OBSERVATIONS ON THE RECENT HISTORY OF LOUGH NEAGH AND ITS DRAINAGE BASIN

By R. W. BATTARBEE
School of Biological and Environmental Studies, and Limnology Laboratory,
The New University of Ulster, Coleraine, Co. Londonderry, N. Ireland†

(*Communicated by R. G. West, F.R.S. – Received* 18 *March* 1977)

[Plates 1–3, pullouts 1–8]

CONTENTS

The present study traces the recent development of Lough Neagh from the microfossil record of the lake sediment. The history of vegetational change in the catchment area is discussed on the basis of pollen analytical information and by reference to primary and secondary documentary historical sources. Changes in the history of the

---

† Present address: University College London, Gower Street, London, WC1E 6BT

[Published 4 January 1978

lake itself are inferred from changes in the relative composition of diatom assemblages in the sediment and from changes in the calculated influx of diatoms to the sediment. The accumulation of sediment in the lake basin is discussed and radiometric data (^{14}C, ^{137}Cs, ^{210}Pb) are used to construct a sediment chronology from which accumulation rates are calculated. It is shown that the rate has increased from about 0.08 cm a^{-1} (where a is the symbol for year) in A.D. 1700 to about 0.8 cm a^{-1} today.

Four major stages in the recent development of the lake are indicated: a pre-disturbance stage (> 2000 B.C. to *ca.* A.D. 1700), a stage of accelerated mineral inwash (from *ca.* A.D. 1700); and two stages of cultural eutrophication (from *ca.* 1915 and from *ca.* 1960 respectively). The eutrophication stages are characterized by increased sediment accumulation rates, increased diatom influx rates, and the emergence of *Stephanodiscus* as the most important diatom genus.

1. Introduction

Lough Neagh is a highly productive lake and its present condition is thought to be closely associated with the input of culturally derived phosphorus and nitrogen from the catchment area (cf. Wood & Gibson 1973). A number of detailed studies have recently highlighted its eutrophic character (for example, Jewson 1975; Carter 1973; Riddolls 1974; Battarbee 1973*a*) and a preliminary account of the history of the lake has been published (O'Sullivan, Oldfield & Battarbee 1973; Battarbee 1973*a*). In this paper new information on the sediment chronology and on the variation in sediment accumulation within the lake basin is presented. The pollen and diatom information is considerably extended and the revised chronology has necessitated a further interpretation of the preliminary results (Battarbee 1973*b*). An attempt is made to examine the recent development of the lake in relation to the changing cultural activities within its drainage basin through time.

Cultural eutrophication has been the subject of considerable research in recent years focusing the attention of limnologists on the biological and chemical consequences of lake enrichment (Edmondson, Andersson & Peterson 1956; Gibson, Wood, Dickson & Jewson 1971) and prompting palaeolimnologists to attempt to identify the record of cultural eutrophication in the sediment column (Digerfeldt 1972; Stockner & Benson 1967).

The sediment record in the case of many lakes indicates that cultural eutrophication is confined to late-nineteenth and twentieth-century pollution by domestic and industrial effluent (cf. Hasler 1947). The present condition of Lough Neagh is also thought to be related to recent enrichment of this kind, but since the lake drains a large basin (figure 1) which has experienced a long history of occupation and agriculture (Evans 1963), man may have had a longer and more varied influence on its development. The pollen as well as the diatom record of the upper sediment has consequently been examined.

(*a*) *The drainage basin*

The Lough Neagh basin was formed during Tertiary times following widespread crustal warping, block faulting, and general subsidence of the Antrim basaltic lava plateau. The subsidence of the centre of the plateau gave rise to a lake which was the ancestor of Lough Neagh (Charlesworth 1960). The Oligocene Lough Neagh clays deposited during this period are evidence of the existence of the former lake. They underlie part of the present lake (figure 2), but are now mainly obscured by a thick cover of glacial drift and outwash deposits associated with the Pleistocene ice-sheets. The drift varies in nature from heavy boulder clays, often

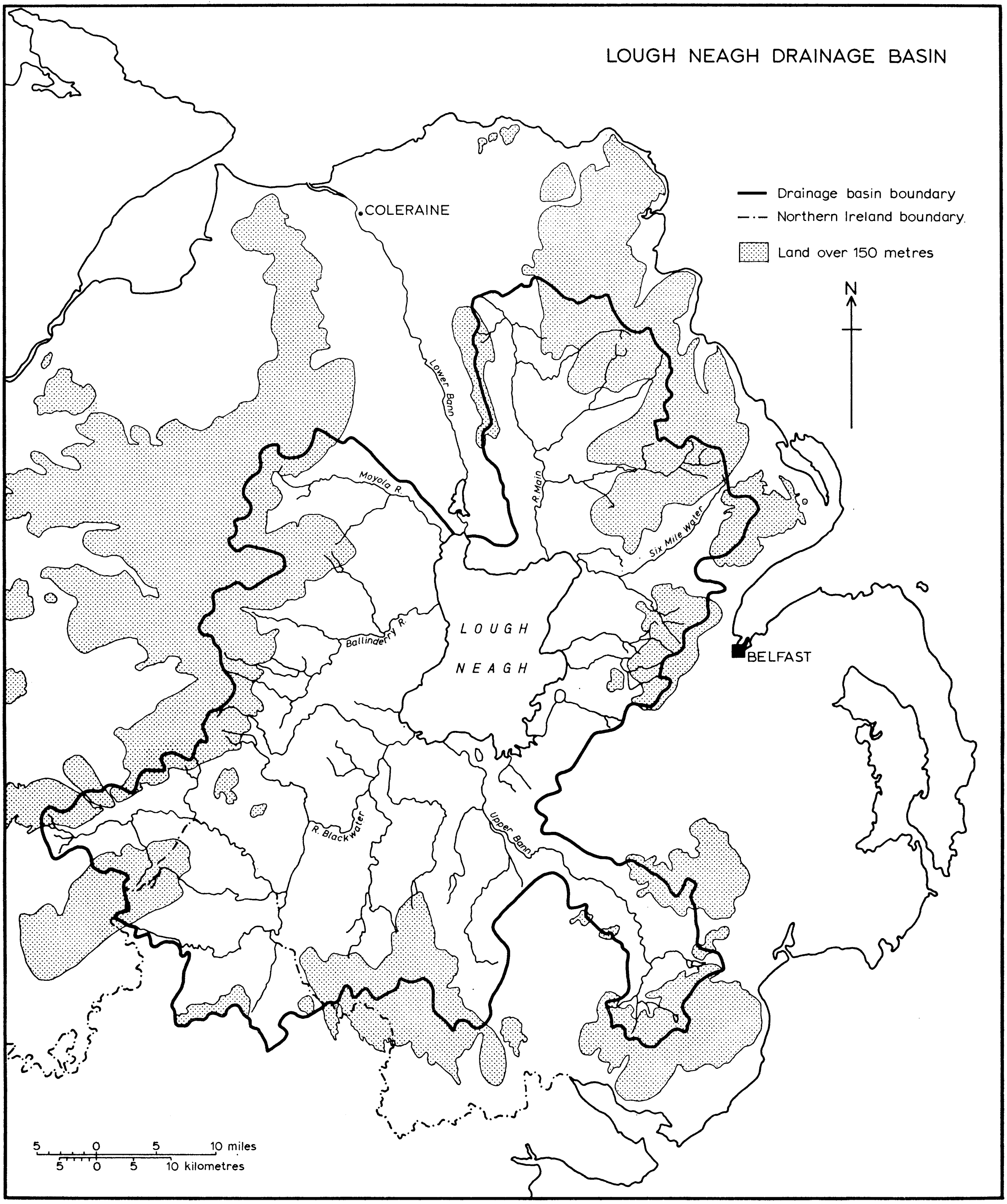


Figure 1. Lough Neagh and its drainage basin.

moulded into drumlins, to sorted clays, silts and sands sometimes in the form of eskers. Sand and gravel features tend to predominate to the west of Lough Neagh, and boulder clay drumlins are found extensively to the south of the lake in Cos. Down and Armagh, and in the lower Bann valley (Stephens 1963).

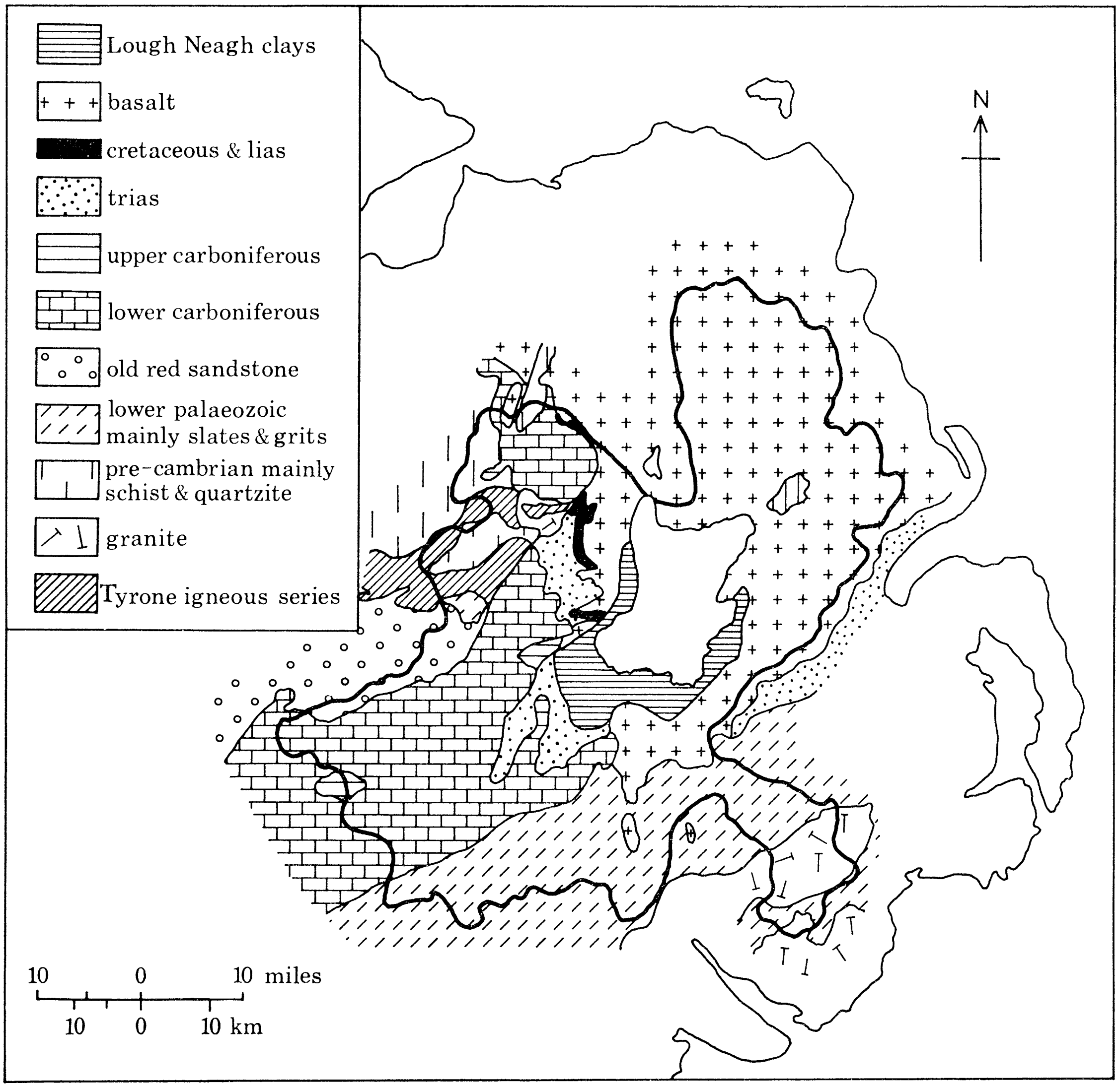


FIGURE 2. Distribution of major rock types in the Lough Neagh drainage basin (after Stephens 1963).

Despite widespread fluvial derangement during the glacial periods, the river pattern had established an arrangement centripetal to the lake following pre-glacial topographic and structural influences. Figure 1 shows the extent of the drainage basin, and shows the six main inflowing rivers, the Ballinderry, Moyola, Main, Six Mile Water, Upper Bann, and Blackwater. The outlet is to the north via the Lower Bann at Toome.

Climatic statistics for Northern Ireland show that the lowland area around Lough Neagh itself receives about 35 in. (890 mm) rainfall per annum while the higher land within the drainage basin receives up to 65 in. (1650 mm). Maximum rainfall takes place most often in December and January. Winds are often strong and mainly from the west and southwest.

The distribution of the main soil types can be seen in figure 3. In the west there are large areas of upland with base-poor soils and blanket peats, and in the south there are extensive lowland tracts of heavy drift soils, often gleyed and with peat accumulation in hollows. Lowland areas to the north and west are also characterized by heavy soils, but have a higher base status while the upland areas of the Antrim Plateau towards the boundary of the drainage basin have greater relief, and are partly covered by blanket peat. Grassland cultivation is the dominant land use in lowland areas although there is a certain amount of tillage on lighter soils. Upland areas are covered by heath and moorland and are used for rough grazing, peat cutting and afforestation.

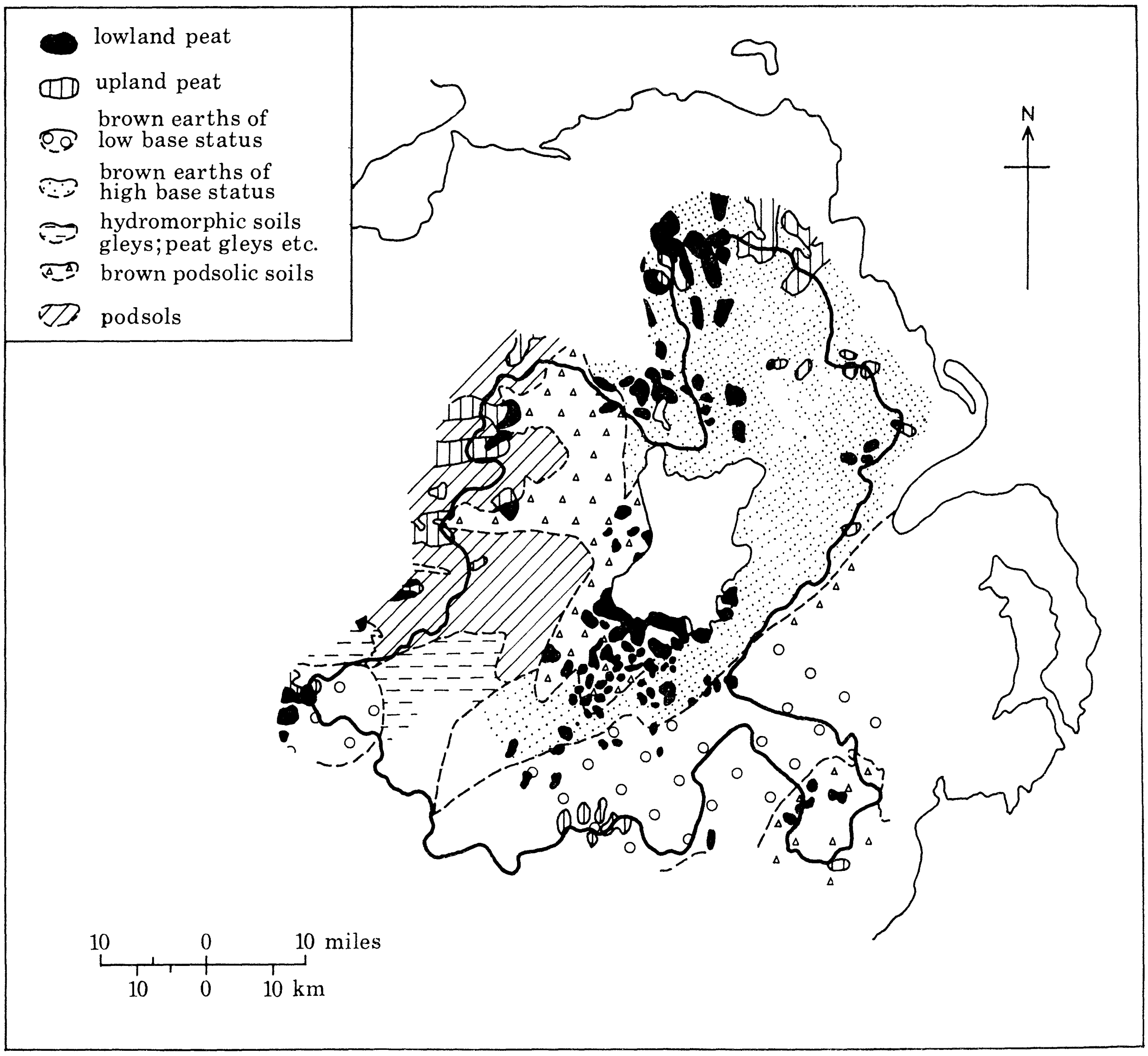


FIGURE 3. Distribution of soil types in the Lough Neagh drainage basin (after McConaghy & McAllister 1963).

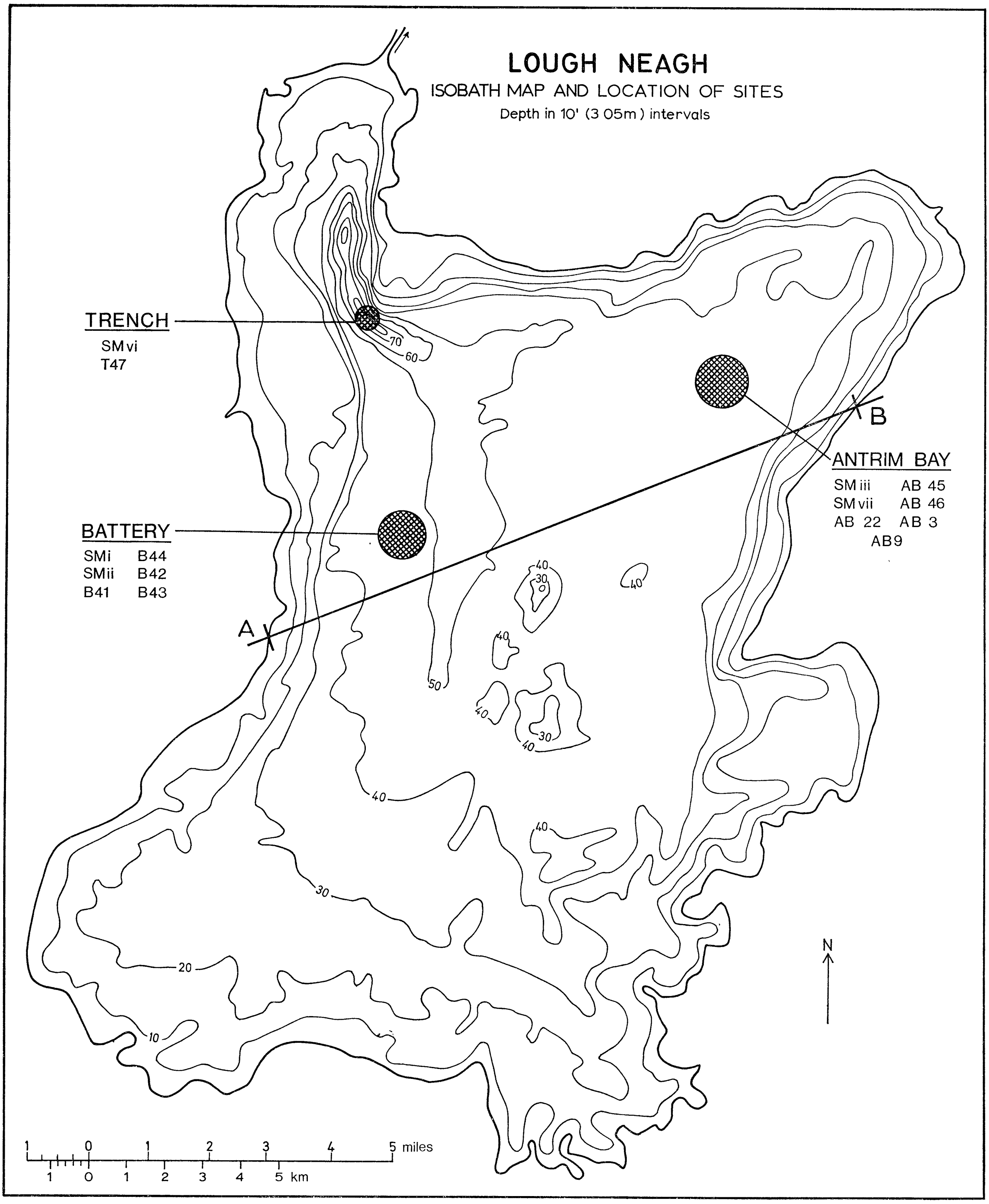


FIGURE 4. Lough Neagh, bathymetry and location of sites.

(*b*) *The lake*

Lough Neagh is the largest freshwater lake in the British Isles, although its level has been lowered twice, in the mid-nineteenth century (McMahon scheme, 1847–58), and in this century (Shepherd scheme, 1930–42) (Government of Northern Ireland 1971). The present area of the lake is 388 km^2 and the lake level is now controlled between 50.00 and 50.50 ft (15.24 and 15.39 m) O.D. (Poolbeg, Dublin Datum). Despite the lake's great extent the mean depth is only about 8 m.

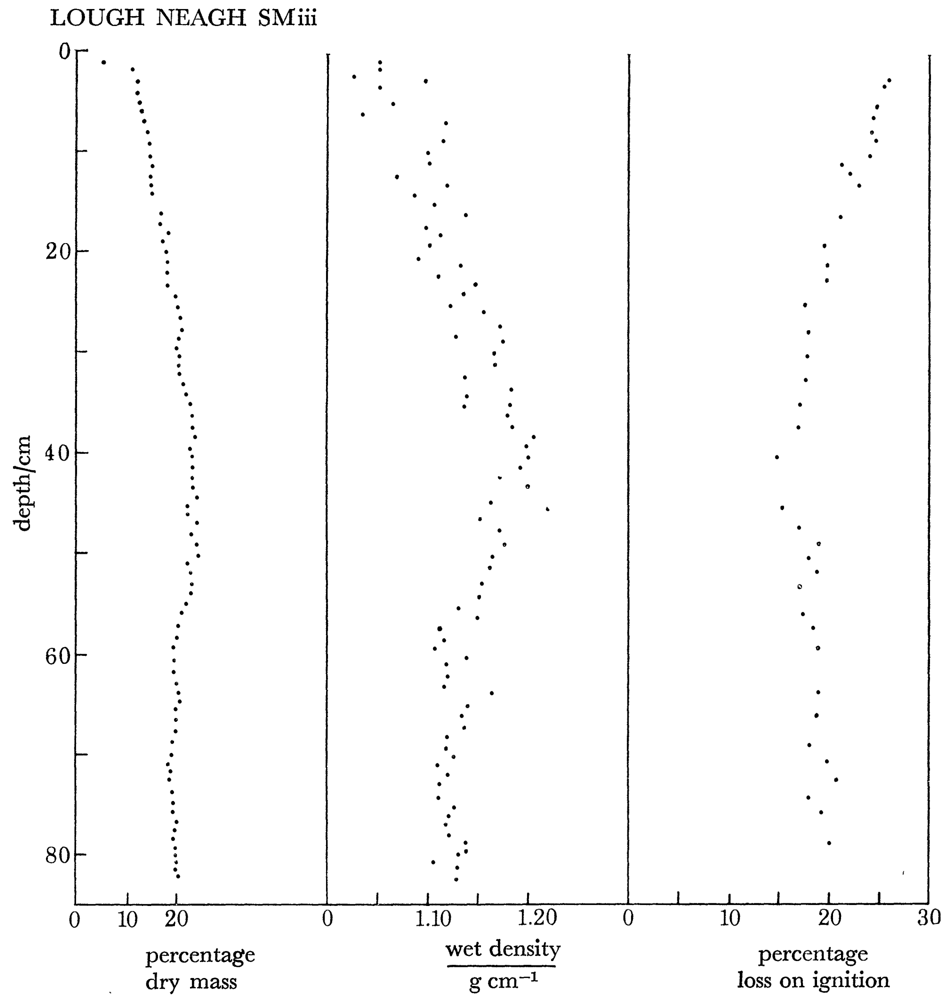


FIGURE 5. Dry mass, wet density, and loss on ignition for a short sediment core (SMiii).

Figure 4 shows a simplified bathymetric map of the lake. There is a distinct shelf round the perimeter of the lake bed, but from about 1.5 km from the shore, this falls away rapidly to a constant level of about 12 m (40 ft). The constancy of this level is one of the most remarkable features of the morphometry. Its uniformity is interrupted only in the centre, where the bed domes up to less than 5 m from the surface, and in the northwest where it dips steeply to form an underwater trench (figure 4). The deepest point in the trench is about 33 m (108 ft) and is also the deepest point in the lake.

Away from the shore area of the lake where sandy inorganic deposits predominate, the sediment consists of a brown–black mud with clay to silt-sized minerogenic particles, diatom frustules, and fine organic material. Analysis of core SMiii shows the water content of the surface mud to be about 95 % but this decreases rapidly with depth to about 85 % at 5–6 cm (figure 5). Below this level the decrease in water content is slower with depth, and at about 50 cm there is an increase in water content downwards, probably related to a change in sediment structure.

The wet density curve has a similar trend. The organic content of the surface sediment as determined by loss on ignition is about 25 % of the dry mass.

2. Methods

(a) *Field sampling*

Sites for sampling and comparative analysis were selected from within the area of the lake enclosed by the 40 ft (12 m) isobath, the area of organic muds and of assumed stratigraphic conformability. The first main site was located about 3 km offshore from the Battery (figure 4) and the second one, almost 10 km to the northeast, half-way between Portlee Point and Ardmore Point outside Antrim Bay. Samples were also taken from the deepest part of the lake from the northwest trench.

On most occasions cores were taken by using the Mackereth one metre minicorer (Mackereth 1969). Some cores were taken using a 3 m long modified version of the Mackereth corer (Makereth 1958). The mini-cores extracted exhibited a perfectly undisturbed mud–water interface, and in most cases the depth of sediment sampled was between 80 and 90 cm. The core tubes were sealed at the top by a screw cap, and at the bottom by a bung and waterproof taping. Care was taken to keep the tubes vertical during transport, and a specially constructed cradle was used into which the tubes could be slotted and held in a stable position.

(b) *Laboratory techniques*

(i) *Core extrusion*

Mini-cores were extruded by the method outlined by Mackereth (1969). As the core was extruded the sediment was sliced off. Most of the cores were sliced either into 1 or 2 cm thick disks. In the sampling of some cores, volumetric samples and subsamples for dry mass and wet density determinations were taken immediately after extrusion; the remaining sediment was dried and stored in Petri dishes.

(ii) *Dry mass, wet volume, wet density, loss on ignition*

The sediment dry mass at each level was determined after drying about 3 g wet mass in an oven at 110 °C for 24 h. Wet volume was measured by using a glass overflow cylinder, the mass of water displaced being equivalent to the sample volume. Wet density was calculated after weighing a sample of known volume by either using the overflow cylinder or vials of known capacity. Loss on ignition was calculated after combustion in a muffle furnace at 550 °C.

(iii) *Pollen preparation*

Pollen was isolated from the sediment following the routine method described by Faegri & Iversen (1964). Seven per cent NaOH was used to remove humic substances, and HF to remove siliceous matter. Erdtman's acetolysis mixture was used to remove cellulose, and the pollen residue was stained with safranin. It was then dehydrated by washing with alcohol and benzene; after transferring to a small tube, silicone oil was added and the remaining benzene was allowed to evaporate (Andersen 1960).

Two slides from each level were prepared by using 22 × 22 mm coverslips, and silicone oil as a mountant. Slides were examined at magnifications between × 400 and × 1250, although most counts were made at × 500 by using a Wild M20 microscope with a × 40 Plan Fluotar objective and × 12.5 eyepieces. Some identifications were made by using an oil-immersion objective at a magnification of × 1250.

(iv) *Diatom preparation*

Diatoms were isolated from sediment by the oxidation of the organic fraction by using H_2O_2. Slides for relative counts were prepared by pipetting 0.2 ml diatom suspension on to a glass coverslip, evaporating, and mounting in Mikrops 163. Slides for absolute counts were prepared by the evaporation tray method (Battarbee 1973*c*). The mean number of valves per sample at each level was estimated and corrected to numbers per cm^3 fresh sediment. Five per cent confidence limits for the counting error were attached and replicate samples were counted every 10 cm (cf. Battarbee 1973*b*). In this paper only the mean values are presented.

The cell volumes of the main planktonic diatoms were measured using a micrometer eyepiece. Results are given in Battarbee (1973*b*).

Relative counts were made at a magnification of × 1250 using a Wild Plan Fluotar × 100 oil-immersion objective and 12.5 eyepieces. The counts of absolute numbers were carried out by using the same objective, but with a × 15 Wild micrometer eyepiece.

(v) *Dating*

^{14}C dates were obtained from the Palaeoecology Laboratory, Queens University Belfast. Details have already been presented (O'Sullivan *et al.* 1973).

^{137}Cs dates were obtained from AERE Harwell (Pennington, Cambray & Fisher 1973). Successive 1 cm subsamples from the upper 20 cm of four mini-cores from the Battery site (figure 4) were used.

^{210}Pb dates were also obtained from AERE Harwell (Pennington, Cambray, Eakins & Harkness 1976). Two series of dates from mini-cores AB46 and B43 respectively were acquired. Each sample measured was 2 cm thick and the samples were spaced at 4 or 8 cm intervals downwards from the sediment surface.

3. Pollen analysis

(*a*) *Presentation of data*

The results of the pollen analyses are expressed in percentage terms in all diagrams. No absolute counts were made. The percentage values obtained for each taxon at each level are shown in the diagrams by horizontal bars.

Diagrams based on both tree sums and total sums are presented for each main sampling site, although in all cases the pollen of *Alnus* has been excluded from the sums. The pollen of aquatic species is also excluded from the total sums, while the spores of non-aquatic species are included. The diagrams based upon a total pollen sum show the frequencies of selected taxa only.

The exclusion of *Alnus* follows the precedent of a number of authors. Fries (1958) removed both *Alnus* and *Salix* from his pollen sums because of possible local exaggeration of the two types, and Oldfield (1963, 1965) has shown a number of ways in which use of a selective pollen sum can aid palaeoecological interpretation. Janssen (1959) also discusses the question of removing *Alnus* and stresses that the sum should comprise 'pollen of plants which grow under the same biotic condition'.

Although *Alnus* grows in damp places throughout the catchment area of Lough Neagh, it is preponderant around much of the lake shoreline, and the contribution it makes to the pollen in the sediment is probably considerable. The exclusion of *Alnus* from the pollen sum, however, is not based on its quantity, but on its variability in the diagrams. A constant quantity of pollen from a local source does not obscure information in a pollen diagram, since the quantities involved are relative to each other. On the other hand, if the amount of local pollen is variable as well as dominant its inclusion can lead to serious loss of information about regional vegetational changes.

In most cases the tree pollen sum adopted in the analyses was 150 (excluding *Alnus*). The total sum varied from sample to sample and was dependant on the total number of grains observed while 150 tree pollen grains were counted. The least total used was 313, the highest 800, while the average number was about 550.

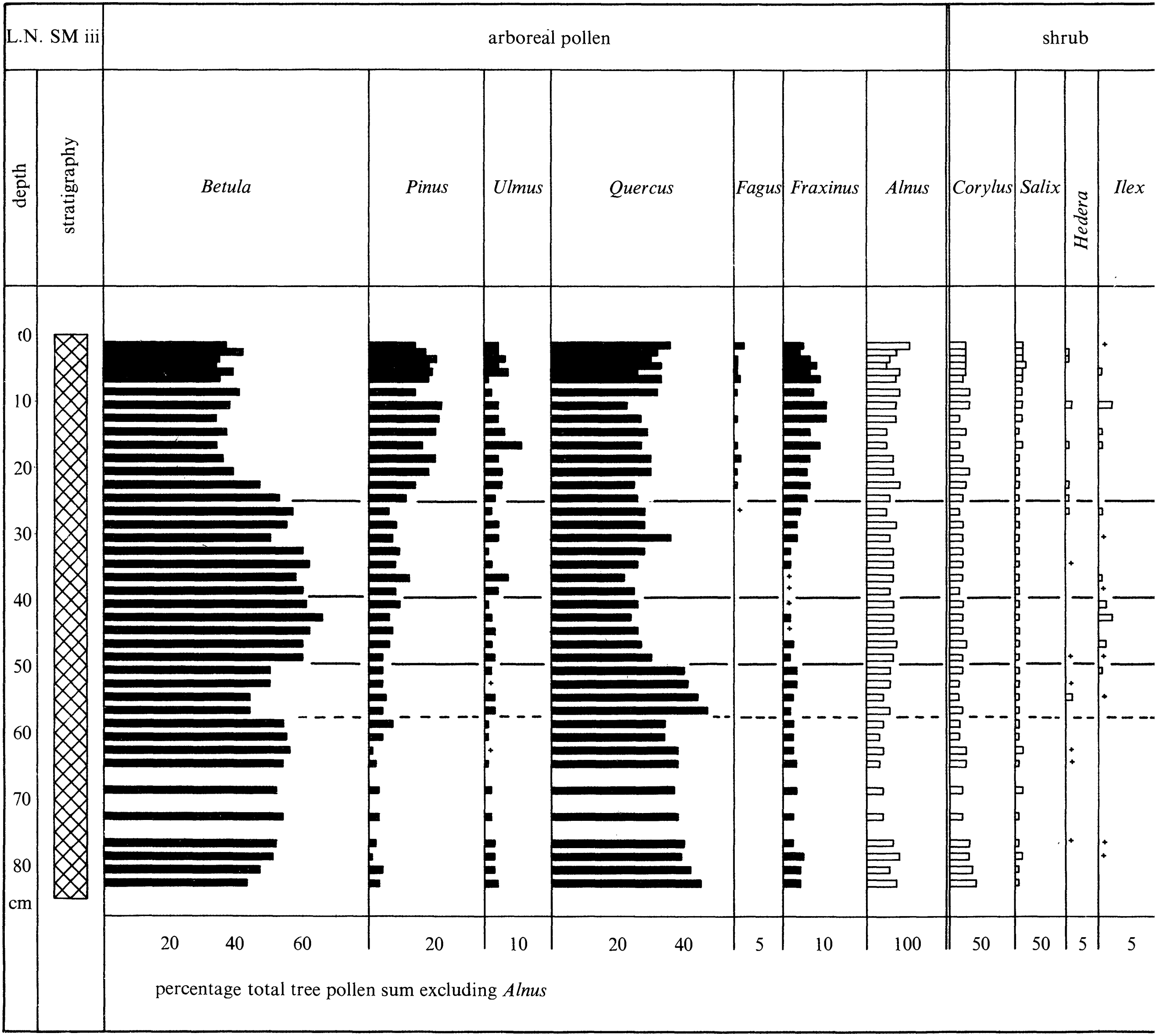
The pollen grains encountered in the counts were mainly common types. Unknown and badly preserved grains were identified by using the pollen key of Faegri & Iversen (1964) and by comparison with reference slides. An attempt was made to separate *Myrica* from *Corylus* pollen but it was unsuccessful and the two pollen types were combined and are shown in the diagrams as a combined '*Corylus*/*Myrica*' group. The cereal type grains were identified as a separate group. They were distinguished by being over 40 µm along their longest axis, and by having a large strongly annulate pore.

(*b*) *Diagram zonation scheme*

The biostratigraphic units identified in the pollen diagrams refer to assemblage zones, and conform to the principles laid down in the 'American commission on stratigraphic nomenclature' (1961). Each assemblage zone is characterized by the consistent proportions of its main diagnostic pollen types. A zone boundary occurs where there is a significant change in these proportions, and subzones can sometimes be identified within the zone.

Since the delimitation of the assemblage zones depends on the reciprocal changes of a number of taxa, the zones have not been given taxonomic names. They are identified instead by a system of lower-case letters (a, b, c, d, ...) used in alphabetical order, with 'a' being assigned to the most recent assemblage. The suffixes 0, 1, 2, 3, ..., *x* refer to subzones within a zone (e.g. a_0, a_1, a_2). The assemblages represented by this system of codes are described in the text (see below).

