Low Wray Bay (Windermere)

[NY 377 013]

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Introduction

Low Wray Bay, Cumbria (Figure 6.1) is the type locality for the Windermere Interstadial (Coope and Pennington, 1977) which occurred after the Late Devensian ice sheet retreated (Dimlington Stadial). The site is situated on the western side of Lake Windermere [NY 377 013], which is 17 km long, 14.8 km^2 in area and reaches a maximum depth of 64 m. This lake basin contains a thick sequence of lacustrine sediments in which are recorded the later stages of Devensian deglaciation, the Late-glacial period and the Flandrian succession. The importance of the site stems from the detail in which this sequence is known, with biological, geochemical and geophysical investigations being carried out since the late 1930s. At Low Wray Bay the thick lacustrine sequence has provided vital biostratigraphical, lithostratigraphical, chronostratigraphical and geochemical evidence for the rapid sequence of environmental changes during the past 15 000 years. The biostratigraphical record obtained from this location is superior to other British sites and has allowed the Windermere Interstadial to be defined on the basis of both lithostratigraphy and biostratigraphy and the sediments also have been radiocarbon-dated in detail. This has helped to define this interstadial in age, allowed international correlation and raised a number of important issues with regard to the biostratigraphy.

Description

The Admiralty Chart (1937) of Lake Windermere was prepared from results of an early echo-sounding survey, which showed a discontinuity in the unconsolidated sediments overlying bedrock. A programme of sediment coring was initiated (Jerkin and Mortimer, 1938) to determine whether this discontinuity represented the interface between glacial clay and post-glacial mud. The results were positive and since this early work more detailed profiles from 'sparker' and 'pinger' seismic profiling have been published (Howell, 1971). These surveys have shown that the North Basin contains 21 m of sediment and the South Basin up to 40 m. Over the submerged ridge with islands, which separates the two deep basins, the water is shallow and the glacial clays are here covered by less than 1 m of post-glacial mud. The stratigraphy above the bedrock showed up to 30-cm-diameter cobble gravels and the sediments above these gravels have been sampled by Mackereth corers (Mack-ereth, 1958). These penetrate to the gravels in shallower water but not in the central parts of the lake, where the sediments are much deeper.

The brown, organic post-glacial muds, which reach a thickness of 5–6 m in the North Basin and *c.* 3 m in the South Basin, represent the deposits of the past 10 000 years and have been shown to be clearly stratified, although in their lower parts they include the occasional slump comparable with the slump structures in the underlying clays (Smith, A.J., 1959; Mackereth, 1966). The pattern of accumulation of these brown muds in the North Basin was first established by pollen analysis of ten cores (Pennington, 1947), where the application of a pollen chronology showed the relative rates at which post-glacial sediment accumulation had taken place in different parts of the basin. Deductions based on this early work have subsequently been confirmed by ^{14}C dating. Two examples of these early pollen diagrams are illustrated in (Figure 6.2) from Low Wray Bay. Plant macrofossils were also analysed by Pennington (1947) from the detritus silt and an example is given in (Figure 6.3). The post-glacial brown mud from the central parts of the South Basin provided the cores on which Mackereth (1971) carried out his pioneering work on the palaeomagnetism of lacustrine sediments. The curve for the horizontal component of remanent magnetization, in a core from which nine ^{14}C dates were obtained, showed regular swings in direction identified with past oscillations. This work has been continued and expanded by Thompson (1975) and Turner and Thompson (1981) and the 'master curve' from Windermere has been used as a basis for comparison for observations on other lake sequences. The secular variations in the magnetic field have been short term and local, involving oscillations in inclination or declination of 20–30° over 2000–3000 years.

Below the brown Flandrian muds there is in all parts of the lake a thick deposit of laminated pink-grey clay in which the paired laminations (couplets) are composed of a fine-grained pink layer and a coarser, greyish-pink layer in which graded bedding is visible (Pennington, 1947). These laminated clays contain a sparse pollen content characterized by *Arternisia* (Pennington, 1980). About 50 cm below the upper boundary of this laminated clay, its lower boundary is formed by a discontinuity. Although the laminated clay is similar over most of the lake floor, everywhere containing about 400 couplets, the underlying sediment below the discontinuity is markedly different in shallower water, in water depths of 10 m or less. In the shallow, littoral areas an organic interstadial deposit is present, but this rapidly wedges out with increasing water depth, and inside the 15 m water-depth contour only a thin layer of grey silt underlies the laminated clay (Pennington, 1947).

This grey silt in the North Basin is coarse and non-fossiliferous, but in the central parts of the South Basin it contains pollen and on both pollen and ^{14}C evidence it has been shown to be correlative with the thicker (*c.* 50 cm) and organic interstadial deposits of the marginal bays (Pennington, 1947). Below these sediments of interstadial age, there is in all parts of the lake a lower laminated clay, in which there is a rapid downward transition from laminated couplets of the same type as in the upper laminated clay to coarser-grained sediment in which the couplets are much thicker and show a stronger colour and particle-size contrast between the two layers of the couplets. In the shallower water areas this deposit is under 50 cm thick and passes down into gravel but outside of these areas there is a great thickness of laminated clay, within which there are thick layers of sand and silt, resembling the turbidites described from Lake Brienz, where the catchment is 18% glaciated (Sturm and Matter, 1978).

