PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Studies of the Post-Glacial History of British Vegetation. VII. Lake Sediments: Pollen Diagrams from the Bottom Deposits of the North Basin of Windermere

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STUDIES OF THE POST-GLACIAL HISTORY OF BRITISH VEGETATION

VII. LAKE SEDIMENTS: POLLEN DIAGRAMS FROM THE BOTTOM DEPOSITS OF THE NORTH BASIN OF WINDERMERE

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[Plate 2]

CONTENTS

Eight pollen diagrams from cores lying approximately on an east to west transect across the North Basin of Windermere and macroscopic plant remains identified from these cores are described and figured.

The marginal cores show a well-developed late-glacial succession of two layers of barren laminated glacial clay, separated by a detritus silt containing plant remains which indicate a cold-temperate birchwood flora; it is suggested that this succession may be correlated with the Upper and Lower *Dryas* clays separated by the cold-temperate Allerød layer of Continental authors.

The post-glacial deposits, which are most completely represented in the deep-water cores, show similar phases of forest history to those already recognized in England and Wales, but the apparent over-representation of *Pinus* in deep-water deposits and the absence of *Fagus* and *Carpinus* introduce complications into any attempt to apply to these deposits the zonation scheme worked out for the East Anglian fenland.

Introduction

The results of an investigation of the stratigraphy and diatom sequence in the Windermere deposits have already been published (Pennington 1943). The present paper deals with the results of pollen analysis of selected profiles on a transect across the lake, and with the macroscopic plant remains found in the deposits, especially those of late-glacial age. Evidence obtained from these latter investigations has made it possible to date the lake deposits with more accuracy than formerly, and by the light it throws on the late-glacial and post-glacial vegetational sequence in the Windermere basin has made it possible to fit this region into the general picture of the Quaternary history of the British Isles. Further examination of the late-glacial plant-bearing layer described in the previous paper has confirmed the view that it represents a late-glacial climate amelioration followed by a colder period and then by the final retreat of the ice. A similar layer has been recognized right across Ireland, and its discovery in England was expected. It seems possible that it may be correlated with a similar succession in Denmark and other parts of north-west Europe, and afford a means whereby the British succession could be linked with the Continental succession and De Geer's geochronology; the evidence in favour of such a correlation is put forward in the course of this paper.

Method

The principles of the pollen-analysis method have been described by Godwin (1934). They apply to subaqueous in the same way as to terrestrial deposits. Samples of the Windermere deposits were obtained by the Jenkin core-sampler, which has already been described (Jenkin, Mortimer & Pennington 1941).

It will be apparent that some of the indicator species—*Fagus*, *Carpinus*—present in the deposits of southern England are absent in Windermere. This makes it difficult to compare the later stages in the two localities, but the earlier post-glacial stages correspond closely, and the Windermere profile carries back the story into the late-glacial period, the deposits of which have not yet been described from southern England, though they have been recognized, e.g. in Cornwall (Godwin 1940*b*).

It seems unlikely that it will ever be possible to obtain any direct archaeological correlation with the Windermere deposits, but the site is in some ways unique in its association of organic deposits with laminated clays which have every appearance of being true waterlain varves, and hence offer a possibility of applying a geochronological time-scale.

Preparation

(1) *Organic muds*

While still wet, the muds readily went into suspension in water, though prolonged stirring was necessary with the clays. Plant remains were extracted by sieving this suspension through a fine sieve (0·16 mm. mesh). In nearly all deposits from deep water the plant remains were in a very finely divided state, but this treatment collected all fragments of recognizable size.

For pollen counts, either fresh wet mud or the sieved suspension after centrifuging was treated by a modification of Erdtman's technique, involving oxidation by sodium chlorate followed by hydrolysis with hot acid. After washing, the samples from marginal sites were then mixed with hot safranin-glycerine jelly and stirred; four comparable slides were then made from this suspension. Samples from deep water were, after acid hydrolysis and washing, boiled from 2 to 3 min. in concentrated hydrofluoric acid to remove silica and silicates; they were then washed first in 7% hydrochloric acid and then in water, and mounted as described. This removal of silica and silicates was necessary in all samples from deep water, in order to obtain a sufficient concentration of pollen for counting. Even so, in some of these samples it was not possible to count more than 100 grains of tree pollen. In most samples, 150 grains of tree pollen were counted.

The results of the pollen counts are expressed as percentages of total tree pollen, *Corylus* and *Salix* not being included in the tree pollen. Non-tree pollens, including *Corylus* and *Salix*, are expressed as percentages of the total tree pollen.

(2) *The laminated clays*

In any attempt to measure or count the varves, the most satisfactory treatment of the laminated clays was found to be to allow the core to dry completely, when a plane surface could be prepared by scraping the clay with a razor. The difference in texture between the summer and winter layers could then be shown up more clearly by treating the core with a mixture of oil and xylol (or petrol) in approximately equal proportions, a method for which I am indebted to Professor T. M. Harris. It was inevitable that cracks and breaks should appear in the core during the drying process; these interfered with the measurement and counting of the varves, and were especially troublesome in the lower part of the laminated clay, where the texture differences were more marked. It seems possible that some technique of impregnation may be found to prevent the cracking on drying. Glycerine, recommended by De Geer, was not satisfactory, since it produced a crumbly texture and made it impossible to prepare the plane surface necessary for microscopic examination. Melted paraffin wax, used by Carruthers (1939) would not penetrate until the clay had dried out sufficiently to initiate cracks; but impregnation with paraffin wax did serve to harden the specimens and render them more portable.

Local influences

In peat deposits formed subaerially, the pollen content may include a component derived from the vegetation which grew on the actual surface of the peat. Godwin (1940*a*) points out that this local component may materially influence the pollen diagrams from Fenland. The Windermere deposits, on the other hand, must have received all their pollen from the surrounding land, since there is no evidence whatever to suggest that the lake level has at any time since the formation of the lake been lower than it is to-day. The changing composition of the pollen content of the lake deposits can therefore be expected to reflect the forest history of the surrounding land, undisturbed by purely local influences.

There is, however, at some horizons, a marked difference between the pollen spectra of similar age from deep- and shallow-water profiles respectively, suggesting that the marginal pollen rain may be different in composition from that reaching the middle of the lake. Other possible causes of this difference, which related chiefly to the proportions of *Pinus* to deciduous pollens, are discussed later.

Though the accumulation of lake deposits is not subject to direct climatic effects such as the possible erosion of peat deposits during a dry period, the pollen diagrams show that the rate of accumulation of deposit must have varied considerably both in different parts of the lake at the same time, and at different times in the same part of the lake. Mitchell (1940) found similar variations demonstrated by the deposits of an old lake basin in Eire. These variations in deposition rate in lakes in glaciated areas must presumably be due to indirect climatic effects; partly to the decrease in readily transported debris as the post-glacial climatic amelioration led to stabilization of the land surface by a plant cover, and partly to the effects of erosion and deposition by wind-produced currents in the water. The effect of these variations is to complicate the interpretation of the pollen diagrams and make it necessary to consider profiles from many parts of the lake before drawing any conclusions about either the relative length of the successive phases of forest history and the climatic periods which they indicate, or the relation of the stratigraphy of the deposits to the time-scale provided by forest history.

Derived pollen from the boulder clay has been shown to be present in lacustrine clay beds in Denmark (Iversen 1936), but in view of the fact that no more than an occasional grain of pollen has been found in the Windermere lower laminated clay, which presumably contains redeposited boulder clay, it is probable that there is very little derived pollen in the succeeding deposits.

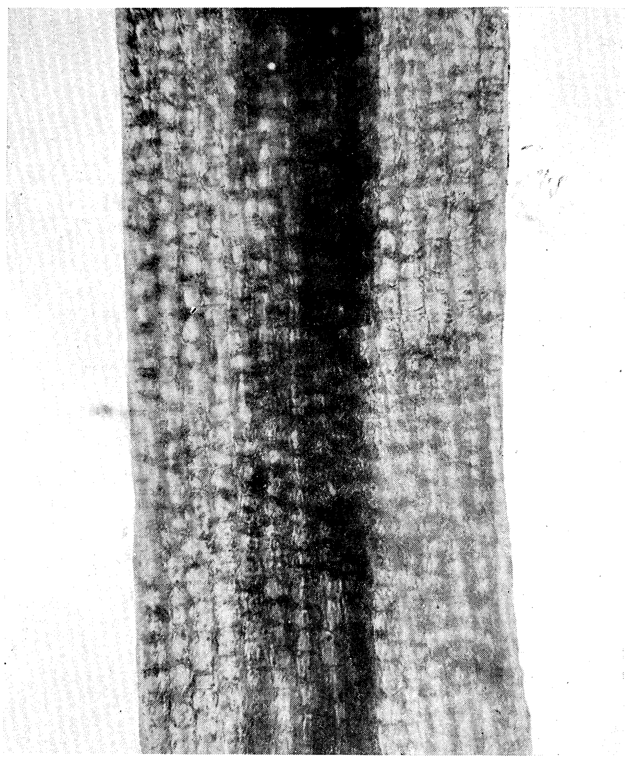
General stratigraphy (notes additional to 1943 paper)

(1) *Laminated clays*

The appearance of the laminated clays forming the lower part of the deposits suggests strongly that the laminations represent varves, or annual laminations formed by the seasonal deposition from glacial drainage into standing water. They could therefore be compared with the Swedish varved clays, deposited by the Scandinavian ice-sheet in a fresh-water portion of the Baltic, which form the basis of De Geer's geochronology (De Geer 1908 et seq.). In his later work (De Geer 1921, 1927, 1929 and 1930) De Geer claimed to have extended the varve correlations not only throughout Sweden but both trans-Atlantically and trans-equatorially. Time and further work will show whether these 'teleconnexions' will stand critical examination, but the correlations and consequent time-scale for Sweden are now generally accepted, and it would appear possible that the correlation might be extended into the British Isles.

Certainly the laminations in the Windermere clays conform closely to De Geer's description of the essential characteristics of a varve (see figure 15*a*, plate 2). Each layer of coarse, more or less sandy material (the deposit of the spring-summer melt), passes gradually upwards into the fine layer of often greasy clay (the finest fraction of the sediment which settled slowly out of suspension, almost certainly under ice, during the winter). The fine layer is then succeeded abruptly by the coarse layer of the following spring melt. Each varve, or annual deposit, therefore consists of the layer which lies between two of these abrupt boundaries, and the thickness of the varve is fairly easy to determine, though the boundary between the coarse and fine deposits of a single year is often indeterminate. This interpretation of the alternations in texture in the clays is borne

(*a*) (*b*)



(*c*)

FIGURE 15. (*a*) Typical varves from the upper laminated clay in Windermere. (*b*), (*c*) Leaf segments of *Myriophyllum* sp. from the detritus silt (Zone II).

(*Facing p.* 140)

out by the observations of Kindle (1930) on sedimentation in a glacial lake—Lake Cavell in the Canadian Rockies, which receives a stream from a glacier ending $\frac{1}{3}$ mile above the lake.

Difficulties may arise in the measurement of varves owing to the presence of deceptive bands resembling the winter layers. Such layers, which De Geer calls digraphs and trigraphs, can often be distinguished by the absence of the typical sharp winter-spring junction, but in varves as narrow as those of Windermere this may be difficult to see. These very narrow varves, here averaging about 1 mm., are what De Geer (1940) terms

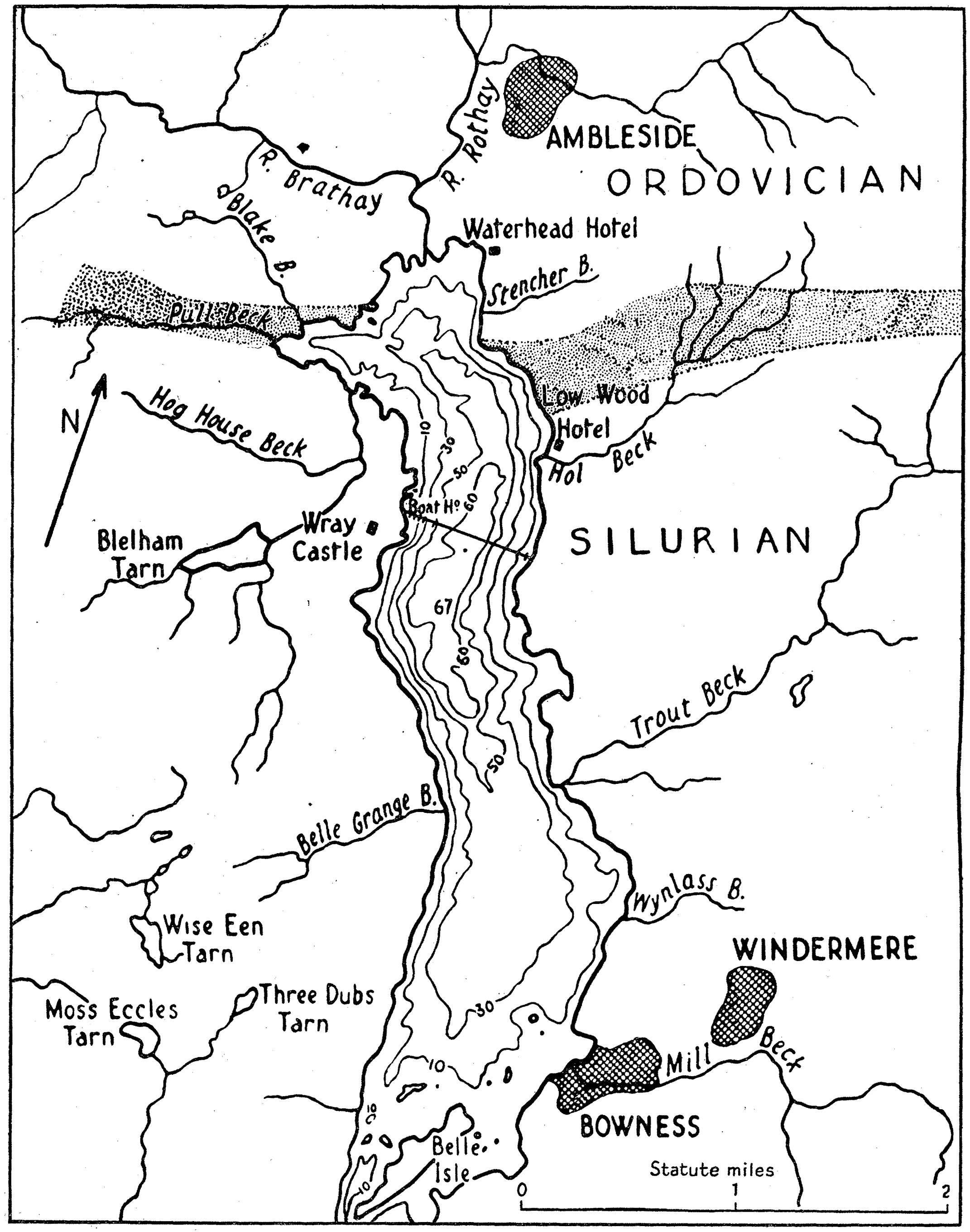


FIGURE 1. Map of the North Basin of Windermere showing approximate positions of cores analyzed and the line of section shown in figure 2.

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'microdistal' varves, which he supposes to have been deposited, in Sweden, at a great distance from the ice border. This would explain the narrowness of the Windermere varves, since all the samples obtained are from positions a mile or more below the delta of the main inflow, and Kindle showed that the greater part of the suspended sediment from the inflow of Lake Cavell was deposited in the delta region.

In Sweden, sections have been found showing the transition from wide varves, measured in centimetres, upwards to such microdistal varves, as the ice border retreated north and hence farther and farther from the section. The Windermere varved clay shows a similar upward passage from the lowest varves, immediately overlying a stony clay equivalent to the boulder clay, and averaging 0·5 to 1·0 cm. in width, upwards to the topmost varves which may be only 0·2 mm. in width. This upward decrease in width of the Windermere varves may well correspond to shrinkage in the size of the glacier supplying the sediment and hence to a decrease in volume of sediment supplied.

Laminated clays have, of course, been found in other parts of northern England (Trotter & Hollingworth 1932) and in Scotland (De Geer 1935) in terrestrial positions. Carruthers (1939) suggests that some at least of the terrestrial laminated clays of north-east England and the Eden valley may be explained as 'the banded dirts of the englacial detritus released by the rising bottom melt', rather than as representing periods of ice recession and deposition in standing water. The Windermere laminated clays, however, strongly resemble the true water-lain microdistal varves described by De Geer, and bear no resemblance to any of the laminated clays described or figured by Carruthers. Faults occur occasionally in the Windermere clays, as in the Swedish varves (De Geer 1940), but never the gross contortions and overfolds shown by some of Carruthers's specimens which he interprets as Alpine structures imposed when the 'banded dirts' were frozen muds. The graded bedding which De Geer describes as typical of varved clays was also recognized in the discussion following Carruthers's paper (1939) as characteristic of waterlain laminated clays, and is shown by all the laminated clays in Windermere.

The general bedding of the Windermere varves is strikingly regular and horizontal, apart from microscopic irregularities in the winter-spring contact planes which give the varves a wavy outline under the microscope (figure 15*a*, plate 2). In places where the lake floor shelves steeply (figure 2, position 4), the laminations often slope at a considerable angle, but the regular bedding is not disturbed by this. Undisturbed varved clays extend into very shallow water—i.e. to within a few yards of the edge of the lake in sheltered positions in the bays; this suggests that the lake level may have been higher when the varves were deposited, since very slight shore erosion would prevent the deposition of such fine material.

