LAKE SEDIMENTS IN NORTHERN SCOTLAND

By WINIFRED PENNINGTON (Mrs T. G. TUTIN),* E. Y. HAWORTH,
A. P. BONNY* AND J. P. LISHMAN
Freshwater Biological Association, Ferry House, Ambleside, Westmorland

With a contribution by J. JOHANSEN,
Danish Geological Survey

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[Plate 33]

CONTENTS

A survey of deep-water sediments in 11 lakes in northern Scotland showed that only under certain conditions does a complete and conformable series of deposits accumulate. In lochs exposed to strong winds there may be no permanent settling of organic sediments in water depths of up to 50 m. Three lake cores (representative of three regions of northern Scotland), which proved to be complete and conformable profiles, were analysed in detail for pollen and certain chemical elements; one was also analysed for diatoms. A series of ^{14}C dates was obtained for two of these profiles.

Changes in pollen content were found to be very consistently related to changes in sediment composition. Pollen zones were defined in terms of characteristic taxa, and variance in sediment composition was expressed as the first component of a Principal Components Analysis; changes in this first component invariably coincided with pollen zone boundaries based on changes in pollen spectra. This close relationship is explained as the consequence of the derivation of these lake sediments from soils on the catchments.

Two important features of soil history emerged from this study: first, the general impoverishment of soils, water and biota due to leaching during the early millennia of the 15 000 years covered by these

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* Present address: School of Biology, University of Leicester.

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profiles, and secondly the changes in pollen spectra which accompanied chemical evidence for the development of peat on certain of the western catchments since *ca.* 3000 B.C.

Complete analysis of a core from Loch Sionascaig in Wester Ross (pollen, chemical and diatom) has provided a history of the soils and the aquatic and terrestrial vegetation of the Inverpolly National Nature Reserve. Pollen analysis of cores from two small lochs supplemented the evidence from Loch Sionascaig as to late-glacial and early post-glacial vegetation history in the far north-west Highlands. Chemical and biological evidence for the history of blanket peat formation on the Sionascaig catchment which was provided by the lake sediments has been supplemented by examination and pollen analysis of four profiles from blanket peat, in all of which the presence of timber within the peat confirms the evidence of the pollen diagrams that pine–birch forest was present in this region during the period between *ca.* 2400 and 1500 B.C.

Complete late-glacial profiles were found in three lochs in Region 1, the far north-west Highlands, and in Loch Tarff above the Great Glen. Our results confirm and extend those from Loch Droma (Kirk & Godwin 1963), proving that those sites in northern Scotland were free of ice throughout the Late-Weichselian period. The sequence of pollen zones – A (*Rumex* zone), B (woody plants zone) and C (*Artemisia* zone) – resembles that which has been found at many sites in Highland West Britain, including the closely dated site at Blelham Bog in the Lake District (Pennington & Bonny 1970). In Region 2, the mountainous part of Wester Ross near Beinn Eighe, lake profiles indicate the input of thick and barren laminated sediments, impenetrable to the corers used, during the final cold phase of the Late-Weichselian (Younger *Dryas* time).

During the preceding Late-Weichselian interstadial, which on the evidence from Loch Droma had begun by *ca.* 10 870 B.C., pollen spectra indicate that the vegetation of northern Scotland must have been *Empetrum* heath, with juniper present at some sites but not at others, and no trees present. Pre-interstadial pollen spectra (*Rumex* zone) resemble plant assemblages found on immature soils. Chemical analyses indicate continuous and uninterrupted processes of soil maturation through pre-interstadial into interstadial time – accumulation of humus, leaching, and chemical weathering with formation of clay minerals. Pre-interstadial and interstadial diatom assemblages at Loch Sionascaig include many alkaliphilous species and some now characteristic of eutrophic habitats; the present acid poverty of this lake and its catchment must be the result of removal of soil bases by late- and post-glacial leaching.

At all sites where it is present, pollen zone C (*Artemisia*) corresponds with sediment of very low organic content, and simultaneous changes in pollen and chemical composition at the boundaries of this zone are interpreted as the results of pronounced and synchronous environmental (climatic) changes at the beginning and end of Younger *Dryas* time.

Above the *Artemisia* zone, pollen spectra, diatoms and chemical analysis all indicate rejuvenation of soils by the effects of the post-interstadial cold period; the biological evidence points to a repetition, at the opening of the post-glacial period, of pre-interstadial to interstadial plant successions, but in a much shorter time. ^{14}C dating at two sites shows that the spread of birch forest in northern Scotland was delayed for up to 1000 years after its establishment in northern England. On the evidence of ESR spectra of the humic acid in the Loch Sionascaig sediment, soils in northern Scotland had become acid before the arrival of forest.

Post-glacial pollen diagrams are divided into a series of Regional Pollen Zones for northern Scotland; in north-west Scotland the boundaries of these zones have been dated by ^{14}C at two sites and the pollen zones correlated with chronozones. Early post-glacial *Empetrum* and juniper zones are followed by a birch–hazel zone; from *ca.* 6000 B.C. onwards the birch–hazel pollen assemblage is replaced progressively by pine–birch. Surviving birch and birch–hazel woods round Loch Sionascaig are interpreted as the relics, on dry flush slopes, of a forest type which was widespread there before 6000 B.C. Chemical evidence suggests that between *ca.* 6000 and 4400 B.C. pine and pine–birch woods were growing on comparatively dry mineral soils, but from *ca.* 4400 B.C. the appearance of alder pollen is accompanied by evidence for solutional transport of iron and manganese from increasingly waterlogged soils. By 3000 B.C. formation of blanket peat must have begun on the Sionascaig catchment. For about another 1000 years pines and birches continued to grow on a peaty substratum. In Region 1 the pine forest ended suddenly at about 2000 B.C.; alternative hypotheses to account for this are examined. In Region 2 the Loch Clair profile shows the continuity of pine–birch forest with the existing Coulin Forest on that catchment. Steeper slopes than in Region 1 must have prevented the general formation of blanket peat, and the poor siliceous soils did not attract prehistoric settlement, so there was no forest clearance, though traces of human influence appear in the pollen spectra from *ca.* 3400 B.C. In Region 3 the sediments of Loch Tarff show a sequence of post-glacial pollen zones which can be related both to the northern Scotland series outlined here and to the Godwin series of zones which has been widely applied in more southern parts of Britain. This is interpreted as the result of the position of Loch Tarff on the margin of an area of natural mixed-oak forest in the Great Glen; its pollen diagram records the expansion of this forest type in the mid-post-glacial period on which the Godwin zonation is based.

1. INTRODUCTION

A core from lake sediments, if complete and conformable, provides an opportunity to study environmental history along several parallel lines. Work on sediments of Lake District lakes, at this laboratory, had shown how the results of such separate lines of inquiry – chemical analysis of sediment composition, pollen analysis, and diatom content – could be integrated into a coherent history of the relation between a lake and its catchment area through the last 15000 years. The object of this study of the history of certain lakes of northern Scotland was to find out how far this correlation between the results of the various forms of analysis could be found in lakes which are broadly similar in morphometry and trophic status but which differ in some environmental factor from Lake District lakes. Three problems of particular interest suggested themselves; first, the nature and thickness of deep-water sediments of freshwater lakes in country differing from the Lake District in bedrock and glacial history, secondly the relation between sediment composition and pollen spectra during the environmental fluctuations of the late-glacial period between about 15 000 and 10 000 years ago, and thirdly certain major changes in sediment composition which in Lake District lakes have been shown to be broadly synchronous at about 3000 B.C. In the Lake District this last horizon coincides at many sites with the first pollen evidence for Neolithic land use, and the problem was to find out whether parallel changes in sediment composition could be found at this date in regions where the natural vegetation and human history were different from those of the Lake District.

As part of the study of the late-glacial period it seemed desirable to investigate how far the close correspondence between those changes in sediment composition which indicate soil maturation on the catchments, and changes in pollen spectra indicative of changes in vegetation, which had been demonstrated for the Lake District, held good in northern Scotland with its different bedrock, different history of deglaciation, and different present vegetation. It was also of interest to find out how far differences in sediments from lake to lake with increasing altitude in the Lake District corresponded with differences between lakes in progressively more northerly latitudes.

At the mid-post-glacial horizon at *ca.* 3000 B.C., significant changes in sediment composition, indicative of an increased erosion rate on the catchments (Mackereth 1966*b*), correspond in the Lake District with the first appearance of pollen of plants associated with human settlement. At this horizon the sudden fall in elm as a percentage of tree pollen, found in all that part of Britain where the forests of that time were of oak, elm, alder and birch, with or without lime, has been variously explained by pollen analysts as the result of climatic change (Iversen 1944) or the influence of Early Neolithic farming (Troels-Smith 1960; Smith 1961, etc.). The fact that in all the large lakes of the Lake District which were studied, the Elm Decline is found associated with a change in sediment composition, might suggest as the cause a climatic change, operating on the erosion rate of the catchment either directly or through changes in the vegetation (Mackereth 1966*b*). However, subsequent detailed study of this horizon in a number of smaller lakes led to the conclusion that the diversity between sites (both in chemical changes and pollen spectra) suggested that variation in the local intensity of Early Neolithic activity (as estimated from archaeological evidence) was the most important factor at work (Pennington 1964, 1965; Tutin 1969). In an attempt to isolate one aspect of climatic history, Mackereth (1966*a*, 1967) developed the study of halogens in the sediment column as a possible index of past changes in the amount of rainfall on the catchment, since halogens are mainly supplied by rain. On all criteria it became apparent that in the Lake District this horizon at *ca.* 3000 B.C. represented a disturbance of the ecological equilibrium of the preceding period, corresponding with the Godwin pollen zone VIIa, which on the evidence of radiocarbon dates from Scaleby Moss (Godwin, Walker & Willis 1957) and the Lake District (Pennington 1970) began at about 5500 B.C. in north-west England.

Therefore it seemed desirable to investigate this horizon in the sediments of lakes in an ecologically contrasted region, outside the present distribution of mixed-oak forest. McVean & Ratcliffe (1962) provided an attempted reconstruction of the distribution of woodland types in the Scottish Highlands 'during the present climatic period but prior to the onset of large-scale human forest clearance' and our sites were chosen from those areas of northern Scotland where these authors consider pine and/or birch to be the naturally dominant tree.

Since few complete profiles of late-Quaternary deposits have been investigated in northern Scotland, this first stage of the work had to be largely exploratory. It was not known in advance whether late-glacial sediments would be present at a site or whether the earliest organic deposits would date from the opening of the post-glacial period, for the history of the deglaciation of northern Scotland is as yet very incompletely known. However, the discovery of a late-glacial site at Loch Droma (Kirk & Godwin 1963) on the main east–west watershed of Scotland in the county of Ross and Cromarty, with organic sediment dated to 10 870 ± 155 B.C. (Q 457), had shown the existence of long late-glacial profiles in areas of the Scottish Highlands which had previously been thought to have remained ice-covered until the opening of the post-glacial period (Charlesworth 1955). The dated profile from Loch Droma agrees with the hypothesis which was developed from work in the Lake District (Pennington 1970) that on detailed analysis it is not possible to describe the late-glacial sequence in parts of western Highland Britain in terms of the generally accepted series of three zones – I (cold), II (mild = Alleröd) and III (cold) – originally established in Scandinavia by Jessen and Iversen. In this paper we shall use a division of the late-glacial period based on a closely dated and analysed profile from Blelham Bog in the Lake District (Pennington & Bonny 1970) which includes a single interstadial beginning nearly a thousand years before Alleröd time: see table 1. The date for organic mud from Loch Droma falls within this interstadial.

The post-glacial vegetation history of northern Scotland is also incompletely known, and at an early stage of our investigations it became clear that the pollen diagrams differed greatly from those of the Lake District and more southerly parts of Britain. It was therefore necessary to obtain radiocarbon dates before horizons recognized in the profiles could be correlated with horizons elsewhere. When two of our profiles had been adequately dated by radiocarbon, a zonation scheme was produced and the floristic data from all profiles described in this paper, referred to these zones for north-west Scotland, was tabulated, and a copy has been deposited with the Royal Society. No attempt has been made to include all taxa which were identified in the pollen diagrams because of the difficulty of reproduction of such large diagrams. The pollen zones will be defined, and those changes in the most important components of the pollen spectra which are interpreted as undoubtedly indicative of changes in the vegetation of the catchment areas are discussed.

The work on Lake District lake sediments showed a relation between sediment composition and environmental changes on the catchments (as demonstrated by pollen analysis) which confirmed the opinion of the chemical limnologists concerned that in lakes such as these, the organic as well as the inorganic fraction of the sediment has been derived from soils on the catchments rather than from production by aquatic macrophytes and algae (Mackereth 1965, 1966*b*; Atherton, Cranwell, Floyd & Haworth 1967; Pennington 1964, 1965, 1970; Tutin 1969). Changes in composition in the course of these sediment profiles must therefore be interpreted mainly as the results of changes in the soils of the catchments and in the rate of erosion of these soils, rather than changes in production within the lake or in trophic status. This conclusion of course differs from that reached by some North American paleolimnologists from study of lakes in the lowlands of eastern and central North America – lakes which originated in glacial modification of the land surface but lie in less mountainous country than the Lake District (e.g. Hutchinson & Wollack 1940; Deevey 1942; Vallentyne 1969, etc.). These investigators concluded that the organic sediment fraction represents primarily the result of organic production within the lake, and interpreted changes in the organic fraction in terms of changing productivity and trophic status of the lakes. Vallentyne (1969), however, draws attention to the difficulty of distinguishing between organic molecules of aquatic and terrestrial origin.

TABLE 1. DIVISION OF LATE-GLACIAL (LATE-WEICHSELIAN) SECTIONS OF THE PROFILES

Jessen–Godwin zones	highland west Britain		
	^{14}C dates	period	pollen zone
	post-glacial (Flandrian)		
	8300 B.C.*		
III (cold)		C, post-interstadial	*Artemisia*
	8800 B.C.*		
II (mild)	Alleröd time	B, interstadial	woody plants
	10000 B.C.*		
I (cold)	Isle of Man 10695 B.C. Blelham Bog 10700 B.C. Loch Droma 10870 B.C.		
	Blelham Bog 11500 B.C. Blelham Bog 12380 B.C.	A, pre-interstadial	*Rumex*
	full-glacial (Weichselian)		

* Dates as given in West (1968) 'based on a number of assays'.

Other dates: Isle of Man, 10695 ± 280 B.C. (Birm. 214); Blelham Bog, 10700 ± 170 B.C. (I 3590), 11500 ± 220 B.C. (I 3596), 12380 ± 230 B.C. (Q 758); Loch Droma, 10870 ± 155 B.C. (Q 457).

A major change in the soils of upland Britain during the post-glacial period has been the development of peat, both basin peat in hollows and extensive spreads of blanket peat on gentle slopes (see, for example, Pearsall 1950; Conway 1954; Godwin 1956; Birks 1972). The high relief of the Lake District has restricted the spread of true blanket peat. One object of our work in northern Scotland was to investigate changes in sediment composition in lakes where deep blanket peat has developed on the catchments.

Our opinion is that for lakes such as those of the Lake District, which lie in the course of vigorous streams in an area of high relief, and high orographic rainfall, it has been adequately demonstrated that the sediment column represents a series of soils derived from the lake catchments, and therefore presents an unrivalled opportunity to study soil history in parallel with the changing composition of the pollen spectra (derived mainly from the vegetation of the soils represented). All our findings from comparable Scottish lakes are consistent with this hypothesis, and so our interpretation of these results will be presented in terms of derivation of lake sediments from the soils of the catchments.

Study of the iodine content of the Scottish lake sediments, in accordance with the ideas of Mackereth (1966*a*) that this element should be present in amounts proportional to the degree of oceanicity of the climate at the time of deposition, produced results which, when compared with those from Lake District profiles, at once indicated a necessary modification of Mackereth's hypothesis, but also a most significant relation between iodine, iodine:carbon ratio, and soil type as deduced from vegetation. These results have appeared (Pennington & Lishman 1971) as a comparative study of the iodine content of lake sediments in different parts of northern Britain.

The chosen Scottish lochs are all oligotrophic with rocky or stony shores and comparatively little marginal vegetation; with two exceptions they are more than 20 m deep, and none possesses marginal areas infilled with lacustrine peat. In general they belong to that class of lake, at least moderately deep and exposed to wind, where the basin is filling from the bottom, not the sides, and there is little or no marginal hydrosere (Tutin 1941; Pennington 1943; Mortimer 1948). Mortimer stresses how in such lakes the fine uniform mud of the central part of the lake is characteristic of that lake and its catchment area. We would emphasize that our results of analysis of deep-water profiles from such fine uniform muds cannot be compared with other lake profiles from littoral deposits sampled through infill of lacustrine peat. Earlier work had shown that in the littoral areas of Windermere, deposits accumulated in bays until the water had shallowed to about 3 m depth, and then deposition ceased, presumably because the zone of continuous disturbance by wave erosion had been reached (Pennington 1947). The shallowest of the Scottish lochs sampled showed evidence of comparable disturbance of upper sediments, but in lakes more exposed to strong winds than any in the Lake District, our results indicated that the 'zone of wave erosion' in which no permanent settling of organic mud is found may extend down to water depths of 50 metres.

Little is known of the processes by which the component materials of lake sediment finally come to rest on the bottom in orderly succession, and part of the study of Scottish lakes was to explore the range of variation in thickness and type of sediment found in different lakes. Even in lakes where the sediment profile appears from analysis to be complete and conformable, recirculation of material from the mud surface has been demonstrated on several criteria. In Blelham Tarn and Esthwaite Water the annual cycle of the diatom *Melosira italica* subsp. *subarctica* indicates resuspension of diatom filaments from the mud surface (Lund 1954); in sediment traps suspended in Windermere, just above the mud surface and 2 m below the water surface, changes in amount and composition of the sediment indicated recirculation of material which had been at least once to the mud surface (Tutin 1955); and in Frains Lake, Michigan, the excess in numbers of pollen grains caught in sediment traps over the numbers calculated to have accumulated in the surface sediment over the same period indicated resuspension of pollen grains from the mud surface (Davis 1968). The amount of deep-water sediment accumulating in a single year must therefore be controlled by several variables. The rate of supply of material is probably determined primarily by the rate of erosion of the catchment (Mackereth 1965, 1966*b*) which represents an integration of climatic, geological and vegetational factors. The fraction of the material supplied which comes to permanent rest at any point on a lake bottom must depend on conditions determined by a complex integration of the effects of morphometry, retention time, stratification (related to temperature) and the degree of exposure to wind. It must be supposed that from many lakes sediment must be lost in the outflowing water. These considerations are of importance with respect to recent attempts to express variables in sediment composition in terms of numbers of micro-fossils or quantities deposited annually per unit surface area of lake mud (Davis & Deevey 1964; Pennington & Bonny 1970; Lawacz 1969). The work on Scottish lakes described in this paper was entirely exploratory in the sense that it constitutes a first examination of their sediments, with the object of selecting those sites most suitable for more detailed and quantitative work.

No mechanical analysis for particle size in these sediments has been attempted, since earlier sedimentological work on Lake District lakes (Richardson 1941; Holmes 1968) had shown the limitations of the simple methods of particle-size assay which were available to us. For example it is of limited significance only to assess the proportion of a sample which is of clay particle size if equipment is not available to distinguish between clay minerals and rock-flour (e.g. quartz) reduced to clay particle size.

Because all the lakes are clearly extremely oligotrophic on any definition of this term, and though as yet no studies have been made, it seems certain that conditions at the mud surface must remain oxidizing throughout the year. Macrophytic vegetation in the photic zone is on the whole sparse, and *Isoetes lacustris* is the most characteristic plant. Details of the macrophytic vegetation of Loch Tarff can be found in Spence (1964) with evidence that there has been little or no change since it was photographed by West nearly seventy years ago.

None of the lakes has reed-swamp or other emergent vegetation over any significant proportion of its surface. This and the position of the sampling sites in the middle of the lakes means that there is no local pollen from vegetation at the sampling site; there is no 'Local' pollen in the sense of Janssen (1966, Fig. 1). The pollen in the sediment sampled has originated as either 'Extra-local', varying in absolute quantity with distance from the source, or from the 'Regional' or 'background' pollen rain which is deposited in equal amounts over a wide area. (Janssen 1966.)

A major factor differentiating the catchments is the extent to which peat has formed. Peat is defined by the Soil Survey as a surface organic layer more than 30 cm thick; thinner organic soils are regarded as the organic horizon of acid soil profiles of the podsol or gleyed podsol type. The peat on the western catchments of northern Scotland is of the general type which Godwin included in blanket peat, but since in many places development began as a basin peat in areas of impeded drainage, from which peat-forming vegetation extended laterally to mantle surrounding slopes (some of which may be flushed with surface drainage) both soligenous and ombrogenous peat is included.

2. Methods

(a) *Methods of sampling*

The sediments in open water in the middle of each lake were sampled using either a 6 m Mackereth corer (Mackereth 1958) or the smaller, modified version of this operated by an Aqualung diver (Walker 1967). The larger corer operates only in water of at least 7 m depth, and does not take a satisfactory core in sediment less than *ca.* 3 m thick; the diver-operated corer samples thinner sediment more satisfactorily but is only 4.3 m (14 ft) long; it can be used in water depths of *ca.* 4.3 m to 18.3 m. The small diameter core obtained with the diver-operated corer is adequate for pollen and inorganic chemical analysis, but does not provide sufficient bulk of material for radiocarbon dating or organic chemical analysis. Satisfactory choice of sampler depends on the depth of water and of sediment in the lake.

Both samplers can be operated using only a light and portable 4.3 m (14 ft) metal dinghy or an inflatable boat, but an outboard motor is required to bring the larger corer to shore when full of sediment, and for safety reasons two boats are advisable. This limits choice of sites to lakes reasonably accessible by Land Rover and trailer, unless much help is at hand to carry equipment and boats. Only one site (Loch Sionascaig) was of sufficient importance to justify the effort needed to carry boat and sampler over trackless ground.

Many Scottish lakes have the underwater profile of a very steep-sided trough. These, e.g. Loch Assynt, were avoided because of difficulties already experienced in the Lake District in finding complete and conformable cores in such lakes. Even in Windermere, where the underwater profile is much less steep, the sediment succession in many places is disturbed by sliding and slumping of late-glacial and early post-glacial sediment (Smith 1959; Mackereth 1966*b*) or unconformities are present where accumulation has not been continuous (Pennington 1947). Cores from the steep-sided troughs of Ennerdale Water and Wastwater were found to contain re-worked late-glacial sediment for some distance up the post-glacial profile, and so were unsuitable for analysis (unpublished data).

Choice of sites was therefore governed by three factors – accessibility, depth of water sufficient for our samplers, and suitable underwater contours.

Cores are extruded from the samplers on the lake shore and supported on Polythene-lined wooden trays, then securely sealed in Polythene sheeting.

(b) *Analysis*

(i) *Pollen*

The methods used were those recommended by Faegri & Iversen (1964) involving treatment of the sample with KOH, then with HF, followed by acetolysis with acetic anhydride plus sulphuric acid. The mountant was safranin-stained glycerine jelly. In late-glacial samples we found it necessary to use a longer treatment with HF than that recommended by Faegri & Iversen, in order to extract sufficient pollen to provide a reasonably significant count from a sample of normal size. We found that a treatment of 1 h in 40 % HF at *ca.* 95 °C made it possible to count pollen in material classified as non-polleniferous after a 5 min boil, and in no instance was any destruction of pollen by the longer treatment detected.

The *identification* of pollen grains follows the key of Faegri & Iversen; this was of course supplemented by constant use of a type collection. No attempt was made, in general, to differentiate pollen types beyond the limits of this key, and the families Scrophulariaceae and

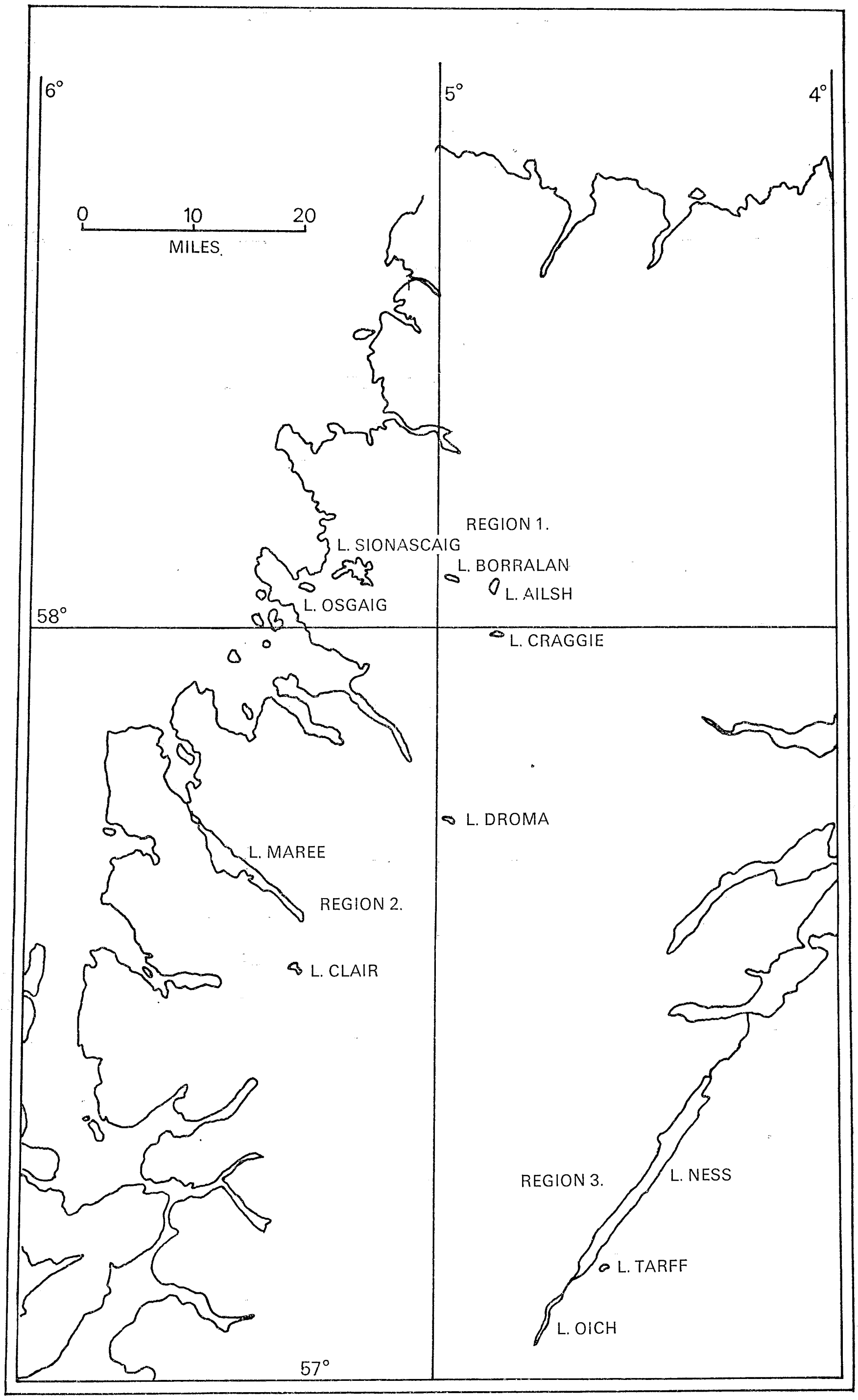

FIGURE 1. Map of northern Scotland, showing sites and regions.

Ranunculaceae could not usually be divided: no attempt was made to use the special keys to the families Gramineae and Cyperaceae.

The following is the meaning of the categories used:

(1) Family name, e.g. Gramineae; family identification certain, no subdivision.

(2) Sub-family name, e.g. Tubuliflorae; family identification certain, no subdivision.

(3) Genus name, e.g. *Quercus*; genus certain, no subdivision.

(4) Genus type, e.g. *Potentilla* type; genus not certain, but one of a group specified by Faegri & Iversen.

(5) Species name, e.g. *Plantago lanceolata*; identification certain.

(6) Section, e.g. *Polygonum* sect. *Persicaria*; genus certain, species within that section (see *Flora Europaea*).

(7) Category, e.g. *Rumex* type *acetosa*, *Polygonum* type *convolvulus*; a category which may include species from different modern genera, but only those originally placed in the same genus.

Identification departed from Faegri & Iversen's treatment in the following respects:

(1) *Corylus* and *Myrica*, *Salix herbacea* and other *Salix* spp. For both these pairs it was found possible to identify typical specimens as diagnosed by Faegri & Iversen, but not possible to separate them quantitatively. Experience showed that when separation into two categories (e.g. *Corylus* and *Myrica*) was attempted, the resultant count could not be repeated on the same traverses of the slides after an interval, showing that with many grains the separation was highly subjective. In certain profiles (figures 22, 23 and 24) those grains of undoubted *Myrica* type have been separated. The presence of undoubted *Salix herbacea* has been indicated on the pollen diagrams.

(2) *Betula nana*. Faegri & Iversen do not separate this type. The presence of grains of the morphology described by Terasmäe (1951) for *B. nana* is indicated on the pollen diagrams. Since prolonged HF treatment as well as acetolysis was required by our late-glacial material, and this affects grain size, no attempt was made to separate *B. nana* quantitatively on grain size (cf. Birks 1968). In our type collection is Scottish material of undoubtedly pure *B. nana* which includes grains with more protuberant pores than fall within the range of morphology described by Terasmäe; therefore we do not give a count of the *B. nana* (Terasmäe type) since we think this may well be an underestimate of the total of *B. nana* grains in a sample.

(3) Identification of *cereal* grains. The conversion factor given in Faegri & Iversen for size increases in grains subjected to the treatment we used was applied to grains of the Gramineae, and grains of which the diameter exceeded 45 μm after conversion were recorded as cereals.

(4) Ericaceae. *Calluna* and *Vaccinium* have been separated from other grains of the Ericaceae on the criteria given by Oldfield (1959).

(5) *Artemisia*. By the use of type slides pollen of *A. norvegica* can be distinguished from that of *A. campestris*, *A. absinthum* and *A. maritima* by the possession of widely spaced spines with broad bases and blunt tips. *A. norvegica* can be distinguished from *A. vulgaris* by the massiveness of the exine in *A. norvegica*. Fossil grains having (*a*) total width of wall, including spines, of more than 2.5 μm and (*b*) a width of more than 0.5 μm for the layer representing fused bases of spines, (peripheral to the columellae) were recorded as *Artemisia* probably (cf.) *norvegica*; both these dimensions are consistently less in *A. vulgaris*.

(6) *Succisa* and *Armeria* pollen have been identified where the grains resemble type slides in all respects (cf. Godwin 1956, Pl. 22).

(7) A category of *triporate grains* in which pore morphology was not sufficiently clear for certain identification, occurring within late-glacial deposits at certain sites, has been distinguished (see Florin 1969, Pl. 1, for photographs of similar grains).

(8) In certain cases one or more genera of a family, but not all those separated by Faegri & Iversen, has been identified, and the rest of the pollen of that family is included in the family total.

(9) *Identification of spores* follows Erdtman, Berglund & Praglowski (1961) for ferns, lycopods and *Sphagnum* spores.

On the diagrams: *Filicales* represents the total of naked Polypodiaceae spores together with *Polypodium*. In some material spores resembling *Dryopteris filix-mas* were well preserved and were separated.

Bryophyte spores = small spherical unornamented objects, 5 μm or less in diameter, staining with safranin in exactly the same way as pollen grains (therefore not fungal spores) and not recognized by algologists as algal structures. They were tentatively identified as bryophyte spores which have lost their outer wall layer and therefore cannot be identified with more precision.

Pollen counts included at least 150 of the grains with which we were concerned – i.e. in late-glacial samples 150 total grains was the minimum counted, and in post-glacial samples 150 tree pollen grains was the minimum. In the topmost samples from lake profiles after deforestation it was not always possible to count 150 tree pollen grains in a reasonable time; these samples were counted to 500 total grains. Our aim was to count as many closely spaced samples as possible, to assess the stratigraphic reliability of the lake profiles, so the pollen sum of each count was kept as low as is consistent with the elimination of most of the chance variation in the values for the main components (Faegri & Iversen 1964, statistical errors, p. 124). The pollen diagrams show that in general the numbers counted were sufficient to eliminate chance zig-zags and show up trends in the pollen curves, but we do of course appreciate that these pollen sums were not enough to give the necessary statistical reliability for any form of numerical analysis of the data. The work described in this paper was all exploratory, with the object of finding complete and conformable profiles; further analytical work on selected problems, including large pollen counts related to volume or weight of the sample (absolute pollen frequency) will follow as the second stage of the project.

(ii) *Chemical*

The methods used were those given by Mackereth (1966*b*) and Pennington & Lishman (1971) with the following modifications.