The site of Jenkin and Mortimer's (1938) original coring in Low Wray Bay provided the first evidence in Britain for the Late-glacial Interstadial, then called the Allerød', which had then just been recognized in Ireland (lessen and Farrington, 1938; Pennington, 1943). The first supporting ^{14}C date (Q294) was obtained by Godwin (1960a) but subsequent work on this profile, and a series of ten ^{14}C dates obtained from a wide-diameter corer, confirmed that an interstadial beginning much earlier than the continental Allerød was represented (Pennington, 1970, 1977). The Late-glacial pollen diagram is illustrated in (Figure 6.4) and a transverse section of Windermere in the latitude of Low Wray Bay showing a section through the deposits is illustrated in (Figure 6.5)

The earliest organic deposits in Low Wray Bay, which contain pollen spectra and annual pollen deposition rates indicative of treeless tundra, have been dated to 14 557 ± 280 years BP and 14 623 ± 360 years BR Prior to these dates seasonal snow melt from the valley glacier led to the deposition of the Lower Laminated Clay, from which no organic remains have been found. In these varved clays there is an upward change in thickness from the lowest varves immediately overlying a stony clay, which average 0.5–1.0 cm, to the upper varves, which may be only 0.2 mm (Pennington, 1943). It can be interpreted as a change from an ice-proximal to an ice-distal position as the valley glacier retreated towards its source during deglaciation. Pennington (1943) also reported that a count of the annual laminations in the Upper Laminated Clay gave 377 as the total, but 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 that period.

The following synthesis of the pollen assemblage zones for Windermere is taken from Pennington (1977). Before *c.* 14 000 years BP there is a *Salix herbacea–Cyperaceae–Lycopodium selago* zone, with such low pollen concentration that annual deposition rates cannot have exceeded 100 grains per cm2 per year, a figure low even for tundra (Davis *et al.,* 1973). Chionophilous (snow bed) and/or fjell field plant communities existed in a periglacial environment, between *c.* 14 000–13 000 years BP (Figure 6.4) shows a pollen zone dominated by 20% *Rurnex* and 25% grass pollen, and pollen concentration is ten times that of the underlying zone. Within this zone appear many taxa suggestive of a climatic amelioration, for example, *Filipendula, Hippopheie* and *Typha latifolia,* together with at the base of this zone a significant increase in percentage and absolute values for juniper and tree birch pollen. Through this zone *Salix herbacea* declines, Cyperaceae values remain low and *Lycopodium selago* disappears. Some undoubted *Betula nana* pollen is present, together with that of *Empetrum, Thalictrum* and Rubiaceae, whilst there is a rich herb assemblage, including *Helianthemum* and *Artemisia.* This climatic amelioration was unaccompanied by a significant expansion of woody plants. The next two pollen assemblage zones illustrate the Windermere Interstadial. Between 13 000 and 12 500 years BP the *Juniperus* zone shows a steep percentage and absolute rise in juniper dated to 13 000 years BP, and the Betula zone between 12 500 and 12 000 years BP shows the maximum percentages of birch (30% of the pollen record or more, corresponding to 800 1000 grains per cm2 per year, which indicates, according to Birks (1973), a canopy cover of at least 50% and exceeds by a factor of four the present deposition rate from park-tundra). The characteristic Late-glacial assemblage of *Henanthemum, Hippophäe* and *Artemisia* reaches its maximum development in this zone and, although it has not been noted in modern vegetation, it must represent a community of unshaded habitats. A local factor probably continued to inhibit the growth of tree birches on some terrain types so that there was a mosaic of woodland and open areas with unstable soils. From 12 000 to 11 800 BP there is a narrow zone of reduced pollen deposition of the more thermophilous taxa, which is dominated by *Betula–Rumex.* It represents a partial regression towards the composition of deposits pre-13 000 years BP and frequencies of grasses, sedges and other herbs were now higher than previously in the interstadial. Between 11 800 and 11 000 years BP the *Betula–Juniperus* zone demonstrates birch woodland, ferns (*Dryopteris* and other, unidentifiable, fern spores) and grass, sedge and *Empetrum* pollen. The inference is of more open woodland than the earlier woodland episode. Disintegration of the plant cover, the most likely cause being thought to be increased snowfall, is marked by a *Cyperaceae–Selaginella* local subzone, where there were reduced frequencies of birch and juniper. Between 11 000 and *c.* 10 500 years BP there were three pollen assemblage zones recognized: *Rumex–Artemisia, Artemisia–Rumex* and *Arternisia–Caryophyllaceae*, which have been dated to the first half of the Younger Dryas period, during which time the varves in Windermere were being deposited from meltwater of the corrie glaciers farther up-valley. The *Artemisia* pollen zones coincide with a distinct lithostratigraphical unit of lower organic content, indicative of periglacial soil movement and identifiable geochemically with the unweathered products of intense periglacial erosion. From about 10 500 to 10 000 years BP there is a herb-dominated pollen assemblage zone that contains much grass, sedge and *Rumex* pollen, and sediment of increasing organic content, which developed as the climate began to ameliorate towards the conclusion of the stadial. The vegetation represents the pioneer stages and soil stabilization after the glacial–periglacial phase.