Zones were determined after comparing the pollen spectra of all available diagrams. This included diagrams from two short cores (SMii and SMiii) and two diagrams by O'Sullivan (O'Sullivan *et al.* 1973) from 3 m cores from Antrim Bay (AB3 and AB9). Although all these diagrams showed similar vegetational changes, the changes do not occur at the same level in different cores, because of variations in the rate of accumulation within the lake (§5). Nevertheless, the similarity of the four cores confirmed the validity of the zonation scheme. Only


L.N. SM iii
arboreal pollen
shrub
depth
stratigraphy
Betula
Pinus
Ulmus
Quercus
Fagus
Fraxinus
Alnus
Corylus
Salix
Hedera
Ilex
0
10
20
30
40
50
60
70
80
cm
20
40
60
20
10
20
40
5
10
100
50
50
5
5
percentage total tree pollen sum excluding *Alnus*

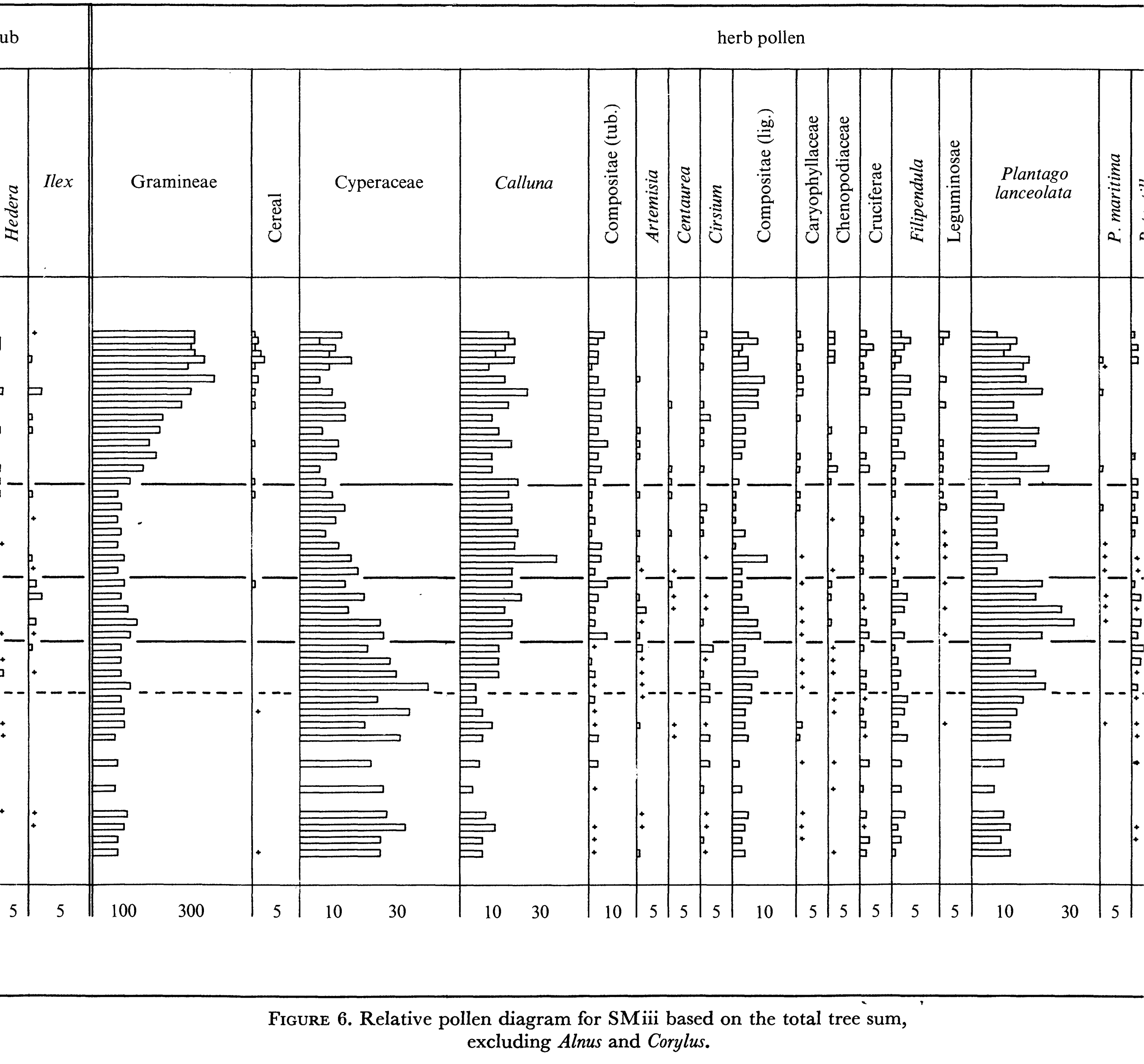
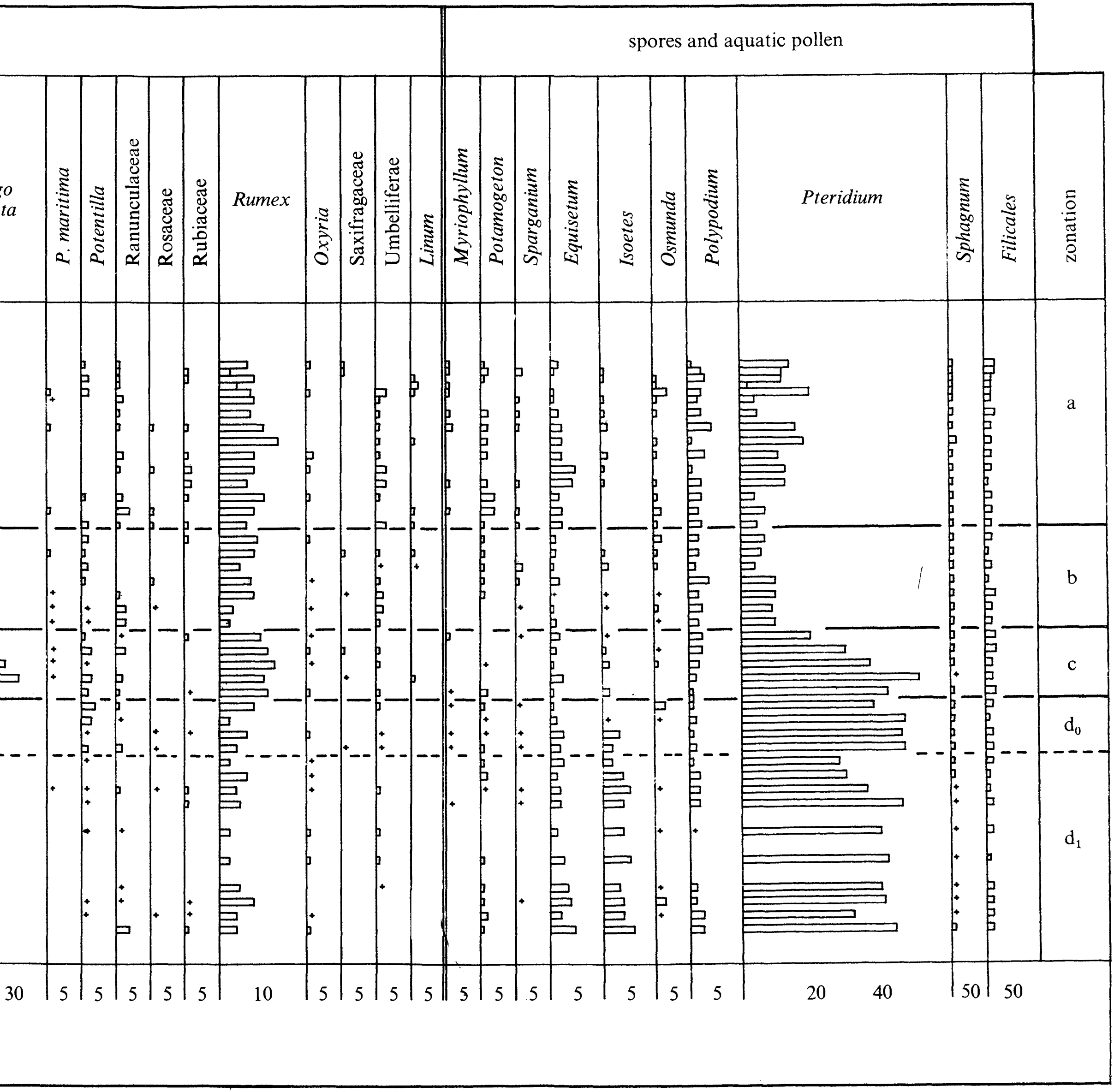
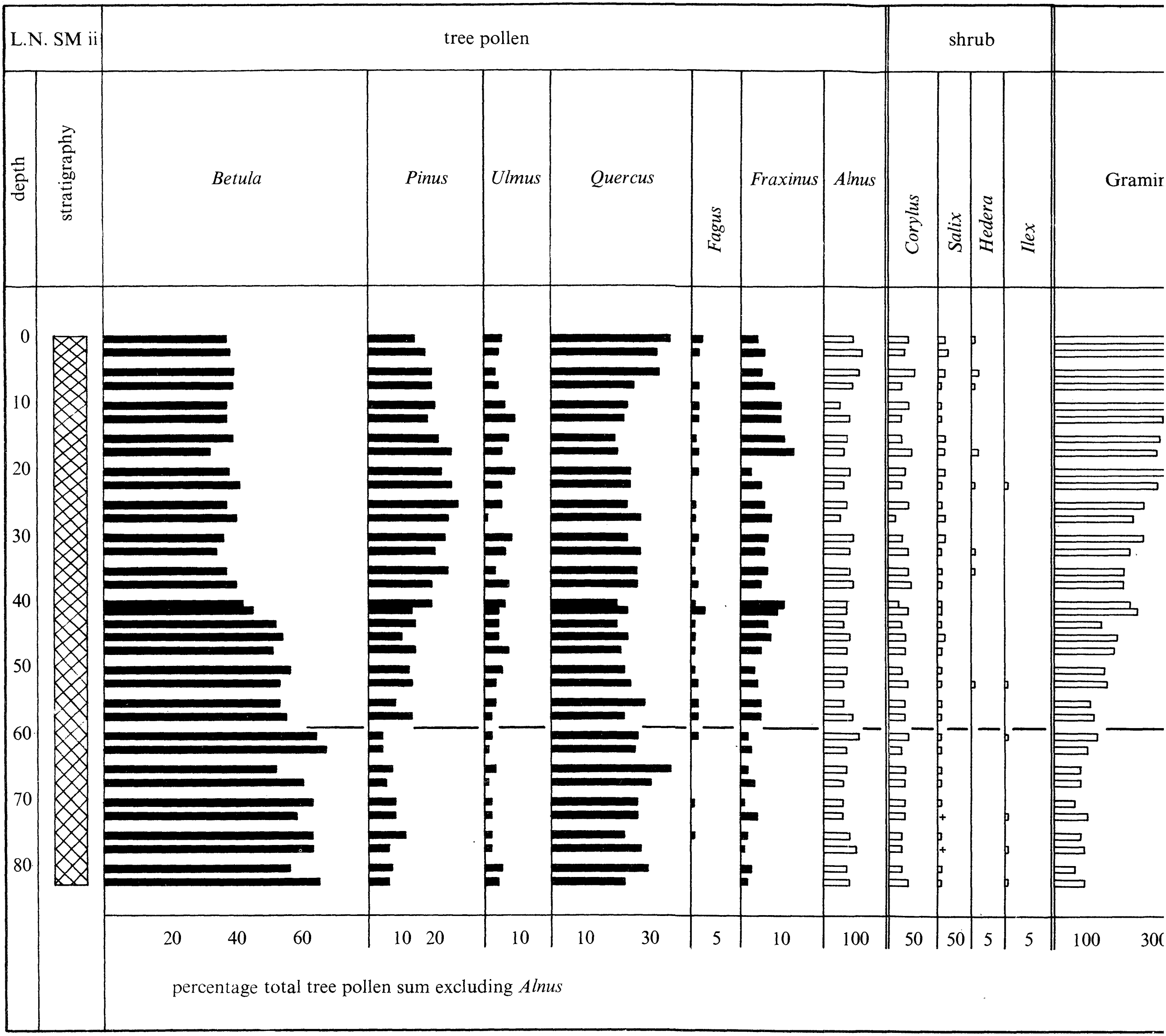


FIGURE 6. Relative pollen diagram for SMiii based on the total tree sum, excluding *Alnus* and *Corylus*.


spores and aquatic pollen
go
ta
P. maritima
Potentilla
Ranunculaceae
Rosaceae
Rubiaceae
Rumex
Oxyria
Saxifragaceae
Umbelliferae
Linum
Myriophyllum
Potamogeton
Sparganium
Equisetum
Isoetes
Osmunda
Polypodium
Pteridium
Sphagnum
Filicales
zonation
a
b
c
d$_0$
d$_1$
30
5
5
5
5
5
10
5
5
5
5
5
5
5
5
5
5
5
20
40
50
50


L.N. SM ii
tree pollen
shrub
depth
stratigraphy
Betula
Pinus
Ulmus
Quercus
Fagus
Fraxinus
Alnus
Corylus
Salix
Hedera
Ilex
Gramin
0
10
20
30
40
50
60
70
80
20
40
60
10
20
10
10
30
5
10
100
50
50
5
5
100
300
percentage total tree pollen sum excluding Alnus

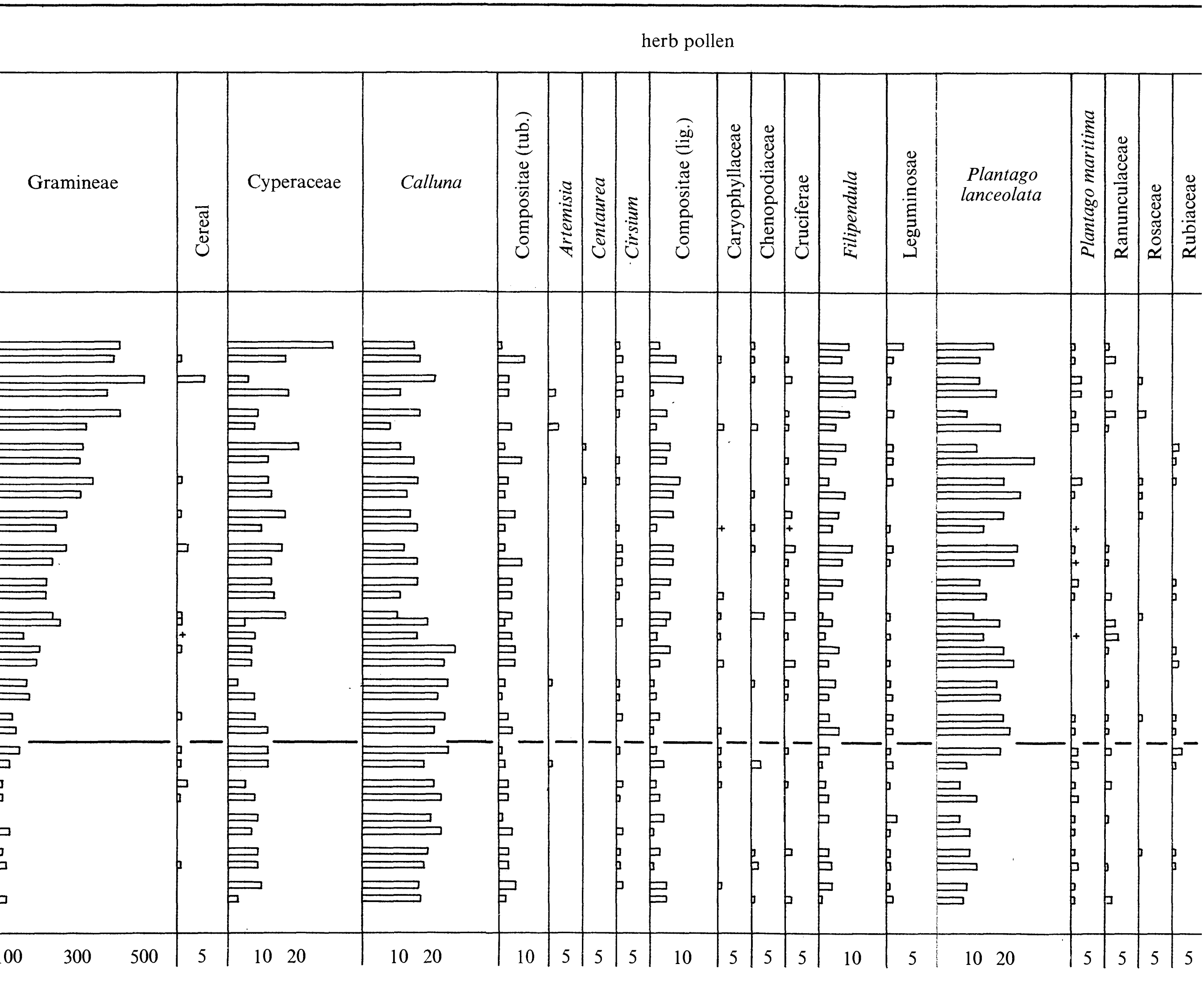
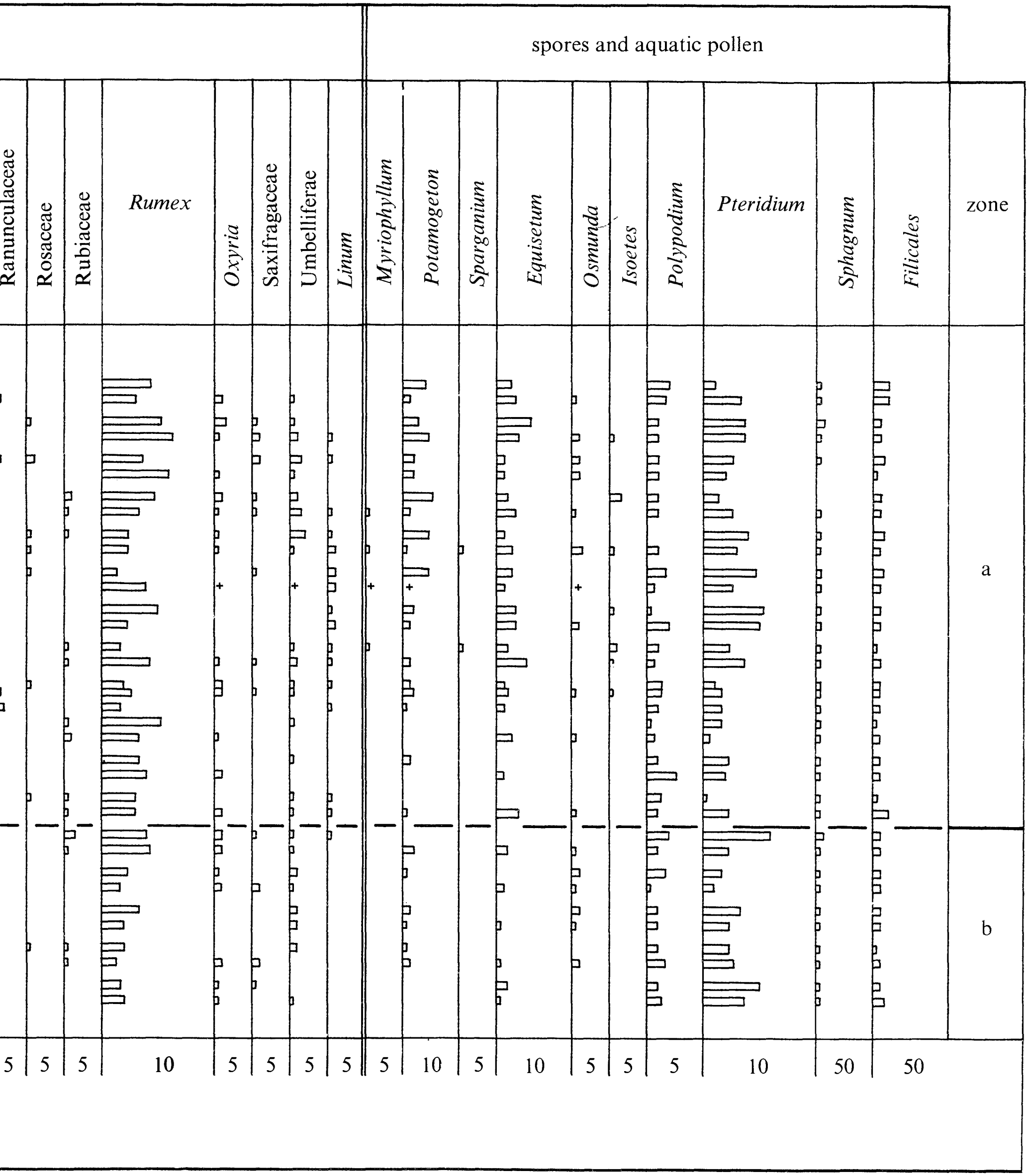


Figure 8. Relative pollen diagram for SMii, based on the total tree sum, excluding *Alnus* and *Corylus*.


spores and aquatic pollen
Ranunculaceae
Rosaceae
Rubiaceae
Rumex
Oxyria
Saxifragaceae
Umbelliferae
Linum
Myriophyllum
Potamogeton
Sparganium
Equisetum
Osmunda
Isoetes
Polypodium
Pteridium
Sphagnum
Filicales
zone
a
b
5
5
5
10
5
5
5
5
5
10
5
10
5
5
5
10
50
50

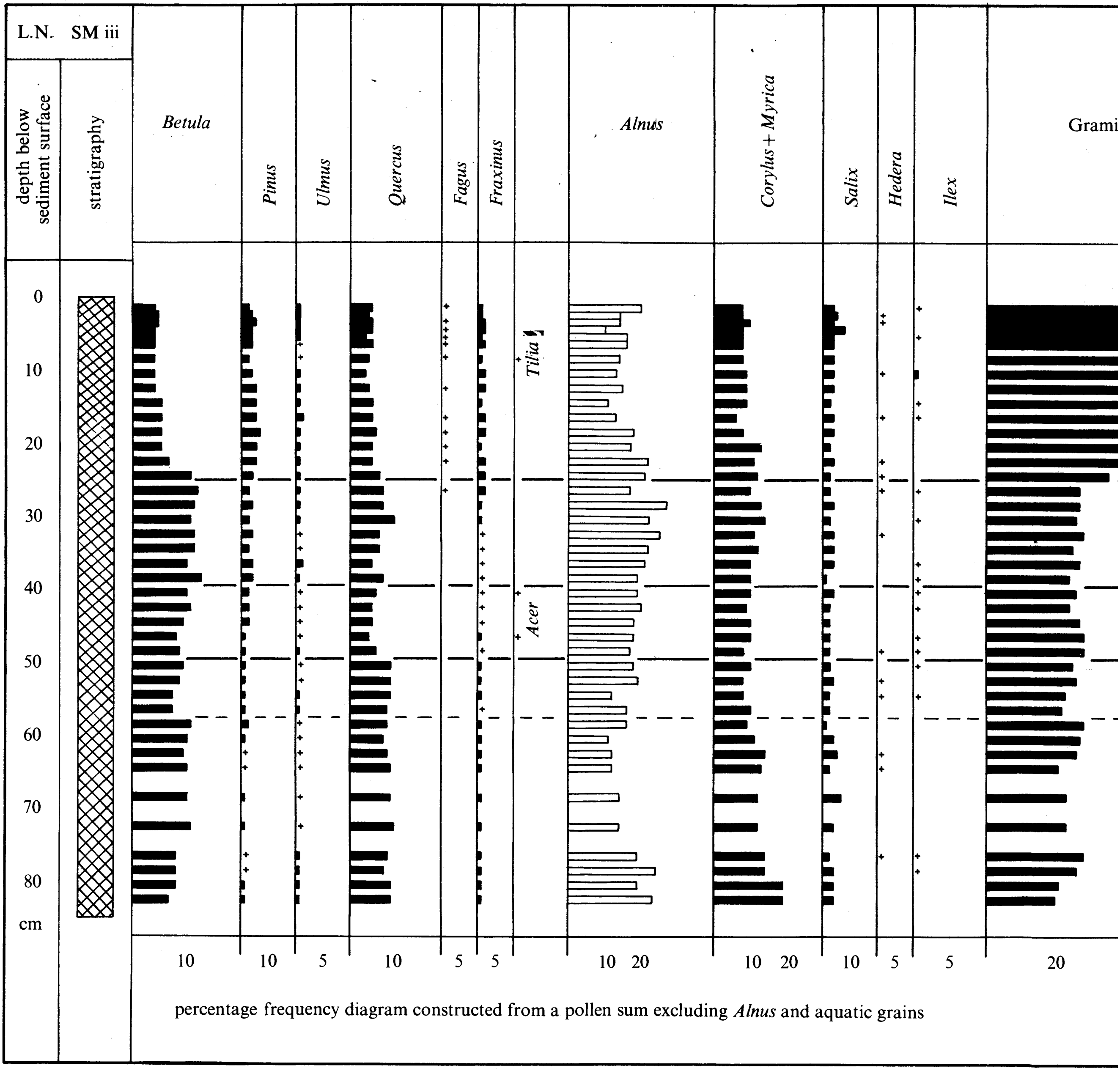
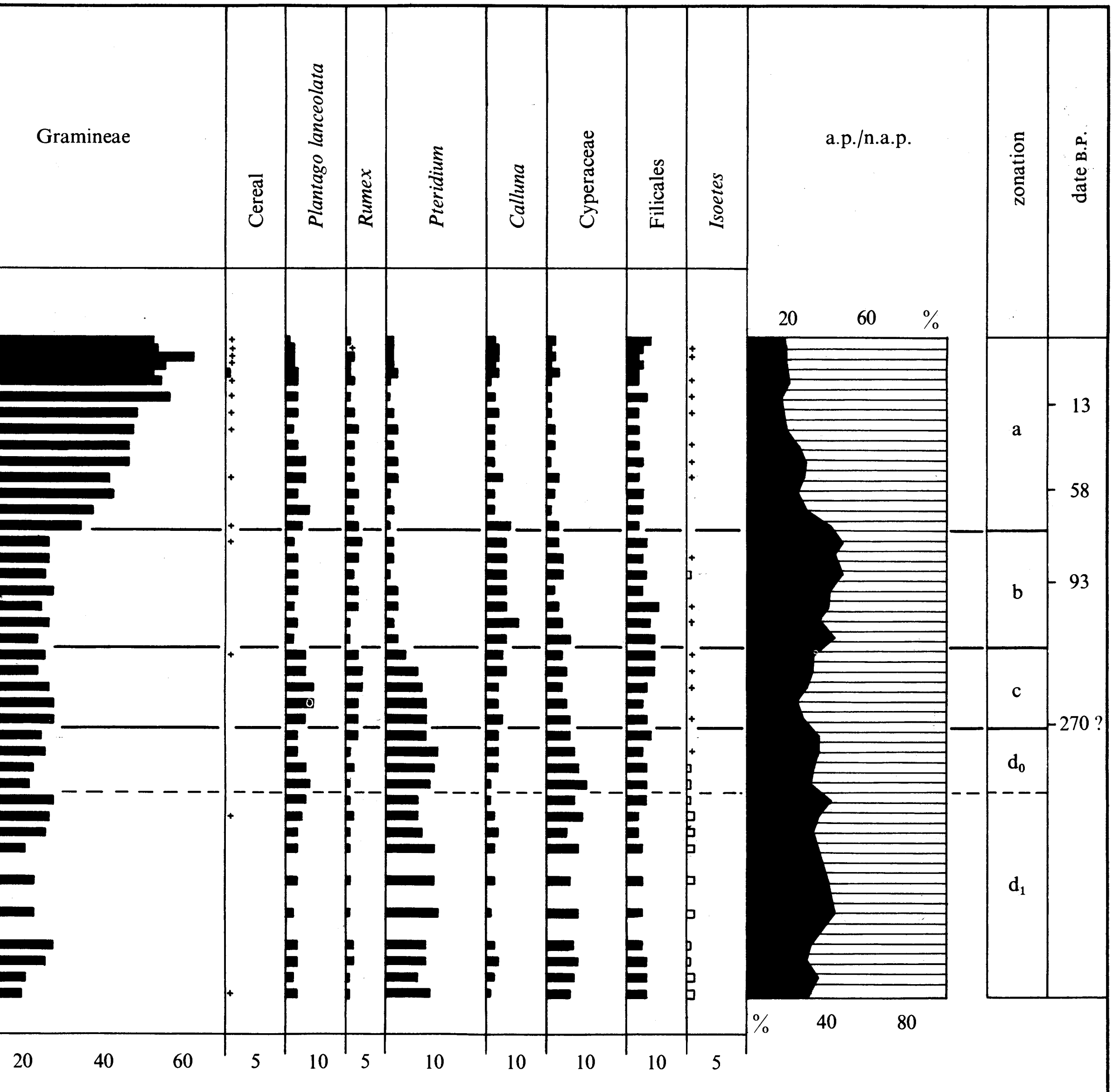


FIGURE 7. Relative pollen diagram for SMiii based on the dry
refer to years B.P. (1969) and are derived from the t



Only selected frequencies are shown.

the dry land pollen sum, excluding *Alnus*. Dates
rom the time–depth data of figure 19.

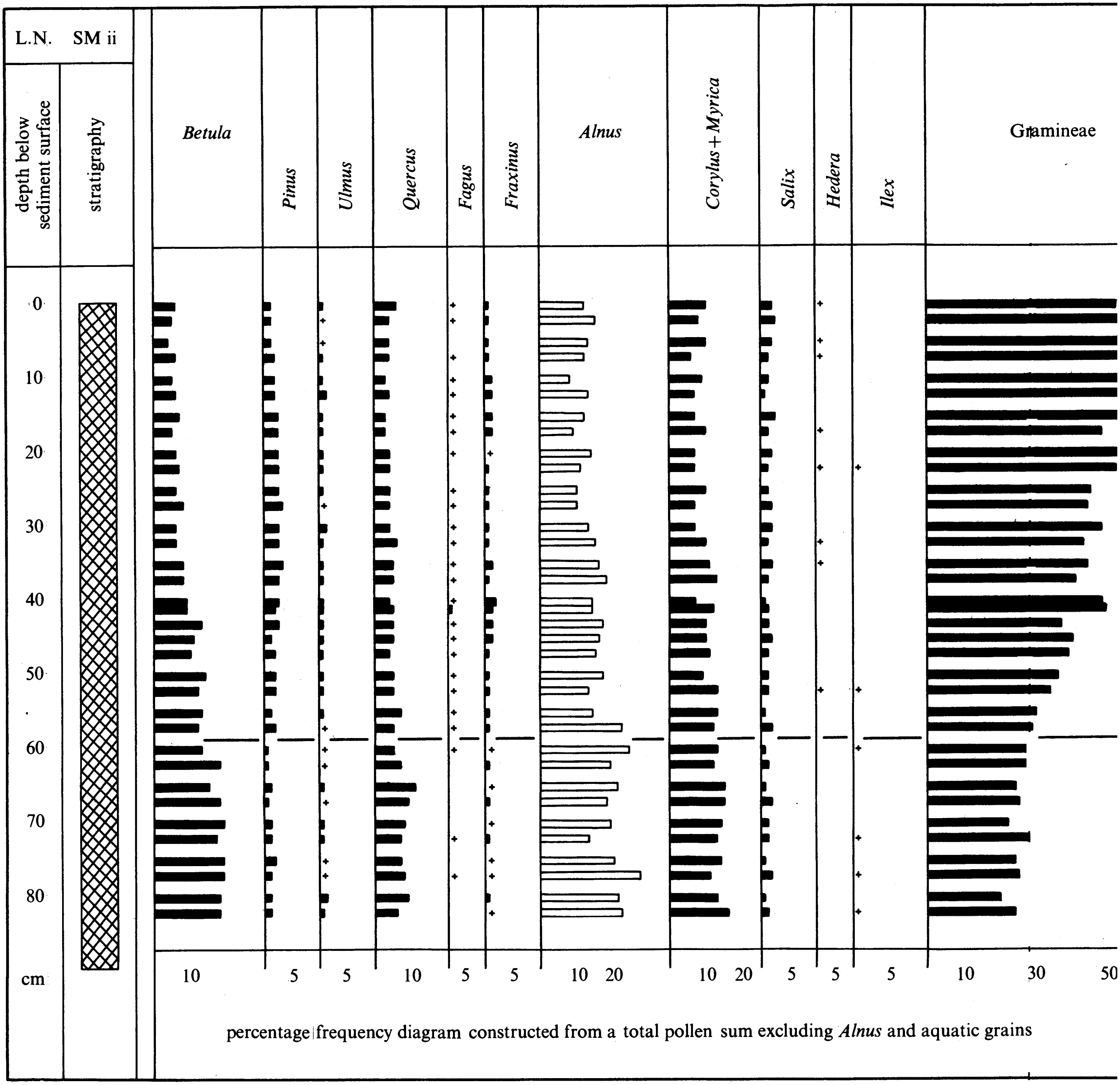
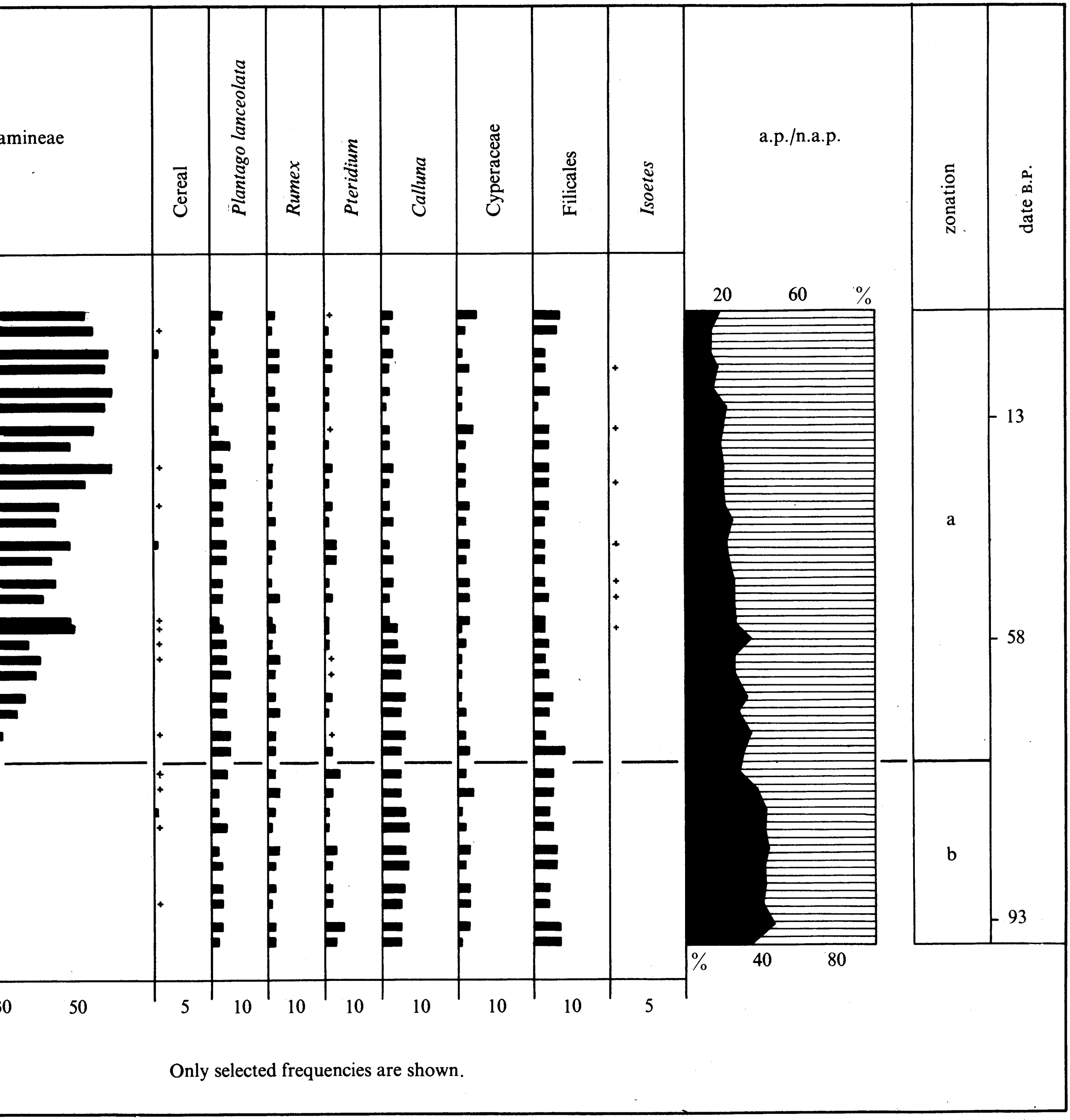


FIGURE 9. Relative pollen diagram for SMii, based on the dr
refer to years B.P. (1969) and are derived from th



Only selected frequencies are shown.

on the dry land pollen sum, excluding *Alnus*. Dates
d from the time–depth data of figure 19.

changes which could be identified in all diagrams were considered important enough to be designated as zone boundaries.

(*c*) *Diagram description*

L.N. SMiii (figures 6 and 7)

Assemblage zone d (> 82–50 cm). The unifying feature of zone d is its high percentage values for the pollen of *Quercus*, being between 35 and 45 % of the tree pollen, and about 10 % of the total pollen. The zone, however, is divided into two subzones d_0 and d_1.

Subzone d_1 (> 82–57 cm) is largely defined in the tree pollen sum diagram (figure 6) on the basis of its high *Betula* values (more than 50 %), low *Calluna* values (*ca.* 5 %), and relatively low *Plantago lanceolata* values (*ca.* 10 %). The relative abundance of *Isoetes* spores is also a feature of the subzone.