Iodine and total halides. Iodine was determined as given by Pennington & Lishman (1971). Total halides was determined on an aliquot from the halide–sodium carbonate extract, using a method based on the displacement of thiocyanate in mercuric thiocyanate by the halide ion and its subsequent reaction with ferric ion liberated from ferric perchlorate to form the coloured complex $[Fe(SCN)]^{2+}$ which is measured spectrophotometrically.

Calcium and magnesium were determined by versenate titration after heavy metals had been removed by precipitation as quinolates.

In the Loch Clair core, *carbon* was determined using the Hewlett Packard 185 CHN analyser. The mineral constituents, *sodium*, *potassium*, *magnesium*, *calcium*, *iron* and *manganese*, after digestion in the usual manner, were analysed using the Perkin Elmer 303 Atomic Absorption Spectrophotometer.

(iii) *Diatom*

The diatoms were cleaned with boiling concentrated sulphuric and nitric acids. This proved sufficient for the lower part of the core but above 3 m the acid-cleaned diatoms tended to mat together and so it was necessary to separate them. Amorphous silica was found to cause the flocculation and this was dispersed by the addition of 1 % sodium carbonate. A stronger solution might have dissolved the diatoms so the method had to be carefully checked. After acid cleaning and washing, about 5 drops of 1 % sodium carbonate was added to approximately 20 ml of suspension and warmed gently for 5 min. This was then neutralized with 2 or 3 drops of 5 % hydrochloric acid and washed by centrifuging with distilled water. Microscopical observations showed that there was no detectable damage to the diatom frustules.

One thousand valves were counted for each sample and each taxon recorded as a percentage of the total. A note was also made of all other taxa on the slide. The percentage analysis has been used because it presents a simple assessment of the whole diatom community without encountering the complexities of relating absolute numbers to a measured volume and hence to annual accumulation.

3. DIVISION OF PROFILES, PRESENTATION AND INTERPRETATION OF DATA

Division of the profiles

Most of the available data on the sequence of changes in sediment profiles covering the last 15 000 years is based on the results of pollen analysis and the vegetational changes deduced from this. These were interpreted by Von Post (1916, 1946) as the results of environmental changes, largely climatic, and the series of pollen zones used in the British Isles by Godwin (1940, 1956) and Jessen (1949) was based on the concept of a series of climatic changes, broadly

TABLE 2. DIVISION OF POST-GLACIAL (FLANDRIAN) SECTIONS OF THE PROFILES

regional pollen zone (NS)	^{14}C dates (Lochs Sionascaig and Clair)	major human interference episodes	pollen zone definition
VI	950 ± 100 B.C.	*ca.* 950 B.C.	*Calluna* zone (local: *Calluna*–*Myrica*–Cyperaceae or *Calluna*–birch–pine)
		ca. 1550 B.C.	
	2070 ± 100 B.C.	*ca.* 2070 B.C.	
V ii	2750 ± 100 B.C.		pine–birch–alder
			end of elm in regional pollen
	3410 ± 110 B.C.	*ca.* 3410 B.C.	
V i			pine–birch–alder, + elm in regional pollen
	4300 ± 140 B.C.		
	4570 ± 145 B.C.		
IV			pine–birch
	5930 ± 160 B.C.		
III			birch–hazel
	6960 ± 130 B.C.		
II			juniper
I			*Empetrum*
transition			*Rumex*–*Lycopodium selago*
	ca. 8300 B.C.* (beginning of Flandrian)		

* West (1968).

For laboratory numbers of ^{14}C dates see figure 18.

synchronous over north-west Europe, with associated changes in vegetation and hence in the pollen spectra. These changes were the bases of the Jessen and Godwin zone boundaries. The profiles from northern Scotland described in this paper cannot be zoned on the Godwin system because the vegetation history of this region has been so different from that of southern Britain that a different sequence of pollen zones is present. West (1970) has recently discussed the problems involved in such a situation, and has shown what method of zonation agrees best with the principles of stratigraphic nomenclature accepted by geologists, but Livingstone (1968) has pointed out how cumbersome it becomes if strictly geological nomenclature of pollen zones is used in discussion of historical ecology. In this paper the pollen zones will be defined in terms of 'biostratigraphic units', but wherever possible the profiles are divided into time units (chronozones) and changes are discussed in relation to periods of time rather than 'zones' of any kind.

For *late-glacial* profiles, results already published (Coope 1970; Pennington 1970; Pennington & Bonny 1970) show that the Jessen–Godwin division of the late-glacial (Late-Weichselian) period (p. 195, table 1) cannot be applied to sites in west Britain (Wales, Isle of Man, Lake District) investigated in detail. Results show evidence for either mild (plants and pollen production) or warm (present distribution of beetle assemblages (Coope 1970)) conditions in western Britain *before* the date of 10 000 B.C. accepted as the beginning of Alleröd time and *below* the birch pollen zone (Jessen–Godwin zone II). There is radiocarbon evidence from three sites (Loch Droma, Blelham Bog, Isle of Man) that the deposits of the lowest pollen zone began to accumulate at a much earlier date than has as yet been found on the continental mainland, and there is no pollen zone in which the spectra resemble those of zone I in Scandinavia. Accordingly it has become necessary to use a division of this late-glacial section of our profiles which differs from the I, II, III zonation (see Pennington & Lishman 1971); this is given in table 1.

In all our Scottish profiles late-glacial percentages of birch and pine remain so low that, comparing them with our absolute pollen diagram from Blelham Bog, we interpret the pollen spectra as produced by locally treeless vegetation, and the tree pollen as the product of distant transport.

Division of the late-glacial profiles is into:

Pre-interstadial sediment, *pollen zone A*, a *Rumex* zone, from the lowest polleniferous sample up to the first major expansion of woody plant pollen.

Interstadial sediment, *pollen zone B*, contains pollen spectra dominated by *woody plants*, at these sites *Empetrum* with or without *Juniperus*.

Post-interstadial sediment, *pollen zone C*, an *Artemisia* zone, contains the highest percentage of *Artemisia* pollen in the profile, with characteristic associates.

In both the Lake District (Pennington 1970) and northern Scotland these changes in the pollen spectra are so consistently accompanied by chemical and lithological evidence for consistent soil changes that we conclude the only possible explanation is that soil and vegetation changes were the result of synchronous climatic changes. Therefore we consider it justifiable to compare the radiocarbon dates from our Lake District sites with Kirk & Godwin's (1963) date from Loch Droma, and to apply these dates broadly to our Scottish sites (table 1). In subdividing the above three pollen zones, however, we make no suggestion that the boundaries of the subzones are necessarily synchronous.

For the position of the *late-glacial/post-glacial* (Late-Weichselian/Flandrian) *boundary*, we adopt the geological definition of the Flandrian as the last 10 000 years, and draw the boundary at the top of the *Artemisia* pollen zone, = the top of the zone of minerogenic sediment, = the end of the post-interstadial cold period (which = Younger *Dryas* in Scandinavia).

In *post-glacial* profiles, recognition of the Godwin zones depends on the expansion of the curves for pollen of deciduous trees – first birch and hazel, then oak, elm, alder and lime, then beech and hornbeam. In northern Britain where beech and hornbeam are not native, recognition of the final Godwin zone, VIII, has always been difficult (Walker 1955, 1966; Pennington 1947, 1964). Pollen of the lime is so rarely found in Scottish deposits that it is doubtful whether the tree ever grew there in any quantity. Elm (*Ulmus glabra*) and oak (*Quercus robur*, *Q. petraea*) are not found in native situations today in the far north and north-west of Scotland, though in certain favourable but restricted areas of the north-east, McVean & Ratcliffe (1962) suggest that oakwood would be the 'natural' forest type in our present climate. Workers on deposits of the Scottish Highlands have found difficulty in using the Godwin zonation because percentages of oak and elm remained so low throughout the profiles (e.g. Vasari & Vasari 1968). Birks (1970) has proposed an alternative scheme of local pollen assemblage zones for the Cairngorm region.

Hibbert, Switsur & West (1971) at Red Moss in Lancashire have correlated pollen assemblage zones with Flandrian chronozones I, II and III by radiocarbon dating. Their definition of their chronozone F II is that it 'begins as the component of the mixed oak forest dominate the forest composition', and ends where 'the values of *Ulmus* pollen fall and man's influence on the pattern of vegetation is evident'. In our profiles from north-west Scotland and the Great Glen region it has been possible to recognize the end of chronozone F II, but in north-west Scotland we found no expansion of any component of the mixed-oak forest on which to recognize the opening of chronozone F II. In this paper we shall present facts to support the argument that edaphic factors prevented the establishment of trees of the mixed oak forest in north-west Scotland; nevertheless in all our profiles it is possible to recognize the horizon F II/III by a fall in *Ulmus* percentages which we interpret as a change in the regional British pollen rain at this time. In their review of dated Flandrian sequences from north-west Europe Hibbert *et al.* (1971) show that 'the horizon of the *Ulmus* decline is broadly synchronous'. This agrees with the hypothesis that there was a change in the regional pollen rain at this time, so that this pollen horizon can be used for dating.

The boundary between Flandrian chronozones F I and F II, however, presents problems. Hibbert *et al.*, in their review, have shown that the rise in percentages of *Alnus* pollen, on which they draw this boundary at Red Moss, is 'diachronous with a clear east-west gradient' in north-west Europe. In our profiles from north-west Scotland (Regions 1 and 2) the pattern of percentage pollen curves did not include any pronounced expansion of the *Alnus* curve, and the first appearance of *Alnus* pollen came higher in the profile than in lake profiles of comparable length from north-west England. In this situation it was necessary to use radiocarbon dating as the only possible basis for correlation of these profiles from north-west Scotland. Three dates were obtained for Loch Sionascaig (Y 2362–4) and six from Loch Clair (I 4812–6, 4967). These proved that the first appearance of *Alnus* in north-west Scotland came 1000 years later than the F I/II boundary at Red Moss and the Godwin zone boundary VIc/VIIa in north-west England (Godwin *et al.* 1957; Pennington 1970).

Each of our profiles has therefore been divided into a sequence of six pollen zones, and evidence is put forward for regarding these as regional zones for the area of northern Scotland shown in figure 1; the zones are Regional Pollen Assemblage Zones (West 1970). Table 3 shows the generally parallel sequence of changes in the pollen spectra and the local differences. At

Table 3. Northern Scotland (NS) regional pollen zones

	zone NS	Clair	Sionascaig	Borralan	Craggie	Tarff	compare Godwin zone
FLANDRIAN	NS VI not	birch–pine–alder–*Calluna*	*Calluna*–grass–sedge–*Myrica*		*Calluna* (peat not analysed) clearance	*Calluna*–alder–birch–pine	
	synchronous NS V ii	pine–birch–alder (no elm)	pine–birch–alder (no elm)		birch–pine–alder (no elm)	birch–pine alder–oak (little elm)	VII b
	NS V i	pine–birch–alder + elm	pine–birch–alder + elm	birch–pine–alder unconformity	birch–pine–alder + elm	birch–pine–alder–oak + elm	VII a
	NS IV	birch–pine–hazel	pine–birch–hazel	birch–pine–hazel	pine–birch–hazel	pine–birch–hazel (+ elm and oak)	VI c
	NS III	birch–hazel (no pine)	birch–hazel (+ 10 % pine)	birch–hazel	birch–hazel	birch–hazel (+ elm and oak)	VI a, b
				birch (+ 5 % hazel)	birch (+ 5 % hazel)	birch (+ 10 % hazel)	V IV
	NS II	juniper (rising birch)	juniper–birch	birch–juniper	juniper	juniper	III–IV
		I–II					
	NS I	*Empetrum*	*Empetrum*	birch–*Empetrum*	*Empetrum*	*Empetrum*	no equivalent
	transition	*Rumex–Lyc. selago*	*Rumex–Lyc. sel.*	not present	*Rumex*	not present	no equivalent
LATE-WEICHSELIAN	C-*Artemisia*	not present	*Artemisia*	*Artemisia*	*Artemisia*	*Artemisia*	III
	B-*Empetrum*	? (not sampled)	*Empetrum*–juniper	*Empetrum*	*Empetrum*	*Empetrum*–juniper	II no equivalent
	A-*Rumex*	? (not sampled)	*Rumex* *Rumex–Lyc. sel.*	*Rumex*	not present	*Rumex* *Rumex–Lyc. sel.*	I

NO POLLEN ? – FULL-GLACIAL

Loch Sionascaig and Loch Clair the dates made possible the construction of an approximately linear depth-time-scale, and when the boundaries of the northern Scotland pollen zones at these two sites are referred to dates on the depth-time-scale, the correspondence is close enough to equate these pollen zones with radiocarbon-dated north-west Scotland chronozones at these two sites (table 4, figure 18) in accordance with agreed stratigraphic procedure (see Hibbert *et al.* 1971, p. 172).

TABLE 4. NORTH-WEST SCOTLAND CHRONOZONES AND A COMPARISON WITH RADIOCARBON DATES FROM NORTH-WEST ENGLAND

NORTH-WEST SCOTLAND (LOCHS SIONASCAIG, CLAIR AND DROMA)
(NWS regional pollen zones have been ^{14}C-dated, and therefore = chronozones)

PERIODS (chronozones)	REGIONAL POLLEN ZONES (NS)	LOCAL ^{14}C DATES			^{14}C DATES BY CORRELATION OF MAJOR ENVIRONMENTAL CHANGES (see p. 203)	JESSEN–GODWIN–POLLEN ZONES
NWS VI	*CALLUNA* (*Calluna*–grass–sedge or *Calluna*–birch–pine)	950 B.C.	PROFILE	PROFILE		VIII
non-synchronous						
NWS V ii	pine–birch–alder (no elm)	2070 B.C. 3410 B.C.			3260 B.C.† —ı—ı—ı—elm decline 3390 B.C.†	VIIb *ca* 3000 B.C.
NWS V i	pine–birch–alder (with elm)	4300 B.C.	SIONASCAIG	CLAIR		VIIa ATLANTIC
NWS IV	pine–birch (no alder)	4570 B.C. 5900 B.C.			no correlation Boreal–Atlantic transition	VIc BOREAL
NWS III	birch–hazel rise of birch curve	6900 B.C.		LOCH		VIb VIa V
NWS II	juniper				7607 B.C.‡ rise of birch curve 7900 B.C.‡ rise of juniper curve	IV
NWS I	*Empetrum*					
trans. →	*Rumex–Lycop. selago*				8300 B.C.	
post-interstadial C	*Artemisia*–mild solifluction →				solifluction in lowlands	III
INTERSTADIAL B 3 2 1	*Empetrum* (with or without juniper)	10870 B.C.	LOCH		8800 B.C. birch 10000 B.C. 10875 B.C.§ rise of juniper curve	II (Alleröd) c b a I c b
PRE-INTERSTADIAL A 3 2 1	*Rumex* – *Artemisia* *Rumex* – *Empetrum* *Rumex* – *Lycop. selago* no solifluction →				no solifluction (up to 1450 ft in Lake District)	a

FULL-GLACIAL

—ı—ı—ı—ı—ı— = correlation, on parallel changes in pollen and sediment composition.

† Angle Tarn and Barfield Tarn (K 1058, 1057).
‡ Scaleby Moss: Q 154. and mean of Q 154. and Q 1
§ Blelham Bog (mean date).

We consider it probable that at the other sites from north-west Scotland – Lochs Borralan and Craggie and the sites of our peat profiles – the boundaries of the northern Scotland (NS) pollen zones are approximately synchronous, but we have no evidence for the dates of the pollen zone boundaries at Loch Tarff in Region 3. The core from this loch was too short (owing to a slow accumulation rate) to permit critical radiocarbon dating, since a 10 cm slice of a Mackereth core is necessary for ^{14}C assay. Table 3 shows how the sequence of pollen zones at Loch Tarff can be related to the Godwin zonation, and we will show how the transition to the pine–birch–alder zone at Loch Tarff (zone boundary NS IV–Vi) has some resemblances, in this profile, to the Godwin zone boundary VIc/VIIa (the Boreal/Atlantic transition) in lake profiles from north-west England.

Interpretation of pollen figures

The pollen diagrams, which include selected taxa but not all those taxa identified (p. 194) give the basic data. All results are expressed as percentages of the pollen sum; for lake sites and Loch Sionascaig peat the pollen sum is the total pollen of land plants, and for other peat profiles the pollen sum is the total arboreal (excluding *Corylus* and *Salix*.) Numbers of spores and pollen grains of aquatic plants are expressed as percentages of the pollen sum. No attempt has been made to process these data in any way, either by choosing alternative pollen sums or by adjusting the percentages to allow for the different pollen productivity of different plants.

Recent work on pollen productivity of the trees of north-west Europe (Andersen 1970) reaches the conclusion that *Pinus*, *Betula*, *Quercus* and *Alnus* are all high pollen producers, *Ulmus* somewhat lower, and *Tilia* and *Fraxinus* are in the lowest group. For the purposes of this paper, then, the four trees with which we are mainly concerned can all be grouped as uniformly high pollen producers, and it is necessary to remember that *Ulmus* will be under-represented by comparison. No recent figures for the pollen productivity of the plants of grassland or heathland, to compare with Andersen's figures for forest trees, are available, so there is as yet no numerical basis on which to assess the number of trees or percentage area of forest represented by any given Arboreal Pollen–Non-Arboreal Pollen (AP–NAP) ratio in north-west Europe.

No attempt will be made to interpret past vegetation in quantitative terms. Much work has been done recently in North America in attempts to produce a quantitative relationship between percentages of pollen of each plant in the surface mud of lakes and the composition of the vegetation round each lake, in terms of numbers of each plant (mainly trees) or the surface area covered by each plant or the community to which it belongs: (McAndrews 1966; Ogden 1969, etc.). Criticism has been levelled at European interpretation of pollen spectra as 'intuitive' (Livingstone 1968) in the absence of such data linking lake pollen spectra with vegetation types.

For the purposes of this paper we are concerned with changes in pollen spectra rather than with reconstruction of vegetation. The lakes studied are all on the course of vigorous streams and will contain pollen from both the air and the surface of the catchment: the pollen spectrum of each sample will include both. Changes in the amount and type of inwashed pollen could result from factors independent of any change in contemporary vegetation. Pollen both from the air and from inflowing water must be subject to complex and climatically determined water movements within the lake before it comes to final rest in the mud (p. 196), and these must be expected to influence the final composition of the pollen spectra.

Earlier studies have shown how the percentage composition of pollen spectra belonging to the same Godwin zone varies from one part of a lake to another. *Corylus* is relatively more

TABLE 5. SURFACE POLLEN SPECTRA

(1) LOCH SIONASCAIG

		Pinus	*Betula*	*Quercus*	*Ulmus*	*Alnus*	total AP	*Ros.* including cf. *Sorbus*	*Corylus* ± *Myrica*	*Salix*	*Juniperus*	*Empetrum*	*Vaccinium*	*Calluna*	Gramineae	Cerealia	*Plant. lanc.*	*Plant.* spp.	*Rumex*	Compositae	Cyperaceae	*Sphagnum*	Rubiaceae	*Potentilla* type	*Filipendula*	Ranunculaceae	Umbelliferae	*Lycopodium* spp.	*L. selago*	*Selaginella*	total ferns	pollen sum
S3	% TPFLP	6	3	< 1	< 1	5	14	1	22	—	< 1	< 1	—	42	10	—	< 1	—	< 1	< 1	9	10	—	< 1	< 1	—	—	< 1	< 1	< 1	4	300
S5	% TPFLP	4	5	< 1	—	4	14	1	25	< 1	< 1	1	< 1	37	9	< 1	< 1	< 1	—	< 1	11	12	< 1	1	< 1	< 1	< 1	< 1	< 1	< 1	3	500

(2) LOCH CLAIR

		Pinus	*Betula*	*Quercus*	*Ulmus*	*Alnus*	total AP	*Ros.* including cf. *Sorbus*	*Corylus* ± *Myrica*	*Salix*	*Juniperus*	*Empetrum*	*Vaccinium*	*Calluna*	Gramineae	Cerealia	*Plant. lanc.*	*Plant.* spp.	*Rumex*	Compositae	Cyperaceae	*Sphagnum*	Rubiaceae	*Potentilla* type	*Filipendula*	Ranunculaceae	Umbelliferae	*Lycopodium* spp.	*L. selago*	*Selaginella*	total ferns	pollen sum
C3	% TPFLP	15	12	< 1	< 1	6	34	1	10	1	< 1	—	< 1	31	9	—	1	< 1	< 1	< 1	4	20	—	1	—	< 1	< 1	< 1	< 1	< 1	7	445
C5	% TPFLP	13	12	—	< 1	3	29	< 1	14	—	< 1	—	1	38	11	—	< 1	—	< 1	—	3	15	—	2	—	—	—	< 1	< 1	—	5	522

TPFLP = total pollen of flowering land plants.

Surface pollen samples, 0–1 cm	(1) Middle of Loch Sionascaig (S3, S5) (2) Middle of Loch Clair (C3) (3) Shallow water of Loch Clair (C5)	Compare % AP with area of existing woodland, figures 2*a*, *b*

compare with present distribution of woodland:	Loch Clair (C3)	Loch Sionascaig (mean)
percentage area woodland within 1 km of lake	25	3
woodland type	pine–birch	birch, birch–hazel birch–rowan
percentage of total pollen	pine 15, birch 12, alder 6 total arboreal 34	pine 5, birch 4, alder 4 total arboreal 14

abundant in littoral than in central deposits (Pennington 1947, 1964; Evans 1970), *Pinus* is relatively more abundant in central than in littoral deposits (Pennington 1947, 1964), and *Alnus* percentages diminish steadily with increasing distance from marginal carr (Franks & Pennington 1961). It seems clear that the processes governing the eventual percentage composition of pollen spectra of mud at any particular point on a lake bottom are very complex, and therefore in lakes such as these it seems unlikely to be possible to arrive at a formula relating a lake mud pollen spectrum quantitatively to the vegetation which produced the pollen. Nevertheless, *changes* in the percentage composition of the pollen spectra must reflect environmental changes, either in the composition of the pollen-producing vegetation or in those conditions in the lake which govern the pollen-collecting situation. In the comments on the results of analysis of these profiles, we shall seek to point out where we consider that integration of all our results helps to suggest which explanation would best fit the facts.

Table 5 gives the composition of the pollen spectra at two places on the mud surface of Loch Sionascaig and Loch Clair. The AP–NAP ratios are compared with the amount and composition of woodland in the immediate neighbourhood of these two lakes (figures 2*a* and *b*, p. 213).

Interpretation of the chemical diagrams

Interpretation of changes in chemical variables has been generally in accordance with the arguments of Mackereth (1965, 1966*b*). However, there are much greater differences between the composition of the source rock of the various parts of northern Scotland than are present in the Lake District, and this is reflected in sediment composition.

The distribution of the following elements was investigated:

Carbon. This provides a more accurate assessment of the organic content than either visual inspection (lithostratigraphy) or loss on ignition. Though geologists speak of 'minerogenic' and 'biogenic' sediment (West 1968) the boundary between these sediment types has not been defined in terms of carbon content. Sediments which appear quite inorganic may contain up to 5 % carbon and much organic matter in microscopic fragments. In description of late-glacial profiles it is more informative to use carbon content than any other variable to distinguish true minerogenic sediment which lacks organic molecules.

Iodine. This element, mainly derived from the oceans and not from the lithosphere, was suggested by Mackereth (1966*a*) as a possible index to the amount of rainfall in the past. Though results have shown no correlation between present rainfall and the amount of iodine in lake sediments, the iodine:carbon ratio is a useful indicator of the derivation of sediment (Pennington & Lishman 1971). Low iodine:carbon ratios characterize neutral or nearly neutral forest soils, and high iodine:carbon ratios are found in acid organic soils and humified peats. In true minerogenic sediment such as varved clays derived from fresh glacial erosion, iodine values are as low as for the lithosphere in general, but higher iodine values are found in hydrated clays representing redeposited mineral soils, since colloidal clay in soils adsorbs iodine from rain.

Iron and manganese, though derived from mineral sources, are useful indicators of biological processes because of their solubility in the reduced state as against their very low solubility in the oxidized form. Mackereth (1966*b*) argues that solutional transport of these elements, indicative of reducing conditions in soils of the catchments, can be correlated in the Lake District with biological activity in the soils, so that minimal solutional transport is found in a lake with low biological productivity in its catchment, such as Ennerdale Water. It seemed to us that solutional transport of iron and manganese must also be associated with the highly reducing conditions of waterlogged soils, and that the distribution pattern of these elements, in conjunction with biological evidence in lake sediments, should throw light on the onset and course of development of blanket peat where this is present on the catchments.

Calcium. The distribution of calcium in the sediment profile of lakes on igneous or Lewisian gneiss rocks brings out clearly the contrast between minerogenic deposits of full-glacial age, which are as rich in calcium as unweathered country rock (cf. table 8) and younger deposits in which the calcium content falls off rapidly due to leaching. In the Lake District this change is reflected in changing vegetation and diatom populations.† *Sodium, potassium* and *magnesium.* Mackereth used the distribution of these elements as indicative of the relative importance of leaching and erosion in the soil régime of the catchments, showing how a high proportion of these elements in the mineral fraction of the sediment corresponded with other evidence for intense soil erosion, transporting bodily into the lake material relatively unleached with respect to sodium, potassium and magnesium. In periods of low erosion rate, i.e. soil stability, on the other hand, mineral material transported into the lakes has been leached of its content of these three bases while in position in the soils, and so periods of soil stability (e.g. times when the forest cover was virtually complete) are shown by sections of the profile low in sodium, potassium and magnesium.

There is an exception to this generalization in that potassium and magnesium are concentrated in certain clay minerals. In the Lake District late-glacial deposits in which clay particle-size predominates are always rich in potassium (Pennington 1970). In these Scottish profiles there is also a strong correlation between the presence of clay particle size and high concentrations of potassium and magnesium.

Changes in the composition of the sediments could in theory be used to set up a series of '*chemizones*' of distinct composition. However, inspection of the curves for these chemical variables shows that the main interest lies in trends – in which different curves follow independent courses. It is not therefore practicable to divide the profiles into a series of chemizones of distinct composition. Unlike the pollen curves, which represent the interdependent fractions of the pollen sum, the chemical curves represent independent variables because the sum of the eight or nine chemical elements represents only part of the total composition of each dry sample; relatively inert quartz and alumina make up the major part (cf. table 8, p. 283).

At the suggestion of Professor P. Greig-Smith, the chemical data were analysed by Principal Components Analysis, incorporating the following steps:

(1) Each variable was standardized – i.e. the value of each variable for each sample was transformed to the number of standard deviations from the mean of that variable.

(2) The correlation matrix between samples was calculated.

(3) Principal Components Analysis was performed on this correlation matrix, giving the latent roots and vectors (only the first four latent roots and vectors were calculated).

(4) The first component, i.e. the first latent vector, which includes a satisfactory amount of the total variance, was plotted graphically.

When this component was compared with the pollen diagrams, each major change in direction of the curve was found to correspond with a pollen zone boundary, showing that many pollen zone boundaries coincide with major changes in sediment composition; comment on the chemical curves is therefore made with reference to pollen zones.

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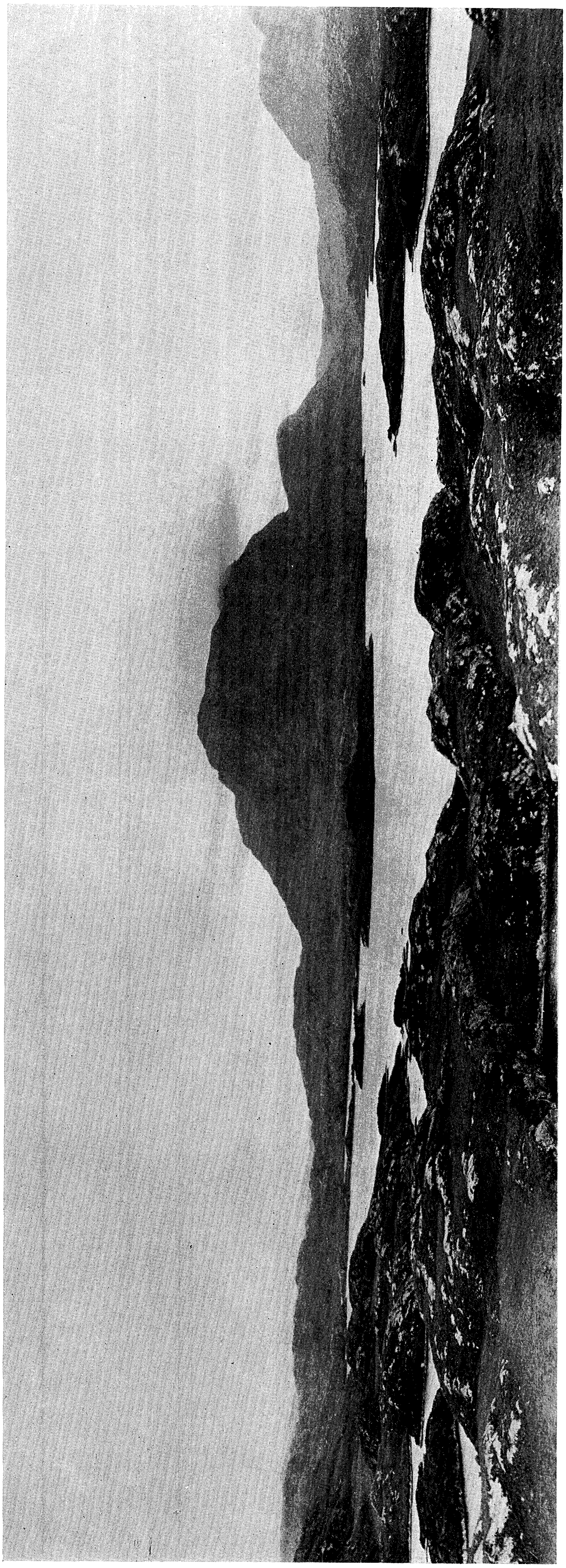
† The data from Loch Tarff (figure 16 and 17, pp. 264 and 265) suggest that a similar pattern may occur in lakes whose catchments lie on metamorphic rocks of the Moine series.



Loch Sionascaig. In the foreground is Boat Bay, surrounded by rocky shores of Lewisian gneiss; in the background are mountains of Torridonian sandstone. The sampling site is in the right middle distance, between the rocky point and the small island.

Diatoms – presentation of data

The diatom diagrams include all those taxa (128) with any stratigraphic pattern in the profile; these are arranged in groups according to pH preference and in order of their occurrence. All other taxa that are present in consistently low percentages or occur rarely have been omitted. The two sections of the profile are (figure 7) the earlier, more alkaliphilous phase, and (figure 8) the later, acidophilous phase.

Ecological groups have been made from the original percentage data on the basis of ecological spectra summarized by Foged (1954). The groups are based on the supposed ecology of the diatoms present and therefore provide an outline of the ecological conditions prevailing at the time of deposition of each sample. In the pH spectrum (figure 9) diatoms are alkalibiontic (restricted to living in water of pH greater than 7), alkaliphilous (most frequently found in water of pH above 7 but also found at pH below 7), acidobiontic (restricted to water of pH less than 7), acidophilous (more frequent in acid water) or they may be indifferent. There are similar divisions according to the preference for salt (chloride) in the Halobian spectrum (figure 9). Halophobous taxa are found mainly in chloride deficient water, whereas halophilous taxa are able to extend into brackish water; true marine and brackish water taxa do not occur in the Loch Sionascaig core (figure 9). The percentage of aerophilous taxa has also been calculated and this includes those forms that can frequently be found on soil or bryophytes (figure 10). Ecological judgements are based mainly on the work of Foged (1953, 1954, 1964, 1968, 1969), Jørgensen (1948), Round (1959), Florin (1970) and Krasske (1932).

4. SITES

(*a*) REGION 1

The far north-west Highlands on the borders of Sutherland and Wester Ross. Site, Loch Sionascaig

In the far north-west of Scotland the striking configuration of the land surface, based on the bold geological contrast between the severely glaciated foreland of Lewisian gneiss and the massive mountains of Torridonian and Cambrian sediments which rise from it, gives rise to a landscape unique in Britain (plate 33). In this region blanket peat has developed to a greater extent than anywhere else on the British mainland, and to lower altitudes, and in the catchments of lakes of this region the formation of this peat must have been the most important aspect of post-glacial soil history.

Over the extensive areas of gneiss in Region 1 the rock is either exposed or covered with peat, and there is very little true soil. Development of blanket peat must have begun in basins in the irregular gneiss surface, and extended laterally to cover flat land and gentle slopes. Round the skirts of the isolated mountain massifs, peat covers the long dip-slopes of the Torridonian Sandstone, and it is only where the mountains rise in steep escarpments that the general mantle of peat is broken (plate 33). East of the Moine Thrust, Lochs Borralan and Craggie occupy hollows in a plateau formed by metamorphic Moine rocks with igneous intrusions; this plateau is partly covered with drift upon which a thick mantle of peat has developed. A great contrast is provided by the outcrops of Durness Limestone, all of limited area, on which free-draining brown-earth soils are found, as in Strath Oykell above and below Loch Ailsh.

