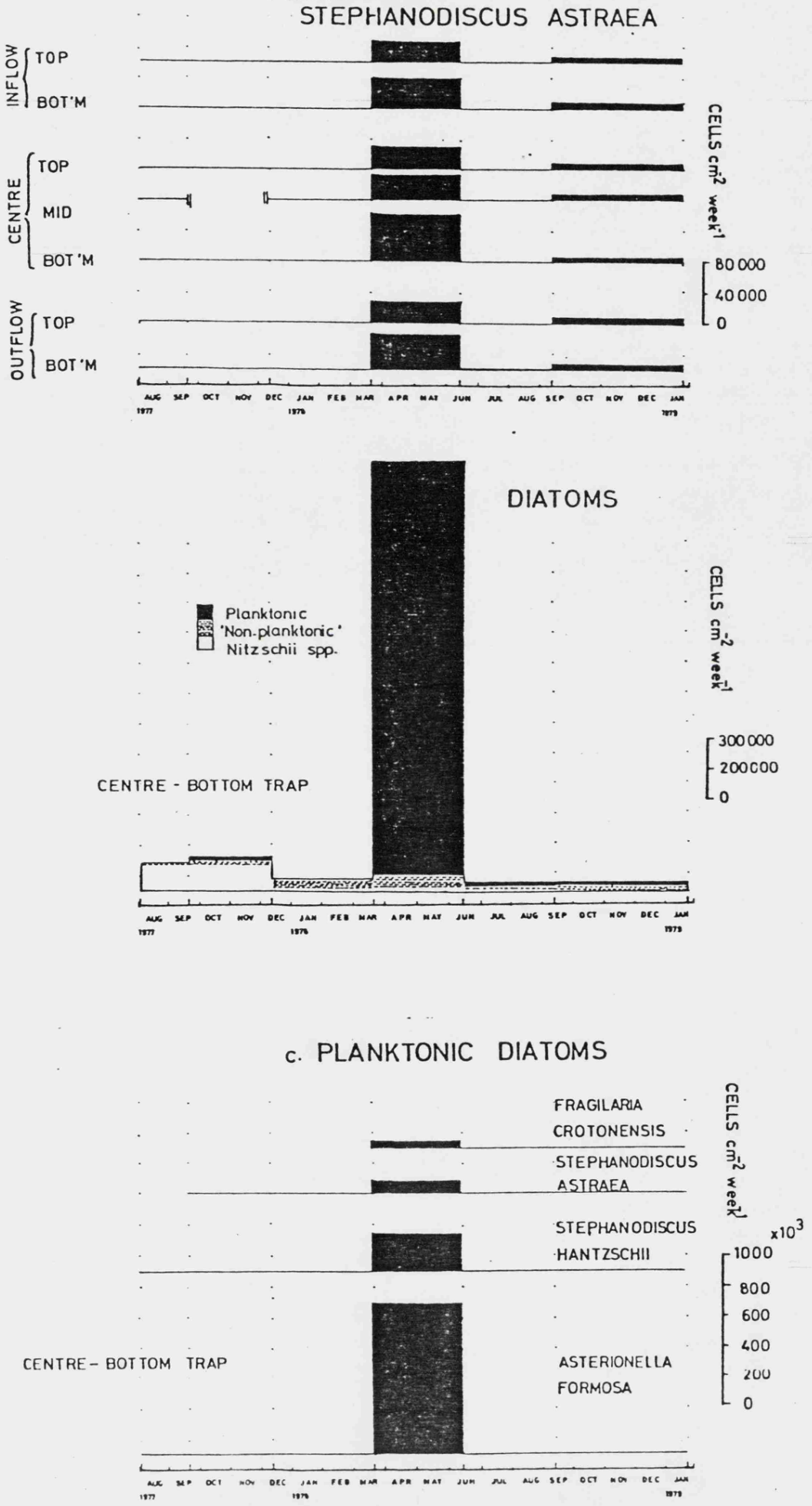

OSCILLATORIA
INFLOW
TOP
BOT'M
CENTRE
TOP
MID
BOT'M
OUTFLOW
TOP
BOT'M
mm cm⁻² week⁻¹
400
200
0
AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC JAN
1977
1978
1979
b, CERATIUM
INFLOW
TOP
BOT'M
CENTRE
TOP
MID
BOT'M
OUTFLOW
TOP
BOT'M
CYSTS cm⁻² week⁻¹
200
0
AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC JAN
1977
1978
1979
c. MELOSIRA VARIANS
INFLOW
TOP
BOT'M
CENTRE
TOP
MID
BOT'M
OUTFLOW
TOP
BOT'M
CELLS cm⁻² week⁻¹
10 000
5 000
0
AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC JAN
1977
1978
1979

figure 7.7


STEPHANODISCUS ASTRAEA
INFLOW
TOP
BOT'M
CENTRE
TOP
MID
BOT'M
OUTFLOW
TOP
BOT'M
CELLS cm-2 week-1
80 000
40 000
0
AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC JAN
1977
1978
1979
DIATOMS
Planktonic
'Non-planktonic'
Nitzschii spp.
CENTRE - BOTTOM TRAP
CELLS cm-2 week-1
300 000
200 000
0
AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC JAN
1977
1978
1979
c. PLANKTONIC DIATOMS
FRAGILARIA
CROTONENSIS
STEPHANODISCUS
ASTRAEA
STEPHANODISCUS
HANTZSCHII
ASTERIONELLA
FORMOSA
CENTRE - BOTTOM TRAP
CELLS cm-2 week-1
x10^3
1000
800
600
400
200
0
AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC JAN
1977
1978
1979

1977 (figure 7.7b). Nitzschia palea dominated the genus and was frequently found attached to the periphery of Microcystis colonies (Reynolds, 1978).

4. DISCUSSION

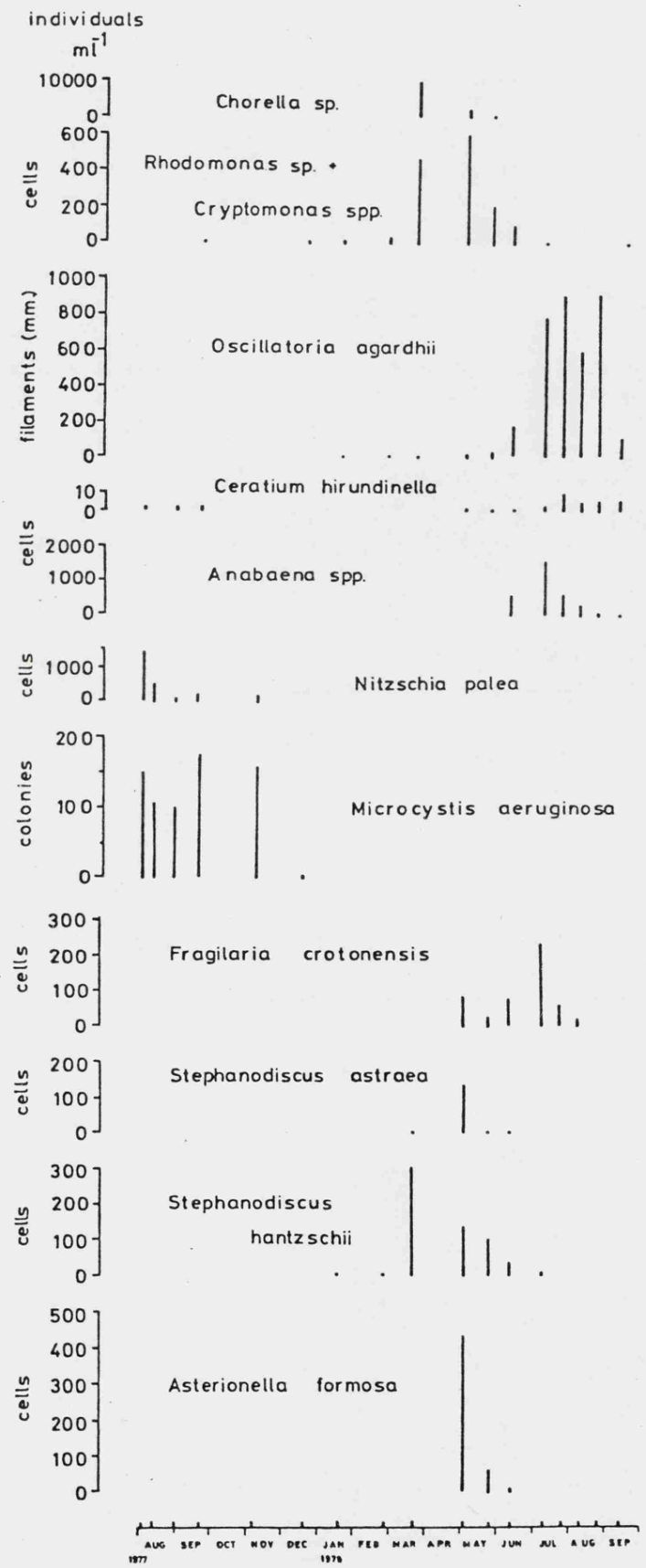
The phytoplankton succession 1977-1978 (figure 7.8) is similar to that described for many previous years by Reynolds (1978). The summer and autumn of 1977 were dominated by Microcystis aeruginosa while in 1978, and atypically for Rostherne Mere, Oscillatoria agardhii was abundant during the summer. The sparse plankton in the early part of 1978 was dominated by Chlorella and the flagellates Rhodomonas and Cryptomonas which were followed by the diatoms Asterionella formosa, Stephanodiscus hantzschii, Stephanodiscus astraea and then the blue-green Anabaena. A small population of Ceratium hirundinella was present during 1978.

Remains of all the above algae were recovered, with the notable exceptions of the unicellular small greens and cryptomonads. A small number of Chlorophyceae were found in the traps but were either degraded or contained intact chloroplasts, and so were assumed to have recently sedimented. The sediments of both Ellesmere Mere (cf. table 4a) and Rostherne Mere contained very few remains of the small algae recorded in the phytoplankton.

Quantitative comparisons between phytoplankton density and their remains in the sediments is often impossible since it is difficult to separate the annual influx to the deposits from older individuals already present. However a rough estimate can be made using the data from the seston traps.

figure 7.8

ROSTHERNE MERE - PHYTOPLANKTON



(from Reynolds - unpublished data)

A quantitative comparison between the phytoplankton and the entrapped algal remains can only be performed approximately because the total number of individuals produced in the plankton, in any one year, cannot be accurately computed. However, crude estimates can be made, probably to within an order of magnitude, from information on standing crop concentrations, expressed per unit area of lake surface. Table 7e compares the estimated areal density of phytoplankters (Reynolds, unpublished data) with the seston trap and core data. The calculation is based upon:

1. The maximum observed population in 0-4.5 m (this will usually be smaller, and never greater, than the total production)
2. The assumption that the natural population is uniformly distributed with depth through 30 m when the lake is isothermal or to the bottom of the epilimnion (5-8 m depth) when the lake is stratified (May to October inclusive)

It is realised that the estimates derived are only approximate and the following factors must be considered.

1. Motile and buoyant phytoplankton may attempt to migrate to a certain depth in the water column (Reynolds, 1976b).
2. Under conditions of moderate turbulence (i.e. sufficient to suspend but not to thoroughly mix), a greater number of non-motile algae (e.g. diatoms) will be present in the euphotic zone where they will be photosynthesising and growing (Lund, 1959).
3. Wind-induced movements can affect the spatial homogeneity of a population (Heaney, 1976).
4. The depth of the epilimnion varies throughout the summer (see (Grimshaw & Hudson, 1970) but 8 m is taken as the best approximation (see Reynolds & Rogers, 1976).

Table 7e Rostherne Mere: phytoplankton - seston - sediment

Alga	Estimated areal density individuals cm^{-2}	Total trapped at depth	individuals cm^{-2}	Cores Y* - Z* individuals cm^{-2}
Stephanodiscus astraea	174 885	30 m	740 496	-
		20 m	578 105 - 518 884	-
		8 m	358 170 - 386 764	477 000 - 223 600
Stephanodiscus hantzschii	385 014	30 m	2968 520	-
Asterionella formosa	591 405	30 m	11 854 080	-
Melosira varians	400	30 m	88 296	-
		20 m	54 096 - 130 368	-
Nitzschia palea	1 151 280	30 m	1 667 100	-
Microcystis aeruginosa	137 280 colonies	30 m	49 678	-
		20 m	102 418 - 174 665	-
		8 m	64 078 - 88 418	-
Oscillatoria argardhii	715 806 mm	30 m	3458 mm	-
		20 m	390 - 15 483 mm	-
		8 m	39 - 130 mm	560 mm
Chlorella	13 153 000	all depths	None	None
Cryptomonas & Rhodomonas	790 320	all depths	None	None

5. The sampling interval may not coincide with the maximum population which in any case may underrepresent the annual production.
6. Trap performance can vary, especially in turbulent flow (Reynolds, 1979c; Pennington, 1974).
7. During isothermal mixing all the traps may be in turbulent water and hence there is the possibility that, potentially, the same diatom (say) may pass near the trap on more than one occasion.