The d_1/d_0 subzone boundary occurs at 57 cm and is marked by a drop in the frequency of *Betula* pollen, clearly seen in both total and tree pollen sum diagrams.

In the three pollen sum diagram there is a large reciprocal increase in the frequency of *Quercus* pollen, but this is not apparent in the total pollen sum diagram where *Quercus* values remain constant over the boundary. The most significant feature of subzone d_0 (57–50 cm) is the large but temporary increase in the frequency of *Plantago lanceolata* pollen. This is accompanied by an increase in *Calluna* percentages and by the virtual disappearance of *Isoetes* spores. At the end of the subzone, the *Plantago lanceolata* values have declined to their former level.

Assemblage zone c (49–39 cm). The boundary between zones d and c is abrupt and involves a marked change in the percentages of a number of taxa. The most significant change is the decline in the *Quercus* curve. In the total sum diagram its percentage value is more than halved, while in the tree pollen sum diagram there is a fall from 40 to 30 %. The rise of the *Betula* values at this level is again seen as a reciprocal change due to the small number of taxa in the tree pollen sum. In fact, the *Betula* values at this level decline slightly in the total pollen diagram. Concomitant with the *Quercus* decline is a strong rise in the frequency of both *Plantago lanceolata* and *Rumex* pollen, and a further rise in the *Pteridium* values (absent from the total pollen diagram) and there is a small but consistent rise in the Gramineae curve throughout the zone.

From the middle to the end of the zone-period there is a rapid decrease in the percentage of *Pteridium* spores while *Plantago lanceolata* and *Rumex* values remain high. The a.p./n.a.p. ratio curve shows that the a.p. % reaches a new minimum of 25% during this zone, but its value increases towards the end of the period, consequent upon the decline of the *Pteridium* and Cyperaceae frequencies.

Assemblage zone b (39–25 cm). A high percentage of tree pollen is the characteristic feature of zone b. The a.p./n.a.p. ratio shows the increased importance of this sort of pollen with the a.p. proportion reaching a maximum of 50 % shortly before the end of the period.

The period begins with the stabilization of *Pteridium* spore percentages at low values, and with much reduced values for *Plantago lanceolata* and *Rumex* pollen. There is also a small but distinct decrease in the Gramineae values in the tree pollen diagram, and reductions in the values for *Filipendula*, and Compositae (Lig.) pollen. These relatively low percentages for the herb pollen types persist throughout the zone. On the other hand, values for *Betula* are high throughout, and there is a marked recovery of the pollen of *Quercus* especially noticeable in the total pollen diagram.

Assemblage zone a (25–0 cm). The boundary between zone b and zone a is well marked by the rapid increase in the frequency of Gramineae pollen, and the decrease in that of *Betula* pollen. Both features are evident in both types of diagram. There is also an expansion in the frequency of *Pinus* pollen at this level seen most clearly in the tree pollen diagram. Since the increase is not as marked in the total pollen diagram, it is perhaps partly due to reciprocity between *Betula* and *Pinus*. The pollen of *Fraxinus* emerges in this zone as an important tree type, and there are almost continuous records of the presence of *Fagus*. *Plantago lanceolata* pollen values increase while those for *Calluna* decrease. The *Calluna* decrease is seen best in the total pollen diagram. There is little change in the frequency of *Rumex* pollen and *Pteridium* spores, although *Pteridium* values increase later in the period (20 cm). This zone also shows increases in the frequencies of many other herb pollen types such as the Compositae group, Caryophyllaceae, *Filipendula*, Leguminosae, Rubiaceae, and Umbelliferae.

The Gramineae proportion of the total pollen increases rapidly at the beginning of this period, and continues increasing to a maximum at 9 cm where it represents 55 % of all pollen in the sum, and almost 400 % of the total tree pollen sum. The increase in the grass pollen is mirrored in the a.p./n.a.p. ratio curve where the n.a.p. types expand to account for over 80 % of all pollen.

L.N. SMii (figures 8 and 9)

Although core SMii contained the same depth of sediment as SMiii, only zones a and b are present. This is due to the faster accumulation rate of the SMii sediment. Nevertheless the changes recorded in the SMii diagrams are substantially the same as for the equivalent time period of the SMiii diagrams.

Assemblage zone b (> 82–59 cm). A comparison of the SMii and SMiii diagrams suggests that the c/b zone boundary would occur in SMii at a level slightly below 82 cm. Zone b in SMii is more extended than in SMiii but records more or less identical spectra of pollen values.

Assemblage zone a (42–0 cm). The boundary changes between zones b and a closely agree with the changes already described for this boundary in SMiii. The values for *Betula* fall rapidly but less abruptly, and those for *Pinus* increase. The increase in Gramineae is also more gradual. The more gradual changes for this boundary in SMii are due to the much faster accumulation rate of the sediment. The Gramineae percentages increase throughout the zone.

4. Diatom analysis

(*a*) *Introduction*

Diatom analyses were carried out on a number of cores including the cores for which pollen diagrams were available, namely SMiii and AB3. In this way the need for stratigraphic correlations in the comparison of diatom and pollen diagrams was avoided. Other cores were analysed to produce additional biostratigraphic information (§5) and to help to assess the variability of the diatom record in the lake. SMiii was a mini-core taken from Antrim Bay (figure 4) and has a relatively slow accumulation rate; AB3, a 3 m core, was also from Antrim Bay but had a more rapid accumulation rate in its upper metre; SMi was a mini-core from the Battery area with a relatively rapid accumulation rate; and SMvi was taken in the Trench area of the lake and also has a relatively rapid accumulation rate.

Both relative and absolute diatom counts were made. Relative counts were carried out on all cores and were aimed at determining the structure and succession of the fossil diatom assemblages in the sediment. Absolute counts were made in order to attempt to estimate changes in diatom palaeo-productivity. Mini-core SMiii was selected as the main core for this part of the investigation.

Camera lucida drawings, light micrographs (plate 1) and stereoscan electron micrographs (plates 2 and 3) were made of most of the abundant planktonic taxa found in the sediment. Identifications were made with the help of the floras of Hustedt (1930, 1930–66) and of Cleve-Euler (1951–53). A list of taxa and micrographs of the more common taxa are presented in the appendix.

Certain taxonomic problems, however, were encountered. In the case of *Tabellaria* the revision of Knudson (1952) has been followed, and the individuals present were all referred to *Tabellaria flocculosa*. Colony morphology is lost upon deposition in the sediment and therefore does not assist species distinction in fossil *Tabellaria* populations. Nevertheless it is clear from early algological records from Lough Neagh that *Tabellaria fenestrata* var. *asterionelloides* (Grun) was extremely abundant in the plankton (West & West 1902, 1906; Dakin & Latarche 1913). Knudson (1952) has renamed this *Tabellaria flocculosa* var. *asterionelloides*, and since all the individuals in the sediment can be referred to the same type the general designation *T. flocculosa* is considered appropriate.

In the case of *Stephanodiscus* two species were encountered for which no reference could be found in the literature. These species have been designated *Stephanodiscus* sp. A and B respectively. *Stephanodiscus* sp. A (diam. 7 μm) can probably be included in the *S. astraea* var. *minutula* group but in the Lough Neagh situation it requires separation from another form of *S. astraea* var. *minutula* (diam. 14 μm) (appendix). *Stephanodiscus* sp. B is also a very small species (diam. 7–8 μm). Its structure is indistinct in the light microscope and so far it has not been possible to examine it with the s.e.m. A number of light micrographs are shown in the appendix.

Broken diatoms were included in the counts. A counting system was adopted whereby only those pieces which contained the valve centre or some other exclusively characteristic feature of the valve were included, e.g. the larger apical inflation in *Asterionella formosa* or the central inflation in *Tabellaria*. In this way the chance of counting the same valve more than once was eliminated.

(*b*) *The relative frequency diagrams*

(i) *Presentation of data*

The succession of planktonic diatoms through the sediment is expressed in percentage frequency diagrams, similar to those used conventionally for pollen studies. The calculated values for the planktonic taxa (+*Navicula cryptocephala*) are represented in the diagrams by horizontal bar lines. The thickness of the bar lines denotes the depth of sediment used in the sample and this can be measured from the vertical axis. In most cases samples 1 or 2 cm thick were used, mainly at 2 cm intervals, although where appropriate, sampling was continuous or more widely spaced.

The non-planktonic species from each core represent only a small fraction of the totals counted (between 3 and 15 %). A list of the frequencies of these taxa (−*Navicula cryptocephala*) for core SMiii may be obtained from the author.

Between 300 and 600 diatoms were counted at each level for the purpose of calculating the percentage frequency of each taxon. The sum used included all types of diatoms since the non-planktonic proportion was never sufficiently large to obscure planktonic fluctuations.

(ii) *Zonation of the diagrams*

The principles used in zoning the diatom microfossil diagrams are the same as those used above for pollen diagrams. However, unlike the pollen zones the diatom zones and subzones are named after the characteristic species of the zone, e.g. *Cyclotella – Tabellaria flocculosa* zone. They have also been allocated symbols for purposes of abbreviation. The order and type of symbol follows the scheme described for pollen except that all diatom zones are prefixed by a capital 'D'. For example, the uppermost diatom zone is designated Da.

(iii) *Description of diagrams*

All cores analysed show remarkably close agreement, and only one core (SMiii) will be described in some detail, while the results from the other cores will be described only in so far as they differ from core SMiii. The diagram from this core and a preliminary description of it has already been presented (Battarbee 1973*b*). It is reproduced here and described in a more detailed way since it has been used as a standard core for the lake, and since the revised chronology has necessitated a reinterpretation of some of its features.

L.N. SMiii Antrim Bay (figure 10)

Zone Dd (Melosira italica *subsp.* subarctica *zone*) (> 82–49 cm). Throughout this zone the percentage frequency of all the main diatom species is quite constant. The dominant taxon is *Melosira italica* subsp. *subarctica*, which accounts for between 60 and 75 % of the valves of all species throughout the zone. Other species of importance are *Cyclotella comensis*, *Stephanodiscus* sp. A, *Tabellaria flocculosa*, and *Asterionella formosa*. *Cyclotella comta*, *C. ocellata*, and *Stephanodiscus astraea* have very low percentage values.

Zone Dc (Cyclotella – Tabellaria flocculosa – Asterionella formosa *zone*) (49–20 cm). The boundary between zones Dd and Dc is marked by a sharp decrease in *Melosira italica* subsp. *subarctica* percentages and a reciprocal increase in the frequencies of *Cyclotella comta*, *C. comensis*, *Stephanodiscus* sp. B and *Tabellaria flocculosa*. The percentage values of these species continue to rise towards the middle of the zone period and reach maximum values between 30 and 35 cm. In addition, at 44 cm the frequency of *Asterionella formosa* increases rapidly, and also reaches a maximum at about 30 cm. While the frequency of *Melosira italica* subsp. *subarctica* is a minimum of 14 % at this level, two new *Melosira* species *M. ambigua* and *M. islandica* subsp. *helvetica* make a brief appearance in the diagram (35–30 cm). Towards the end of the zone. *A. formosa*, *T. flocculosa* and *C. ocellata* begin to show declining frequencies, and the values for *M. italica* subsp. *subarctica* begin to recover.

Zone Db (Melosira italica *subsp.* subarctica – Stephanodiscus astraea *zone*) (20–9 cm). The beginning of zone Db is marked by the fall of *Cyclotella comensis* frequencies and the increase in those of *Stephanodiscus astraea*. During this zone the values for *S. astraea*, which is present at about the 1 % level throughout the preceding zone, gradually expand, while those for *Tabellaria flocculosa* gradually decline. *Stephanodiscus dubius* appears in the diagram for the first time, while *M. islandica* subsp. *helvetica* reappears. Other significant changes during this zone include the reduction to zero of the frequencies of *C. comensis*, *Synedra rumpens*, *Stephanodiscus* sp. B and *Navicula cryptocephala*, an erstwhile important benthic diatom.

Zone Da (Melosira italica *subsp.* subarctica – Stephanodiscus astraea – S. astraea *var.* minutula *zone*) (9–0 cm). Except for *Melosira ambigua*, which is important at the beginning of zone Da,

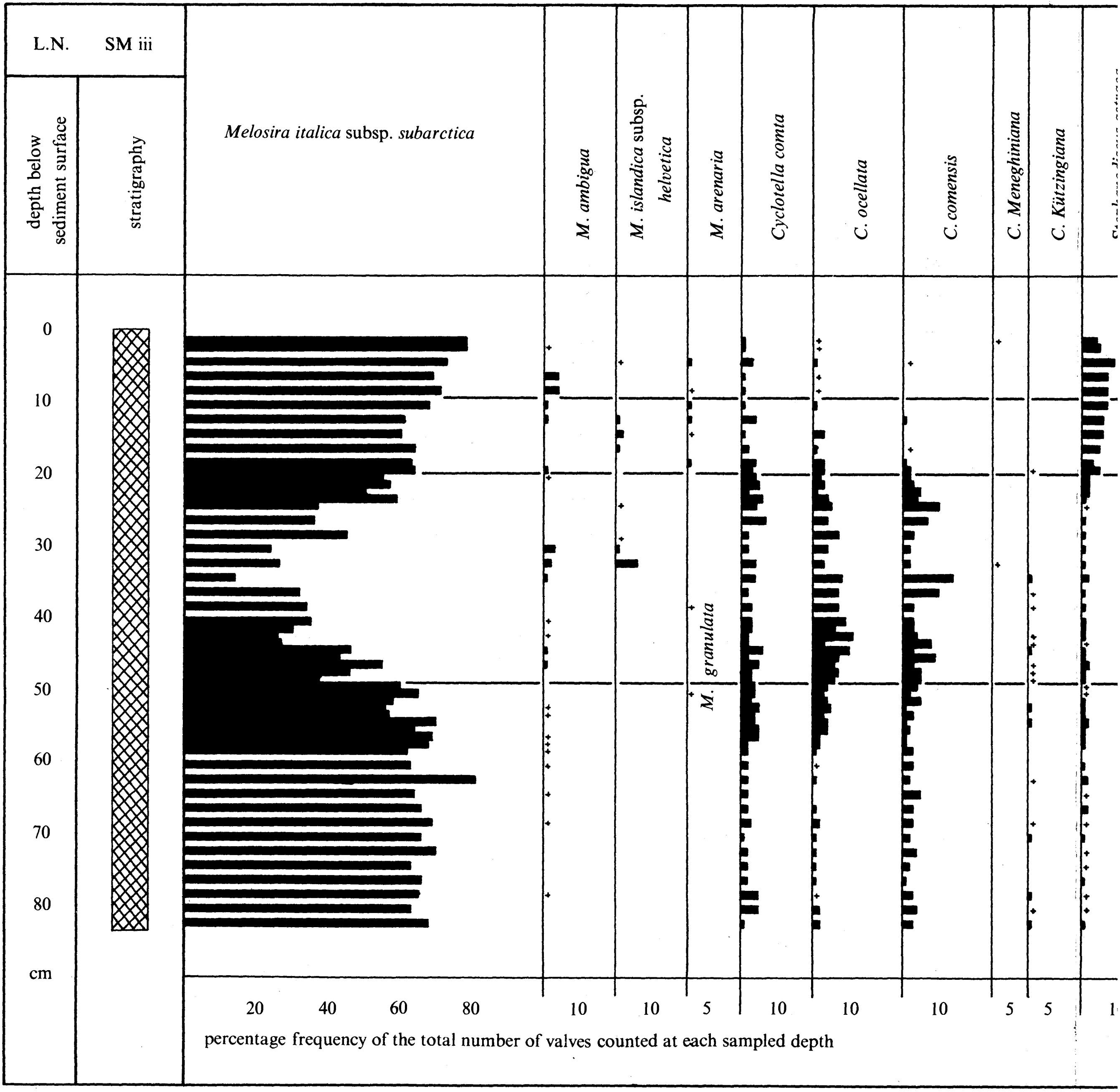
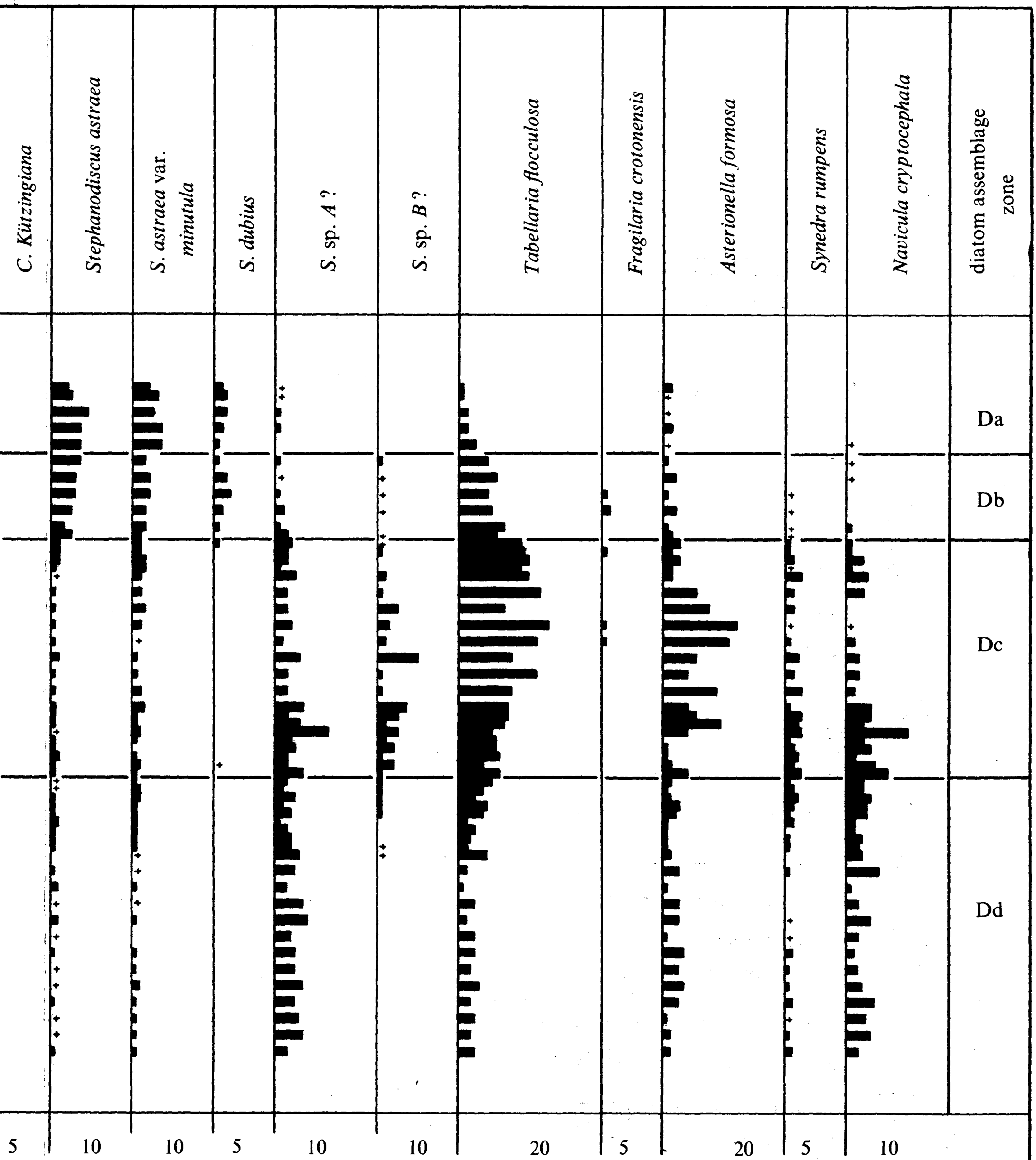


Figure 10. Relative diatom diagram for SM iii (from



Non-planktonic taxa, except *Navicula cryptocephala*, are excluded from the diagram.

iii (from Battarbee 1973*b*).

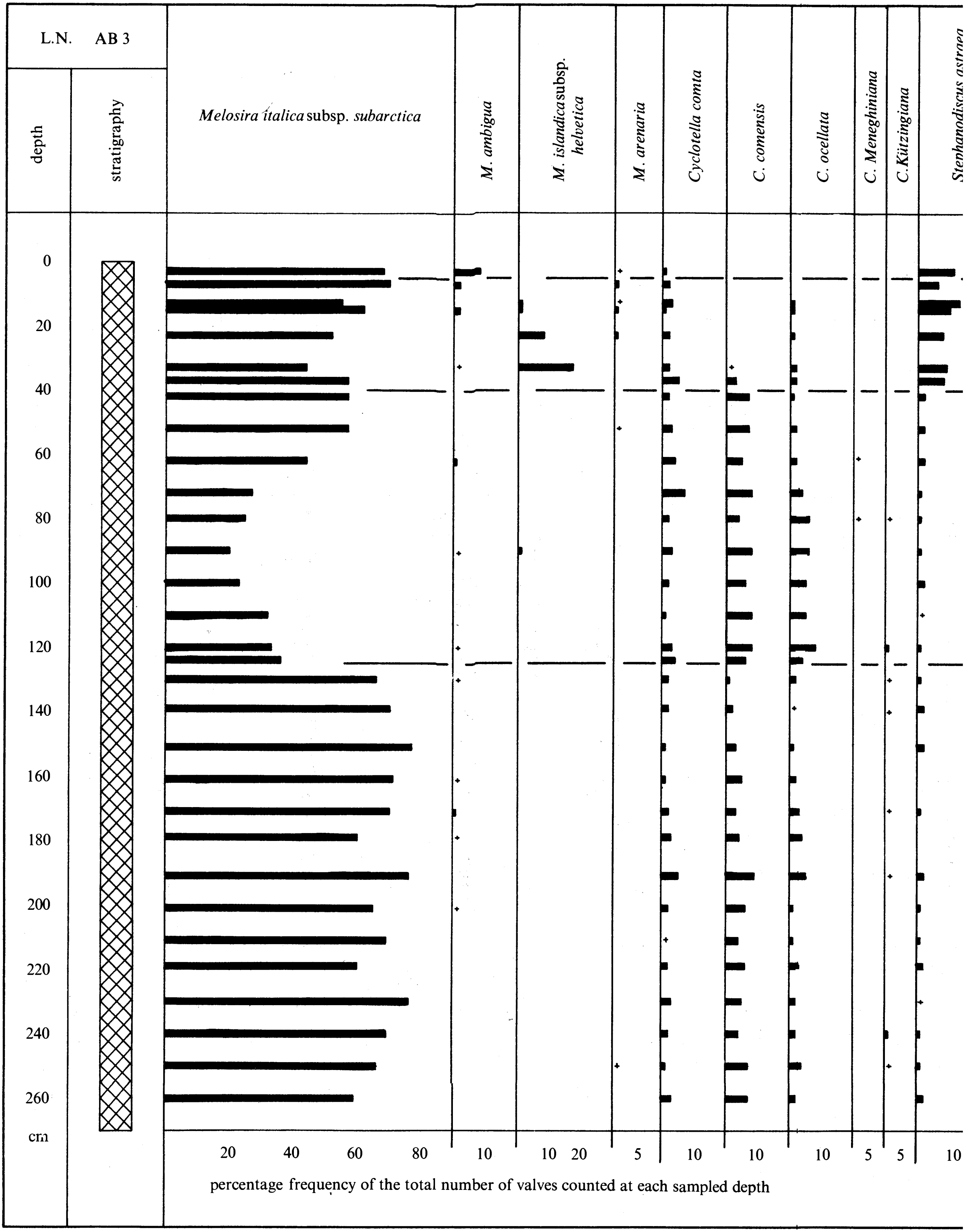
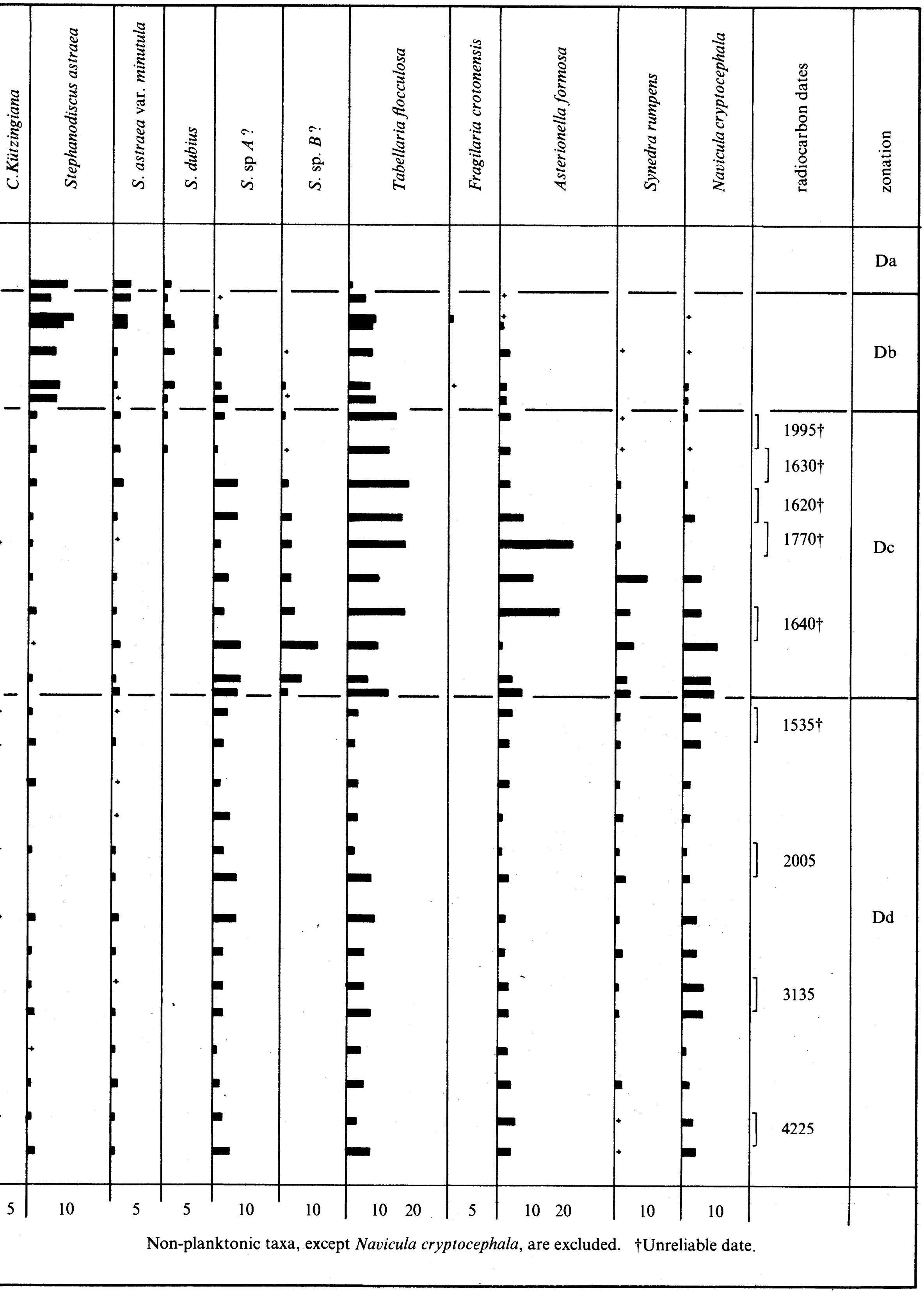


Figure 11. Relative diatom diagram



Non-planktonic taxa, except *Navicula cryptocephala*, are excluded. †Unreliable date.

diagram for AB3.

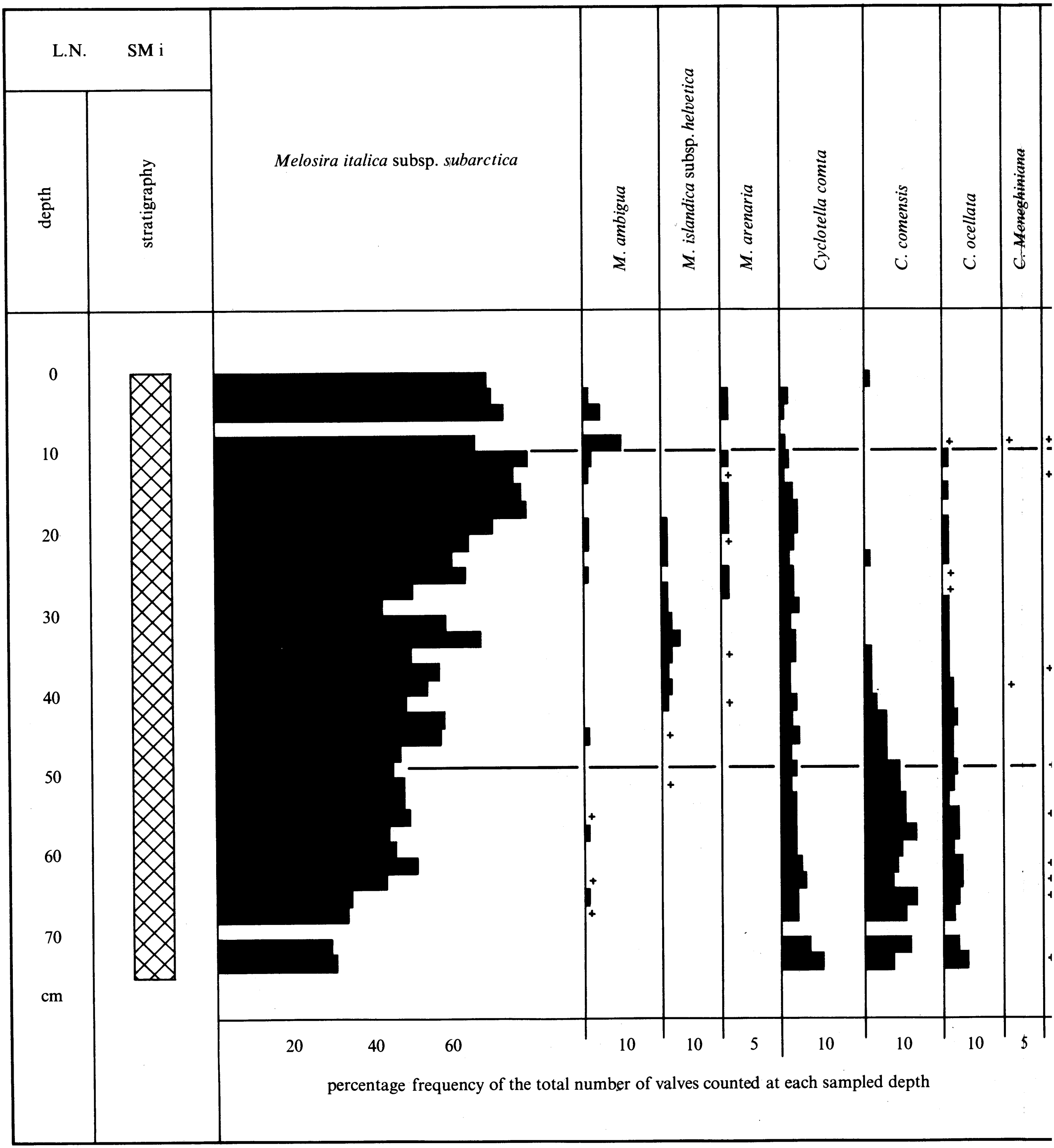
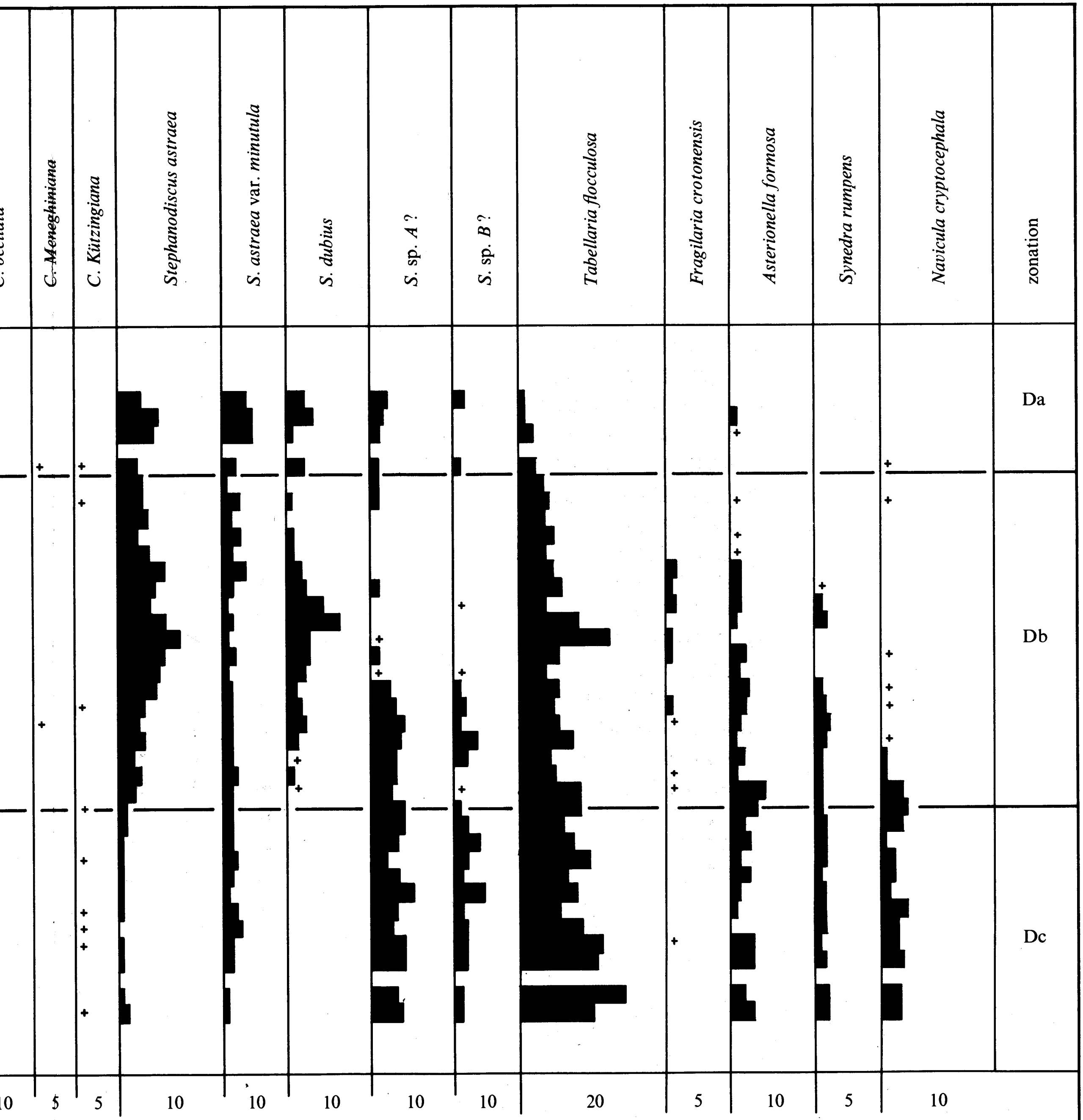


Figure 12. Relative diatom



Non-planktonic taxa, except *Navicula cryptocephala*, are excluded.

ve diatom diagram for SMi.