An important question was to what extent the wide areas of this region which are now blanket bog were ever forested. In the Hebrides and Shetlands there is little evidence for the presence of trees other than small birches during the period of peat formation (Blackburn 1946; Hawksworth 1970). On the mainland, however, there are many sites where the wood of good-sized pine and birch trees is preserved in peat sections, and one of these, at Badentarbat, within Region 1, has been described with radiocarbon dates for the wood (Lamb 1964). Lamb points out that strong winds are now the most important factor limiting tree growth in this region. The total annual rainfall is lower than that of the mountains and inner valleys of the Lake District, but there are more rain days in the year and the precipitation–evaporation ratio is greater.

The sites sampled were:

LOCH OSGAIG (1 by 2.5 km, max. depth 50 m, altitude 22 m (72 ft))

This loch lies south-west of Loch Sionascaig at the root of the Rhu Coigach peninsula, completely exposed to winds off the sea from south-west to just west of north. Its northern shore is drift-covered, the southern Torridonian Sandstone. It is only rarely that this loch is calm enough to work from a boat, so it was explored for sediment by an aqualung diver; in water of up to 15 m depth he found no sediment except ripple-marked sand.

LOCH NA MOINE MOIRE (1 by 1 km, altitude 73 m (240 ft), not sounded)

This small loch near to Loch Sionascaig is a true rock basin filling a hollow in the gneiss; there is little soil on the catchment which is nearly all bare rock or wet peat. The bottom was explored with a surface mud-sampler and in spite of repeated attempts no sample could be obtained, so it seems probable that there is little or no sediment on the bottom of this loch.

LOCH AILSH (1 by 2 km, max. depth 8 m, altitude 152 m (498 ft))

The importance of this loch, in the upper course of the River Oykell, is that it is the only accessible loch in this part of Scotland lying behind a high frontal valley moraine of the type ascribed by Kirk & Godwin (1963) to the final cold phase of the late-glacial period. The catchment is also of interest in the diversity of the bedrock. Unfortunately its sediment proved to be a coarse silty mud which cannot be successfully sampled with Mackereth corers, and it was not possible to obtain cores of the lowest deposits; the incomplete cores obtained were not analysed.

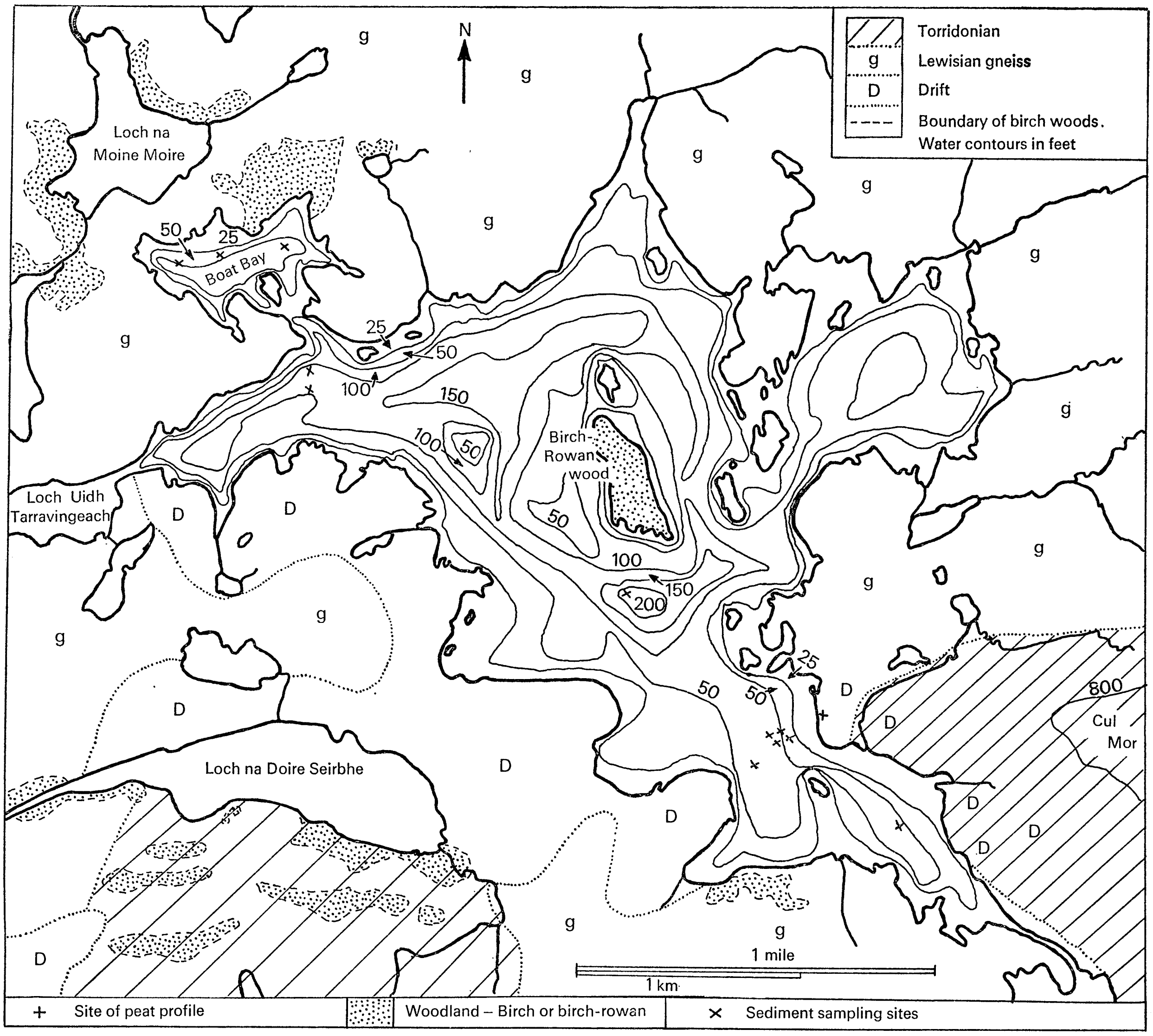
LOCH BORRALAN (1.6 by 0.4 km, max. depth 7 m, altitude 139 m (460 ft))
LOCH CRAGGIE (1 by 0.4 km, max. depth 13 m, altitude 154 m (507 ft))

These two relatively small lochs both lie on moorland, west and east respectively of the main watershed of Scotland in that latitude, between the drainage basins of the Rivers Kirkaig and Oykell. They were chosen partly as sites offering a comparison with that at Loch Droma, 20 miles to the south (Kirk & Godwin 1963), and partly in the hope that their post-glacial sediments might throw light on the history of development of the thick mantle of blanket peat which covers the plateau to the south and south-east.

Good profiles were obtained from both lochs for late-glacial sediments. Post-glacial organic muds showed evidence of unconformity in Loch Borralan, where the core came from water less

FIGURE 2. Maps of two lochs showing underwater contours, sampling sites, solid geology, and woodland on catchment. (Contours from Murray & Pullar 1910). (2*a*) Loch Sionascaig: the position of drift marked on this map was taken from the geological map in Murray & Pullar (1910), and supplemented from personal observation. (2*b*) Loch Clair: the drift edition of Sheet 82 (1 in O.S. Geol. Surv. Scotland) shows 'Morainic deposits with some undifferentiated Boulder Clay' over all of this area except for a small part of the outcrop of Torridonian and Lewisian gneiss immediately east of the River Coulin between the two lochs, and alluvium along the outflow from Loch Clair.

(*a*) Loch Sionascaig



(*b*) Loch Clair

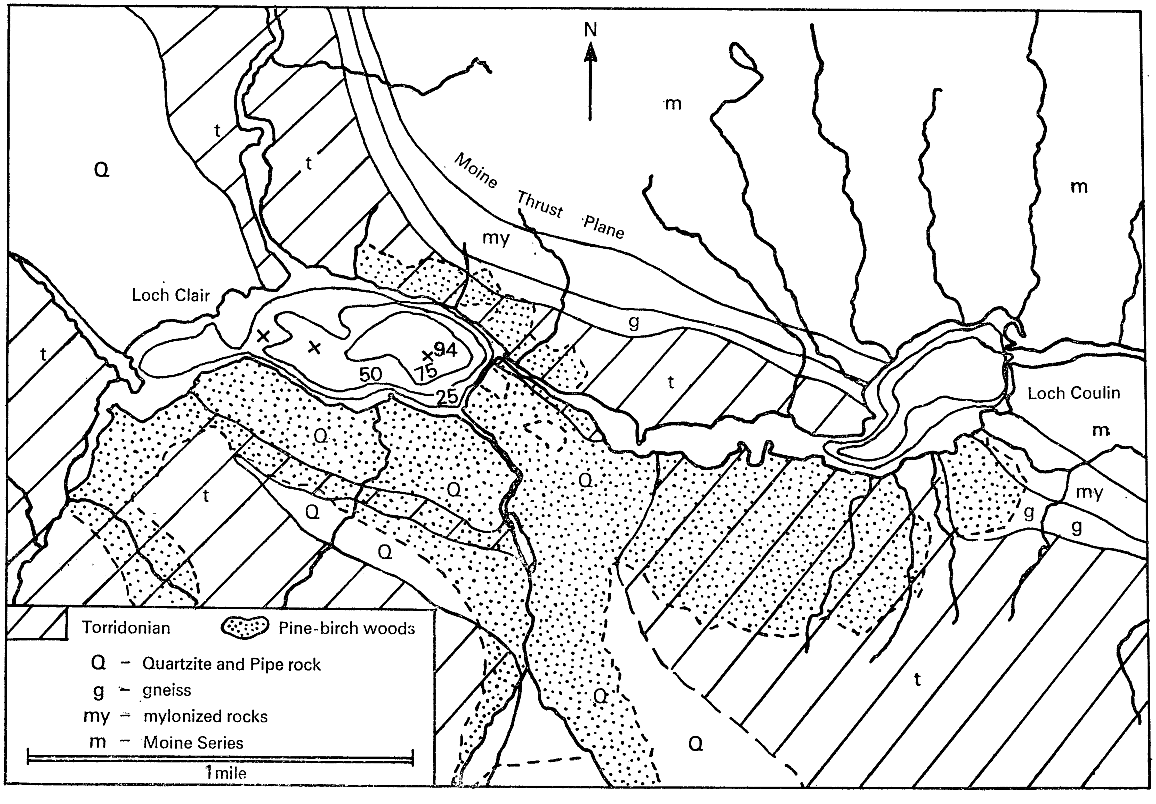


FIGURE 2. For legend see facing page.

than 4 m deep, and in the core from Loch Craggie the post-glacial deposit became uncompacted and disturbed at the level where it showed evidence of derivation from inwashed peat.

LOCH SIONASCAIG (irregular shape, area 607 hectares, max. depth 70 m, altitude 74 m (243 ft)) (figure 2*a* and plate 33)

This loch was chosen for detailed work because it resembles Windermere in surface area and depth, and so provides a comparable lake in a climatically contrasted region where blanket bog descends almost to sea level, and where there is strong exposure to westerly winds from off the sea, which is only two miles away. The morphometry of Loch Sionascaig is closely related to the bedrock, for it lies across the boundary between Lewisian gneiss, with an undulating surface of knolls and hollows which is continued under the waters of the loch, and the red arkoses of Torridonian Sandstone which form the massive mountains Cul Mor, Cul Beag and Stack Polly round the head of the main loch. This upper arm of the main loch, which overlies Torridonian rocks, has more regular underwater contours than the parts on the gneiss, but even this part is broken by small islands (figure 2*a*). All shores of the loch are rocky; the gneiss is often precipitous (plate 33).

There is no drift on the gneiss, and the hard surface of this rock so resists erosional and chemical weathering that there is little true soil except on steep slopes coinciding with the present distribution of birchwoods, or the sites of former crofts. The birchwoods are characteristic of this part of northern Scotland, and are confined to steep slopes, often determined by faulting (shear-belts, see Craig 1964), where the gneiss is not smooth hard rock but is broken to form a stony soil – a dry flush habitat. On the Torridonian Sandstone round the eastern part of Loch Sionascaig some drift is present, providing deeper soils; on steeper slopes both drift and sandstone carry areas of birchwood on well-drained brown soils, but these are restricted in extent and peat has developed over much of the drift and the Torridonian sediments. Only above the steep escarpments (plate 33) does peat disappear and montane heath vegetation replace that of bog.

An unpublished soil map of the Inverpolly Reserve, available for study at the Edinburgh office of the Nature Conservancy, confirms that over all this wide area the soils are either peat or have an equally acid though shallower organic horizon; the only areas where brown forest soils are mapped are either existing areas of birchwood or the site of former crofts, now *Agrostis–Festuca* grassland. The mineral soils beneath the organic layer are uniformly coarse-textured and poor in exchangeable bases. Very little soil material of clay-particle-size is produced by the weathering of the Torridonian sandstone, and on the gneiss there is less than 10 % clay in those mineral soils which exist. It seems clear that these coarse-textured mineral soils must have been rapidly impoverished by leaching in this highly oceanic climate, so that most favourable conditions for retrogressive vegetation successions leading to blanket bog must have been present (Iversen 1964). Iversen emphasizes how the accumulation of a thick organic horizon impedes drainage and leads to waterlogging even in the absence of an impermeable iron pan; in this catchment the topography of the bedrock (the ill-drained hollows in the surface of the solid gneiss and the wide gently sloping terraces of the sandstone) must have intensified the process of waterlogging and formation of thick peat. Steep slopes and dry flushes are the only features to have preserved free-draining soils and mesotrophic plant communities.

The gneiss, though resistant to subaerial weathering, is not a fundamentally poor material like the sandstone. Analyses of gneiss from the Lochinver area (Peach 1907) show a calcium content comparable with that of unweathered Borrowdale volcanic rock (table 8). Work in the

Lake District already cited had shown a high content of calcium and other bases in full-glacial sediments, comparable with that of unweathered source rock, and a rapid fall in these elements through late-glacial into post-glacial sediments. This was found to be related to a more calcicole assemblage of higher plants and diatoms in late-glacial and earlier post-glacial times than subsequently (Round 1961; Pennington 1964; Haworth 1969). It can be explained as the result of the intense mechanical erosion of hard igneous rock during a glaciation, providing readily available bases in rock flour during the late-glacial stage, but followed by a return to base-poor conditions as the fresh drift became rapidly leached by the high rainfall of a mountain district. Loch Sionascaig seemed to offer a promising site at which to investigate the response of lake biota to this situation, so full diatom analysis was carried out on this profile (p. 228).

The vegetation of the Sionascaig catchment is described in publications of the Nature Conservancy (Annual Reports, H.M.S.O.). The blanket-bog vegetation is similar to the western blanket-bog of McVean & Ratcliffe (1962) with *Calluna*, *Trichophorum cespitosum*, *Eriophorum* spp. and *Myrica gale*, together with *Sphagnum* spp., *Narthecium ossifragum* and *Drosera*. In places where it is flushed, particularly with water from more basic gneiss, *Carex* spp. and *Molinia caerulea* are found.

The dominant tree of the birchwoods is given by the Nature Conservancy as *Betula pubescens*; probably this is subspecies *odorata*. Hazel (*Corylus avellana*) is present on the more base-rich soils in some quantity, and rowan (*Sorbus aucuparia*) is regularly present in the birchwoods, and forms several acres of pure rowan wood on one of the largest islands in the loch. Some of the birchwoods have a herb flora similar to the *Betula*-herb *nodum* of McVean & Ratcliffe (1962) but cannot be ascribed to that *nodum* because of the regular presence of *Vaccinium myrtillus* in locally leached situations on knolls. In fact these woods present the appearance of a soil and vegetation mosaic determined by local variations in bedrock, flushing and leaching, so that species of both *noda* of McVean & Ratcliffe are present (Betuletum–Oxaleto–Vaccinetum and *Betula*–herb *nodum*). Some of the woods consist entirely of old birch trees with a grassy ground flora and are not regenerating; in others, particularly the more open, birch seedlings and saplings are present.

Loch Sionascaig (sediments)

No sediment could be found in those parts of the loch which lie over gneiss, except in the almost enclosed inlet Boat Bay (plate 33), where a wet black unstratified and highly organic material resembling peat was sampled by the corer. In other places on the gneiss (see figure 2*a*) both the Mackereth corer and a surface mud-sampler came up empty, in water depths of up to 50 m. In contrast, within that part of the loch which runs up between Cul Mor and Cul Beag and where the shores carry drift deposits, three cores of true lake sediment, up to 6 m in length, were obtained (see plate 33, middle distance, for sampling site). The presence of deep sediment was proved here over an area at least 25 m in diameter, but since conditions calm enough for coring occur so seldom on this loch, it was not possible to plot the limits of the area where sediment is present. It seems probable that true lake sediment is present only over a very limited area of the bottom of Loch Sionascaig, though around the steep rocky margins of that part of the loch on the gneiss, peaty material from hollows in the gneiss has been washed into the lake. It is not clear whether the most important factor determining sediment accumulation was the presence of source material for lake sediment in the drift round that part of the lake, or the comparative shelter from winds off the sea found in that south-easterly area of water.

The core 6 m long contained about 5.5 m of brown organic mud, and below this a succession of clays and slightly organic silts which at once suggested the presence of late-glacial deposits;

at its base the core just penetrated a firm silty clay which proved to be entirely inorganic and barren and was therefore of full-glacial age.

LOCH SIONASCAIG (Analysis of sediments, figures 3 to 10)

This profile was unique in our experience of lake cores in the absence of abrupt lithological changes; broken lines in the stratigraphic column in figures 3 to 5 indicate the approximate horizons where one type of deposit graded into another, but no clear lithostratigraphic boundaries could be drawn. Whatever criterion was adopted to distinguish between late-glacial and post-glacial deposits, a well-developed Transition zone was recognized.

Stratigraphy

Full-glacial, 602 *to* 599 cm

The basal 3 cm of this core was a firm grey silt containing some sand which set hard on drying. The lowest 2 cm, with distinct chemical composition (figure 5) contained no pollen, spores or organic fragments. Within the next centimetre (599 to 600) the transition to late-glacial deposits is shown by sparse pollen grains of the same taxa as are found just above, and a few bryophyte spores. In the sample 598 to 599 cm it was possible to count 100 grains and this is taken as the base of late-glacial sediments; the major change in composition of the sediment occurs at 600 cm.

Late-glacial, 599 *to* 540 cm

The upper boundary of late-glacial sediment at 540 cm is not visibly distinct in the gradual lithological changes in this profile, but 540 cm represents the top of the *Artemisia* pollen zone and the horizon where the carbon curve begins a steep rise to its post-glacial values, so is clearly the top of the late-glacial section on the definition adopted (p. 203). The late-glacial sediments are clays and silts of very low organic content in pre-interstadial and interstadial sections, and inorganic clays and sands in the post-interstadial section. The organic content of pre-interstadial and interstadial sediments is similarly low but qualitatively different; in pre-interstadial deposits it consists of fine plant detritus, mainly unidentifiable moss fragments, but within interstadial deposits there is structureless organic matter, associated with a gradual upward change from pink to grey sediment. This we interpret as evidence for biological activity, with reduction of red oxidized iron, in the interstadial soils which formed the source of the lake sediment. No late-glacial sediment in any of these lakes has the brown colour given by humic compounds, however.

Transitional, 540 *to* 528 cm

Lithologically and on pollen content this section constitutes a transition, but on carbon content it is the base of this zone which coincides with the steep rise used to define the base of the post-glacial deposits (figure 5). Within this zone there is, however, no trace of the brown colour of biogenic sediment or of the flocculation of clay colloids by humic compounds found in the lowest post-glacial mud at Lake District sites (Holmes 1968).

Post-glacial, 528 *to* 0 cm

This section consists entirely of brown flocculated mud, and the lowest pollen zone, the *Empetrum* zone, corresponds with the basal Flandrian pollen zone at our other sites (table 3).

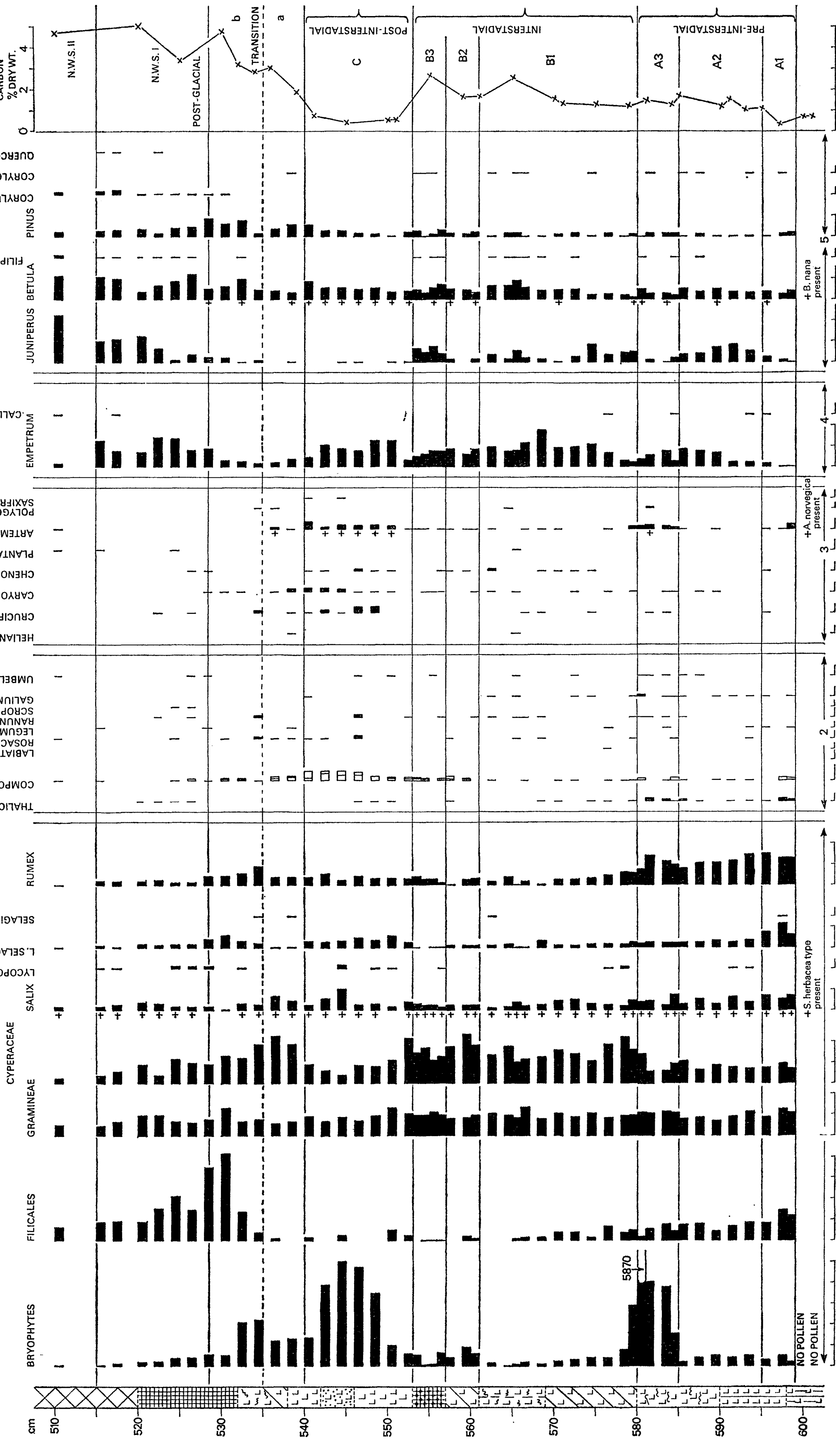


FIGURE 3. Loch Sionascaig: late-glacial pollen diagram. For key to the stratigraphic symbols, see figure 14. Taxa are arranged in the following groups: 1, characteristic late-glacial taxa interpreted as members of pioneer communities; 2, herbs; 3, taxa characteristic of open communities; 4, Ericales; 5, *Juniperus*, *Betula*, *Filipendula* – taxa indicative of temperate conditions – with *Pinus* and coryloid pollen of unknown origin.

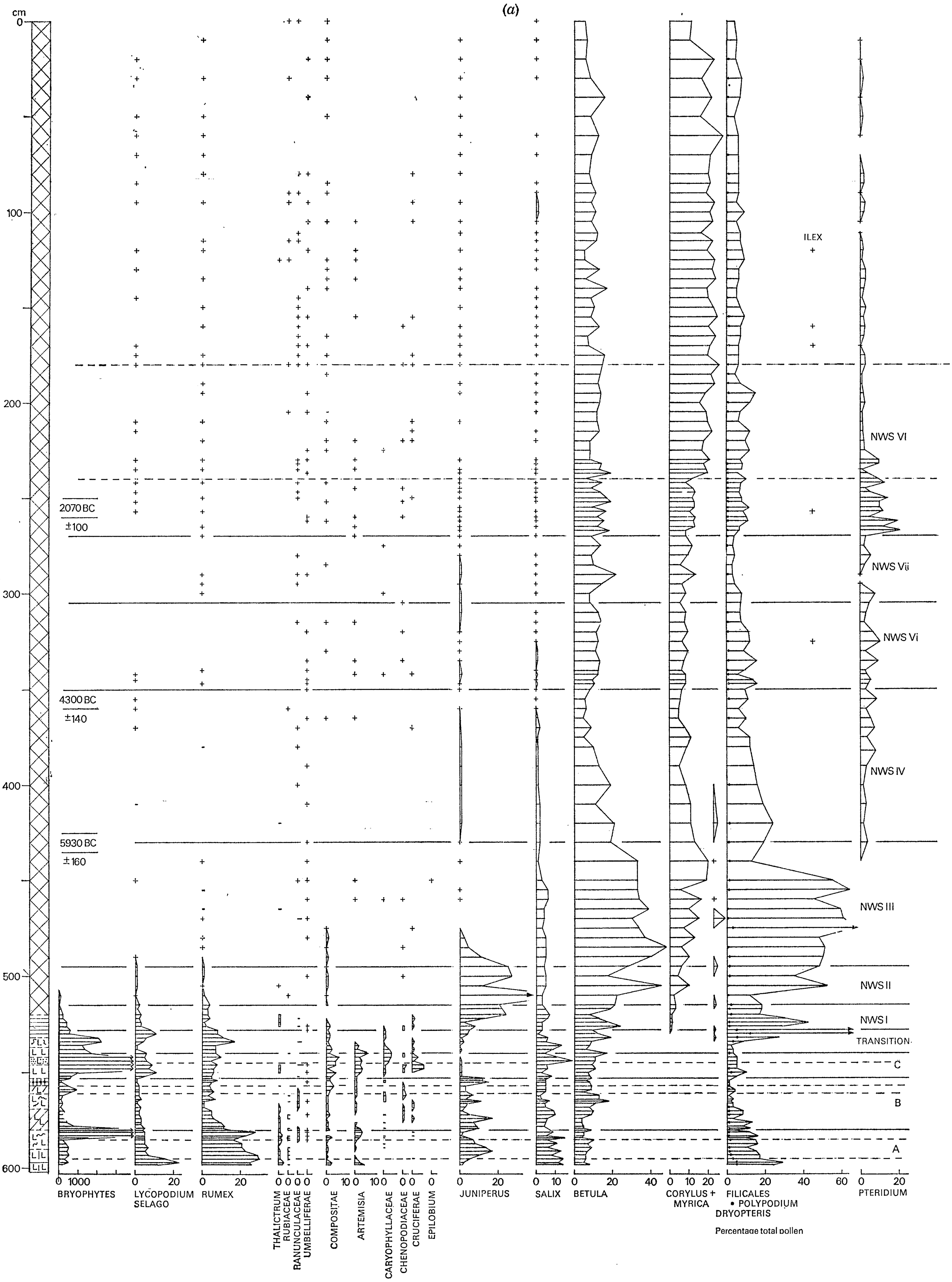


FIGURE 4. For legend see facing page.

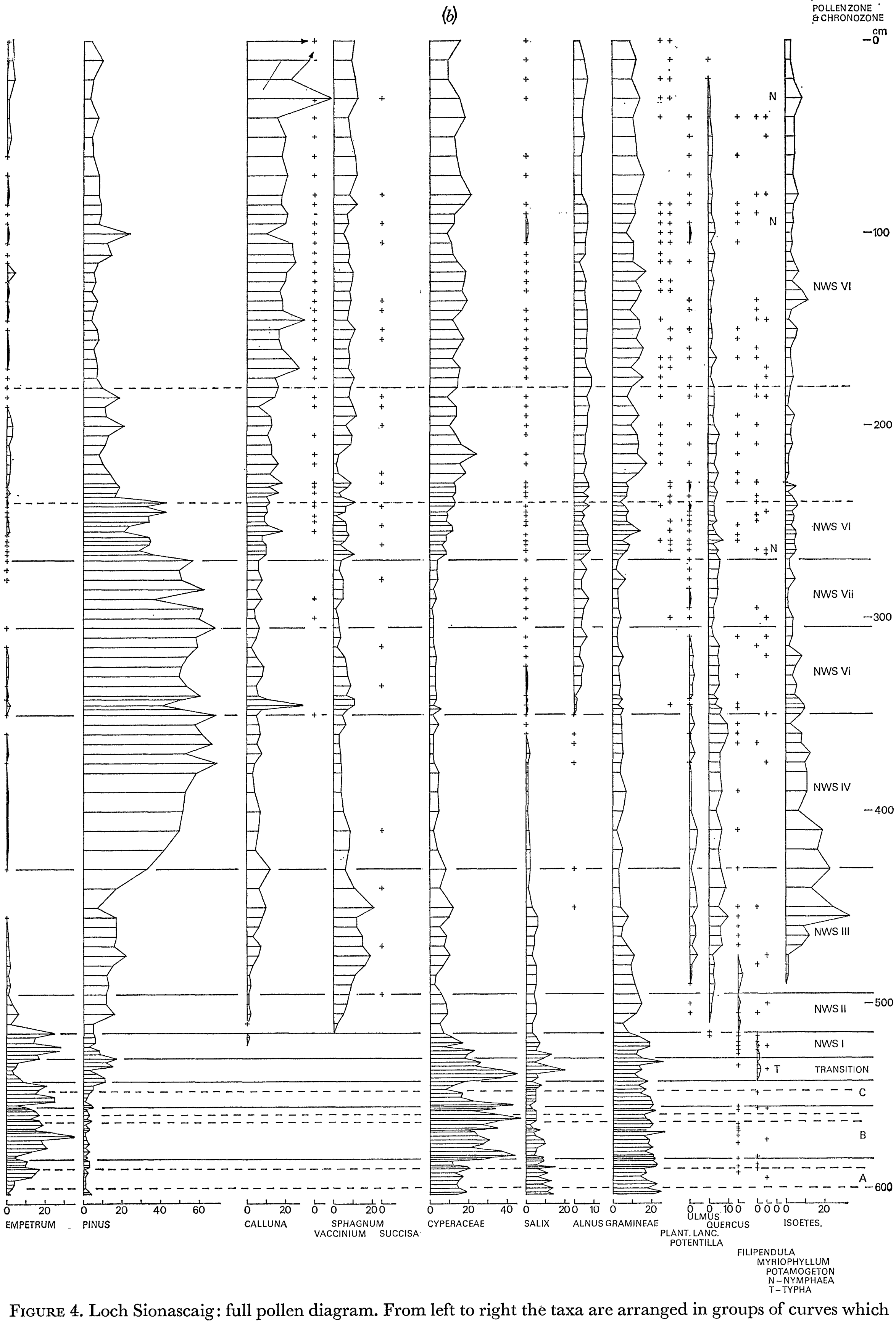


FIGURE 4. Loch Sionascaig: full pollen diagram. From left to right the taxa are arranged in groups of curves which show some correlation. 1, Late-glacial taxa which almost disappear in post-glacial; 2, *Juniperus* – replaced in zone NS III by *Betula–Corylus*-ferns; 3, *Empetrum* – replaced above zones III–IV by *Pinus–Calluna–Sphagnum–Pteridium*; 4, Cyperaceae and Gramineae; 5, *Salix–Alnus*; 6, *Quercus*, *Ulmus*, *P. lanceolata* etc. – all of minor importance.

FIGURE 5. Loch Sionascaig: late-glacial chemical diagram, divided horizontally at pollen zone boundaries.