Despite the approximate nature of the estimates, the difference between the phytoplankton density and the total number of algal remains is typically within an order of magnitude, for the resistant algae (table 7e). Not unexpectedly the largest differences are to be found amongst those algae which have not been recorded in the recent sediments. Therefore more than 13 million Chlorella and 700 000 Cryptomonads which potentially could have sedimented onto 1 cm^2 of lake bed either decomposed rapidly or were consumed by grazing zooplankton. Small algae were difficult to see in fresh sediment but it is extremely unlikely that such large numbers would have been entirely overlooked. Reynolds (1976) found few cryptomonads in seston traps placed in Crose Mere and raised every 3-4 days. Almost all the recoveries were made in July when he observed a seasonal minimum of zooplankters, especially herbivorous rotifers, which reduced the grazing pressure on the potential food organisms.

The traps caught very little of the large Oscillatoria crop in 1978. The mean filament length increased with depth which may indicate greater disintegration or decomposition in the upper traps. However Gibson & Stevens (1979) found the average length of Oscillatoria agardhii

filaments in Lough Neagh was greatest at the beginning of the year but shortened as the nutrient concentration in the water fell. It is possible that the larger filaments in the bottom traps may have sedimented from early populations while the short filaments reflect later populations. The mean filament length in the phytoplankton of Rostherne Mere (table 7d) was greatest for the first few months in the year. However very few of these long filaments were present (figure 7.8) and even during the summer the mean length in the plankton was > 220 µm, compared with circa 50 µm in the upper traps. The traps raised in January 1979 contained virtually no Oscillatoria despite the sizeable planktonic population present when the traps were set. This is interpreted as indicating that unhealthy or moribund cells quickly disintegrate and decompose. Lund (1978) observed the rapid disintegration of Oscillatoria populations in Blelham Tarn (in 1973) by firstly parasitism and grazing followed by sudden lysis.

The areal density of planktonic diatoms in the seston corresponds, within an order of magnitude, to the estimates derived from the plankton counts. Reynolds (1976) also found a rough correlation between catches of Melosira granulata in seston traps, situated near the sediment surface of Crose Mere, and the standing crop.

Melosira varians was commonly recorded in the seston trap material but only rarely in the plankton. It is typically found in the muds, often in ponds, ditches and slow flowing rivers (West & Fritsch, 1927) and in Rostherne probably flourishes in the inflows and littoral areas. The density of entrapped frustules was up to three orders of magnitude greater than the estimate derived from the standing crop (Table 7b). The lateral dispersion of Melosira varians to the deep water traps suggests that this alga is rapidly resuspended in the littoral zones and subsequently deposited.

The greater number of algal remains were recovered from the traps during, or just after, periods of abundance in the open water (cf. Gasith, 1976; Reynolds, 1976b). For example there were few 'out of season' diatoms found in the centre bottom traps (figure 7.6b). This may be indicative of either little resuspension of particular, small, algae or a small crop of littoral species. Rostherne Mere has a relatively small littoral area and steep gradients (see bathymetric map - figure 7.1); therefore not only is a small proportion of the lake suitable for littoral algae but also only a small area is subjected to turbulent mixing (cf. Pennington 1974). Rostherne has a sparse macrophyte community and during the last fifteen years the previously common lilies have declined markedly (T. Wall - personal communication) and hence the number of epiphytes may be small.

Unless resuspended by wave action breaking the sediment surface it is likely that most algae on the sediments are protected from subsequent movement by the laminar sub-layer at the sediment-water boundary. Smith (1975) states:

> "... algae in lakes which, if they have settled on the bed, are not likely to be lifted back up in the current".

The degree of resuspension may be affected by the cell morphology and specific gravity, plus the position of the alga relative to the interface. Melosira varians commonly forms large, "fluff-like" balls (J.W.G. Lund - personal communication) and as such may extend out of the boundary layer to be either resuspended or 'rolled' down the lake bed. The latter is a form of sediment focussing (tendency for sediment to accumulate in the deepest part of the basin) which Lehman (1975) states may be greater in basins shaped like a hyperboloid, such

as Rostherne. Few frustules, or aggregates, of Melosira varians would be noted in the plankton if either they were rolled down the bed or resuspended in highly turbulent conditions (e.g. in gales and storms) which may not coincide with a sampling date. It would appear that the alga is rapidly removed from the littoral areas since it was only trapped in quantity following periods of abundance and not throughout the year. It may be expected that a large, light alga such as Microcystis would also be susceptible to resuspension especially as it sinks in autumn when resuspension, in stratified lakes, is typically greatest (Davis, 1973). Similar to Melosira varians, small numbers of Microcystis aeruginosa were found in the traps throughout the year but only 1-7% could be described as 'out of season'. Trap recoveries of Microcystis aeruginosa are also comparable with the cycle of buoyancy and vertical distribution given, for Rostherne Mere, by Reynolds & Rogers (1976).

The annual increment of seston accumulation in 1978 was 1.24-2.02 cm while the depth collected in the last five months of 1977 was 2.21-3.92 cm (if the January to August figures for 1978 are added to the latter estimate the annual increment becomes circa 3.13-4.84 cm). The difference between the figures is attributable to the large number of Microcystis colonies in the seston in 1977. This is in accordance with the observed acceleration in the rate of sediment accumulation, in the sediment cores, associated with the increased frequency and standing crop of Microcystis in the mere since the late nineteen-fifties (see Chapter 5).

Therefore the seston traps have shown that algal sedimentation in Rostherne Mere is discrete, and there is little areal variation in the deeper areas of the lake. There is good correspondence between

standing crop and algal remains, although many small unicellular, non-diatomaceous algae decompose rapidly or are consumed by herbivores and were not observed in the seston or cores.

CHAPTER EIGHT

GENERAL DISCUSSION AND CONCLUSIONS

CHAPTER EIGHT: GENERAL DISCUSSION AND CONCLUSIONS

1. ALGAL PRESERVATION

This study has shown that only specific algal remains are preserved in the recent sediments of certain lakes (table 8a). The algal assemblages found in these British sites are similar, in composition, to those recorded in the U.S.S.R. sapropel deposits. The algal taxa which are preserved in the deposits typically include the dominant summer species and often represent the bulk of the annual biomass, for example Ceratium hirundinella or Microcystis aeruginosa in Ellesmere Mere and Rostherne Mere and Aphanothece elebans in Upton Broad. Algae which are not recorded in either this study or in the sapropel deposits are typically the smaller, unicellular, algae; for example Chorella, Monoraphidium, Cryptomonas and Rhodomonas. Remains of filamentous algae were not observed in the sediments below the flocculant surface layers, (e.g. Spirogyra - Upton Broad; Oscillatoria - Esthwaite Water and Rostherne Mere) but the akinetes of the filamentous blue-greens Anabaena and Aphanizomenon were frequent.

a. Dinophyceae

Dinoflagellates, and in particular taxa resembling the genus Ceratium, have been found as fossilised cysts in Lower Cretaceous strata (Wall & Evitt, 1975; see also Sarjeant 1974). However records of Ceratium preservation in freshwater sediments are sparse. Korde (1966) observed that Ceratium and Peridinium remains were exclusive to the topmost deposits of the U.S.S.R. sapropels and Nipkow (1927) recorded cysts of Ceratium hirundinella in the varved sediments of

Table 8a Non-siliceous algal remains in lake sediments (below 5 cm)

	Esthwaite	Priest Pot	Upton	Ellesmere	Rostherne	U.S.S.R. sapropels
1. Dinophyceae						
Ceratium	●			●	●	
Peridinium						
2. Cyanophyceae						
Anabaena	●			●	●	●
Aphanizomenon				●	●	●
Aphanocapsa						●
Aphanothece			●		●	●
Gloeocapsa						●
Gloeothece						●
Gloeotrichia						●
Lyngbya						●
Microcystis	●			●	●	●
Phormidium						●
2. Chlorophyceae						
Botryococcus						●
Coelastrum				●	●	●
Cosmarium			●			●
Euastrum						●
Pediastrum		●	●	●	●	●
Scenedesmus		●	●	●	●	●
Staurastrum	●		●	●	●	●
4. Euglenophyceae						
Trachelmonas	●					

Lake Zürich. Nipkow explicitly mentioned the presence of cysts that formed during the years 1915-1925 but when these varves were examined, in a core taken in 1972, not a single cyst was observed and Wall & Evitt concluded that they had decomposed. The cysts of Ceratium hirundinella in the sediments of Rostherne Mere, although devoid of contents, are recognisable in material likely to be over 100 years old and this appears to be the longest record for the preservation of this alga.

b. Cyanophyceae

The colonial blue-green algal remains recorded in the sediments of Rostherne Mere, Ellesmere Mere and Upton Broad bear a striking resemblance to the Cyanophyceae remains found in the sapropel deposits:

> "Colony-forming blue-green algae like, for instance, certain representatives of the genera Gloeocapsa, Gloeothece, Microcystis, Aphanocapsa and Aphanothece are very well preserved in certain oozes; also preserved are the mucous mass surrounding them and all the layered membranes which usually exhibit slightly contabescent [= atrophied] pale cells. It has been found that these forms are particularly well preserved in calcareous deposits" (Korde, 1966).

Microcystis has only recently (after 1958) become abundant in Rostherne Mere but the Aphanothece elebans found in Upton Broad are probably up to 400 years old, comparable with some of the sapropel remains. Aphanothece (= Coccochloris) elebans was also found in the sediments of Mud Lake, Florida (Bradley & Beard, 1969).

Akinetes of Anabaena and Aphanizomenon were recorded in sediments over 100 years old from Rostherne Mere. These were found to be viable in sediment over 70 years old in the case of Anabaena and over 35 years for Aphanizomenon.

The sediments of Lake Zürich contain filaments of Oscillatoria (Nipkow, 1920) but Kelts & Hsü (1978) described these as "decaying threads". A large standing crop of Oscillatoria in Rostherne Mere has given a future opportunity to study its preservation in the sediments although observations of entrapped seston indicated that the filaments may disintegrate rapidly (see also Lund, 1978).

c. Chlorophyceae

Apart from the desmids, green algae are often poorly represented in lacustrine sediments. Pediastrum is highly resistant to decomposition and its preservation is widespread. Coelastrum, recorded in the Meres sites, appeared less resistant but was recorded by Birks (1976) in the deposits of Wolf Creek, Scenedesmus was common in the deposits of the very rich ponds of Priest Pot and Elterwater - inner basin, however there was no evidence of long-term preservation (but see Birks, 1976). Korde (1966) also recorded Botryococcus, Phacotus and Tetraedron in the sapropel deposits; these algae are all present, albeit in small numbers, in the phytoplankton of Ellesmere Mere (Reynolds, 1973) but were not observed in the sediments.

Desmids are frequently preserved in the sediments of acid waters and in peat borings (e.g. Messikommer, 1938). The commonly found species are Cosmarium, Euastrum and Staurastrum. Korde (1966) states that Closterium, Penium and Microsterias disintegrate readily. Species of Staurastrum were recorded in most of the sites investigated in this study.

d. Euglenophyceae

A small number of Trachelmonas were recorded in the superficial sediments of Esthwaite and, in particular, Blelham Tarn.

e. Cryptophyceae

This is a very common group in the phytoplankton of the lakes studied but is not well preserved in the sediments. The seston data from Rostherne Mere indicates that few individuals reach the sediments, the remainder either decompose or, more probably, are consumed by herbivores in the water column.

f. Chrysophyceae

Only the siliceous cysts and scales are found in the sediments.

g. Bacillariophyceae

The silica frustule of the diatoms is highly resistant and found in most lacustrine sediments.

h. Xanthophyceae and Rhodophyceae

No individuals of these groups were recorded in this study or by Korde (1960, 1966), but representatives are not common in the phytoplankton of the lakes studied and so the likelihood of finding remains was slight.

2. DECOMPOSITION

If the algae in the surface sediments are decomposed more slowly than the phytoplankton are sedimented onto the lake bed then algal remains will tend to accumulate.