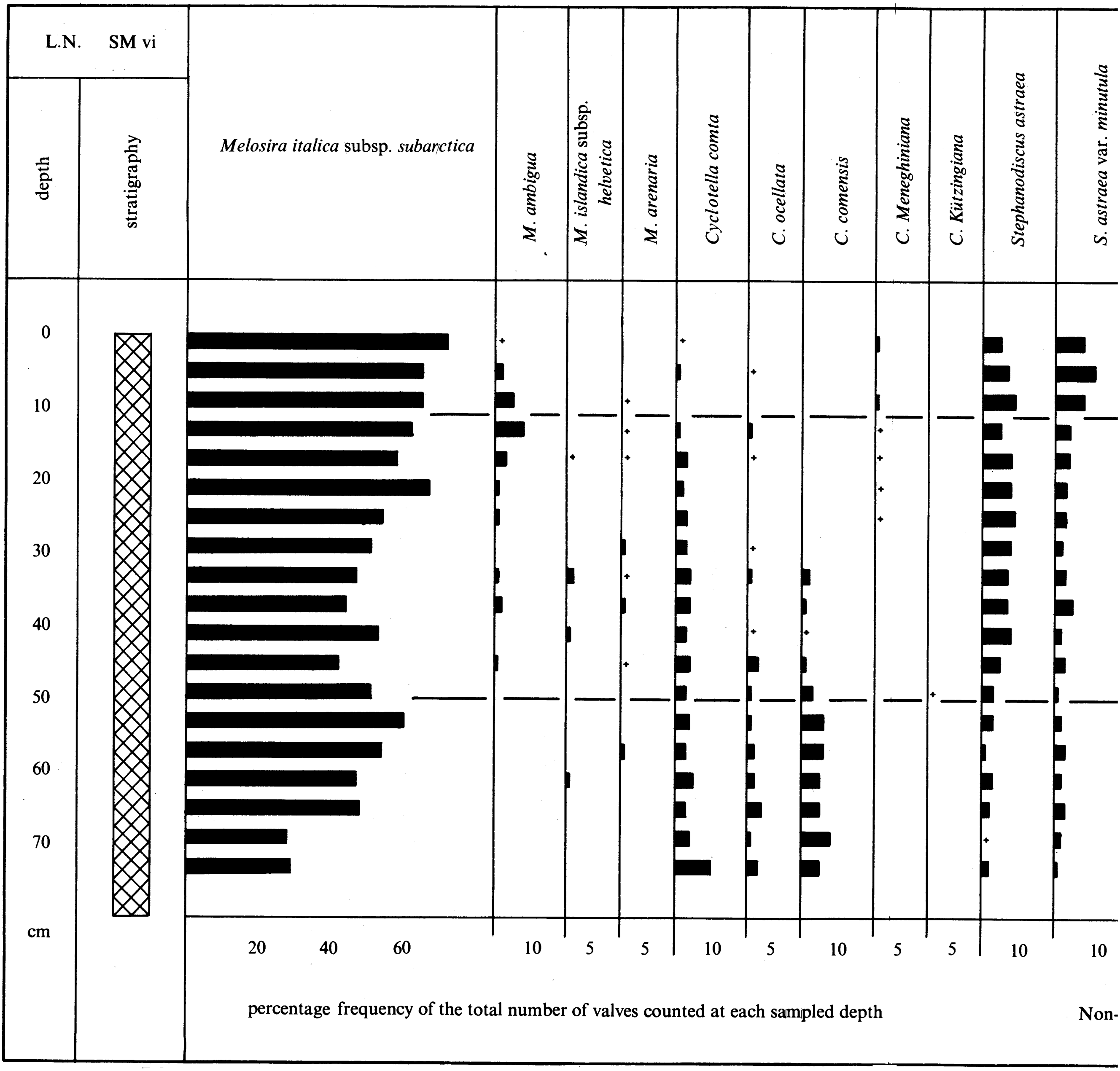
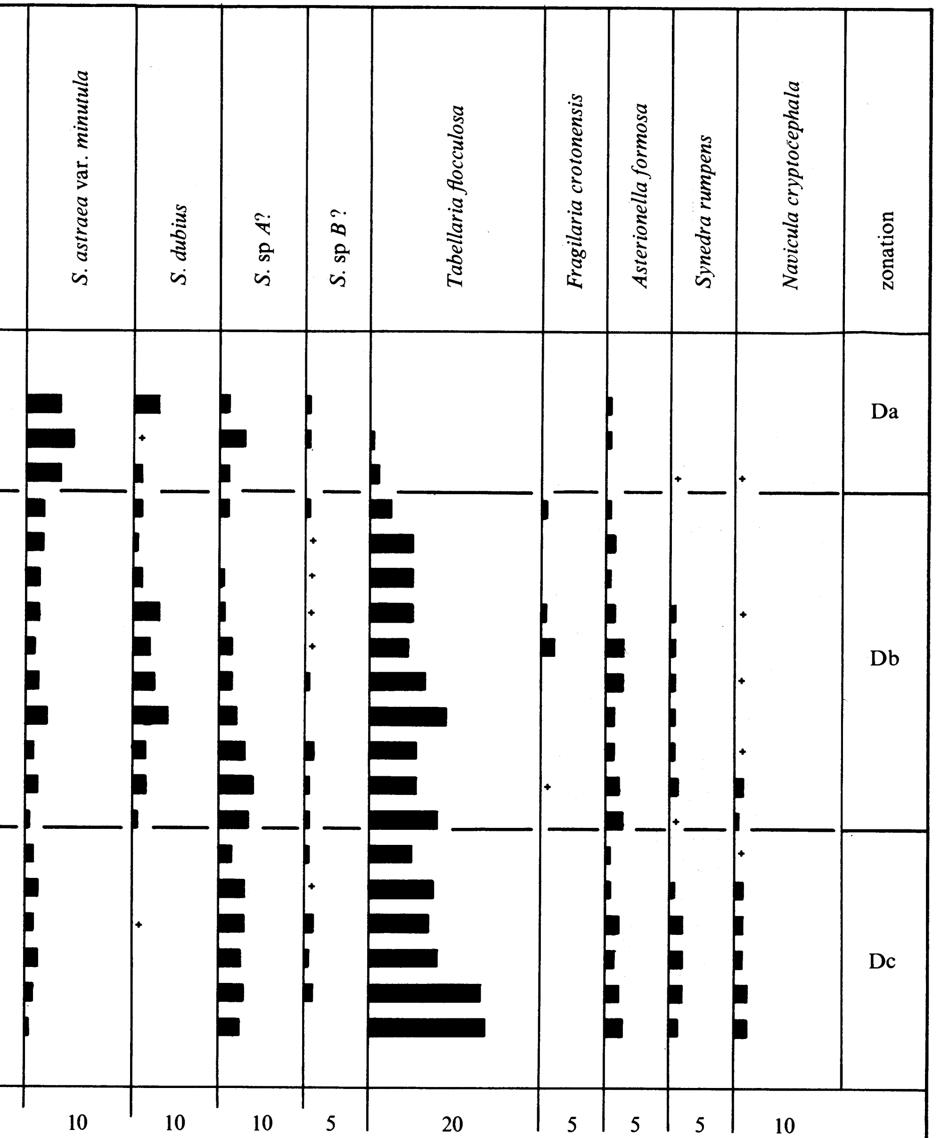


Figure 13. Relative diatom diagram for SMvi.



Non-planktonic taxa, except *Navicula cryptocephala*. are excluded.

for SMvi.

the diatom flora of the top 9 cm bears a strong resemblance to that found in the lake today consisting of very high percentage frequencies of *Melosira italica* subsp. *subarctica*, with the co-dominance of *S. astraea* and *S. astraea* var. *minutula*. Another feature of the zone is the progressive decline of *Tabellaria flocculosa*. In addition to the decrease and virtual disappearance of some species in zone Db (above) other taxa, *A. formosa*, *S.* sp. A, *C. ocellata*, *C. comta* and *M. ambigua* disappear in zone Da. The uppermost 5 cm of the diagram show a diatom assemblage dominated only by the three species diagnostic of the zone.

L.N. AB3 Antrim Bay (figure 11)

Core AB3 was taken close to SMiii in Antrim Bay. This 3 m core, the lower part of which has been ^{14}C-dated, contains a much longer record of lake history than the 1 m cores.

The succession of diatom assemblages shown in the diagram is very similar to the succession described for SMiii. Zone Dd is more extended than in SMiii from more than 260 to 125 cm deep, during which no significant relative changes occur. The change from Dd to Dc is even more marked than in SMiii with a distinct increase in the percentage frequency of all main types except *Melosira italica* subsp. *subarctica*, the proportion of which decreases abruptly between 129 and 123 cm.

Zone Dc extends from 125 to 40 cm, and the changes in the assemblage apparent from the diagram are almost identical with those of SMiii. At the Dc/Db boundary *Cyclotella comensis* declines and *Stephanodiscus astraea* increases, as in SMiii. Zone Db extends from 40 to *ca.* 5 cm and is different from SMiii only in that *Melosira islandica* subsp. *helvetica* assumes greater significance with a peak of 17 % at 32 cm.

While the boundary between zone Db and Da appears paradoxically in AB3 at 5 cm (cf. 10 cm SMiii) it is evident that about 5 cm of the sediment record is missing from the top of the diagram. The *Melosira ambigua* increase for AB3 shows obvious truncation compared with all other diagrams, and in addition the *Tabellaria flocculosa* decrease appears too recent. This truncation is a consequence of taking core AB3 with a full length Mackereth corer, which often misses the top few centimetres, unlike the mini-corer which takes the mud/water interface. The real level of all the samples from this core is therefore approximately 5 cm lower than the levels shown in the diagram.

L.N. SMi Battery (figure 12)

Zone Dd is absent, and a comparison of figure 12 with the diagrams already described (figures 10 and 11) shows that the base of SMi is located about midway through zone Dc, where *Melosira italica* subsp. *subarctica* is at a minimum. The proportions of species throughout the zone is identical to the record from Antrim Bay.

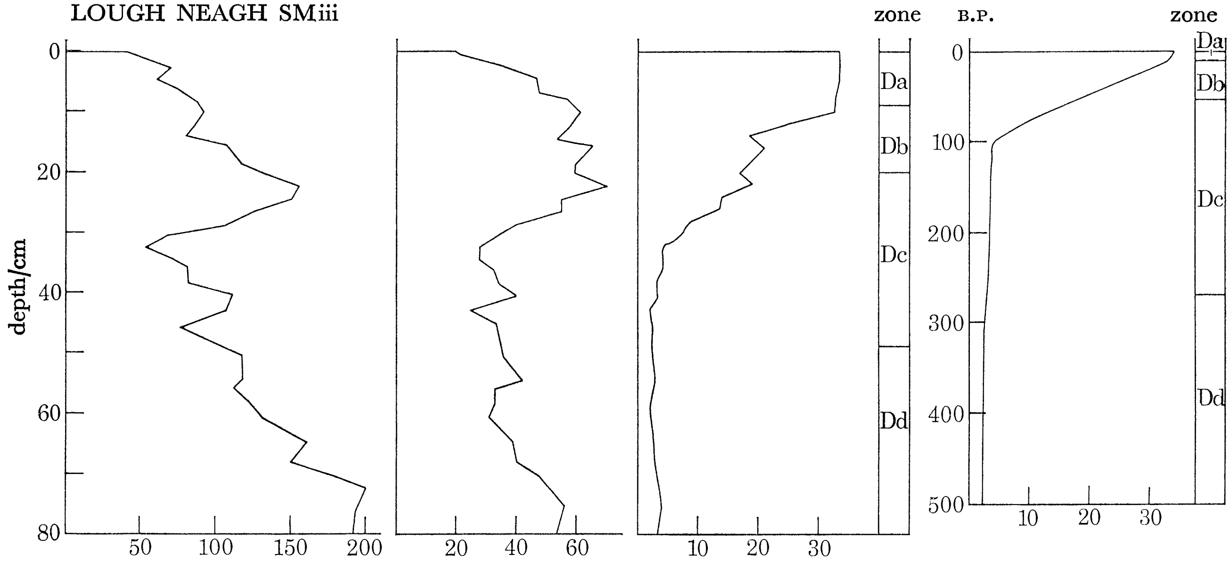
The Dc/Db boundary occurs at 49 cm and is characterized, as in the previous diagrams by a fall in *Cyclotella comensis* frequencies, an increase in *Stephanodiscus astraea* frequencies and the appearance of *S. dubius* and *M. islandica* subsp. *helvetica* in the diagram. Zone Db extends from 49 to 10 cm, and shows the changes that occur in a more detailed way than the cores from Antrim Bay. There is a peak in the frequency of *S. dubius* at 26 cm, and the suggestion of a peak of *S. astraea* somewhere between 30 and 25 cm, with percentages declining towards the end of the zone, before the secondary increase in zone Da.

At 10 cm the increase of the frequency of *S. astraea* var. *minutula* values characterizes the beginning of zone Da. *T. flocculosa* values decline to a very low level during this uppermost zone and *S. astraea* and *M. italica* subsp. *subarctica* values are high.

L.N. SMvi Trench (figure 13)

Although the Trench was discounted as a main sampling area one mini-core was taken to discover whether there was any difference in the diatom record and/or the accumulation rate between the Trench and the other sites.

The accumulation rate of SMvi was found to be similar to SMi, and the bottom 24 cm of the core (74–50 cm) relates to the latter part of zone Dc. Zone Db extends from 50 to 11 cm, and shows characteristic changes in the proportions of the various taxa, although *M. islandica* subsp. *helvetica* does not have the same significance as in some diagrams, and the primary peak of *S. astraea* located at 30 cm in SMi does not appear in this diagram. The transition from Db to Da at 11 cm is typical.



(*a*) 10^{-6} × valve number per cm^3 fresh sediment (*b*) cell volume/mm^3 per cm^3 fresh sediment (*c*) total volume influx/(mm^3 cm^{-2} a^{-1}) (*d*) total volume influx/(mm^3 cm^{-2} a^{-1})

FIGURE 14. (*a*) Diatom concentration for core SMiii, converted to (*b*) cell volume per cm^3 fresh sediment (main planktonic taxa only); (*c*) data of (*b*) corrected for accumulation rate and expressed in terms of annual influx plotted against depth; (*d*) annual influx plotted against time.

(*c*) *Absolute frequency data*

While indications of the productivity of the lake in the past may be obtained from the relative composition of the fossil assemblages, more direct evidence can be obtained by counting absolute numbers and calculating the influx of the various taxa and groups of taxa into the sediment. The influx values, however, refer to the annual accumulation of cells at the point on the sediment surface from which the core was taken. No attempt was made to estimate mean values by carrying out counts on a number of cores.

Battarbee (1973*b*) presented absolute frequency data for cores SMiii and SMii from Lough Neagh and showed the need to make corrections for differences in cell volume and for changes in sediment accumulation rate in the calculation of diatom influx. The revision of the sediment chronology since then has indicated that accumulation rates in the uppermost sediment are higher than originally appreciated. The earlier data have consequently been recalculated. The results are shown in figure 14, where (*a*) and (*b*) show cell number and cell volume against depth and (*c*) and (*d*) show the result of the accumulation rate correction.

The influx in figure 14 appears constant during most of the early part of the curve. In the upper part, however, from about 28 cm there is evidence of a significant increase and the top few centimetres show a second large increase. Figure 14*d* shows the same data plotted against time, and emphasizes the contrast between former and contemporary influx volumes.

From the percentage frequency data for SMiii (figure 10) the absolute volumes of the individual taxa cm^{-2} a^{-1} can also be calculated. The curves for the most important taxa are plotted in figure 15*a* and *b*. Comparisons of these diagrams with the total volume influx curve, and with the percentage frequency diagrams for SMiii should be made. In most instances a change in absolute volume totals of the various taxa is associated with a change in relative proportions, but there are a number of important differences. First, the top 5 cm show little change in the relative proportions of *Melosira italica* subsp. *subarctica* and *Stephanodiscus astraea* (figure 10), but figure 15 shows dramatic increases in their influx. Secondly, the greatest volume of *Tabellaria flocculosa* valves in the diagram appears after rather than at the same time as its peak in relative importance, and thirdly, the marked changes in the total volume curve (figure 14*c*) discussed above at 28 and 5 cm do not directly correspond to the marked changes of species composition in the relative diagrams (i.e. 20 and 10 cm).

5. BIOSTRATIGRAPHY, CHRONOLOGY, AND ACCUMULATION RATES

(*a*) *Biostratigraphy*

In the absence of clear lithostratigraphic changes in the uppermost sediment, core correlation, and the assessment of variations in accumulation rate has been based on biostratigraphic information from pollen and diatom diagrams. In all, 15 cores were used of which 13 were mini-cores and two were 3 m cores. The pollen zonation of the two 3 m cores is described in O'Sullivan *et al.* (1973) and the way in which this compares to the pollen zonation used above is indicated in table 3. The diatom zonation has already been described although for biostratigraphic purposes diatom assemblage zone Dc (see figure 10) has been divided at the point where *Melosira italica* subsp. *subarctica* has its minimum (i.e. 34 cm), creating two subzones, Dc_1 and Dc_2.

Although the diatom diagrams all exhibited the same sequence of changes it was clear that there were strong accumulation rate differences between cores and that approximately half had considerably faster accumulation rates than the remainder. Table 1 shows the mean thicknesses of each assemblage zone in each group of cores. While there was substantial variability in the accumulation rate of the 'fast' group, taken as a whole these cores had an accumulation rate 2–3 times faster than the slow group over the period of the upper two zones. However, 'fast' and 'slow' cores occurred with an equal frequency at both main sites and the mean thicknesses for the two sites, 10 km apart, are very similar (table 1). In other words, there is far greater variation within sites than between sites, suggesting that mean accumulation rates, at least throughout the deeper areas of the lake, may be expected to be fairly uniform.

A comparison of the biostratigraphy of the two 3 m cores shows that over the total length of the cores (240 cm) equivalent time periods are represented. Again, however, there is little

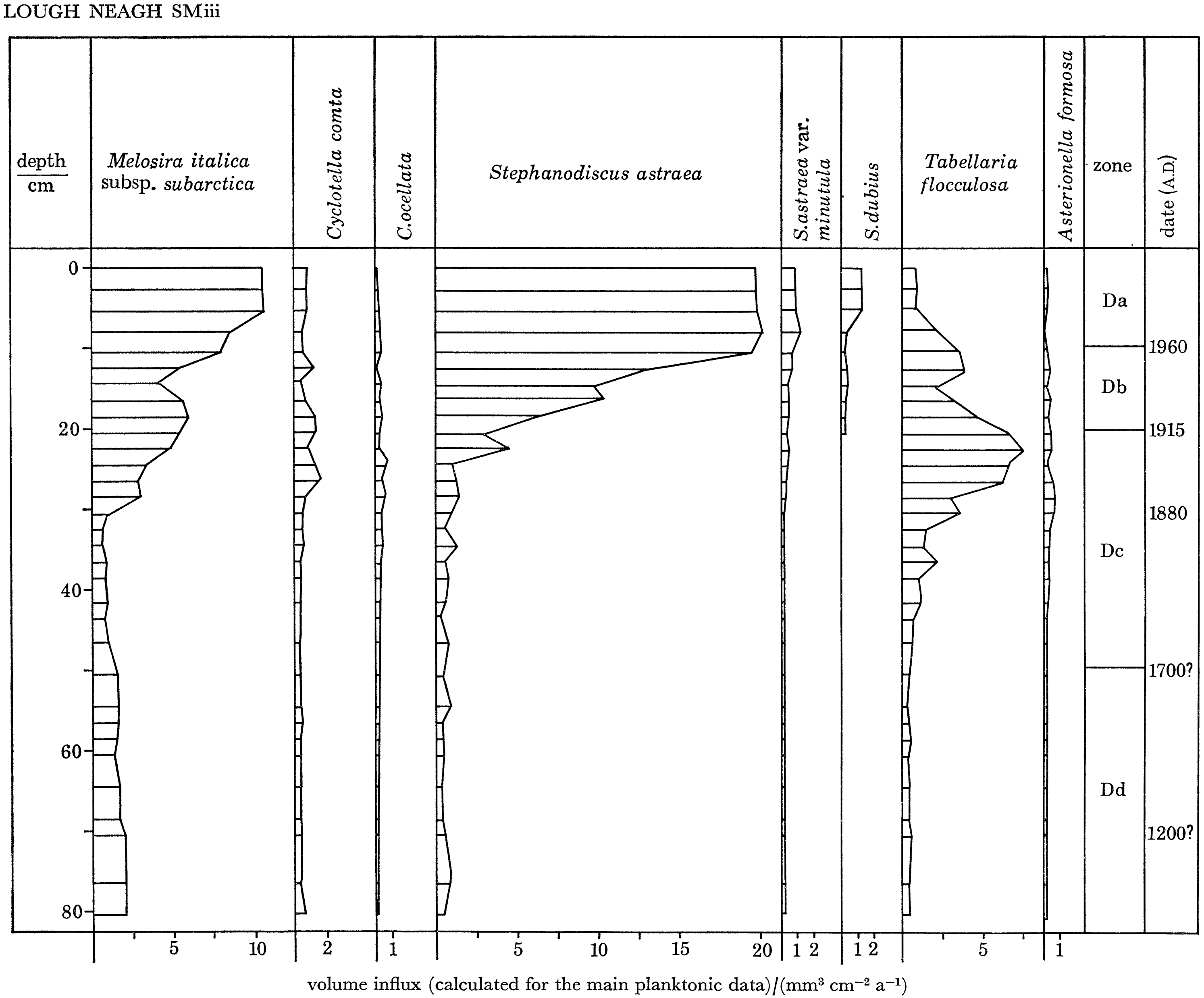


FIGURE 15(*a*). For description see opposite.

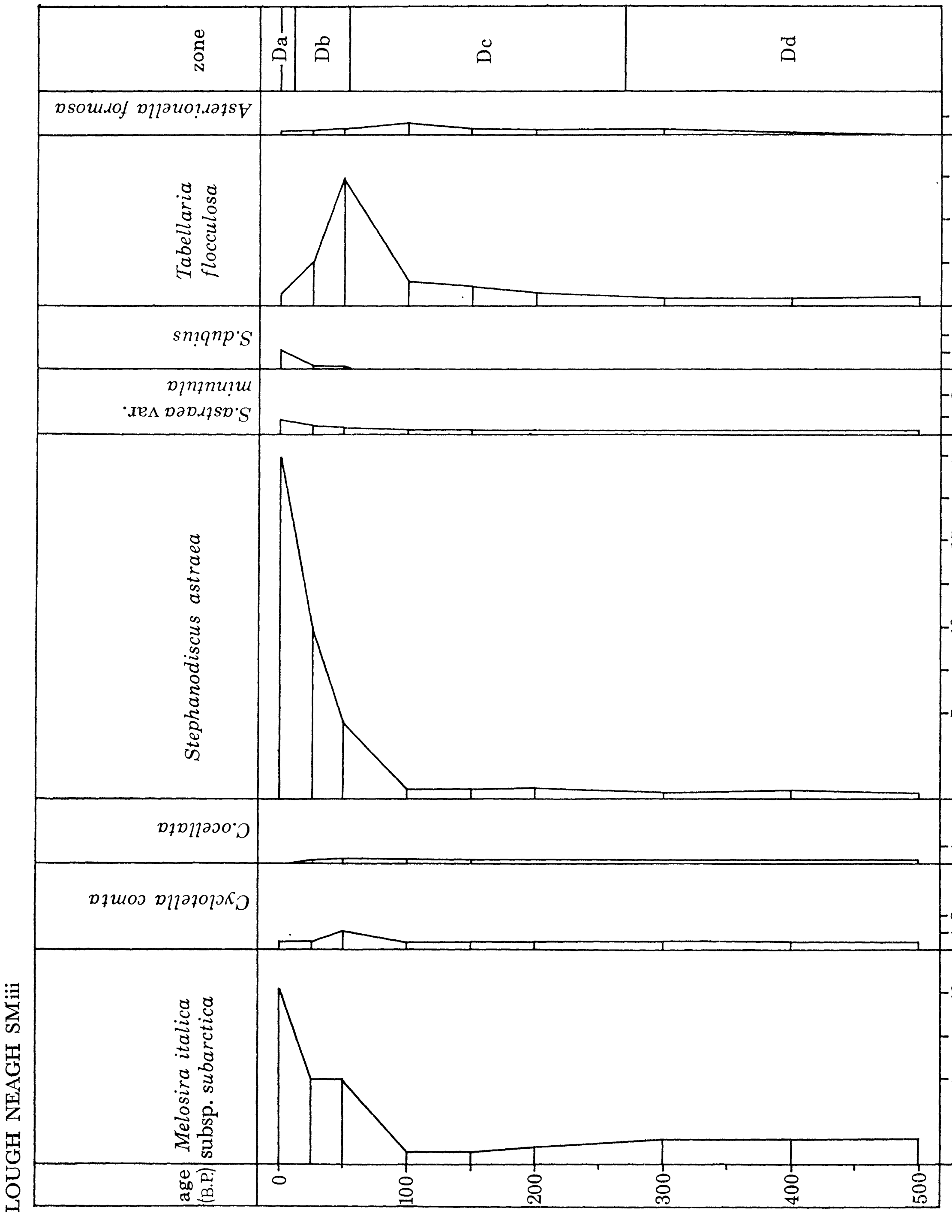


FIGURE 15. Annual influx of selected taxa for core SMiii plotted against (*a*) depth, and (*b*) time.

agreement in the shorter term, with, for example, AB9 accumulating sediment relatively rapidly at a time when a hiatus appears in AB3 (cf. O'Sullivan *et al.* 1973), and AB3 undergoing much more rapid accumulation during zones A, B and C.

It is probable that this pattern of sediment accumulation is characteristic of the lake as a whole. Such fluctuations recorded in time are clearly a consequence of contemporary variations in space. How such variations are caused is not known, but since the water column remains well mixed and the sediment surface in the vicinity of the Antrim Bay and Battery sites has little gradient, it is likely that the variations are related more to post-depositional movements of sediment than to primary sedimentation of material into preferred areas. Such movement would be responsible for producing fluctuating accumulation rates, and, where removal of sediment from one area is not balanced by new net accumulation, for exposing and removing sediment already accumulated. The hiatus of AB3 may therefore be expected as may periods of apparently very slow accumulation at other sites.

TABLE 1. MEAN THICKNESSES (IN cm) OF DIATOM BIOSTRATIGRAPHIC ZONES

(Figures in parentheses refer to number of cores.
F = Fast; S = Slow; AB = Antrim Bay; B = Battery; T = Trench.)

zone	F	S	AB	B	T	mean
Da	12.1 (7)	8.0 (5)	9.6 (5)	10.2 (5)	13.0 (2)	10.4 (12)
Db	41.0 (7)	12.4 (5)	33.8 (5)	20.2 (5)	39.5 (2)	29.1 (12)
Dc_1	29.8 (5)	9.3 (6)	19.0 (4)	17.0 (6)	18.5 (2)	17.8 (12)
Dc_2	35.0 (1)†	19.9 (7)	22.3 (4)‡	21.2 (4)§	—	21.7 (8)‖

† Relates to AB3.
‡ Relates to AB3 and 3 slow cores only.
§ Relates to 4 slow cores only.
‖ Relates to mean of AB3 and 7 slow cores.

(*b*) *Chronology*

Preliminary chronological data, some of a tentative nature, were presented in an earlier report (O'Sullivan *et al.* 1973). Radiocarbon dating was found to be ineffective in dating the uppermost sediment of Lough Neagh and dates derived indirectly from palaeomagnetic and pollen analytical evidence were used. The more recent acquisition of ^{210}Pb and ^{137}Cs dates has indicated errors in this earlier provisional chronology and revisions and extensions to it are made in this paper.

(i) ^{14}C

The results of the ^{14}C dating have already been presented (O'Sullivan *et al.* 1973). Only the three lowermost dates from core AB3 were considered reliable. The remaining dates appeared too old, possibly because of contamination from older carbon derived from eroding soils and peats in the drainage basin.

The three dates used here are as follows:

reference number	$\frac{\text{depth}}{\text{cm}}$	$\frac{\text{age}}{\text{a B.P.}}$
UB-572	168–178	2005 ± 90
UB-573	208–218	3135 ± 105
UB-574	248–258	4280 ± 120

The dates UB-573 and UB-574 were corrected for the 'de Vries' effect by using the Suess Calibration Curve (Suess 1970).

(ii) ^{137}Cs

The results of the ^{137}Cs analyses can be seen in figure 16. It is apparent that B1 and B2 are significantly different from B3 and B4, reflecting strong differences in accumulation rate. The 1963 peak in concentration in both B1 and B2 is clear. In core B1 a significant increase in ^{137}Cs in the sediment corresponding to the 1954 increase in fallout appears to have taken place between 8 and 7 cm, but in core B2 it is not clear whether this occurs between 8 and 7 or 12 and 11 cm. A certain amount of downward transfer of ^{137}Cs may be implied. Cores B3 and B4 have double peaks. The lower of the two peaks may relate to the 1959 maximum in fallout (Cambray *et al.* 1972) and the upper to the 1963 maximum. The 1954 increase does not appear to be represented.

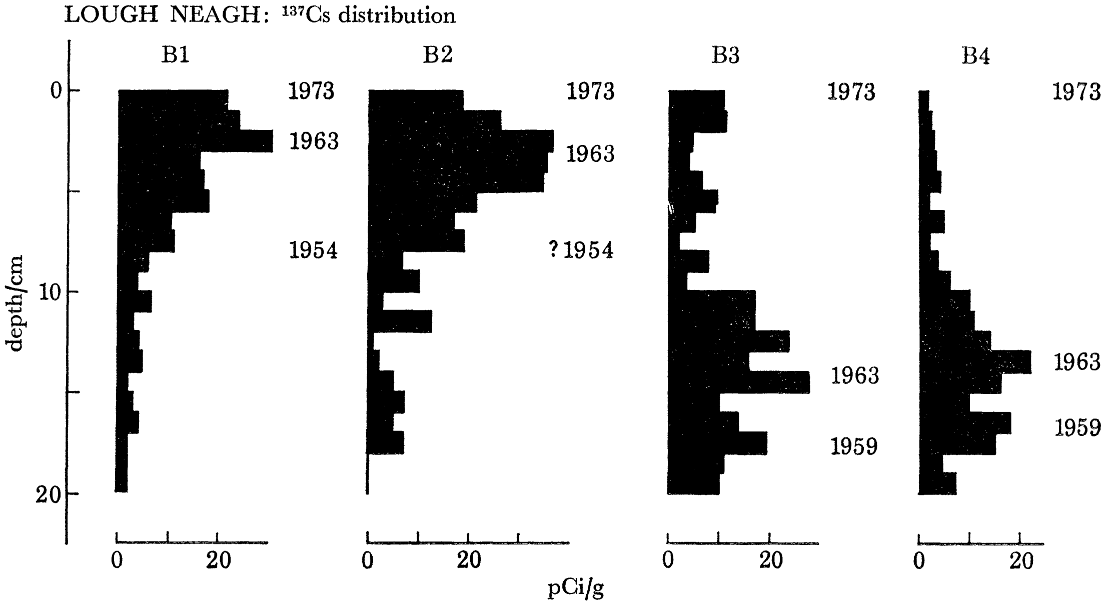


FIGURE 16. ^{137}Cs distribution in the top 20 cm of four cores from Lough Neagh.

A detailed diatom analysis of the top 10 cm of B2 was carried out in order to determine the biostratigraphic position of the ^{137}Cs peak. The diatom diagram and the B2 ^{137}Cs curve is shown in figure 17. If the 1963 level is taken at 4.5 cm depth, this then occurs slightly after the *Melosira ambigua* peak and the *Tabellarea flocculosa* fall, and at about the same time as the beginning of the increase in the frequency of *Stephanodiscus astraea* var. *minutula*. This is slightly after the Db/Da boundary.

(iii) ^{210}Pb

Of the two cores used for ^{210}Pb dating, one (AB46) possessed a relatively high accumulation rate while the other possessed a lower accumulation rate. Because of the rapid accumulation of AB46 the background level of ^{210}Pb is not reached in this core. The analysis, however, gives a detailed series of dates from 1906 to the present day (table 2, figure 18). The B43 data go further back in time and background levels of ^{210}Pb are reached at about 45 cm. The analysis gives a series of dates from about 1840 through to the present day (table 2, figure 18).

Diatom analysis of both cores was carried out to compare the biostratigraphic relations of the dates and to enable transference of the dates to other cores. The stratigraphic boundaries Da/Db and Db/Dc have been drawn in the diagram (figure 18) and the difference in the accumulation rates of the two cores is exemplified by the curves for the frequency of *Stephanodiscus astraea.* The assumed synchroneity of the biostratigraphic boundaries is perfectly confirmed.

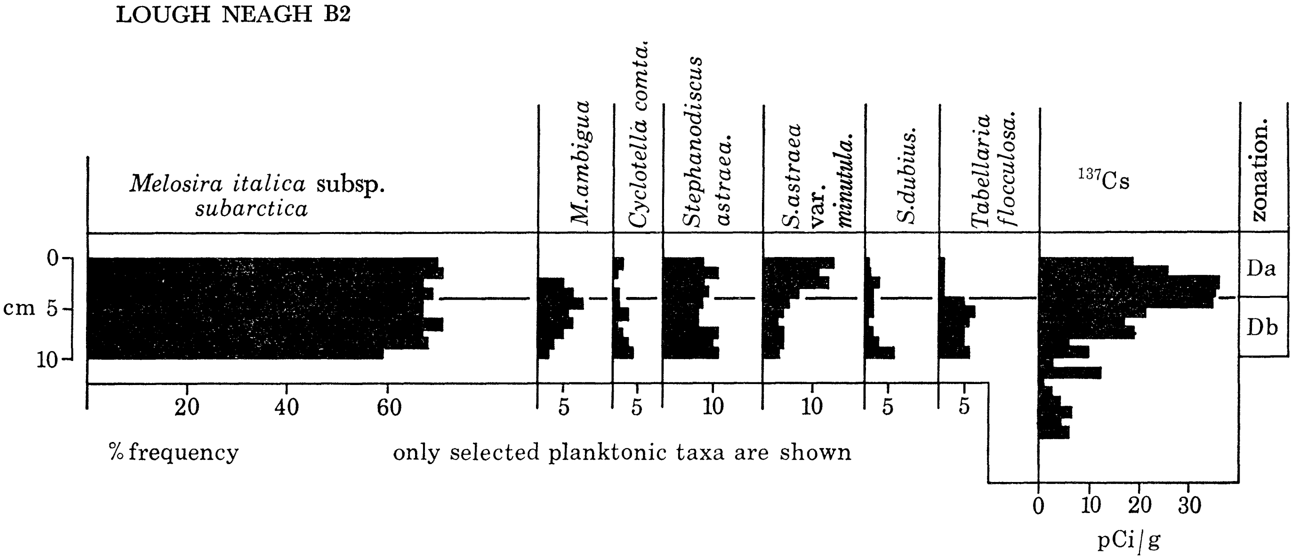


FIGURE 17. Diatom biostratigraphic correlation with the ^{137}Cs peak of core B2.

TABLE 2. ^{210}Pb DATES FOR CORES B43 AND AB46

depth cm	date (A.D.) B43	depth cm	date (A.D.) AB46
4–6	1965 ± 4	12–14	1963 ± 4
12–14	1950 ± 4	16–18	1960 ± 4
20–22	1921 ± 5	20–22	1954 ± 4
24–26	1910 ± 6	24–26	1952 ± 4
32–34	1886 ± 10	28–30	1948 ± 4
40–42	1844 ± 21	32–34	1942 ± 4
		36–38	1937 ± 4
		40–42	1931 ± 5
		44–46	1928 ± 5
		48–50	1924 ± 5
		52–54	1921 ± 5
		56–58	1918 ± 5
		60–62	1909 ± 5
		68–70	1906 ± 5

(iv) *Summary*

By using the biostratigraphic information, ^{137}Cs dates from cores B1–B4 and ^{210}Pb dates from cores B43 and AB46 were transferred to cores AB3 and AB9. Time–depth curves for the two 3 m cores were thereby obtained and are shown in figure 19*a* and *b*.

It is clear from the diagrams that an undated gap exists between the two dated parts of each core. It corresponds to approximately 1850 years. For AB3 the sediment gap is relatively small, about 65 cm; for AB9 the gap is about 130 cm. There is a difficulty in linking the two parts of the curves together since the accumulation rates of the two dated segments are clearly different, and since changes in accumulation rates through time are likely to have occurred during the period of the gap. From a comparison of the AB3 and AB9 pollen biostratigraphy (O'Sullivan *et al.* 1973) the gap is approximately equal to pollen subzone D_3 in AB3, and subzones D_1, D_2, and D_3 in AB9. It appears that AB9 was undergoing continued and relatively rapid accumulation during this time while in AB3 a considerable section of sediment corresponding to D_1 and D_2 is missing. However, the accumulation of D_3 in both cores covers a roughly equal vertical distance and would therefore have accumulated at a similar mean rate.

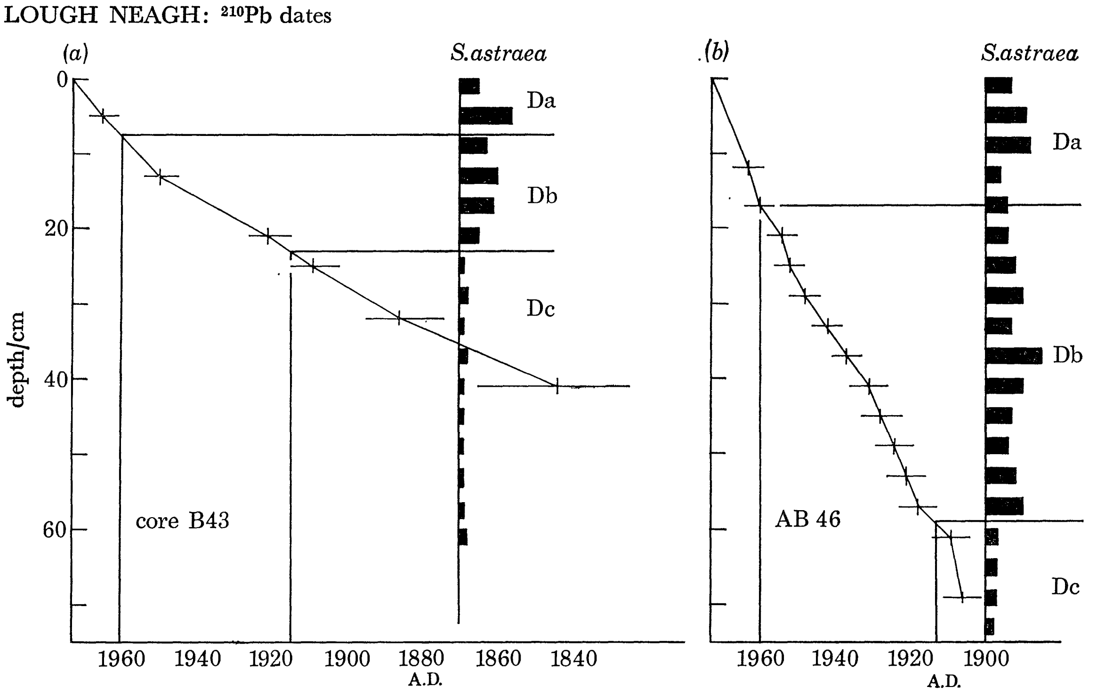


FIGURE 18. ^{210}Pb dates for cores B43 and AB46. The respective curves for the frequency of *Stephanodiscus astraea* with depth are included.