In deep water, i.e. within the 35 m. contour, the laminated clays often show marked sloping of the bedding planes, probably formed as the clay deposits filled up hollows in the original lake floor. In some positions, the very marked differences between the laminated clays in core samples taken within a few feet of each other (i.e. without moving the pontoon's anchors) suggest that deposition of the varves in deep water was by no means uniform, and that by some means marked discontinuities arose. In shallow water on both sides of the lake, however, the varve series appears very uniform in all sections taken, and conspicuous varves can be correlated easily with the naked eye.

Measurement of the varves. Hitherto, only preliminary attempts to measure the varves have been made, and there are still considerable difficulties to be overcome, owing partly to the difficulty of distinguishing digraphs and trigraphs in such very narrow varves, and partly to the wavy outlines of the boundaries which make it difficult to measure the width of

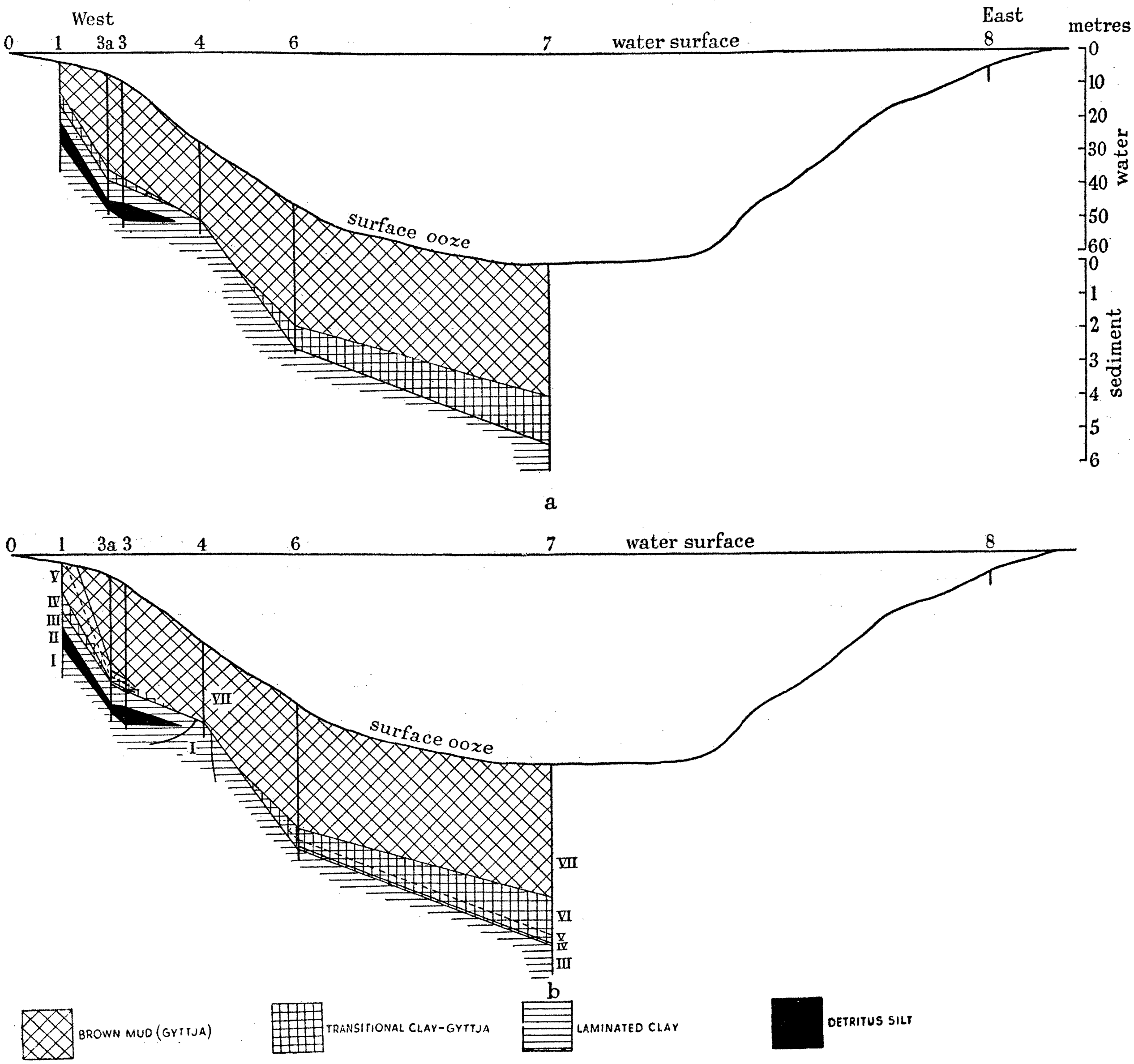

Figure 2. (*a*) Diagrammatic section, east to west, across the North Basin of Windermere, showing stratigraphy of deposits. (For more detailed map and section, see Pennington 1943.) (*b*) Diagrammatic east to west section showing stratigraphy with pollen zonation superimposed. (Continuous lines represent boundaries between zones; broken line represents approximate boundary between Zones V and VI; stratigraphy indicated by shading.)

each varve with accuracy. The narrowness of the varves makes it necessary to use a microscope with a graduated mechanical stage. Though in shallow water the widest and most conspicuous varves can be recognized with ease and correlated from one core to another, some difficulty has been experienced with the intervening narrow varves, and the relation of the varve series in shallow water to that in the deep central region has not yet been worked out. Before any attempt at correlation with the Swedish diagrams is made, it will be necessary to work out many diagrams from different cores so that a representative series for the lake as a whole, exclusive of local variations, is obtained (De Geer 1940). It is hoped that this may form the next stage in investigation of the Windermere deposits. Only when the improved model of the core-sampler can be made will it be possible to obtain the full sequence of the laminated clays in deep water, since the length of core obtainable at present (6·5 m.) penetrates only the topmost part of the clay in deep water, where the maximum thickness of deposit is found (figure 2).

(2) *Detritus silt layer within the laminated clay*

In shallow water, the lower laminated clay consists of relatively wide varves at the base; these pass upwards into narrow varves which may be only 0·2 mm. thick. These narrow, microdistal varves grade upwards into a deposit of unlaminated pinkish grey clay, which in turn passes gradually into a layer of grey detritus silt. This reaches its maximum thickness of about 50 cm. in water of 3 to 10 m. depth, and becomes thinner as the water depth increases, until it disappears at about the 25 m. contour. Within this contour, the layer of grey detritus silt is not represented, but at the same horizon in the laminated clay there may occur either a very narrow layer of unlaminated clay or an interruption in the regular sequence of varves. The grey detritus silt is everywhere capped by a layer of grey clay 2 to 5 cm. thick, which may contain plant remains. This grey clay grades upwards, within the next 1 to 2 cm. thickness, into the upper laminated clay, which consists throughout of very narrow microdistal varves.

The clays consist mainly of very minute particles, which remain suspended almost indefinitely in water, plus a varying proportion of fine gravel particles, 0·5 mm. or more in diameter. In the grey layer of detritus silt the mineral particles are mainly of the fine sand or silt grade—i.e. coarser than the clays, with fine gravel particles in addition. The detailed stratigraphy of the grey layer varies from place to place (figure 11), and it may contain layers which are almost entirely clay.

The detritus consists almost entirely of plant remains in a more or less finely divided state; these occur mainly towards the top of this layer and are sometimes found in bands of almost pure plant detritus.

This layer of grey detritus silt, which apparently represents a temporary change of climate and deposition, has been found, in the water depths stated above, on both sides of the lake in the latitude of Low Wray Bay, and all along the western shore from the mouth of Blelham Beck to High Wray Bay. It therefore seems fair to conclude that it is widely developed in the North Basin in shallow water. From purely stratigraphical evidence it could be supposed that this layer was formed during a warm period in which glacial drainage was no longer entering the lake, and that this warm period was followed by a return of a colder climate which again produced glaciers in the upper valleys, the drainage from which led to the deposition of the upper laminated clay. It will be shown later that the pollen and plant remains found within the layer of detritus silt confirm this hypothesis, and support the correlation with the Allerød deposits of north-west Europe which was tentatively put forward in a former paper (Pennington 1943).

Zoning of pollen diagrams

(1) *Marginal profiles*

(*a*) *Late-glacial*

The period generally recognized as the late-glacial corresponds (Godwin 1940*a*) with that of the upper and lower *Dryas* clays separated by the cold temperate Allerød deposits described by continental workers (e.g. Jessen 1935; Gross 1937; Nilsson 1935; and Schutrumpf 1936); these three layers form Zones I to III in the zonation scheme adopted by Jessen for Denmark (Jessen 1935) and Ireland (Jessen & Farrington 1938). Godwin (1940*b*) suggests that if and when corresponding late-glacial deposits are found in this country, a similar zonation should be adopted.

The stratigraphy of the Windermere deposits suggested what has since been borne out by the pollen diagrams—i.e. that here the lower laminated clay, grey detritus silt and upper laminated clay probably represent respectively Zones I, II and III, which in Denmark are represented by the lower *Dryas* clay, the Allerød deposits and the upper *Dryas* clay. This succession of deposits indicates that in both localities the climatic succession was: first, a cold period (shown by the Arctic *Dryas* flora of the lower *Dryas* clay in Denmark and by the evidence for glacial drainage shown by the lower laminated clay in Windermere) followed by a cold temperate period, that is, a climatic amelioration (shown by the plant species identified from the Allerød deposits and from the grey detritus silt layer in Windermere) followed by a return of cold conditions (producing the upper *Dryas* clay in Denmark and the upper laminated clay in Windermere). Jessen & Farrington (1938) tentatively correlate with the succession in Denmark that which occurs in several filled-up lake basins in Ireland, where the cold periods of Zones I and III are represented by clays or solifluction earths, Arctic plants having been recovered from the upper (Zone III), while between them is a lake mud containing remains of temperate plants. Since in all three countries the second cold period is followed by post-glacial deposits, this cold period may be interpreted as corresponding to the last major halt, or possibly slight advance, of the retreating ice-sheet. The question of how far this last cold period may be regarded as contemporaneous in the three countries will be discussed later.

Zone I—lower laminated clay. Pollen is here practically absent, which agrees with what Jessen & Farrington found in this zone in the Irish profiles from Ballybetagh and Ralaghan, and Mitchell (1940) in the lacustrine deposits at Dunshaughlin, Co. Meath. (Mitchell found that in the blue-grey sandy clay which represents this zone at Dunshaughlin, the only vegetation remains were a few moss stems. Similar moss stems occur in the Windermere deposits in the silty clay forming the transition from this zone to the next.)

Zone II—grey detritus silt. The lowest deposit which contains any appreciable quantity of pollen is the silty clay forming the transition from Zone I to Zone II. Here the non-tree pollen, mainly grass, is high relative to the tree pollen, and *Salix* pollen is relatively abundant; the tree pollen is practically entirely *Betula*, with a very little *Pinus*. As the more or less clayey transitional deposits pass upwards into detritus silt, the ratio of both non-tree pollen and of *Salix* pollen to tree pollen falls sharply, indicating replacement of open vegetation by *Betula* woodlands as the climate became warmer. Towards the top of the detritus silt the relative amounts of grass and of *Salix* to tree pollen again rise, presumably corresponding with the fall in temperature at the end of the warm period. The resultant concave shape of the curves for non-tree pollen (*NTP*), grass and *Salix* pollen (figures 3, 4 and 10) is characteristic of all pollen diagrams from the Allerød deposits (Jessen 1939; Nilsson 1935; Gross 1937). Pollen of *Myriophyllum alterniflorum* occurs as scattered grains throughout this layer, though never in any great quantity.

Zone III—upper laminated clay. Pollen is very sparse in this deposit, and not even by boiling twice in hydrofluoric acid was it possible to obtain a sufficient concentration to yield counts which are statistically significant. This again agrees with conditions in the Irish profiles. The transition between Zones II and III is marked by a sharp rise in *Pinus* pollen, and *Pinus* also forms a high percentage of the tree pollen at the end of this zone—i.e. the III to IV transition (figures 3 and 4). The evidence available for the laminated clay suggests that what little tree pollen is present is mainly *Pinus* throughout; this may indicate that in the absence of local pollen, *Pinus* transported from a distance was more important than in the preceding and following periods, when local pollen was abundant. The apparent absence of local pollen during this period strengthens the hypothesis that it was one of intense cold with only sparse vegetation.

(*b*) *Post-glacial*

The top of the laminated clay is taken as marking the end of any intense glacial activity in the Lake District, and the succeeding deposits are therefore classed as post-glacial. In the marginal profiles these deposits consist of brown detritus mud (gyttja) which in places (mainly in sheltered positions where the water is 2 to 5 m. deep) contains a very high proportion of plant fragments so that the deposit resembles a fine peat. The deposit in deeper water or more exposed positions contains a much higher proportion of mineral material, fewer plant remains, and much less pollen. A layer of whitish clay containing abundant diatom skeletons but very little carbonaceous material occurs in a definite relation to the mouth of each small inflow stream, in the bays where sampling has taken place.

The zonation scheme adopted by Godwin for East Anglia (1940*a*) and the rest of England and Wales (1940*b*, 1945), does not correspond with Jessen's zonation of Danish (1935) and Irish (1938) diagrams, but it is hoped that with further publication a common scheme will be evolved. It is proposed, at present, therefore, as far as possible, to apply to the Windermere deposits the zonation system originally worked out by Godwin (1940*a*) for the East Anglian fenland, and then applied by him to the profiles from other parts of England and Wales (1940*b*). In the later post-glacial zones this system cannot be applied very closely to the Windermere diagrams, and it may be that these will show more affinity with Jessen's Irish diagrams than with those from the east and south of England.

Zone IV—Betula-Pinus *zone*. This zone is conspicuous in the marginal profiles, where about 30 cm. of deposit fall within it (figures 3, 4 and 10). *Pinus* shows a sharp fall from the high percentage present at the III to IV transition, presumably as with increasing warmth the production of local tree pollen, mainly *Betula*, diminished the importance of *Pinus* pollen transported from a distance (cf. Jessen, as quoted by Mitchell, 1940). *Betula* is by far the most important tree in this zone, providing about 90% of the total tree pollen. *Corylus* and *Quercus* are present, sometimes discontinuously, in very small quantities; the other warmth-loving trees are absent. The end of the zone is marked, as in East Anglia (Godwin 1940*a*), by a sharp fall in the non-tree/tree pollen ratio, suggesting that with increasing temperature the forest cover was becoming denser. There is a conspicuous *Salix* maximum in this zone in the Windermere deposits, which agrees with Jessen's Irish diagrams from Ballybetagh and Ralaghan, but differs from profiles from Shropshire (Hardy 1939) and East Anglia (Godwin 1940*a*), where the *Salix* maximum does not occur until Zone V.

Zone V—Pinus *zone*. This zone is not so well marked as in East Anglia (Godwin 1940*a*), but in each profile from shallow water there is a maximum of *Pinus* with a corresponding decrease in *Betula*, about 50 cm. above the top of the laminated clay, at the beginning of the sharp rise in *Corylus* (figures 3 and 4). Above this horizon, however, *Betula* again becomes more abundant than *Pinus*, so that the graphs for these two trees are not strictly comparable in the diagrams from Windermere and from the east of England respectively, but this persistence of *Betula* as the dominant tree throughout Zone V and the earlier part of Zone VI is characteristic of most profiles from the west of England and Wales (Godwin 1940*b*, figures 5, 6). *Quercus* is present in small amounts, *Alnus* and *Ulmus* either absent or very scanty, and *Tilia* completely absent. *Salix* decreases in this zone until it is practically absent. *Corylus* begins to expand very rapidly, as in most British profiles, and reaches the very high values characteristic of northern and western sites.

Zone VI—Pinus-Corylus *zone*. In the early part of this zone, *Betula* is still the dominant tree, and the *Corylus* curve shows a single very pronounced maximum which may reach 80% of the total tree pollen. *Ulmus* and *Quercus* appear to have spread very little, corresponding with other northern sites, but one profile (figure 10) shows a small maximum of *Ulmus*. *Tilia* is absent, *Alnus* and *Salix* practically so. This early part corresponds to the subzone distinguished by Godwin as VI*a*.

In other parts of England, the second subzone, VI*b*, is distinguished by an increase in *Quercus*, but this is not apparent in Windermere, where this subzone is obscure. Throughout the latter two-thirds of Zone VI, *Betula* and *Corylus* decrease steadily. In the latter part of this zone, *Pinus* shows a second maximum as in some other British sites; this is rapidly followed by a very sudden expansion of *Quercus* and particularly *Alnus*, with a corresponding abrupt decrease in *Betula* and *Pinus*. This rapid advance of *Quercus* and *Alnus* falls into what is distinguished as subzone VI*c* in the rest of England and Wales. In Windermere, round the margin of the lake, it corresponds exactly with a stratigraphic change from brown gyttja to a whitish clay. The secondary expansion of *Pinus* at the beginning of VI*c* is in many parts of western Europe correlated with a dry period giving a growth of *Pinus* on the dry bog surfaces; in Windermere this maximum may indicate growth of *Pinus* on drying bog surfaces in the drainage basin. The very sudden expansion of *Alnus*, replacing *Pinus*, almost certainly indicates increasing wetness (the Boreal-Atlantic contact), and the stratigraphic change to what is apparently an alluvial clay deposited off each stream mouth is additional evidence for increased wetness of climate. The clay is rich in lake diatoms, and so is obviously waterlain.