After death, usually caused by unfavourable chemical and physical conditions, the algal cells autolyse during which time the soluble compounds, such as phosphate, are rapidly released and decomposition will commence (Golterman 1972). There is little evidence of bacteria attacking live, active algae (cf. Frankland, 1974), but bacterial decomposition is necessary to mineralize the main part of the cell constituents (e.g. the proteins).

Compared to the macrophytes, the phytoplankters contain very little structural organic matter and are relatively easily decomposed (Godshalk & Wetzel, 1977). Thus much of the annual autochthonous production is rapidly decomposed and only a small fraction actually enters the sediments (Saunders, 1976). Deevey & Stuiver (1964) estimated that about 25% of the annual production of the eutrophic Linsley Pond was incorporated into the bottom sediments. Golterman (1976) estimated that 50-80% of the phytoplankton from a Dutch lake was oxidised by bacteria in the epilimnion and easily decomposable compounds (e.g. sugars, proteins and fats) were recycled within a matter of a few days. Ohle (1956) has suggested that the organic matter produced in the photic zone is decomposed and reconstituted into photosynthetic matter two or three times before it settles in the hypolimnion.

A review by Frankland (1974) showed that typically one third to two thirds of algal organic matter resists decomposition. The rate of decomposition varies with the plant and the environment. The initial

disintegration of the organism may occur very rapidly but laboratory experiments indicate that this is followed by a slower, almost undetectable, decomposition (Foree & McCarty, 1970; Jewell & McCarty, 1968; but see Jones, 1976).

A change in environmental and biological conditions may have a significant effect on the rate of decomposition. Foree & McCarty (1968) cite temperature, pH, bacterial seeding, algal species and algal cell composition as important factors. Jewell & McCarty (1968) obtained almost complete inhibition of decomposition at 4°C and Golterman (1971) also found low temperature restraint with lake water experiments. Godshalk & Wetzel (1977) observed that low temperatures and a lack of oxygen reduced the rate of decomposition of macrophyte remains.

Alexander (1965) noted that the major accumulations of organic remains in nature were generally found at sites which were mostly or entirely anaerobic. However once a zone becomes anoxic, decomposition does not cease, since bacterial respiration will continue with nitrate or sulphate as the electron acceptor. The inactivity of micro-organisms may be attributed to (Alexander, 1965) :

i. partial or total resistance of the substrate to decomposition

ii. a particular environment or local condition not conducive to microbial life or to the degradation of a specific compound.

Although the siliceous remains, such as diatom frustules and Chrysophyceae cysts, fulfil condition (i) the non-siliceous algal remains obviously can, and are, degraded in certain lakes. The presence of a bacterial inhibitor was hypothesised as a factor for the preservation of Aphanothece in Mud Lake, Florida (Bradley & Beard, 1969). Foree & McCarty (1968) give examples of microbial inhibition as :

i. high sulphide concentrations

ii. high levels of aromatic bactericides

iii. high acidity, leading to inhibitory pH levels.

High sulphide levels can be attained as a result of sulphate reduction. However in natural situations a significant portion of the sulphides can escape, either by diffusion or by the release of hydrogen sulphide gas (Foree & McCarty, 1968). The sediments of both Upton Broad and Rostherne Mere both smelt strongly of sulphide. However most of the gas present in the cores is likely to be methane (cf. Chen et al.,1972; Howard et al., 1971; Snodgrass, 1976) although the methane/sulphide interaction is not one of simple inhibition and is more complex (cf. Zeikus, 1977).

3. SITES OF PRESERVATION

Throughout this study the sites containing algal remains in Britain have been compared with the U.S.S.R. sapropel deposits. Before assessing whether the sediments of Rostherne Mere, Upton Broad and Ellesmere Mere could be described as 'sapropel' it is first necessary to study the characteristics of the Russian deposits.

Korde (1960) defines a sapropel as :

> "... a modern or subfossil colloidal deposit of small grain size in a continental lake; it contains much organic material and many identifiable remains of microscopic organisms, a certain amount of inorganic material of biological origin, and foreign mineral substances. A sapropel differs from a peat deposit in having structure of small scale ...."

Korde makes the differentiation between lake deposits and sapropels at an organic content of 15%. Lake muds have less than 15% organic matter while sapropels 'proper' have greater than 50% organic matter and a 'depleted' sapropel contains 15-50%. To take an example, the topmost sediments (down to 30 cm) from Lake Bol'shoi Taras-Kul' are a brown-green, semiliquid with an organic content of 79% and composed predominantly of Cyanophycean remains, cladoceran head shells, sponges and protozoa.

The relationship between ignition loss and true carbon is approximately 2:1 in samples of a high organic content (Mackereth, 1966) and so the surface sediments of Priest Pot are the only ones studied that could be described as sapropel 'proper' on the basis of organic content (table 8b) while the remainder are, apparently, 'depleted' sapropels. The deposits of Upton Broad which contain few mineral particles and are overwhelmingly dominated (at least by volume) by algal remains only have a surface carbon content of 22% (see also Moss et al., in press) while the algal oozes of the U.S.S.R. have values in excess of 40% (Korde, 1960, 1966). The sapropel deposits must contain a negligible amount of allochthonous material since the organic carbon content of planktonic algae is typically 40 to 50%, although diatoms may be less (Lund, 1964 and personal communication).

The sediments and algal remains of Rostherne Mere, Upton Broad and, to some extent, Ellesmere Mere show some correspondence to the sapropel deposits in that they are dominated by "organic material and many identifiable remains of microscopic organisms" (Korde, 1960). These three lakes show some similarities to each other and also some differences from the remainder of the sites investigated (table 8b). For example :

Table 8b : Site Comparison

	Hypolimnetic oxygen deficit during summer	surface sediments permanently de-oxygenated	BENTHOS: oligochaetes	BENTHOS: chironomids	BENTHOS: chaoborus	ALGAE: Cyanophyceae	ALGAE: Ceratium	ALGAE: Chlorophyceae	% Carbon in surface sediments	Sedimentation rate (post 1963) [mm yr^{-1}]	algal remains (0-30cm)
1. ROSTHERNE	■	■	○	○	○	●●●●	●●●●	●●	19	12	●●●●
2. ELLESMERE	■	□	–	●	–	●●●●	●●●	●●	22	-	●●●●
3. UPTON	□	■(?)	–	–	–	●●●●	●	●●●	22	10	●●●●
4. PRIEST POT	■	□	–	–	–	●	○	●●●●	27	-	●●
5. ELTERWATER (IB)	■	□	–	–	–	●	○	●●●●	11	4	●
6. ESTHWAITE	■	□	●●●●	●	●	●●●	●●●●	●●●	13	9	●
7. BLELHAM	■	□	●	●	●●●●	●●●	●●●	●●●	16	7	●
8. GRASMERE	■	□	●●●	–	–	●●●	●	●●●	12	5	●
9. WINDERMERE (SB)	□	□	●●	●●●	○	●●●	●●●	●●●	9	4	●
10. WASTWATER	□	□	●	●	○	●	○	●●	9	2	○

Key Present: ■ Absent: □ No Record –
Abundant: ●●●● Frequent: ●●● Occasional: ●● Rare: ● None ○

Data : PENNINGTON (1978) C. analysis on 2,3,4.– J.P. LISHMAN
REYNOLDSON - personal communication
TAIT-BOWMAN (in REYNOLDS, 1979a)
REYNOLDS (1973, 1978)
GORHAM et al (1974) LUND (1979 - unpublished data)
IRISH (unpublished data)

i) Rostherne and Ellesmere contain little benthic fauna (no data available for Upton Broad)

ii) The sediments are deoxygenated for part, if not all, the year. The presence of the sulphur bacterium Achromatium on the mud-water interface of Upton Broad may indicate anoxic sediments despite the shallow water depth

iii) The lakes have large standing crops of algal taxa which are not rapidly decomposed or consumed by herbivores (e.g. colonial blue-greens)

iv) The rate of sediment accumulation is high (although the mean annual increment has been lower in Upton Broad prior to 1935 - Moss et al., in press)

It is beyond the scope of this study to investigate which of the above factors either cause, or are a result of, the conditions acting to preserve algal remains in lacustrine sediments. However the feature commonly found at sites of algal preservation is the high productivity of resistant taxa.

High algal productivity can either be planktonic (e.g. Rostherne Mere) or benthic (e.g. Upton Broad) but if planktonic, the algal remains must reach the lake bed and not decompose in the epilimnion to a degree making identification impossible. The aerobic decomposition of organic debris in the sediments or in the water, below the thermocline, may de-oxygenate the sediments and subsequently, depending on the lake morphometry, the hypolimnion. The organic, seasonally reduced, sediments of the productive Esthwaite Water contain many benthic animals; however the lack of benthos in the deep-water sediments of some Shropshire-Cheshire meres can be related to the early onset of summer stagnation and hypolimnetic deoxygenation (Tait-Bowman, 1976 - cited in Reynolds,

1979a). The 'lifeless' zone of Rostherne Mere is thought to be a result of the continually deoxygenated sediments (Brinkhurst & Walsh, 1967), a condition which is maintained despite the overlying oxygenated waters during the winter. However, the invertebrate community can be, in some part, responsible for oxygenating the superficial sediments since the stirring created by the action of burrowing animals increases the influx of oxygenated water into the sediments, in addition to facilitating the movement of dissolved gases and solutes (Petr, 1977) although this necessitates the presence of oxygen in the water above the sediments. Laboratory experiments by Zvetkova (1973 - cited in Petr, 1977) showed that the rate of biochemical oxidation of organic matter increased 1.5-2.0 times in the presence of tubificids. However it is not stated whether the animals digest the algal remains or stimulate the bacteria which then decompose the algae at a higher rate. Moreover the absence of benthos is not a necessary criterion for the preservation of algal remains since the algal ooze of Mud Lake, Florida, consists predominantly of the faecal pellets produced by chironomid larvae (Bradley & Beard, 1969) while the sediments of Upton Broad are similarly described by Moss et al. (in press). The waters of both lakes are very shallow (< 1 m) and oxygenated, although the surface sediments are possibly anaerobic. However Upton Broad is floored by a mat of living algae which may restrict the bacterial decomposition of the sediments beneath since it has been suggested that live algae have a defence against bacteria (cf. Oppenheimer & Vance, 1960; Golueke & Oswald, 1966). Beneath the layer of live algae the sediments may be reduced and decomposition correspondingly slow.

Rostherne Mere and Esthwaite Water are similar in that both produce, or have produced, large crops of Ceratium hirundinella, the

remains of which are found in the mature sediments of Rostherne but not in Esthwaite. In Chapter 3, two hypotheses were put forward for the presence of a limited number of algal remains in the productive lakes of the English Lake District. Firstly it was suggested that the remains which showed some resistance (i.e. Ceratium cysts rather than cells of Rhodomonas) decomposed within circa 3 years but the thickness of sediment deposited during this period was greater in the productive, rather than the unproductive, lakes and more concentrated in remains because of the larger crops. Secondly it was postulated that decomposition was slower in the richer lakes in which the hypolimnion became deoxygenated during the summer (cf. Pennington, 1978). Expanding the second hypothesis, it follows that with an increasing autochthonous contribution to the sediments, and concomitant deoxygenation, decomposition may proceed at such a rate that only the easily mineralized algal taxa would decay, leaving the more resistant remains e.g. Microcystis colonies, Anabaena akinetes and Pediastrum cell walls (but not the contents). Therefore this latter hypothesis suggests that if Esthwaite became increasingly productive then algal remains would be more likely to be found, providing the phytoplankton consisted of some fairly resistant species (see table 8a).

Sewage oxidation ponds, and similar water bodies, may not preserve microscopic remains because of the algal composition rather than the sedimentary environment. The easily decomposed and/or consumed small, unicellular Chlorophyceae and cryptomonads are characteristic of the plankton from such small lakes. The grazing food chain, composed of fauna such as cladocerans, copepods, rotifers and protozoans, may preferentially take the smaller green algae, particularly the filter feeders, and in small water bodies vast algal populations (mainly

nannoplankton) may be removed by grazing (see review by Lund, 1965). Sushchenya (1961 - cited in Lund, 1965) found that the larger algae, which are so often the predominant components of large populations and surface blooms in lakes, were not utilised by the zooplankton present. Experiments by Golueke, Oswald & Gotaas (1957) showed that the anaerobic digestion of algal cultures proceeded at a slower rate, and the break-down was less rapid or complete, than that of either raw sewage or a mixture of sewage plus algae. The algal sludge which remained contained a large proportion of intact cells of Scenedesmus and Chlorella species (although they could not be sub-cultured). Golueke et al. suggest that the limited bacterial activity in the algal digesters was due to microbial inhibition as a result of ammonia production. This theory is in accordance with that of Bradley & Beard (1969) for Mud Lake, who also postulated bacterial inhibition. The sealed and anaerobic flasks containing plankton and sediment from Esthwaite Water contained intact horns from the Ceratium cells after six months while they were fragmented in flasks which were left open (Chapter 7).