If it is assumed that during pollen zone D the accumulation rate for AB9 was approximately constant, the parts of the curve can be joined together by a straight line. The validity of this assumption is open to question for the reasons given above, but in the absence of other dates it is the only one that can be made, and does represent the line of the mean accumulation rate over the period of the gap. By comparison the possible accumulation pattern of AB3 over the same period can be worked out. The hiatus, equivalent to D_1 and D_2 of AB9, then covers a period of about 1200 years.

From the AB9 and AB3 time–depth curves, the diatom and pollen zone boundaries were dated (table 3). The Dd/Dc diatom zone boundary occurs within the undated section but on the basis of the assumptions used above it can be estimated to occur at about A.D. 1700. The Db/Dc boundary falls within the compass of the ^{210}Pb time-scale and is dated to about A.D. 1915, while the Db/Da boundary occurs at about A.D. 1960.

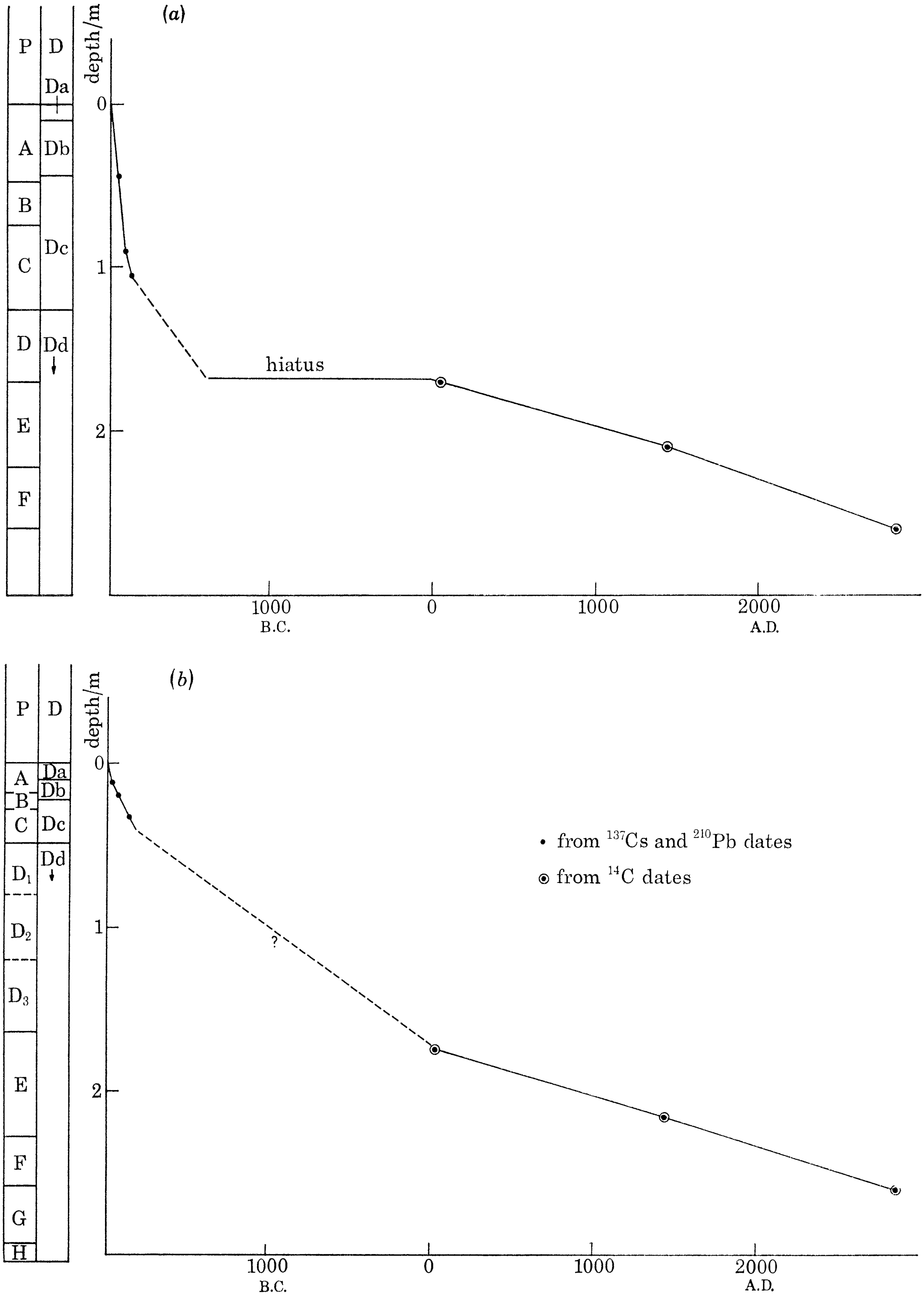


FIGURE 19. Time–depth curves for (*a*) AB3 and (*b*) AB9. The gap between the lowest ^{210}Pb date and the uppermost ^{14}C date is indicated by a dashed line. The two left-hand columns refer to the pollen (based on O'Sullivan *et al.* 1973) and diatom biostratigraphic zonation schemes repectively.

TABLE 3. DATES ASSIGNED TO ZONE BOUNDARIES DERIVED FROM ^{14}C, ^{210}Pb, ^{137}Cs DATES, AND BY EXTRAPOLATION BETWEEN THEM

(Dates are subject to at least the counting errors of the original measurements.)

	zone boundary		assigned age
diatom	Da/Db		A.D. 1960
	Db/Dc_1		A.D. 1915
	Dc_1/Dc_2		A.D. 1880
	Dc_2/Dd		A.D. 1700?
pollen	—	a/b†	A.D. 1890
	—	b/c	A.D. 1800?
	C/D_1‡	c/d_0	A.D. 1700?
	—	d_0/d_1	A.D. 1620?
	D_1/D_2	—	A.D. 1200?
	D_2/D_3	—	A.D. 500?
	D_3/E	—	50 B.C.
	E/F	—	2100 B.C.

† Pollen zonation symbols used in the present study.
‡ Pollen zonation symbols used by O'Sullivan *et al.* (1973).

(*c*) *Accumulation rates*

From the chronological information, the accumulation rate of the individual zones of all analysed cores was determined and mean accumulation rates for each zone were then calculated (table 4). The change in mean accumulation rate with depth and with time is shown in figure 20. The curves suggest that substantial increases in the rate have taken place over recent centuries, from about 0.08 cm a^{-1} in 1700 to a calculated rate of 0.93 cm a^{-1} at the present time. However, allowing for compaction of the uppermost sediment, the current mean rate is probably closer to about 0.8 cm a^{-1}.

TABLE 4. MEAN ACCUMULATION RATES (cm a^{-1})

(F = Fast; S = Slow; T = Total. Numbers in parentheses refer to number of cores analysed.)

	$\bar{X}$ (F)	$\bar{X}$ (S)	$\bar{X}$ (T)
diatom zones			
Da	1.1 (7)	0.73 (8)	0.95 (15)
Db	0.91 (7)	0.28 (8)	0.65 (15)
Dc_1	0.85 (5)	0.28 (8)	0.51 (13)
Dc_2	0.19 (1)	0.11 (8)	0.12†
Dd	0.09 (1)	0.07 (1)	0.08 (2)
pollen zones			
D_1	0.09 (1)	0.07 (1)	0.08 (2)
D_2	—	0.07 (1)	0.07 (1)
D_3	—	0.07 (1)	0.07 (1)
E	0.03 (1)	0.03 (1)	0.03 (1)
F	0.03 (1)	0.03 (1)	0.03 (2)
G	—	0.03 (1)	0.03 (1)

† Calculated from mean of $\bar{X}$ (F) and $\bar{X}$ (S) for Dc_2.

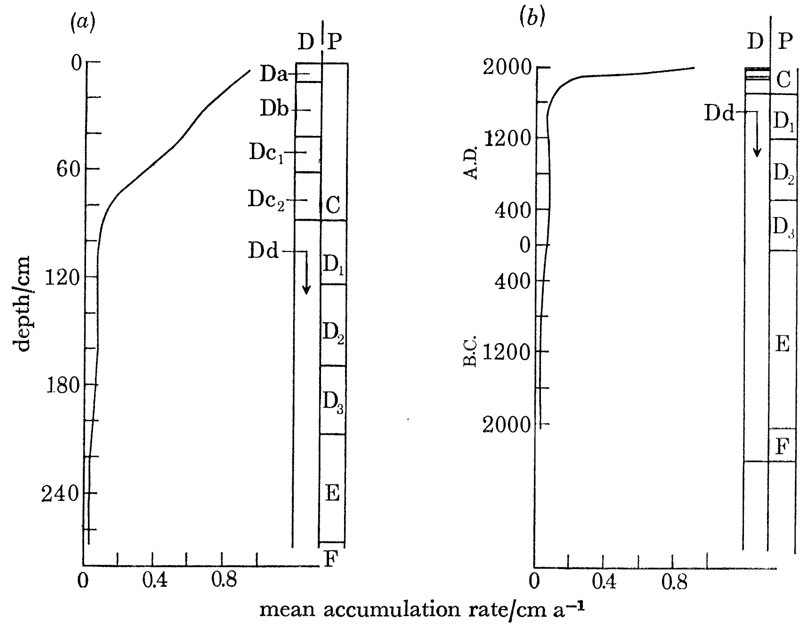


FIGURE 20. Mean sediment accumulation rate plotted against (*a*) depth and (*b*) time, calculated from the data from fifteen cores.

6. DISCUSSION

(*a*) *Introduction*

The non-marginal sediments of a lake usually contain a complex mixture of detrital material derived both from the lake and the drainage basin of the lake. For small lakes with simple catchment areas the allochthonous sedimentary record can sometimes be closely related to specific and localized ecological changes in the catchment area. Lough Neagh, however, has a large and varied catchment and pollen in the sediment must be derived from an area at least as big as the drainage basin. Unless localized changes are repeated contemporaneously on a regional basis they are unlikely to be reflected by changes in the fossil microflora. Pollen changes are therefore assumed to indicate events and trends of regional scale.

In contrast to the size and complexity of the drainage basin, the lake system itself is comparatively simple. The lake in the main part consists of a single shallow basin which enables water to be freely interchanged, and the local winds, which are often strong and are prevalent throughout the whole year, ensure that the water is continually mixed both vertically and horizontally. Thermal stratification occurs very rarely and then only for brief periods (Gibson *et al.* 1971). Abundant evidence exists to indicate the efficiency of the mixing process. The cell numbers of algae per litre lake water and the chemistry of the lake water show little variation from station to station (Gibson *et al.* 1971), and the diatom and pollen diagrams from different areas of the lake show almost identical percentages (cf. figures 6–9, 10–13). This is most striking in the case of the pollen diagrams since the pollen is derived almost exclusively from outside the lake system and since the drainage basin itself exhibits a wide variation in the geography of its plant communities.

It is considered, therefore, that a small number of core samples may adequately represent the recorded history in the lake sediment as described by the relative diagrams. Only in one

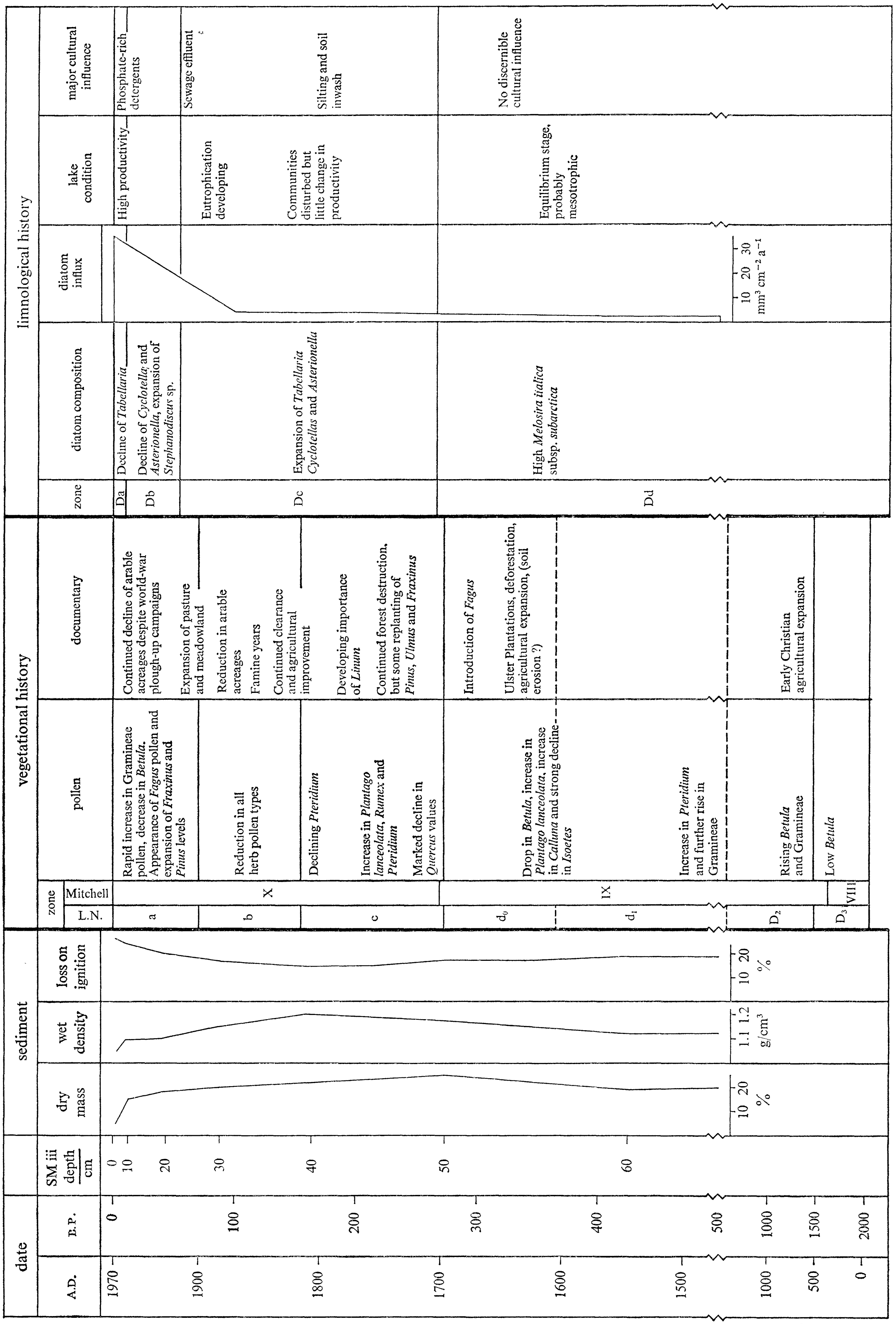


FIGURE 21. Summary diagram.

respect, the wide fluctuations in accumulation rates from core to core (§5), does the sedimentary record appear variable. This phenomenon is not fully understood but, with the exception of one or two cores in which hiatuses have been detected, the stratigraphic record appears to be uninterrupted. However, because of this variability in accumulation rate and because fewer cores were analysed the absolute data is less representative than the relative data. It is known that the pattern of absolute numbers through time for SMiii is closely repeated at the Battery site for a core with a faster accumulation rate (cf. Battarbee 1973*b*) but analyses of more cores are needed before *average* influx rates can be estimated. Nevertheless it can be assumed that the SMiii absolute data describe *changes* in influx which are of significance to the total system (cf. Battarbee 1978).

A summary diagram of results is shown in figure 21.

TABLE 5. COMPARISON OF LOUGH NEAGH POLLEN ZONES AND DATES WITH THE ZONATION SCHEME OF MITCHELL; ALL DATES ARE APPROXIMATE

	Lough Neagh			Mitchell (1965)	
historical period	zone	core	date A.D.	zone	date A.D.
1. Early Christian – plantation, A.D. 550–1600	D_2	AB9	500–1200	IX	300–
	D_1	AB9	1200–		
	d_1	SMiii	1200–		
2. Plantation – famine, A.D. 1600–1850	D_1	AB9	–1700	IX	–1700
	d_1	SMiii	–1620		
	D_0	SMiii	1620–1700		
	c	SMiii	1700–1800	X	1700–
	b	SMiii	1800–		
3. Famine – present day, A.D. 1850–1970	b	SMiii, SMii	–1890	X	–1970
	a	SMiii, SMii	1890–1970		

(*b*) *The vegetational record*

O'Sullivan *et al.* (1973) from the analyses of 3 m cores (AB3 and AB9) demonstrated the progressive but discontinuous deforestation of the Ulster landscape over the last 5000 a. The diagrams presented here, one SMiii (figures 6 and 7) with a typically 'low' accumulation rate and the other SMii (figures 8 and 9) with a much higher accumulation rate, are based on minicore data and expand the detail of the pollen record for about the last 700 a and the last 100 a respectively. They cover the period in which dramatic changes in the biological character of the lake appear to have taken place.

Table 3 sets out the dates assigned to the various pollen assemblage zones and indicates how the zones identified in SMiii overlap and correlate with the zones of O'Sullivan *et al.* (1973). Agreement between the two is not precise in every case mainly because a smaller sampling interval (2 cm) is used in SMiii. Table 5 shows the way in which the pollen assemblage zones are related to the various historical periods and shows how the zones and dates for Lough Neagh compare to Mitchell's zonation scheme (Mitchell 1965).

The beginning of the SMiii diagram (figures 13, 14, subzone d_1) is dated to about A.D. 1200, approximately correlating with the D_2/D_1 boundary of O'Sullivan *et al.* (1973) in AB9 (table 5). At this time the south of Ireland was experiencing an expansion of agricultural activity as a result of Anglo-Norman influences (Mitchell 1965). Norman power, however, was considerably less in Ulster than in the rest of Ireland (Beckett 1958; Otway-Ruthven 1951) and significant forest clearance in the Lough Neagh catchment during the twelfth, thirteenth and fourteenth centuries may not be expected. McCracken (1947) believes that up to the end of the sixteenth century Ulster was a heavily wooded place although, with the exception of the northwest shoulder of Lough Neagh, the woodland was 'probably not dense oak forest, but shrubby brush wood, intermixed in places with bog. This brush would be alder and willow in the marshy areas, with holly, ash, hazel, and oak scrub in the drier parts.' A common description of Ulster at this time was 'very woody and boggie'. Despite these views, however, the pollen diagram during the d_1 subzone shows that non-tree pollen frequencies are consistently high, indicating that the proportion of open or cleared land in the centuries leading up to the Tudor incursions at the end of the sixteenth century may have remained quite large.

Plantation – famine, A.D. *1600–1850*. Perhaps the most comprehensive land-use change in the history of Ulster occurred during the seventeenth century. The clearance of woodlands, first by the Tudors for military purposes at the turn of the century and then by English and Scottish for domestic and agricultural purposes later in the century, has been described and discussed by McCracken (1944, 1947, 1959, 1971). By the end of the seventeenth century most of Ulster's woods had been removed, although isolated stretches of forest existed into the eighteenth century (McCracken 1971). The planters were predominantly agrarian and contemporary sources indicate the large areas of land cleared for agriculture and the adoption by the settlers of a cattle-based economy (Moody 1939). A stimulus to increased tillage was also provided and the acreage of land under oats, rye, barley and flax expanded (Moody 1939). Deforestation at this time was also being carried out for its own sake, exploiting the timber as a raw material for making houses, for shipbuilding, in tanneries, ironworks, and for the making of pipe staves (McCracken 1971).

Immigration continued through into the eighteenth century and agricultural expansion carried on up to the time of the 1847 famine. Even at the turn of the eighteenth century it was said that, in Tyrone, every year added to the quantity of land brought into culture (McEvoy 1802), although according to Connell (1950) these increases may have been brought about more by the improvement of bog and fenland than by forest clearance.

While there can be little doubt that the present-day landscape, almost completely devoid of deciduous woodland, was being created during these centuries, a certain amount of plantation was being carried out. First, many landholders undertook voluntary planting round their estates either for decoration or for shelter, and secondly, more direct planting was encouraged by Government statutes as an attempt to replace lost forest (McCracken 1971; Pimlott 1952 McEvoy 1958). The trees especially planted were pine, elm, ash and beech, the latter being introduced in the seventeenth century.

Many of these land use changes are clearly expressed in the SMiii pollen diagram. At 57 cm in figures 6 and 7, subzone d_0 begins dated to about A.D. 1620. There is a decrease in birch pollen values and increases in those of *Plantago lanceolata* and *Pteridium*. There is little or no increase in the Gramineae frequency, but the beginnings of a new phase of forest clearance and expanding agricultural activity are probably signified. The behaviour of the *Isoetes* curve in relation to the *Calluna* curve provides the clearest evidence. This is seen best in the percentage total tree-pollen diagram (figure 6). Tutin (1969) in a diagram from Devoke Water in the English Lake District, has shown that the decrease of *Isoetes* and the increase of *Calluna* coincided with the inwash of soils. *Isoetes* does not tolerate silting, and *Calluna* pollen is often thought to reach lake sediments by secondary deposition (Tutin 1969). The Lough Neagh diagram may be interpreted in a similar way. Figure 21 shows increases in sediment density, percentage ash mass, and percentage dry mass at about 55 cm, and initial apparent magnetic susceptibility values which are thought to be directly related to soil erosion (Thompson, Battarbee, Oldfield & O'Sullivan 1975) also peak at about the same level. The ^{14}C dates above this level show definite signs of contamination by older carbon (O'Sullivan *et al.* 1973) and an increase in sediment accumulation rate also occurred (§5). A considerable increase in the amount of allochthonous material reaching the lake and the lake sediment at this time would appear to have been the result of soil disturbance in the catchment area following the removal of areas of woodland. Shortly afterwards (d_0/c boundary, A.D. 1700) an intensification of the disturbance and of clearance activity is suggested. *Quercus* frequencies suffer a large decline and Gramineae, *Plantago lanceolata* and *Rumex* values all expand and the increase in ash values (figure 5) probably suggests that higher levels of soil erosion and soil inwash are being maintained.

Mitchell (1965) recognizes a major change in land-use history at about A.D. 1700. However, his zone X (figure 21) is related to evidence for replanting rather than for further forest destruction. Documentary sources indicate that replanting of the type referred to by Mitchell did take place in Ulster, but except in the case of pine, there is little indication of this in the SMiii diagram during zone c. The c/b zone boundary is dated to about A.D. 1800, and rather surprisingly the pollen changes suggest a return to more wooded conditions. This is not upheld by documentary evidence (McCracken 1971) and it may be that the higher birch values, which are one of the main causes of the increase in a.p. values, is related to the input of pollen from local scrub-woodland especially around the lake itself, and not to a more regional trend.

Famine – present day, A.D. *1850–1970*. Although Ulster suffered far less than other provinces in the 1847 Famine, the famine had a considerable influence on land-use changes during the second half of the nineteenth century. The decline in population in conjunction with the repeal of the corn laws promoted the consolidation of holdings by landlords and the conversion of arable land into pasture (Beckett 1958). In Ireland as a whole the area under tillage fell almost continuously after 1851. Although there was a temporary revival in World War I, it continued to decline throughout the 1920s and reached an all time low in 1932 (Meenan 1970). This decrease was mirrored almost exactly by a reciprocal increase in the area of meadow and pasture. A further reduction in tillage and increase in pasture also appears to have taken place since World War II.

A certain amount of replanting was carried out in the late nineteenth century, probably stimulated by the availability of government loans (Pimlott 1952). Small woods of beech, pine, and spruce were planted and beech especially was often planted along field boundaries and roadsides. The systematic planting of coniferous forest, however, began only in the twentieth century with large areas being planted in the years after 1945.

On the basis of the adopted chronology the years immediately following the 1847 Famine are represented in the SMiii diagram at a level midway through zone b. The pollen frequencies, however, show no significant variations at this level. It is not until a depth of 25 cm (zone b/a transition) dated to about 1890 that there is a marked change in the SMiii diagram (figures 6, 7). This level is also clearly shown in the SMii diagrams (figures 8, 9) though the transition is at about the 42 cm level and is more gradual. Gramineae frequencies expand rapidly, *Plantago lanceolata* pollen frequencies increase, while birch and oak frequencies suffer a decline, and the a.p./n.a.p. ratio shows a strong relative decline of tree pollen frequencies. The pollen record, however, is ambiguous. The documentary evidence indicates that the decline in tree pollen frequencies through zone a is not to be interpreted as a sign of woodland clearance but as an indication that the farm economy was changing from arable cultivation to a grass-pasturage system. In fact the area of woodland may have expanded and more beech, elm, ash and pine pollen are recorded during the phase. There is little indication in the pollen diagrams, however, of the more recent planting of coniferous forest.

Evidence for the age and nature of land-use change in the Lough Neagh catchment has been obtained from documentary records and from pollen analysis. The chronology of the pollen changes shows that there is considerable agreement between the two types of data, allowing the combined evidence for terrestrial ecological change to be compared with the evidence for phytoplankton change in the lake.

(*c*) *The diatom record*

(i) *Problems of interpretation*

While the pollen record in the lake sediment provides information on environmental change in the catchment area, the diatom record can provide evidence for past lake conditions. However, in the same way that pollen analysis is beset with problems of representivity, there are a number of reasons why the assemblages of diatom taxa found at different levels in the sediment can not necessarily be regarded as direct counterparts of the diatom communities from which they were derived. Losses through dissolution, breakage, and through out-flow, and complications due to sediment mixing and resuspension are all important.

Broken diatoms are a problem in microfossil counts if fragments are very small and cannot be identified. In the Lough Neagh sediments broken valves are common but in most cases the fragments are large enough to recognize, and they can be included in the counts. Diatom dissolution may be a more serious problem than breakage. Differential dissolution will lead to incorrect estimates of relative frequency, and if dissolution involves the complete disappearance of the valve it will naturally cause reductions in total abundance, and hence incorrect estimates of palaeoproductivity. A number of studies have been made on the solubility of opaline silica (Lewin 1961; Juse 1966; Jørgensen 1955) and while the evidence is conflicting there is little doubt that under suitable circumstances considerable quantities of SiO_2 can be released from lake sediments, probably directly or indirectly from the dissolution of diatom frustules. The sediments of Lough Neagh are very rich in diatom frustules, but when viewed with the scanning electron microscope it is apparent that the valve surface of many individuals is pitted and corroded, that the pores are considerably widened, and that girdle bands are usually missing (cf. appendix plate 2). In addition, each summer a considerable quantity of soluble silica appears in the lake water (Dickson 1975; Gibson, personal communication) at a time of year when input from the drainage basin is at its lowest and incapable of contributing the quantities necessary to account for the increase (Battarbee 1973*a*). For example, in 1970 the stored dissolved silica in the lake rose from 0.670 mg/l in June to 5.040 mg/l in October, while over the same period of time only enough to raise the concentration by 0.82 mg/l was added by the major rivers.

It is probable therefore that diatom silica is being recycled. However, it is interesting to note that many of the weakly silicified planktonic diatoms (e.g. *Asterionella formosa*, *Fragilaria crotonensis*) are well represented in the sediment, and that the scanning electron microscope rarely indicates valves which are very badly corroded. Plate 2 (appendix) shows some of the worst examples. Perhaps it is possible quantitatively to account for the summer silica release purely by the partial dissolution of frustule surfaces, by the dissolution of the more labile constituents of the cell and by the release of non-diatom silica. If so then the number and volume, if not the mass, of frustules in the sediment may be quantitatively representative of past lake production. Unfortunately it is difficult to assess past lake conditions and the dissolution of frustules would be related to changes in various other factors such as the amount of sediment mixing and resuspension, the intensity of faunal activity in the uppermost sediment, the rate of sediment accumulation itself, as well as to changes in the chemistry of the mud–water interface.

Outflow losses can also reduce the level of representivity. While such losses can occur in eel guts and by fish harvesting, the most important loss is water-borne. The number of cells involved will vary with river flow and lake throughout time, the seasonal crop productivity and periodicity, and according to the particular taxa involved. Losses of this nature are likely to be fairly constant over a period of years unless changes occur as a result of a permanent alteration in one of the variables. For example, more diatoms will tend to be retained in the lake by a reduction in peak discharge since this occurs during the spring diatom growth period. The various flow controls at Toome on Lough Neagh since about 1850 may be significant in this respect. Secondly, a change in taxa may lead to a different differential loss of species; the buoyancy characteristics of different species may be important in this case (cf. Lund 1959). Thirdly, a change in seasonal periodicity (e.g. due to nutrient uptake changes) will change the pattern of outflow. The development of silica limitation during recent years (Gibson *et al.* 1971) in Lough Neagh will have caused relatively more of the crop to grow in the months of high water discharge.

It is difficult to quantify this type of loss for times in the past. However, in 1970, observations during routine phytoplankton counts indicated that the concentration of algal cells in outflow down the River Bann was similar to the concentration observed in the lake water itself. The total loss could be estimated from lake population figures and R. Bann discharge figures. It was calculated that 0.657 mg SiO_2/l as diatom, representing about 8 % of the total diatom crop, was lost through discharge in 1970. The figure for 1969 was about 6 % (Battarbee 1973*a*; Wood, personal communication).

While breakage, dissolution and outflow loss will tend to reduce the total number of frustules in the sediment, resuspension and the lateral movement of material from littoral areas will tend to increase the number of frustules preserved in the central areas of lake basins, and, by introducing benthic and epiphytic taxa, it will also tend to diversify the fossil microflora. The proportion of non-planktonic taxa in the total of diatoms recorded varies from 5 to 20 % for core SMiii. It is difficult to deduce the precise origin of these taxa although in most cases it can be assumed that they derive from the littoral areas of the lake itself and not from external upstream habitats. As such they should also reflect environmental conditions within the lake system. Diatoms resuspended and transferred to the central areas of the lake, however, are not confined to taxa from littoral habitats. Although difficult to quantify, it is likely that a considerable number of planktonic diatoms initially sedimenting in littoral areas will also be transferred to deeper water areas causing influx quantities calculated for those areas to be consequently exaggerated. For Lough Neagh this problem may not be as great as for deeper lakes with more confined areas of mud accumulation, although the continued turbulence of the Lough Neagh water probably provides an efficient transfer mechanism.

(ii) *Major stages of lake development*

Despite the constraints imposed on the interpretation of fossil data by the difficulties outlined above, the sedimentary record can indicate the timing and in many cases, the nature of past environmental changes. Ecological interpretation can be attempted both on the basis of the general characteristics of the assemblages and, where available, from autecological information. The classification of the various taxa into pH groups (cf. Hustedt 1937–39) is shown in the appendix. The pH system is used by many authors (Foged 1968, 1953, 1954; Nygaard 1956; Round 1957; Digerfeldt 1972) and there is reasonable agreement in the literature on the designation of many of the taxa. Changes in the relative importance of the various groups through time indicate major changes in the pH and water chemistry of the lake (cf. Meriläinen 1969) and the grouping of taxa into life-form categories can also be of use. Changes in the relative frequency and in the absolute abundance of individual taxa and groups of taxa, however, form the main basis of this discussion.

Although sediment accumulation rate varies considerably from place to place in the lake (§5) all the cores analysed contained an almost identical sequence of diatom assemblages. Core SMiii was adopted as the main core, because of its more representative accumulation rate and because the main pollen diagram was also derived from it. Stratigraphic correlation of pollen and diatom results is therefore precise. On the basis of the relative diatom analysis four main periods in the history of the lake were recognized:

(1) equilibrium period (> 2000 B.C. to A.D. 1700)
(2) period of accelerated mineral inwash (from about A.D. 1700)
(3) cultural eutrophication I (from about A.D. 1915)
(4) cultural eutrophication II (from about A.D. 1960)

Equilibrium period. The period of lake equilibrium is represented only in diagrams AB3 and SMiii where it is called zone Dd (figures 10, 11). The term equilibrium is used since the whole zone reflects the existence of a very stable diatom community. In figure 10 it is represented by only 33 cm of sediment, but in AB3 (figure 11) it can be seen to extend down to a depth of at least 250 cm which, from the ^{14}C results, is dated to about 4000 B.P. Since the upper boundary of the period occurs at about 250 B.P. the diatom stability and possibly the lake condition in general was unchanging for almost 4000 a, through the whole of the Bronze and Iron ages, possibly up to the close of the seventeenth century. These early periods were characterized by forest clearance and agricultural expansions (Evans 1963; Eogan 1964), yet disturbance in the catchment area had insufficient influence on the water chemistry of the lake to affect the composition of the diatom flora. The fossil assemblage of zone Dd appears to represent the state of the lake before cultural disturbance.

The flora is dominated by *Melosira italica* subsp. *subarctica*, which forms 60 % by number and volume throughout the period. This species has been described both living and fossil from the British Isles and throughout the world from lakes of greatly different types. Molder & Tynni (1967), Hustedt (1930) and Cleve-Euler (1951) describe it as common in oligotrophic to mesotrophic cold water lakes. Foged (1954) describes it as an alkaliphilous species. Lund (1954, 1971) has studied its ecology in detail in the English Lake District where it is also found in a wide range of lakes. He suggests that its ability to compete with other diatoms rests on its capacity for over-wintering on the sediment surface, and that the mixing of lake water is favourable in lifting the diatom from the sediment into the photic zone (Lund 1954). In Lough Neagh the species is dominant in the phytoplankton at the present time (Gibson *et al.* 1971), indicating its ability in some lakes to flourish in alkaline, nutrient rich waters.

Other important species present during zone Dd are *Cyclotella comta*, *C. comensis*, *C. ocellata*, *Tabellaria flocculosa*, *Asterionella formosa* and *Stephanodiscus* sp. A. This combination of species suggests that the lake was considerably less eutrophic than at the present time. Figure 14*c* and *d* also indicates a far lower diatom productivity during this equilibrium period than at present, with influxes of about 3.5 $mm^3 cm^{-2} a^{-1}$.

Period of accelerated mineral inwash. A major change in the structure of the fossil diatom assemblage occurs at a level in the sediment dated to about A.D. 1700. From this time onwards the diagrams show that the diatom percentages never again attain stability. The decrease in the percentage of *Melosira italica* subsp. *subarctica* occurs very rapidly and *Stephanodiscus* sp. B, a small diatom as yet unidentified, appears. The expansion of the frequencies of *Cyclotella* and *Tabellaria* are also characteristic of the change. *C. comensis* and *C. ocellata* are recorded by Foged (1968) as 'indifferent' species, i.e. species which prefer a more or less neutral pH. *Tabellaria flocculosa* is recorded as being an acidophilous species by Foged (1968) and Hustedt (1930). However, since the taxonomic revision of *Tabellaria* by Knudson (1952, 1954) *T. flocculosa* now also includes the planktonic forms of *Tabellaria fenestrata* (Grun) and the acidophilous references may not therefore be appropriate. Indeed its wider range of alkalinity tolerance is indicated by its presence in Zurichsee (Nipkow 1927), its growth in Lough Neagh until recent times, and its abundance in Lake Windermere (Pennington 1943). *Asterionella formosa*, another species which expands in zone Dc is reported from a wide range of lakes. Its occurrences in Ireland are mainly from eutrophic waters (Round & Brook 1959), and Evans (1970) and Pennington (1943) consider it as an indicator of enrichment in the English Lake District. Rawson (1956) and Beeton (1963) on the other hand refer to it as growing in oligotrophic lakes.

The conflicting views on the ecology of the various species make it difficult to interpret the significance of the sudden change in the diatom composition at the Dd/dC boundary (figure 21). The diatom influx data (figure 15) suggest that there was no increase in productivity at this time, in fact a decrease in productivity may well be indicated, especially since the loss on ignition values tend to decrease somewhat at this level (figure 21).

The significance of the change may be related to external influences. It has been argued above that pollen changes and changes in the sediment structure of core SMiii a little below this level are evidence for a comparatively sudden acceleration in the rate of soil inwash from the catchment area consequent upon seventeenth century forest clearance and agricultural expansion. The coincidental changes in the pollen and diatom record appear significant, and it is possible that the diatom changes are related to the disturbance in the catchment. If this is so the disruption of the long-established equilibrium at this time represents the first recognizable change in the lake system to be brought about as a result of cultural activity.

The shape of the diatom curves after the Dd/Dc boundary shows that the composition of the diatom flora in the lake continued to change with *Tabellaria flocculosa* especially expanding at the expense of *M. italica* subsp. *subarctica*. At this level in the sediment, where *Melosira italica* subsp. *subarctica* is at a minimum the short cores SMi and SMvi begin (figures 12, 13). The recovery of the *Melosira* curve from about the middle of the zone can therefore be seen in all diagrams.