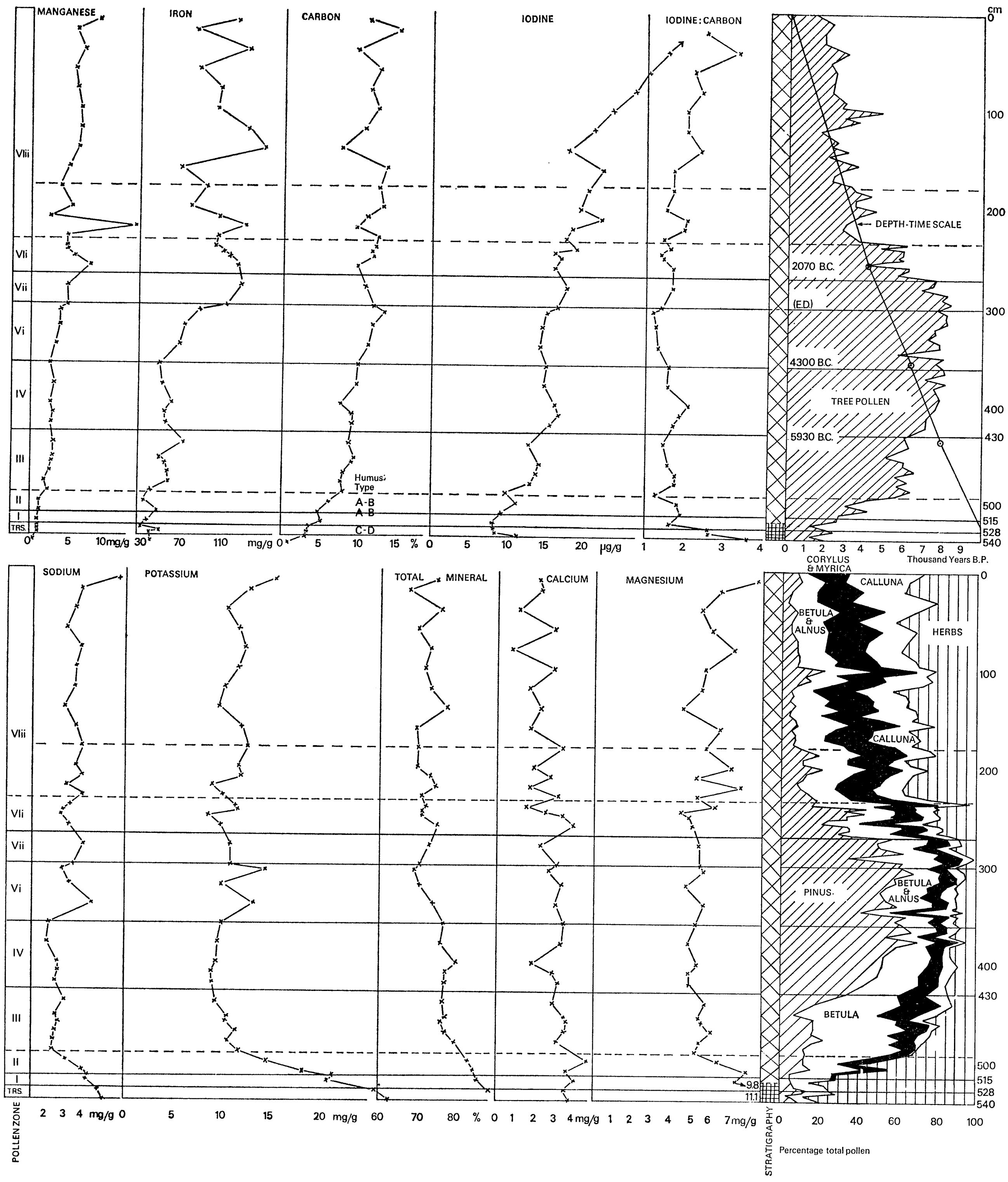


FIGURE 6. Loch Sionascaig: post-glacial chemical diagram, divided horizontally at pollen zone boundaries, with analyses of composition of pollen spectra.

At 300 cm the colour changes from dark brown to almost black, with a corresponding increase in water content and visible change to wetter and less firm mud. The section 456 to 300 cm showed a faint banding of darker and lighter layers, but these were too faintly marked to define and analyse separately; they became less distinct as the core oxidized. Above 300 cm banding was present, but even less distinct, because of the generally dark colour. Chemical evidence will be presented to link these colour changes and banding of the sediment with increasing mobility of iron and manganese in the soils of the catchment as peat bog formed and extended. On the time-scale provided by radiocarbon dating (figure 18) these faint bands were too wide to be interpreted as annual.

Pollen analysis

Late-glacial, 599 *to* 540 cm (figure 3)

Pollen zone A, the *Rumex* pollen zone, corresponding with pre-interstadial sediment, has 20 to 35 % *Rumex* type *acetosa* pollen throughout, and is subdivided:

Pollen subzone A 1, a *Rumex–Lycopodium selago*-fern subzone, has maximum late-glacial percentages of *L. selago* and fern spores, plus continuous presence of *Artemisia.*

Pollen subzone A 2, a *Rumex–Empetrum*-juniper subzone, has higher percentages of juniper (10 to 20 %) than subzones below and above, and discontinuous *Artemisia.*

Pollen subzone A 3, a *Rumex–Artemisia*-bryophyte zone, has 2 to 4 % *Artemisia*, a maximum of bryophyte spores (400 to 500 % pollen) and lower values for woody plants than subzones below or above.

Pollen zone B, the woody plants zone, corresponding with interstadial sediment, is here an *Empetrum*-juniper–sedge zone, subdivided into:

Pollen subzone B 1, *Empetrum* subzone, *Empetrum* maximum, 20 to 30 %.

Pollen subzone B 2, *Empetrum*-sedge–bryophyte subzone; *Empetrum* percentages lower and sedge higher than in subzone B 1, juniper curve discontinuous.

Pollen subzone B 3, *Empetrum*-juniper–sedge zone: juniper 10 to 15 %.

Pollen zone C, the *Artemisia* zone, corresponding with post-interstadial sediment, has continuous values for *Artemisia* but not exceeding 5 %, with 5 to 10 % *Lycopodium selago*, and continuous representation of other Compositae, Cruciferae, Caryophyllaceae and Chenopodiaceae. Bryophyte spores reach high values, comparable with A 3, and juniper is absent or less than 1 %.

The *Empetrum* pollen in this zone is interpreted as at least in part the result of solifluction of interstadial soils (cf. p. 261).

Artemisia norvegica pollen is present throughout this zone, and the increased percentages of *Salix* are attributed to *S. herbacea.*

Transitional, 540 *to* 528 cm

Transitional pollen zone, a *Rumex–Lycopodium selago* zone, contains much sedge pollen in its lower part and a maximum of fern spores in its upper part. Lower percentages of *Empetrum* than found since subzone A 1 are characteristic of this zone.

Post-glacial, 528 to 0 cm (figure 4)

Here the northern Scotland regional pollen zones are equated with chronozones for north-west Scotland; the depth-time-scale is given in figure 18 and the inferred dates for the chronozone boundaries in table 4.

Flandrian pollen zones

NS (*NWS*) *I, Empetrum zone,* is well defined at this site with no stratigraphic complications. *Empetrum* percentages are 20 to 30 %, and the juniper curve rises steeply through this zone from 5 to 25 %, suggesting a rapid rise in temperature (Iversen 1960). There is no increase in the percentage of *Betula* pollen from the late-glacial samples; this indicates little or no increase at this time in pollen production by birches at the source of this birch pollen. Characteristic late-glacial taxa – *Rumex, Thalictrum,* Gramineae, Cyperaceae, *Salix, Lycopodium selago* and bryophytes – decline as percentages through this zone, but may well have maintained or increased their pollen production (Pennington & Bonny 1970).

NS (*NWS*) *II,* the *Juniper zone,* contains 25 to 40 % juniper pollen and irregularly rising percentages of *Betula* and *Corylus*: at this site these two taxa begin their expansion at the same level. *Calluna* pollen and *Sphagnum* spores appear for the first time. In the course of this zone characteristic late-glacial taxa disappear from the counts except for grasses, sedges and *Salix*, each reduced to *ca.* 5 %.

Quercus was recorded from each sample in this zone, and two grains of *Ulmus* were found. An increase in pine pollen from 5 to 15 % is impossible to account for except by postulating a real increase at the source of the pine pollen, because the moderately high percentages of juniper and birch found here indicate local presence (cf. Pennington & Bonny 1970) and in the local presence of these high pollen producers it is impossible to attribute an increase in the percentage of pine to an increased representation of the regional (distant-transport) pollen component (cf. Jessen 1949; West 1961).

NS (*NWS*) *III, the birch–hazel zone,* is not here divided (table 3). Birch pollen is 30 to 50 % and *Corylus* type 10 to 20 % of the total. Some of the *Corylus* type may be *Myrica* but there is no appreciable amount of undoubted *Myrica* present. *Pinus* percentages are 10 to 20 % throughout, *Quercus* 10 %, *Ulmus* 5 %, and *Salix ca.* 5 % until the topmost part of this zone. There are high percentages of fern spores of the naked Polypodiaceae type throughout this zone.

The very low percentages of hazel pollen distinguish the pollen spectra of this zone from those found in the birch–hazel zone at all our sites outside north-west Scotland – i.e. Loch Tarff and the Lake District – and make it impossible to equate this zone with any stage in the Godwin series of zones.

NS (*NWS*) *IV, the pine–birch zone,* represents at Loch Sionascaig the time between the radiocarbon dates of *ca.* 5930 and *ca.* 4300 B.C. on this profile.

Through this zone pine percentages rise from *ca.* 20 % to over 60 %, and those of birch fall from over 20 % to under 10 %. Percentage figures for pine pollen must be interpreted with caution; the water depth at this site (20 m) is equal to part of the central area of Windermere where pine is greatly over-represented compared with its percentages in shallower water (Pennington 1947). Therefore no attempt can be made to interpret these figures in terms of the relative importance of pine and birch as forest trees locally, but as pine percentages rise at the base of this zone, the assemblage so characteristic of the preceding zone –birch–hazel–fern spores–*Salix*– falls off. Since fern spores are outside the pollen sum of interdependent percentages, the evidence is in favour of an absolute decrease in the birch–hazel–fern–willow assemblage.

Quercus, Ulmus, and *Calluna* pollen percentages show no significant change from the previous zone; grass, sedge and *Sphagnum* spores show a constant though small reduction from values in zone NS III.

NS (*NWS*) *V*, *the pine–birch–alder zone*, is subdivided:

NS (*NWS*) *V i*, *pine–birch–alder with elm*, represents at Loch Sionascaig the time between the radiocarbon date of *ca.* 4300 B.C. and the first break in the curve for elm pollen, which on the depth-time-scale falls at very near 3000 B.C. *Salix* becomes discontinuous and *Alnus* appears as a continuous curve, but percentages of alder remain very low (less than 10 %) by comparison with most other lake sites at this date. It is clear that not only did the alder reach north-west Scotland comparatively late, but it cannot have established itself as a dominant of wet habitats there as it did further south. At the opening of this zone is an episode in which *Calluna* percentages temporarily increase at the expense of pine, *Sphagnum* spores increase, and *Quercus* percentages fall permanently. At *ca.* 4300 B.C. the stable vegetation of the previous *ca.* 1700 years was apparently disturbed; from the pollen curves a pre-Neolithic anthropogenic effect might be suspected (cf. Smith 1970), but as we shall see, chemical evidence is in favour of increased waterlogging of local soils as the primary cause. Pollen figures suggest that oak was present in the 'extra-local' pollen rain at Loch Sionascaig until *ca.* 4300 B.C. but thereafter in the regional pollen rain only.

NS (*NWS*) *V ii*, *pine–birch–alder with discontinuous elm*, covers the period from *ca.* 3000 B.C. until the first major fall in pine percentages, with a corresponding increase in *Calluna*, marks the NS zone boundary V/VI, somewhat below the local radiocarbon date of *ca.* 2070 B.C. There is little change in pollen percentages, except elm, from the previous zone, and closely spaced analyses of the 3000 B.C. horizon at 300 cm revealed no other change in pollen spectra (figure 13). From this we conclude that only the regional pollen component of elm was changed at 3000 B.C. – there was no local vegetation change at Loch Sionascaig.

NS (*NWS*) *VI*, *the* Calluna *zone*, of non-synchronous onset, is at Loch Sionascaig subdivided as follows:

Subzone VI i begins at *ca.* 2400 B.C. (time-scale) and ends at some time after the local radiocarbon date of 2070 B.C. ± 100. Pine percentages fall steeply, *Pteridium* spores reach a maximum, and there is an increase in pollen of *Calluna*, grasses, sedges and other herbs, including a few grains of *Plantago lanceolata*. These pollen taxa suggest a herbaceous assemblage of fairly dry pine-woods, increasing in percentage representation as the pollen contribution from the pines was reduced and, possibly, inwash of organic soils containing *Pteridium* and *Calluna*. The presence of *P. lanceolata* does of course suggest strongly the presence of man.

Subzone VI ii, beginning at 240 cm, is distinguished by a sudden increase in percentage representation of obviously *Myrica* type pollen grains, together with sedge pollen, and a second steep fall in pine percentages. *Calluna* percentages show a smaller increase. This indicates an association between a fall in pine and an increase in sedge-bog myrtle pollen at some time soon after 2000 B.C. – this is the first undoubted expansion of the taxa of blanket bog vegetation.

Subzone VI iii, beginning at 180 cm, has lower percentages of birch and higher values for *Calluna*; fern spores also decrease. The pollen spectra at 180 cm show a strong resemblance to those of Mr Johansen's peat profile (figure 23) at the horizon where birchwood in the peat was dated to *ca.* 1500 B.C., when allowance is made for the local pollen component at the peat site. Mr Johansen interprets his pollen spectra from this horizon as indicative of human activity, and the presence of charcoal suggests that fire played a part in the destruction of birchwoods at that time (pp. 244–245).

In the top 170 cm of the core the pollen percentages of pine, birch and alder each average between 5 and 10 % of the total, which is scarcely significantly higher than in the surface pollen spectra (table 5). In three samples at 100 to 111 cm, *Pinus* percentages exceed 10 % with corresponding reductions in *Calluna* and sedge. This could represent the pollen contribution of very few pines (since each tree produces so much pollen compared with a deforested landscape) and no separate zone has been distinguished for this reason. Above this level it can be supposed that the pine pollen has come from the regional pollen rain of northern Scotland, for no native type of pinewood is present within *ca.* 12 miles of the loch, and this consists of only small fragments at Rhidorroch (Steven & Carlisle 1959).

Macroscopic plant remains

In the fine deep-water deposits of this core macroscopic plant remains were few. Dr J. Dickson identified the following:

Salix herbacea leaves, 566 to 569 cm (zone B1), 589 cm (zone A2).

Rhacomitrium cf. *lanuginosum*, 532 cm (Transition zone), 566 to 569 cm (zone B1), 583 cm (zone A3), 589 to 595 cm (zone A2), 598 cm (zone A1).

Antitrichia curtipendula, 568 cm (zone B1).

Chemical analysis

Full-glacial, 602 *to* 599 cm (figure 5)

The barren sediment at the base of this profile is richer in calcium and magnesium than any higher sample or any sample from Loch Tarff or Loch Clair; this suggests an origin in drift derived from the gneiss (cf. table 8)

Late-glacial, 599 *to* 540 cm

(1) *Pre-interstadial*, Rumex *pollen zone*, *A*. In the two lower pollen subzones, A 1 and 2, the sediment has less calcium and magnesium and more carbon and iodine than the full-glacial. More pronounced changes in sediment composition coincide with the pollen zone boundary A 2/3; potassium and magnesium increase together, indicating clay minerals, calcium and sodium decrease together, and iron and manganese increase in constant ratio. These changes suggest an input of (1) clay minerals produced by weathering, and (2) mineral material of different composition from that which provided the source of full-glacial sediment.

(2) *Interstadial*, Empetrum *–juniper pollen zone*, *B*. In the lowest pollen subzone, B 1, carbon and iodine (indicative of humus accumulation and soil biological activity) reach their maximum late-glacial values; iron, potassium and magnesium decrease from their A3 values, and the calcium curve follows an irregular course. Leaching is indicated, but the occasional high calcium values seem to imply that inorganic soil material still fairly rich in this base was still present on the catchment.

Pollen zone B2 corresponds with a return to a sediment rich in potassium and magnesium, resembling subzone A3. Both B2 and A3 sediment composition suggests increased erosional transport of clay minerals, but in neither subzone is the carbon content reduced.

Pollen zone B3 is lithologically distinct – a grey silt without visible organic remains but having carbon values almost as high as any in the interstadial. High calcium and low iron values associated with this late-interstadial type of organic matter have been found at Lake District sites also (Pennington 1970).

(3) *Post-interstadial*, Artemisia *pollen zone*, *C*. The sediment of very low carbon content

between 540 and 553 cm coincides exactly with pollen spectra characteristic of the plants of disturbed soils. In composition the sediment is pink clay and sand, as low in carbon as full-glacial sediment but of a different mineral composition, with much less calcium and magnesium but more iron and manganese. This suggests that whereas full-glacial sediment came from the drift which originated from gneiss, the minerogenic sediment of the post-interstadial cold period (Younger *Dryas*) was derived from Torridonian Sandstone in the catchment area. The absence of varving in this sediment contrasts with Windermere and other Lake District lakes where high corries are present in the catchment, and indicates the absence of any active corrie glacier from this catchment (contrast Loch Clair, p. 249).

(4) *Transitional* – Rumex–Lycopodium selago *pollen zone*. Many of the rapid changes in composition characteristic of the base of the post-glacial sediment profile are completed within this zone – contrast many Lake District lakes and see p. 277. Carbon and iodine rise through the zone, while potassium, magnesium and total mineral content fall steeply. Higher values for iron and manganese and lower for sodium and calcium in the mineral fraction indicate that from the end of the late-glacial period, the mineral sediment transported into the lake from its catchment resembled in composition the Torridonian Sandstone rather than the gneiss or drift from the gneiss.

Post-glacial, 528 *to* 0 cm (figure 6)

(5) *Pollen zones NS* (*NWS*) *I and II*. During the time represented by these two pollen zones, continued increases in carbon and iodine indicate both increasing accumulation of organic matter and biological activity in the source soils (Mackereth 1967). Analysis by Professor R.D. Haworth (Atherton *et al.* 1967) showed a transition from circumneutral humus (Class II ESR spectra) in the Transition zone to acid (Class I ESR spectra) humus in pollen zone NS I. Today the soils of the catchment are differentiated into a larger area of acid soils and a limited area of brown forest soils which are only moderately acid (pH 5.5 to 6). The change in type of inwashed humus between 528 and 520 cm probably marks the time when the major change in soil type took place, and this is supported by the diatom evidence (p. 238). Throughout the sediment of zones NS I and II the continued fall in potassium, sodium and magnesium illustrates the progressive depletion in these bases of mineral sediment entering the lake. Iron and manganese remain steady at slightly below the lithosphere average.

(6) *Pollen zone NS* (*NWS*) *III*. The lower boundary of this zone, dated to *ca.* 7000 B.C. at Loch Sionascaig and Loch Clair, coincides with the beginning of a rise in iron and manganese to levels far above the lithosphere average. The erosion indicators (sodium, potassium and magnesium) reach equilibrium in this zone, so the transport of iron and manganese must have been by solution and not erosional (Mackereth 1966*b*). Solution of iron and manganese followed by precipitation into the lake sediments implies reducing soils and an oxidized lake; Mackereth postulated soil biological activity as the cause of reducing conditions, but waterlogging is a potent cause. *Sphagnum* spores first appear in the pollen spectra at the level where iron and manganese curves begin to rise, and these results suggest that waterlogging of soils and the development of basin peat began, probably first in ill-drained hollows in the undulating surface of the gneiss, at about 7000 B.C.

(7) *Pollen zone NS* (*NWS*) *IV*. The summation of chemical variation shown in the first component of the principal component analysis (figure 18) emphasizes the equilibrium reached by all chemical variables in pollen zone NS IV, the pine–birch zone, that is, during the period from

ca. 5900 to *ca.* 4300 B.C. Mackereth (1966*b*) would interpret this as a period of soil stability, during which minima on the sodium and potassium curves indicate maximum efficiency of leaching. Absence of any further increases in iron and manganese through this zone, indicating no increase in solutional transport of these elements, shows that the area of waterlogged (reducing) soils did not extend during this period. If this is accepted as evidence for a dry period, it began at about the same time as the late-Boreal dry period in East Anglia (Godwin 1956) and north-west England (Pennington 1970). The iodine curve shows no increase through this zone, but in view of proof that the organic matter was already acid, and little existing knowledge of what controls the high retention of iodine in acid soils, no firm conclusions about rainfall can be drawn from this iodine curve.

(8) *Pollen zone NS* (*NWS*) *V i.* The lower boundary of this zone, dated to *ca.* 4300 B.C., coincides with the beginning of a major change in sediment composition. Iron and manganese increase through this subzone to a maximum in the next subzone, the carbon content increases and so does the proportion of the erosion indicators sodium and potassium within the mineral sediment. These facts could be explained by postulating an increase in rainfall and rising water tables, leading to increased erosion of soils on the catchment which by that time were sufficiently acid to have accumulated a distinct organic horizon; erosion of this would increase the organic content of the lake sediments, and further erosion would lead to downcutting of watercourses into mineral soil as yet unleached of sodium and potassium.

(9) *Pollen zone NS* (*NWS*) *V ii.* Though there are no *local* changes in pollen content at the zone boundary NS V i/ii, there are further changes in sediment composition which indicate further acceleration of solutional transport of iron and manganese, interpreted as the most rapid expansion of peat bog in the history of this site. In order to account for the high values of iron and manganese reached at this horizon and on the whole maintained for the rest of the profile, something analogous to the formation of 'bog iron ore' must be supposed – values more than twice the average for the lithosphere are reached. In addition to transport as dissolved ferrous salts, iron is present in bog water as part of stable humic complexes, and on precipitation in oxidizing lakes, ferric hydroxide may be flocculated by negatively charged colloidal silica to produce iron-bearing clay minerals. Manganese, also very readily soluble in reducing conditions when humic compounds are present, is precipitated in oxidizing lakes as black oxide (Rankama & Sahama 1949; Mackereth 1966*b*). We would therefore explain the change in colour of the Sionascaig mud from 300 cm upwards to an almost black colour, as due to the presence of much oxidized manganese (cf. figure 6), and the change to a less firm and wetter sediment as due to the incorporation of colloidal complexes of iron, humus and silica (see also p. 201). The increase in iodine and iodine:carbon ratios at 300 cm could also be explained by the accelerated formation of acid peat on the catchment and its redeposition in the lake.

Chemical evidence is therefore that the changes could be explained by a wide extension of waterlogged soils and peats from *ca.* 3000 B.C., and that the period of maximum impact of these changes coincides with the time from *ca.* 3000 until *ca.* 2400 B.C. (pollen zone NS V ii) during which there are no pollen indications of disturbance of the forest.

(10) *Pollen zone NS* (*NWS*) *VI.* The broken lines (figures 4 and 18), which indicate deforestation horizons within zone NS VI, correspond with minima on the iron curve. In view of our knowledge that the local forest was growing on peat, it is tempting to suggest that the curve for total iron is accurately indicating the extent of solutional transport of that element, and that minima on the iron curve indicate periods when the peat surface was dry and oxidizing; this would

explain the deforestation horizons as the results of destruction, by man or by natural fires, during dry periods. The charcoal in the Sionascaig peat profile would support this explanation (figure 23). There is no increase in the erosion indicators, sodium, potassium and magnesium, until the topmost 20 cm of the profile.

TABLE 6. LOCH SIONASCAIG: STRATIGRAPHY, POLLEN ZONES AND DIATOM ZONES

stratigraphy	pollen–characteristic taxa	interpretation	soils	depth cm	pollen zone
organic mud, almost black, and rather wet	fall in birch on peat		bog peat	100 iii	
	second fall in pine; increase in *Myrica*			180 ii 240	VI
	increased *Calluna*, grass, sedge, bracken fall in pine	deforestation 2070 ± 100 B.C.	drier peat possible	i 270	
	pine–birch–alder (no elm)	forest on peat	expansion of bog	270–300	V ii
organic mud, dark brown, and firm	pine–birch–alder (+ elm in regional pollen)	forest on wetter soils	development of waterlogged soils	300–350	V i
	pine–birch	4300 ± 140 B.C. pine invading poorer soils 5930 ± 160 B.C.	soils not wet	350–435	IV
	birch–hazel–ferns	fern-rich birchwoods + some hazel	some wet soils–*Calluna Sphagnum*	435–495	III
organic mud, light brown, and firm	juniper, increasing birch	shrubby juniper invaded by birch	humus becomes acid	495–515	II
	Empetrum	*Empetrum* heath		515–528	I
clay-mud, pinkish grey	*Rumex–Lycopodium selago*–sedge–willow	resemble pioneer communities	bases declining steeply	transition 540	
pink clay	*Artemisia*–Caryophyllaceae–Compositae–bryophyte spores	taxa of discontinuous plant communities with disturbed soils	*solifluction* almost completely minerogenic sediment, differing from full-glacial	540–554	C
organic silt moss fragments	B 3 554–7 *Empetrum*–juniper B 2 557–61 *Empetrum*–sedge B 1 561–80 *Empetrum*	taxa of treeless heath	organic silt, evidence for soil maturation	554–580	B
clay with silt	A 3 580–5 *Rumex–Artemisia*–bryophytes A 2 585–95 *Rumex–Empetrum* A 1 595–99 *Rumex–Lycopodium selago*	taxa of pioneer communities	silt of increasing organic content– no solifluction	580–599 599	A
silt and sand	BARREN	FULL-GLACIAL	SEDIMENT		

Diatom analysis

Introduction

The sediment profile of Loch Sionascaig is of special interest because it contains an apparently complete and continuous record of the diatoms from the late-glacial up to the present day and shows several features that have not been found elsewhere. The length of the late-glacial profile has made possible a fairly precise analysis of the different types of sediment within this period.

The lake is oligotrophic and a chemical analysis of the water shows that it is very low in total ions and has a pH of around 6.0. Its proximity to the west coast of Scotland and the effect of westerly winds is reflected by the high figures for sodium and chloride ions, 0.365 and 0.438 m-equiv./l respectively, which account for about half the ionic concentration. The water of the lake is very clear.

Table 6 (*cont.*)

SDZ	depth in core/cm	diatoms–characteristic taxa	new taxa	ecological remarks
9	10–100	similar to SDZ 8	—	redeposition of taxa more typical of late-glacial conditions, including alkali-biontic taxa
8	120–260	high % of *Eunotia* and *Cyclotella* spp.; increases of *Denticula tenuis* and *Anom. exilis* var. *lanceolata*	*Navicula petersenii, Eunotia acmocephala*	acidophilous % decreasing slightly
7	295–340	rise in *Melosira distans* var. *alpigena, Eunotia* spp., *Cyc. kützingiana, Frustulia rhomboides* var. *saxonica*; decreases in *Synedra acus* var. *radians* and *Fragilaria virescens*	—	a maximum of acidophilous taxa and slight increase in halophobous taxa
6	360–450	*Cyclotella comensis* dominant; increases of *Achnanthes minutissima, A. microcephala, Anom. exilis, Anom. serians* var. *brachysira*	*Anom. serians, A. follis, Peronia heribaudii, Achnanthes depressa, Melosira tenella, Navicula scutiformis, N. subtilissima, Pinnularia alpina, P. silvatica, Tetracyclus lacustris*	acidophilous % and taxa increasing, upper limit of alkalibiontic and halophilous taxa. Alkaliphiles decreasing
5	470–520	*Fragilaria* spp. decreasing; increases of *Melosira distans* var. *alpigena, Anom. exilis, Synedra acus* var. *radians, Asterionella formosa* and *Tabellaria* spp.	*Nitzschia ignorata* var. *longissima, Achnanthes pseudoswazi, Navicula* sp. S 80	decrease in alkaliphiles
4	522–540 post-glacial	*Fragilaria* spp. dominant, plus other spp. that characterize SDZ 1	*Melosira distans* var. *alpigena, Cyclotella comta, Achnanthes pseudosuchlandtii, Navicula fracta, Surirella elegans*	an assemblage similar to that of SDZ 1 and high % of alkaliphiles
3	late-glacial 542–550	peaks of *Cymbella ventricosa, Fragilaria vaucheriae, F. elliptica, Amphora ovalis* var. *libyca, Ceratoneis arcus, Stauroneis anceps, Navicula schassmannii*	*Navicula contenta* var. *parallela, Pinnularia suchlandtii*	most taxa scarce: fewer diatoms in samples 544 and 548: increase in aerial taxa (figure 7)
2	554–578	increase in *Cyclotella* spp., *Tabellaria* spp., *Achnanthes linearis, A. levanderi, A. suchlandtii, A. microcephala* and *Anom. exilis*	*Ceratoneis arcus, Surirella ovata, Cymbella sinuata, Amphipleura pellucida, Asterionella formosa, Melosira islandica* spp. *helvetica, Achnanthes gracillima*	fewer alkaliphiles due to decrease in *Fragilaria* spp: halophiles present between 565 and 575
1	581–597 597	45 % *Frag. pinnata*, 30 % *Fragilaria* spp. + *Epithemia* spp., *Synedra parasitica, Diploneis elliptica*	*Achnanthes calcar, A. clevei, Melosira teres, Campylodiscus noricus* var. *hibernica, Navicula costulata*	mainly alkaliphilous taxa, almost no acidophiles (figure 7)

BARREN FULL-GLACIAL SEDIMENT

The lake shores are covered with boulders and sand and there are thin patches of aquatic macrophytes in the littoral regions, e.g. *Juncus, Lobelia* and *Potamogeton* spp. There are plenty of small streams and wet seepages where *Menyanthes trifoliata, Ranunculus flammula* and *Potamogeton* spp. grow. The diatoms found in these habitats include; *Anomoeoneis exilis, A. serians* var. *brachysira, Tabellaria flocculosa, Frustulia rhomboides* var. *saxonica, Eunotia lunaris, E. pectinalis* var. *minor* fo. *impressa, E. acmocephala, Synedra ulna, S. acus* var. *radians, Achnanthes minutissima* and *Cymbella microcephala*. Along the shore-line there are wave-eroded peat sections and *Frustulia rhomboides* var. *saxonica* and *Pinnularia silvatica* are found on the wet faces of these. All these

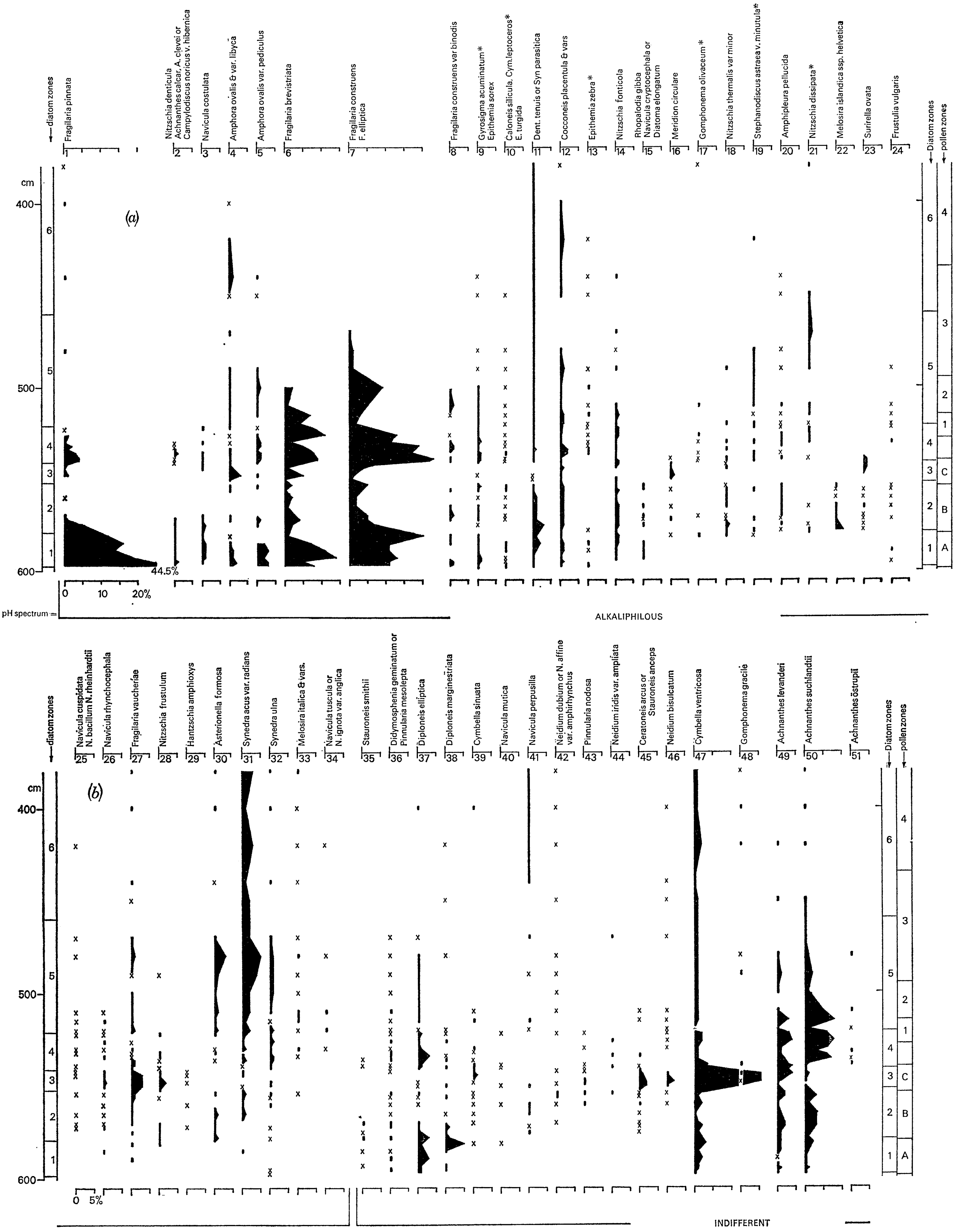


FIGURE 7. For legend see facing page.