Zone VII—alder-mixed oak forest zone. The subsequent phases in the forest history of the Windermere region are not well represented in the marginal profiles, since the three cores examined all show truncation of the upper deposits to a greater or lesser extent (possible reasons for this truncation will be discussed later). The longest marginal profile (figure 4) shows that above the VI*c*/VII boundary, *Alnus* continues to expand until values up to 60% of the total tree pollen are reached, *Quercus* meanwhile falling off. *Tilia* appears and expands early in Zone VII in this profile (contrast diagrams from the south and east where *Tilia* appears earlier, i.e. in VI); *Ulmus* remains fairly constant at 10 to 15%. The expansion of *Pinus* at the extreme top of this profile agrees with what is found in the most recent deposits in deep water, and in this marginal site it probably indicates discontinuity in deposition during the phases after the early part of Zone VII.

(2) *Profiles from the middle of the lake*

(*a*) *Late-glacial*

In most of the cores obtained from deep water the late-glacial deposits are entirely inorganic, consisting of laminated clays with sometimes thin layers of sand or unlaminated clay. The grey detritus silt of shallow water which, it has been suggested, represents Zone II, or the Allerød layer, is not found within the 15 m. contour, but in some places in deeper water there is, at what is apparently a similar horizon, in the laminated clay, a narrow band of grey silty clay or an interruption in the regular bedding of the varves. This presumably indicates an interruption in the deposition of the varves at the time when the detritus silt was forming in shallow water, i.e. Zone II, followed by the regularly bedded varves of Zone III.

(*b*) *Post-glacial*

Zone IV—Betula-Pinus *zone*. The most striking feature of the pollen diagrams from deep water as compared with those from shallow water is the immense preponderance of *Pinus* in the early post-glacial zones in deep water. In the middle of the lake, the *Betula* phase of Zone IV is either absent (figure 8) or represented only by a small maximum of *Betula* in the 10 to 15 cm. of deposit immediately above the top of the laminated clay (figure 9).

Zone V—Pinus *zone*. The phase of tremendous dominance of *Pinus* extends from the top of this narrow Zone IV (or, where this is absent, from the top of the laminated clay) to the horizon about 1 m. above this, where *Pinus* is replaced by the rapidly expanding *Alnus*, i.e. Zone VI*c*. Within this metre of deposit, tree pollen other than *Pinus* is exceedingly sparse, and the only means of determining the boundaries of Zones V/VI is provided by the curve for *Corylus*. If *Corylus* is expressed as percentage of the total tree pollen, its curve has no definite form, but if the amount of *Corylus* is expressed as a percentage of the tree pollen *excluding Pinus*, a very sharply defined peak corresponding to that shown by *Corylus* in marginal profiles is obtained. This peak, the sharp rise of which determines the boundary between Zones V and VI*a* occurs about 25 cm. above the top of the laminated clay. Zones IV and V are therefore represented by a much greater thickness of deposit in shallow water than in the middle of the lake.

Zone VI—Pinus-Corylus *zone*. The complete dominance of *Pinus* over all the other trees is maintained, with *Corylus* (expressed as percentage of tree pollen minus *Pinus*) falling steadily from its single maximum, until the horizon is reached at which *Pinus* falls off very abruptly and is replaced by the broad-leaved trees (VI*c*). *Alnus*, *Quercus* and *Ulmus* all expand simultaneously, and *Betula* also shows a percentage increase, but this is almost certainly not an absolute increase, but only relative, due to the decrease in *Pinus*. This sudden expansion of the broad-leaved trees corresponds, just as it does in shallow water, with a distinct stratigraphical horizon—here the topmost of the narrow clay bands. The implications of this will be discussed after the series showing the transition from marginal to central profiles has been considered.

Zone VII—Alder-mixed oak forest zone. The early part of this zone resembles the same horizon in the marginal profiles, with *Tilia* coming in just above the expansion of *Alnus*. Instead of the truncation which is present in all marginal profiles, however, 3 to 4 m. of brown gyttja are present above the VI*c*/VII transition in deep-water profiles, and no consistent change in the proportions of the tree pollens takes place until the topmost 50 cm. of deposit are reached. *Pinus* falls off very rapidly just above the VI*c*/VII transition, and practically disappears for several metres of deposit. There is no trace of any increase in *Betula*, and this, combined with the complete absence of *Fagus* and *Carpinus*, makes it impossible to apply any further the zonation worked out for East Anglia and the rest of England and Wales. Possibly the Windermere diagrams may have more affinities with Jessen's hitherto unpublished profiles from Eire.

Pinus, after its virtual disappearance some 2 m. below the mud surface, reappears at about 50 cm. below the mud surface and increases rapidly, until in the surface deposits it may reach 50% of the total tree pollen. This suggests that the native *P. sylvestris* may have died out at some point in Zone VII, and that the reappearance of *Pinus* pollen in the most recent deposits may be due to planting.

The curve for grass pollen shows a steady rise from shortly after the beginning of Zone VII onwards, but the rise is greatly accelerated some 50 cm. below the point where *Pinus* reappears (figures 8, 9). The implications of this will be considered later.

(3) *Series of pollen diagrams along a transverse section of the North Basin of the lake*

The eight cores on which pollen analyzes have been made form approximately a transverse section across the North Basin. A more detailed individual consideration of these cores will trace the transition from the marginal to the central stratigraphical and pollen sequence.

(*a*) Cores 1 and 2, marginal, figures 3 and 4. These are from water of 3 and 3·5 m. depth respectively. Core 1 represents conditions off the stony shore in the middle of the curve of Low Wray Bay, and core 2 is from a position 150 yards to the north of this, in a sheltered site off the mouth of a small inflow stream near the northern horn of the bay (figure 1). The late-glacial zones correspond almost exactly in these two cores; the post-glacial sequence is more complete in the second. Though the two cores are not on the same transect across the lake, they illustrate two types of marginal sequence which may occur in closely adjacent positions.

Zones I, II and III are represented by the stratigraphical succession described in the preceding section as typical of the late-glacial deposits in the lake. Zone II, the detritus silt, is thicker (61 cm. as against 54 cm.) and contains more organic remains in core 1, from nearer the shore, probably due to the drift of sediment controlled by the water currents prevailing at the time. The pollen curves for the late-glacial correspond exactly in the two diagrams (figures 3 and 4), with *Betula* making up more than 90% of the pollen in the detritus silt, *Pinus* occasional, and *Quercus* appearing at the top. The curves for *Salix* and grass pollen have the concave shape characteristic of deposits of the Allerød oscillation. The upper laminated clay (Zone III) corresponds exactly in these two cores, there being about six conspicuous grey varves which can be readily correlated with the naked eye.

Zone IV is also closely similar in the two cores. Stratigraphically it is a clay-gyttja in which the clay content decreases rapidly on passing upwards from the top of the upper laminated clay. The point at which this pinkish clay-gyttja passes upwards into brown detritus gyttja is indeterminate, but corresponds approximately with what appears to be the IV/V transition, i.e. the point where a maximum of *Pinus* begins to develop and about the point where the falling grass crosses the rising *Corylus* curve. Zone IV therefore almost corresponds with this clay-gyttja in these two cores, the latter being about 25 cm. thick and Zone IV 25 to 35 cm., according to where the boundary is fixed.

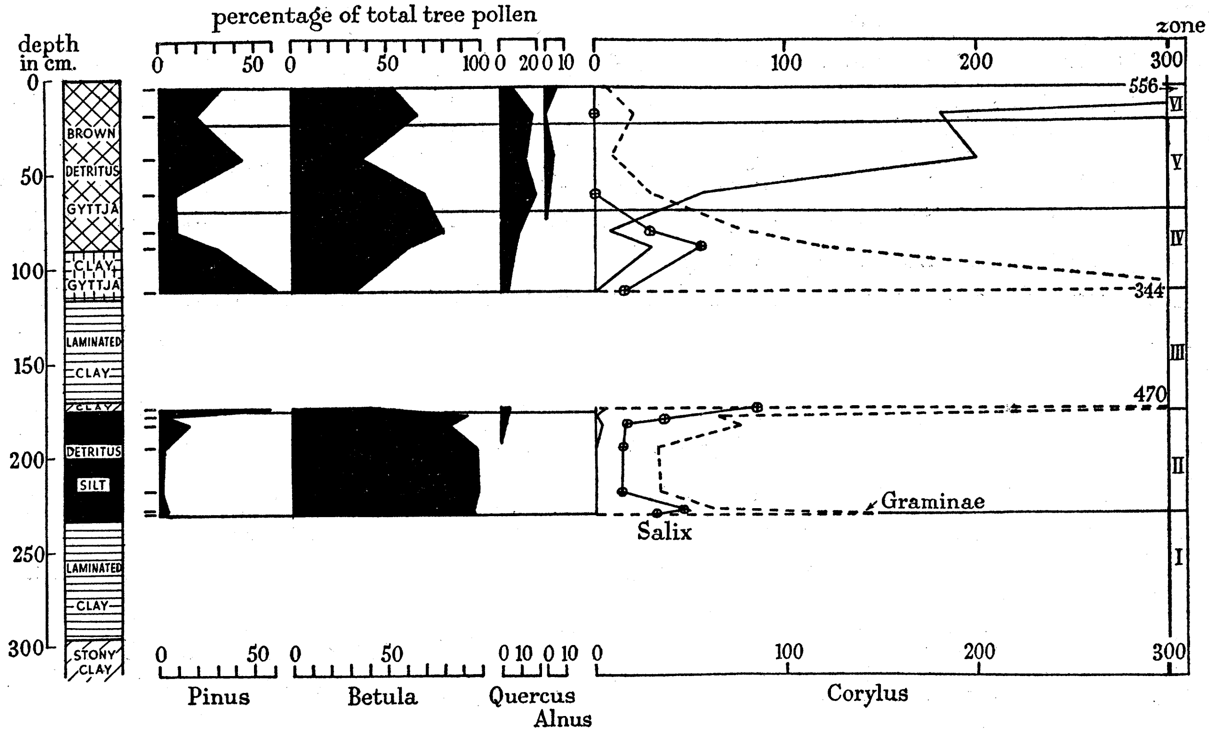

FIGURE 3. Pollen diagram from core 1, in 3 m. of water in Low Wray Bay (littoral).

Zones V and VI*a* are again exactly similar in the two cores, with *Betula* recovering its dominance after the small *Pinus* maximum of Zone V, and *Corylus* rising extremely steeply to very high values. The deposit is a brown detritus gyttja containing very abundant plant remains in a finely divided state. So abundant are these vegetable fragments that the gyttja has an appearance approaching that of a very fine peat.

The topmost deposits of core 1 (apart from possibly 1 or 2 cm. of unconsolidated surface ooze which tends to wash out of the sampler) belong to Zone VI*a*—i.e. are of Boreal age. This truncation of the profile suggests that the deposits continued to accumulate until the surface was built up into the zone of wave erosion, after which no further deposition was possible. The present depth of water at this site at mean lake level is 3 m.

The post-glacial deposits of core 2 (water depth 3·5 m.) extend for a further 2·5 m. above the horizon at which core 1 is truncated; presumably this represents deposition in a hollow in the late-glacial lake floor. Zone VI shows the features described in the preceding section, and covers a total thickness of about 2 m. The marked stratigraphical change from gyttja to whitish clay which accompanies the rapid expansion of *Alnus* and (less strikingly) *Quercus*, in VI*c*, has already received comment. Along the western shores of the North

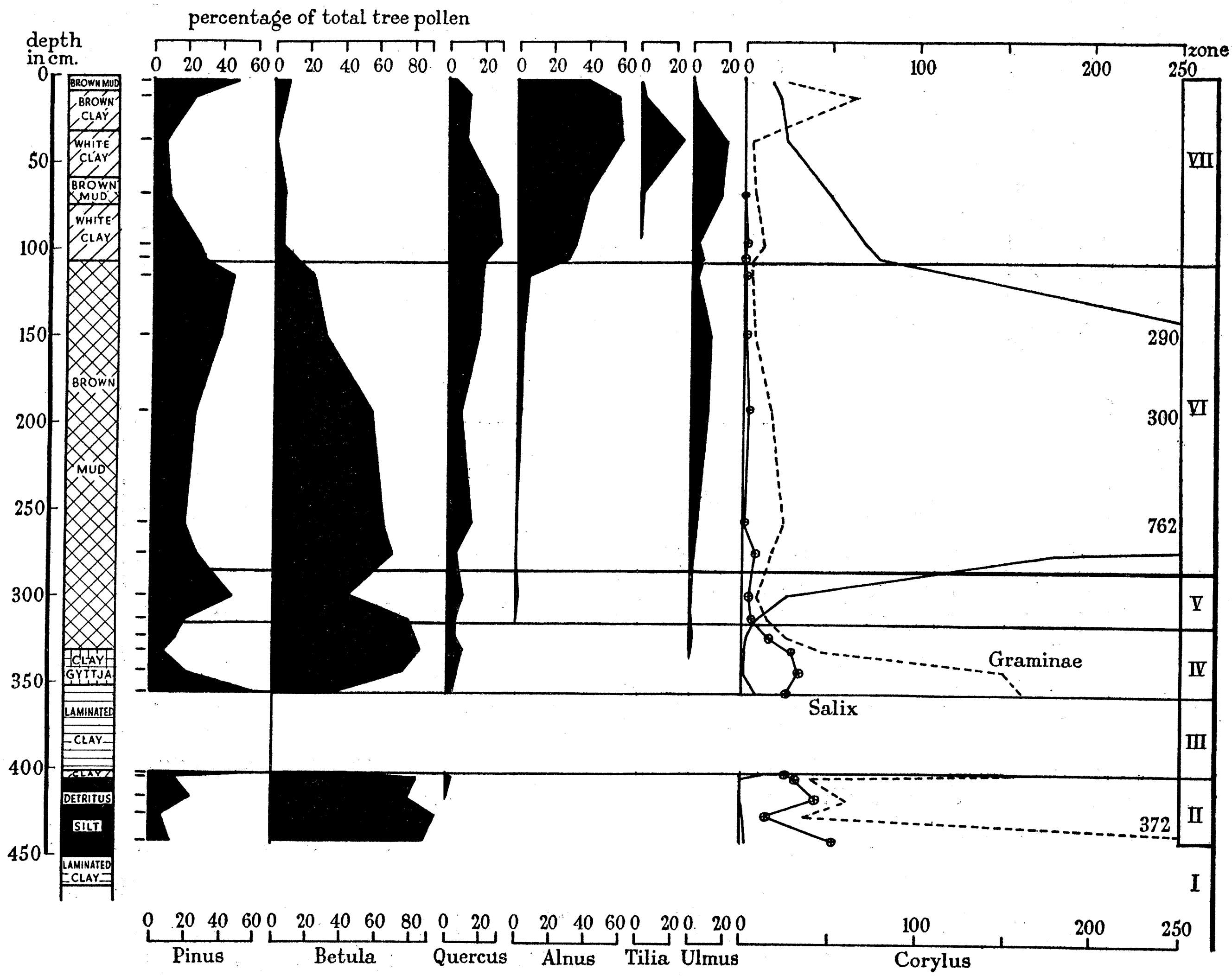

FIGURE 4. Pollen diagram from core 2, in 3·5 m. of water in Low Wray Bay, 150 yards north of core 1. (Cores 1 and 2 are separated by a jutting promontory of rock.)

Basin this clay is thickest off the mouths of small inflow streams (core 2 being from such a position), from which it thins out both laterally and towards the middle of the lake, but further analysis will be necessary in order to determine its depth-time relationships at the margin of each deposit.

In Zone VII *Pinus* falls off rapidly to very low values, and *Tilia* shows an expansion (characteristic of early Zone VII in all the Windermere diagrams) followed by a rapid falling off. *Alnus* maintains its predominance until the topmost 10 cm. is reached; here *Pinus* shows a rapid expansion corresponding with the stratigraphical change from the topmost part of the clay, here brown and indurated, to soft black, more or less unconsolidated gyttja. Comparison with the profiles from the middle of the lake suggests that the black gyttja containing *Pinus* is recent, so it appears that this core was truncated about 90 cm. above the base of Zone VII; the *Pinus*-containing gyttja may be unconsolidated deposit still undergoing wave erosion, or it may be that changes in the prevailing wind and hence in currents have made accumulation possible again in this position after a discontinuity.

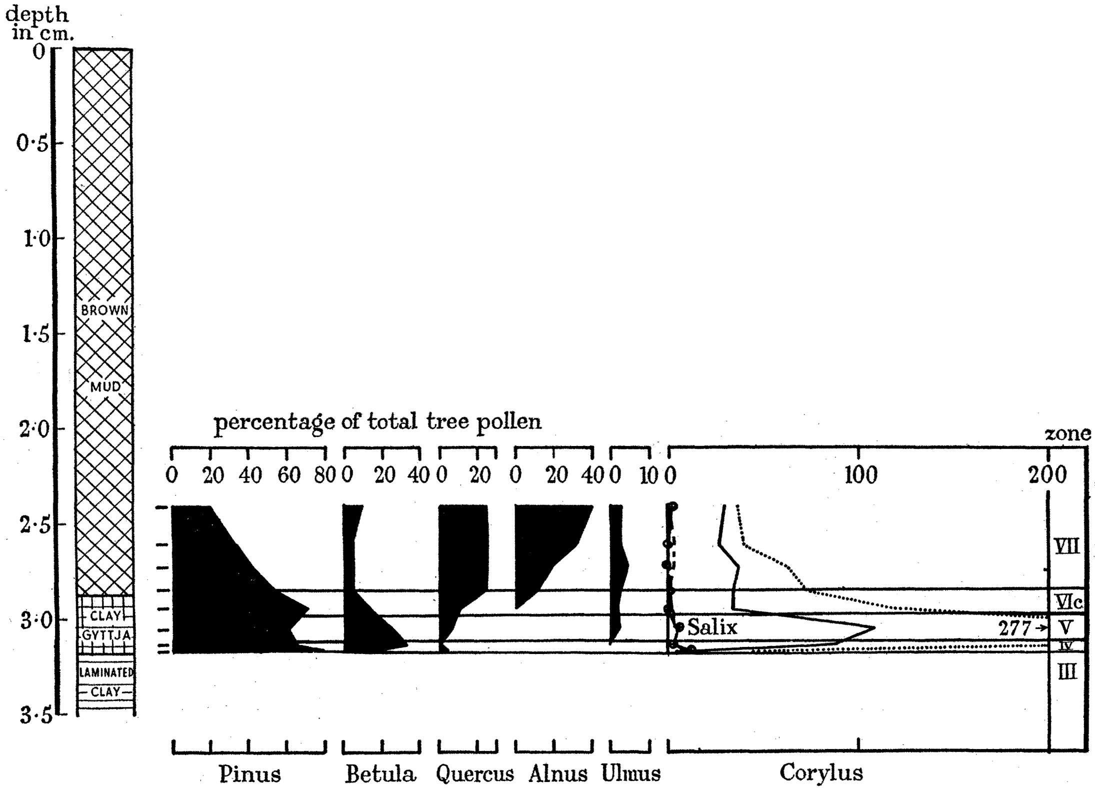

FIGURE 5. Pollen diagram from core 3*a*, in 7·6 m. of water in Low Wray Bay. Dotted line shows *Corylus* expressed as percentage of tree pollen minus *Pinus*.