The accumulation of algal-rich organic muds has also been reported to take place in aerobic environments. Beauchamp (1964) describes the shallow-water sediments of Lake Victoria as ".. partly broken down plankton and vegetable detritus, which is dominated by a micro-organism that almost achieves the status of a pure culture...". This ooze contains few invertebrates and does not decompose unless boiled. The sediments contain large quantities of nutrients which are in critically short supply in the lake water. Beauchamp also mentions the possibility that the deep water sediments of Lakes Tanganyika and Nyasa (max. depths 1200 m and 700 m respectively) are devoid of benthos since the overlying waters are anaerobic.

Bradley (1966) examined four sites where algal oozes are accumulating, Lakes Victoria and George in Africa and Mud Lake and Saddlebags Lake in Florida, U.S.A. All four have oxygenated, clear water and are fringed by a dense mat of vegetation which filters out most of the inflowing allochthonous material. The gelatinous oozes of these lakes are comprised of faecal pellets ("copropel") containing few living bacteria and no fungi. Freshly killed fish were placed in the deposits of Saddlebags Lake for three months but did not decay, despite a water temperature of circa 25°C. Bradley suggests that the deposits in these four lakes may be the modern equivalent of the beginnings of fossil fuels, in particular oil shale. Air-dried algal ooze was visually indistinguishable from oil shale, and had a similar carbon-hydrogen ratio. The carbon content of the sediments of Mud Lake was about 58% and had a calorific value which is 32% greater than peat and 40% lower than the organic component of an oil shale. Russian sapropels have also been considered as the ultimate sources of mineral oil, some coals and oil shales (Korde, 1960). Pilot plants were constructed in Petrograd in 1918 to use sapropel as a fuel (it has also been used as a feedstuff for pigs and chickens, as a fertiliser and as a medicine). "Boghead coal" which may be found in the U.K., France and Australia (where it is known as kerosene shale or "coorongite") consists primarily of the alga Botryococcus (usually B. braunii Kützing) and has an inorganic content of less than about 25% (Blackburn & Temperley, 1936). Boghead coal appears to be similar to the "balkhashite" found in the U.S.S.R. which is also composed of Botryococcus braunii (Zalessky, 1914, 1926).

Although the exact nature of sapropel is uncertain since its formation is apparently poorly understood the algal oozes observed by Bradley (1966) and, perhaps, those described in this study show some similarities. The reason for the lack of decomposition of the algal

remains is also unknown and further, bacteriological, research may be rewarding. There is no evidence to suggest that the factors which inhibit or slow the rate of decomposition in one lake are identical to those in another. In Rostherne Mere, for example, the high productivity and perpetual anoxia of the sediments may be directly or indirectly involved while the benthic blue-green algae in Upton Broad may inhibit microbial decomposition. It is interesting to speculate (cf. Bradley, 1966) that these present day accumulations of algae may be a source of particular fossil fuels.

4. CONCLUSIONS

The recent lake sediments from sites studied in highland Britain contained few non-siliceous algal remains. The superficial sediments of the productive lakes contained more identifiable remains but below the oxidised microzone, preservation was generally poor.

The siliceous remains in the sediments of Grasmere and Elterwater (inner basin) corresponded to the recorded alterations in the phytoplankton associated with recent changes in sewage treatment. In common with other Cumbrian lakes the increased input of nutrients has resulted in larger crops of Asterionella formosa. The outer basins of Elterwater receive torrential flood waters which disturb the sediment stratigraphy. The mean annual rate of sediment accumulation in Grasmere has increased; apparently caused by the survival of autochthonous material from the greater standing crops observed in recent years.

The sediments of three lowland lakes, Ellesmere Mere, Upton Broad and Priest Pot, contained many algal remains, although preservation varied specifically and between lakes. Many of the larger phytoplankton (e.g. Microcystis, Anabaena, and Ceratium) of Ellesmere Mere are preserved but few of the smaller Chlorophyceae and cryptomonads were observed. The deposits of Upton Broad are dominated by remains of the benthic blue-green alga, Aphanothece elebans which are preserved for up to 500 years.

The deep water sediments of Rostherne Mere, which are permanently anaerobic and support no benthos, contained a wealth of algal remains. The correlation between the algal stratigraphy and the past phytoplankton records enabled the establishment of an 'algal

chronology' which provided independent verification of the radionuclide dating. The presence of calcite bands in the deep-water cores and the fine biostratigraphy indicates that the sediments are not disturbed, either by bioturbation or physical processes. Rostherne Mere has previously been described as 'guanotrophic' but evidence from the algal record, the calcite layers and recent figures for gull ejestion refute this suggestion. Cores from the deep-water site showed no significant qualitative differences but there were quantitative areal variations. Preservation in cores from shallower, oxygenated water was poor, and the algal stratigraphy did not correspond to the documented record.

Viable akinetes, up to 70 years old, of Anabaena and Aphanizomenon were recovered in the sediments from Rostherne Mere. Therefore blue-green resting spores may not only ensure the short term survival of the algae but also provide a longer term strategy.

Cysts of Ceratium hirundinella, recovered from Esthwaite Water, required a maturation period of about 5 months and thereafter may provide the inoculum for the planktonic population. Germination of the cysts may be retarded by anoxia; subsequent decomposition leaves the cyst wall plus a recognisable residue, both of which are preserved in certain sediments.

The algal remains caught in seston traps placed in Rostherne Mere, closely followed a period of abundance in the plankton; few 'out of season' algae were trapped. The absence of small algae (e.g. Chlorella and Rhodomonas) in the entrapped seston indicates that they are selectively grazed or decompose rapidly.

The reason why certain lake sediments preserved particular non-siliceous algal remains is unknown. The rate of bacterial decomposition may be restricted by long periods of anoxia in the

deep-water sediments of highly productive lakes. Alternatively a mat of living algae may inhibit bacterial decomposition in the oxidised surface sediments of shallow lakes.

Sediments which could be described as analogous to the U.S.S.R. sapropels were not observed, although the deposits of Upton Broad, Rostherne Mere and Ellesmere Mere do show some similarities. Algal oozes, such as sapropel, may be the precursors of some fossil fuels.

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PRIMARY DATA

GRASMERE

(core GM/M22)

Diatoms

(valves per 0.1 µl fresh sediment)

Depth (cm)	a	b	c	d	e	f	g	h	i
0-1(a)	620	40	12	67	0	0	0	211	950
(b)	557	28	10	74	0	4	0	251	924
(ave)	589	34	11	71	0	2	0	231	937
1-2	2477	46	19	166	0	0	0	421	3129
2-3	2486	66	26	181	0	0	0	442	3201
3-4	3478	189	22	271	0	0	0	881	4841
4-5	2636	137	21	109	0	4	0	672	3579
5-6(a)	1438	137	29	35	0	28	0	908	2575
(b)	1206	126	23	36	0	41	0	742	2178
(ave)	1322	132	26	35	0	35	0	825	2377
6-7	657	17	34	17	0	91	0	1296	2112
7-8	147	17	27	5	0	108	0	2056	1360
8-9	8	5	23	0	7	177	0	737	957
9-10	169	5	23	0	4	326	0	706	1258
10-11(a)	106	8	27	4	21	554	0	800	1520
(b)	67	8	38	1	12	539	0	742	1407
(ave)	87	8	33	3	17	547	0	771	1464
11-12	117	17	55	3	26	502	0	1383	2103
12-13	91	14	47	2	56	167	0	1273	1650
13-14	62	13	71	2	78	87	0	1250	1563
14-15	146	17	58	3	37	55	0	1288	1604
15-16(a)	76	21	98	0	60	46	0	1341	1643
(b)	95	21	77	2	46	36	0	1255	1532
(ave)	86	22	88	1	53	42	0	1298	1588
16-17	51	17	64	0	159	78	0	1114	1483
17-18	47	17	55	0	172	214	0	1066	1571
18-19	42	7	48	3	147	199	0	987	1433
19-20	150	14	55	1	213	323	0	1477	2233
24-25	46	15	56	0	104	184	0	1618	2023
29-30	10	14	32	2	56	61	28	803	1006
34-35	22	20	30	0	62	419	67	872	1492
39-40	4	27	40	0	59	327	44	1228	1729
44-45	5	17	38	0	54	193	43	758	1108
49-50	23	39	85	0	84	118	56	1949	2345

a Asterionella formosa
b Tabellaria flocculosa var. asterionelloides
c Tabellaria flocculosa
d Cyclotella pseudostelligera
e Cyclotella comta
f Cyclotella comensis
g Cyclotella kutzingiana
h others
i total

ELTERWATER - INNER BASIN

(core ELT-M01)

Diatoms

(valves per 0.1 µl fresh sediment)

Depth (cm)	a	b	c	d	e	f	g	h	i	j	k
0-1(a)	1	35	30	438	41	61	0	0	0	969	1575
(b)	0	33	45	557	20	61	0	0	0	1159	1875
1-2	0	26	55	785	31	61	0	0	0	963	1921
2-3	0	30	39	507	42	58	0	0	2	1253	1929
3-4	0	32	16	294	49	58	0	1	0	1310	1759
4-5	0	22	18	163	35	61	0	1	0	1164	1463
5-6(a)	0	36	11	105	36	82	0	1	0	1193	1463
(b)	0	15	14	77	29	59	1	1	0	1227	1423
6-7	0	19	11	96	53	48	1	1	0	1217	1446
7-8	0	26	14	78	49	86	1	3	0	1297	1554
8-9	0	14	16	46	47	73	1	0	0	1395	1591
9-10	1	14	12	17	33	90	1	1	0	1432	1601

a Stephanodiscus astraea
b Melosira italica
c Synedra spp
d Asterionella formosa
e Tabellaria flocculosa var. asterionelloides
f Tabellaria flocculosa
g Cyclotella comensis
h Cyclotella comta
i Cyclotella menenghinia
j others
k total

ELTERWATER - MIDDLE AND OUTER BASINS

(cores ELT-M23 and ELT-M24)

Diatoms

(valves per 0.1 µl fresh sediment)

Depth (cm)	a	b	c	d	e	f	g
Middle Basin							
0-1	157	23	22	3	1	0	0
1-2	261	8	28	14	0	0	0
2-3	59	21	33	16	0	1	0
3-4	26	14	20	2	0	1	0
4-5	26	17	27	0	0	1	1
5-6	28	18	34	2	0	2	0
6-7	24	19	35	4	1	0	0
7-8	1	11	30	0	0	1	1
8-9	3	17	30	0	0	1	0
9-10	0	13	41	3	0	0	0
Outer Basin							
0-1	45	2	13	0	0	0	0
1-2	68	4	33	3	0	0	0
2-3	102	6	30	0	0	0	0
3-4	121	11	29	0	0	1	0
4-5	79	11	35	2	0	0	0
5-6	103	13	31	0	0	2	0
6-7	96	2	21	0	0	0	0
7-8	16	6	36	0	0	0	0
8-9	38	8	29	0	0	0	0
9-10	15	5	18	0	0	0	0

a Asterionella formosa
b Tabellaria flocculosa var. asterionelloides
c Tabellaria flocculosa
d Melosira italica
e Stephanodiscus astraea
f Cyclotella comensis
g Cyclotella comta

PRIEST POT

(core PP-M30)

Algal remains

(individuals per 0.1 µl fresh sediment)

Depth (cm)	Scenedesmus with chloroplasts	Scenedesmus without chloroplasts	Scenedesmus total	Pediastrum
0–1	601	280	881	0
2	340	301	641	0
3	77	305	382	1
4	28	318	346	0
6	18	266	284	1
8	26	113	139	0
10	0	5	5	0
12	4	21	25	0
14	4	2	6	0
16	0	5	5	1
18	0	4	4	0
20	1	2	3	0

PRIEST POT

(core PP-M30)

Diatoms

(valves per 0.1 µl fresh sediment)