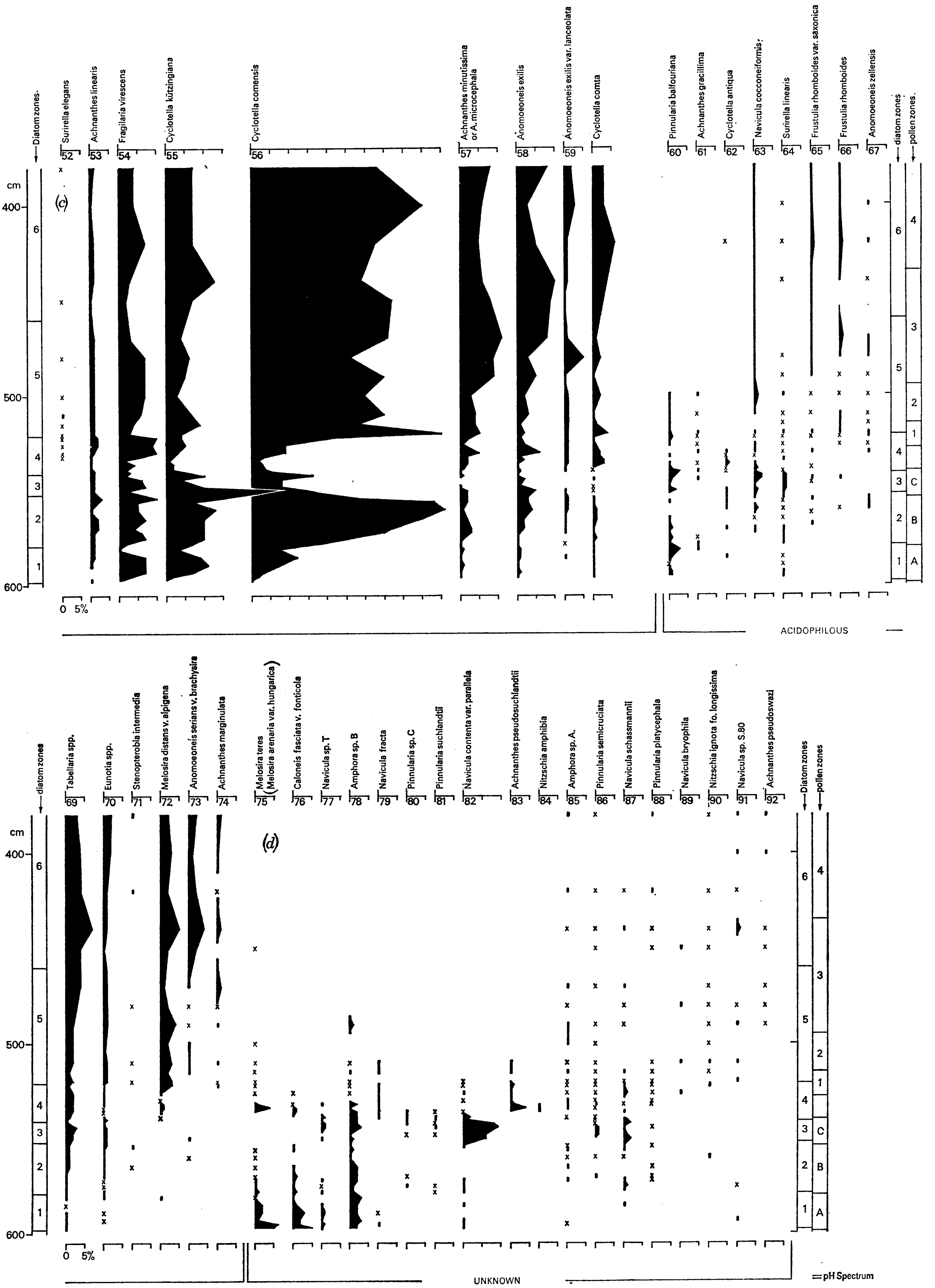


FIGURE 7 (*a* TO *d*). Percentages of selected taxa are plotted against core depth. This figure covers zones 1 to 6 in which many alkaliphilous diatoms occur. Taxa are arranged according to their pH preference and in order of occurrence. Alkalibiontic taxa are included with alkaliphilous taxa and starred. Where two or more taxa are listed, their distribution in the core is more or less identical, so an average curve has been used to save space.

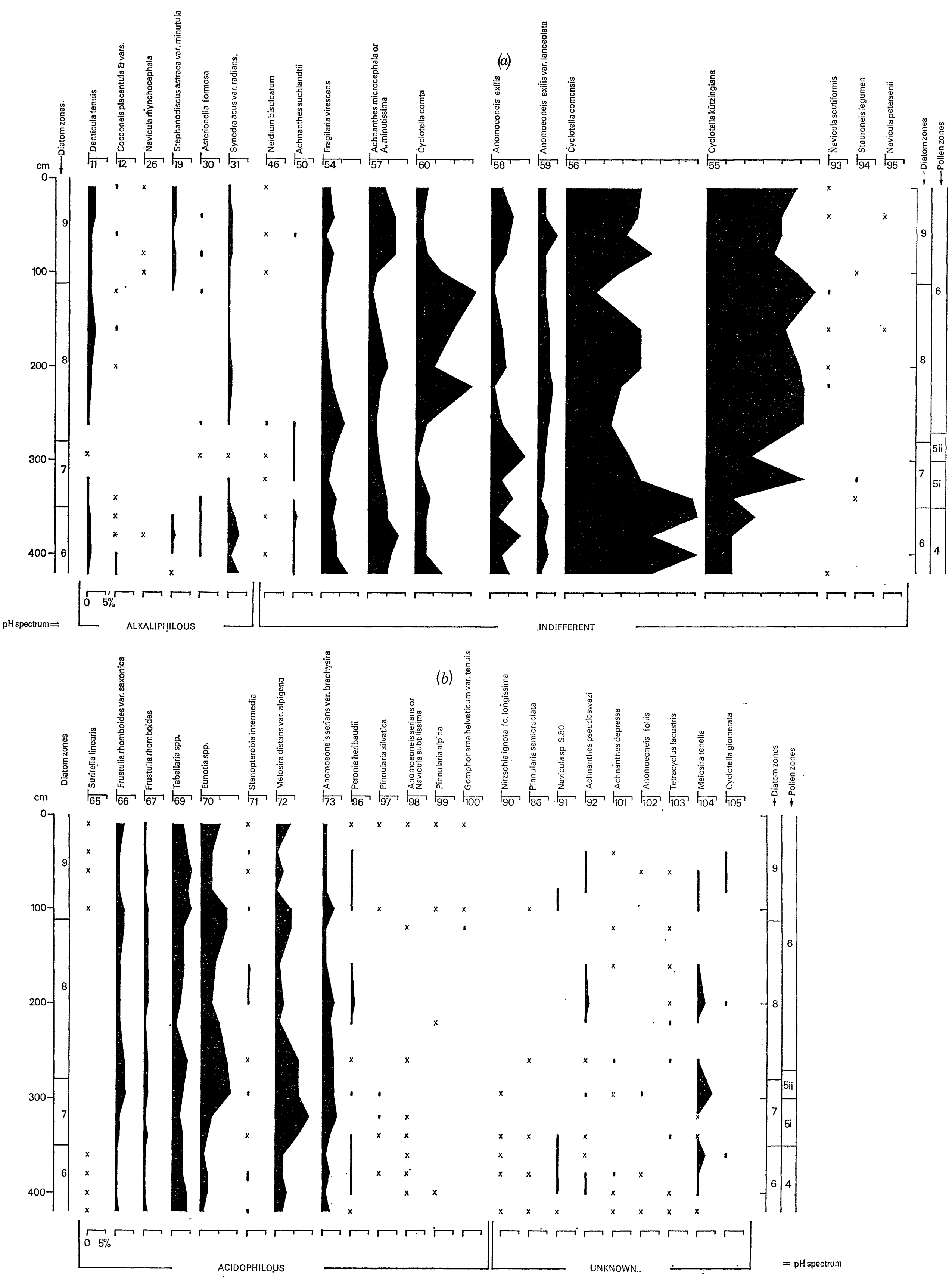


FIGURE 8 (*a*, *b*) Percentages of selected taxa plotted against core depth as in figure 1, for zones 6 to 9. 320 to 420 cm appears on both figures.

communities explain the diatom content of the recent sediments of the loch, with the exception of redeposited material.

Diatom frustules are usually abundant in lake sediments and are representative of the diatoms that lived in the lakes or in the surrounding drainage area, in the pools, streams or bogs. They are therefore useful tools for work on the history of the lake itself. The remains of other algae can also be found in sediments, but these are not sufficiently representative of any one group and are not always easily identified to species level so they are of limited use in historical research. The diatom changes in the core can be related to changing ecological conditions and as more diatom profiles are analysed the picture of these changes becomes clearer. The interpretation of these profiles is limited by our present knowledge of the ecology of some of the taxa, especially of those from oligotrophic waters.

The diatom stratigraphy of the Loch Sionascaig core is shown in table 6 and figures 7 and 8. The divisions into diatom zones have been made according to the changes in the diatom assemblages and are, at this point, unrelated to the lithostratigraphy or to any of the other analyses of the same core. These are therefore diatom (assemblage) zones, referred to by the prefix SDZ (Sionascaig Diatom Zone). This is in accordance with the definition of an 'Assemblage zone' that has been made by West (1970). The relations of these zones to the pollen zones is also shown. (The full list of taxa appears in appendix 1.)

Discussion

The changes in the diatom flora of the lake are fairly gradual ones and it is only in the late-glacial (late-Weichselian) and early post-glacial (transition and early Flandrian) that these changes are great enough or rapid enough to make marked differences between one sample and another. Once the early Flandrian is past the changes are much less obvious, there are slightly fewer taxa and these show changes at different levels; there are also very few taxa which are specific to the upper zones, in contrast to the large number that are restricted to the lower ones (figures 7 and 8).

In general the dominant taxa of any sample are those with an indifferent or wide ecological range. It is only in the lower part of the core that the dominants, i.e. *Fragilaria* spp. are taxa preferring an alkaline environment. *Cyclotella comensis*, *C. kützingiana* and *C. comta* are all widely distributed and can be found in productive Loch Leven as well as in acid, unproductive Loch Sionascaig. In contrast, most of the taxa with more restricted ecology are scarce in the samples, sometimes only at the level of 'presence or absence', but they still suggest patterns of restriction to one zone or another. Some taxa are recorded in the literature so rarely, or in such general accounts that their ecology is virtually unknown but their presence here does suggest that they have a definite ecological niche and do not tolerate much change in their environment.

Cyclotella spp. are the most abundant diatoms in nearly all the samples, especially in the upper part of the core. In the late-glacial and early post-glacial *Fragilaria* spp. are also abundant and there is an interdependence between the percentages of these two genera which is due to the method of analysis. The pattern of changes in *Cyclotella comensis* in diatom zones 1 to 4 is therefore exaggerated as it is mainly determined by the proportions of *Fragilaria* spp. present. These percentages are high enough for a change in one taxon to affect other taxa with high percentages but for the other genera, with low percentages, the effect is almost negligible.

One possible reason for the abundance of *C. comensis* in the core could be that its shape and size make it less vulnerable to damage by any movement in the sediment. Thus the size of its contribution to the diatom community is over-emphasized although it is certainly always abundant.

The *Fragilaria* spp. that dominate the earliest diatom zone, SDZ 1, are generally recorded from the bottom mud in the littoral or shallows of alkaline, eutrophic lakes in Europe (Hustedt 1939; Jørgensen 1948). The same taxa were also found in Iceland by Østrup (1918), Petersen (1928) and Mölder (1951). The latter collected these taxa from lakes and streams at or near the margins of the glaciers along with *Tabellaria flocculosa*, *Melosira varians*, *Anomoeoneis exilis*, *Synedra nana*, *Diatoma hiemale* var. *mesodon*, *Opehora martyii* and *Meridion circulare*.

The other taxa present in SDZ 1 also indicate a somewhat alkaline environment in which there is a community of predominantly benthic diatoms either living *in situ* at the bottom of a very clear lake or being brought in from the littoral regions or streams by water movement and deposited at the core site. Many of these taxa were found in calcareous springs and streams by Round (1957*a*). The alkaline environment in a lake results from the inwash of inorganic material and nutrients eroded or leached from the land. The increasing percentage of planktonic taxa suggests that this zone occurred at a time of change and is perhaps merely a transitional stage between the full glacial period and SDZ 2.

In SDZ 2 *Fragilaria* spp. all decrease in percentage and are succeeded by *Cyclotella comensis* and *C. kützingiana*, this suggests that the contribution to the sediments from the littoral zone has decreased and that the plankton community has perhaps increased (figure 10*b*). This is substantiated by the appearance of *Asterionella formosa* and *Melosira islandica* subsp. *helvetica* as these are planktonic and they occur in rather more alkaline and nutrient rich situations than the present-day lake provides. *Melosira islandica* subsp. *helvetica* is known as a cold water form with a temperature range of 2 to 13 °C and a pH range of 6.9 to 9.8 (Rodhe 1948). This taxon and others that occur in SDZ 2 suggest that the water continues to be alkaline because of the input of inorganic nutrients, but that there is a trend towards a more acid environment in the upper limit of the zone. *Achnanthes microcephala* and *A. minutissima* are increasing and other acidophiles, e.g. *Frustulia rhomboides*, *F. rhomboides* var. *saxonica*, *Anomoeoneis serians* var. *brachysira*, *A. zellensis*, *Pinnularia nodosa*, *Cymbella perpusilla* and *Eunotia* spp. all appear. This trend might have continued along the lines of the eventual change in the lake that occurred in the post-glacial but for the reversion to the colder climate and the renewed input of mineral materials. SDZ 2 occupies exactly the same horizon as the Late-Weichselian interstadial (B) and this is cited (see p. 225) as the time of maximum accumulation of humus in the late-glacial period; it was therefore a time of maximum soil stability when less mineral material was washed into the lake. This may explain the decrease in the percentages of *Fragilaria* spp., either because they are no longer being moved to the core site with eroded sediments, or because they prefer a more minerogenic environment than occurs in SDZ 2.

The change to SDZ 3 is shown by a marked decrease in many of the diatoms and sharp increases in some that have previously shown no pattern, including taxa which can be found on mosses or soils (figure 10*a*). This, plus an increased proportion of mineral sediment to the numbers of diatoms found on a slide, suggests that some of the diatoms have come from outside the lake, brought in by solifluction during the cold period. There is nothing to suggest that life in the lake itself ceased. *Cyclotella* spp. are found in increasing percentages in this zone and the major taxa include *C. comensis*, *C. kützingiana*, *Fragilaria brevistriata*, *F. elliptica*, *F. construens*, *F. virescens*, *Achnanthes levanderi* and *Navicula radiosa*. The increase in *F. vaucheriae* is interesting because this diatom has been found in quantity among the loose particles in a stream that

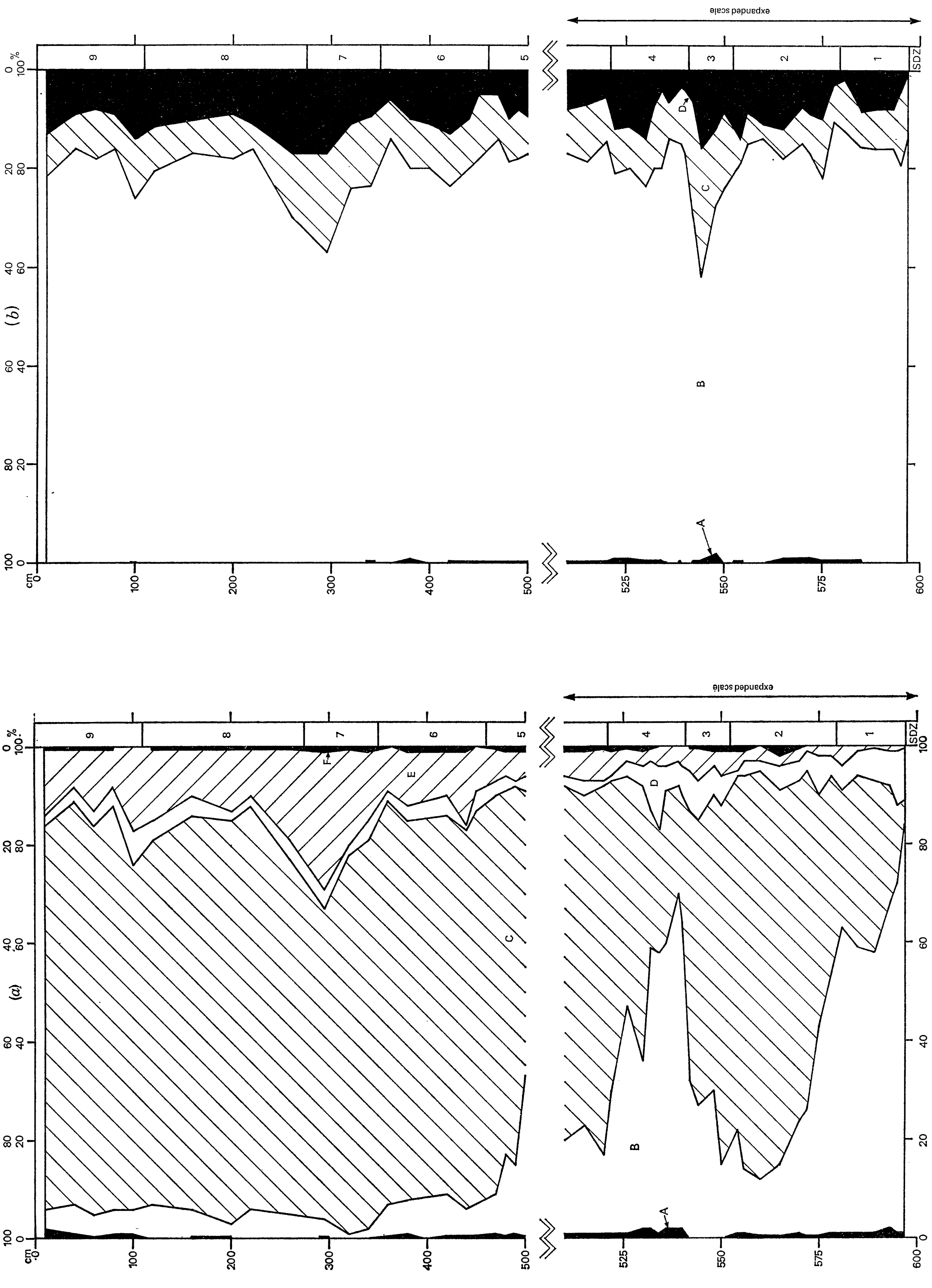


FIGURE 9. (*a*) pH spectrum: the proportion of the total ascribed to (A) alkalibiontic, (B) alkaliphilous, (C) indifferent, (D) unknown, (E) acidophilous or (F) acidobiontic pH groups. (*b*) Halobian spectrum: the proportion of the total assemblage known to be (A) halophilous, (B) indifferent, (C) unknown or (D) halophobous.

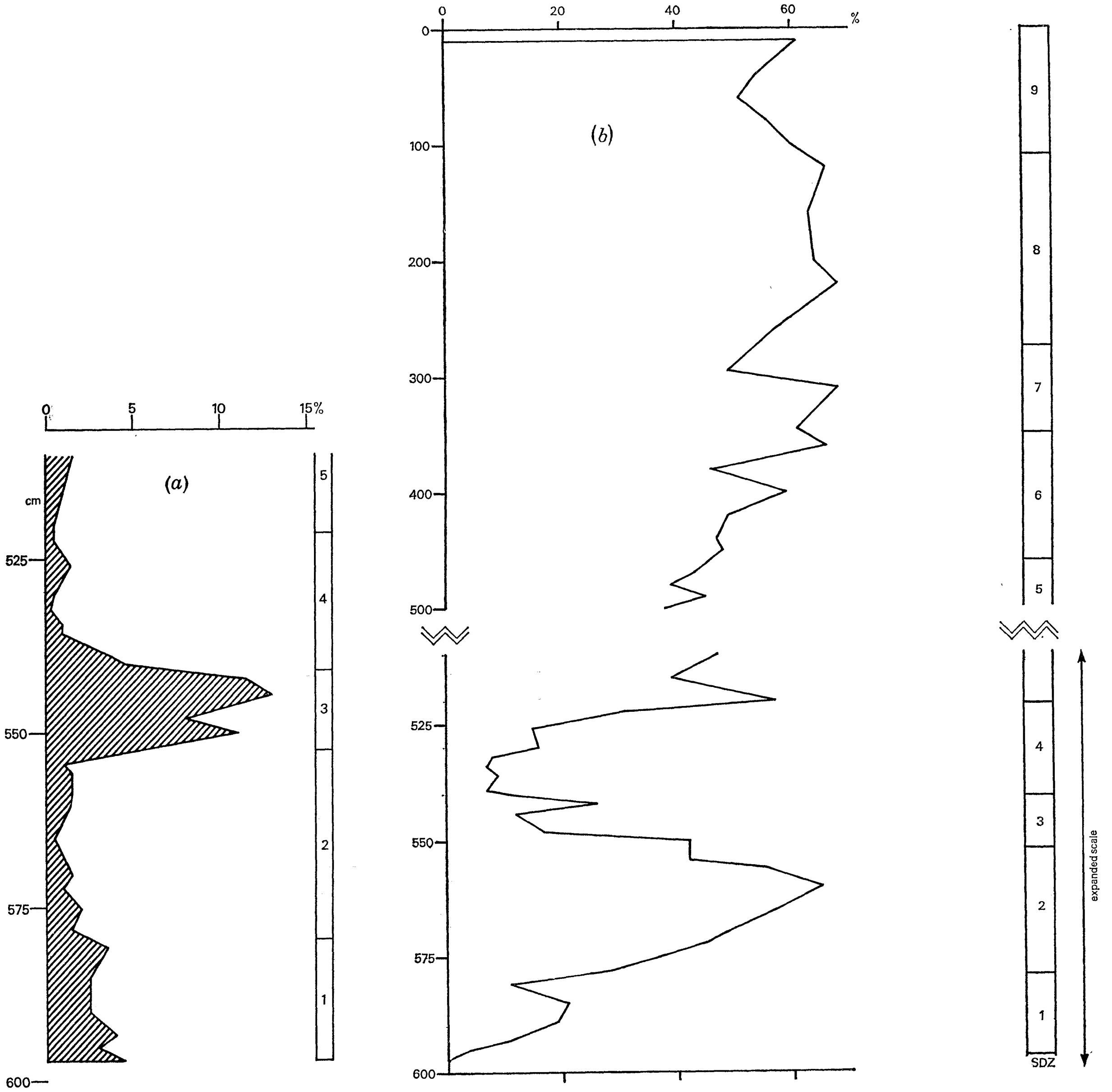


Figure 10. (*a*) Percentage of diatoms in the assemblage that can occur as aerial forms in soils, on bryophytes, etc. Zones 1 to 4 only. (*b*) Percentage of planktonic specimens in the assemblage.

passes through a slate quarry and collects the dust from diamond saws (E. Y. Haworth, unpublished). Round Loch Sionascaig it may have been living on mineral particles in the local streams or in the littoral zone. It is also frequently found in calcareous streams (Round 1957*a*) and is cited as being a benthic form in eutrophic lakes or ponds (Jørgensen 1948).

SDZ 4 indicates a return to the same kind of diatom assemblage as occurred in zones 1 and 2, although the sequence of events is less obvious than at the beginning of the late-glacial. A probable reason is that the diatoms of SDZ 4 were preceded by a well-established flora in SDZ 3, whereas the flora of SDZ 1 was more of a 'pioneer' one. Even so, there is some change in the assemblage between 532 and 530 cm which, coupled with a change in the lithostratigraphy from a pinkish grey clay to a light brown clay mud, suggests that this is where taxa cease to be swept in from the littoral regions and the situation becomes similar to that of SDZ 2; and this can be seen by reference to the alkaliphilous percentages (figure 9*a*). There are also a number of taxa that appear for the first time (above 530 cm) which differentiate SDZ 4 from SDZ 2 even though the environment in the lake must have been similar.

The general pattern of the late-glacial and early post-glacial diatoms in Loch Sionascaig appears to be governed by the type of material washed into the loch, as this is the source of inorganic and organic nutrients. An early, mainly benthic phase (SDZ 1) is followed by a planktonic phase of some apparent stability, but with signs of increasing acidity (SDZ 2) which is curtailed by the renewed cold phase and the input of freshly weathered inorganic nutrients in SDZ 3. After the cold phase the diatom community is again influenced by inorganic nutrients in SDZ 4.

This pattern in Sionascaig includes two stages that have not been apparent in other lakes studied; these are, first, the planktonic stage, SDZ 2 and secondly, the assemblage of the cold phase, SDZ 3. Diatom profiles from other British lakes, e.g. Blelham (Evans 1970), Kentmere (Round 1957*b*), Loch of Park (Alhonen 1968), usually show a continuation or even a climax of the *Fragilaria* and *Epithemia* assemblage in the Jessen–Godwin zone II (see table 1 on p. 195 for correlation with the zonation for north-west Scotland) and plankton is poorly represented. This has been thought to be typical of the late-glacial period but it now appears that this is only true for the smaller, shallower lakes. So far Loch Sionascaig is the only large, deep lake from which a 'mid-lake' diatom profile has been studied as in Windermere, Pennington (1943) described a late-glacial profile on the basis of shallow water cores only, because no deep-water facies of the interstadial is present in the north basin of this lake. There is no obvious explanation for the apparent lack of plankton during the late-glacial in lakes where plankton is present throughout the post-glacial; they are hardly likely to have been shallower than at the start of the post-glacial but the sediments at the core sites may have continued to include more material from the littoral margins or from outside the lakes than is found at Sionascaig. There are diatom profiles described for lakes in Northern Europe but the only ones known to include sediments of the last interstadial of the late-Weichselian are from some Danish sites (Foged 1965; Fjerdingstad 1954) where *Mastogloia* and *Gomphonema* spp. dominate and not *Fragilaria*. Many of the Scandinavian lakes were originally part of the Baltic Sea and so begin with a marine phase.

In many profiles there is also an absence or scarcity of diatoms during Godwin zone III; none have the same kind of assemblage that is found in the comparable zone at Loch Sionascaig (SDZ 3), where a well-developed lake flora was present apparently without interruption. This again may be due to the size and shape of the lake and to the amount of material washed in (p. 239). SDZ 3 is only 12 cm thick, whereas the average thickness of zone III deposits in the other lakes cited is about 20 cm.

The changes in the Sionascaig core appear very precise with taxa being limited to certain levels, e.g. *Achnanthes calcar*, *A. pseudosuchlandtii* and *Nitzschia denticula*, but the proportions in which some of these taxa occur are so low that it will probably be necessary to find another lake profile with a similar succession to confirm that these changes have not just been caused by the chances of sampling. In this core not only do some taxa appear characteristic of 'late-glacial' conditions but, on the basis of the zonation here described, it should be possible to cite some taxa as characteristic of certain parts of the profile even though the reasons why they are so restricted are not yet clearly understood. *Fragilaria* spp., *Epithemia* spp., *Achnanthes calcar*, *Navicula costulata*, *Nitzschia denticula*, *Campylodiscus noricus* var. *hibernica* and *Diploneis elliptica* are all characteristic of zones 1 and 4, while *Cyclotella* spp., *Melosira islandica* subsp. *helvetica*, *Asterionella formosa*, *Amphipleura pellucida*, *Surirella ovata* and *Navicula perpusilla* are characteristic of SDZ 2 as well as occurring in part of zone 4. In SDZ 3 *Fragilaria vaucheriae*, *Cymbella ventricosa*, *Navicula contenta* var. *parallela* and *Pinnularia suchlandtii* are characteristic, and SDZ 4 is typified by *Achnanthes pseudosuchlandtii*, *Navicula fracta* and *N. tuscula* as well as those taxa previously mentioned. Further investigations are needed before it is known whether these can be generally applied to late-glacial sediments in Britain.

The most marked change in the diatom assemblage occurs between 522 and 520 cm when the diatoms cease to be of the 'late-glacial' type. Some of the alkaliphilous taxa disappear at this boundary and the rest decrease in percentage throughout SDZ 5 and 6. The halophilous taxa also disappear in SDZ 6 (figure 9*b*). These are all replaced by increases in the percentages of *Achnanthes microcephala*, *A. minutissima*, *Anomoeoneis exilis* and *Melosira distans* var. *alpigena* and this results in a maximum of acidophilous taxa in SDZ 7 (figure 9*a*). This is interpreted as the response to the changing chemistry and pH status of the waters of the loch caused by degradation of the local soils. This is confirmed by the chemical evidence and the fact that SDZ 7 has features related to possible redeposition, e.g. many broken and eroded diatoms, appears consistent with the interpretation of increased erosion of mineral and organic soil from about 4300 B.C. (p. 227).

The presence of many diatoms that are typical of *Sphagnum* assemblages, e.g. *Frustulia rhomboides* var. *saxonica*, and the increase of iron in the sediments in SDZ 7 both suggest waterlogged and therefore reducing acid soils and the build up of peat on the catchment area. At this same level the acid-cleaned diatoms become clumped and this may be due to the tendency of SiO_4^{4-} ions to aggregate into a neutral silica sol in acid water (Hutchinson 1957 and p. 227) and the small amount of sodium carbonate added to the solution is obviously just sufficient to break this up. The inwash of acid peat may be the cause of this aggregation, but it does not appear to increase the percentages of acidophilous diatoms as the highest percentages have already occurred in SDZ 7. The only characteristic that separates SDZ 9 from SDZ 8 is the inclusion of taxa of 'late-glacial' type. These three diatom zones are all consistent with the onset of blanket bog in the catchment area, as demonstrated by the pollen and chemical analyses and represent the truly acid period of the loch's history spanning the last 6500 years.

The diatom profile suggests that the change early in the post-glacial, from an alkaline, slightly nutrient-rich lake to an acid, oligotrophic one has been rather more extreme in Loch Sionascaig than the same change in the other lakes cited. There is a richer assemblage of diatom taxa in the late-glacial and early post-glacial of Sionascaig than is found in other lakes and this quickly disappears to be replaced by an acidophilous assemblage which also includes many species of *Eunotia* and *Pinnularia* which are not recorded in the other profiles which have been analysed. Some of these, of course, are from lakes which show evidence of cultural enrichment resulting from human settlement (e.g. Windermere (Pennington 1943)) and Loch Sionascaig with its uninhabited catchment would be expected to differ from these.

According to the postulated time scale the change to oligotrophy took place during the first 1000 years of the post-glacial in Sionascaig (see figure 18). This is less than a third of the length of time postulated for the similarly alkaline phase in Blea Tarn in the English Lake District which existed until the Boreal/Atlantic transition (Godwin zone VI/VII a boundary *ca.* 5500 B.C.) (Haworth 1969) and where the change in the diatom assemblage was not nearly so marked.

Synthesis of evidence from pollen, diatom and chemical analysis

Table 6 compares division of the Loch Sionascaig profile on pollen and on diatom stratigraphy. Both pollen grains and diatom frustules first appear at approximately the same horizon, which is defined as the lower boundary of late-glacial sediment (599 to 597 cm).

Late-glacial

Diatom biostratigraphy divides this profile into three parts which correspond with the three pollen zones.

In *pre-interstadial sediments* pollen taxa of the *Rumex* zone indicate a land vegetation of open communities possibly comparable with those of immature soils recently exposed by glacier retreat (p. 274). The diatom assemblage is overwhelmingly dominated by alkaliphilous taxa, including some species found near glaciers today, and contains mainly benthic forms. The implied high base-status of local waters is explained by chemical analysis of the basal sediments, showing a high content of calcium and other bases (figure 5 and table 8).

In *interstadial* sediments pollen of woody plants of closed communities accompanies a diatom assemblage which includes more planktonic and fewer alkaliphilous taxa. All the evidence points to a more stable land surface with reduced movement of mineral sediment; that is, to a situation in which leaching predominates over erosion. The rapidity with which leaching of the fresh drift had reduced the total salt content of local waters is shown by the change from the presence of halophile diatoms, below 565 cm, to an increase in diatoms indicative of acid conditions in the uppermost part of this zone, but the change in pollen spectra through sub-zones B 1, 2 and 3 can be explained more easily as the result of a temperature oscillation than by soil changes.