(*b*) Core 3, in 10 m. of water, and in addition the basal part of core 3*a* from 7·6 m. of water was analyzed. In these cores the upper and lower laminated clays resemble the corresponding deposits in the marginal profiles, but the intervening detritus silt is much thinner there than in cores 1 and 2, and is very different in character. Whereas in those cores Zone II is a detritus silt which in places becomes almost pure plant detritus, in cores 3 and 3*a* the corresponding deposit contains much less organic matter, practically no plant remains, and very little pollen, and it is practically a pure silt with a little clay admixture.

So sparse is the pollen in this silt that it was not possible to construct any pollen curves for the late-glacial in these cores. The few counts available show that *Pinus* is more abundant than *Betula* in the silt layer. From its position between the upper and lower laminated clays this layer must be correlated with Zone II in the marginal profiles, and there *Betula* is dominant throughout this zone. The relative increase in *Pinus* on passing into deeper water may be due to the same causes as the corresponding phenomenon in the post-glacial deposit, which is discussed at the end of this section.

In these two cores, Zones IV, V and VI are very narrow compared with the marginal sites (figures 5 and 6), and it is difficult to define their boundaries accurately. After an initial phase of high *Pinus* at the transition from the upper laminated clay to the post-glacial deposits, there is in both cores a narrow layer where *Betula* is present in appreciable quantity, this *Betula* phase being better developed in 3*a* (7·6 m.) than in 3 (10 m.). *Pinus*, however, remains the dominant species throughout these early zones in both cores. In 3*a*, *Corylus* shows a well-marked single maximum with its peak (Zone VI*a*) just above the

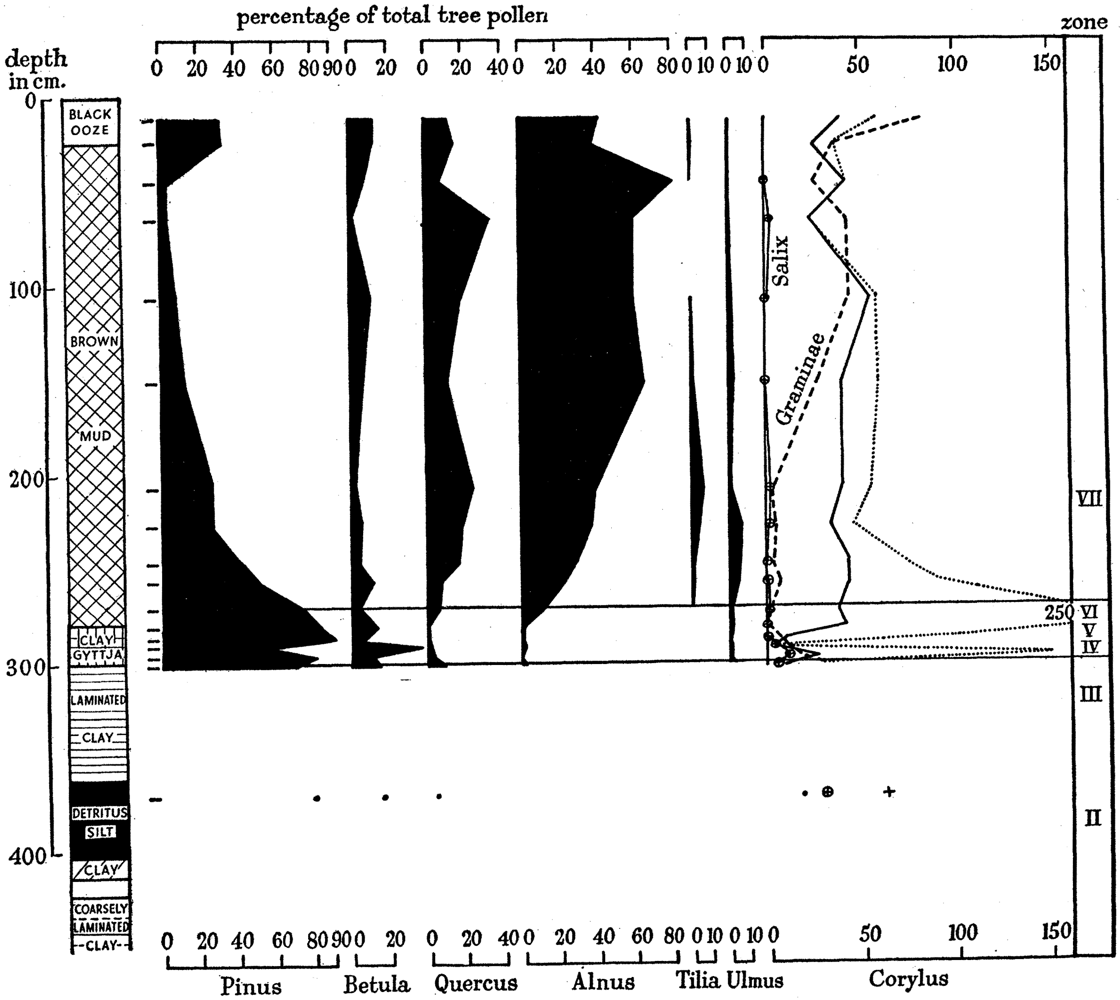

FIGURE 6. Pollen diagram from core 3, in 10 m. of water in Low Wray Bay.

Betula maximum, and the *Corylus* curve retains this form when *Corylus* is expressed as percentage of total tree pollen minus *Pinus*. In core 3, *Corylus* shows no maximum when plotted as percentage of total tree pollen, but if plotted as percentage of total tree pollen minus *Pinus*, a conspicuous maximum appears at a corresponding horizon to that in core 3*a*, i.e. just above the *Betula* maximum. In both cores the *Corylus* maximum (Zone VI*a*) is followed almost immediately by the very rapid expansion of *Alnus* and *Quercus* with corresponding decrease in *Pinus*, characteristic of Zone VI*c*, and the subsequent form of the pollen curves is similar to that already described for Zone VII. At 1 m. below the mud surface, *Tilia* and *Ulmus* practically disappear—this may represent Zone VII*d* and correspond with the similar disappearance of these two species at the top of the diatomaceous white clay in core 2. The deposits of cores 3 and 3*a* are stratigraphically uniform (brown gyttja) from Zone VI*c* until the 20 cm. of surface ooze is reached. *Pinus* then shows the marked increase which has already been mentioned as occurring in the recent deposits.

These two cores therefore show two striking differences from the marginal cores. First, there is the compression of Zones IV, V and VI into about 25 cm. of deposit as compared with 250 cm. in core 2, and the fact that all three pollen zones are here included in the stratigraphical zone of clay-gyttja, whereas in cores 1 and 2 Zone IV covered the entire thickness of this deposit. Secondly, there is the overwhelming dominance of *Pinus* in these early zones, contrasted with the same zones in the marginal profiles, where *Pinus* occurs in roughly the same (or somewhat smaller) proportions to the other trees as at corresponding levels in pollen diagrams from the rest of England (Godwin 1940*b*). In immediately post-glacial times, therefore, deposition must have been much more rapid at the margins (3 m.) than in water 7 to 10 m. deep, and the deposit in the more central position was clay-gyttja throughout the period until the Boreal-Atlantic transition, whereas at the margin this facies developed only in Zone IV, being followed by detritus gyttja in Zones V and VI.

(*c*) Core 4, from 27 m. of water. The present floor of the lake slopes steeply at this point (figure 2), and the junction between the top of the laminated clay and the post-glacial gyttja shows that the late-glacial lake floor also sloped steeply. It was immediately evident from the stratigraphy of this core that a discontinuity was present at the top of the laminated clay, which was overlain by brown detritus gyttja without any trace of the transitional clay-gyttja present in both deeper and shallower water. The whole of the laminated clay in this core resembles the lower laminated clay rather than the upper, because the laminations are all relatively wide. The total thickness of the detritus gyttja (brown mud) is here much less than in cores from either deeper or shallower water. All these factors agree in suggesting that a strong unconformity is present, and pollen analysis confirmed this (figure 7). The relatively wide laminations of the clay place it in Zone I, which means that the whole of Zones II and III are missing. The base of the gyttja (brown mud), i.e. at the contact of this deposit with the laminated clay, has a pollen spectrum characteristic of Zone VII, with *Alnus* reaching nearly 40%, high *Quercus*, *Tilia* present, and *Betula* and *Pinus* present in only small quantities. The pollen curves above this point take the form characteristic of Zone VII in Windermere, and there is the usual increase in *Pinus* corresponding with the development of the surface ooze. It is obvious that in this core there are missing not only Zones II and III, but also IV, V, VI and the early part of VII (before the appearance of *Tilia*). Clearly either the conditions during the period of formation of Zones II/VII*a* were such that no deposition took place, or else violent erosion removed these deposits before the deposition of the existing gyttja—i.e. approximately Zone VII*c*. The former explanation seems more probable, since it is easier to imagine climatic plus topographical conditions which would produce an off-shore current preventing deposition, than to suggest any possible cause of sufficiently powerful erosion in this depth of water.

(*d*) Cores 6, in 46 m. of water, and 7, in 65 m. of water. Both these cores are from the middle of the lake, and their position on the profile of this transect is shown in figure 2*b*. Core 7 is from the deepest central part of the lake, i.e. about 600 yards to the south of the line of the transect. The two cores correspond almost exactly with each other, except that in core 7 each post-glacial zone and stratigraphical horizon is expanded as compared with core 6, the total thickness of deposit above the laminated clay being 5·3 m. in core 7 compared with 4·2 m. in core 6.

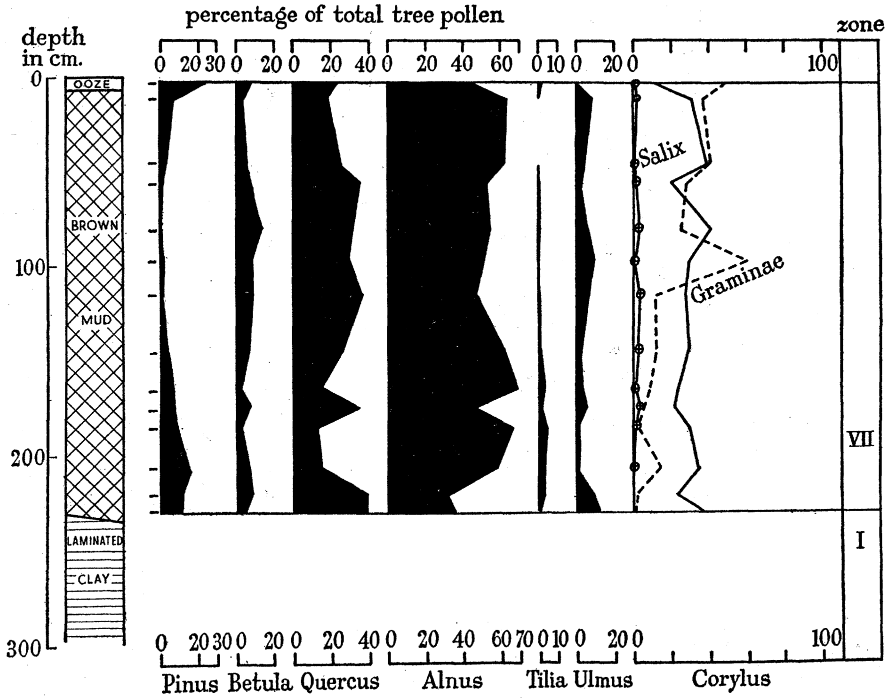

FIGURE 7. Pollen diagram from core 4, in 27 m. of water outside Low Wray Bay.

The pollen diagrams from these cores have already been described. Zones IV, V and VI are difficult to distinguish, since the enormous preponderance of *Pinus* pollen (average 90%) masks the other changes. Pollen other than *Pinus* is very sparse. The very high peak of the *Corylus* maximum which appears when *Corylus* is plotted as percentage of the tree pollen minus *Pinus* fixes the horizon of Zone VI*a*, but otherwise no boundaries can be assigned to these first three post-glacial zones. The thickness of deposit included in these zones is 50 cm. in core 6 and 140 cm. in core 7, and in each core this corresponds exactly with the stratigraphical zone of clay-gyttja, or zone of narrow clay bands (the latter referring to the narrow bands of pink unlaminated clay which are present in the clay-gyttja in deep water (Pennington 1943)). In each core, the topmost of these narrow clay bands corresponds exactly with the rapid expansion of the broad-leaved trees (particularly *Alnus*) with corresponding decrease in *Pinus*, i.e. the Zone VI*c*/VII boundary. The pollen curves for Zone VII have already been described, as also has the increase in *Pinus* corresponding with the surface ooze.

(*e*) Core 8, marginal, from 4·8 m. on the eastern side of the lake. This core corresponds almost exactly with the marginal cores from the western shore, being intermediate between cores 1 and 2 in most respects. The late glacial zones and Zone IV correspond exactly in all three cores; core 8 is truncated very early in Zone VII, and the thickness of deposit in Zones IV to VI is rather less than in core 2 (figure 10).

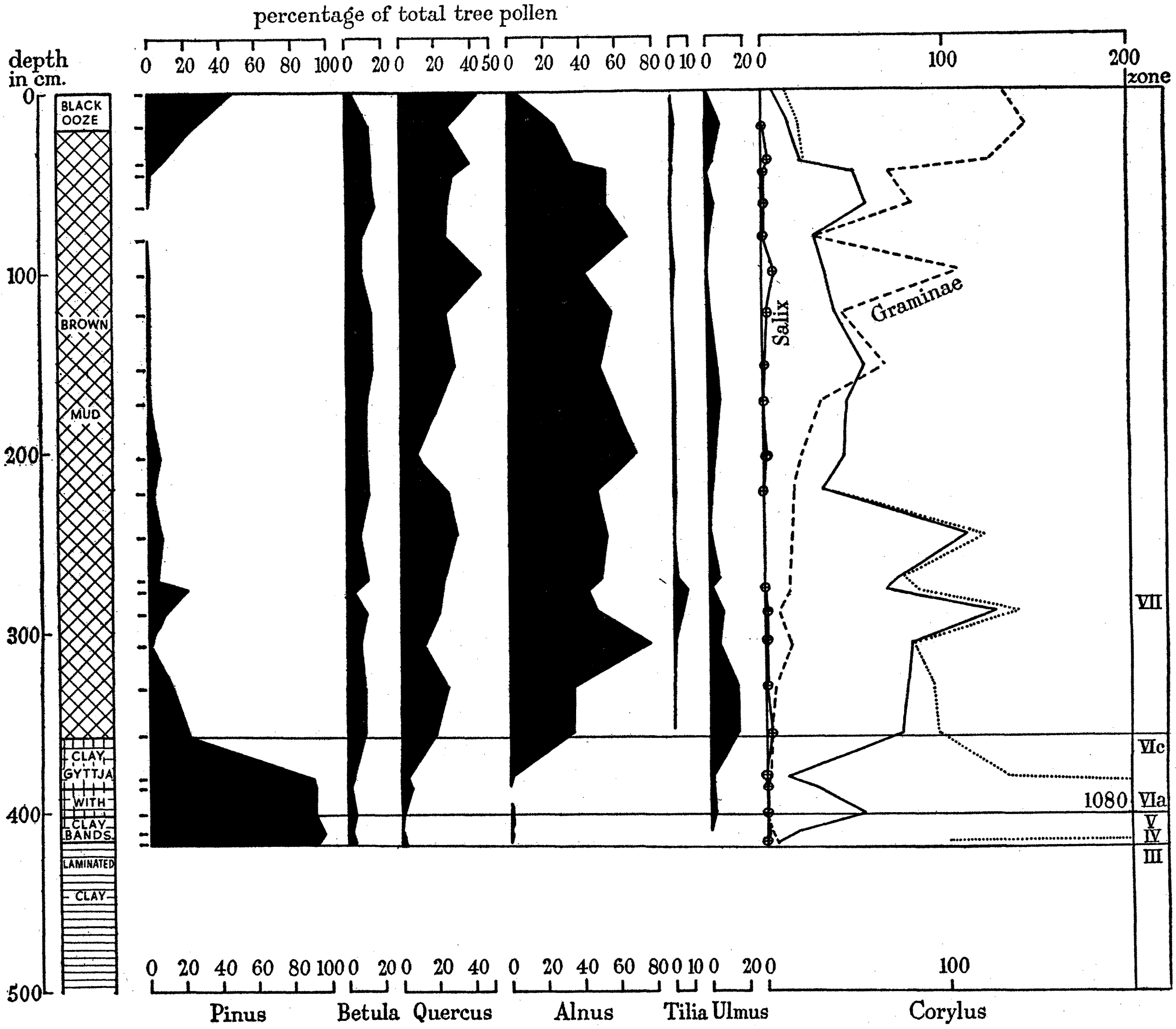

FIGURE 8. Pollen diagram from core 6, in 46 m. of water outside Low Wray Bay. Dotted line shows *Corylus* expressed as percentage of tree pollen minus *Pinus*.