The rise of *M. italica* subsp. *subarctica* and the decline of *Asterionella formosa* in the upper part of zone Dc may indicate a tendency to return to the conditions represented by zone Dd. From the ^{210}Pb dating the *Melosira* increase occurs in the second half of the nineteenth century when arable acreages were declining in favour of pastureland. The intensity of erosion may have been sufficiently reduced to encourage the resurgence of the flora characteristic of the equilibrium period. However, any tendency towards the establishment of stable conditions seems to have been completely destroyed around the turn of the century by the appearance of a new influence – the domestic sewer.

Cultural eutrophication I. By A.D. 1900 Lough Neagh was receiving sewage and effluent from a population of about 60000 and from a number of industrial premises. In 1896 Lurgan began extracting water from the lake and returning wastewater to it. The development and increased use of piped water and piped sewage during these years produced a new pattern of phosphorus discharge in the drainage basin. When sewage was used as land fertilizer little of the phosphorus entered the drainage waters due to the capacity of most soils to adsorb it (cf. Biggar & Corey 1969). For this reason the direction of effluent water into the rivers and into the lake itself, bypassing the soil system, must have caused a considerable increase in the supply of available phosphorus to the lake.

A major change in the structure of the diatom assemblage probably corresponding to this influence occurred about 1915 according to the ^{210}Pb dating. The change is characteristically shown in all diagrams where it is represented by the Dc/Db boundary, and the most consistent feature of the change is the replacement of *Cyclotella* species by *Stephanodiscus* species, especially *S. astraea.*

The absolute diagram for SMiii (figure 15) show most clearly the increase in importance of *S. astraea* at this level. *Stephanodiscus dubius* is also a species which occurs for the first time here, and its presence is confined to the uppermost zones. Another notable feature is the decline and disappearance of the only benthic diatom frequently found in the sediment, *Navicula cryptocephala,* possibly due to the restriction of its habitat by a decrease in the photic depth, or to a statistical swamping out of its numbers due to the relative increase in the cells of planktonic taxa.

The species of *Stephanodiscus* are thought to be found especially in waters where the pH is constantly above 7 (Hustedt 1939; Foged 1968) and are classified by Hustedt (1939) as alkalibiontic. The diatom change is thus seen as indicating that the lake was becoming more alkaline, and considerably more productive.

It is interesting to compare this evidence from the structural change in the fossil assemblages with the palaeo-productivity evidence. If it is assumed that there was little or no change in the relative diatom dissolution rate, the total diatom influx curves (figure 14*c*, *d*) indicate that the diatom productivity may have in fact increased before this change in the flora. The total curve begins to increase from a depth of 27 cm, and possibly indicates that enrichment through the 20 years or so before 1915 increased the total productivity of the *Tabellaria/Cyclotella* community of zone Dc before this community was replaced by expanding *Melosira* and *Stephanodiscus* populations in zone Db.

A consequence of the increase in biological productivity appears to have been a rapid acceleration in the rate of sediment accumulation to between 0.5 and 1.0 cm a^{-1} (§5). The combination of this with accurate dating has enabled events of the last century to be recorded in considerable detail. In addition it has also allowed the sedimentary information to be correlated with documentary sources and with the work of early algologists. A re-examination of some of the samples collected by West & West (1902, 1906) from Lough Neagh shows that *Cyclotella comensis* and *C. ocellata* were present in the lake in 1900 and 1901. These are not recorded by Dakin & Latarche and cannot be found in Dakin & Latarche samples still extant. This may be because such small taxa are not readily retained in a plankton net. It is significant, however, that the Dakin & Latarche samples do show traces of *Stephanodiscus dubius* and that West & West's samples do not. These species differences appear to agree excellently with the microfossil data and tend to confirm that this particular change recorded in the sediment (i.e. Dc/Db) was taking place in the early years of the twentieth century.

Dakin & Latarche (1913) observed that enormous quantities of *Tabellaria* were growing in the lake in 1910. The sediment record, however, shows that in the longer-term context the dominance of *Tabellaria* was beginning to decline as the role of the *Stephanodiscus* species began to expand. Core SMi with a faster accumulation rate than SMiii over this period shows more clearly the changes taking place during the last 60 years. Both *Stephanodiscus astraea* and *S. dubius* reach significant peaks and then decline rising again in the uppermost zone, *M. islandica* subsp. *helvetica* also appears, increases and then declines.

Throughout this zone the influx curves for *Stephanodiscus* show the continuous increase in accumulation taking place, *S. astraea* establishing itself as the dominant species (figure 15).

Cultural eutrophication II. The latest phase of lake history is registered in the uppermost centimetres of the sediment. *Stephanodiscus astraea* remains important, there is an expansion of *S. astraea* var. *minutula* and there is a sudden decrease in the frequency of *Tabellaria*, a diatom which now seems to have disappeared from the lake completely (cf. Gibson *et al.* 1971). This change is marked in the diagrams by the Db/Da boundary and both ^{210}Pb and ^{137}Cs dating indicate that it occurred about 1960. In SMiii zone Da is represented by the uppermost 10 cm. The influx diagram shows that the total quantities of diatoms being incorporated with the sediment at this point reaches a new maximum of about 32–33 $\mathrm{mm^3\,cm^{-2}\,a^{-1}}$, indicating a higher diatom productivity during these years than ever before (figure 14*c*, *d*). The strong absolute increase in *Melosira* and *Stephanodiscus* values is not apparent from the relative diagram (figure 10) since, except for the increase in *S. astraea* var. *minutula* and the decrease in *Tabellaria flocculosa*, no significant relative change in the composition of the diatom flora took place.

The increase in diatom productivity inferred from the influx data and the change in species composition shown in the relative diagrams towards a *Melosira* and *Stephanodiscus* dominated diatom microflora suggest that the lake was being further enriched. It is estimated that the lake is now receiving effluent directly or indirectly from about 300000 people. The extension of the sewerage network and the building of sewage treatment plants since the war has facilitated the direct input of phosphorus-rich effluent water to the lake. And while the number of people in the sewerage system has increased, the phosphorus output *per capita* has also increased considerably especially since the mid 1950s when phosphate detergents were introduced (Devey & Harkness 1973). Phosphorus from agricultural sources has also increased since the war especially in the form of fertilizer and animal manure, but it is considered in the case of Lough Neagh that domestic sources are now a more important source than land drainage (Wood & Gibson 1973; Smith, personal communication).

(*d*) *Conclusion*

The analyses have shown that the historical record contained in the sediment by the diatoms and the pollen is remarkably consistent within the lake. The record reflects changes in the diatom flora of the lake and changes in the vegetation of the catchment area. Most of the changes are interpreted as being the result of human influence and the evidence suggests that this influence has become progressively stronger with time.

The lake appears to have been unaffected by cultural activity until about the seventeenth century when deforestation and agricultural expansion probably promoted an acceleration in soil erosion and in soil inwash, causing a substantial change in the diatom microflora of the lake. No evidence for an increase in productivity is registered, however, until the last decade of the nineteenth century when rapid increases in sediment accumulation and in the influx of diatoms indicate the beginning of cultural eutrophication. By about 1915 the composition of the diatom flora had changed radically as *Stephanodiscus* spp. replaced *Cyclotella* spp., and as the use of Lough Neagh for waste disposal by peripheral towns increased. The extension of the sewerage network probably encouraged the continued enrichment of the lake through the twentieth century and it is likely that the introduction of phosphate detergents in the 1950s added considerable impetus to the process. The information from the uppermost sediment shows how the diatom influx dramatically increased in the last two decades and how the diatom flora has become to be dominated solely by *Melosira* and *Stephanodiscus* spp.

This study has not only suggested how man may have influenced the development of Lough Neagh over recent centuries; it has also suggested a number of more general conclusions. First, it has exemplified the influence of the catchment area on a lake by the input, and changes in input, of both particulate and dissolved allochthonous substances. Secondly, it has demonstrated the rapid increase in sediment accumulation rate (§5) that can be expected as a by-product of eutrophication (cf. Battarbee & Digerfeldt 1976). Thirdly, it has demonstrated the sensitivity of the diatom microflora to environmental change, and has suggested that taxa of the *Stephanodiscus* genus may be significant organisms for indicating developing eutrophication. Fourthly, it has shown that palaeolimnological techniques can make an important contribution to the understanding of limnological problems, especially where traditional relative counting methods are supplemented by influx estimates of biomass through time.

Other palaeolimnological analyses could usefully add to the data presented in this study. Blue-green algae are the dominant phyto-plankters of the lake at present and their history could be traced by palaeo-pigment analysis. In addition, while a thorough analysis of the history of the midge fauna of the lake has been carried out (Carter 1973) the analysis of the remains of zooplankton populations in the sediment could provide additional information relating to the history of a different level in the trophic system. Improved interpretation of all palaeolimnological analyses, however, requires a greater knowledge of the processes of sedimentation and resuspension in the lake, and of the functioning of the mud–water interface in relation to the diageneses, preservation, and recycling of sedimented material.

I should like to express my sincere thanks to B. Harrigan and J. Grimes for assistance with field work, to D. Anderson for carrying out certain laboratory analyses, to D. Loughrey and Shirley Keeley for drawing the diagrams, and to S. Lowry for his careful operation of the s.e.m. and for preparing the photographic plates. R. Cambray and J. Eakins of AERE Harwell were responsible for the ^{137}Cs and ^{210}Pb analyses, while the ^{14}C dating was carried out at the Palaeocology Laboratory, Queens' University Belfast, by G. Pearson. Some of the preliminary work on the manuscript was carried out while I was a Royal Society Research Fellow visiting the Department of Quaternary Geology, Uppsala, between 1971 and 1973. I should like to thank Professor L.-K. Königsson for putting the facilities of the Department at my disposal. I should also like to thank Dr Maj-Britt Florin of Uppsala for her kindness and generosity during my stay in Sweden and for sharing her remarkable knowledge of diatom taxonomy with me. Dr K. Crabtree, Miss E. Y. Haworth, Dr J. W. G. Lund, Mr B. Paddock, Mr R. Ross, Miss P. Sims, Dr F. E. Round, Dr P. E. O'Sullivan and Dr G. Digerfeldt have all given considerable assistance at some stage and I should like to record my thanks to them. Professor F. Oldfield, Professor R. B. Wood, Professor J. H. Tallis and Dr J. W. G. Lund have read and commented on the manuscript. Professors Oldfield and Wood have been continuing sources of advice and encouragement in the last eight years and I owe each a great debt of gratitude. The work has been supported by the New University of Ulster (1968–71) and (since 1970) by the Natural Environment Research Council.

REFERENCES

American commission on stratigraphic nomenclature 1961 Code of stratigraphic nomenclature. *Bull. Am. Ass. Petrol. Geol.*, **45** (5), 645–655.

Andersen, Sv. Th. 1960 Silicone oil as a mounting medium for pollen grains. *Danm. geol. Unders.* IV r, BD4, Nr 1, 1–24.

Battarbee, R. W. 1973*a* A pollen and diatom study of the Late-Flandrian sediments of Lough Neagh, Northern Ireland. D.Phil. thesis, The New University of Ulster.

Battarbee, R. W. 1973*b* Preliminary studies of Lough Neagh sediments. II. Diatoms from the uppermost sediment. *Quaternary plant ecology* (ed. H. J. B. Birks & R. G. West), pp. 279–289. Oxford: Blackwell.

Battarbee, R. W. 1973*c* A new method for estimating absolute microfossil numbers with special reference to diatoms. *Limnol. Oceanogr.* **18** (4), 647–653.

Battarbee, R. W. & Digerfeldt, G. 1976 Palaeoecological studies of the recent development of Lake Växjösjön. I. Introduction and chronology. *Arch. Hydrobiol.* **77** (3), 330–346.

Battarbee, R. W. 1978 Relative composition, concentration, and calculated influx of diatoms from a sediment core from Lough Erne, N. Ireland. *Pol. Arch. Hydrobiol.* (in the press).

Beckett, J. C. 1958 *A short history of Ireland.* London: Hutchinson University Library.

Beeton, A. M. 1965 Eutrophication of the St Lawrence Great Lakes. *Limnol. Oceanogr.* **10**, 240–254.

Biggar, J. W. & Corey, R. B. 1969 Agricultural drainage and eutrophication. In *Eutrophication: causes, consequences and correctives.* Proceedings of a Symposium, National Academy of Sciences, Washington.

Cambray, R. S., Fisher, E. M. R., Brooks, W. L. & Peirson D. H. 1972 *Radioactive fallout in air and rain: results to the middle of 1971.* AERE-R6923. London: HMSO.

Carter, C. E. 1973 A study of Chironomidae (Diptera) of Lough Neagh. D.Phil thesis, The New University of Ulster.

Charlesworth, J. K. 1960 The geology of N.E. Ireland. *Proc. Geol. Ass., Lond.* **71**, 429–459.

Cleve-Euler, A. 1951–3 Die Diatomeen von Schweden und Finland. *K. Svenska Vetensk Akad. Handl* (Fjärde Serien).

Connell, K. H. 1950 The colonisation of waste land in Ireland 1750–1845. *Econ. Hist. Rev.* **3**, 44–71.

Dakin, W. J. & Latarche, M. 1913 The plankton of Lough Neagh. *Proc. R. Irish Acad.* B **30**, 20–96.

Devey, D. G. & Harkness, N. 1973 The significance of man-made sources of phosphorous: detergents and sewage. *Water Res.* **7**, 35–54.

Dickson, L. 1975 A silica budget for Lough Neagh 1970–1972. *Freshwater Biol.* **5**, 1–12.

Digerfeldt, G. 1972 The post-glacial development of Lake Trummen. Regional vegetation history, water level changes and palaeolimnology. *Folia limnol. scand.* **16**, 1–104.

Edmondson, W. T., Andersson, G. C. & Peterson, D. R. 1956 Artificial eutrophication of Lake Washington. *Limnol. Oceanogr.* **1**, 47–53.

Eogan, G. 1964 The later bronze age in Ireland in the light of recent research. *Proc. prehist. Soc.* **30**, 268–351.

Evans, E. E. 1963 The prehistoric and historic background. In *Land use in Northern Ireland* (ed. L. Symons). London: University of London Press.

Evans, G. H. 1970 Pollen and diatom analyses of late Quaternary deposits in the Blelham Basin, North Lancashire. *New Phytol.* **69**, 821–874.

Faegri, K. & Iversen, J. 1964 *Textbook of pollen analysis.* Oxford: Blackwell Scientific Publications.

Foged, N. 1953 Diatoms from West Greenland. *Meddr. Grønland.* **147**, Nr 10.

Foged, N. 1954 On the diatom flora of some Funen lakes. *Folia limnol. Scand.* **6**, 1–75.

Foged, N. 1958 The diatoms in the basalt area and adjoining areas of Archean rock in West Greenland. *Meddr. Grønland.* **146**, Nr 4.

Foged, N. 1968 Diatomeerne i en postglacial boreprøve fra buden af Esrom Sø, Danmark. *Medd. Dansk Geol. Fören.* **18.**

Fries, M. 1958 Vegetationsutveckling och odlingshistoria i Varnhemstrakten. En pollennalytisk undersokning i Västergötland. *Acta phytogeogr. suec.* **39.**

Gibson, C. R., Wood, R. B., Dickson, E. L. & Jewson, D. H. 1971 The succession of phytoplankton in Lough Neagh 1968–70. *Mitt. int. Verin. theor. angew. Limnol.* **19**, 146–160.

Government of Northern Ireland 1971 Lough Neagh working group. Advisory Report. 2 vols.

Hasler, A. D. 1947 Eutrophication of lakes by domestic drainage. *Ecology* **28**, 383–395.

Hustedt, F. 1930 *Die Süsswasser flora Mitteleuropas.* Heft 10. *Baccillariophyta (Diatomeae).* Jena.

Hustedt, F. 1930–66 Die Kieselalgen: Deutschlands, Östereichs und der Schweiz unter Berücksichttigung der übrigen Länder Europas sowie der angrenzenden Meeresgebiete. Band VII: Dr L. Rabenhorst's Kryptogamen-Flora von Deutschland, Östereich, und der Schwiez.

Hustedt, F. 1937–9 Systematische und ökologische Untersuchungen über den Diatomeen-Flora von Java, Bali und Sumatra. *Arch. Hydrobiol.* (Suppl.) 15, 16.

Janssen, C. R. 1959 *Alnus* as a disturbing factor in pollen diagrams. *Acta bot. neerl.* **8**, 55–58.

Jewson, D. H. 1975 Physiological and ecological aspects of photosynthesis by the phyto-plankton in Lough Neagh with special reference to light. D.Phil thesis, The New University of Ulster.

Jørgensen, G. 1955 Solubility of the silica in diatoms. *Physiologia Pl.* **8**, 340–345, 846–851.

Juse, A. 1966 Diatomeen in Seesedimenten. *Arch. Hydrobiol. Berh. Ergebn. Limnol.* **4**, 1–32.

Knudson, B. M. 1952 The diatom genus *Tabellaria*. 1. Taxonomy and morphology. *Ann. Bot., Lond.* **16**, 421–440.

Knudson, B. M. 1954 The ecology of the diatom genus *Tabellaria* in the English Lake District. *J. Ecol.* **42**, 345–357.

Lewin, J. C. 1961 The dissolution of silica from diatom walls. *Geochim. cosmochim. Acta.* **21**, 182–198.

Lund, J. W. G. 1954 The seasonal cycle of the plankton diatom *Melosira italica* (EHR) Kutz. subsp. *subarctica* O. Mull. *J. Ecol.* **42**, 151–179.

Lund, J. W. G. 1959 Buoyancy in relation to the ecology of the freshwater phytoplankton. *Br. phycol. Bull.* no. 7, 1–17.

Lund, J. W. G. 1971 An artificial alteration of the seasonal cycle of the plankton diatom *Melosira italica* subsp. *subarctica* in an English Lake. *J. Ecol.* **59**, 521–533.

Mackereth, F. J. H. 1958 A portable core sampler for lake deposits. *Limnol. Oceanogr.* **3**, 181–191.

Mackereth, F. J. H. 1969 A short core sampler for subaqueous deposits. *Limnol. Oceanogr.* **14**, 145–151.

McConaghy, S. & McAllister, J. S. V. 1963 Soils. In *Land use in N. Ireland* (ed. L. Symons). London: University Press.

McCracken, E. M. 1944 The composition and distribution of woods in N. Ireland from the sixteenth century down to the establishment of the Ordnance Survey. M.Sc. thesis, Queens University Belfast.

McCracken, E. M. 1947 The woodlands of Ulster in the early seventeenth century. *Ulst. J. Archaeol.* **10**, 15–25.

McCracken, E. M. 1959 The woodlands of Ireland circa 1600. *Irish Hist. Stud.* **11**, 271–296.

McCracken, E. M. 1971 *The Irish woods since Tudor times. Their distribution and exploitation.* Newton Abbott: David and Charles.

McEvoy, J. 1802 *Statistical survey of the county of Tyrone.* Dublin: Grainsberry and Campbell.

McEvoy, T. 1958 Forestry in Ireland. *Advmt Sci., Lond.* **56**, 307, 316.

Meenan, J. 1970 *The Irish Economy since 1922.* Liverpool: University Press.

Meriläinen, J. 1969 Distribution of diatom frustules in recent sediments of some meromictic lakes. *Mitt. int. Verein. theor. angew. Limnol.* **17**, 186–192.

Mitchell, G. F. 1965 Littleton Bog, Tipperary: An Irish vegetational record. Reprint from the Geological Society of America special paper 84.

Molder, K. & Tynni, R. 1967 Über Finnlands rezente und subfossil Diatomeen 1. *C. r. Soc. geol. Fin.* **29**, 199–217.

Moody, T. W. 1939 *The Londonderry plantation*, pp. 1609–1641. Belfast: Mullan.

Nipkow, F. 1927 Über das Verhalten der Skelette planktischer Kieslalgen im geschichteten Tiefenschlamm des Zürich und Baldeggersees. *Schweiz. Z. Hydrol.* **4**, 71–120.

Nygaard, G. 1956 The ancient and recent flora of Diatoms and Crysophyceae in Lake Gribsø. In *Studies on the Humic Acid Lake Gribsø* (ed. K. Berg & I. C. Petersen), *Folia Limnol. Scand.* no. 8.

Oldfield, F. 1963 Pollen analysis and man's role in the ecological history of the southeast Lake District. *Geogr. Ann., Stockh.* **14**, 23–40.

Oldfield, F. 1965 Problems of mid-post-glacial pollen zonation in part of North-west England. *J. Ecol.* **53**, 247–260.

O'Sullivan, P. E., Oldfield, F. & Battarbee, R. W. 1973 Preliminary studies of Lough Neagh sediments. 1. Stratigraphy, chronology and pollen analyses. In *Quaternary Plant Ecology* (ed. H. J. B. Birks & R. G. West), pp. 267–278. Oxford: Blackwell.

Otway-Ruthven, J. 1951 The organisation of Anglo-Irish agriculture in the Middle Ages. *J. R. Soc. Antiq. Ir.* **81**, 1–13.

Pennington, W. 1943 Lake sediments; the bottom deposits of the north basin of Windermere with special reference to the diatom succession. *New Phytol.* **43**, 1–27.

Pennington, W. 1964 Pollen analyses from the deposits of six upland tarns in the Lake District. *Phil. Trans. R. Soc. Lond.* B **248**, 205–244.

Pennington, W., Cambray, R. S., Eakins, J. D. & Harkness, D. D. 1976 Radionuclide dating of the recent sediments of Blelham Tarn. *Freshwater Biol.* **6**, 317–331.

Pennington, W., Cambray, R. S. & Fisher, E. M. R. 1973 Observations on Lake sediments using fallout ^{137}Cs as a Tracer. *Nature, Lond.* **242**, 342–346.

Pimlott, J. 1952 The history of afforestation in N. Ireland. *Advmt Sci., Lond.* **35**, 297–303.

Rawson, D. S. 1956 Algal indicators of trophic lake types. *Limnol. Oceanogr.* **1**, 18–25.

Riddolls, A. 1974 Aspects of nitrogen fixation by blue-green algae in Lough Neagh. D.Phil. thesis, The New University of Ulster.

Round, F. E. 1957 The late-glacial and post-glacial diatom succession in the Kentmere valley deposit. *New Phytol.* **56**, 98–126.

Round, F. E. & Brook, A. J. 1959 The phytoplankton of some Irish loughs and an assessment of their trophic status. *Proc. R. Irish Acad.* B **60**, 167–191.

Stephens, N. 1963 Geology and physiography. In *Land use in N. Ireland* (ed. L. Symons). London: University Press.

Stockner, J. G. & Benson, W. W. 1967 The succession of diatom assemblages in the recent sediments of Lake Washington. *Limnol. Oceanogr.* **12**, 513–532.

Suess, H. E. 1970 Bristlecone pine calibration of the radiocarbon time-scale, 5200 B.C. to the present. *Proc. Nobel Symposium* **12**, 303–309. (Uppsala 1969, ed. I. Olsson).

Thompson, R., Battarbee, R. W., Oldfield, F. & O'Sullivan, P. E. 1975 Magnetic susceptibility of lake sediments. *Limnol. Oceanogr.* **20** (5), 687–698.

Tutin, W. 1969 The usefulness of pollen analysis in interpretation of stratigraphic horizons, both late-glacial and post-glacial. *Mitt. int. Verein. theor. angeww Limnol.* **17**, 154–164.

West, W. & West, G. S. 1902 A contribution to the fresh-water algae of the North of Ireland. *Trans. R. Irish Acad.* **32** B, 1–100.

West, W. & West, G. S. 1906 A comparative study of the plankton of some Irish lakes. *Trans. R. Irish Acad.* **33** B, 77–116.

Wood, R. B. & Gibson, C. E. 1973 Eutrophication and Lough Neagh. *Water Res.* **17**, 173–187.

APPENDIX A. DIATOM LIST AND ILLUSTRATIONS

Diatom list

The following table comprises a list of the diatom taxa encountered during the diatom counts, and shows the pH categories into which each was placed.

taxon	alkali-biontic	alkali-philous	indifferent	acido-philous	unknown
Melosira italice subsp. *subarctica* O. Müll	.	×	.	.	.
M. granulata (Ehr) Ralfs.	.	×	.	.	.
M. arenaria Moore	.	×	.	.	.
M. ambigua (Grun) O. Müll	.	×	.	.	.
M. islandica subsp. *helvetica* O. Müll	.	×	.	.	.
Cyclotella comta Kütz	.	.	×	.	.
C. Kützingiana Thwaites	.	.	×	.	.
C. Meneghiniana Kütz	.	×	.	.	.
C. comensis Grun	.	.	×	.	.
C. ocellata Pant	.	.	×	.	.
Stephanodiscus astraea (Ehr) Grun	×	.	.	.	.
S. astraea var. *minutula* (Kutz) Grun	×	.	.	.	.
S. dubius Hust.	×	.	.	.	.
S. sp A	.	.	.	.	×
S. sp B	.	.	.	.	×
Tetracyclus lacustris Ralfs	.	.	.	.	×
Tabellaria flocculosa (Grun) Knudson	.	.	.	.	×

taxon	alkalibiontic	alkaliphilous	indifferent	acidophilous	unknown
Diatoma vulgare var. *grandis* (W. Smith)	×	.	.	.	.
D. elongatum Agardh	.	.	.	.	×
D. elongatum var. *minor* Grun	.	.	.	.	×
Opephora Martyi Héribaud	.	×	.	.	.
Fragilaria crotonensis Kitton	.	×	.	.	.
F. capucina var. *lanceolata* Grun	.	.	.	.	×
F. vaucheriae (Kutz) Petersen	.	×	.	.	.
F. leptostauron (Ehr) Hustedt	.	.	.	.	×
F. construens (Ehr) Grun	.	×	.	.	.
F. construens var. *binodis* (Ehr) Grun	.	×	.	.	.
F. construens var. *venter* (Ehr) Grun	.	×	.	.	.
F. construens var. *exigua* (W. Smith) Schulz	.	.	.	.	×
F. pinnata Ehr	.	×	.	.	.
F. brevistriata Grun	.	×	.	.	.
F. inflata (Heiden) Hust	.	.	.	.	×
Asterionella formosa Hass	.	×	.	.	.
Synedra ulna (Nitzsch) Ehr	.	×	.	.	.
S. ulna var. *impressa* Hust	.	.	.	.	×
S. acus Kütz	.	×	.	.	.
S. rumpens Kütz	.	×	.	.	.
Eunotia alpina (Naeg) Hust	.	.	.	.	×
E. praerupta Ehr	.	.	.	.	×
Cocconeis placentula var. *euglypta* (Ehr) Cleve	.	×	.	.	.
C. thumensis A. Mayer	×	.	.	.	.
C. diminuta Pant	×	.	.	.	.
C. disculus Schum	.	×	.	.	.
C. pediculus Ehr	.	.	.	.	×
Achnanthes minutissima Kütz	.	.	.	.	×
A. exigua Grun	.	×	.	.	.
A. calcar Cleve	.	.	.	.	×
A. lanceolata Breb	.	×	.	.	.
A. clevei Grun	×	.	.	.	.
Rhoicosphenia curvata (Kütz) Grun	.	×	.	.	.
Gyrosigma attenuatum (Kütz) Rabh	×	.	.	.	.
G. spencerii (W. Smith) Cleve	×	.	.	.	.
Diploneis ovalis (Hilse) Cleve	.	×	.	.	.
D. ovalis var. *oblongella* (Naegeli) Cleve	.	.	.	.	×
Navicula pseudocutiformis Hust	.	.	×	.	.
N. cryptocephala Kütz	.	×	.	.	.
N. hungarica Grun	.	×	.	.	.
N. hungarica var. *capitata* (Ehr) Cleve	.	×	.	.	.
N. jarnefeltii Hust	.	.	.	.	×
N. radiosa Kütz	.	.	×	.	.
N. tuscula (Ehr) Grun	×	.	.	.	.
N. tusculoides Cleve-Euler	×	.	.	.	.
N. scutelloides W. Smith	×	.	.	.	.
N. oboensis (Cleve) Hust	.	×	.	.	.
Pinnularia fasciata Lagerstedt	.	.	.	.	×
P. gibba Ehr	.	.	.	×	.
Amphora ovalis Kütz	.	×	.	.	.
A. ovalis var. *pediculus* Kütz	.	×	.	.	.
Cymbella microcephala Grun	.	×	.	.	.
C. turgida (Gregory) Cleve	.	×	.	.	.
C. ventricosa Kütz	.	.	×	.	.

taxon	alkali-biontic	alkali-philous	indifferent	acido-philous	unknown
C. hybrida Grun	.	.	.	.	×
C. affinis Kütz	.	×	.	.	.
C. sinuata Gregory	.	.	×	.	.
C. cuspidata Kütz	.	.	.	.	×
C. aspera (Ehr) Cleve	.	×	.	.	.
Cymbellonitzschia diluviana Hust	.	.	.	.	×
Gomphonema acuminatum var. *coronata* (Ehr) W. Smith	.	×	.	.	.
G. olivaceum (Lyngbye) Kütz	×	.	.	.	.
G. olivaceum var. *calcarea* Cleve	×	.	.	.	.
G. constrictum Ehr	.	.	.	.	×
Epithemia argus Kütz	×	.	.	.	.
E. muelleri Fricke	.	×	.	.	.
E. turgida Kütz	×	.	.	.	.
E. zebra Kütz	×	.	.	.	.
E. sorex Kütz	.	×	.	.	.
Rhopalodia gibba (Ehr) O. Müll	.	×	.	.	.
Nitzschia dissipata (Kütz) Grun	.	×	.	.	.
N. fonticola Grun	×	.	.	.	.
N. palea (Kütz) W. Smith	.	.	×	.	.
N. sinuata var. *tabellaria* Grun	.	.	.	.	×
N. gracilis Hantzsch	.	.	×	.	.
N. frustulum var. *subsalina* Hust	.	×	.	.	.
N. Kützingiana Hilse	.	×	.	.	.
Cymatopleura elliptica var. *hibernica* (W. Smith) Hust	.	×	.	.	.
Surirella turgida W. Smith	.	.	.	.	×
S. ovata Kütz	.	.	.	.	×
total	17	42	10	1	23

DESCRIPTION OF PLATE 1. (all magn. × 1200)

1. *Melosira italica* subsp. *subarctica* O. Müll.
2. *Melosira italica* subsp. *subarctica* (different focus).
3. *M. ambigua* (Grun.) O. Müll.
4. *M. ambigua* (different focus).
5. *M. islandica* subsp. *helvetica* O. Müll.
6. *M. islandica* subsp. *helvetica* (different focus).
7. *Cyclotella comta* Kütz.
8. *C. ocellata* Pant.
9. *C. ocellata* Pant.
10. *C. comensis* Grun.
11. *C. Kützingiana* Thwaites.
12. *C. Meneghiniana* Kütz.
13. *Stephanodiscus astraea* (Ehr) Grun.
14. *S. astraea* (different focus).
15. *S. astraea* var. *minutula* (Kütz) Grun.
16. *S. astraea* var. *minutula* (Kütz) Grun.
17. *S.* sp A.
18. *S.* sp A.
19. *S. dubius* Hust.
20. *S.* sp B.
21. *S.* sp B.
22. *Tabellaria flocculosa* (Grun) Knudson (girdle view).
23. *Tabellaria flocculosa* (Grun) Knudson (valve view).
24. *Asterionella formosa* Hass.
25. *Synedra rumpens* Kütz.
26. *Navicula cryptocephala* Kütz.
27. *Diatoma elongatum* var. *minor* Grun.
28. *Rhoicosphenia curvata* (Kütz) Grun (girdle view).
29. *Cymbellonitzschia diluviana* Hust.

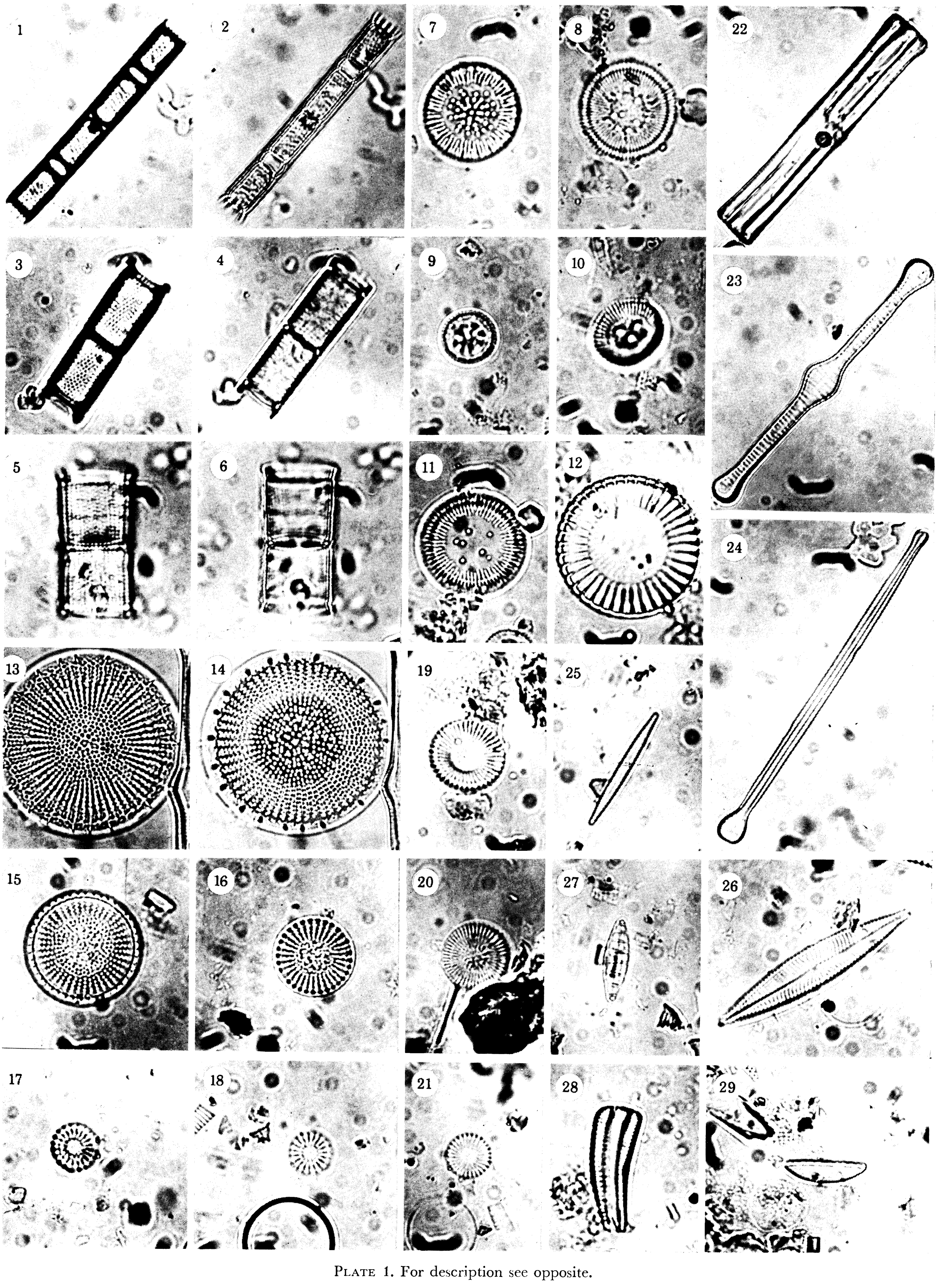
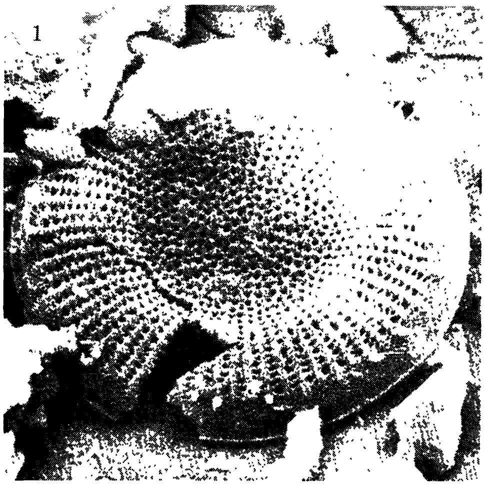
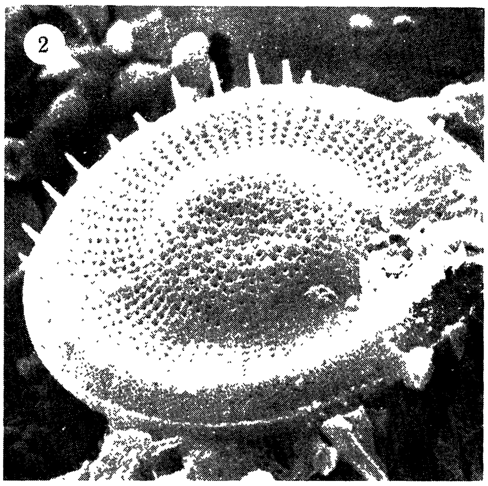


PLATE 1. For description see opposite.