The interpretation from pollen analysis was confirmed by study of the coleopteran remains (Coope, 1977), which showed that sediments dating from *c.* 14 000 years BP already contained a temperate insect fauna. No fossils, however, have yet been found from the Lower Laminated Clays, but even in the lowest interstadial sediment there are none of the obligate arctic–alpine species that were a characteristic element of the pre-interstadial faunas elsewhere in Britain. Yet species that are characteristic of the present-day Lake District are present and they include a suite of species that are either absent from the more northerly parts of Europe or are very rare there. These relatively southern, thermophilous species are not present in the upper part of the interstadial sequence and in their place there is the first incoming of the more northern species, heralding the truly arctic faunas of the Loch Lomond Stadial. Both the rise to, and fall from, a thermal maximum early in the interstadial appear to have been rapid and the decline is estimated to have involved a reduction of *c.* 3°C in mean temperatures of the warmest month (Coope, 1977; Atkinson *et at.,* 1987). About 12 000 years BP the thermophiles died out and were replaced by species that now possess more northerly distributions and indicate a cool-temperate climate. In the later stadial deposits no insect remains have been found from Low Wray Bay.

Interpretation

The importance of this work in the Windermere basin and particularly the Low Wray Bay succession is that it has been used to define the type locality of the Windermere Interstadial. Coope and Pennington (1977) suggest that this locality has several advantages as the standard reference section. There is a continuous sedimentary sequence and the lake sediments reflect the terrestrial as well as the lacustrine environment. The position of the lake is central in the British Isles and the lake received glacial drainage, both in the closing phases of the main Devensian glaciation and during the period between 11 000 and 10 000 ^{14}C years BP, which is correlated with the Loch Lomond Stadial (Sissons, 1974). The interstadial sediments are most fully developed in Low Wray Bay in the lake marginal area, where the sediments contain both pollen and the macroscopic remains of plants and animals that have been washed into the lake by small streams.

Detailed analyses of the section at Low Wray Bay show that the lower boundary of the interstadial sediments may be drawn at different horizons, depending on the criteria that are adopted. (Table 6.1) shows the position of the Windermere Interstadial according to lithostratigraphical, palaeobotanical or palaeoentomological criteria, from which it is possible to have alternative views based on a climatic interpretation. In terms of lithostratigraphy the upper boundary of the Lower Laminated Clay (Pennington, 1943) is interpreted as representative of the termination of the main Devensian glaciation, where there is a climatic change from a glacial to a non-glacial environment and a change to the grey organic layer. The junction has been dated to 14 623 ± 360 years BP. Above the Lower Laminated Clay the lowest sediments are almost entirely minerogenic with very sparse fragments of plant and animal tissue. The change to biogenic sediment is gradual and there is no clearly discernible boundary between clay and organic silt. At *c.* 15 cm below the top of the organic silt is a persistent horizon of grey silt containing rock fragments. The base of the Upper Laminated Clay defines the start of Loch Lomond Stadial sedimentation in this area and the sediments are interpreted as annual varves deposited in the lake when there were glaciers in the higher parts of the Windermere catchment. The postulated limits of these glaciers based on geomorphological evidence have been given by Sissons (1980).

The biostratigraphy is summarized in (Table 6.1). The environmental interpretation based on both floral and faunal biostratigraphy gives a consistent ecological picture throughout most of the time represented by non-glacial sediments. On the palaeobotanical definition of 'interstadial', which is an environment capable of supporting a vegetation of woody plants, only part of the non-glacial sediments can be described as an interstadial. The usefulness of the palaeobotanical definition is that comparison between British sites indicates the presence of a generally distinctive vegetation of woody plants between the ^{14}C dates that delimit the woodland biozone in Windermere, so that the particular environment required by a vegetation of woody plants appears to have been restricted to the period between *c.* 13 000 and 11 000 ^{14}C years BE Below this woodland biozone the plant remains define two botanical subzones within a herbaceous biozone. Pollen data equate the lower of these with present alpine vegetation in northern Europe. The first pollen grains do not occur until 13 863 ± 270 years BP. In the upper biozone the assemblage of herbs identified includes species that do not grow in the Arctic today and both pollen and macroscopic evidence shows that tree birches were present but did not expand into woodland, which is interpreted as indicative of conditions not generally favourable to trees. Only within the herbaceous biozone is there any discrepancy between the interpretations based on botanical and entomological data. Throughout the two subdivisions the fauna show a continuous development but even at the base there are no alpine species present. A number of insect species occur that, although widespread in Europe today, are absent from arctic areas and the alpine zones of mountains. This suggests that at least during the Rumex–Gramineae pollen zone, temperate climatic conditions prevailed. There are several comparable localities, often with much richer insect assemblages than at Windermere, now known from Britain, always in the same palynological context, where climatic warming is indicated by the insect data well before the start of the woodland biozone.