In *post-interstadial* sediments the *Artemisia* pollen zone includes taxa characteristic of disturbed soils, and abundant bryophyte spores; the diatoms of zone SDZ 3 include forms found in soils and among terrestrial bryophytes, and these micro-fossils are found in mineral sediment attributed on chemical grounds to solifluction of interstadial soils. The continued presence of aquatic diatoms through this zone leads to the same conclusion as the chemical analysis of the mineral sediment, which indicates an origin in weathered soils rather than freshly eroded source rock. This means there was no glaciation even on the surrounding mountains sufficient to produce milky waters and turbid lakes (contrast Windermere). Nevertheless, the numbers of diatoms and pollen grains in the sediment are low because of dilution by material from mineral soils.

The *Transitional, Rumex–Lycopodium selago* pollen zone includes most of diatom zone SDZ 4 in which alkaliphilous taxa once more predominate. On both pollen and diatom evidence, this zone represents a return to pre-interstadial conditions as a result of soil rejuvenation on the catchment by frost-disturbance during the post-interstadial cold period.

Post-glacial

Pollen zones NS I and II (528 to 495 cm) and *diatom zone SDZ* 5 (520 to 470 cm) both show certain resemblances to the plant succession of the late-glacial interstadial, the land vegetation changing from herbs to *Empetrum*–juniper heath, and the diatom assemblage changing to one with fewer alkaliphiles and more planktonic species. Chemical evidence for a rapid increase in total organic matter is accompanied by evidence for a qualitative change to acid humic compounds above 520 cm. This agrees exactly with the decrease in alkaliphile diatoms in SDZ 5 above 522 cm – 'the most marked change in the diatom assemblages' (p. 238), and indicates rapid reduction in the base-status of the majority of local soils at an early stage in the post-glacial period, *before* the spread of forest locally.

Diatom zone SDZ 6, within which both percentages and numbers of species of acidophilous diatoms increase and alkalibiontic and halophilous taxa disappear, corresponds with the upper part of the birch–hazel *pollen zone NS III* and the pine–birch *pollen zone IV*. This indicates that both aquatic and terrestrial plant communities responded almost at the same time to the declining base-status of local soils and waters. By the date of zone boundary NS III/IV (*ca.* 6000 B.C.) pine–birch forest must have replaced the more base-demanding birch–hazel over most of the catchment except for the flushed soils.

Diatom zone SDZ 7 corresponds with *pollen zone NS Vi*, the pine–birch–alder zone during which elm was present in the regional pollen rain. The lower boundary coincides with the horizon where chemical evidence indicates increased solutional transport of iron and manganese, presumably from soils which were becoming waterlogged and reducing. Pollen and chemical evidence therefore agrees to indicate extension of waterlogged soils through the period 4300 to 3000 B.C., culminating in accelerated growth of peat from *ca.* 3000 B.C. The maximum in acidophilous taxa and slight increase in halophobous diatoms in this zone agree entirely with the other evidence.

From the top of diatom zone SDZ 7 at 295 to 100 cm, the diatoms of *diatom zone SDZ* 8 show comparatively minor changes, but this section of the profile includes major changes in pollen spectra, with a steep fall in pine percentages, interpreted as the result of the destruction of a pine forest growing on peat and its replacement by the taxa of blanket bog communities: the evidence is not sufficient to indicate conclusively whether the destruction was by man or natural causes. The deforestation did not have any significant effect on the diatom flora of the streams and lake – this agrees with the absence of chemical evidence for any increased erosional transport of mineral elements. The waters must be supposed to have reached their present acid and unproductive state before the pine forest was destroyed, and the death of pines on a peat substratum did not result in any increased erosion of mineral soils, though there is some evidence for inwash of organic soils and their contained micro-fossils (p. 224).

Diatom zone SDZ 9, covering the topmost metre of sediment, corresponds with pollen subzone NS VI iii, in which percentages of tree pollen fall to the very low levels found in the surface muds (table 5). The evidence for redistribution of late-glacial diatoms during the historic period (p. 238) suggests a changed pattern of water movements in the lake, with resuspension of old sediment which lay near the mud surface in shallower water. In this rocky-shored lake (plate 33) it seems unlikely that changes of water level could be invoked as the cause of resuspension and redeposition of sediment, for there is no sediment present in the littoral zone which would be affected by changes in water level. It seems more likely that increased turbulence resulting from more frequent wind-disturbance could account for this re-deposition of sediment.

Additional pollen analysis

(i) *Loch Borralan, Loch Craggie*

These two relatively small lochs both showed evidence of wind disturbance of their upper post-glacial sediments, so no complete analysis of their profiles was attempted. Pollen analysis of the late- and early post-glacial deposits, however, showed no evidence of disturbance or unconformity, so analysis was continued up to the horizon where disturbance was found. In

Loch Borralan, less than 4 m deep at the sampling site, the unconformity shown by pollen analysis (figure 20) was of the kind found in Windermere where deposits have built up into the zone of wave erosion and orderly deposition has ceased. In Loch Craggie the topmost 2 m of the core resembled the redeposited peat found in Boat Bay of Loch Sionascaig (p. 215) – an unconsolidated and doubtfully stratified deposit unsuitable for preparation of a pollen diagram.

One object in sampling the sediments of these two lochs was to investigate the late-glacial sequence for comparison with that at Loch Droma; like Loch Droma, Loch Borralan and Loch Craggie lie close to the main east–west watershed of Scotland, and their positions to east and west of this offered the opportunity to compare their late-glacial sequences with each other and with Loch Droma, 32 km (20 miles) to the south. Both lochs provided an interesting late-glacial profile (table 7).

A second object was to find out whether any clearly marked human influence on the pollen spectra could be found, particularly in Loch Borralan. On the north side of this loch, and between it and Loch Craggie, many small chambered cairns are marked on the 1 in Ordnance Survey map and are visible on the ground, though none is of a quality to rate a mention in the general accounts of chambered cairns of recent authors (Daniel, in Piggott 1962); (Feachem 1963). Daniel estimates the dates of the settlement of this part of Scotland by the people who built the chambered cairns as *ca.* 2700 B.C. until 1300 B.C. This seemed a promising area in which to investigate whether changes in sediment composition are found in association with traces of human modification of the vegetation of the catchments, as they are in the Lake District during this period (Pennington 1970). The disturbance of the upper half of the Loch Borralan core defeated this object, but an undoubted clearance horizon was found in Loch Craggie at a horizon so placed relative to the elm decline (3000 B.C.) that it seemed certain that it dates from within Daniel's estimate of the chambered cairn period.

A third object was to find another profile, for comparison with Loch Sionascaig, in which the history of the development of blanket peat was recorded. The profile from Loch Craggie provided this, but confirmed the findings from Loch Sionascaig (Boat Bay) that once a mantle of blanket peat has formed as the surface deposit of a catchment, material from it predominates as a source of lake sediment and may give rise to an unconsolidated form of sediment, unsuitable for analysis.

Loch Borralan (figures 19, 20)

Full-glacial 247 *to* 242 cm. The basal 5 cm, a clay-silt, contained only sparse pollen grains; these included some of the types recorded above 242 cm, but also *Pinus* and *Corylus*-type grains interpreted as secondary.

Late-glacial 242 *to* 162 cm, In stratigraphy and pollen zones this section strongly resembled the sequence at Loch Sionascaig and Loch Tarff (see figure 19 and table 7). Local features of the pollen spectra are low percentage values for *Lycopodium selago* spores and the absence of more than the occasional grain of juniper pollen.

Subdivisions of the three late-glacial pollen zones are as follows:

Pollen zone A, *Rumex* zone. *Rumex* percentages usually more than 40.

Pollen subzone A 1, a *Rumex*–grass–*Salix* subzone, has many herbaceous taxa present, and no *Empetrum*.

Pollen subzone A 2, a *Rumex*–*Empetrum* subzone, has 5 to 20 % *Empetrum* and fewer herbaceous taxa than A 1.

Pollen subzone A 3, a *Rumex–Artemisia*–bryophyte subzone, with other Compositae, Caryophyllaceae and *Lycopodium selago* continuously present: *Empetrum* absent or less than 2 %.

Pollen zone B, *Empetrum* zone, has *ca.* 20 % *Empetrum* and only occasional grains of juniper; this is the only profile where B 3 is defined in which it is not a juniper zone.

Pollen subzone B 1, *Empetrum* subzone, *Empetrum* maximum, 20 to 25 %.

Pollen subzone B 2, *Empetrum–Artemisia*–bryophyte subzone; *Empetrum* falls.

Pollen subzone B 3, *Empetrum–Rumex* subzone; *Empetrum* rises.

Pollen zone C, *Artemisia* zone, has a continuous curve but low values for *Artemisia*, lower values for *Empetrum* than B, maximal values for the profile for sedge pollen and bryophyte spores, and continuous curves for Compositae, and *Lycopodium selago*.

At the upper boundary of pollen zone C is a layer of small stones (interpreted as the result of the melting of a dirty ice cover) and what appears to be an unconformity.

Post-glacial 162–0 cm, (including a major unconformity). Figure 20 and table 3 show how the early post-glacial deposits include a conformable sequence of pollen zones which, like those at Loch Tarff and Loch Craggie, can be related on the one hand to a series of regional pollen zones for northern Scotland, but on the other hand show a parallel sequence to the Godwin zones III–IV to VI c. Pine does not reach such high percentages as at Loch Tarff or the western sites; birch and hazel show correspondingly higher percentages in zone NS IV (or VI c). Though an unconformity distorts the opening of pollen zone NS V i (pine–birch–alder) it is clear that above this level pine percentages are lower than alder (cf. Loch Tarff). Percentages reached by oak and elm are lower than at Loch Tarff, and comparable with the western sites.

Salix maintains values of 5 to 10 % through the early post-glacial zones until the lower boundary of the alder zone (the unconformity). From this it would appear that there has always been some development of marginal carr, so the high percentages of alder in the second part of the post-glacial period most probably result from this. No regional significance can be attached, therefore, to the respective percentage values for alder, birch and pine, for birch too may have been present in a fen carr on the almost flat and ill-drained land which stretches from the eastern end of Loch Borralan to the watershed.

Loch Craggie (figures 21, 22)

Late-glacial 390 *to* 372 cm. Figure 21 shows the stratigraphy of the lower part of this core, which contained in its basal 3 cm pollen spectra characteristic of pollen subzone A 3. Pre-interstadial and post-interstadial deposits were clays; the interstadial sediment was a silty clay with no visible organic content:

Pollen subzone A 3 is a *Rumex–Artemisia*–sedge–*Lycopodium selago*–bryophyte subzone, differing from all other Scottish sites in that *Rumex* percentages are lower than in pollen zone B (cf. Blea Tarn (Pennington 1970)).

Pollen zone B, the *Empetrum* zone, contains a well-marked *Empetrum* maximum (10 to 40 %) but cannot be subdivided at this site. Very little juniper is present, and *Artemisia* has a continuous curve through this zone – the only Scottish site where this is so.

Pollen zone C, the *Artemisia* zone, contains an interesting pollen assemblage. *Artemisia* values are high (25 %) – exceeding those at any other of these sites except Loch Tarff – associated with high *Salix* percentages including much *S. herbacea* type, Caryophyllaceae, *Lycopodium selago*, *Selaginella*, *Saxifraga* type *oppositifolia*, one grain each of *Koenigia* and *Helianthemum*, and a peculiarly crumpled ericaceous grain (most probably *Empetrum*).

Transitional 372 *to* 368 cm. This pollen zone, in which *Empetrum* is very scarce and *Rumex* exceeds 20 %, corresponds with the upper part of the transitional zone at Loch Sionascaig; at Loch Craggie there is no expansion of *Lycopodium selago*.

Post-glacial 368 cm to surface (analysed to 170 cm). Figure 22 shows that pollen zones NS I to IV follow a similar pattern to Loch Borralan except that percentages of *Quercus* (5 to 10 %) are higher. The later NS pollen zones, V i, V ii and VI, follow in an apparently conformable profile, and NS VI, the *Calluna* zone, is well established before the core becomes unconsolidated and unsuitable for analysis at 170 cm. Percentages of pine in zones NS IV and V are higher than at Loch Borralan, and those of *Corylus* type much lower (20 as against 40 %). There is a particularly interesting reciprocal relation between pine and alder percentages in pollen zone NS V i which suggests how necessary it is to obtain absolute pollen figures before attempting to reconstruct vegetation from percentage figures.

The zone boundary NS V i/V ii, drawn at the first break in the elm curve and dated to 3000 B.C. by analogy with Loch Sionascaig, shows an interesting decrease in pollen of *Salix* and *Alnus* together with an increase in percentages of pollen of the taxa of bog communities – Cyperaceae, *Sphagnum*, *Myrica*-type, *Calluna* and grasses. This agrees with the chemical evidence at Loch Sionascaig (p. 227) to suggest an expansion of peat communities at this time; our interpretation would be that the wide expanse of thick blanket peat between Loch Craggie and Loch Borralan, on the almost flat watershed moor, developed on top of an ill-drained *Alnus–Salix* carr at about 3000 B.C., but in the absence of any analysis of this peat this interpretation must be tentative.

The zone boundary V ii/VI is defined by a further increase in *Calluna* percentages, which coincides with a steep fall in *Pinus* percentages, just as at Loch Sionascaig. Shortly above the zone boundary the appearance of *Plantago lanceolata* and a grain of cereal pollen indicate human influence, but there is no change in the percentage of *Betula* and *Quercus* pollens. Though *Quercus* may be derived entirely from the regional component, *Betula* must have been locally present; the indication is therefore that man was not clearing birch woodland in the neighbourhood. As at Loch Sionascaig, the evidence cannot prove whether the decline of the pine forest came about primarily by failure of regeneration as the thickness of peat increased, or as the result of deliberate burning or felling of a forest already in precarious balance, but the two diagrams suggest that the pine decline was approximately synchronous at the two sites, and followed a wide expansion of bog communities.

If it is justifiable to correlate the two diagrams, from sites *ca.* 24 km (15 miles) apart, then the pollen of *Plantago lanceolata* and a cultivated cereal at Loch Craggie, together with a curve for *Empetrum* pollen suggesting an expansion of heath vegetation, fall well within the period 2700 to 1300 B.C. suggested by Daniel for the chambered cairns people.

The further expansion of peat bog indicated by pollen spectra from the zone boundary NS V i/VI onwards must have led to the change in the type of sediment at Loch Craggie (from 170 cm upwards) as the mantle of peat extended over most of its drainage basin.

(ii) *Peat profiles from Region* 1

The lake profiles from Lochs Sionascaig and Craggie show how the development of blanket peat on the catchments in Region 1 has affected the composition and microfossil content of lake sediments. Four peat profiles from Region 1 were investigated in an attempt to correlate changes in the pollen spectra of lake profiles with the history of former forests now represented by layers of buried wood in peat.

No direct comparison of percentage pollen spectra can be made between peat and lake sites, because the size of the local component at the peat sites is not known. However, we consider that both types of site must record synchronous changes in the 'extra-local' and 'regional' pollen components defined by Janssen (1966), and therefore that zone boundaries, based on changes in the proportions of alder (extra-local at both kinds of site) and regional pollen types such as the elm in northern Scotland, can be defined and correlated between lake and peat sites in the same area.

Figures 4 and 23 provide comparable diagrams from respectively a lake and a peat site less than 300 m apart – see figure 2*a*. Radiocarbon dates of 2070 ± 100 B.C. at the lake site and 1520 ± 100 B.C. at the peat site permit approximate correlation by time; in the history of deforestation shown by both pollen diagrams there are some clear differences. Below the deforestation horizon (zone NWS V ii in figure 4 and below 90 cm in figure 23) there is a higher percentage of pine than birch pollen in lake sediment but more birch than pine in peat; above the deforestation horizon (after 1500 B.C.) percentages of birch pollen remain unchanged in lake sediment but decline to low values in peat.

(*a*) *Loch Sionascaig* (NC 129128), by J. JOHANSEN (figure 23)

This peat exposure is on the shore of Loch Sionascaig; at the base of the peat is gravel which may once have formed the lake shore. Above this is a layer of peat, 1 to 2 cm thick, containing the moss *Hyocomium flagellare* B. & S. This oceanic moss must have been growing on the gravel and thus started the humus accumulation. Then comes 120 cm of blanket peat, with no stratification except for a layer of *Betula* twigs at 76 cm below the present surface. The peat consists mainly of undeterminable detritus with roots and bark of trees; higher up the profile come *Calluna* wood, some *Carex* nutlets, and a few seeds of *Potentilla erecta*. Charcoal is present (see figure 23) but the pieces were too small to be determinable.

The pollen sum included total land plant pollen and pteridophyte spores; *Sphagnum* spores were excluded. A curve for the amount of charcoal has been drawn – in each slide the charcoal particles from an area containing 100 pollen grains were measured, the size figures for each slide were added up, and the relative amount of charcoal in each sample was then expressed graphically.

A sample of the birch wood at 76 cm was dated at the carbon-14 dating laboratory in Copenhagen and gave the date 1520 ± 100 B.C. (K 1302).

The pollen diagram. In the diagram (figure 23) we see the remains of the pine forest, as well as birch and alder, disappear completely as *Calluna* comes to occupy the area. In this development man and his grazing animals must have been very active, even though leaching and soil changes probably initiated the decline of the forest. On the evidence of the amount of charcoal present in the peat since about 1520 B.C., regular burning of the vegetation on the peat must have taken place since that date, but small quantities of charcoal are present below the 1520 B.C. horizon, and from these there is no proof of human settlement in the area. Natural fires do occur, and when, as before 1520 B.C., there are no certain traces of human influence in the pollen spectra, it would be reasonable to attribute the charcoal to natural causes. At 90 cm the presence of charcoal coincides with a fall in pine pollen and the first marked rise in *Calluna* percentages; this could be interpreted as the first evidence for anthropogenic clearance of pine in order to encourage the growth of *Calluna*.

However, it is not until about 74 cm, corresponding with the date of 1520 ± 100 B.C., that we have a clear landnam. From this level upwards there is a continuous curve for charcoal, and vegetation changes which can only be explained as the results of human activity. The pine must henceforward have been suppressed by fire. *Betula* pollen shows one further rise, but after that birches must have been prevented from regeneration at this site by grazing and burning. *Alnus* pollen also disappears. Gramineae, *Potentilla erecta* and *Pteridium* have maxima in the early stages of the landnam, presumably in response to increased light intensity following clearance.

The *Myrica* curve is not easily understood. Its sudden dominance must be supposed to indicate wetter conditions, locally or regionally. The subsequent fall might be the result of a return to drier conditions, but it may perhaps be the outcome of human interference, as *Calluna* and grasses are more desirable plants for grazing than *Myrica*. It appears from the curves that the *Corylus*-type grains which could not be referred with certainty to either genus were in fact *Myrica*.

The human occupation reflected in this diagram must have been a pastoral one, with land use aimed at producing grassland and heather moor for domestic animals. *Calluna* is an important fodder plant, its evergreen shoots providing all the year round feed for sheep and other animals. It is favoured by burning at intervals but does not tolerate too vigorous burning (McVean 1964). Some of the minima on the curve for *Calluna* pollen may be the results of harmful burning; compare the curve for charcoal fragments. *Polygala*, which appears soon after the landnam, is an indicator of grazing; it is a small plant, dependent on the absence of tall competing species, and as *Polygala* is not eaten, it thrives well on grazed ground.

It therefore seems clear that the formation of peat and decline of the forest began before man came to this area, but it seems equally clear that human settlement was disastrous to the remaining forest. From the time of human settlement, burning and grazing effectively prevented any further forest regeneration, though before the settlement a certain amount of regeneration had taken place.

(*b*) *Badentarbat* (NC 013101)

This profile was found at the site from which two radiocarbon dates, 2470 ± 102 B.C. (NPL 13) and 2270 ± 105 B.C. (NPL 14), had been obtained from pine wood found 0.9 m (3 ft) below the peat surface by the late Dr T. G. Longstaffe (Lamb 1964). We were directed by Mrs T. G. Longstaffe to the identical site, on bare low moorland *ca.* 500 m inland from Achiltibuie, south-east of Loch Osgaig at the root of the Rhu Coigach peninsula – a site extremely exposed to winds from off the sea. Lamb describes how trunks and stumps of pine are exposed over a wide area in the eroding peat, which must formerly have been at least 1.2 m (4 ft) thick and is developed on top of a thin mineral soil overlying boulders. Our profile represents the side of a pit which we dug to a depth of 50 cm beside a vertical pine stump *in situ*; above this stump was an eroding and isolated mass of peat about 80 cm high. No pollen samples were taken from the oxidized peat above the base of this isolated mass of peat, since pollen destruction was suspected.

The pollen diagram, figure 24*a*, shows that peat began to form here in pollen zone NWS V i (that is, between *ca.* 4300 and 3000 B.C. at Loch Sionascaig) and the high values for grass pollen suggest that the peat developed above a *Phragmites* fen or *Molinia* marsh. 10 cm above the base of the peat it becomes brown and fibrous, typical *Calluna–Sphagnum–Eriophorum* peat, and percentages of pollen of the bog taxa *Calluna*, *Erica*, Cyperaceae and *Narthecium* increase. The zone boundary NWS V i/V ii, the elm decline (*ca.* 3000 B.C.) falls in peat containing these high percentages of bog pollens, and immediately above this horizon comes a great increase in *Sphagnum* spores. Then the bog taxa decrease, and high percentages of pine (about 40 %) are found in the peat which surrounds the pine stump. At the top of the stump, which projects from the present main surface of the peat, the wood gives the appearance of a natural fracture; Lamb (1964) quotes Godwin (in litt.) for an account of the way in which trees growing on waterlogged peat rot and fracture at ground level. In peat at the base of the now isolated portion percentages of Cyperaceae rise to high values (75 % of the total) suggesting inundation of the forest floor.

This diagram suggests that wet peat with bog vegetation developed on this site from some time before 3000 B.C. until some time later, when pines colonized a drying bog surface (dates from pine wood, *ca.* 2470 and 2270 B.C.). Indications of renewed flooding of the bog surface are found at the level at which stumps *in situ* appear to have broken. High percentages for *Calluna* and *Empetrum* in the pine layer (figure 24*a*) support the interpretation of the pine forest as the vegetation of dry peat. No evidence of anthropogenic effects except for two isolated grains of *Plantago lanceolata* was found.

(*c*) *Druim Bad a'Ghaill* (NC 072117)

On this flattish topped ridge, 137 m (450 ft) high, between the catchments of Loch Osgaig and that of the River Polly (the outflow from Loch Sionascaig), an extensive mantle of blanket peat has developed and has been much cut for fuel. A cut face beside the road showed a layer of pine branches and pieces of wood at its base; by digging below this we were able to sample 20 cm below the present water table, but could not get down to mineral soil, lacking any means to drain the hole.

The tree pollen spectra (figure 24*b*) show that the lowest samples reached fall in zone NWS V ii, since there is no more than 1 % *Ulmus* in the arboreal pollen. Changes just at the wood layer – falling pine and rising curves for *Calluna*, grasses and sedges, but no rise in *Corylus–Myrica* or *Myrica*-type – define the same pollen zone boundary V ii/VI i as at Loch Sionascaig. 20 cm above this, further increases in *Calluna* and Cyperaceae, with steep rises in *Myrica*-type and grass curves, together with *Sphagnum* spores, defines a zone boundary VI i/ii very similar to that at Loch Sionascaig. The two sites also agree in that a continuous curve for *Plantago lanceolata* begins at the zone boundary V ii/VI i.

This profile indicates that pine trees were growing on peat on an exposed summit ridge 137 m (450 ft) above the sea just before the time-horizon in the peat which by firm pollen correlation with the Loch Sionascaig profile is dated to 2070 ± 100 B.C. At both sites the steep fall in percentages of pine pollen (V ii/VI i) precedes the major expansion of pollen of blanket bog taxa (VI i/VI ii), and within zone VI i there is sufficient *Plantago lanceolata* to suggest the local presence of man, but no expansion of this curve to suggest settlement.

(*d*) *Strath Oykell* (NC 329129)

The mosaic of soil parent material in upper Strath Oykell, resulting from structural complexity (Craig 1964) results in strong vegetation contrasts (McVean & Ratcliffe 1962, p. 67). This valley seemed a promising site in which to explore the history of a catchment showing such contrasts in soil and vegetation today. When it proved impossible to obtain a complete core from Loch Ailsh, we explored Strath Oykell above this loch for peat profiles likely to record vegetation history.

Pine stumps are common in eroding peat sections along the main valley and up the tributary Alt Sail an Ruathair; local observers told us that this forest layer in the peat extends some distance over the hills south-east towards An Stuc (360 m; 1195 ft). The present surface of the peat has clearly been much modified by cutting for fuel when there were worked crofts in the upper strath. Our section came from a site *ca.* 500 m south-east of the junction between the Oykell and Alt Sail an Ruathair, where the ground rises gently from the flood plain. At the site there is now 115 cm of peat between the present surface and the top of the mineral soil (a very thin drift on boulders). The present water table is only a few centimetres above the top of the mineral soil. A large pine stump, vertical and *in situ*, extended from 30 to 77 cm below the present surface, and *ca.* 20 cm below that was a layer of birch twigs in the peat (figure 24 *c*). Part of the profile passed through a pit between the main roots of the pine stump, and here the material was darker in colour, dry and crumbly, and much more highly humified than the rest of the peat.

The pollen diagram shows that the base of this profile dates from pollen zone IV (i.e. before 4300 B.C. at Loch Sionascaig). In the topmost layers containing mineral soil, pollen of *Corylus* type is abundant, also fern spores. These are common in mineral soils in the Lake District (Pennington 1964), but the presence of quantities of almost certain *Corylus* pollen in the local soils in Strath Oykell is of interest, in view of the very low *Corylus* percentages in the lake sediments of north-west Scotland. Other pollen in the basal layers of the peat includes high percentages of birch, willow, grass and sedge, with particularly high values for *Filipendula*. There must have been a valley carr fen at this place at the time when peat began to accumulate; abundant *Sphagnum* spores indicate local waterlogging, and *Drosera* pollen suggests that acid habitats were already present. The high *Corylus* values and a grain of *Helianthemum* pollen indicate the presence of better drained and less acid habitats, at the same time. The base of the alder curve, in peat with a layer of birch wood, defines the zone boundary IV/V i (4300 B.C. at Loch Sionascaig) at the 105 cm level.

Pollen zone V i at this site includes two local subzones, because the upper part of zone V i – the dry humified organic material, which is mor rather than peat – between the pine roots, has very distinctive pollen spectra. Subzone V i a (Strath Oykell) has pollen spectra with relatively low percentages of non-arboreal pollen, composed largely of birch, *Corylus* type, alder and pine; the presence of birch twigs in the peat and a rising *Calluna* curve suggests local birchwood, streamside alders, and a local substratum rising progressively above ground water level.

In subzone V i b (Strath Oykell) there are high percentages of *Salix* which must indicate local presence. The roots of the pine stump are surrounded by material containing pollen spectra with a characteristic assemblage – a maximum of *Potentilla* type, *Calluna*, *Melampyrum*, with continuous curves for *Succisa*, *Filipendula*, Compositae and Leguminosae, and intermittent records for *Juniperus*, *Empetrum* and *Vaccinium*. Since no identification to a species is possible for *Potentilla* and *Melampyrum*, recognition of a plant community must be tentative, but if these pollen types represent *P. erecta* and *M. silvaticum*, the above list suggests comparison with species lists given by Steven & Carlisle (1959) for the field communities of native pine-woods – e.g. p. 307, Community No. 6, soil 'moist, podsolized, with 2.5 to 5 cm of raw humus or peat'. It seems reasonable to suppose that this humified material containing these pollen spectra, together with sufficient elm pollen to date it to before 3000 B.C., represents the raw humus of a pine-wood at this site. It is not of course possible on this evidence to determine whether the preserved pine tree took part in the formation of this pine-wood soil or whether it belongs to a later generation of trees which drove its roots deep into organic soil formed by previous generations.

The main body of this stump is found in *peat*, containing the pollen spectra of zone V ii, above the elm decline. Pine percentages reach their maximum contribution to arboreal pollen, and this tree may well have been contemporaneous with the forest at Badentarbat dated to

2400 to 2200 B.C. The decline in pine pollen and increase in *Calluna*, grass and sedge which defines the zone boundary V ii/VI i coincides with the top of this stump. 20 cm above this comes the same steep rise in *Myrica*-type and sedge pollen used to define the boundary VI i/VI ii at Sionascaig and Druim Bad a'Ghaill.

At this Strath Oykell site, as at Loch Sionascaig and the Druim Bad a'Ghaill site near that loch, the steep fall in pine percentages at the zone boundary V ii/VI i falls just below the first appearance of a continuous curve for *Plantago lanceolata*.

The four peat profiles

In Mr Johansen's pollen diagram (figure 23) we would draw the zone boundary NWS V ii/VI i at 90 cm and VI i/ii at 70 cm. Therefore the position of all the buried wood in these four profiles falls within the period of chronozones NWS V ii and VI i (*ca.* 3000 to 1520 B.C.). Since the roots of these stumps found *in situ* must penetrate organic soil of greater age than the tree, the evidence is that these trees began to grow later than 3000 B.C. The ^{14}C date for wood at Badentarbat agrees with this stratigraphic evidence – 2470 ± 102 B.C. Chemical evidence from Loch Sionascaig and the peat profiles themselves indicate widespread formation of blanket peat from *ca.* 3000 B.C. onwards. It would be expected that the state and vegetation of this peat surface would fluctuate in response to climatic changes. This evidence that pine trees were numerous on the peat of north-west Scotland between *ca.* 2470 and 2070 B.C. is in favour of a comparatively dry state of the peat surface during this time.

There is no clear evidence to link the steep fall in pine pollen at all sites at the zone boundary V ii/VI i with the activities of man. This zone boundary coincides with the beginning of a continuous curve for *Plantago lanceolata* pollen at two sites (Druim Bad a'Ghaill peat and in the profile from Loch Sionascaig) but no trace of human influence can be found in the pollen diagram from Badentarbat at the steep fall in pine percentage which defines this zone boundary. The second fall in pine percentages in Loch Sionascaig peat and lake profiles is not represented at the other peat sites because of destruction of the upper peats; dated to 1520 ± 100 B.C. by birchwood in Loch Sionascaig peat, it shows strong evidence for forest clearance by man.

Region 1. *Summary*

Conclusions reached from study of Region 1 were therefore as follows:

(i) The Late-Weichselian profiles present in three lakes mean there was no general ice-cover in north-west Scotland in late-glacial time.

(ii) Correlation with the Loch Droma profile shows that by *ca.* 10870 B.C. the dominant vegetation of Region 1 was *Empetrum* heath, and somewhat organic silts containing diatoms of base-rich habitats were accumulating in the lakes. There is no evidence for the presence of trees in late-glacial times.

(iii) General changes in sediment composition which coincide with an *Artemisia* pollen zone indicate solifluction but no renewal of glaciation in Younger *Dryas* time.

(iv) Post-glacial vegetation history includes: (*a*) a period of *Empetrum* and juniper heath without trees: (*b*) A period of birch–hazel forest with lower percentages of hazel than at other sites in Britain. (*c*) A gradual and not necessarily synchronous replacement of birch–hazel by pine–birch forest as the dominant forest type as soil impoverishment proceeded, with a corresponding decline in base-status of lake waters. (*d*) A natural retrogressive succession towards blanket-bog from just before 4000 B.C., accelerated at *ca.* 3000 B.C. with increased inwash of peaty material into lakes at the horizon where elm pollen (interpreted as part of the Regional pollen component) becomes much reduced. (*e*) A regional fall in pine pollen at *ca.* 2000 B.C with preservation of pine wood dating from the previous centuries in rapidly growing blanket peat; this fall in pine predates immediately the first traces of human influence in some but not all pollen diagrams. (*f*) The period of rapid expansion of blanket peat with *Myrica* was followed by further clearance of pine and birch at *ca.* 1500 B.C. by fire; undoubted traces of human influence are found in pollen diagrams at this horizon. (*g*) The final phase in which pollen spectra resemble those produced by today's vegetation (plate 33) – no regeneration of trees after 1500 B.C.

(*b*) Region 2

Wester Ross, east of Beinn Eighe. Site, Loch Clair

In this part of Wester Ross the solid geology presents a complex picture, with outcrops of gneiss, Torridonian Sandstone and Cambrian rocks to the west of the Moine and Kishorn Thrusts, while to the east, intensely deformed rocks of the Moine series crop out in the upper catchment of Loch Clair (Johnson & Stewart 1963; Craig 1964). West of the thrusts are high rugged mountains of Torridonian and Cambrian rocks, mainly sandstones and quartzite, but including Cambrian pipe-rock and fucoid beds; These reach over 909 m (3000 ft) in Beinn Eighe and Liathach. East of the thrusts the Moine schists form lower and less rugged moorland. In strong contrast with Region 1, nearly all the lower ground (valleys and lower moorlands) of this catchment carries a drift cover, with conspicuous morainic ridges in the valley of the Coulin river, both above Loch Coulin and between Loch Clair and Loch Maree. At the north-west end of Loch Clair there is an extensive spread of hummocky moraine (kame and kettle) which is continuous up to the low watershed with Upper Glen Torridon. There is as yet no factual information on the age of these morainic features, but the fact that no late-glacial organic deposit has been found in any of four cores from Loch Maree and 15 from Loch Clair, which all penetrate into barren glacial sediment, agrees with the hypothesis that these moraines may date from the final cold phase of the late-glacial (Younger *Dryas* time, here called post-interstadial).