(4) *Conclusions drawn from zonation of pollen diagrams*

The width of the zones in shallow water and deep water respectively shows that in late-glacial and early post-glacial times, organic deposits accumulated much more rapidly at the margins than in deep water, where deposition was very slow. Deposition at the margins apparently ceased when the mud surface came within about 3 m. of the water surface. The shore-line of Low Wray Bay on the position of the transect is stony and the site of core 1 (3 m. water depth) was the shallowest place where the bottom was consistently soft. It is known from recent sedimentation experiments (Pennington, in preparation) that turbulence in the lake water may pick up sediment which has already been deposited on the bottom, even in water depths considerably greater than 3 m. These results of observations

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in Low Wray Bay suggest that where the shore-line is stony to a depth of about 3 m., no further accumulation of sediment is taking place, and therefore in such a position under present circumstances the lake floor will never rise above the water-line; therefore there is no hydrosere (Tutin 1941).

Mitchell (1940) found that in the old lake basin at Dunshaughlin, Co. Meath, the early post-glacial zones were very narrow in the central part of the basin—i.e. that here also deposition was rapid at the margins compared with the centre in the early post-glacial

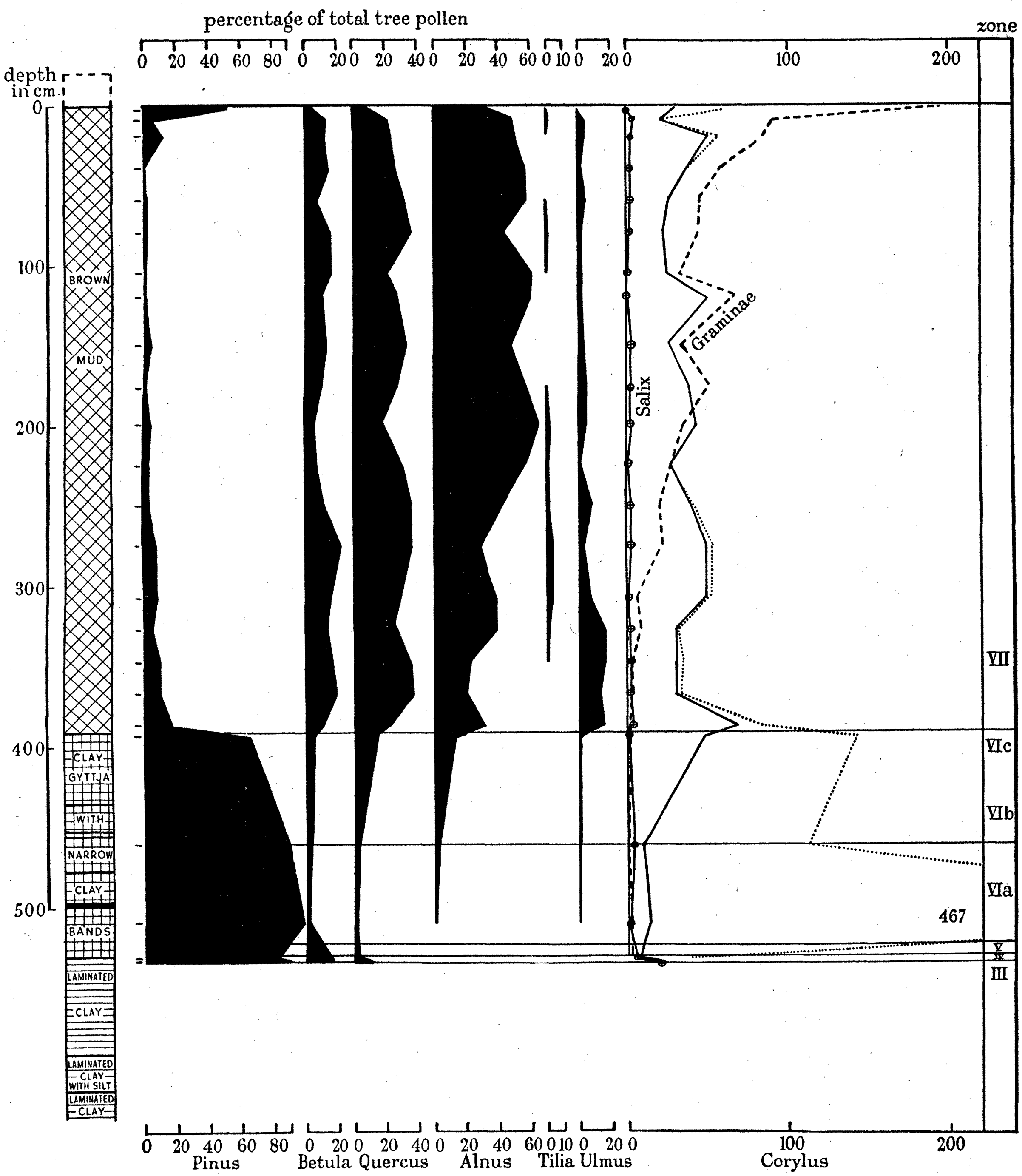

FIGURE 9. Pollen diagram from core 7, in 65 m. of water. Dotted line shows *Corylus* expressed as percentage of tree pollen minus *Pinus*.

stages. At Dunshaughlin, however, the marginal accumulation continued until the deposits were built up above water-level, and in time the shallow basin was almost completely filled by this process combined with more rapid accumulation of detritus mud in the centre during and after Zone VII (Jessen's zonation—'the first period in which *Alnus* reaches a dominant position'). Comparing figure 2*b* with Mitchell's figure 7, it will be seen that appreciable deposition in the central part of Windermere began at about the same period but was much more rapid, presumably because of the much greater volume of sediment entering the lake. The differences can all be related to the great contrast in size and shape between the two basins, the late-glacial floor of Windermere forming a basin, reaching a maximum depth of *c*. 70 m., and with an area that of the present lake,

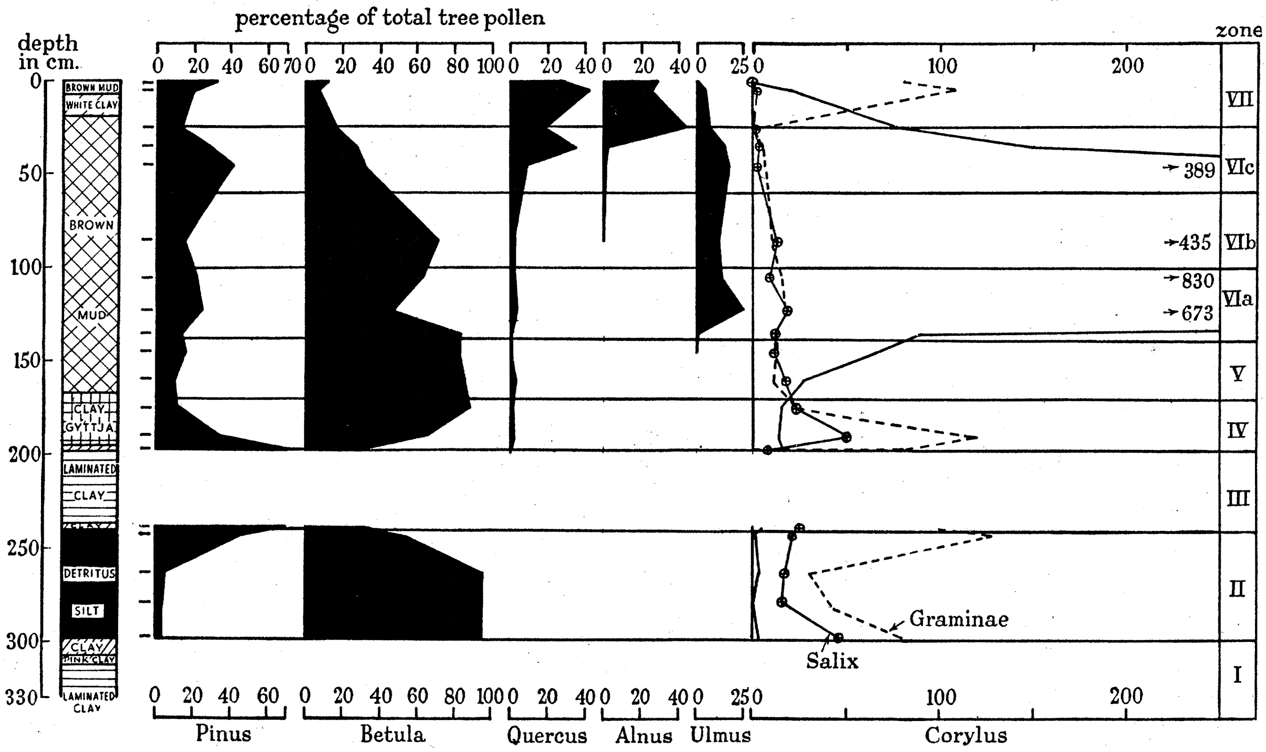

FIGURE 10. Pollen diagram from core 8, in 4·8 m. of water off Ecclerigg House.

whereas at Dunshaughlin the late-glacial basin was only about 6 m. deep and 1 mile long by ½ mile wide. This means that wave action would be very much restricted in the Dunshaughlin basin compared with Windermere, so that the marginal deposits accumulated continuously until they reached water-level, when peat formation began. These two lake basins are an interesting example of the contrast in the method of filling up of a small shallow and a large deep lake respectively.

Considering the pollen zonation in relation to the stratigraphy, while the late-glacial Zones I, II and III correspond exactly with stratigraphical horizons, the early post-glacial zones present a more complex picture. In both marginal and central positions, the earliest post-glacial deposit is a transitional clay-gyttja, thicker in the centre than at the margins and containing a characteristic diatom flora (Pennington 1943). It was formerly assumed that this clay-gyttja (or 'zone of narrow clay bands' in deep water) was contemporaneous in deep and in shallow water, but the results of pollen analysis show that this is not so. In the marginal sites, the clay-gyttja corresponds approximately with Zone IV, but in deep water the zone of narrow clay bands includes Zones IV, V and VI, so that only the basal part, at most that below the lowest clay band, is contemporaneous with the shallow-water clay-gyttja. The upper part of the zone of narrow clay bands in deep water is therefore contemporaneous with 'brown mud' (detritus gyttja) in shallow water. In the intermediate water depths where the lake floor shelves steeply, pollen analysis has confirmed the results of stratigraphical observation—i.e. that there is a strong unconformity (figure 2*b*).

The distribution of *Pinus* pollen shows two striking features. Its frequency is high at the beginning and end of Zone III, and possibly also in the main part of Zone III. Jessen (1929) suggests that this apparent importance of *Pinus* in cold periods may be due to the undue prominence of pollen transported from a distance when local pollen is sparse. Groschopf (1936) quotes evidence (Knoll 1932) that long-distance transport of *Pinus* does not occur to any great extent, but believes that differential settling of pollen may occur in lake deposits (Ernst 1934) where a marked dominance of *Pinus* may occur.

This last is interesting in view of the second striking feature in the distribution of *Pinus* pollen in Windermere, which is its extremely high frequency in the middle of the lake in Zones IV, V and VI, while at the margins the frequency of *Pinus* in these zones is much lower. A similar example of difference in composition of the pollen spectrum of marginal and central deposits is recorded by Härri (1940) from a Swiss 'moss' which was originally a moraine-dammed lake; here *Fagus* is better represented in the centre and *Abies* at the margins. Such a difference may be explained either by a difference between the local (marginal) pollen rain and the general (regional) pollen rain which reaches the middle of the lake, or by differential settling or preservation of the pollen of various species in deep and in shallow water.

In Windermere there is no positive evidence that *Pinus* was so overwhelmingly dominant in the regional pollen rain as it is in the deposits from the centre of the lake. In the nearest terrestrial profiles analyzed (e.g. Hardy 1939) *Pinus* is present in Zones IV, V and VI in proportions approximately similar to those found at the same horizons in the marginal deposits of Windermere—i.e. there is much less *Pinus* pollen in these terrestrial deposits than in the central deposits of Windermere. Moreover, the Boreal hazel maximum, which is a feature recognized throughout north-west Europe to the west of Ireland, becomes apparent in the central deposits of Windermere only when *Corylus* is plotted as a percentage of tree pollen minus *Pinus*. This suggests that the spectrum of the marginal deposits gives the truest picture of the amount of *Pinus* in the drainage basin as a whole, and that *Pinus* is strongly over-represented in the centre.

No quantitative estimates have been made of the absolute frequency of *Pinus* and the deciduous pollens, but it is obvious that the marginal deposits are much richer in pollen than are those in the centre. Pollen of the deciduous trees is very sparse throughout the central deposits; the relative abundance of pollen in the lower central deposits is due entirely to the great quantities of *Pinus* pollen present. It therefore appears that relatively little pollen except that of *Pinus* becomes incorporated in the central deposits, so that whenever *Pinus* is present in the vegetation it becomes over-represented in these central deposits.

Further experimental work would probably help to elucidate the reasons for this. A pollen count from the surface mud in the centre of the lake gave a spectrum containing 50% *Pinus*; this appears to be an over-estimate of its proportion in the surrounding vegetation, but it is not possible to say this with certainty until we know more of the relative amounts of pollen produced by different trees. The sources of the pollen which becomes incorporated in the central deposits could be investigated by examining the content of (1) the inflow water, and (2) the pollen rain reaching the water surface in the middle of the lake; this would show whether *Pinus* is already over-represented in this. If not, it is probable that differential settling or differential preservation favours the accumulation of *Pinus* rather than the deciduous pollens.

The change from the marginal type of deposit to the central in which *Pinus*, if occurring, is over-represented, occurs in 4 to 10 m. of water in Low Wray Bay, and coincides with a stratigraphical change from very organic brown mud (gyttja) containing abundant plant detritus, to the much less organic brown mud characteristic of the centre of the lake. The absolute pollen frequency is high in the marginal gyttja and low in deposits from water of more than 8 m. deep. It seems likely that this depth of water indicates the position, on this transect, of the boundary between the deposits of predominantly littoral origin and those originating from material carried in by the inflow.

The curve for grass pollen expressed as percentage of the total tree pollen shows the characteristic concave shape in Zones I, II and III, indicating that woodland had more or less replaced open grassland at the height of the climatic amelioration in Zone II. Grass pollen is again abundant at the opening of Zone IV, and falls rapidly throughout this zone with the advance of the forest cover. In Zone VI*c* the relative amount of grass pollen slowly begins to rise, and this rise is greatly accelerated in the topmost 1 to 1·5 m. of deposit (figures 7, 8 and 9). This rise may indicate forest clearance (cf. Iversen 1941) while this topmost 1 to 1·5 m. was accumulating; if so, forest clearance in the district probably began 2000 to 2500 years ago. For a discussion of this point see Pearsall & Pennington (1947).

Macroscopic plant remains

(1) *From late-glacial detritus silt*

All the late-glacial plant remains which have been recovered came from this detritus silt layer; no plant remains have been found in either the upper or the lower laminated clay in any part of the lake. The detritus silt contains plant remains only in the marginal cores—i.e. those from very shallow water. The plants listed here were all found in cores 1, 2 and 8 already described, or in cores from equally shallow water in the bays in the western shore between High Wray Bay and the mouth of Blelham Beck. In water deeper than 5 m. the deposits of this layer are mainly inorganic with very little plant detritus.