The first thermophilous insect assemblages have been dated to 13 938 ± 210 years BP. The difference between the biostratigraphies probably reflects the quicker response time of insect communities to climatic warming and has important implications for other stadials or interstadials that have been defined only on the basis of the pollen record.

Using modern examples from Greenland and southern Norway, Pennington (1973, 1977, 1980) suggested that the botanical evidence indicated that the early pollen assemblages from *c.* 14 000 to 13 000 years BP can be correlated with the high-altitude and pioneer plant communities of presently glaciated parts of southern Norway that have an oceanic periglacial climate. The arrival of tree birches before 13 000 years BP suggests that by that time the climate was as favourable as today in the inland parts of southwest Greenland but some factor, such as dryness and a short growing season, prevented their expansion to form continuous woodland. During that part of the Windermere Interstadial most favourable to plants and when woodland grew, temperatures must have exceeded those of south-west Greenland today. In the uplands, such as at Blea Tarn, where dwarf shrub heath with a varying proportion of sedges formed the interstadial vegetation, conditions appear to have been within the range now found on the outer coasts of West Greenland from *c.* 70°N southwards. During the cold period of the Younger Dryas the vegetation – and hence probably the climate – was different from that of the early period and less oceanic. The closest parallel found seems to be the continental low arctic (periglacial) vegetation of central West Greenland and comparisons suggest a highly differentiated pattern of snow cover and corresponding vegetation mosaic.

Why juniper increased before birch in the early part of the Windermere Interstadial needs some discussion, as there is evidence for tree birches already being present before this phase. Godwin (1975) in discussing the ecology of juniper, gives the evidence for its present status as a dominant above the present tree-line in northern Britain, a habitat which suggests that in some respects it is less exacting than birch. The data presented by Birks (1973) on modern pollen rain within juniper communities shows, however, that the high percentages found within this pollen assemblage zone can be matched only in tall dense thickets *of Juniperus communis* species and not by the more prostrate forms found at higher altitudes. The increase is clearly a response to climatic amelioration but it is still not clear why juniper and not birch expanded first.

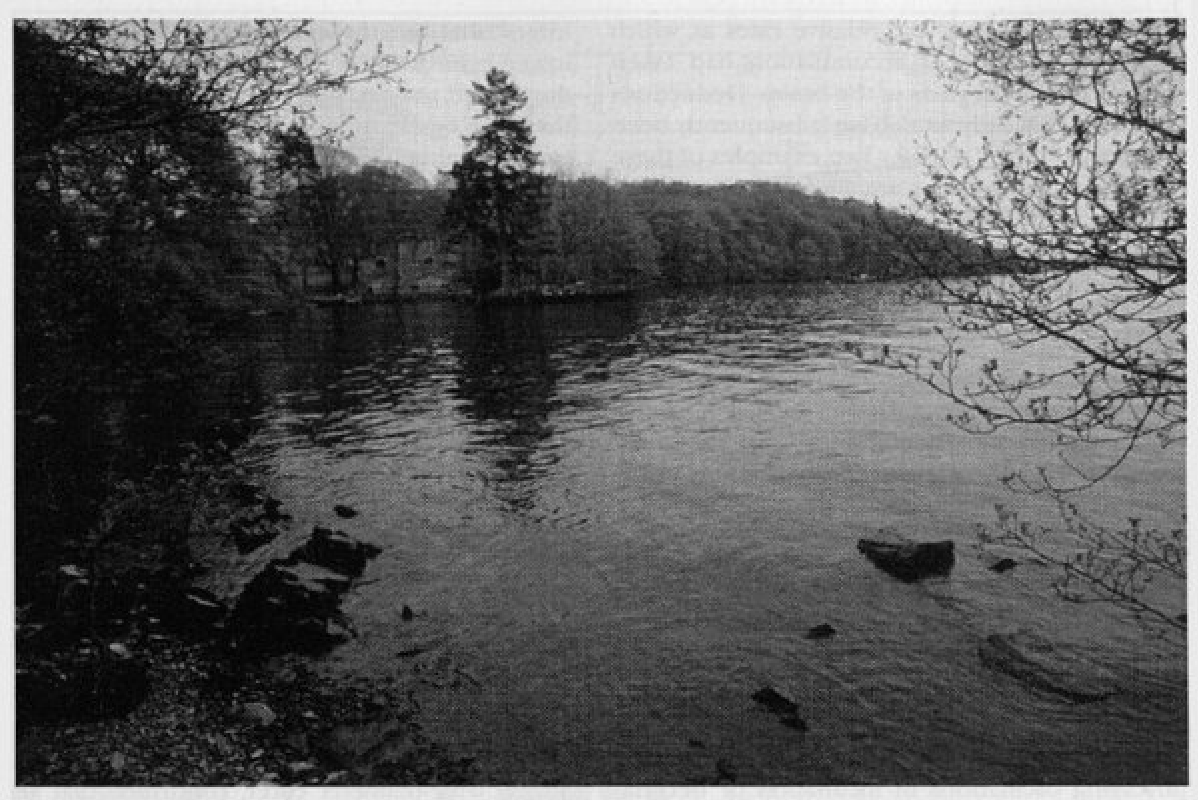
The chemical investigations reported by Mackereth (1966) add detail to the environmental changes discussed so far. The changes in carbon content could be related either to a fluctuating rate of production and deposition of organic matter, or to a fluctuating rate of erosion of mineral material. The data on carbon content alone offer no means of distinguishing the relative importance of these processes but it is considered that the maximum accumulation of biogenic sediments takes place during ecologically stable interglacial climates and that minimum organic matter concentrations are found under glacial conditions, when all the soils have been destroyed by glacial erosion and deposits consist of rock flour and minerogenic sediments. This argument can be carried a stage further so that in periods of high erosion rate soil material rich in K, Na and Mg is rapidly transferred to lake basins, whereas in periods of low erosion rate these elements are rapidly removed by leaching from the catchment surface. The material that is transferred to the lakes is relatively poor in K, Na and Mg. Thus elements such as these which exhibit recurrent trends have been interpreted as an indication of erosional activity within catchments. Substantial percentages of Na and K in the mineral sediments have been interpreted as a reflection of intensive erosion of mineral soil and a low leaching level because these elements are soluble and so usually susceptible to removal in downward-percolating water. Small percentages of these elements in minerogenic sediments have been linked to reduced erosion and increased leaching. For Windermere there are relatively high concentrations of erosion indicators in both the pre-interstadial and post-interstadial deposits. There is a minimum concentration in interstadial deposits, where the maximum values for total carbon show maximum humus accumulation in the maturing soil profiles. These relationships were first shown in a series of lakes in the Lake District, including the South Basin of Windermere.