Depth (cm)	a	b	c	d	e	f	g	h	i
0–1	233	13	1472	23	3	4		154	1902
3–4	784	66	2328	102	8	28		432	3752
7–8	736	160	2528	48	12	40		828	4352
11–12	960	176	2556	40	12	40	4	1060	4848
15–16	888	164	2052	68	28	76	0	1388	4668
19–20	544	136	2760	44	48	160	4	2676	6380

a Asterionella formosa; b Fragilaria crotonensis;
c Cyclotella pseudostelligera; d Cyclotella menenghiniana;
e Tabellaria flocculosa var asterionelbides; f Tabellaria flocculosa;
g Cyclotella comta; h others; i total

UPTON BROAD

(core UPT-M28)

Algal remains

(individuals per 0.625 µl fresh sediment)

Depth (cm)	a		b		c	d		e	f	g
	+chloroplasts-		+chloroplasts-			+chloroplasts-				
0-1	135		29		9	174	0	35	2	
4-5	203		56		9	159	4	37	1	
8-9	334		81		5	61	4	34	5	
12-13	276	37	62	3	0	27	9	14	0	
16-17	360	101	81	12	0	25	24	7	2	
20-21	115	64	51	15	4	0	15	3	0	
24-25	121	97	31	14	2	0	21	0	6	
28-29	123	102	9	6	5	23		1	7	1
34-35	130	98	28	11	2	9	8	0	5	0
39-40	3	174	6	8	4	0	10	3	12	1
44-45	4	186	1	8	2	0	10	0	2	2
49-50	0	206	12	13	3	0	3	0	2	5
54-55	0	259	2	7	2	0	5	0	3	10
59-60	0	297	0	11	0	0	6	0	3	1
64-65	0	253	1	23	1	0	3	0	4	3
69-70	0	11	0	3	0	0	0	0	1	14
74-75	0	1	0	1	1	0	1	0	4	25
Bottom	0	0	0	1	0	0	2	0	2	14

a Aphanothece elebans (colonies)
b Aphanothece elebans fo. minor (colonies)
c Staurastrum spp (cells)
d Scenedesmus (colonies)
e Chlorophyceae (colonies/cells)
f Pediastrum (colonies)
g Cosmerium (cells)

UPTON BROAD

(core UPT-M28)

Diatoms

(valves per 1 µl fresh sediment)

Depth (cm)	a	b	c	d	e	f
0-1	0	110	20	11345	0	11495
19-20	1	0	25	5020	4	5048
39-40	0	0	10	15	0	29
59-60	6	0	2	0	0/2	27
Bottom	4	0	0	0	9	8

a Asterionella formosa
b Synedra acus
c Navicula spp
d Fragilaria spp
e Cyclotella pseudostelligera/comta
f Total diatoms

Depth (cm)	a	b	c	d	e	f	g
0-1	0	0	0	10	0	0	10
19-20	0	0	0	0	0	1	0
39-40	0	0	0	0	1	1	0
59-60	1	4	2	0	0	0	0
Bottom	0	4	0	0	0	0	0

a Tabellaria flocculosa
b Melosira italica
c Stephanodiscus hantzschii
d Cocconeis spp
e Diatoma sp
f Cymbella spp
g Pinnularia spp

Fragilaria species (circa 500 counted)

Depth	0-1	19-20
F. construens	5%	48%
pinnata	18%	10%
brevistriata	57%	34%
elliptica	19%	5%
others	0	3%

ELLESMERE MERE

(core ELS-M25)

Algal remains

(individuals per 5 µl fresh sediment)

Depth (cm)	a (i)	a (ii)	b	c	d	e	f	g	h	i
0-1	37	65	24	33	3	27	22	20	156	
1-2	55	143	54	53	7	51	51	57	213	1
2-3	13	115	28	85	6	53	77	35	122	1
3-4	3	118	8	115	4	32	46	28	106	2
4-5	5	99	14	70	4	36	70	31	81	0
5-6	1	74	57	45	13	47	95	8	87	-
6-7	0	39	54	53	10	42	108	12	96	
7-8	0	48	21	73	3	49	110	6	94	
8-9	0	91	42	79	13	58	108	4	294	
9-10	2	60	39	140	4	30	77	3	258	
10-11	0	165	67	63	9	39	75	6	333	
11-12	0	87	33	77	7	27	69	2	307	
12-13	0	40	12	49	4	18	67	4	443	
13-14	0	49	26	126	10	7	40	1	310	
14-15	0	30	10	62	12	12	37	2	257	
15-16	0	44	14	170	4	18	74	4	342	
16-17	2	28	8	98	6	22	84	2	294	
17-18	2	86	76	138	18	30	108	8	650	
18-19	0	38	86	124	8	30	78	0	612	
19-20	0	58	34	184	12	20	70	0	678	
24-25	0	26	10	148	8	52	86	2	1154	
29-30	0	134	8	68	6	44	134	4	1138	
34-35	0	66	12	8	0	12	100	6	888	
39-40	0	80	12	22	2	6	138	2	1686	
44-45	0	38	14	6	0	8	156	4	1394	
49-50	0	14	4	32	6	12	222	2	1390	

a Ceratium (cysts) (i) contents (ii) no contents
b Microcystis (colonies)
c Anabaena (akinetes)
d Aphanizomenon (akinetes)
e Staurastrum (cells)
f Pediastrum (colonies)
g Coelastrum (colonies)
h Stephanodiscus astraea (cells)
i Scenedesmus (colonies)

ELLESMERE MERE

(core ELS-M25)

Diatoms

(valves per 0.2 µl fresh sediment)

Depth (cm)	a	b	c	d	e	f	g	h	i	j	k
0-1	2164	14	307	39	9					170	2703
1-2	1528	6	274	40	2					162	2012
2-3	1772	6	326	56	4					190	2360
3-4	1762	16	506	136	6					280	2706
4-5	3200	12	602	148	26					340	4334
5-6	3166	8	872	146	34					262	4488
6-7	3462	12	482	262	28					282	4528
7-8	3336	22	286	250	34					364	4292
8-9	2826	48	424	162	36					386	3882
9-10	3050	38	356	168	18	6				360	3992
10-11	3228	52	544	294	12	42				430	4604
11-12	4296	48	572	244	6	66				396	5628
12-13	4394	56	1086	290	4	68	2		0	400	6300
13-14	1666	66	374	382	2	16	0	1	0	402	2908
14-15	1344	24	362	248	2	8	8	2	0	320	2318
15-16	1632	30	518	426	0	4	2	0	0	462	3074
16-17	1140	50	690	700	0	2	4	0	0	380	2966
17-18	3386	68	1002	336	2	2	0	0	2	550	5348
18-19	1930	54	394	130	4	0	6	0	0	350	2868
19-20	1768	80	456	160	0	2	2	0	0	290	2758
24-25	3052	176	100	256	4	0	0	0	2	522	4114
29-30	1234	80	152	116	10	14	0	0	0	356	1966
34-35	2126	102	74	80	14	150	18	4	0	424	2992
39-40	788	144	112	134	2	2	2	0	0	470	1654
44-45	490	90	218	338	0	4	0	2	0	378	1522
49-50	1016	158	120	128	2	8	8	2	0	488	1930

a Stephanodiscus hantzschii
b Stephanodiscus astraea
c Asterionella formosa
d Melosira granulata
e Fragilaria crotonensis
f Stephanodiscus hantzschii (B)
g Cyclotella comta
h Cyclotella comensis
i Tabellaria flocculosa
j others
k total

ROSTHERNE MERE

(core RM-M18)

Nitrogen and Water Content

Depth (cm)	%N i	%N ii	% N mean	% Water
0-1	1.155	1.348	1.25	96.79
1-2	1.155	1.155	1.16	95.48
2-3	1.540	1.348	1.44	94.94
3-4	.963	1.155	1.06	95.39
4-5	.963	.963	.96	94.41
5-6	2.158	2.158	2.16	96.03
6-7	1.439	1.439	1.44	94.75
7-8	1.618	1.439	1.53	95.24
8-9	1.439	1.259	1.35	95.81
9-10	1.259	1.259	1.26	93.90
10-11	.719	.899	.81	92.98
11-12	.719	.899	.81	91.38
12-13	.899	.899	.90	90.77
13-14	.719	.719	.72	90.87
14-15	1.079	.899	.99	93.98
15-16	.899	1.079	.99	91.70
16-17	.554	.739	.65	91.68
17-18	.924	.739	.83	92.41
18-19	.739	.739	.74	93.41
19-20	.924	.924	.92	93.37
20-21	.924	1.100	1.01	93.31
21-22	1.109	1.109	1.11	93.48
22-23	.924	.924	.92	92.19
23-24	.739	.924	.83	88.54
24-25	.732	.782	.76	89.41
25-26	.915	.732	.82	89.89
26-27	.732	.732	.73	88.49
27-28	.732	.732	.73	86.95
28-29	.732	.915	.82	88.56
29-30	1.099	1.282	1.19	89.25
34-35	.732	.732	.73	85.51
39-40	.732	.732	.73	86.30
44-45	.732	.549	.64	81.64
49-50	.549	.549	.55	88.74
59-60	.549	.549	.55	85.51
69-70	.549	.549	.55	85.24
79-80	.549	.549	.55	82.18

ROSTHERNE MERE

(core RM-M18)

Percentage Carbon and Carbon/Nitrogen ratios

Depth (cm)	C i	C ii	C mean	C/N i	C/N ii	C/N mean
0-1	18.72	18.50	18.61	16.20	13.72	14.96
1-2	18.35	18.05	18.20	15.88	15.64	15.75
2-3	19.12	17.53	18.32	12.41	13.01	12.71
3-4	16.05	17.08	16.57	16.67	14.79	15.73
4-5	16.86	15.97	16.42	17.52	15.59	17.05
5-6	21.58	22.39	21.99	10.00	10.38	10.19
6-7	17.43	18.17	17.80	12.12	12.63	12.37
7-8	14.91	15.43	15.17	9.22	10.73	9.97
8-9	18.47	17.16	17.80	12,84	13.61	13.23
9-10	16.25	16.62	16.43	12.91	13.20	13.05
10-11	14.06	13.58	13.82	19.56	15.12	17.33
11-12	13.65	12.82	13.24	18.98	14.26	16.62
12-13	11.74	13.10	12.42	13.07	14.57	13.82
13-14	11.29	10.25	10.78	15.71	14.26	14.98
14-15	13.93	12.47	13.20	12.91	13.87	13.39
15-16	13.93	14.90	14.41	15.49	13.81	14.65
16-17	11.36	11.12	11.24	20.50	15.05	17.77
17-18	13.52	13.60	13.55	14.63	18.39	16.51
18-19	12.88	12.48	12.68	17.42	16.88	17.15
19-20	15.43	15.27	15.35	16.70	16.53	16.61
20-21	15.51	15.11	15.31	16.79	13.63	15.21
21-22	15.91	16.47	16.19	14.35	14.85	14.60
22-23	14.55	15.43	14.99	15.75	16.70	16.23
23-24	13.75	13.67	13.72	18.61	14.80	16.71
24-25	12.01	12.01	12.01	16.39	16.30	16.35
25-26	13.25	11.30	12.28	14.47	15.44	15.00
26-27	12.55	11.69	12.12	17.13	15.97	16.55
27-28	12.39	11.38	11.89	16.92	15.54	16.23
28-29	12.32	12.94	12.63	16.82	14.13	15.48
29-30	15.04	14.96	15.00	13.69	11.67	12.68
34-35	9.60	8.82	9.21	13.11	12.04	12.58
39-40	9.52	10.06	9.79	12.10	13.74	13.37
44-45	8.59	7.89	8.24	11.72	14.36	13.04
49-50	9.14	8.83	8.99	16.65	16.07	16.36
59-60	9.14	8.83	8.99	16.65	16.07	16.36
69-70	8.36	8.36	8.36	15.21	15.21	15.21
79-80	8.20	7.96	8.08	14.92	14.49	14.71

ROSTHERNE MERE

(core RM-M06)

Ceratium

(cysts per 5 µl fresh sediment)