The lowest and, therefore, presumably the oldest organic remains found in the lake were almost leafless moss stems, apparently much eroded, present in the greyish pink clay forming the transitional deposit between the lower laminated clay (Zone I) and the detritus silt (Zone II). Mitchell (1940) found similar moss stems occurring as the oldest

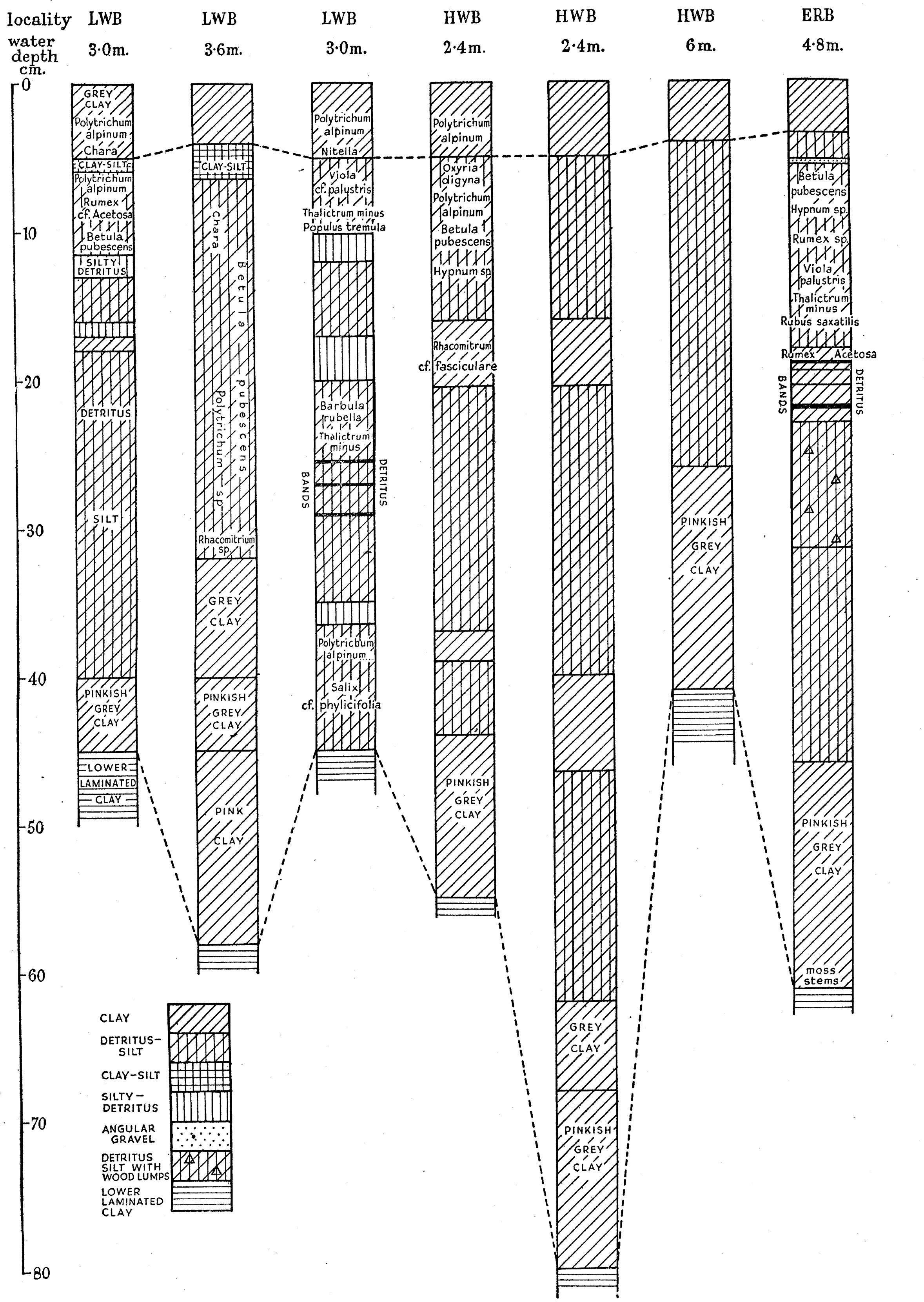

FIGURE 11. Stratigraphy of detritus silt layer (Zone II) in several cores, showing position of plant remains identified. Localities: LWB = Low Wray Bay; HWB = High Wray Bay; ERB = Ecclerigg.

organic remains in a former lake basin in Ireland, at the base of Zone II. There seems no possibility of identifying the moss stems from Windermere unless specimens in a better state of preservation are found, but it was apparently a long-stemmed, probably creeping type.

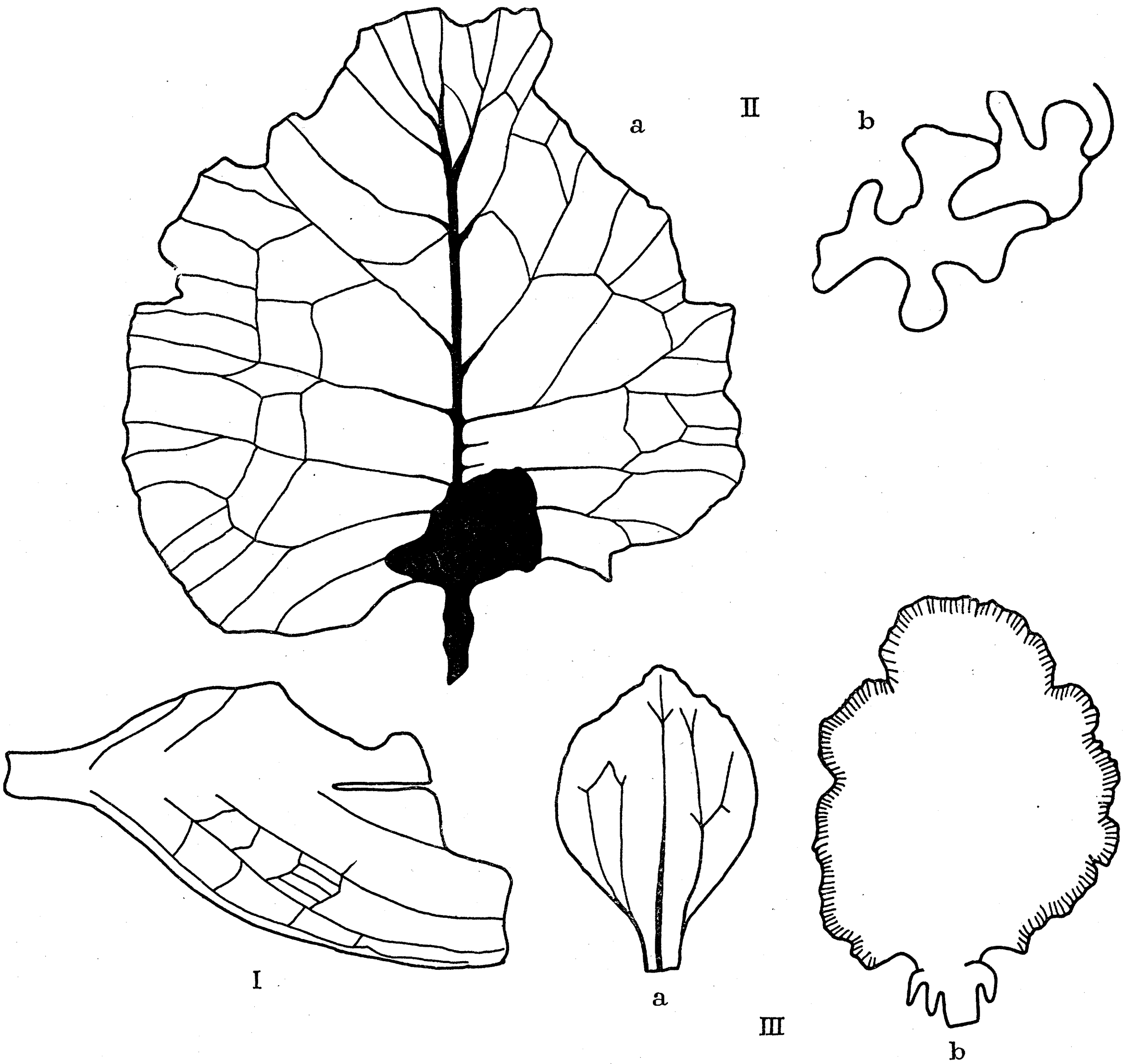

FIGURE 12. Plant remains from the detritus silt layer (Zone II) in shallow water. (I) Leaf fragment tentatively identified as *Salix phylicifolia*, from base of detritus silt. (II) (*a*) Perianth segment of *Rumex*, probably *R. acetosa*; (*b*) Epidermal cells of (II *a*), showing sinuose margins. (III) *Oxyria digyna*, fragments of perianth.

The grey-pink clay passes upwards into a transitional clay-silt, containing stems and leaves of mosses belonging to the genera *Hypnum* and *Rhacomitrium*, and leaves identified as those of *Polytrichum alpinum*. One fragment of a larger leaf (figure 12) resembles *Salix phylicifolia*, which Jessen & Farrington (1938) record from what they regard as Zone II at Ballybetagh, near Dublin, and Hartz & Milthers (1901) from Zone I at Allerød; in all instances the fossil leaf is distinguished from *S. repens* by its flat margin, the margin of the leaf of *S. repens* being recurved. The Windermere specimen is, however, too fragmentary to be identified other than tentatively. (The present distribution of *S. phylicifolia* in northern Britain is along streams on limestone above the 600 ft. contour (Pearsall in litt.).) In this transitional clay-silt the pollen diagrams show that the ratio of non-tree pollen (mainly grass) to tree pollen was high; in conjunction with the above plant list this may be regarded as indicating that the vegetation was open and included at least some species having a northern distribution at the present day.

The transitional clay-silt passes upwards into the main detritus silt, which is in parts very rich in plant remains. This corresponds to the horizon where *Betula* pollen is very strongly dominant—i.e. Zone II, and probably represents a period when birch woodland was the prevailing vegetation, since the ratio N.T.P./T.P. is low. Catkin scales and fruits of *Betula* corresponding to those of *B. pubescens* Ehrh. em. Koch (Lindman 1926) occur throughout this middle part of Zone II, and are commonest about two-thirds of the way up (table 1); this appears to have been the height of the birchwood phase. No remains of *B. nana* were found in any layer in Windermere. The pollen grains of *Betula* from the late-glacial layers were all measured, but the size-frequency graphs gave no consistent indication of a bi-modal curve, such as would have been expected had the smaller grains of *B. nana* been present (Godwin 1934). Moss stems and leaves, some in a fairly good state of preservation, are common, including *Barbula* cf. *rubella*, *Rhacomitrium* cf. *fasciculare*, *Rhacomitrium* spp., *Hypnum* spp., etc. Other terrestrial plants identified from this phase of Zone II are *Rubus saxatilis* (seed), *Viola palustris* (seed), *Thalictrum minus* (fruit), *Menyanthes trifoliata* (seed), *Andromeda polifolia* (leaf fragments) and *Populus tremula* (catkin scale) (figures 13 and 14). Fruits and perianth segments of a *Rumex* were common in the upper part of this horizon; the perianth segments (see figure 12) were fairly large, cordate at the base, without tubercles, and with undulated margins to the epidermal cells, and the nut was 3 to 3·5 mm. long. This suggests that the species was *R. Acetosa,* but does not exclude *R. arifolius* (recorded by G. C. Druce three times from the Scottish mountains), or *R. thyrsiflorus* (a Scandinavian species). Jessen (1938), recording *R. Acetosa* from the lake mud which he regards as the equivalent of the Allerød layer at Ballybetagh, near Dublin, comments that 'it goes far up over the forest limit in Scandinavia'. It is possible that the occurrence of *R. Acetosa* in considerable quantity in the deposit above the maximum *Betula* development indicates the beginning of cooler conditions with consequent decrease in tree growth, but since it is such a common plant in the district to-day this is by no means conclusive.

Unidentified fragments of the leaves of broad-leaved plants, twigs and bark are very common in this main part of the detritus silt. Many of the larger leaf fragments are almost certainly those of a large-leaved *Betula,* but are too small to be identified with certainty. The most abundant of all the plant remains in this layer are the leaf segments of *Myriophyllum,* which in places occur as an almost pure deposit (figure 15 *b*, *c*, plate 2). Like most of the organic remains they appear to have suffered considerable erosion; it is therefore impossible to determine their original length, and hence not possible to refer them to a species with any certainty. The segments are more slender than seems usual in *M. spicatum,* and on the whole they are wider than the long segments of the aquatic form of *M. verticillatum,* so it is reasonable to suggest that they are most likely to be *M. alterniflorum.* This would agree with the fact that the only *Myriophyllum* pollen found in this layer is that of

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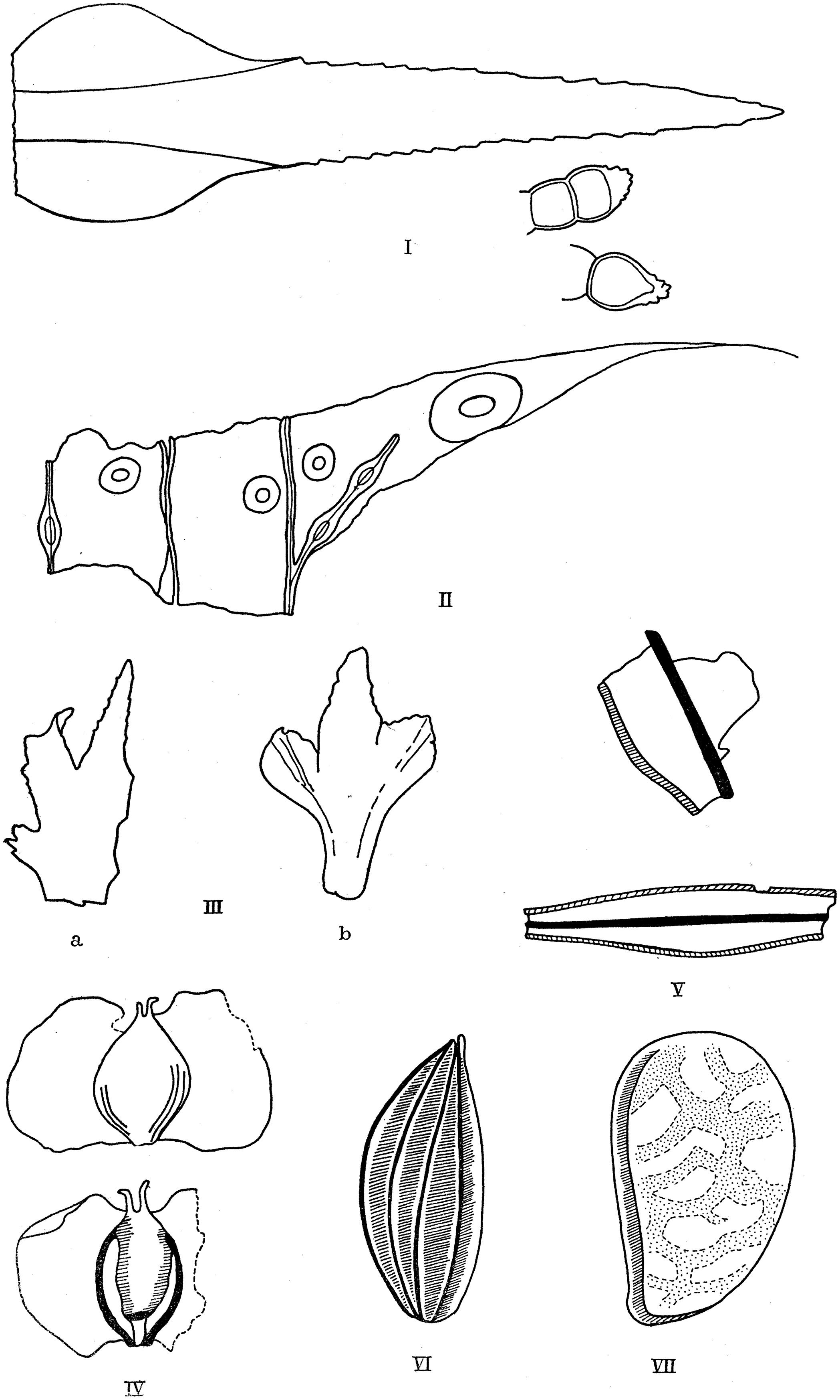

FIGURE 13. Plant remains from detritus silt layer (Zone II) in shallow water. (I) Leaf of *Polytrichum alpinum*, showing characteristic cells at apex of lamellae. (II) Tracheids, probably *Pinus*. (III) Catkin scales, (*a*) *Populus tremula*; (*b*) *Betula pubescens*. (IV) Fruits of *Betula pubescens*. (V) Leaf fragments of *Andromeda polifolia*. (VI) Fruit of *Thalictrum minus*. (VII) Seed of *Rubus saxatilis*.

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M. alterniflorum, but is, of course, in no sense proved by this. Whatever the species it seems certain that a luxuriant littoral growth of *Myriophyllum* was a feature of the lake vegetation during this period.

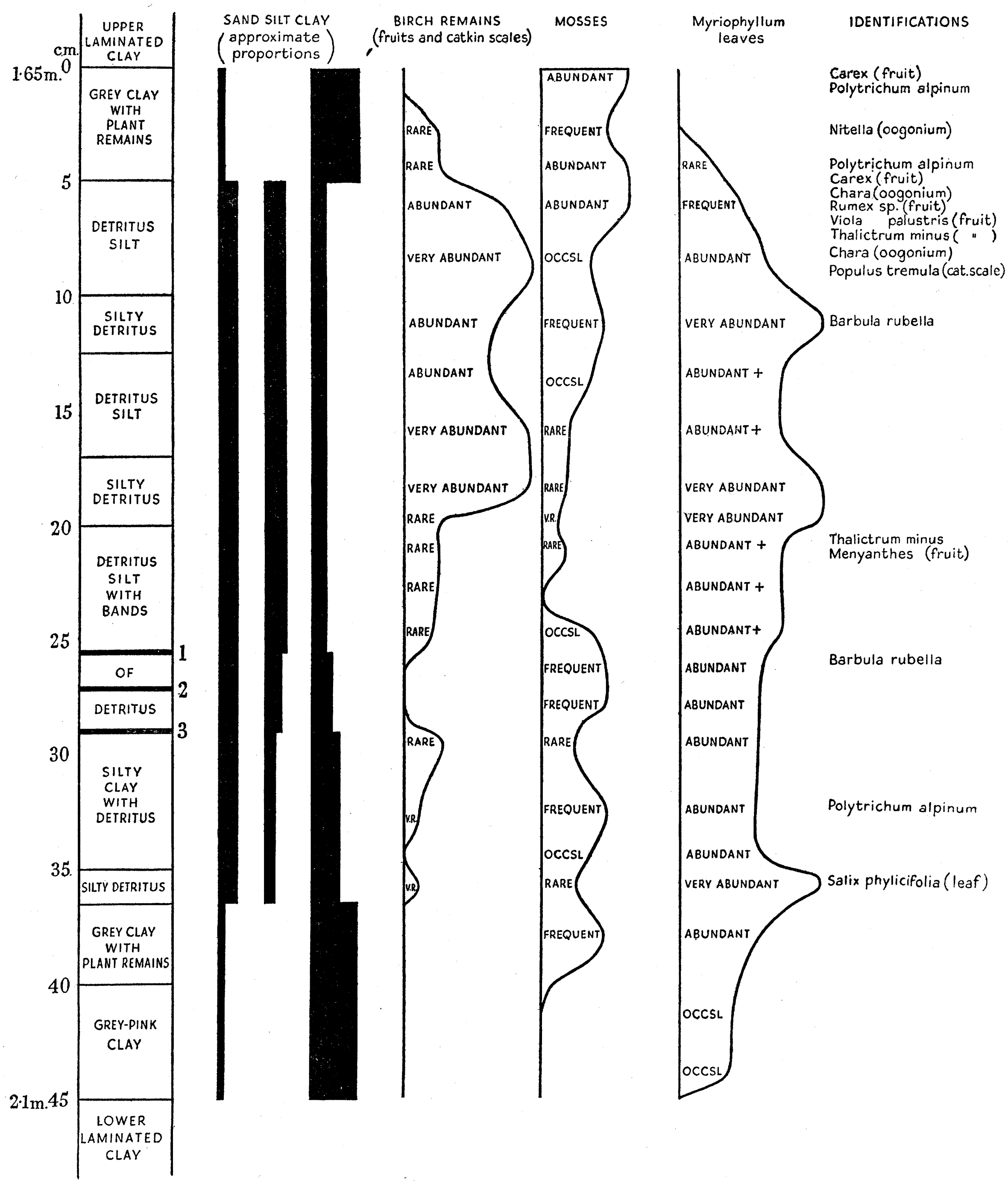

FIGURE 14. Distribution of the plant remains in the detritus silt in core 1.