The original suggestion by Pennington (1943) that the great increase in the numbers of the diatom *Asterionella* in the uppermost 20 cm of sediment represented a change in lake biology consequent on the growth of lake-side villages and the increasing input of sewage and sewage effluents from the mid-nineteenth century, has been substantiated by radionuclide dating of these recent sediments (Pennington, 1973).

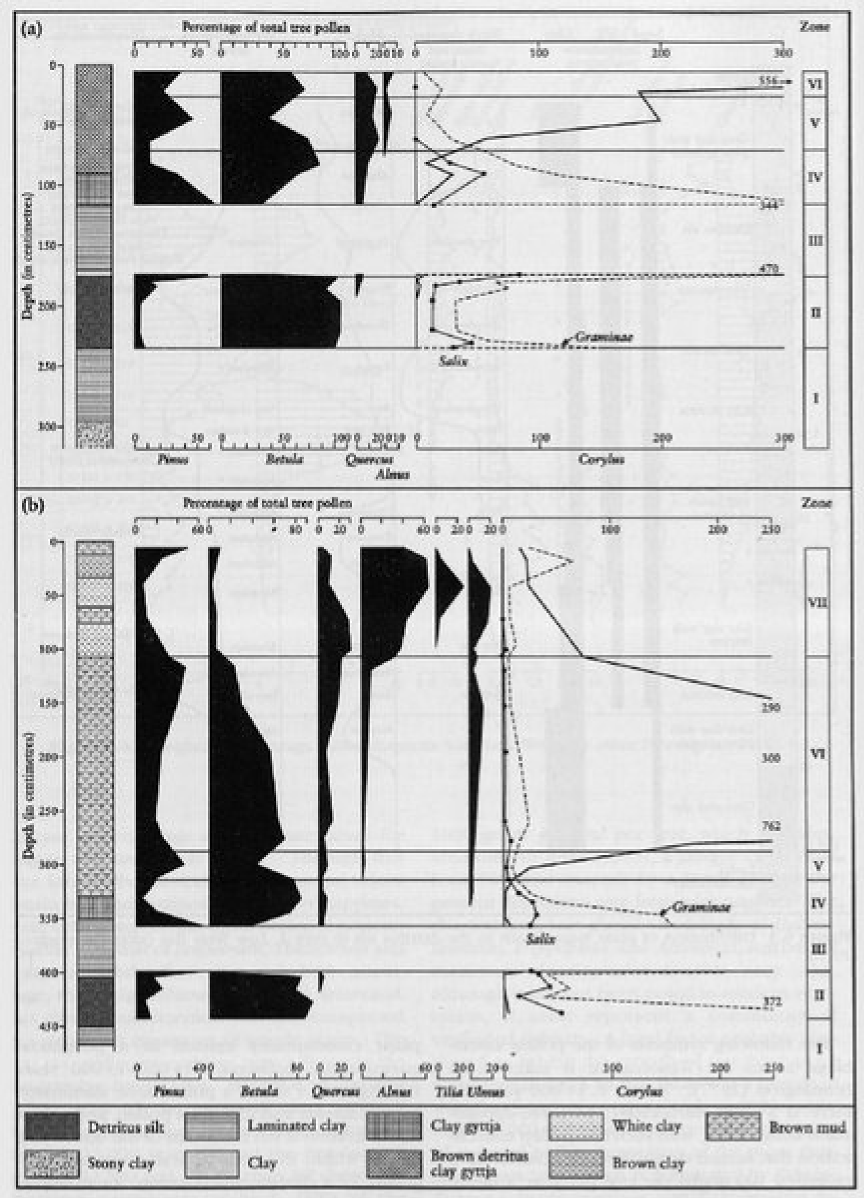
Conclusions

The published analyses for the Low Wray Bay sequence provide a particularly full data set for environmental reconstruction, including stratigraphy and diatoms (Pennington, 1943), pollen analyses and macroscopic plant remains (Pennington, 1947, 1970, 1977, 1981; Godwin, 1960a), geochemistry (Pennington and Lishman, 1971; Pennington, 1977) and insect remains (Coope, 1977). From this evidence it has become the national type site for the Late-glacial Windermere Interstadial and it has illustrated many difficulties in defining chronostratigraphy on the basis of different types of biostratigraphy. It is also the site of the 'master curve' for the changing magnetic declination.