Depth (cm)	i	ii	iii	mean
0-½	54 (44)	60 (50)	42 (33)	52
½-1	361(334)	388(358)	408(387)	386
1-2	76 (44)	74 (33)	88 (42)	79
2-3	83 (10)	70 (8)	63 (8)	72
3-4	2	5 (2)	1	3
4-5	4	4	1	3
5-6	0	0	1	0
6-7	1	3	2	2
7-8	11	16	9	12
8-9	194	202	177	191
9-10	168	200	228	199
10-11	175	172	164	170
11-12	113	94	145	117
12-13	30	31	38	30
13-14	21	9	14	15
14-15	5	5	4	5
15-16	1	1	1	1
16-17	2	3	5	3
17-18	5	6	4	5
18-19	14	14	22	17
19-20	12	11	11	11
20-21	1	0	1	1
21-22	20	14	41	25
22-23	220	164	192	192
23-24	60	53	54	56
24-25	174	174	210	186
25-26	124	192	154	157
26-27	170	192	202	188
27-28	46	62	52	53
28-29	20	22	56	19
29-30	8	8	8	8
34-35	92	92	54	79
39-40	58	70	90	73
44-45	112	164	114	130
49-50	30	38	14	27
59-60	72	70	70	71
69-70	102	106	110	106

brackets denote number of cysts with intracellular contents

ROSTHERNE MERE

(core RM-M06)

Microcystis

(colonies per 5 µl fresh sediment)

Depth (cm)	i	ii	iii	mean
0-½	134	149	138	140
½-1	389	319	281	330
1-2	48	52	40	47
2-3	20	31	37	29
3-4	375	432	375	394
4-5	226	241	229	232
5-6	320	277	304	300
6-7	185	222	247	218
7-8	426	376	280	361
8-9	108	131	126	122
9-10	52	34	35	40
10-11	9	15	14	13
11-12	16	9	18	14
12-13	207	160	201	189
13-14	237	242	296	258
14-15	386	358	388	377
15-16	564	561	524	550
16-17	352	338	327	339
17-18	258	296	243	266
18-19	285	238	266	263
19-20	270	265	401	312
20-21	305	218	269	264
21-22	94	85	145	108
22-23	21	24	30	25
23-24	73	84	112	90
24-25	42	26	48	39
25-26	10	18	14	14
26-27	10	10	14	11
27-28	12	8	8	9
28-29	10	20	14	15
29-30	52	60	76	63
34-35	6	16	2	8
39-40	4	4	2	3
44-45	0	0	0	0
49-50	0	0	0	0
59-60	0	0	2	
69-70	0	0	0	

ROSTHERNE MERE

(core RM-MO6)

Stephanodiscus astraea

(cells per 5 µl fresh sediment)

Depth (cm)	i	ii	iii	mean
0-½	2	2	2	2
½-1	0	0	0	0
1-2	9	7	12	9
2-3	7	4	4	5
3-4	6	10	8	8
4-5	48	44	15	36
5-6	597	579	588	588
6-7	4265	4888	3523	4225
7-8	173	182	137	164
8-9	204	233	216	218
9-10	578	733	810	707
10-11	846	725	670	747
11-12	96	101	105	101
12-13	55	60	37	51
13-14	32	35	28	32
14-15	29	22	24	25
15-16	50	50	54	51
16-17	210	215	246	224
17-18	470	446	435	450
18-19	187	197	255	213
19-20	347	363	277	329
20-21	182	152	183	172
21-22	453	407	515	458
22-23	1427	1165	1720	1437
23-24	3681	4063	3196	3647
24-25	938	1282	1352	1191
25-26	1606	1710	1746	1687
26-27	1632	1914	1648	1731
27-28	3036	3000	2730	2922
28-29	3208	3280	3448	3312
29-30	1200	990	1280	1157
34-35	2138	2164	2206	2169
39-40	7040	6536	8160	7245
44-45	13216	10928	11408	11851
49-50	6808	7144	8516	7509
59-60	13056	10240	9664	10987
69-70	13232	14176	12096	13168

ROSTHERNE MERE

(core RM-M06)

Anabaena

(akinetes per 5 µl fresh sediment)

Depth (cm)	i	ii	iii	mean
0-½	0	0	0	0
½-1	0	0	0	0
1-2	0	2	4	2
2-3	0	0	0	0
3-4	0	0	0	0
4-5	8	20	1	10
5-6	0	0	0	0
6-7	0	0	0	0
7-8	1	1	0	1
8-9	1	1	0	1
9-10	7	0	6	4
10-11	0	0	3	1
11-12	6	12	26	15
12-13	30	26	22	26
13-14	8	8	10	9
14-15	1	11	2	5
15-16	0	4	1	3
16-17	0	0	3	1
17-18	3 (2)	10 (9)	3 (2)	5
18-19	2 (2)	5 (4)	19 (19)	9
19-20	7 (4)	1 (1)	31 (29)	13
20-21	3 (1)	0	9 (7)	4
21-22	9 (1)	6	23	13
22-23	139 (1)	123	138	133
23-24	13	23 (1)	27 (2)	21
24-25	146 (90)	256(188)	368(310)	257
25-26	206(170)	528(608)	316(282)	350
26-27	286(234)	492(434)	482(424)	420
27-28	150(132)	124 (94)	174(154)	149
28-29	76 (40)	246(146)	62 (28)	128
29-30	92 (76)	40 (28)	46 (18)	59
34-35	48 (18)	26 (10)	30 (6)	35
39-40	14	48 (42)	10 (2)	24
44-45	4	20 (20)	4	9
49-50	90 (30)	42	16 (8)	49
59-60	30 (2)	4 (2)	10	15
69-70	24 (20)	80 (72)	117(111)	74

Numbers in brackets denote akinetes in aggregates

ROSTHERNE MERE

(core RM-M06)

Aphanizomenon and Staurastrum

(akinetes/cells per 5 µl fresh sediment)

Depth (cm)	Aphanizomenon i	ii	iii	mean	Staurastrum i	ii	iii	mean
0–½	1	0	0	0	0	0	0	0
½–1	4	4	2	3	1	0	0	0
1–2	46	31	68	48	1	2	1	1
2–3	1	0	0	0	9	0	2	4
3–4	2	2	2	2	0	0	1	0
4–5	25	29	11	22	0	0	0	0
5–6	2	1	2	2	0	2	1	1
6–7	1	0	1	1	0	1	0	0
7–8	1	2	0	1	1	0	1	1
8–9	1	8	1	3	2	2	1	2
9–10	1	2	4	2	2	2	3	2
10–11	1	1	1	1	5	1	2	3
11–12	2	1	5	3	7	1	2	3
12–13	4	3	2	3	0	0	0	0
13–14	1	1	1	1	2	2	0	1
14–15	1	0	1	1	1	0	2	1
15–16	2	0	0	1	0	0	2	1
16–17	1	2	0	1	0	0	1	0
17–18	0	1	0	0	0	0	0	0
18–19	0	0	0	0	1	1	2	1
19–20	3	1	2	2	6	3	2	4
20–21	2	1	2	2	3	0	4	2
21–22	18	3	10	10	6	4	5	5
22–23	36	40	52	44	20	13	17	17
23–24	6	10	6	7	1	2	6	3
24–25	22	22	30	25	4	0	2	2
25–26	24	28	42	31	6	6	2	5
26–27	44	30	42	39	2	4	6	4
27–28	16	12	18	15	12	4	2	6
28–29	54	61	30	48	12	2	8	7
29–30	20	10	26	19	10	6	4	7
34–35	18	12	12	14	2	2	6	3
39–40	20	10	6	12	10	2	8	7
44–45	0	2	4	2	12	16	16	15
49–50	2	4	8	5	6	12	12	10
59–60	0	0	0	0	12	12	6	10
69–70	0	0	0	0	8	16	10	11

ROSTHERNE MERE

(core RM-M06)

Algal remains

(mean of 3 subsamples, individuals per 5 µl fresh sediment)

Depth (cm)	a	b	c	d	e	f
0-½	52	140	2	0	0	0
½-1	386	330	0	0	3	0
1-2	79	47	9	2	48	1
2-3	72	29	5	0	0	4
3-4	3	394	8	0	2	0
4-5	3	232	36	10	22	0
5-6	0	300	588	0	2	1
6-7	2	218	4225	0	1	0
7-8	12	361	164	1	1	1
8-9	191	122	218	1	3	2
9-10	199	40	707	4	2	2
10-11	170	13	747	1	1	3
11-12	117	14	101	15	3	3
12-13	30	189	51	26	3	0
13-14	15	258	32	9	1	1
14-15	5	377	25	5	1	1
15-16	1	550	51	3	1	1
16-17	3	339	224	1	1	0
17-18	5	266	450	5	0	0
18-19	17	263	213	9	0	1
19-20	11	312	329	13	2	4
20-21	1	264	172	4	2	2
21-22	25	108	458	13	10	5
22-23	192	25	1437	133	44	17
23-24	56	90	3647	20	7	3
24-25	186	39	1191	257	25	2
25-26	157	14	1687	350	31	5
26-27	188	11	1731	420	39	4
27-28	53	9	2922	149	15	6
28-29	19	15	3312	128	48	7
29-30	8	63	1157	59	19	7
34-35	79	8	2169	35	14	3
39-40	73	3	7245	24	12	7
44-45	130	0	11851	9	2	15
49-50	27	0	7509	49	5	10
59-60	71	1	10987	15	0	10
69-70	106	0	13168	74	0	11

a Ceratium (cysts)
b Microcystis (colonies)
c Stephanodiscus astraea (cells)
d Anabaena (akinetes)
e Aphanizomenon (akinetes)
f Staurastrum (cells)

ROSTHERNE MERE

(core RM-M06)

Diatoms

(valves per 0.2 µl fresh sediment)

Depth (cm)	a	b	c	d	e	f	g	h	i
0-½	27	1	53	42	5	1	0	133	262
½-1	45	0	179	16	6	0	0	93	339
1-2	1861	8	170	1600	30	8	0	720	4397
2-3	4946	14	414	2882	20	4	0	1194	9474
3-4	1093	3	53	134	5	3	0	173	1464
4-5	598	9	79	704	8	4	0	256	1658
5-6	347	80	164	422	5	0	0	159	1177
6-7	559	322	124	2654	24	0	0	256	3939
7-8	810	5	246	641	12	2	45	351	2112
8-9	1690	29	84	617	32	9	817	507	3785
9-10	809	62	6	437	88	3	117	194	1716
10-11	2186	102	39	1221	213	3	13	451	4228
11-12	1842	12	44	740	5162	6	0	546	8352
12-13	630	8	17	266	991	3	0	259	2174
13-14	606	4	10	76	55	30	0	206	987
14-15	2850	6	60	226	24	20	0	314	3500
15-16	778	13	33	246	12	27	0	221	1300
16-17	1500	31	79	887	29	31	0	326	2883
17-18	179	40	9	759	13	20	0	154	1178
18-19	934	46	58	7468	32	12	0	314	8864
19-20	904	42	80	8926	64	30	0	562	10608
20-21	1970	38	14	692	768	58	0	402	3942
21-22	1932	62	6	1102	3464	26	0	350	6942
22-23	1987	193	6	1807	4724	30	0	558	9305
23-24	2910	204	4	3732	4356	28	0	580	11814
24-25	868	82	18	2544	1618	28	0	338	5496
25-26	4894	258	8	4646	4934	58	0	638	15436
26-27	3664	224	16	12072	2764	40	0	868	19648
27-28	1678	956	10	4886	1460	54	0	846	9890
28-29	2428	328	14	2988	2256	34	0	1056	9104
29-30	2732	146	6	2702	522	38	0	914	7056
34-35	208	196	6	7998	958	30	0	646	10042
39-40	1840	736	2	6732	20	26	0	860	10216
44-45	1070	560	0	1380	0	62	0	1044	4116
49-50	1778	1106	0	3360	0	82	0	2658	8984
59-60	706	876	0	2310	0	26	0	922	4840
69-70	307	706	0	2264	0	32	0	904	4276
Replicates									
5-6	449	75	205	372	14	2	0	197	1314
10-11	2254	75	31	937	183	10	12	381	3883
15-16	930	5	32	186	34	30	0	237	1454
20-21	1760	24	14	444	520	38	0	310	3110
25-26	4488	160	0	4600	4648	4	0	572	14472
29-30	2922	216	16	2940	576	38	0	964	7672
49-50	1220	948	0	1066	2	102	0	1588	5926

a Asterionella formosa; b Stephanodiscus astraea;
c Nitzschia palea; d Stephanodiscus hantzschii;
e Melosira granulata f Melosira varians;
g Cyclotella pseudostelligera; h others; i total

ROSTHERNE MERE

(core RM-M17)

Algal remains

(individuals per 5 µl of fresh sediment)