In all the cores examined the detritus silt is overlain by 2 to 5 cm. of grey clay containing plant remains which forms the topmost deposit of Zone II. Plant remains, like the pollen, are sparser in this clay than in the detritus silt, but the leaves of *Polytrichum alpinum* are common, and the fruit and perianth segments of *Oxyria digyna* were found at the base of this clay in one core (figure 12). Fruits of *Carex* and *Scirpus* spp. are also common. *Oxyria* *digyna* is recorded by Jessen (1938) from Zone III at Ballybetagh; its present distribution is markedly Arctic-Alpine. Its appearance here at the top of Zone II, accompanied by *Polytrichum alpinum*, a mountain and moorland species, together with the fact that here the N.T.P./T.P. ratio again becomes high, suggests that this 2 to 5 cm. of grey clay was deposited under conditions colder than the preceding, when the climate was again becoming severe. The grey clay is everywhere overlain by horizontally bedded laminated clay (Zone III), showing that there were again glaciers in the drainage basin.

Correlation of this late-glacial detritus silt with the Allerød layer of north-western Europe which has been recognized in Ireland. All the evidence from Windermere, from stratigraphy, pollen analysis and macroscopic plant remains, supports the veiw that this detritus silt represents a temporary period of relative warmth during the retreat of the ice-sheet. That this period was not of interglacial magnitude is shown by the relative narrowness of its deposits (maximum 50 cm.) and by the fact that it is overlain only by a comparatively thin deposit of laminated (and therefore presumably waterlain) clay. This shows that there was no readvance of ice over the site after the temperate period, but presumably only a downward movement of valley glaciers from the central mountains towards the lake. This is in contrast with the interglacial deposits of the neighbouring coastal plain (Kendall 1881; Eastwood, Dixon, Hollingworth & Smith 1931) where peat beds containing the remains of temperate plants are sometimes several feet thick and are overlain by boulder clay, presumably deposited *in situ*. It would appear probable that the layer of detritus silt in Windermere was produced as the result of a temporary fluctuation during the final retreat of the ice—i.e. subsequently to the formation of the upper layer of boulder clay on the coast.

The deposits of a similar climatic fluctuation, involving a temporary warmer period, have been described by many continental workers, and correlated with Jessen's zonation in Denmark, where the deposits of Zone II (the temperate or cool-temperate period) are known as the Allerød layer, from the locality where they were first described (Hartz & Milthers 1901). Deposits referable to the 'Allerød period', i.e. Jessen's Zone II, have been discovered in west Norway (Nordmann 1912; Faegri 1936), south Sweden (Nilsson 1935), north Germany, east Prussia and the Baltic States (Gross 1937, 1938), as well as in Denmark. Mention has already been made of the late-glacial lake mud found in Ireland which has been tentatively correlated by Jessen with the Danish Allerød (Jessen & Farrington 1938; Mitchell 1940). These deposits all agree in possessing certain characters which are also possessed by the Windermere deposits described in this paper as Zone II. Typically the temperate or cool-temperate 'Allerød layer' consists of a fresh-water deposit resting on the clay of Zone I, which is either boulder clay, or clay containing Arctic plants, or laminated clay resting on glacial sands or boulder clay, as in Windermere. The overlying deposit of Zone III is not a boulder clay deposited *in situ*, but usually a clay which may contain Arctic plants, or else, as in Ireland, an unsorted mineral deposit apparently originating by solifluction. In each locality the deposit of Zone III is the uppermost (and hence the latest) deposit showing any trace of Arctic influence, and each of the above authors places the late-glacial/post-glacial boundary at the upper limit of Zone III. This agrees completely with the succession in Windermere.

The plants identified, either by pollen or macroscopic plant remains, show that the vegetation of the Windermere region at this period had many features in common with that of the continental localities described by the above authors. At the height of the climatic amelioration, the prevailing vegetation was woodland, predominantly the large *Betula* species (*i.e.* other than *B. nana*), with some *Pinus* and *Populus tremula* (Jessen 1939; Gross 1937). If plants have been identified from the underlying and overlying deposits (usually clays) some Arctic-Alpine species are usually included (Jessen 1935, etc.; Hartz & Milthers 1901); in Denmark Zones I and III are known as the lower and upper *Dryas* clays, and *D. octopetala* commonly occurs at these horizons in other localities. No trace of this species has been found in Windermere, but three species, *Polytrichum alpinum*, *Oxyria digyna* and *Salix phylicifolia*, having a northern distribution have been found at the base and top of Zone II. *Myriophyllum alterniflorum*, common in Zone II in Windermere, is a species characteristic of late-glacial and pre-Boreal deposits (Nilsson 1935; Erdtman 1943; Von Post 1935). The flora of the Allerød layer, cool-temperate at the height of the period, contrasts with that of interglacial deposits in Denmark, in which remains of a warmth-loving flora, mixed oak forest with *Tilia*, *Acer campestre* and *Carpinus Betulus*, indicate that the summers in this interglacial period were warmer than at the present day (Jessen & Milthers 1928).

(2) *From post-glacial deposits*

Most of the plant remains in the deep-water deposits are too finely divided to be identified, though an exception occurs in the layers of what is apparently flood debris which occur in positions off the mouths of larger inflow streams (Pennington 1943).

In very shallow water, where the post-glacial deposits above the basal clay-gyttja consist of very organic gyttja with large quantities of visible plant remains (see previous section), the leaf segments of *Myriophyllum*, probably *alterniflorum*, are abundant in Zones IV and V, but not in later deposits. Fragments of leaves, twigs and bark, and pieces of wood up to 1 cm. cube, occur occasionally in these deposits. The wood is much decayed, and it has not yet been possible to identify it by microscopic examination.

General discussion

(1) *Dating the deposits; possible correlations*

(*a*) *Late-glacial.* Evidence has been given in the preceding section for correlating the late-glacial sequence in Windermere with that found in Ireland and north-west Europe. If this evidence is accepted, it establishes that, both in north-west England and Ireland on the one side and north-west Europe on the other, there occurred a temporary warmer period with temperate or cold-temperate birchwoods, during the last stages of retreat of the Quaternary ice-sheets. The cold period following this warmer period represented the last appreciable advance or halt of the Quaternary ice, and the deposits of this cold period contain the last records of Arctic-Alpine plants in lowland districts. The deposits of the temporary warm period, the Allerød, have been recognized all round the southern edge of the Scandinavian ice-sheet, from western Norway to western Russia (see previous section). In Ireland the deposits so far described indicate that a similar climatic oscillation occurred during the final retreat of valley glaciers from the mountains of Wicklow and north-west Ireland (Jessen & Farrington 1938; Mitchell 1940).

In all these localities the sequence of deposits shows that the last cold period was followed by the gradually improving climate of the post-glacial period, the climatic sequence being that described by Blytt & Sernander—i.e. a gradual increase in average temperature through the dry pre-Boreal and Boreal periods, followed by the wet warm Atlantic period in which occurred the so-called climatic optimum, followed by decreasing temperature. Forest development as shown by pollen analysis followed a parallel course through open birchwood, birch-pine, pine forests, and then the incoming of mixed oak forest with alder at the opening of the Atlantic period. This parallel development of climate and vegetation strongly suggests that the last cold period on the margins of the north-west European centres of glaciation was roughly contemporaneous in all these localities (Zeuner 1946), since to suppose otherwise would be to assume that the succeeding phases of forest development were not contemporaneous, and if this were so it is difficult to understand why they followed such a parallel course in localities from western Ireland and Norway to western Russia.

If it is found possible to correlate the series of varves in Windermere with the Swedish series, this should give valuable evidence of this question of contemporaneity of the Allerød layer in the different localities, though the interpretation of the varves which occur in Zone I (i.e. below the lake mud) at Allerød itself appears still to be controversial (De Geer 1916; Nordmann 1922; Milthers 1927). The time-scale based on the Swedish varves, developed by De Geer (1908 et seq., 1940) appears to be the most promising source of a late-glacial chronology on which direct time correlations could be based. The difficulties incurred in measurement of the Windermere varves have been discussed, but it is probable that improvements in technique may enable these difficulties to be overcome.

Meanwhile the Windermere varves have provided one positive piece of evidence in favour of direct correlation with the continental succession. It is now generally considered by continental workers (Gross 1937; Gams 1938), in spite of the earlier controversies, that the cold period which followed the Allerød oscillation was that during which the Fennoscandian moraines were formed—i.e. the last major halt of the retreating Scandinavian ice-sheet. De Geer (1910*b*) pointed out that this period when the ice border was stationary at the Fennoscandian moraines was the last period when an Arctic marine fauna flourished in the Baltic. Also (1908) he showed, from varve counts on a transect at right angles to the general trend of these moraines, that the ice border remained stationary for between 100 and 200 years, and then retreated only very slowly during the next 300 years—i.e. that the cold period lasted 400 to 500 years. A count of the annual laminations in the upper laminated clay of Windermere (i.e. the cold period following the deposition of the detritus silt which is correlated with the Allerød layer) gave 377 as the total, and if the grey clay-silt layer containing *Oxyria digyna* at the base of the laminated clay is included, 400 to 500 years would be a reasonable estimate for this period. (It should, however, be noted that this figure of 377 annual laminations could be altered very considerably if composite varves (cf. De Geer's digraphs and trigraphs) were regarded as several distinct narrow varves, and that until direct comparison has been made with De Geer's Swedish material the counting method must be regarded as somewhat subjective.) In addition, De Geer's estimate of the length of this period differs from that of Sauramo (1939), who estimated the period of formation of the Salpausselkas, in Finland, as *c.* 700 years.

There does, however, appear to be sufficient evidence available on which to build a tentative correlation of these English late-glacial deposits with those of Ireland and the Continent. Assuming that the deposits of Zone II (the Allerød layer) are contemporaneous in Windermere and Ireland, the upper laminated clay of Windermere (Zone III) would be contemporaneous with the valley glaciation of the Wicklow mountains (Jessen & Farrington 1938) which took place while the solifluction layer of Zone III was forming at Ballybetagh. According to Charlesworth (1939) and Farrington (1945) this Wicklow valley glaciation (=the Athdown mountain glaciation) probably belongs to the cold period of the Antrim coast readvance which followed that during which the readvance of Scottish ice on to the coast of Cumberland occurred (Charlesworth 1939). This period of the Scottish (Solway) readvance would therefore be that during which Zone I or the lower laminated clay was formed in Windermere, and the latter is therefore dated as contemporaneous with the Upper (Red) Boulder Clay of the Cumberland coast, which is considered to be the deposit of this readvance of the Scottish ice (Eastwood *et al.* 1931; Trotter & Hollingworth 1932). This agrees with the conclusion of these latter workers that during this period any advance of the glaciers in the centre of the Lake District was confined to the upper ends of the valleys and that there was no outward movement of the Lake District ice beyond the boundary of the mountain group (Hollingworth 1931). That is, it seems probable that the drainage from these glaciers was producing laminated clays in Windermere but that the ice front did not reach the lake. On the other hand, there is no evidence of a break between the lower laminated clay and the underlying stony clay, so it is conceivable that this latter may represent the deposits of the valley glaciers at the height of the period of the Scottish readvance, followed by laminated clays as the retreat at the end of the period began; but it seems more likely that the basal stony clay is the deposit of the ice of the preceding period —i.e. the main glaciation of the north-west (Eastwood *et al.* 1931)—which presumably deposited the morainic dam at the foot of the lake. The laminated clay of Zone III on this correlation would represent a cold period later than that of the Scottish readvance, with valley glaciers in the Lake District corresponding to the valley glaciation of the Wicklow mountains and possibly to the valley glaciation of the Scottish Highlands (Movius 1942), but possibly not (Farrington 1945).

Table 1 shows these tentative correlations with what are regarded as the corresponding deposits on the Continent, if it is accepted that Zone II in Windermere corresponds to the Allerød amelioration of Jessen and the other continental workers quoted. It should be noted that the correlation of Zone III in Windermere (upper laminated clay) with both Zone III in Ireland (the Athdown mountain glaciation) and the formation of the Fenno-scandian (*Ra*) moraines, is confirmed by Farrington's suggested correlation of these two latter periods (Farrington 1945). In the opinion of most Quaternary geologists there is as yet insufficient evidence for any correlation between the glacial periods of the British Isles and those of Europe, so the only correlations suggested are those for which evidence has been brought forward, and no attempt has been made to suggest any correlation with the Alpine glacial periods, though from those suggested by Gams (1938) and others (Movius 1942; Zeuner 1945) the most likely correlation seems to be to regard Zone I, which in Britain is probably equivalent to the Solway Scottish readvance, as equivalent in Europe to the Bühl Stadium or Würm III in the Alps. This agrees with the suggestion of

Table 1. Table of tentative correlations; time-scale based on data from De Geer and Tage Nilsson; for later work of Liden and Sauramo on varve datings see Zeuner (1946).

Zone	Windermere	North-west England	Ireland	Denmark	Sweden	Date (De Geer)
VI*c*	Top clay band					
VI*b* VI*a* V IV	Clay-gyttja		Post-glacial mud	Post-glacial mud	Retreat of ice to bipartition at Ragunda	6,800 B.C.
III	Upper laminated clay	Possibly valley glaciation in Lake District	Antrim coast readvance valley glaciers in Wicklow Mts., solifluction layer, Ballybetagh	Upper *Dryas* clay	Ice border halted at Fenno-scandian moraines	7,874 B.C.
II	Detritus silt with *Betula pubescens*, *Pinus sylvestris*		Mud with *Betula pubescens*, *Pinus sylvestris* at Ballybetagh, etc.	Allerød layer mud with *Betula pubescens*, *Pinus sylvestris*	Allerød layer	8,300 B.C.
I	Lower laminated clay Stony clay	Scottish (Solway) readvance upper boulder-clay of Cumbrian coast Main glaciation of north-west (Hunstanton boulder-clay glaciation)	Carlingford readvance	Lower *Dryas* clay		10,000 B.C.

Trotter & Hollingworth (1932), and fits in with what Boswell (1936) and Bisat (1940) regard as the most likely correlation, if it is assumed that the Solway Scottish readvance belonged to the next cold period following the advance of the ice to the York moraines and deposition of the Hunstanton boulder-clay, which they regard as being most probably equivalent to Würm II.

De Geer (1925 et seq.) considers that 8300 to 7874 B.C. is the probable extent of the cold period during which the ice border was more or less stationary in the region of the Fennoscandian moraines, and that the Allerød layer was probably formed at some time between 10,000 and 8300 B.C. (see also Movius 1942). The relation of these dates to the time-scale already suggested for the Windermere deposits (Pennington 1943), based on sedimentation rates, will be discussed in the following section.

(*b*) *Post-glacial.* If it is correct to correlate Zone III, the upper laminated clay, with the period of formation of the Fennoscandian moraines, the date of the top of the laminated clay in Windermere is about 7874 B.C. according to De Geer's time-scale. He considers that the post-glacial period began in Sweden with the bipartition of the retreating ice at Ragunda, 1074 years later, i.e. 6800 B.C. Swedish workers (Nilsson 1935) consider that in south Sweden, this was the approximate date of the transition from the period of the hazel maximum to the incoming of the mixed oak forest, and that the peak of the hazel maximum occurred between 7500 and 6800 B.C. Nilsson gives 6200 B.C. as the possible date of the Boreal-Atlantic transition, i.e. the boundary between Zones VI and VII in Godwin's scheme. In the Windermere deposits, this horizon is marked by the very sudden expansion to dominance of *Alnus*, and on the time-scale published for the Windermere deposits (Pennington 1943) falls between 6000 and 6300 B.C.