Loch Clair (1 km × 1.5 km, max. depth 31 m, altitude 92 m (303 ft))

This loch consists of a rather regularly shaped basin *ca.* 1 km in diameter with a shallow north-westward extension. Much of the southern side of the lake is still forested and this lake was chosen to contrast with those of Region 2 where the catchments are now almost completely deforested and peat-covered. Though it lies within 6 miles of the west coast, at the head of Upper Loch Torridon, this loch is almost completely sheltered from winds off the sea by high mountains. It is, of all those studied, the lake considered to be least subject to wind disturbance.

Loch Clair and the whole of its immediate catchment lie on sedimentary rocks (sandstones and quartzites) and in this differ from all the other Scottish lakes and catchments studied. The upper parts of the Clair catchment which lie on Moinian rocks drain first into the shallow (13 m) Loch Coulin, above Loch Clair. Drift soils developed on sandy drift cover the lower parts of Loch Clair catchment. Where drainage is good, there is no superficial organic layer and the soil approximates to a greyish brown earth in the areas which now carry birchwoods: in the areas of native-type pines the soil profile has a superficial organic layer and in places a leached horizon. Over those areas where drainage is impeded and *Sphagnum* is present, a layer of peaty humus or thick peat has formed on top of the gleyed mineral soil. In stream sections the stumps of ancient pines are present within this thick peat, but deep peat has formed only as local patches, presumably because of the generally steep slopes. Pines having the broad crowns of native trees survive on higher parts of the catchment, including drift-covered slopes of the valley above Loch Coulin, on well-drained soils.

The Coulin Forest of pine and birch on the south-west side of Lochs Clair and Coulin has been described by Steven & Carlisle (1959), who give details of its recent history and planting. Failure of pines planted *ca.* A.D. 1900 has been attributed to poor drainage. No natural regeneration of pine is now going on; deer graze in much of the area, but there is no evidence as to whether regeneration is being prevented by grazing. Pine and birch are found in single-species stands and in all mixtures; there is a higher proportion of birch (both in the areas which at some time have been planted and in the more natural woodland on the hills above) than in the pinewood at Coille na Glas Leitire on Beinn Eighe, the nearest place where pine is regenerating (McVean & Ratcliffe 1962). Steven & Carlisle emphasize that bog communities are more extensive than in Coille na Glas Leitire, and point out that 'the natural drainage is poor in these woods'. It appears that a soil development progressively more unfavourable to the regeneration of pine is going on, as accumulation of thicker and thicker layers of mosses and raw humus is accompanied by progressively deteriorating soil drainage – cf. Iversen (1964). Shallow peaty soils (organic horizon less than 30 cm) with the communities of western blanket bog (McVean & Ratcliffe 1962) are found over much of the catchments of the two lochs, including some of that part marked as forest on the map given by Murray & Pullar (1910) from which figure 2*b* is taken. Stumps of pine in these areas are evidence for felling within the present century, but it is clear that lack of soil drainage presents the major obstacle to re-establishment of a Scots pine forest over this area. Surviving pines of native type are all found on steep slopes or on well-drained drift.

Loch Clair was therefore chosen for study as an example of a lake within a wholly pine-birchwood area, where it seemed likely that semi-natural forest survived into the present century, but is now in precarious ecological equilibrium from mainly natural causes.

Fifteen cores were taken and the stratigraphy recorded. Results of analysis of one core from the deepest central area are presented.

Stratigraphy

No stratigraphic evidence for late-glacial deposits recording interstadial and post-interstadial conditions was found. In all cores the basal minerogenic deposit passed upwards into organic mud through a complex of increasingly organic layers of different colour, texture and composition, but there was no suggestion in the stratigraphy of a more organic interstadial sediment overlain by minerogenic post-interstadial deposit. Pollen analysis confirmed the impression given by the stratigraphy, that the basal minerogenic sediment dates from the post-interstadial cold period (C). At no site did the corer penetrate through this basal sandy sediment to older late-glacial deposits, so there is no evidence as to whether or not the latter are present in this basin. It is, however, clear that the deposits of the post-interstadial cold period at Loch Clair differ very greatly from those in Loch Tarff, Loch Sionascaig, Loch Borralan and Loch Craggie.

Late-glacial 600 *to* 518 cm (*basal minerogenic deposit*)

In the core analysed this section consisted almost entirely of laminated sands and silts, except for the basal 5 cm in which no laminations could be seen. The laminations consisted of alternating layers of predominantly sand- and silt-particle size, but the separation (as judged by microscopic examination) was not complete, so the sandy layers contained some particles of smaller size, and the silt layers contained some clay. The deposit was not plastic, but held its shape when extruded from the coring-tube. No organic particles could be found on microscopic examination, either fresh or after the usual preparation for pollen analysis. There was no pollen present. Each pair of laminations (of larger and smaller particle size) was quite distinct at both upper and lower boundaries; in this the deposit differed from true varves which show graded bedding, the coarser layer passing gradually upwards into the fine winter layer (cf. Windermere (Pennington 1947)). The coarser sandy layers in Loch Clair appeared to consist predominantly of quartz particles. No chemical analysis was done. All sediment was grey in colour.

In two other cores, from somewhat shallower water, the core-sampler penetrated through the laminated sediment into an unsorted deposit, predominantly silty, which flowed slowly when extruded from the corer, and in this resembled the basal sediment from Loch Oich and Loch Tarff (p. 267). In one core from near the shore, water-depth 6 m, coarse sand was found below this unsorted deposit; this sand was the lowest deposit reached.

Post-glacial (i) 518 *to* 472 cm

This section of the deposits was a complex of more and less organic layers, lithologically transitional between late- and post-glacial but referred on pollen analysis to the base of the Flandrian.

Post-glacial (ii) 472 *to* 0 cm

This section consisted throughout of organic mud, brown in colour and having the appearance produced by flocculation of clay colloids by humic acid, but in the section 472 to 276 cm this was frequently interrupted by layers of a distinct sediment type, with sand or medium-coarse plant detritus. These layers were not found in cores from somewhat shallower water, and appear to be confined to that part of the lake between the inflow and the deepest central area. Throughout this section (472 to 0 cm) the mud contained more sand than has been found elsewhere in deep-water sediment; this we attribute to the nature of the bedrock.

Five samples for ^{14}C dating were chosen carefully from homogeneous sections of the core. The dates when plotted against depth fell near a straight line (see figure 18). A sixth sample, which included one of the detrital layers, gave a date older than the underlying sample.

Pollen analysis

Post-glacial 516 *to* 0 cm (figure 11)

Between 516 and 518 cm it is difficult to assess the significance of the pollen assemblage, which includes high percentages of *Rumex* and *Lycopodium selago* but also much *Empetrum* and very high values for *Polypodium* spores. It can most easily be explained as a mixture within the lake of material containing pollen of the Transition zone (*Rumex* and *L. selago*) and of NS I (*Empetrum*) – but the very high values for *L. selago* and *Polypodium* suggest the additional influence of selective preservation of heavy-walled spores resistant to oxidation.

516 to 510 cm represents a narrow *Empetrum* zone without juniper. Above this comes a deposit so constituted that it forms an interruption in the regular sequence of pollen zones, and illustrates how the pollen spectra of a lake deposit can depend entirely on the original source material of the sediment. Those layers which contain the pollen spectra of the *Empetrum* zone consist of alternate laminations of sand and dark-coloured humus which includes many fungal hyphae. This laminated material alternates with layers of grey-brown silty mud in which juniper and birch pollen and bryophyte spores, together with naked Polypodiaceae spores, are abundant. This deposit is interpreted as indicative of repeated interruption of the orderly

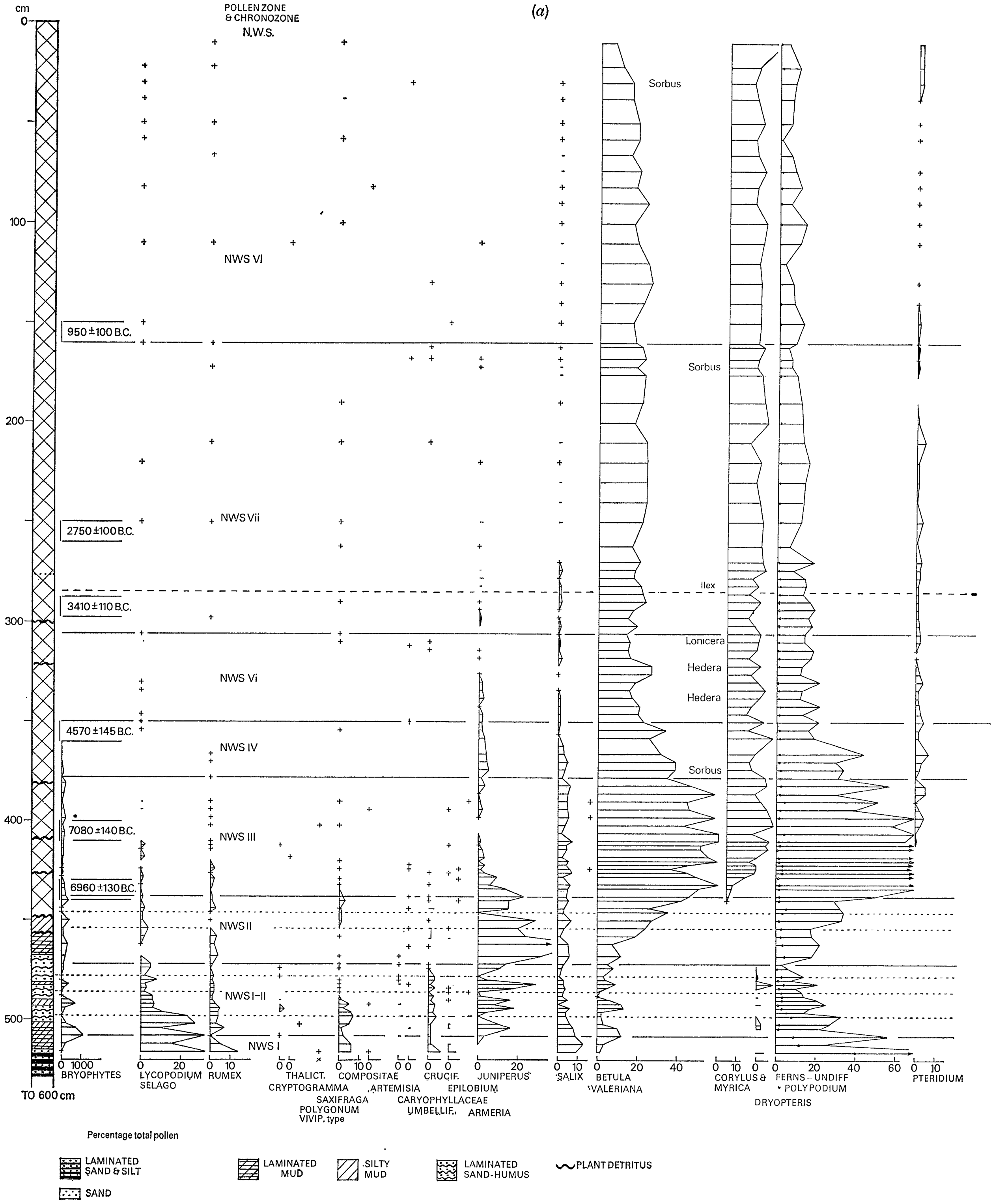


FIGURE 11 (*a*) and (*b*). Loch Clair: full pollen diagram. For arrangement of taxa, see figure 4.

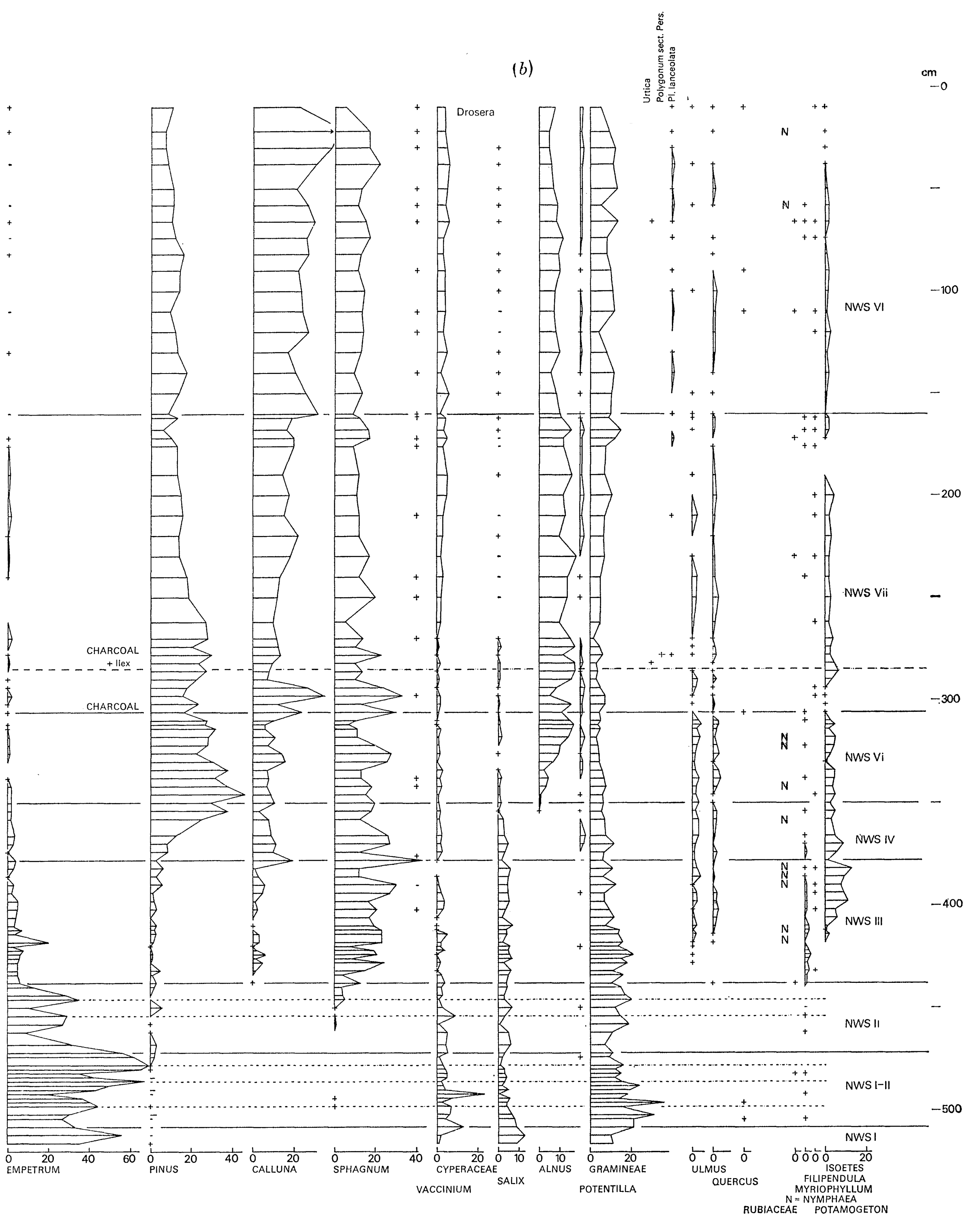


FIGURE 11. For legend see opposite.

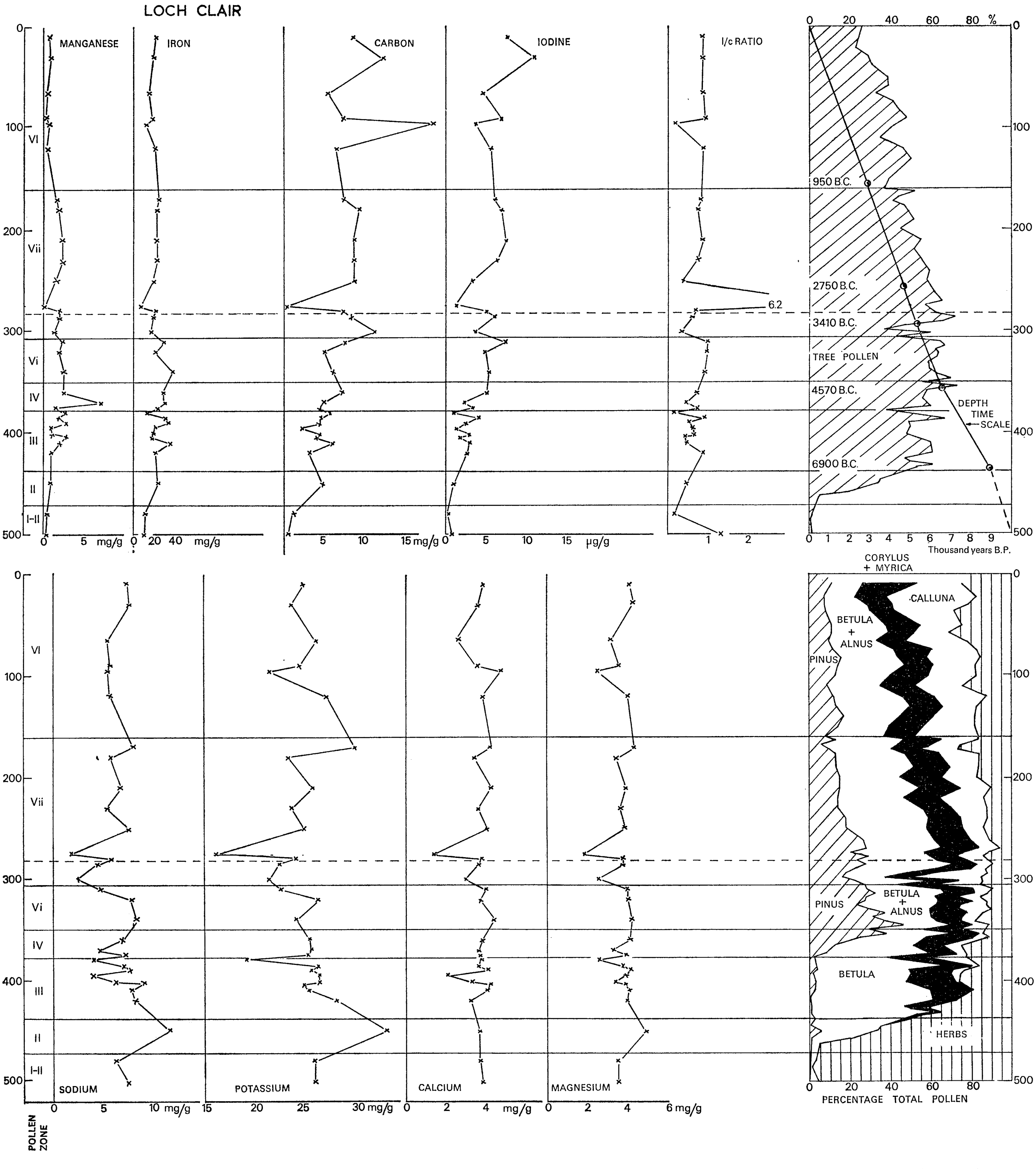


Figure 12. Loch Clair: full chemical diagram, divided horizontally at pollen zone boundaries, with analyses of composition of pollen spectra.

deposition of juniper-rich lake mud by inwash of sandy soils on which *Empetrum* had been growing, these soils incorporating acid dark humus with fungal hyphae. This deposit is therefore placed in a transitional zone I–II.

It is not possible to determine from this evidence whether *Empetrum* communities on acid soils co-existed with juniper–birch–fern communities as part of an edaphically determined mosaic, or whether it must be supposed that by the time the juniper–birch–fern community was well established, the *Empetrum* period was past and the pollen secondary.

A tentative interpretation of this unusual deposit is that within this drainage basin, at this early post-glacial stage, there remained enough snow and ice on the higher parts to produce a succession of melt-water floods as the temperatures rose, and that each flood carried into Loch Clair soil from the hills on which *Empetrum* had been growing, at a time when juniper and birch were colonizing the low ground around the lake.

NS (*NWS*) *II*, the *juniper zone* proper, must represent a time of more stable land surface without these sandy flood layers, but fluctuations in juniper and *Empetrum* pollen percentages indicate two more episodes of inwash of *Empetrum*-rich material. Many taxa of late-glacial affinities – *Lycopodium selago*, Caryophyllaceae, Compositae and Cruciferae – disappear at the base of this zone. Percentages of *Betula* rise steadily from 10 to 40 % through the juniper zone; *Pinus* remains less than 5 % and no *Corylus* was found.

NS (*NWS*) *III*, the *birch–hazel zone*, is not divided at this site, for the main expansion of hazel percentages took place very soon after the opening of the birch zone at 6960 ± 130 B.C. Birch percentages reach their maximum, hazel does not exceed 30 %, *Ulmus* and *Quercus* appear but as less than 5 %; *Salix* persists at 5 to 8 %. In contrast with this zone at Loch Sionascaig, *Pinus* remains at low percentages. *Empetrum* falls to low values at the opening of this zone; *Calluna* and *Sphagnum* first appear. High maxima of fern spores (50 to more than 60) characterize this zone. *Valeriana*, *Epilobium* and Compositae are present.

NS (*NWS*) *IV*, the *pine–birch zone*, though covering approximately the same period of time as at Loch Sionascaig (figure 18) differs from that site in that pine percentages are low (less than 10 %) at the opening of the zone, and increase steadily through it to more than 40 %; *Calluna* and *Sphagnum* reach higher percentages. Birch and fern spores fall as pine rises. *Quercus*, *Ulmus* and *Salix* percentages remain low; herbaceous taxa reach minima for the profile.

NS (*NWS*) *V i*, *the pine–birch–alder with elm zone*, covers the time between the local radiocarbon dates of 4570 and 3410 B.C. (± 145 and 110 respectively.) Pine percentages fall (40 to 20 %) as those of alder rise (0 to 15 %); birch values remain at about 20 %.

Zone-boundary NS V i/V ii, 306 *to* 278 cm.

This section of the profile incorporates a stratigraphic complex which was analysed in detail (figure 13). The continuous curve for elm is broken for the first time, at a point where charcoal and fine plant detritus together with some coarse silt, indicating an interruption in orderly deposition, are incorporated into the lake mud. The sample for dating was selected so as to avoid any layer of different composition from the mud (298 to 288 cm), particularly avoiding charcoal and plant detritus. The date of 3410 ± 110 B.C. confirms the identification of this horizon as contemporaneous with the Elm Decline in regions of mixed oakwoods.

Figure 11 and 13*b* show details of the pollen analysis, calculated as respectively percentages of total pollen and of arboreal pollen. Figure 11 shows that over the section 306 to 294 cm birch, pine and alder all decline as a percentage of the total – i.e. there is a reduction in total pollen

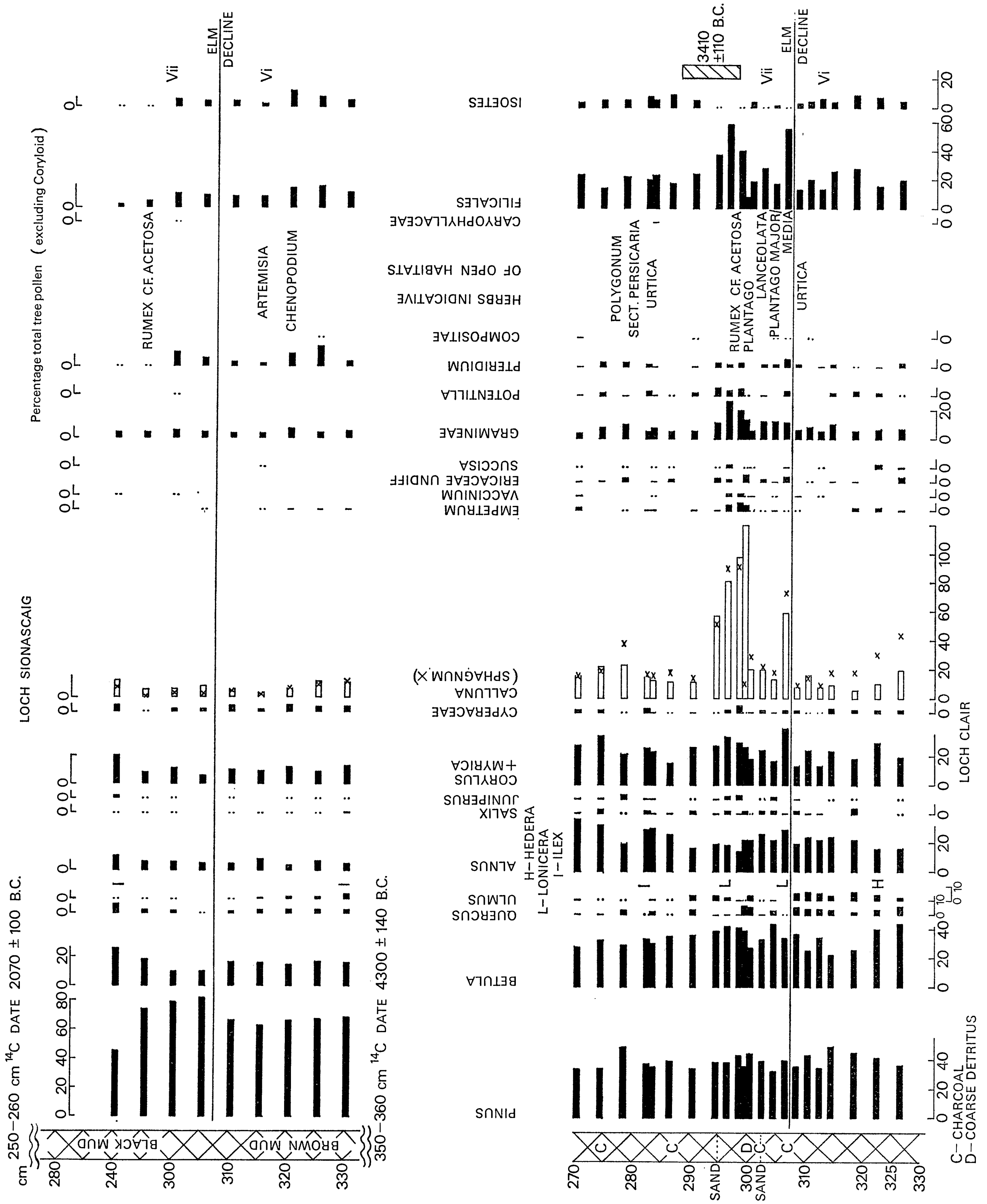


FIGURE 13. The horizon at 3000 B.C. – Lochs Sionascaig and Clair compared.

contributed by trees. *Calluna* and grass pollen increase in both pollen sums just above the first break in the elm curve. The close correlation between *Calluna* and *Sphagnum* spores (figure 13*b*) both mirroring the pine curve (figure 11), suggests an interplay between pollen of pine trees on the one hand and *Calluna–Sphagnum* (possibly the community of the forest floor) on the other. These three curves show no relation with those of birch or alder. Charcoal is present from 306 cm upwards. These facts could be explained by a forest fire, reducing pollen production by all trees but especially pine, and increasing therefore the percentage contribution from non-arboreal taxa – *Calluna*, grass and *Empetrum* pollen, *Pteridium*, other ferns; and *Sphagnum* spores. At the same horizon new herbs appear in the counts: *Vaccinium*, *Succisa*, Compositae (*Taraxacum* type) Rubiaceae (*Galium* type), Cruciferae and Umbelliferae. These could be explained as the result of a reduction in production of tree pollen which allowed the appearance in the counts of the pollen of woodland and woodland margin plants. In the section 298 to 278 cm appear for the first time the pollens of several plants usually associated with human influence: *Plantago lanceolata*, *Rumex*. cf. *acetosella*, *Urtica* cf. *dioica* and *Polygonum* sect. *Persicaria*. These suggest strongly that human influence was at work in the forests round Loch Clair at this time, but of course the pollen figures cannot show whether the fire which gave rise to the charcoal was caused by man or by lightning.

From 275 cm upwards the pollen percentages return to those of zone V i, except for *Ulmus*, henceforward scarce and intermittent. The episode of human interference with the forest was therefore of short duration.

NS (*NWS*) *V ii, the pine–birch–alder zone without elm*, covers the time from just after 3410 B.C. until *ca.* 950 B.C. (The upper boundary of this zone is not expected to be synchronous at different sites.) Throughout this zone there is no marked change in pollen spectra, but a gradual fall in pine percentages from 30 to 15 %, and a corresponding rise in birch from 20 to 30 %. This seems to indicate no more than a change in proportion of these two trees, and a gradual increase in *Calluna*. This contrasts strongly with the profound changes taking place at Loch Sionascaig during this period.

NS (*NWS*) *VI, the* Calluna*–pine–birch–alder zone*, has higher percentages of *Calluna* than previous zones, but no marked increase in the assemblage of taxa characteristic of blanket bog. Table 5 compares the pollen spectra of the surface muds with those of Loch Sionascaig.

Chemical analysis

Late-glacial

The barren laminated sediment was not analysed.

Post-glacial (figure 12)

Analysis was begun at 500 cm where the carbon curve begins to rise: this was in material transitional between pollen zones NS I and II (I to II). Both individual curves and the Principal Components Analysis indicate a situation completely different from the other Scottish and Lake District sites. We attribute this to the composition of the source material of these sediments, since both Torridonian sandstone, and Cambrian quartzite are sedimentary rocks poor in bases, and break down to coarse siliceous sands with little or no clay fraction. The strikingly high values for potassium can be explained by the richness of the Cambrian pipe-rock in this element (Craig 1964).

The irregular course of the chemical curves shows a general heterogeneity of composition and no marked trends of any kind. The carbon curve rises in the usual way through pollen zone II, but does not reach 10 %. Some minima on this curve correspond with visible layers of sand or silt. The carbon curve maintains its values to the surface, which agrees with the pollen spectra (which show no evidence of complete forest clearance) to show that there was no acceleration of erosional transport of soil material. The curves for sodium, potassium and magnesium agree with this.

Region 2. Summary

Conclusions reached from study of Region 2 were therefore as follows:

(i) Deposits of the final Late-Weichselian cold phase (post-interstadial = Younger *Dryas*) in Lochs Clair and Maree comprise much thicker and coarser minerogenic sediment than in Region 1. Deposition from active ice is indicated by varving of the deposits, which were too thick to permit penetration to the base by our samplers.

(ii) Post-glacial vegetation history at Loch Clair shows the same sequence of changes as in Region 1 until just before 3000 B.C. Here an unsorted inwash layer of sand, small stones and coarse plant detritus interrupts orderly deposition of sediment, at the horizon where elm pollen virtually disappears. The presence of charcoal and cultural pollens immediately below and above this layer suggests a local and temporary episode of anthropogenic disturbance of a pine forest. Above this layer no further evidence of forest clearance or accelerated inwash of peat is found at Loch Clair. Pollen percentages indicate that pine–birch forest persisted on this catchment, though with gradually diminishing success, into the present era. We conclude that steeper slopes, and reasonably well-drained soils on sandy drift, prevented the general development of peat bog which replaced the pine–birch forest of Region 1.

(*c*) REGION 3 *The Great Glen. Site, Loch Tarff*

All the lakes of the Great Glen area and their catchments lie on metamorphic rocks – schists and granulites of the Moine series, now regarded as contemporaneous with the Pre-Cambrian Torridonian sediments. Over much of the area these have not yet been mapped in any detail; no analyses of their composition could be found. There is much drift present on these catchments but no drift maps are available. The presence of thick deposits of varved clay in Loch Ness, and of clayey sediment in Loch Tarff and Loch Oich, indicates that part at least of the country rock breaks down to clays. The semi-fluid and unsorted deposit of clay, silt and sand which forms the basal sediment of Loch Tarff and is present below the organic mud of Loch Oich differs in lithology from any other lake sediment as yet found in the Lake District or Northern Scotland.

Loch Tarff (1 km × 1 km, max. depth 29 m, altitude 289 m (965 ft))

This small lake on the moorland above Loch Ness is roughly triangular, with an irregular bottom and several islands. It is surrounded by well-drained hill slopes with much rock outcrop; the soils are shallow and peaty with a thin surface organic horizon above a more or less leached or gleyed mineral horizon. There are patches of basin peat in hollows but no general development of thick peat, partly because of free drainage and partly because the rainfall in this part of central northern Scotland is rather low (94 cm (37 in) at Fort Augustus and 116.8 cm (46.8 in) at 385 m (1262 ft) in Glen Tarff).