Depth (cm)	a total	(full)	b	c	d	e	f	g
0-½	20	(1)	110	279	2	10	2	10
½-1	111	(81)	173	83	0	2	1	10
1-2	201	(155)	126	35	2	32	0	16
2-3	153	(17)	72	44	11	16	3	74
3-4	5	(1)	94	73	12	8	5	65
4-5	6		810	59	4	3	0	5
5-6	9	(1)	422	112	2	14	1	11
6-7	9		254	57792	0	1	1	21
7-8	4		863	209	3	4	2	5
8-9	98	(2)	248	292	1	3	7	13
9-10	477		232	313	18	10	2	5
10-11	374	(1)	78	1047	0	2	10	3
11-12	79	(1)	49	111	62	15	2	4
12-13	29		264	148	32	16	1	4
13-14	19		743	56	23	2	1	4
14-15	8		675	80	7	1	2	1
15-16	5		303	173	72	0	0	10
16-17	7	(1)	824	916	27	2	2	3
17-18	93		452	74	28	0	9	9
18-19	11		549	668	13	0	0	13
19-20	1		231	183	23	0	2	11
20-21	46		36	437	10	7	16	14
21-22	236		18	1574	40	24	50	7
22-23	72		178	2614	16	0	12	14
23-24	62		130	1522	68	4	8	12
24-25	318		26	1760	446	6	12	38
25-26	164		30	1442	180	16	4	18
26-27	42		32	7472	84	2	18	22
27-28	10		122	1244	22	0	26	18
28-29	18		42	1606	26	2	36	24
29-30	62		4	4240	38	6	12	10
34-35	270		14	6976	0	0	38	4
39-40	120		0	11216	0	0	14	2
44-45	6		0	9552	0	0	8	12
49-50	22		4	12992	0	0	4	0

a Ceratium (cysts)
b Microcystis (colonies)
c Stephanodiscus astraea (cells)
d Anabaena (akinetes)
e Aphanizomenon (akinetes)
f Staurastrum (cells)
g Pediastrum (colonies)

ROSTHERNE MERE

(core RM-M18)

Algal remains

(individuals per 5 µl of fresh sediment)

Depth (cm)	a		b	c	d	e	f	g
	total	(full)						
0-½	58	(39)	136	133	1	3	4	20
½-1	65	(40)	141	128	5	4	2	21
1-2	94	(43)	157	119	6	1	4	18
2-3	116	(61)	178	132	5	5	8	30
3-4	103	(44)	178	106	0	0	8	40
4-5	69	(12)	217	145	17	3	15	60
5-6	14	(1)	616	154	17	8	0	19
6-7	5		373	122	1	0	0	5
7-8	7		517	2405	0	3	1	9
8-9	9		673	4016	0	0	7	2
9-10	47		266	321	0	1	2	6
10-11	329		157	445	0	5	2	6
11-12	342		104	2853	4	0	26	8
12-13	229		70	583	3	2	8	4
13-14	34		48	168	57	13	1	2
14-15	14		399	83	30	2	0	12
15-16	3		776	41	1	1	1	0
16-17	7		226	46	0	2	3	8
17-18	6		479	64	0	0	1	6
18-19	9		831	607	5	1	0	3
19-20	31		459	344	53	0	3	5
20-21	17		589	349	13	2	9	9
21-22	6		582	516	91	2	7	30
22-23	15		317	340	89	7	21	13
23-24	247		185	1893	168	30	66	28
24-25	251		193	2051	96	13	60	17
25-26	88		148	2864	56	6	8	6
26-27	166		26	2346	310	6	11	21
27-28	134		28	2224	338	8	6	40
28-29	88		84	6000	222	8	16	26
29-30	18		46	2768	54	8	14	24
34-35	156		10	4256	18	10	4	4
39-40	116		8	4720	2	2	22	10
44-45	8		0	12320	0	0	4	0
49-50	62		0	4640	0	0	8	0
59-60	18		2	10048	2	2	14	10
69-70	36		0	1456	0	0	4	4
79-80	16		0	3020	0	0	92	0

a Ceratium (cysts)
b Microcystis (colonies)
c Stephanodiscus astraea (cells)
d Anabaena (akinetes)
e Aphanizomenon (akinetes)
f Staurastrum (cells)
g Pediastrum (colonies)

ROSTHERNE MERE

(core RM-M27)

Algal remains

(individuals per 5 µl of fresh sediment)

Depth (cm)	a		b	c	d	e	f	g	h	i
	total	(full)								
0-1	4	(2)	24	0	0	0	7	1925	2	0
1-2	7	(0)	42	0	0	0	4	960	2	0
2-3	28	(4)	55	0	2	5	13	154	2	0
3-4	54	(2)	48	6	4	2	24	114	3	0
4-5	39	(3)	57	2	1	2	34	106	3	0
5-6	26	(1)	34	8	8	3	31	138	28	1
6-7	45	(2)	38	6	1	2	38	132	32	5
7-8	15	(1)	16	2	1	3	41	256	26	12
8-9	26	(1)	23	2	2	6	36	316	16	3
9-10	32	(0)	19	2	0	3	14	641	17	9
10-11	36	(2)	17	1	5	1	2	328	28	7
11-12	31	(0)	24	4	3	1	18	221	17	9
12-13	20	(0)	6	9	1	3	8	163	10	2
13-14	16	(0)	18	11	2	4	15	221	7	8
14-15	16	(0)	10	4	2	0	14	187	11	10
15-16	7	(0)	8	2	2	0	2	126	0	0
16-17	14	(0)	2	7	0	1	4	157	0	0
17-18	29	(0)	3	9	1	5	2	174	0	1
18-19	19	(0)	1	8	1	5	4	406	0	0
19-20	19	(0)	0	1	0	2	0	170	0	1

a Ceratium (cysts)
b Microcystis (colonies)
c Anabaena (akinetes)
d Aphanizomenon (akinetes)
e Staurastrum (cells)
f Pediastrum (colonies)
g Stephanodiscus astraea (cells)
h Coelastrum (colonies)
i Scenedesmus (colonies)

ROSTHERNE MERE

(core RM-M33)

Algal remains

(individuals per 5 µl of fresh sediment)

Depth (cm)	a	b	c	d	e	f	g total (full)	h	i	j	k	l
0-1	796	0	51	77	2	1	2 (1)	9	9	5	11	7
1-2	322	25	5	68	0	4	8 (1)	13	7	4	7	5
2-3	283	13	2	41	2	2	32 (1)	9	17	2	3	11
3-4	291	0	0	77	2	2	24 (0)	2	10	4	5	10
4-5	245	0	2	54	0	1	5 (0)	3	15	10	2	11
5-6	264	3	0	66	0	0	8 (0)	2	30	6	7	15
6-7	323	8	0	56	0	0	24 (0)	0	183	12	3	8
7-8	681	22	0	58	0	0	52 (0)	0	149	6	3	8
8-9	383	2	0	41	0	0	37 (1)	0	45	4	0	10
9-10	497	38	0	27	0	1	12 (0)	0	65	12	3	6

a Stephanodiscus astraea (cells)
b Melosira arenaria (cells)
c Oscillatoria agardhii (filaments)
d Melosira varians (cells)
e Scenedesmus spp (colonies)
f Coelastrum sp (colonies)
g Ceratium hirundinella (cysts)
h Microcystis spp (colonies)
i Anabaena (akinetes)
j Aphanizomenon (akinetes)
k Staurastrum (colonies)
l Pediastrum (colonies)

ROSTHERNE MERE - SESTON TRAPS

Dates :	Start	3-8-77	IV	16-6-78
	I	22-9-77	V	12-9-78
	II	13-12-77	VI	24-1-79
	III	22-3-78		

1. Volume
(ml)

		I	II	III	IV	V	VI
Inflow	- top	100	125	23	24	26	36
	- bottom	110	130	29	30	45	43
Centre	- top	100	130	21	19	20	32
	- middle	180	-	25	26	20	40
	- bottom	30	115	28	34	9	35
Outflow	- top	50	120	23	27	19	30
	- bottom	160	100	28	32	20	38

2. Microcystis spp
(colonies/5 µl fresh seston)

		I	II	III	IV	V	VI
Inflow	- top	129	124	10	4	15	3
	- bottom	173	119	17	4	30	3
Centre	- top	156	109	10	0	11	2
	- middle	191	84	7	0	27	4
	- bottom	117	115	18	0	32	3
Outflow	- top	178	106	10	0	10	1
	- bottom	263	155	4	0	38	2

3. Stephanodiscus astraea
(cells/5 µl fresh sediment)

		I	II	III	IV	V	VI
Inflow	- top	2	2	75	4642	337	1327
	- bottom	5	3	64	5458	258	1200
Centre	- top	1	5	128	6610	366	1563
	- middle	3	3	79	5158	278	1167
	- bottom	6	2	67	7292	210	1196
Outflow	- top	5	2	114	4426	304	1732
	- bottom	13	3	44	5784	382	1268

4. Ceratium hirundinella
(cysts/5 µl fresh sediment)

		I	II	III	IV	V	VI
Inflow	- top	2	1	1	0	4	10
	- bottom	0	0	0	0	2	28
Centre	- top	0	2	0	0	3	23
	- middle	0	2	1	0	1	21
	- bottom	2	2	0	0	1	20
Outflow	- top	1	1	0	0	3	24
	- bottom	0	1	0	2	3	22

5. Melosira varians
(cells/5 µl fresh sediment)

		I	II	III	IV	V	VI
Inflow	- top	0	40	132	1098	53	77
	- bottom	0	42	201	1046	36	662
Centre	- top	0	7	136	980	22	108
	- middle	0	9	158	956	17	99
	- bottom	0	16	166	876	21	90
Outflow	- top	0	13	219	1646	33	105
	- bottom	0	22	61	1170	29	90

6. Pediastrum spp
(colonies/5 µl fresh sediment)

		I	II	III	IV	V	VI
Inflow	- top	9	6	4	22	43	8
	- bottom	15	6	6	24	40	6
Centre	- top	5	5	12	14	34	16
	- middle	3	2	11	2	62	19
	- bottom	6	10	10	10	48	23
Outflow	- top	24	4	6	14	34	17
	- bottom	13	15	8	16	73	13

7. Oscillatoria agardhii
(filaments and mm/5 µl fresh sediment)

		I	II	III	IV	V nos	V mm	VI
Inflow	- top	-	-	-	-	8	0.5	-
	- bottom	-	-	-	-	194	10	-
Centre	- top	-	-	-	-	34	2	-
	- middle	-	-	-	-	3032	259	-
	- bottom	-	-	-	-	574	133	-
Outflow	- top	-	-	-	-	39	2	-
	- bottom	-	-	-	-	92	5	

8. Anabaena spp
(akinetes/5 µl fresh sediment)

		I	II	III	IV	V	VI
Inflow	- top	0	1	0	0	17	3
	- bottom	0	0	1	0	8	1
Centre	- top	2	1	0	2	44	1
	- middle	1	0	0	0	30	5
	- bottom	0	0	0	0	48	1
Outflow	- top	0	0	0	12	40	0
	- bottom	0	0	0	0	68	0

9. Staurastrum (Coelastrum) [Ankyra]
(cells-colonies/5 µl fresh sediment)

		I	II	III	IV	V	VI
Inflow	- top	2	1	0	16(0)	52(4)	10 [6]
	- bottom	2	0	0	2(2)	42(13)	16 [2]
Centre	- top	3	1	0	4(52)	59(6)	12 [3]
	- middle	5	1	1	2(24)	47(11)	16 [13]
	- bottom	2	1	1	4(8)	38(17)	11 [14]
Outflow	- top	1	1	0	6(10)	50(1)	11 [14]
	- bottom	4	0	0	8(14)	66(28)	13 [13]