This time-scale for the Windermere deposits was based on the present rate of sedimentation of mineral matter, knowledge of the water content (i.e. the packing factor) at successive levels in the deposits, and the assumption that the rate of sedimentation of mineral matter has been approximately constant since the immediately post-glacial stages, but was rapid at the close of the late-glacial period (Pennington 1943). On this time-scale the date of the top of the laminated clay is about 8560 B.C. compared with 7874 B.C. on De Geer's geochronology. Since the estimate of the present sedimentation rate is probably an under-estimate rather than an over-estimate, and the estimated rate for the late-glacial/post-glacial transition is somewhat arbitrary, it is not surprising that the above calculation rather over-estimated the length of the period. The Allerød oscillation probably occurred at some time between 10,000 and 8300 B.C. (De Geer etc., see Movius 1942), and since the laminated clay of Zone I below the Allerød layer is the oldest waterlain deposit, the estimate of about 12,000 years as the age of the lake (Pennington 1943) agrees reasonably well with this. This fairly good agreement between the two time-scales suggests that the assumptions about sedimentation made in the previous paper are reasonably true, in so far as they apply to deep water.

(2) *Results of pollen analysis in relation to previous work on the deposits*

(*a*) *Diatom zonation.* When the zonation based on pollen analysis is compared with the diatom zonation already published (Pennington 1943), some discrepancies are apparent, but a consideration of the conditions of formation of the deposits suggests an explanation of this.

In the late-glacial period, zonation based either on pollen analysis or on the diatom flora corresponds with the sharp stratigraphical boundaries between the lower laminated clay, the detritus silt ('grey layer') and the upper laminated clay. The laminated clays contain few or no organic remains; thus all the available evidence suggests that these, i.e. Zones I and III, represent periods when there was practically no organic production in the lake or vegetation round its shores. The diatom flora of Zone II contains some planktonic species, but the bulk of the diatom population consists of heavy bottom-dwelling littoral species, and no diatoms are found at this horizon in deep water. This agrees with the type of diatom population which other workers (Brander 1935) have found to be characteristic of cold or cold-temperate periods such as the immediately post-glacial phase in the Baltic region.

A similar diatom population is found in the immediately post-glacial deposits of Windermere, and here the apparent discrepancy between the diatom and pollen zonation arises. The predominantly bottom-dwelling diatom flora, here characterized by *Melosira arenaria* var. *hungarica* is confined to the clay-gyttja (Zone IV) in shallow water, but apparently persists throughout the zone of narrow clay bands in deep water. These two deposits were therefore regarded as belonging to the same time-zone, but pollen analysis has shown that the zone of narrow clay bands in deep water includes Zones IV, V and VI, so that only the basal part of this deposit (i.e. that below the lowest clay band) can be equated with the clay gyttja in shallow water. A quantitative survey of the diatom population in deep water, in the deposits between the lowest and the topmost clay band (Pennington 1943, figure 9) shows that the large, mainly bottom-dwelling species, reach their maximum numbers in association with each narrow clay band, i.e. just above or below each band of pure clay. The deposits intervening between the clay bands are, in appearance and organic content, very similar to those of the overlying brown mud (gyttja). It is therefore suggested that the large bottom-dwelling diatoms are here mainly secondarily deposited—i.e. that the great floods or breachings of glacial dams in the upper valleys, which produced the clay bands, also carried down these large diatoms from the earlier deposits of smaller, possibly now drained, glacial lakes in the upper valleys of the main inflows.

Above the upper limit of the bottom-dwelling diatom flora characterized by *Melosira arenaria* var. *hungarica*, the diatom flora is very uniform, and no further zones could be distinguished until the *Asterionella* ooze was reached. Pollen analysis has provided a method by which certain horizons in the upper gyttja deposits can now be recognized.

(*b*) *Stratigraphical results*. The contribution of pollen analysis to the elucidation of the late-glacial stratigraphy has been to confirm the view that the period of interruption in the regular varve deposition which in shallow water led to the formation of detritus silt was in fact a temporarily warmer climatic period. Since the laminated clays contain practically no pollen or organic remains, any possible explanation of the marked irregularities sometimes found in the deep-water laminated clays must await further geological investigation, notably of the varve sequences. These irregularities may be due to channels in the late-glacial deposits, grounding of icebergs, the presence of persistent blocks of dead ice, or to slumping of the deposited clays similar to that described in Palaeozoic submarine clays (Heim, 1908).

The evidence of pollen zonation shows that the immediately post-glacial deposits of Zone IV were, like the late-glacial Zone II, deposited much more rapidly at the margins than in the middle of the lake, where Zone II is not represented by any deposit and Zone IV is very narrow. The material forming these two zones was therefore presumably derived from littoral erosion, and possibly, during the colder parts of the periods, from solifluction. In Zones V and VI, on the transect investigated, the deposits at the margins are considerably thicker than those in the centre, but the difference between marginal and central thickness is less than in the earlier zones. The truncation of the marginal profiles 3 to 4 m. below the water surface suggests that however much material is available, no further accumulation takes place on a stony shore such as Low Wray Bay once this water depth is reached. The material forming the deep-water deposits is probably derived chiefly from the main inflow and organic production within the lake; this would at least partially explain the relatively slow accumulation in Zone IV, 10 to 15 cm. in about 400 years—first because it would be expected that at this early stage in the lake's post-glacial history the bulk of the sediment entering the lake by the inflow would be coarse and hence rapidly deposited in the delta region (Pearsall 1921 etc.; Kindle 1930), and secondly because both the low temperature and the low concentration of nutrient salts would restrict organic production in the lake (Pearsall 1921, etc.). If the above time estimate is correct, the average annual increment in Zone IV is seen to be about 0·2 to 0·3 mm., and the water content of this deposit is about 50%, while at present in this position the annual increment is about 2·5 mm. with a water content of 93%; the ratio of sedimentation rates of solid matter in the immediately post-glacial period to that at present is therefore about 1:10 in annual thickness, and 5:7 in volume of solid matter deposited. The corresponding ratio for the amount of carbon deposited per annum is 1:7. This means that the sediment accumulating in the middle of the lake each year in immediately post-glacial times was of about five-sevenths the volume of solid matter and about one-seventh the volume of organic matter of the sediment accumulating at present. The previous assumption (Pennington 1943) that sedimentation of mineral matter was relatively rapid in this immediately post-glacial period is therefore proved to be wrong when applied to the middle of the lake; only at the margins and probably in the delta region is it true.

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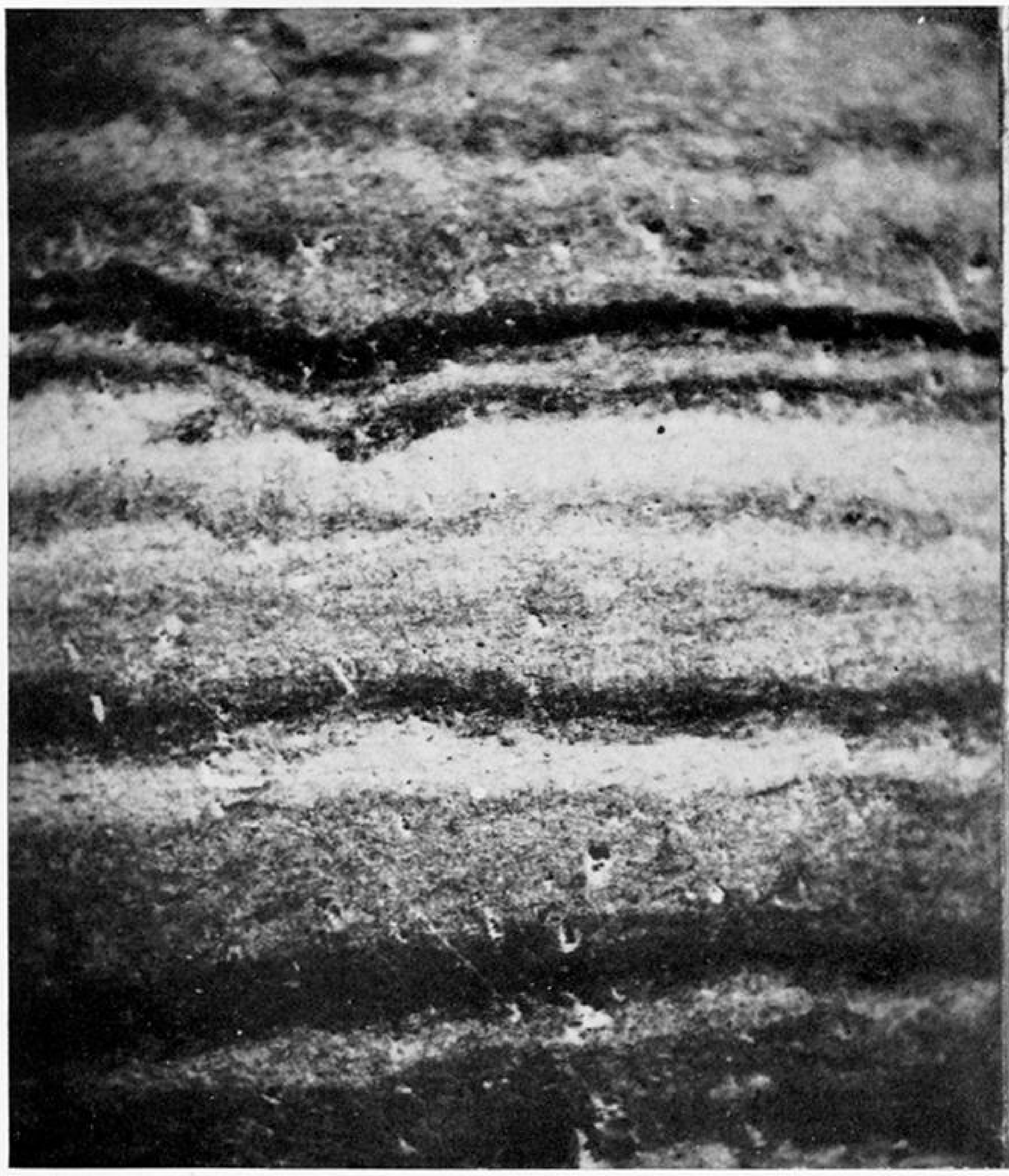
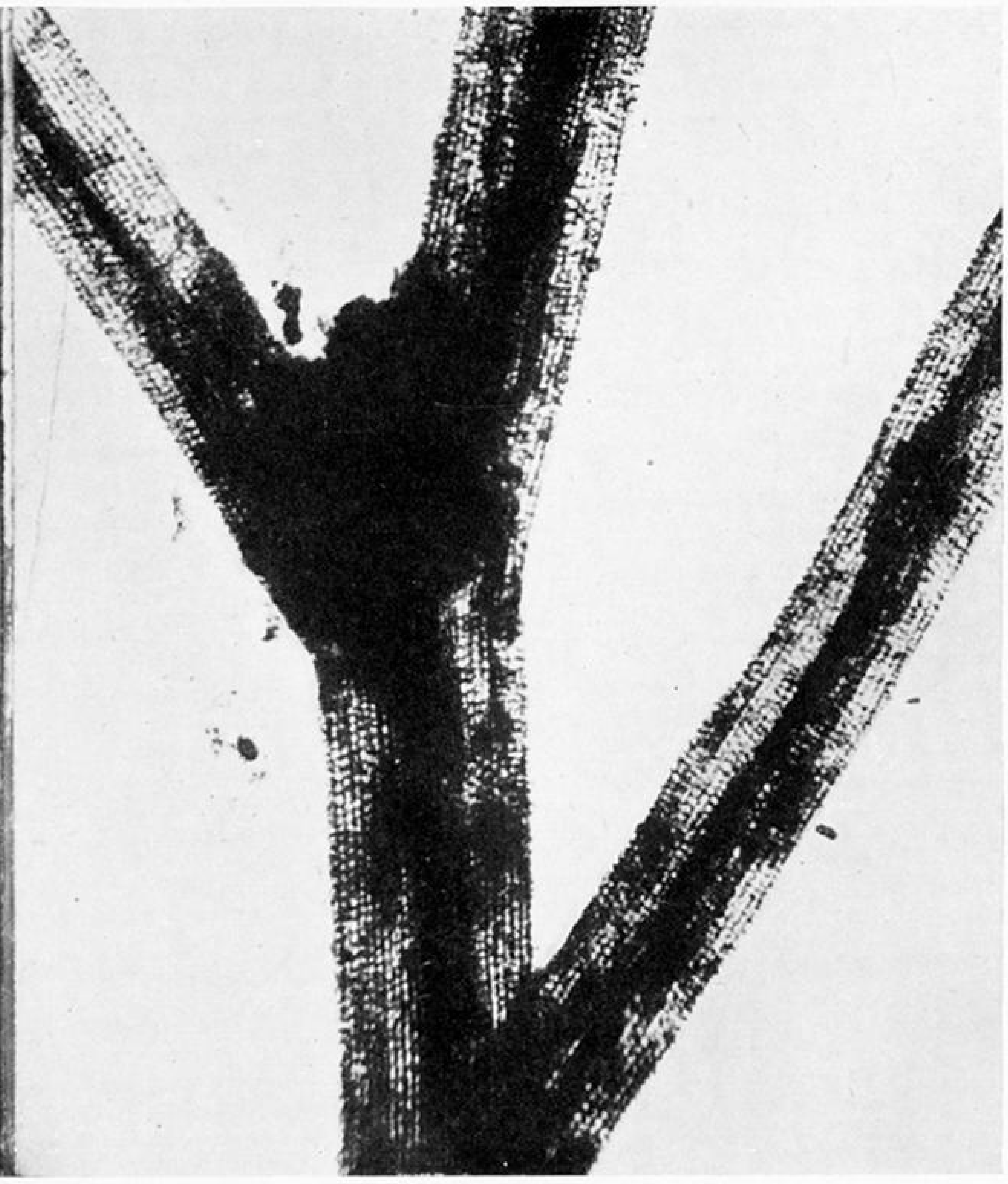
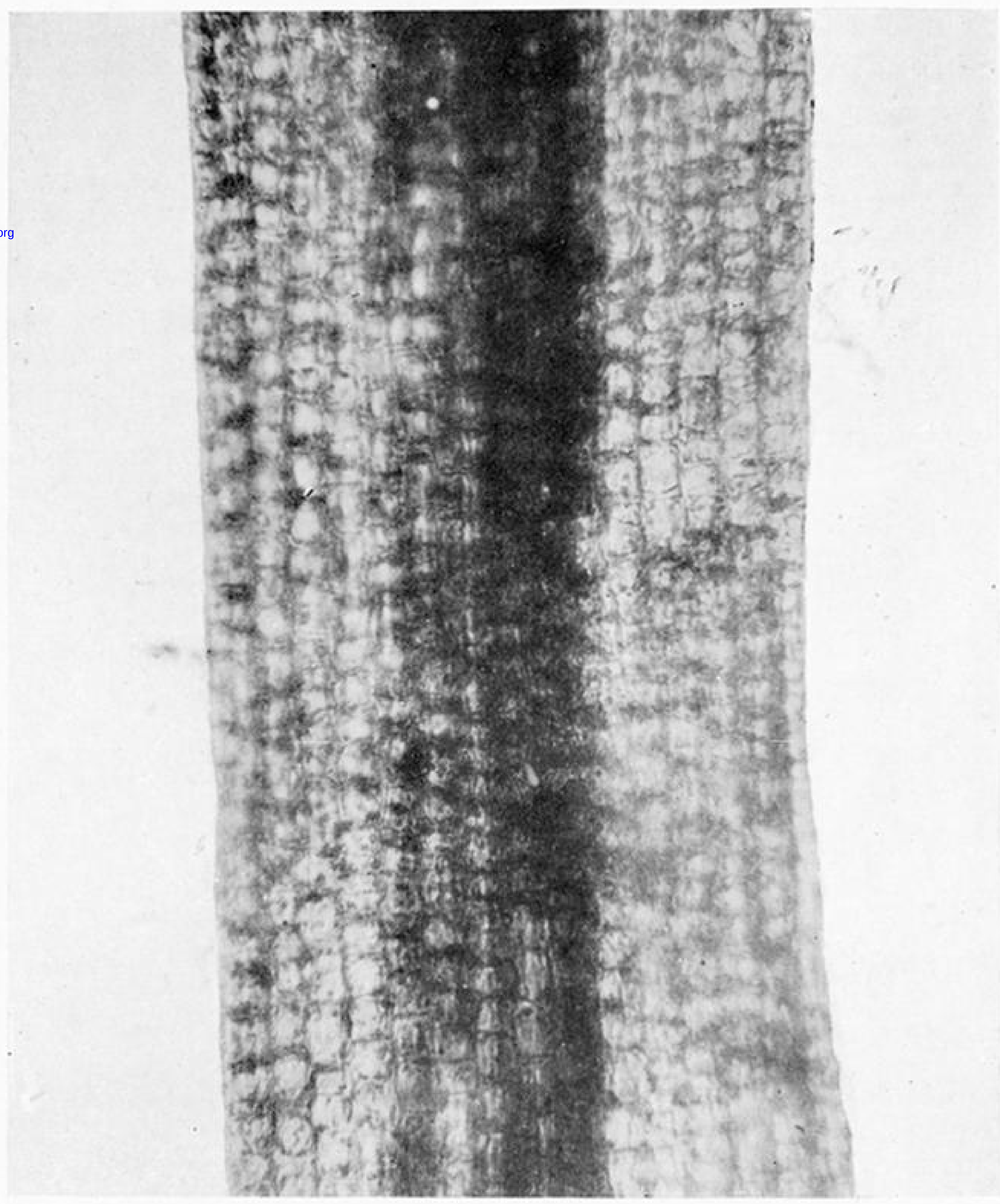


(*a*)



(*b*)



(*c*)

FIGURE 15. (*a*) Typical varves from the upper laminated clay in Windermere. (*b*), (*c*) Leaf segments of *Myriophyllum* sp. from the detritus silt (Zone II).