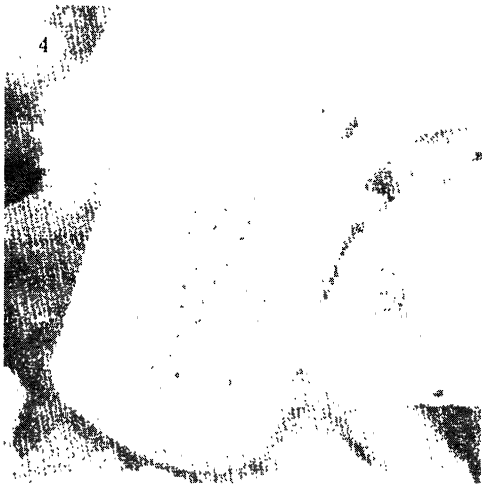
DESCRIPTION OF PLATE 2

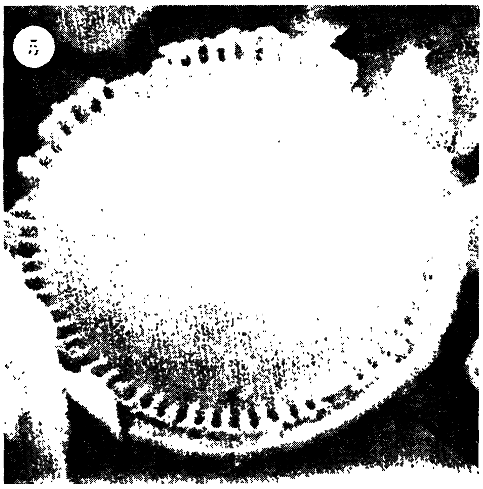
1. *Stephanodiscus astraea* (Ehr) Grun (magn. 1670). Valve fractured and pores widened, spines short or missing.
2. *S. astraea* (Ehr) Grun (magn. 1800). Valve largely intact and uncorroded.
3. *Melosira italica* subsp. *subarctica* O. Müll (magn. 4570). Valve badly corroded, some pores coalescing.
4. *M. italica* subsp. *subarctica* O. Müll (magn. 5110). Well-preserved valve.
5. *Cylotella comensis* Grun (magn. 4270). Rim of valve and pieces of mantle missing.
6. *C. comensis* Grun (magn. 3700). Rim and mantle intact.
7. *C. ocellata* Pant (magn. 4160). Rim of valve completely corroded.
8. *C. ocellate* Pant (magn. 4020). Valve intact.

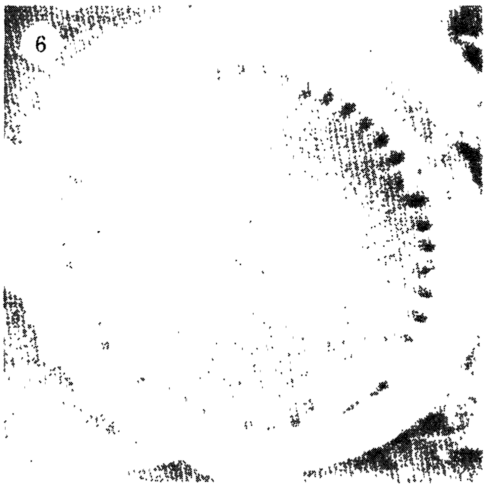

1

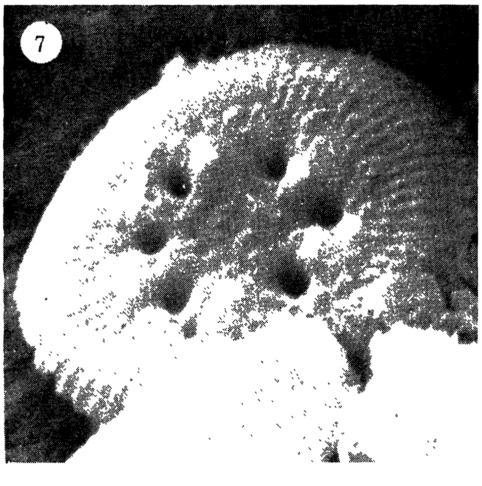

2

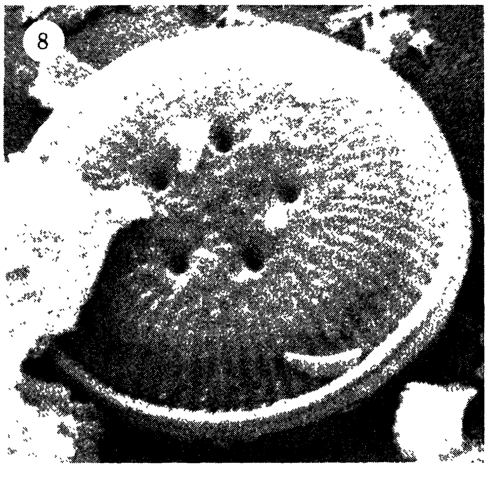

3

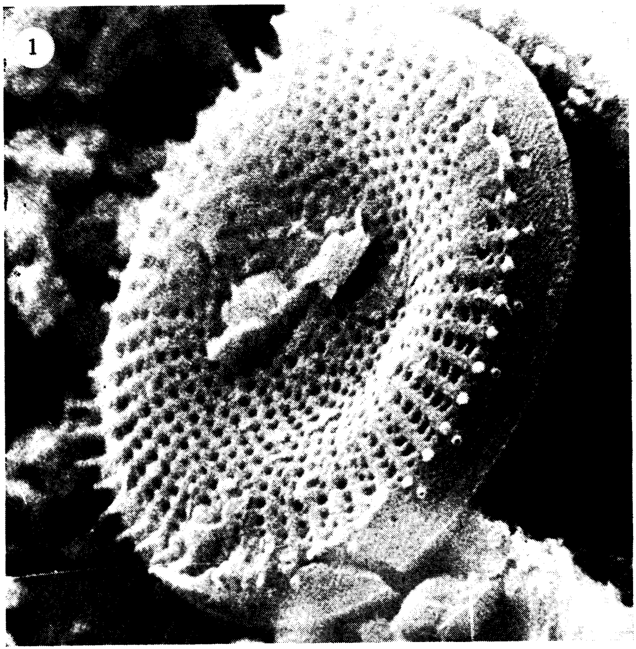

4

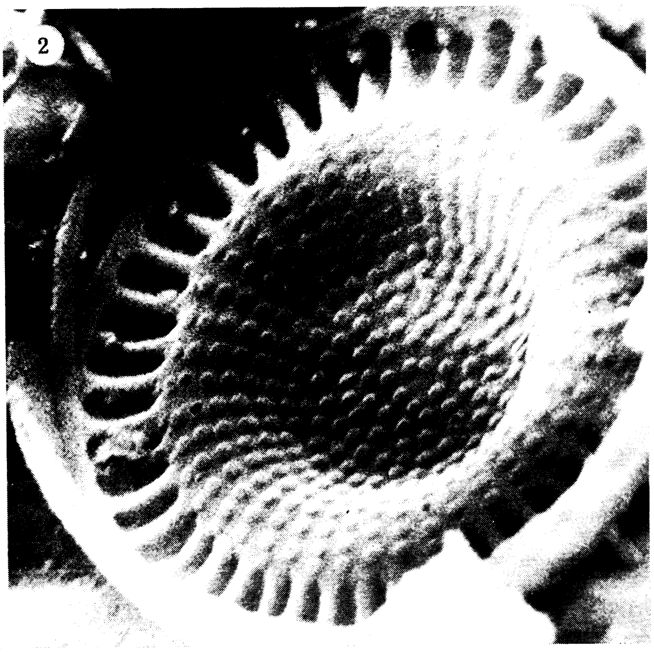

5


6

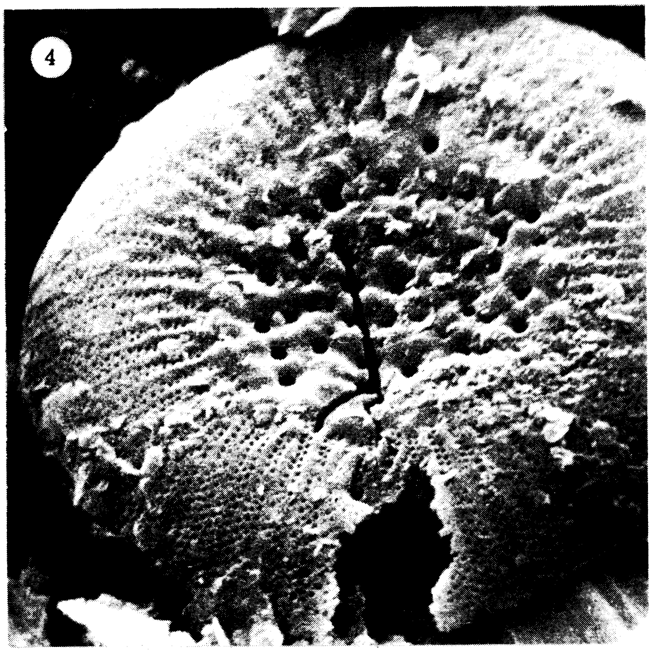

7

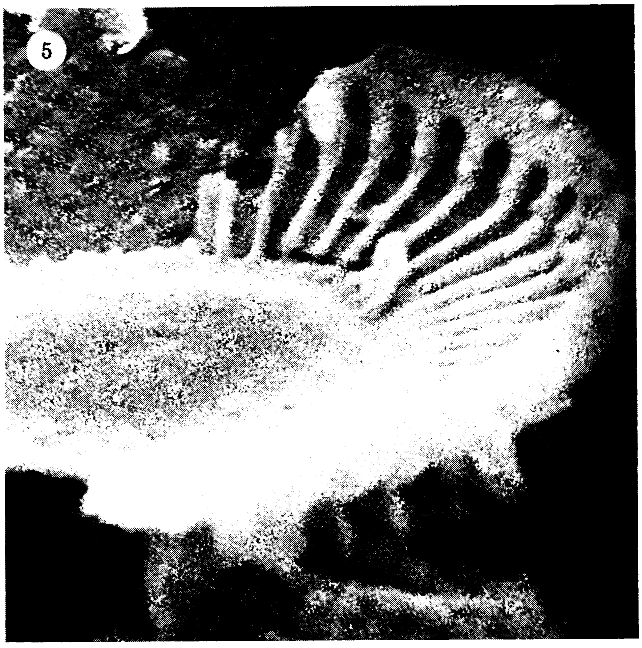

8


①


②


③


④


⑤


⑥

PLATE 3. For description see opposite.

Description of plate 3

1. *Stephanodiscus astraea* var. *minutula* (Kütz) Grun (magn. 3860).
2. *S. dubius* Hust (magn. 5770).
3. *Cyclotella comta* Kütz (magn. 2540).
4. *C. comta* Kütz (magn. 5260).
5. *C. Meneghiniana* Kütz fragment (magn. 5240).
6. *Tabellaria flocculosa* (Grun) Knudson (magn. 2960).

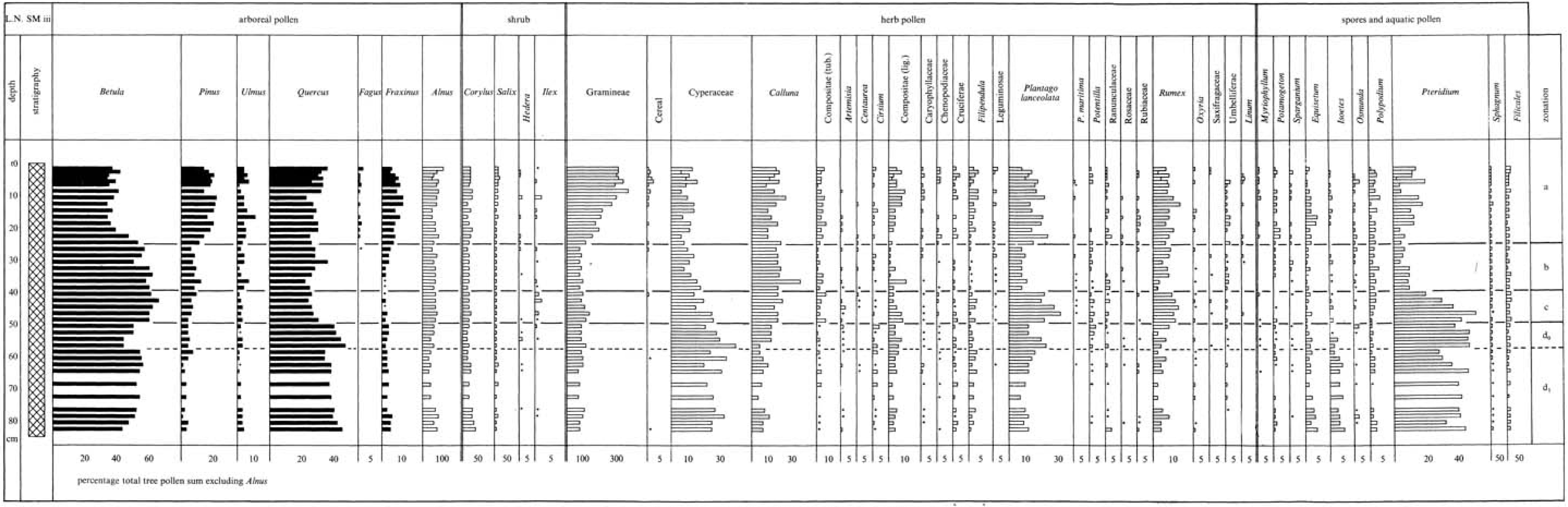


FIGURE 6. Relative pollen diagram for SM iii based on the total tree sum, excluding *Alnus* and *Corylus*.

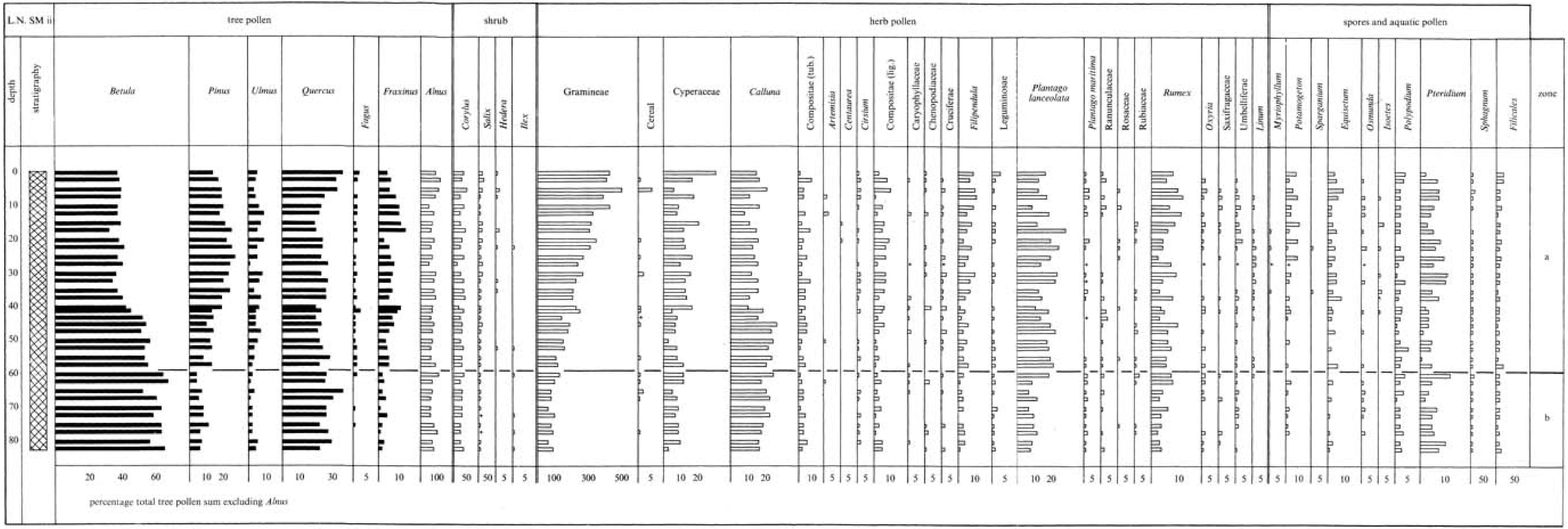
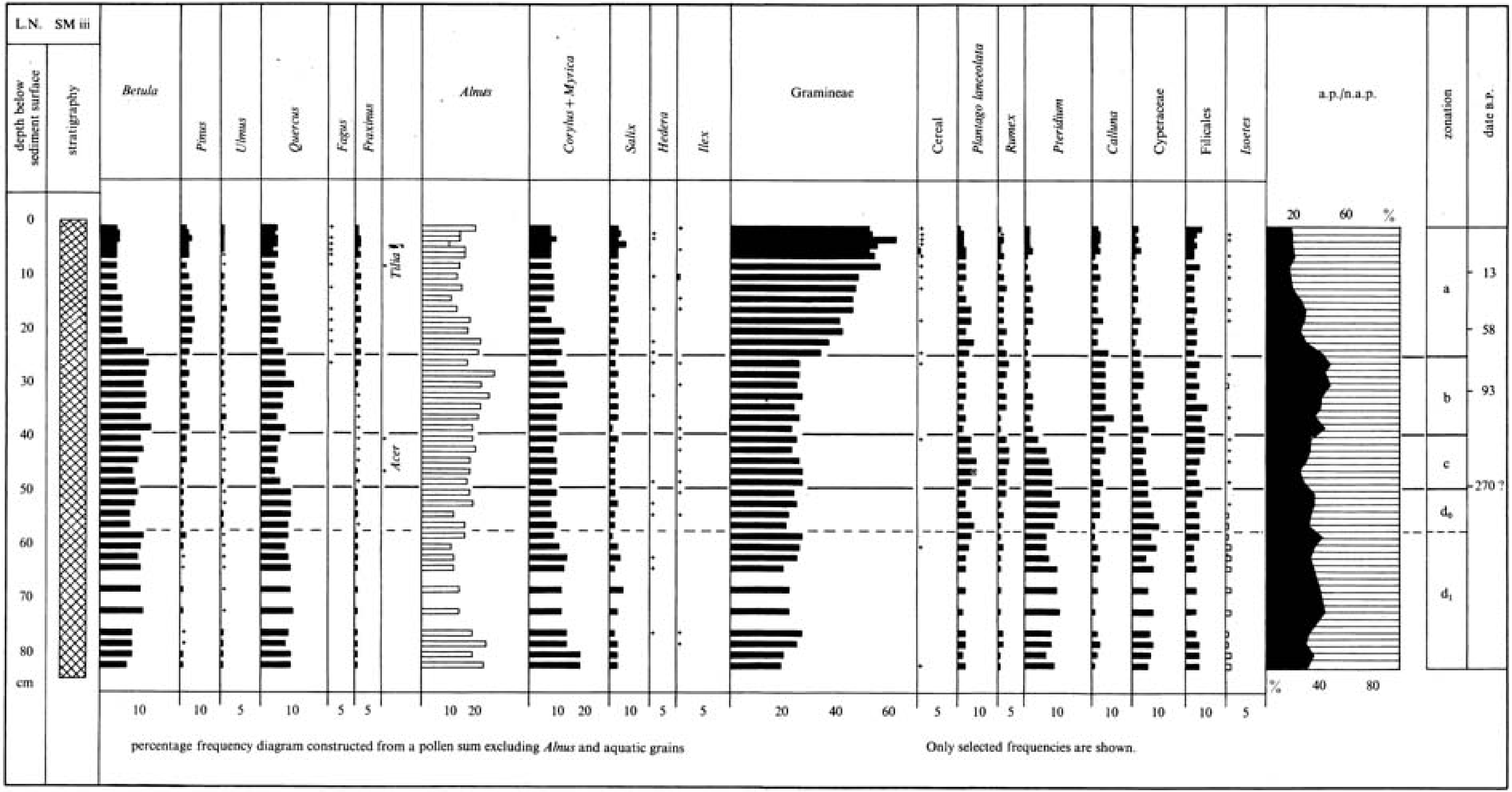


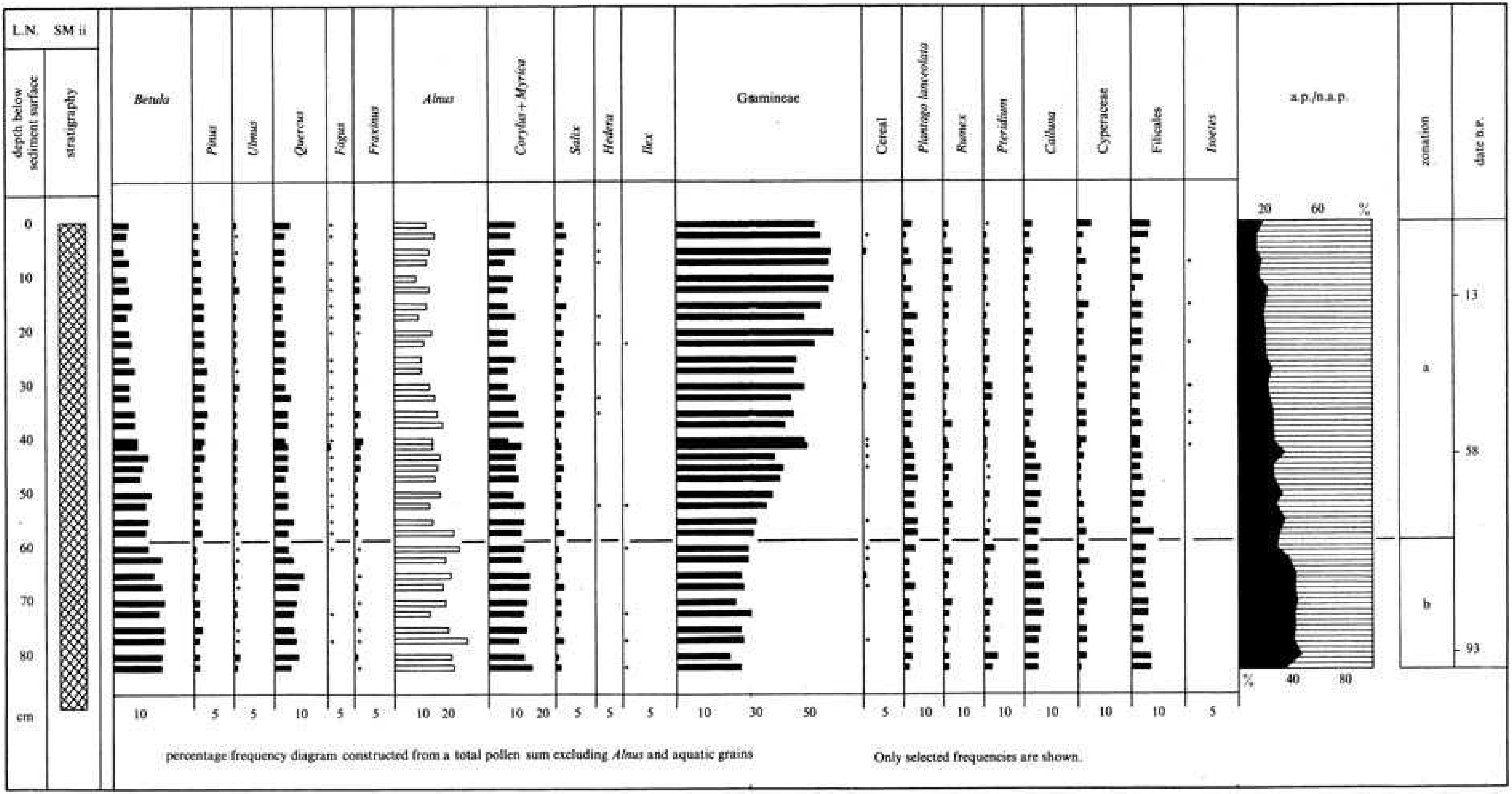
FIGURE 8. Relative pollen diagram for SMii, based on the total tree sum, excluding *Alnus* and *Corylus*.



percentage frequency diagram constructed from a pollen sum excluding *Alnus* and aquatic grains

Only selected frequencies are shown.

FIGURE 7. Relative pollen diagram for SMiii based on the dry land pollen sum, excluding *Alnus*. Dates refer to years B.P. (1969) and are derived from the time–depth data of figure 19.



percentage frequency diagram constructed from a total pollen sum excluding *Alnus* and aquatic grains

Only selected frequencies are shown.

FIGURE 9. Relative pollen diagram for SMii, based on the dry land pollen sum, excluding *Alnus*. Dates refer to years B.P. (1969) and are derived from the time-depth data of figure 19.

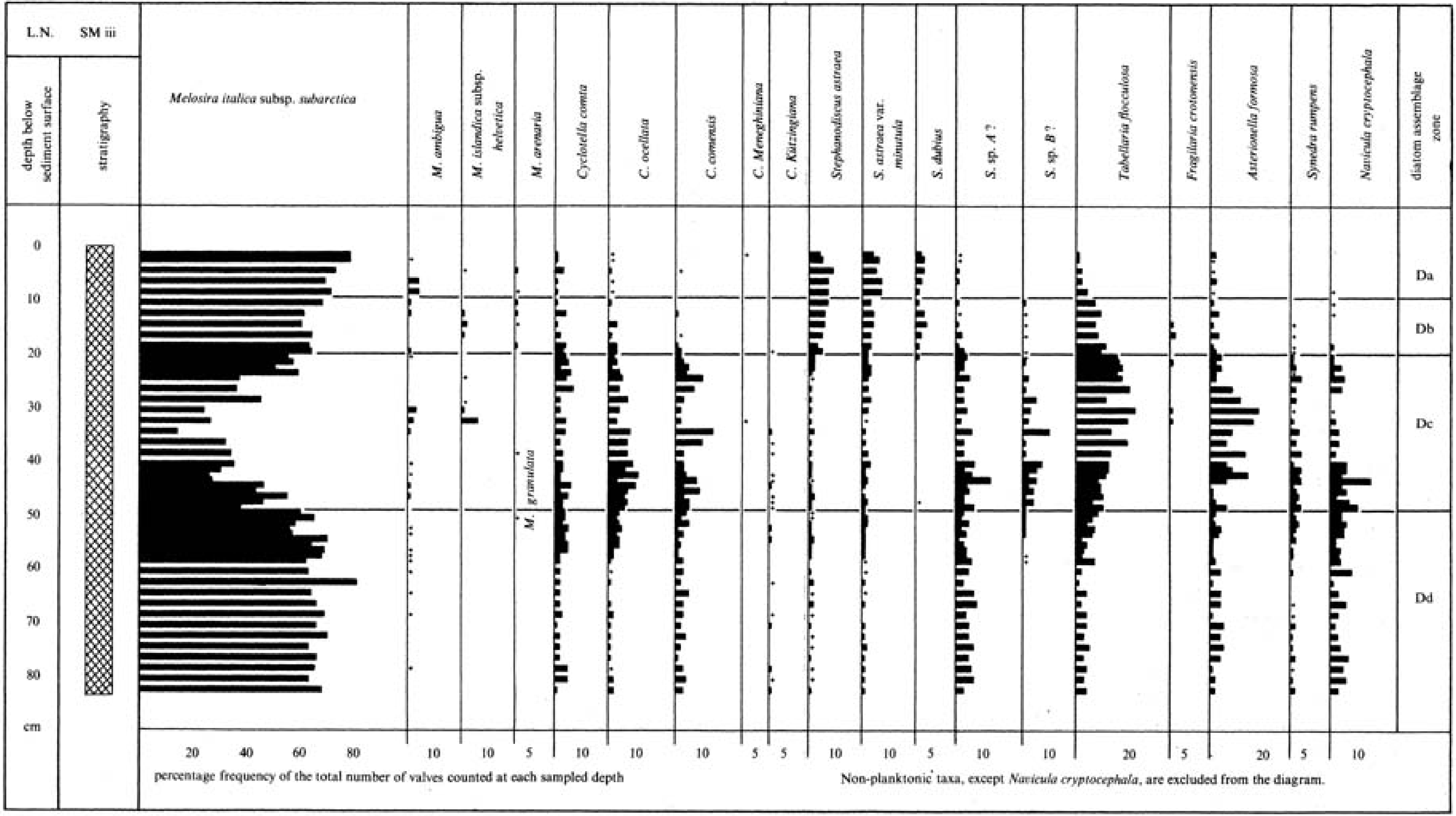


FIGURE 10. Relative diatom diagram for SMiii (from Battarbee 1973*b*).

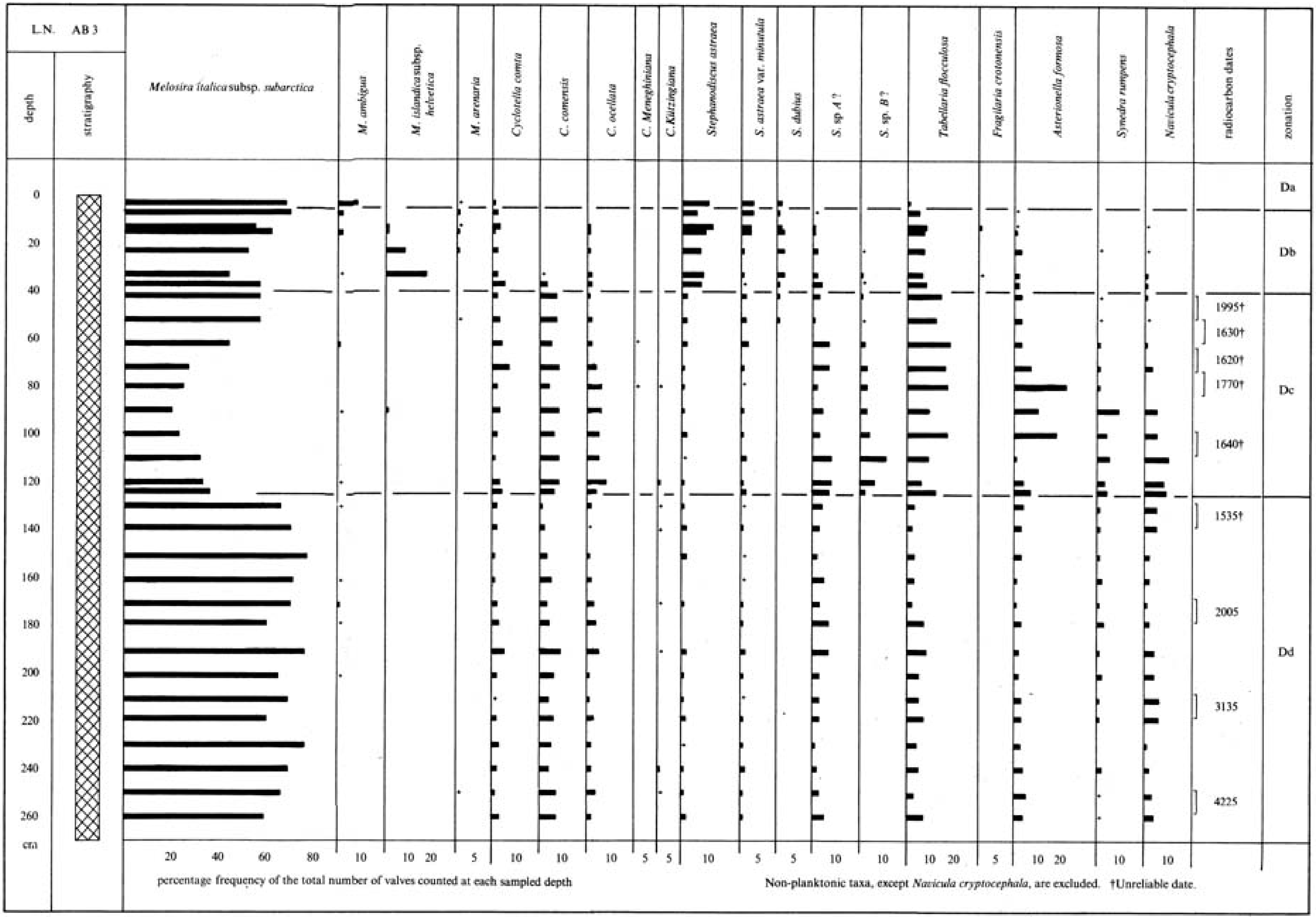


FIGURE 11. Relative diatom diagram for AB3.

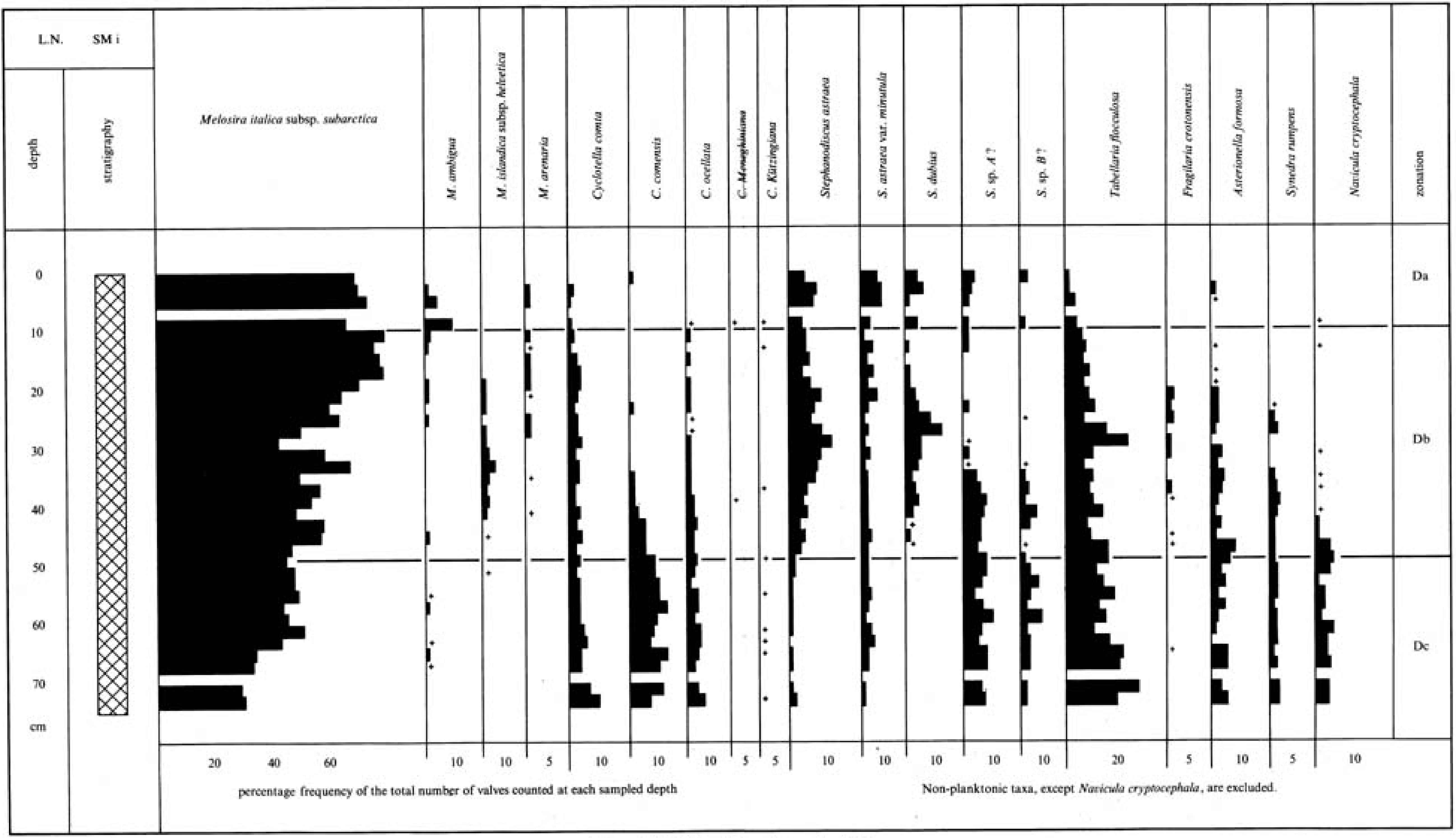


FIGURE 12. Relative diatom diagram for SMi.