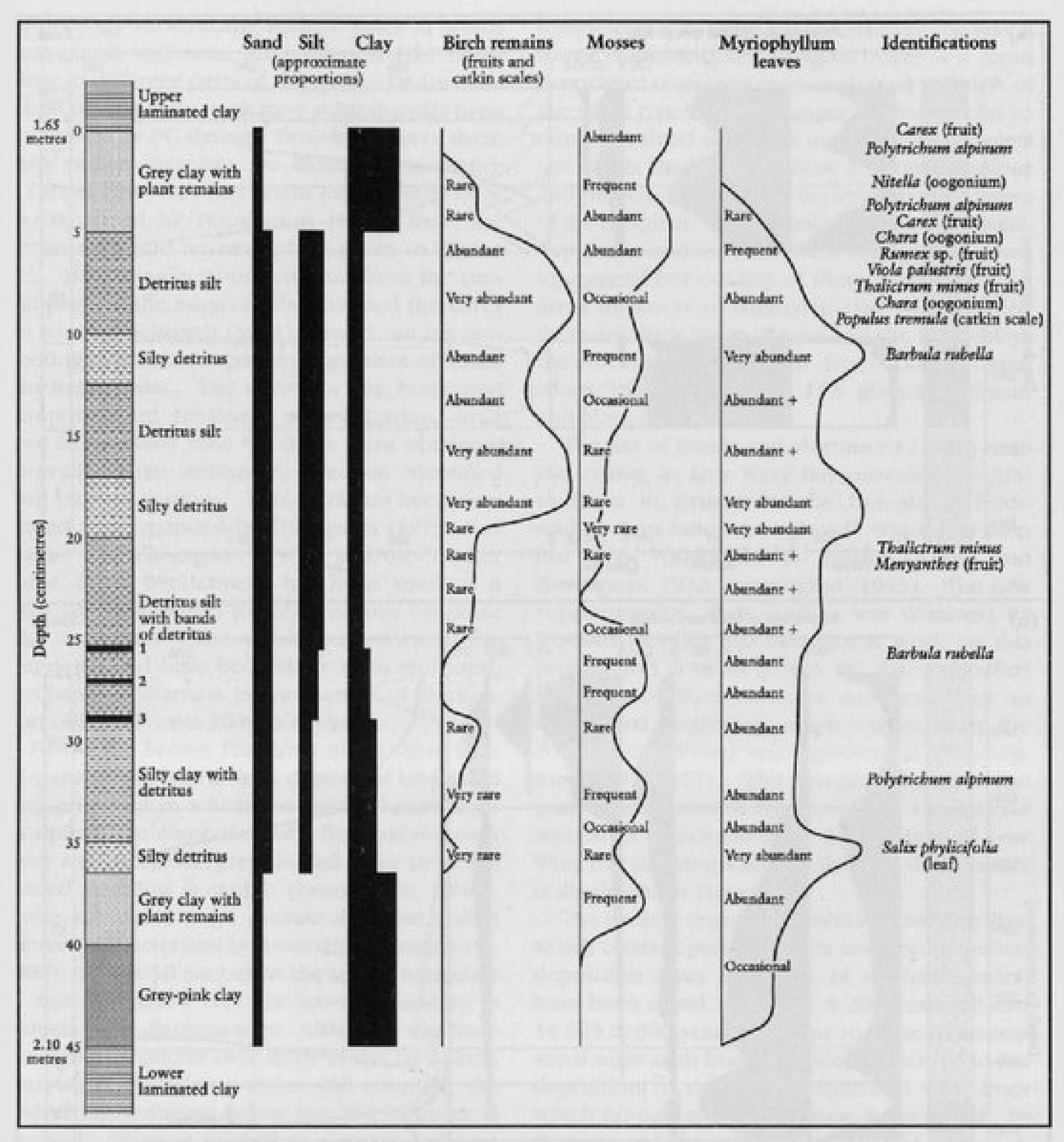
References



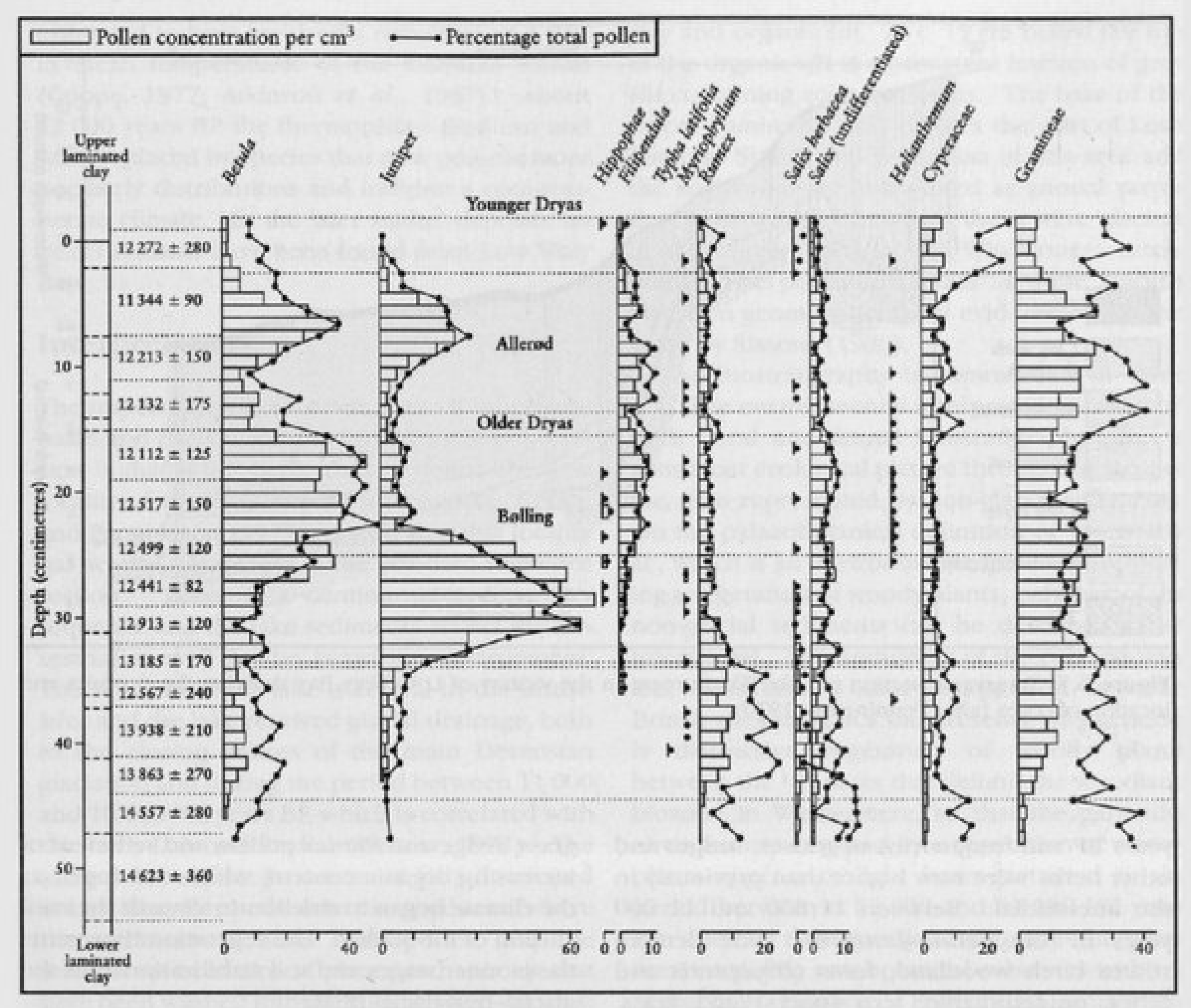
(Figure 6.1) Low Wray Bay, Windermere. View looking north. (Photo: D. Huddart.)