ESTHWAITE WATER - *Ceratium* cysts

'full' and ('empty') cysts per 5 µl fresh sediment

Date	0-1 cm	1-2 cm	2-3 cm	3-4 cm	4-5 cm
1977					
25 Jan	56 (1)	27 (0)	1 (0)	-	-
8 Feb	57 (1)	137 (0)	4 (0)	-	-
22 Feb	21 (1)	79 (2)	267 (0)	-	-
8 Mar	55 (4)	68 (6)	44 (0)	-	-
15 Mar	28 (4)	109 (2)	32 (3)	-	-
22Mar	89 (5)	19 (1)	6 (3)	-	-
30 Mar	90 (12)	94 (10)	42 (13)	-	-
6 Apr	49 (14)	30 (11)	2 (1)	-	-
13 Apr	35 (8)	65 (8)	11 (0)	-	-
19 Apr	40 (6)	259 (32)	219 (33)	-	-
26 Apr	31 (12)	107 (23)	1 (1)	-	-
3 May	24 (20)	64 (18)	18 (6)	-	-
17 May	26 (25)	124 (72)	74 (32)	-	-
24 May	14 (24)	14 (47)	29 (37)	-	-
31 May	40(23)	31 (32)	18 (14)	-	-
8 June	28 (32)	42 (44)	0 (6)	-	-
14 June	10 (22)	77 (88)	6 (77)	-	-
21 June	10 (23)	24 (28)	0 (6)	-	-
28 June	62 (49)	19 (49)	43 (59)	-	-
6 July	4 (13)	7 (19)	7 (23)	-	-
12 July	2 (4)	17 (22)	47 (40)	-	-
19 July	14 (20)	19 (46)	0 (23)	-	-
26 July	26 (22)	12 (7)	0 (8)	-	-
2 Aug	17 (24)	7 (8)	19 (20)	-	-
12 Aug	13 (12)	16 (25)	14 (14)	-	-
16 Aug	34 (26)	58 (60)	24 (40)	-	-
6 Sept	7 (21)	0 (9)	14 (82)	-	-
28 Sept	29 (31)	19 (35)	44 (55)	46 (54)	15 (17)
4 Oct	18 (50)	64 (47)	43 (34)	3 (7)	7 (11)
13 Oct	48 (45)	89 (51)	45 (74)	1 (17)	1 (11)
18 Oct	120 (15)	476 (9)	48 (64)	11 (61)	4 (16)
25 Oct	733 (23)	77 (107)	89 (205)	17 (25)	2 (22)
1 Nov	1516 (40)	439 (31)	319 (74)	301 (32)	10 (24)
8 Nov	136 (29)	1 (15)	4 (2)	5 (2)	0 (2)
15 Nov	192 (17)	732 (38)	32 (31)	22 (63)	0 (32)
29 Nov	422 (78)	66 (72)	214 (69)	7 (8)	4 (40)
20 Dec	207 (63)	443 (48)	57 (76)	2 (29)	4 (42)
1978					
17 Jan	83 (49)	39 (39)	17 (10)	9 (10)	5 (1)
14 Feb	355 (44)	736 (62)	3 (16)	10 (16)	2 (4)
28 Feb	246 (46)	322 (41)	21 (79)	6 (54)	4 (2)
4 Mar	12 (3)	373 (21)	28 (62)	44 (24)	24 (44)
25 Apr	218 (37)	395 (81)	9 (27)	18 (2)	0 (4)
23 May	30 (24)	49 (19)	155 (105)	81 (99)	12 (80)
27 June	260 (170)	36 (88)	6 (32)	12 (24)	4 (4)
28 July	24 (25)	133 (106)	98 (123)	4 (22)	6 (12)
29 Aug	69 (66)	42 (58)	71 (67)	427 (194)	21 (23)
29 Sept	59 (52)	39 (119)	40 (92)	59 (127)	8 (20)
7 Nov	407 (93)	49 (70)	13 (172)	5 (196)	3 (62)

ALGAL REMAINS - HIGHLAND BRITAIN

(individuals per 5 µl fresh sediment)

1. ELTERWATER (ELT-J68)

Depth (cm)	0-1	1-2	2-3	3-4	4-5
Scenedesmus	14	21	34	43	38
Anabaena	2	2	3	5	0
Chlorophyceae	3	8	5	3	2
Volvox	1?	0	1	0	0
Cosmarium	0	1	0	1	2
Pediastrum	0	0	1	0	0
Staurastrum	0	0	0	1	0

2. GRASMERE (GM-M22)

Depth (cm)	0-1	1-2	2-3	3-4	4-5
Staurastrum	53	29	9	4	2
Chlorophyceae	7	0	0	0	0
Anabaena	0	0	1	0	0

3. CONISTON (deep water material)

NO REMAINS

4. WASTWATER (deep water material)

NO REMAINS

5. WINDERMERE : south basin (SB-M20)

Depth (cm)	0-1	1-2	2-3
Staurastrum	63	6	0
Ceratium	11	4	1

6. CAM LOCH (CAM-M15)

Depth (cm)	0-1	1-2	2-3
Anabaena	20	1	18

7. LOCH BORROLAN (BOR-M14)

NO REMAINS

8. BLELHAM TARN (BLE-M10)

Depth (cm)	0-1	1-2	2-3	3-4	4-5
Trachlemonas	23	41	13	11	7
Staurastrum	11	7	2	1	1
Ceratium	1	2	1	0	2
Microcystis	1	1	1	1	1
Pediastrum	0	1	0	0	0
Scenedesmus	0	0	0	1	3
Anabaena	0	0	0	0	10

9. LOCH BORRALIE (BRL-G01)

Depth (cm)	0-1	1-2	2-3
Staurastrum	2	1	0
Pediastrum	0	1	0

10. LOCH NA'THUILL (NAT-G02)

NO REMAINS

11. LOCH URIGILL (URG-G03)

Depth (cm)	0-1	1-2	2-3
Anabaena	5	3	1

(URG-M13)

Anabaena	15	21	0

12. ESTHWAITE WATER (EST-J67)

Depth (cm)	0-1	1-2	2-3	3-4	4-5
Ceratium	500(407)	119(49)	185(13)	20(5)	65(3)
Microcystis	24	11	6	5	0
Anabaena	77	123	3	1	8
Staurastrum	16	29	18	27	15

Also observed: Trachelmonas, Scenedesmus

ESTHWAITE JENKIN CORES

depth (cm)	number of Ceratium cysts/50 µl fresh sed.				
	12.10.76	10.11.76	8.12.76	21.12.76	25.1.77
0-1	86	420	304	344	560
1-2	86	145	76	1287	272
2-3	0	26	311	42	6
3-4	1	17	146	20	0
4-5	0	7	6	4	4
5-6	0	4	6	20	0
6-7	0	29	0	12	2
7-8	0	4	0	0	2
8-9	0	0	0	2	0
9-10	0	0	0	8	0
10-11	0	0	0	0	0
11-12	0	0	0	0	0

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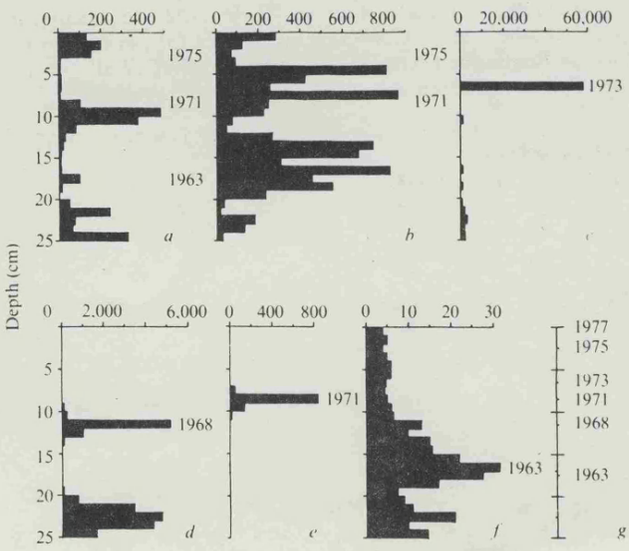
Confirmation of ^{137}Cs dating by algal stratigraphy in Rostherne Mere

THE deep sediments of Rostherne Mere, Cheshire (National Grid Reference SJ 745843) offer a promising situation in which to study the relationship between biological stratification and radionuclide dating in the absence of gross bioturbation. The mere is small (46.5 hectare), but relatively deep (30 m maximum), and is reported to be largely devoid of benthic fauna in the persistently deoxygenated deep sediments[1]. The sediments of Rostherne Mere contain the remains of a great variety of algae, in addition to diatoms. The preservation of non-siliceous algae is uncommon, although found in the sapropel deposits of the USSR[2]. In Rostherne the empty spores of *Ceratium hirundinella* O.F. Mull., *Anabaena* species and *Aphanizomenon flos-aquae* (L) Ralfs are recognisable, as are colonies of *Microcystis* species and cells of *Staurastrum* species. The phytoplankton of Rostherne Mere has been recorded at intervals since 1912 (refs 3–5) and sampled more frequently from 1962 (refs 6–8). The recent records (Table 1) show fluctuations in summer dominance, mainly between *Ceratium hirundinella* and *Microcystis aeruginosa* Kütz. emend., but blue–green algae have become increasingly dominant[9]. These changes, combined with occasional maxima of the diatoms *Melosira granulata* (Ehr.) Ralfs, *Cyclotella pseudostelligera* Hust. and *Stephanodiscus astraea* (Ehr.) Grun., can be correlated with algal assemblages in the sediments and permit these to be accurately dated. We now report that such algal remains from the lake sediment have been used to establish a detailed chronology which is shown to confirm the ^{137}Cs dating method.

Three 1-m cores[10] extracted from the deepest area of the mere were examined throughout for algal remains, and all showed the same well-defined stratigraphy. The algal species which are most numerous in the upper 25 cm of the cores are shown in Fig. 1 (*a–e*), and the patterns found reflect the changes in plankton dominance. Thus an 'algal chronology' can be constructed by comparing the sediment biostratigraphy with the observed and dated records of the plankton (Fig. 1*g*). The fact that the remains of many different algae are recognisable in the bottom deposits of Rostherne Mere permits a detailed correlation. Hence, the *Ceratium*-dominant years of 1963, 1971 and 1975 are allocated to the 17-cm, 9-cm and 3-cm horizons, respectively (Fig. 1 *e,d*).

Two of the cores were dated by the distribution pattern of ^{137}Cs (refs 11,12). Sections 1 cm thick were dried and analysed by γ-ray spectrometry[13] using a germanium (lithium) detector. The position of greatest concentration of ^{137}Cs, corresponding to 1963, occurred at a depth of ~17 cm in both cores and this demonstrates consistency between the cores and also agrees

Fig. 1 Algal and caesium stratigraphy. *a*, *Ceratium hirundinella* spores; *b*, *Microcystis* spp. colonies; *c*, *Stephanodiscus astraea* cells; *d*, *Melosira granulata* cells; *e*, *Cyclotella pseudostelligera* cells; *f*, caesium-137 pCi per section; *g*, algal chronology. *a–c*, Numbers expressed per 5 μl of fresh sediment, *d,e*, per 0.1 μl of fresh sediment. A 1-cm thick section of a core contains 29 ml of fresh sediment.



with the chronology established from the algal record. The ^{137}Cs profile from one of the cores is shown in Fig. 1 *f*. An earlier core dated by the ^{137}Cs method and reported by Gaskell and Eglinton[14] showed about half the accumulation rate of the present cores. Such variations in accumulation rate at different locations are not unusual and have been discussed elsewhere[15].

The deep sediments of Rostherne Mere have proved to be an ideal environment for the preservation of a variety of non-siliceous algae. Much of the sediment volume is derived from the high algal productivity of the mere, and these autochthonous deposits give a detailed insight into past phytoplankton communities. Also, the high rate of sediment accumulation (~1 cm yr^{-1}) ensures that a 1-cm slice provides adequate resolution of annual increments. The apparent absence of large benthic animals ensures that the ordered structure of the stratigraphic column is not likely to be grossly disrupted by bioturbation, and this is confirmed by the identical position of the ^{137}Cs peak in both the cores analysed.

Such conditions will not necessarily apply in other lakes, where there may be greater diffusion in the sediment column or

Table 1 Collected phytoplankton data 1962–77

Year	*C. hirundinella*	*Microcystis* spp.	*S. astraea*	*M. granulata*	*C. pseudostelligera*
1977	Rare	Abundant	Rare	Rare	Rare
1976	No record	—	—	—	—
1975	Abundant	Rare	No record	No record	No record
1974	No record	—	—	—	—
1973	Common	Abundant	Abundant	Common	Rare
1972	Common	Abundant	Common	Common	Rare
1971	Abundant	Rare	Rare	Rare	Common
1970	No record	—	—	—	—
1969	No record	—	—	—	—
1968	Rare	Rare	Rare	Abundant	Rare
1967	Common	Common	Common	Rare	Rare
1966	Rare	Abundant	Common	Common	Rare
1965	Common	Abundant	Common	Common	Rare
1964	Common	Abundant	Common	Common	Rare
1963	Abundant	Abundant	Rare	Rare	Rare
1962	Rare	Abundant	Rare	Rare	Rare

Sources: 1962–63, ref. 6; 1964–66, ref. 7; 1967–77, ref. 8. No data available for 1976, 74, 70 and 69.

more significant contribution from the catchment. Rostherne Mere is unusual because of the high autochthonous contribution to the sediment and small inflow of fine particulate allochthonous material. This is the first site in Great Britain at which independent evidence has been found for the validity of the dating of lake sediments provided by ^{137}Cs.

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