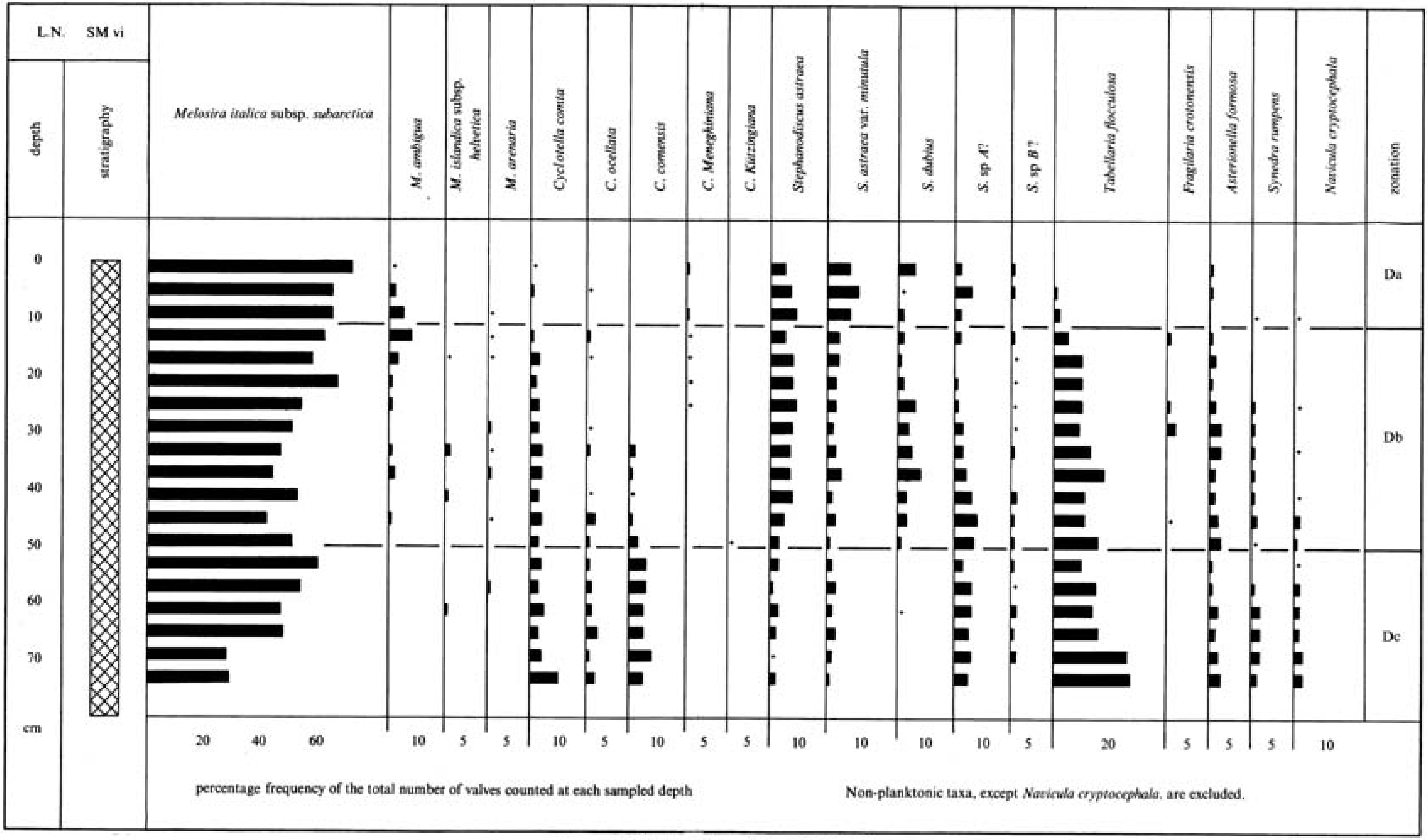


FIGURE 13. Relative diatom diagram for SM vi.

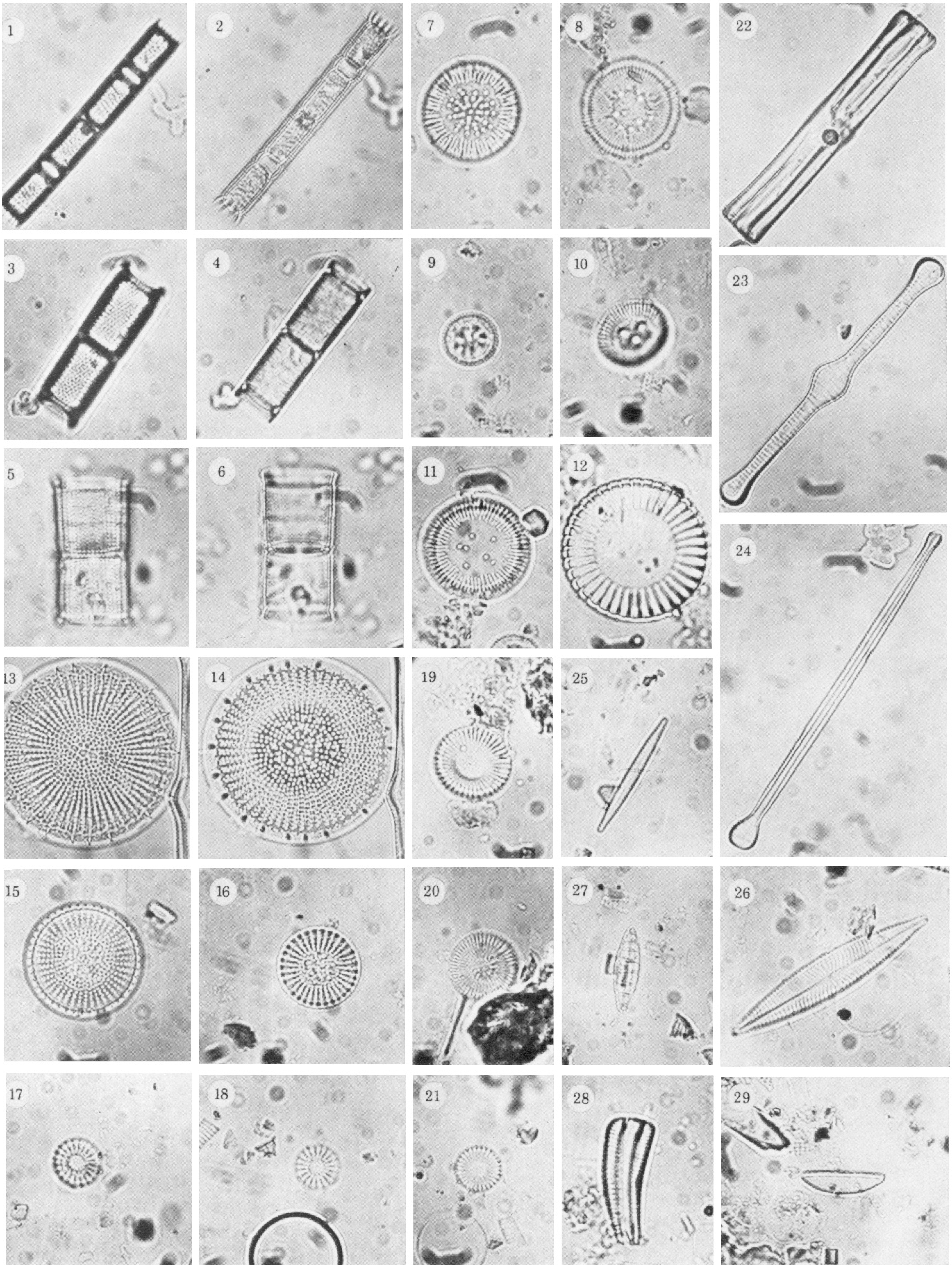
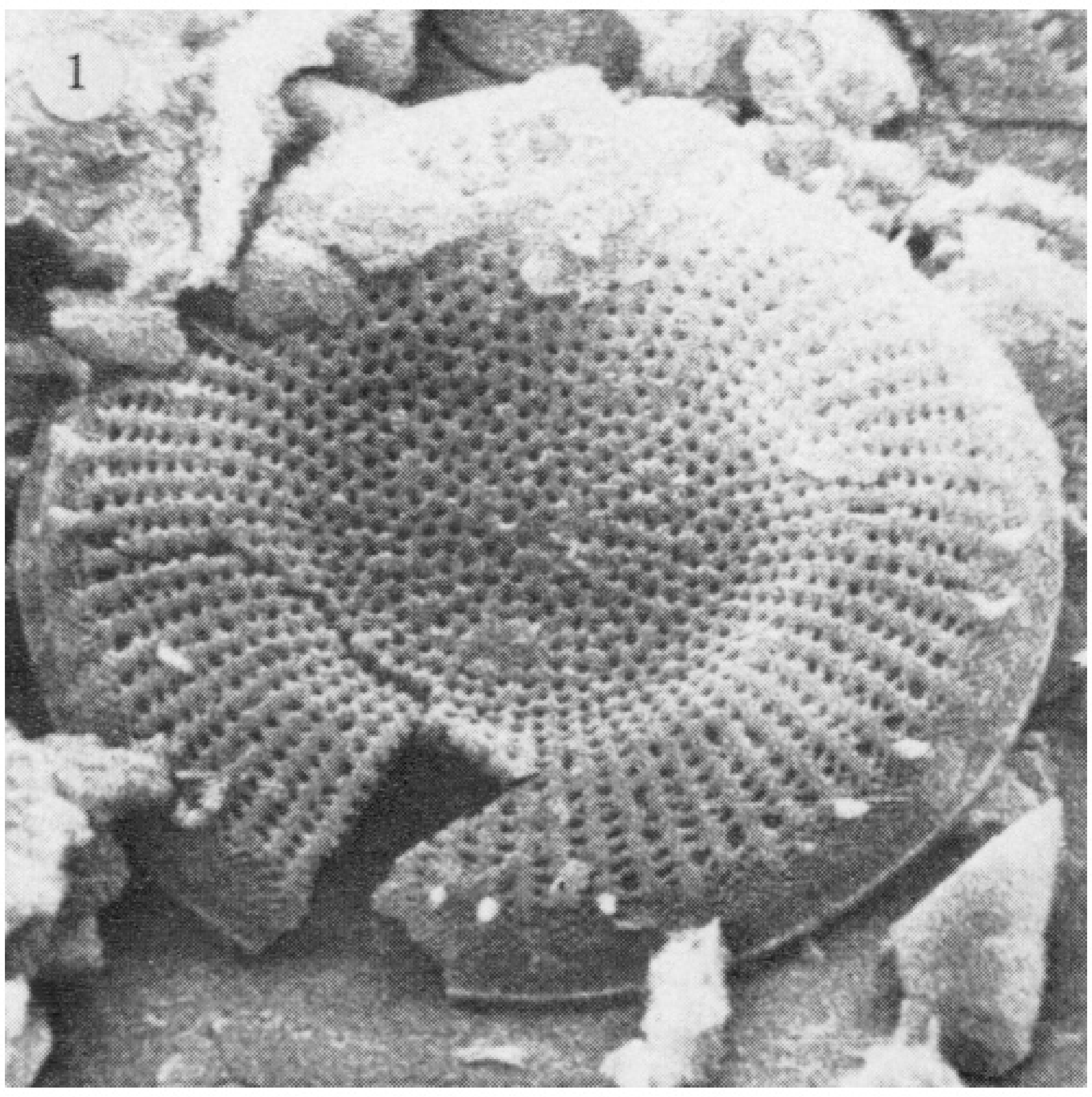
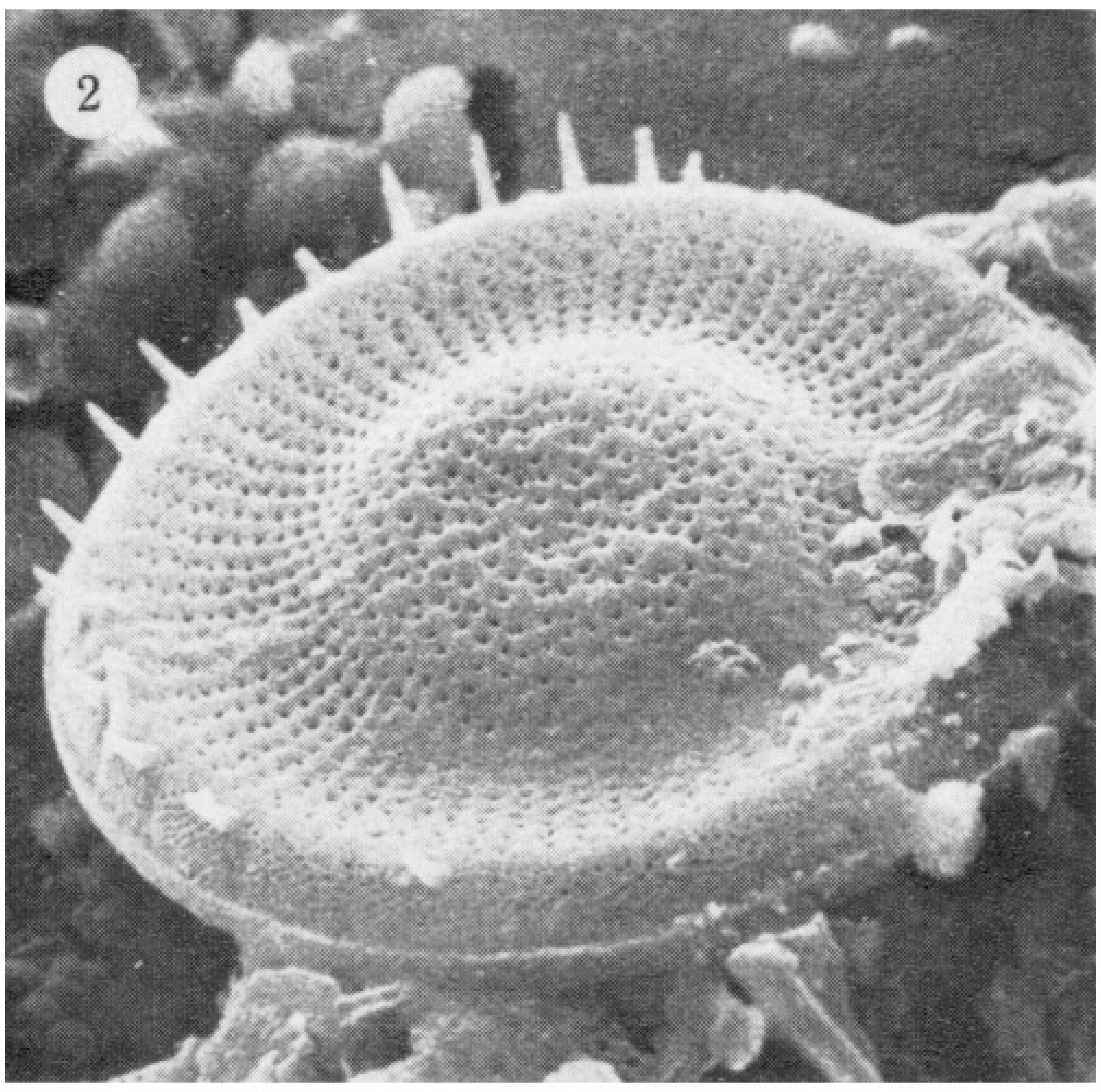
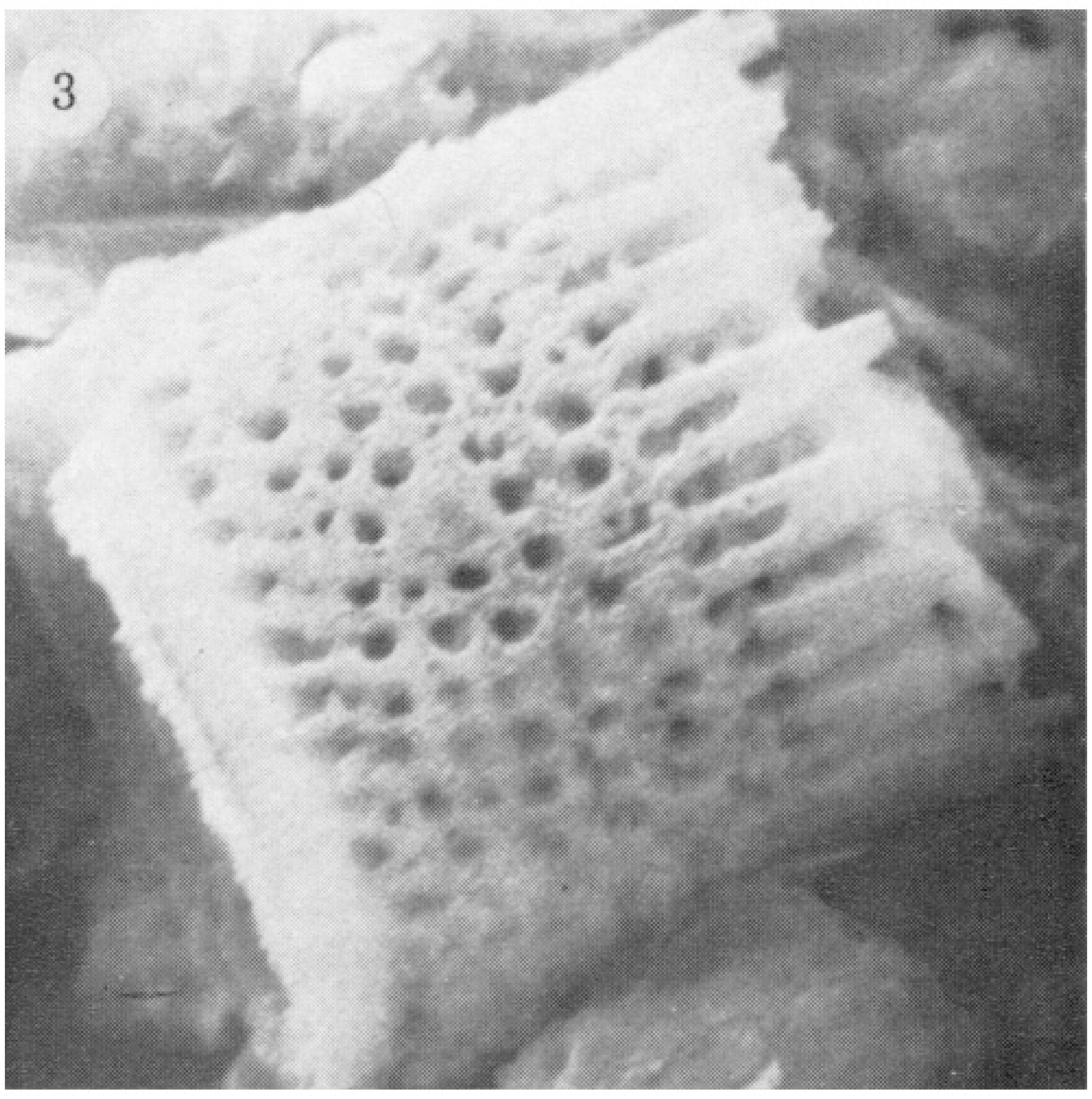
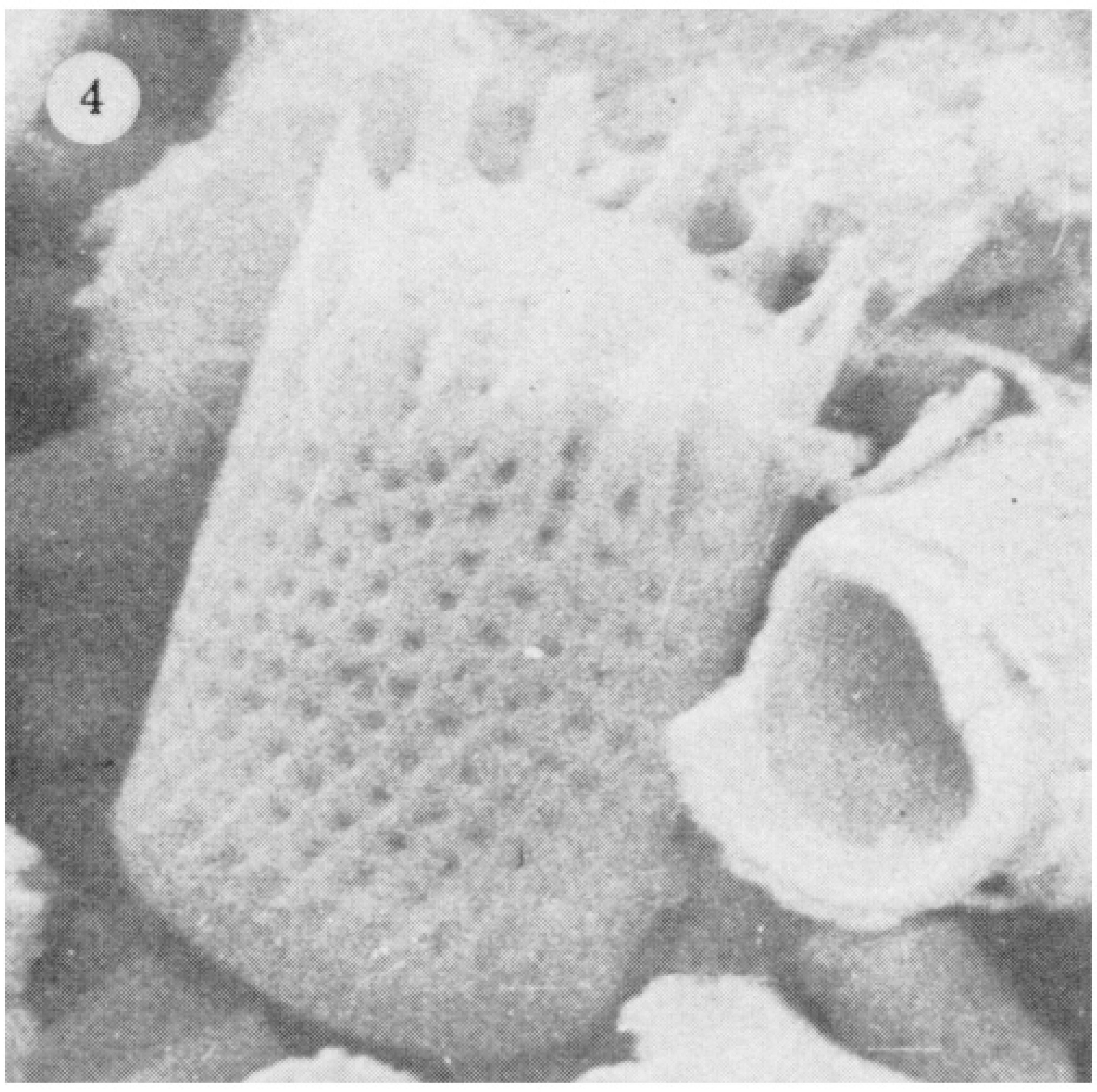


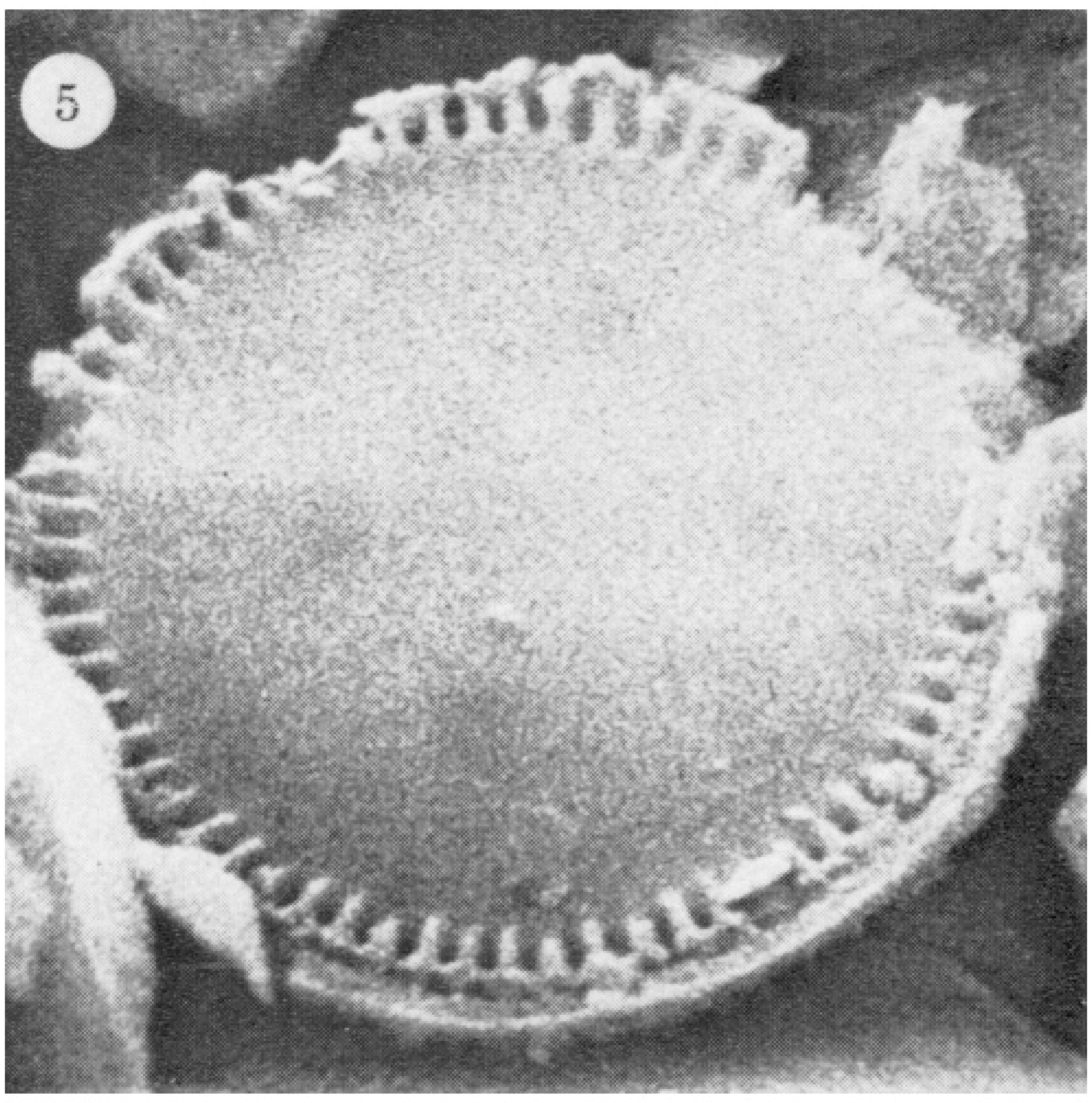
Plate 1. For description see opposite.

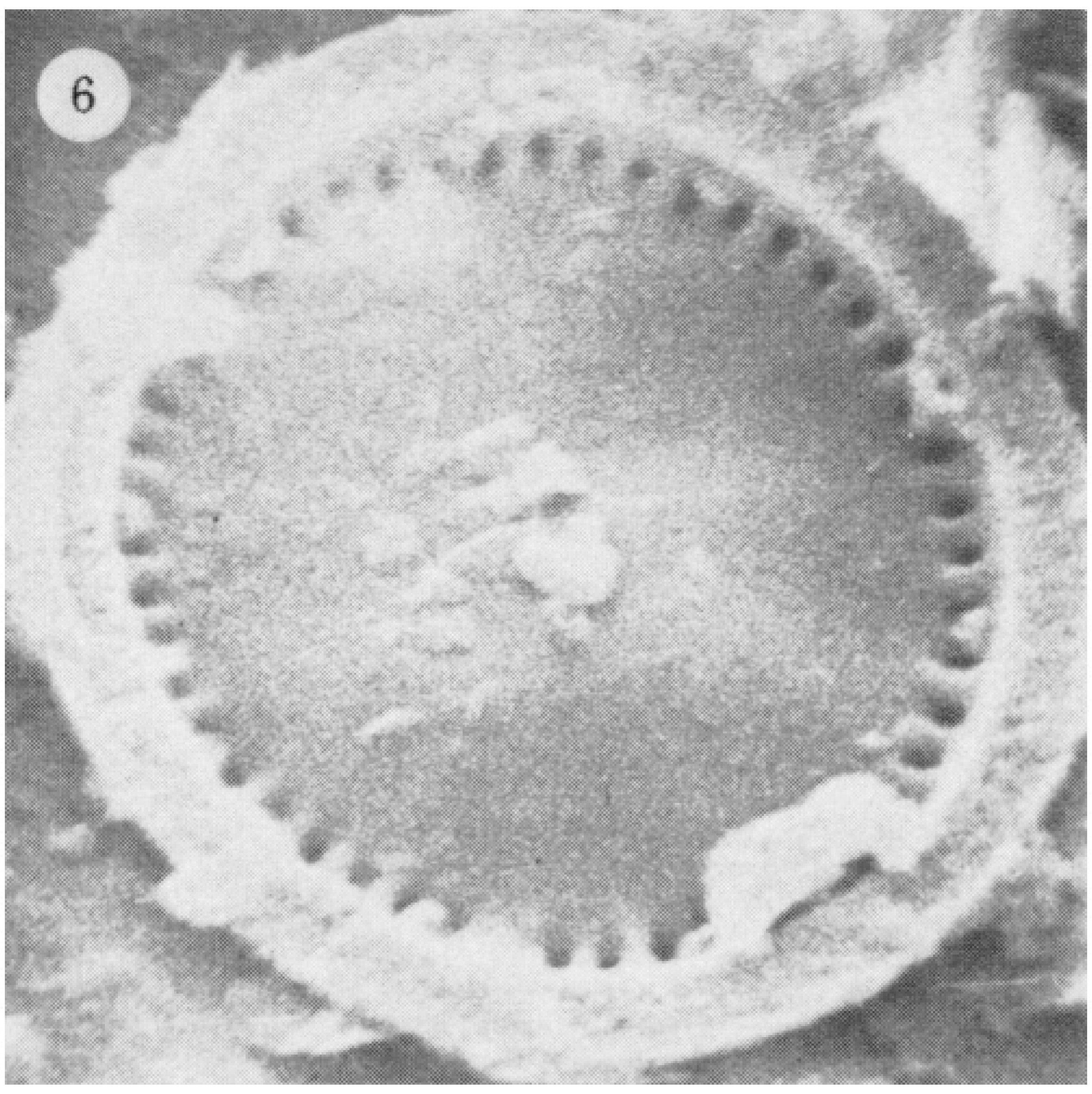

1

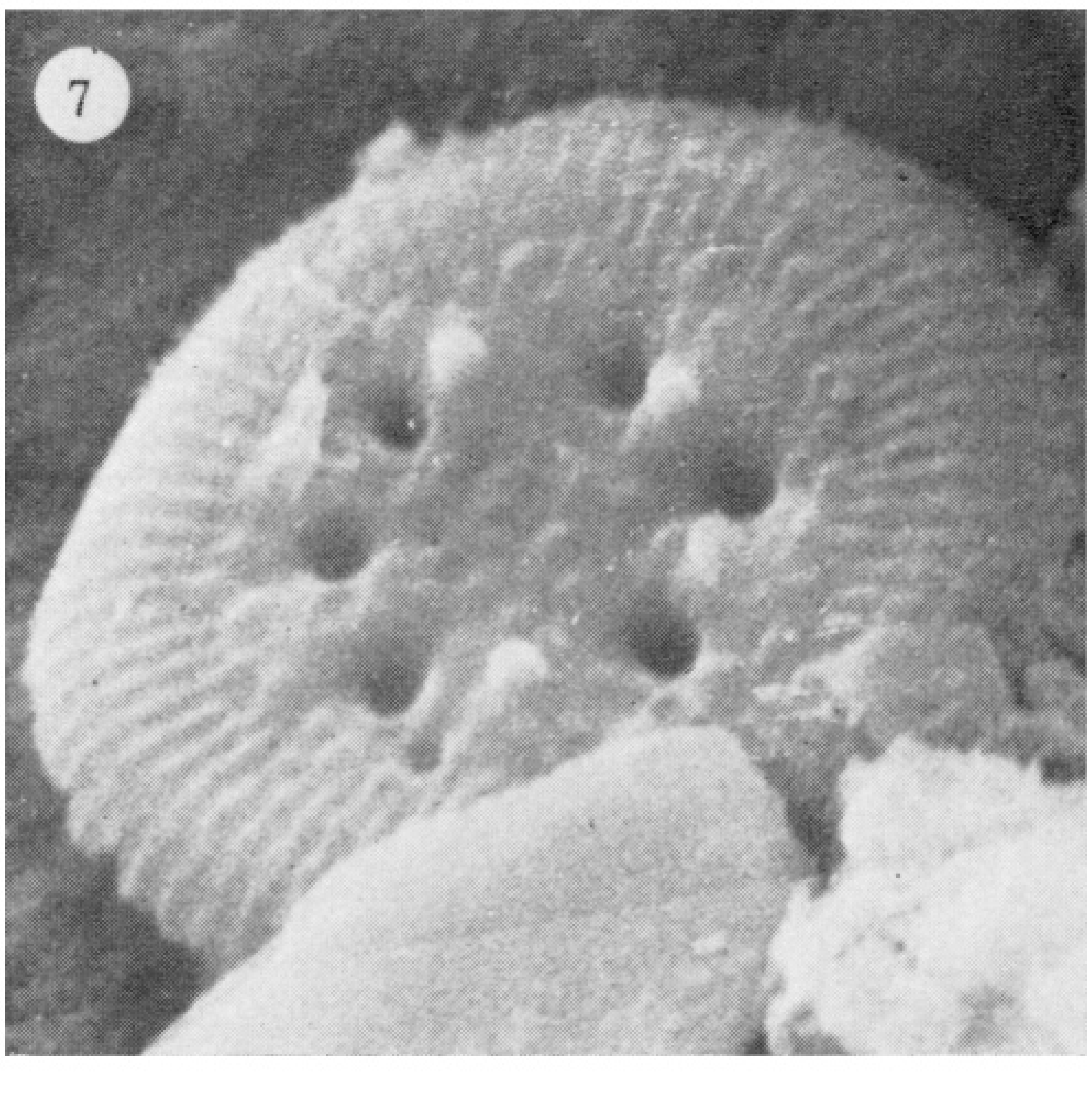

2


3


4


5


6


7

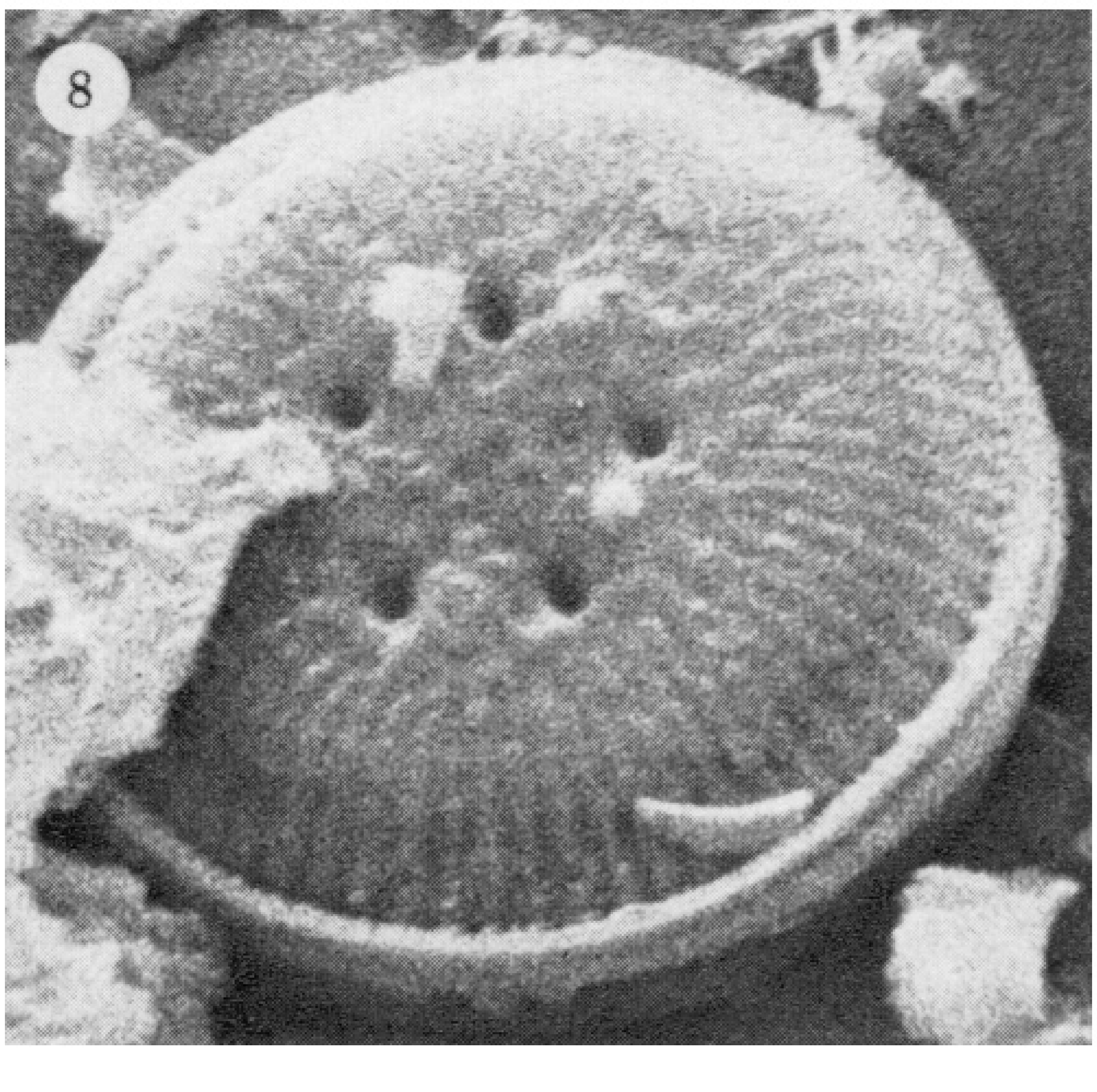

8

Plate 3. For description see opposite.