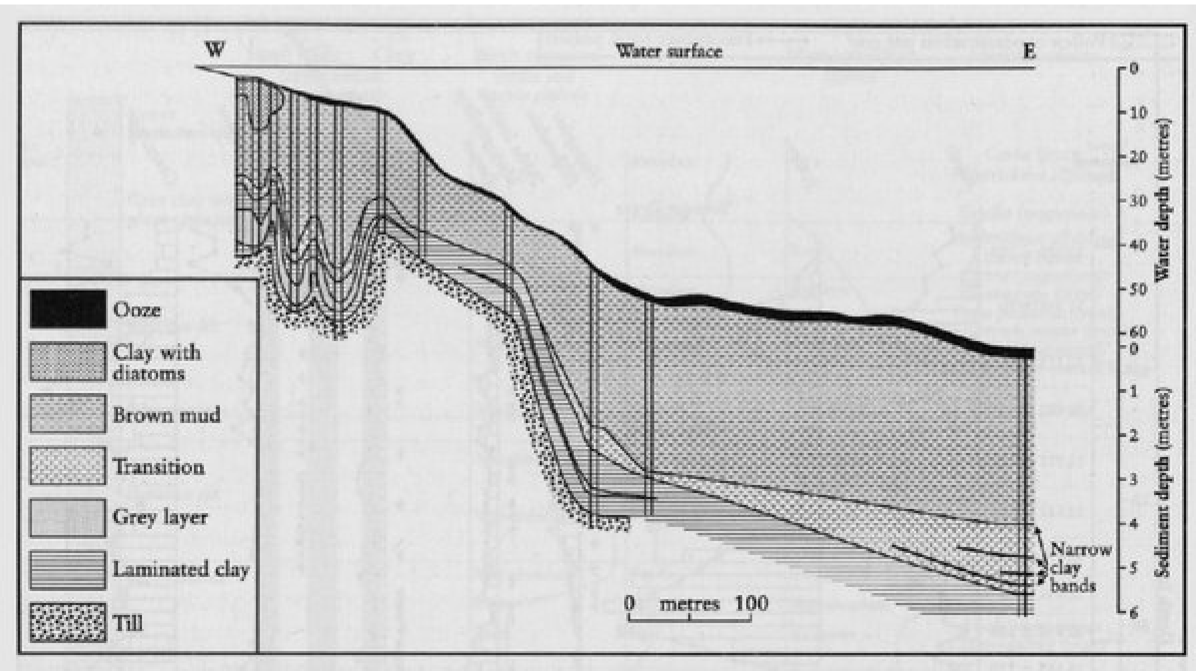
(Figure 6.2) Examples of pollen chronology from the North Basin, Windermere at different locations (see (Figure 6.5) in Low Wray Bay: (a) core 1; (b) core 2 (after Pennington, 1970).



(Figure 6.3) Distribution of plant macrofossils in the detritus silt in core 1, Low Wray Bay (after Pennington, 1970).



(Figure 6.4) Late-glacial percentage pollen diagrams from Low Wray Bay (after Pennington, 1970).



(Figure 6.5) Transverse section of Lake Windermere in the vicinity of Low Wray Bay showing the deposits and location of cores (after Pennington, 1970).

Lithology	Fossils: Plants	Fossils: Animals – Coleoptera	Fossils: Animals – Others	^{14}C dates	Interpretation: Environment	Interpretation: Climate	Duration of interstadial climate: WP	Duration of interstadial climate: GRC
Rock fragments increase Upper laminated clay	*Artemisia* p.a.z. Pollen very sparse	Sparse fauna with characteristic arctic–alpine species	Trichoptera larvae (↑)	(11 000)	Seasonal melt from mountain glaciers in Lake District corries	Very cold		
Becoming less organic Maximum carbon – Organic detritus silt	Tree birch macroscopics Cyperaceae *Betula–Juniperus* p.a.z.	Woodland species present Fauna less rich, without 'southern' species	Cladocera – decline to 0 Chironomidae larvae (↑) *Cristatella* statoblasts (↑)	SRR-669 11 344 ± 90	Increased snowfall, declining temperatures, increased soil erosion Re-establishment of *Betula–Juniperus* woods	Cool temperate, becoming colder towards the top	↑	↑
Paler silt with rock fragments	*Betula–Rumex* p.a.z.	*Helophorus glacialis*	Cladocera reduced	SRR-670 12 213 ± 150	Increased soil erosion, woodland reduced	Sudden cooling		
Maximum carbon – Organic detritus silt	*Betula* p.a.z. *Juniperus* p.a.z.	Sparse fauna at base, becoming richer towards the top; species present that are absent from arctic Europe		SRR-672 12 112 ± 125 SRR-673 12 517 ± 150 SRR-675 12 441 ± 82 SRR-676 12 913 ± 120 (13 000)	Maximum environmental diversity of Windermere; interstadial (woodlands established)	Temperate throughout	↓	
Somewhat organic silt Carbon content increasing	*Rumex*–Gramineae p.a.z. Tree birches present		Cladocera suddenly increased	SRR-677 13 185 ± 170 SRR-679 13 938* ± 210 SRR-680 13 863* ± 270	Phase of pioneering flora and fauna, vegetation rich in herbs, including species which do not grow in the arctic today; although tree birches are present, no development of woodland	Plant evidence inconclusive on temperature, but some factor unfavourable to trees Temperate throughout on insect evidence		
Slightly organic silt	*Salix herbacea*–Cyperaceae–*Lycopodium selago* p.a.z. Moss stems	Very sparse fauna, no alpine species		SRR-681 14 557 ± 280 SRR-682 14 623 ± 360	Plants compare with Middle Alpine zone of north-west Europe Insect fauna lacks any alpine species and suggests early pioneer fauna	Plant evidence suggests alpine conditions Insects inconclusive, but no evidence to support alpine conditions		↓
Clay	No plant fossils							
Lower laminated clay					Seasonal melt from mountain glaciers	Very cold		

(Table 6.1) Correlation table for the lithostratigraphy, biostratigraphy and chronostratigraphy of the Late Devensian deposits at Low Wray Bay, Windermere (after Coope and Pennington, 1977). p.a.z.: pollen assemblage zone.