The catchment area is largely deforested and acid moorland, with Callunetum and hill grassland, but clumps of birch and scattered trees of pine remain, and the loch islands are thickly wooded with birch and willow. The present vegetation appears to be mainly anthropogenically determined by the usual moorland practices of grazing and limited burning, and no attempt has been made to relate the vegetation of this moorland to communities described by McVean & Ratcliffe (1962). This catchment resembles many in the Lake District – e.g. that of Devoke Water at 233 m (766 ft) (Pennington 1964; Tutin 1969) – in giving clear indication of the derivation of heather moor and hill grassland from upland woodland.

Deciduous woodland, including oak, is still present in the Great Glen within a mile of Loch Tarff; McVean & Ratcliffe (1962) regard this as the 'natural' forest type of all the Great Glen. This site at Loch Tarff is therefore almost on the boundary between McVean & Ratcliffe's two forest types – pine–birch and oak–birch.

A single core taken in 11 m of water included the full post-glacial and late-glacial succession in the uppermost 2.5 m; below this was 1.5 m of practically barren sediment, semi-fluid and unstratified, including sand, silt and clay and showing thixotropy.

Stratigraphy

(i) *Full-glacial* 600 *to* 258 cm

The basal 3.5 m of this core was of minerogenic sediment from which no micro-fossils except sparse pollen grains could be recovered. Pollen grains found in seven samples of this material were added together to give a pollen spectrum representative of this unstratified material; see base of figure 14. Much of this pollen was poorly preserved; probably most of these sparse pollen grains are secondary.

(ii) *Late-glacial* 258 *to* 230 cm

The sample 257 to 258 cm contained pollen in such quantity that 100 grains could be counted from a prepared sample of normal size, and this was taken as the base of the late-glacial section. The upper limit of late-glacial sediment was clearly defined by a lithostratigraphic change from clay to organic mud which was found to correspond with the top of the *Artemisia* pollen zone. At the base of the late-glacial section there was a very gradual change from grey full-glacial minerogenic deposit to a more brownish clayey silt (see figures, 14 and 16). The clay forming the uppermost late-glacial layer was very clearly defined from 235 to 230 cm. No late-glacial deposit had the appearance of biogenic lake mud, and there was no visible lithological boundary between pre-interstadial and interstadial sediment.

(iii) *Post-glacial* 230 *to* 0 cm

At 230 cm there was a sharp stratigraphic boundary between the topmost late-glacial clay and organic mud of rapidly increasing organic content which showed the texture change associated with flocculation of clay colloids by humic compounds (Holmes 1968) characteristic of the base of post-glacial muds in the Lake District. The lower part, 230 to 177 cm, was more grey and obviously less organic than the darker sediment above 177 cm; 25 cm below the mud surface there was a change to blacker, wetter surface mud.

Pollen analysis

Late-glacial 258 *to* 230 cm (figure 14)

Pollen zone A, the *Rumex* zone, corresponding with pre-interstadial sediment, has 20 to 30% *Rumex* type *acetosa* pollen throughout, and is subdivided into:

Pollen subzone A 1, a *Rumex–Lycopodium selago*–fern subzone, with maximum late-glacial percentages of *L. selago* and fern spores.

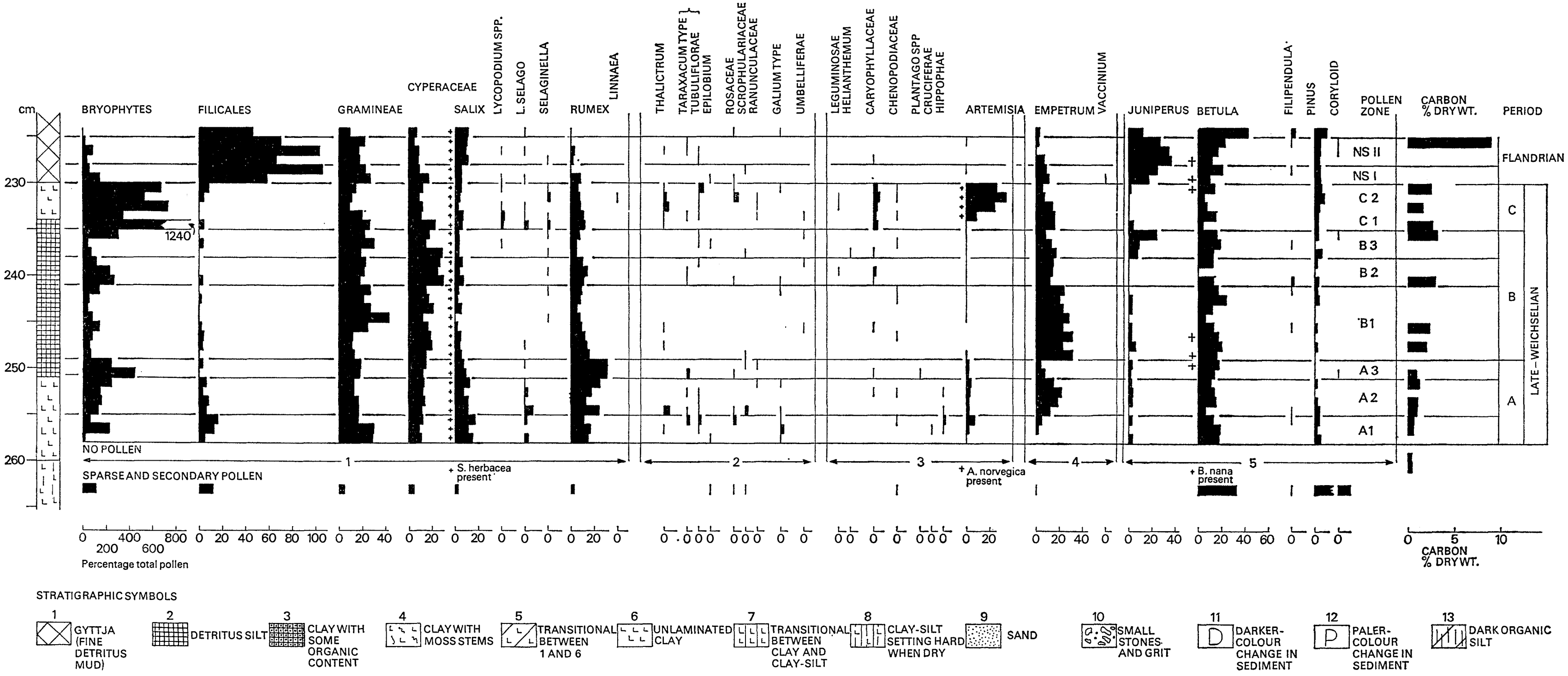


FIGURE 14. Loch Tarff: late-glacial pollen diagram; for arrangement of taxa see figure 3.

Pollen subzone A 2, a *Rumex–Lycopodium selago–Empetrum* subzone, with more than 10 % *Empetrum*.

Pollen subzone A 3, a *Rumex*–bryophyte subzone; bryophyte spores more than 200 % total pollen, *Empetrum* less than 10 %.

Pollen zone B, the woody plants zone, corresponding with interstadial sediment, is here an *Empetrum*–juniper zone, subdivided into:

Pollen subzone B 1, *Empetrum* subzone, *Empetrum* maximum, 20 to 30 %.

Pollen subzone B 2, *Empetrum*–sedge–*Rumex*–bryophyte subzone; *Empetrum* percentages lower and sedge higher than in subzone B 1, juniper 1 % or less.

Pollen subzone B 3, *Empetrum*–juniper subzone: *Empetrum* 10 to 15 %, juniper 10 to 24 %.

Pollen zone C, the *Artemisia* zone, corresponding with post-interstadial sediment, has more than 20 % *Artemisia* pollen, continuous representation of other Compositae, Caryophyllaceae and *Thalictrum*, *Lycopodium selago*, and bryophyte spores are numerous (more than 500 % total pollen).

The *Empetrum* pollen present in deposits of this zone is interpreted as at least in part the result of solifluction of interstadial soils containing this pollen: cf. Blea Tarn in the Lake District (Tutin 1969).

Post-glacial 230 *to* 0 *cm*

Since this profile was too short for radiocarbon dating (p. 207) it has been divided into a sequence of pollen zones which can be correlated both with our series of regional pollen zones from northern Scotland and with the Godwin zones, remembering there is no evidence for synchroneity with either (table 3).

Flandrian pollen zones

NS I, Empetrum *zone* (see figure 14). This zone is very narrow, and from the abruptness of the stratigraphic change and change in pollen spectra at 230 cm, it is possible that an unconformity is present. The percentages of *Empetrum* are lower than in this zone at other sites; grass sedge and fern spores are abundant.

NS II, *Juniper zone* is defined by juniper percentages of more than 20 %. Through this zone rising percentages of tree birch pollen balance falling percentages of herbs – *Rumex*, grasses and sedges. Pollen spectra in this zone resemble those of the transitional Godwin zone III–IV which is often used at the base of Flandrian profiles in England to define the juniper zone (e.g. Pennington 1970, Fig. 3).

NS III, Betula *zone* is at this site subdivided:

Subzone NS III i is a birch–willow–fern zone, with *ca.* 50 % birch, 5 to 10 % hazel, 10 to 15 % *Salix* and more than 50 % fern spores. Two grains of *Quercus* were found; pine percentages *ca.* 5 % as throughout earlier zones.

Subzone NS III ii is a birch–hazel zone, with *ca.* 40 % birch, 30 to 40 % hazel, 2 to 5 % oak and elm, and pine rising continuously through the zone from below 5 to over 20 %.

The sequence of changes in pollen percentages found in pollen zone NS III at Loch Tarff resembles in general those of Godwin zones IV, V, VI a and VI b in northern England, but the actual percentages are very different; there is much less hazel, oak and elm. The division of zone NS III into a lower birch and a higher birch–hazel subzone agrees with two sites from

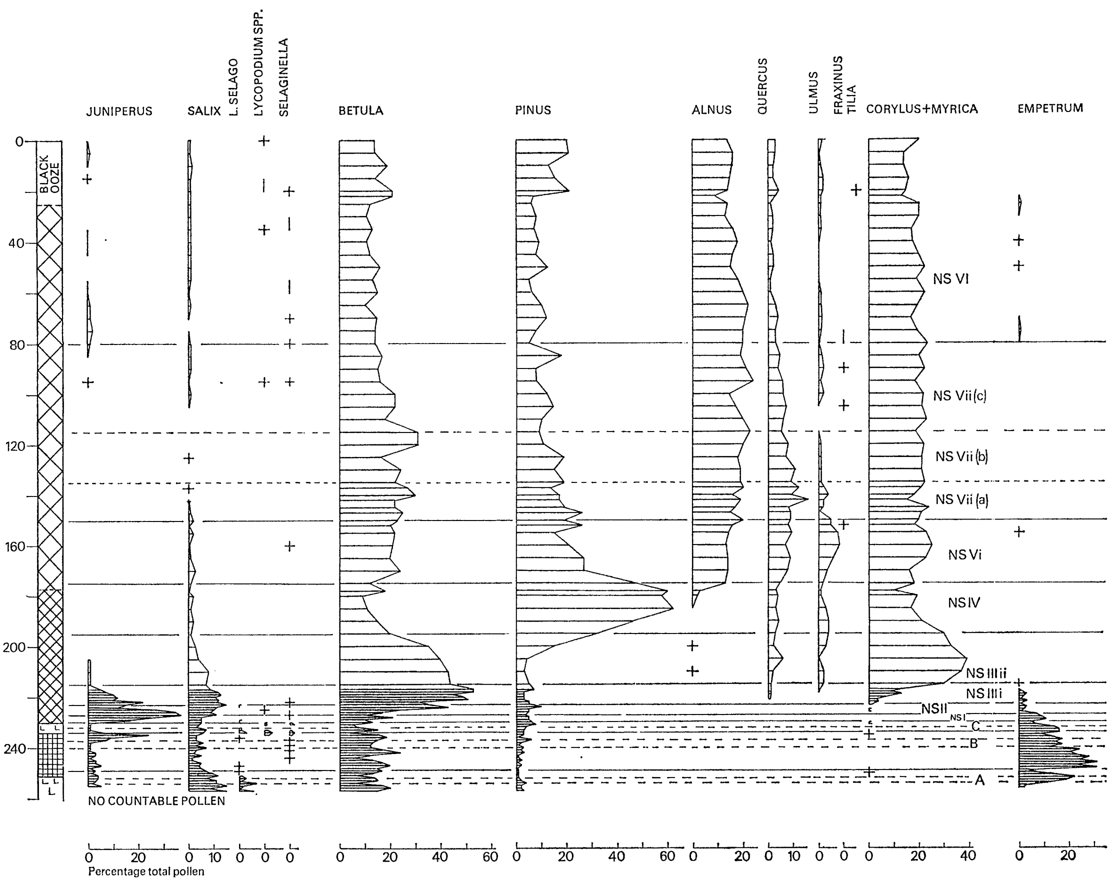


FIGURE 15. For legend see facing page.

northern Scotland (Lochs Borralan and Craggie, figures 20 and 22); this subdivision is not found in north-west Scotland (Lochs Sionascaig and Clair, figures 4 and 11).

NS IV, pine–birch zone has at this site up to 60 % pine pollen, 10 to 20 % birch, and continuous (but less than 5 %) representation of oak and elm. The course of the pollen curves resembles that found in Godwin zone VIc at upland sites in the Lake District (Devoke Water and Burnmoor Tarn – Pennington 1964, 1970) and there dated to just before 5500 B.C., though the percentage of pine is much higher at Loch Tarff and there is more oak in the Lake District. But clearly there was much local variation in the composition of pollen spectra in northern Britain at this date, for at Scaleby Moss, in the same county as the Lake District sites, deposits of similar date contained very little pine pollen (Godwin *et al.* 1957).

NS V, the pine–birch–alder zone is subdivided:

NS V i, pine–birch–alder subzone with elm opens at Loch Tarff with the same fall in percentages of pine and rise in percentages of alder as is found at the Godwin zone-boundary VIc/VIIa, the Boreal/Atlantic transition, at sites in north-west England where pine was present. Within this zone at this site *Ulmus* reaches 8 % of total pollen, the highest value we found in northern Scotland.

NS V ii, the pine–birch–alder subzone without elm, opens with changes in the pollen curves which resemble the Elm Decline at more southern sites except that the fall is from 8 % only, and at least 20 % of pine is still present. Subdivision of this subzone is made on changes in pollen curves generally interpreted as indicative of anthropogenic deforestation episodes.

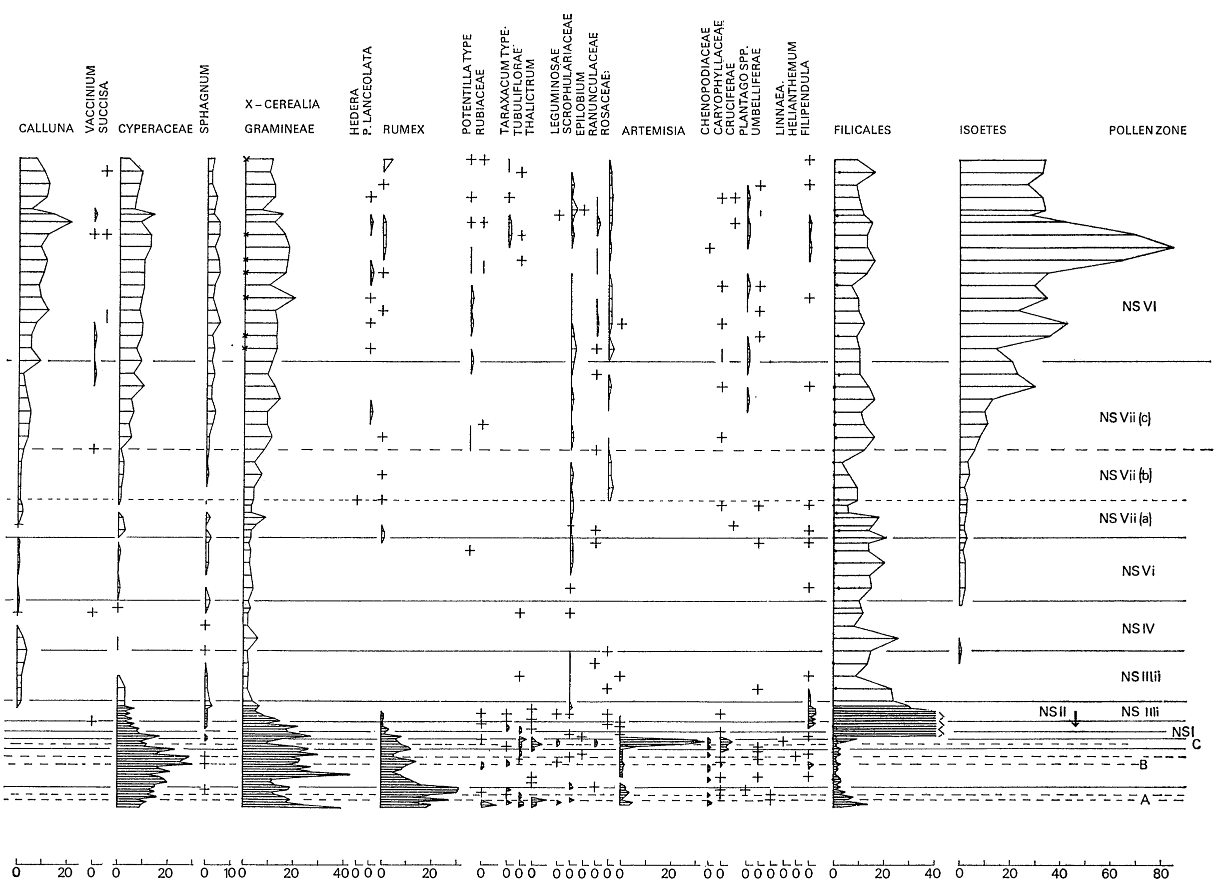


Figure 15. Loch Tarff: full pollen diagram.

In *subzone V ii a*, elm falls for a second time, from 5 to 1 %, there is a maximum of grass pollen together with increases in sedge and *Calluna*.

In *subzone V ii b*, elm pollen remains at 1 % and there is an increase in the proportion of non-arboreal pollen.

In *subzone V ii c*, the elm curve becomes discontinuous and there is a rise in percentages of *Calluna*, grasses and sedges; *Plantago lanceolata* pollen appears for the first time.

In subzone V ii it is therefore possible to trace similar changes in pollen spectra to those which follow the Elm Decline in the Lake District, and have there been attributed to prehistoric land use.

NS VI, the Calluna *zone*, is at this site a *Calluna*-pine–birch–alder zone and is interpreted as indicative of the spread of heather moor but no complete deforestation. The association with *Calluna* in this zone of *Empetrum*, juniper, *Selaginella* and *Lycopodium* spp. suggests a dry heath vegetation; there is no expansion of the herbs associated with hill grassland that are found in the Lake District – *Potentilla*, *Rumex*, Rubiaceae (*Galium* type), Compositae, etc. – following anthropogenic clearance of hill woodland.

Chemical analysis

Full-glacial

Figure 16 shows that the unstratified sediment below 258 cm has a fairly uniform composition except for a variable iron content.

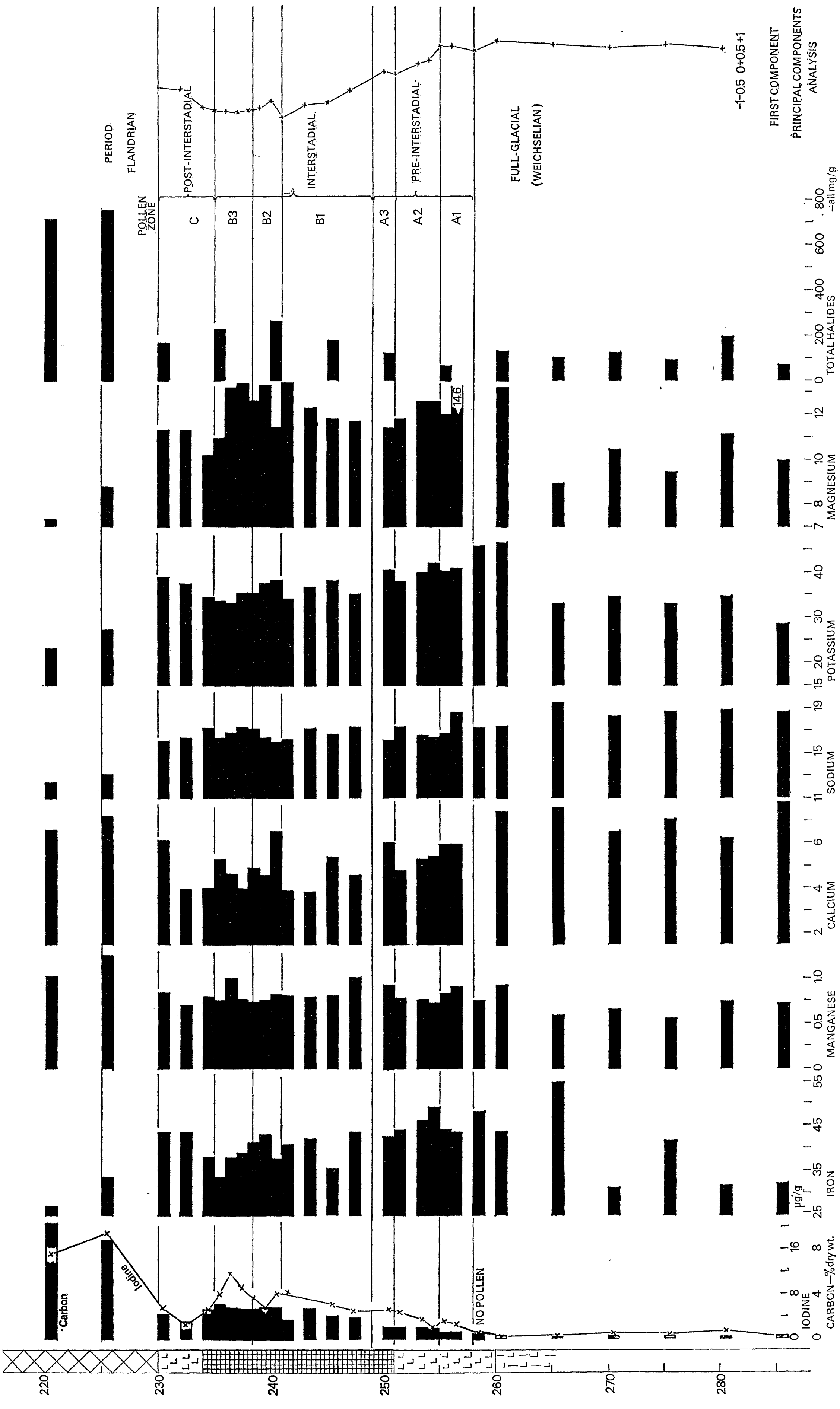


FIGURE 16. Loch Tarff: late-glacial chemical diagram, divided horizontally at pollen zone boundaries.

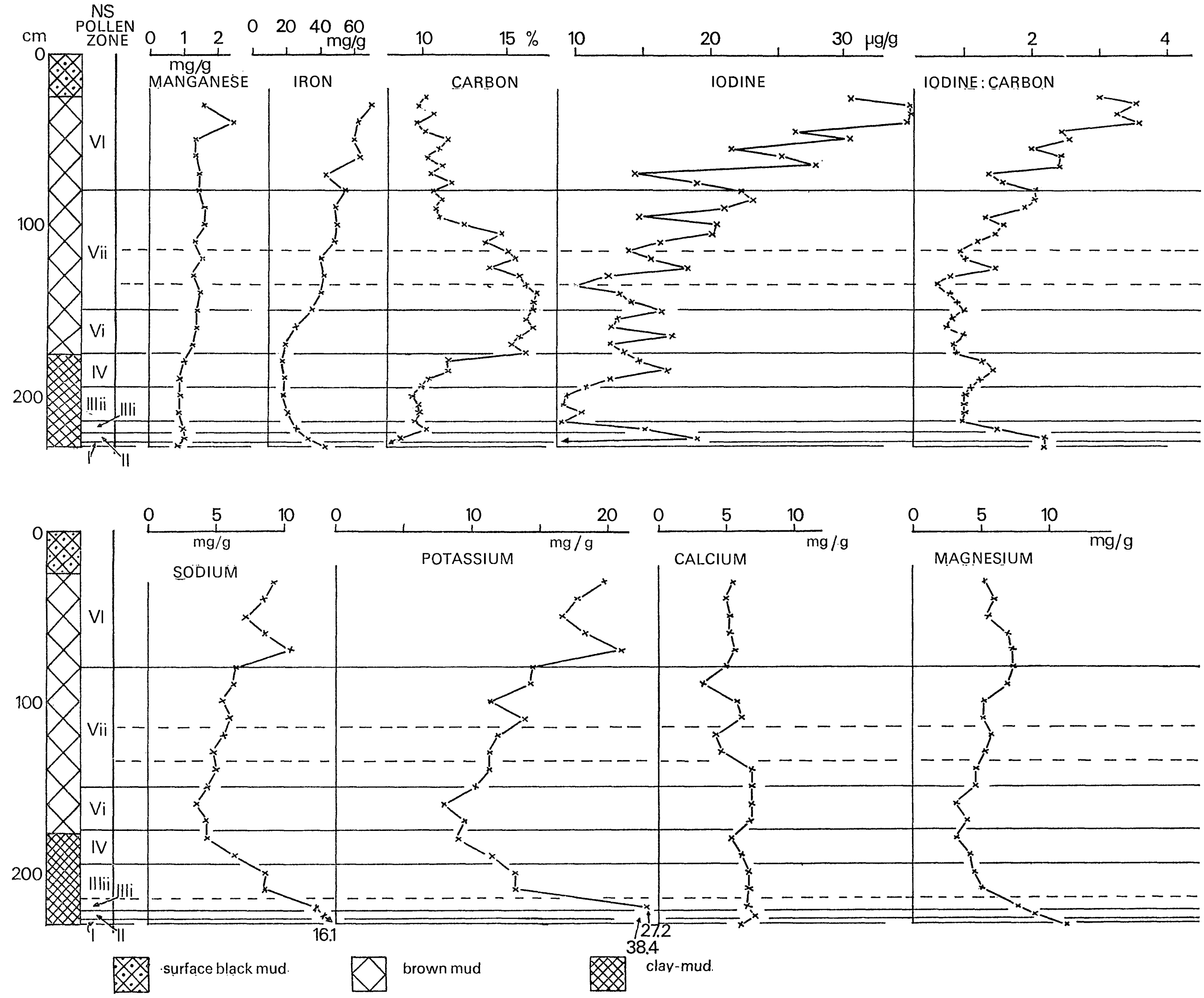


FIGURE 17. Loch Tarff: post-glacial chemical diagram, divided horizontally at pollen zone boundaries.

Late-glacial 258 *to* 230 cm

Figure 16 shows how the late-glacial section of this profile, as defined by pollen analysis, is distinguished on chemical composition from underlying full-glacial and overlying post-glacial sediment. Accumulation of carbon and iodine in pre-interstadial and interstadial sediment agrees with the findings at Loch Sionascaig, but in this profile from Loch Tarff, the slightly brown interstadial sediment is consistently more organic than pre-interstadial deposits. Lower values for calcium and sodium in late-glacial than in full-glacial sediment indicate the progress of leaching as soils became stabilized. High values for potassium and magnesium in late-glacial sediments are attributed to the formation of clay minerals by chemical weathering, with consequent concentration in the sediments of these elements – a process which appears to have begun just below the level at which pollen is first found.

The summation of chemical variance shown by the first Principal Component (figure 16) indicates pollen zones A 2 and B 1 as the periods during which maximum change in sediment composition took place. Pollen zones A 3 and B 2 correspond with sections of the profile where this process of change in composition was halted or reversed; this corresponds with the interpretation of these pollen zones as the result of comparatively minor climatic recessions (cf. pp. 225 and 275).

The post-interstadial section (230 to 235 cm) shows unusually little difference in carbon content from interstadial sediments, surprising since it is so lithologically distinct – a clay. It is lower in potassium and magnesium than pre-interstadial and interstadial deposits, so it is supposed that the clay is rock flour, not rich in clay minerals. (This illustrates the necessity 'to distinguish between the *size* fractions "clay" and "silt" and the *mineral* populations "clay minerals" and "rock flour"' (Holmes 1968).) We would suggest that this post-interstadial sediment originated in interstadial soils, sludged into the basin during a period of cold climate (= the *Artemisia* pollen zone) and that within this material, rock flour of clay particle size, but as yet unweathered, diluted the organic horizon and weathered material of the interstadial soils. The iodine content of this material, which is much greater than that of the lithosphere, agrees with the postulated origin in soils: see Pennington & Lishman (1971, p. 108). The absence of any increase in calcium content to values comparable with sediment of full-glacial age shows that there was no deep erosion into completely unleached glacial drift.

Post-glacial 230 *to* 0 cm

The early post-glacial section is distinguished by progressive decline in the mineral elements except calcium (the most soluble, so already fully leached) as the erosion rate fell with the spread of post-glacial forest. Increase in organic matter as the mineral elements declined brought about a gradual change in appearance of the sediment, and this is completed by the horizon of visible stratigraphic change at 177 cm.

The mid-post-glacial chemical equilibrium coincides with pollen zone NS V i, which we have compared to Godwin zone VII a, the Atlantic period, (p. 207) though we have at Loch Tarff no information about the date of the lower boundary of pollen zone NS V i. We consider, however, that the zone boundary NS V i/ii must be contemporaneous with the Elm Decline, which means that the end of the period of chemical equilibrium came at the same time as it did in the larger lakes of the Lake District (Mackereth 1965, 1966 *b*) and Blea Tarn (Tutin 1969).

From the zone boundary V i/V ii upwards, increases in the amounts of sodium, potassium, magnesium and iron indicate increased erosional transport of soils as yet unleached of these elements; the course of the pollen curves (figure 15) compared with the chemical diagram (figure 17) shows the positive correlation between pollen evidence for deforestation episodes (the broken lines in the figures) and accelerated erosion of mineral soils. Continuously falling values for carbon indicate that the input was of predominantly mineral soils, not organic soil horizons, and this agrees with the topography of this catchment, where well-drained slopes surround the lake and there is no extensive development of deep peat. The most striking difference between the composition of the Loch Tarff sediments and those of comparable Lake District lakes is the very high iodine content of the upper sediments of Loch Tarff; this is correlated with the development of acid mor soils in this catchment, where the pollen spectra (p. 263) indicate a succession from pine–birch woods to *Calluna* heath or moor with anthropogenic deforestation. Lake District profiles record a change from upland oak–elm–birch woods to hill grassland with herbs, and the difference is apparent in the chemical composition of the lake sediments.

Other sites in Region 3

Cores were obtained from two other lochs in the Great Glen but these proved to be unsuitable for full analysis.

Loch Ness (40 km × 1.45 km, max. depth 230 m, altitude 15.2 m (50 ft)

Loch Ness was chosen as an example of a large lake in which water movements of considerable strength (due to wind displacement leading to internal seiches) had been demonstrated (Mortimer 1955). It is more exposed to wind than any Lake District lake because of funnelling of prevailing winds along the steep fault-determined trough of the Great Glen; the length of the lake gives a fetch of 22 miles. Underwater contours (Murray & Pullar 1910) show the extreme steepness of the sides of the basin, so sampling was restricted to the ends of the loch, in water not more than 50 m deep, where it was hoped to avoid the secondary deposition which would be expected on the floor of the main trough.

No depth of organic mud was found in these places, though we suppose it may be present at the bottom of the deep trough. Four cores were obtained from the north-western (outflow) end of the loch, and two from the south-western end near Inchnacardoch Bay; they were from 3 to 6 m in length and consisted mainly of grey microlaminated glacial clay, the laminations showing graded bedding from silt to clay particle size, with no organic content or micro-fossils. At some places this clay formed the surface deposit, and at others it was overlain by up to 50 cm of brownish and unstratified clay-mud, which was in places soft and in others contained harder lumps. Further exploration of the ends of the loch with a surface mud-sampler confirmed the absence of true stratified organic lake mud.

The most probable explanation of the absence of stratified organic deposits down to at least 50 m water-depth in Loch Ness is that water movements are sufficiently strong to prevent permanent and orderly settling of organic particles, so that the surface of the bottom sediments is either of glacial clay or of inorganic sediment randomly mixed with temporarily settled organic matter. Mortimer (1955) showed that large vertical oscillations of the isotherms are built up in windy weather during the period of summer stratification, that these operated down to at least 60 m during his observations, and persisted as internal seiches during calmer intervals. Their effect must be to transfer into deeper water any sediment temporarily settled on the bottom in water depths of less than 60 m. The glacial clays, composed in part of the finest clay-size particles, must have been deposited in Loch Ness under climatic conditions very different from those of the present – almost certainly under a regular winter ice-cover.

Samples from the varved clay were analysed for total halogen content. The results (appendix 2) show that at no horizon is there a significantly higher halogen content than that found in the varved clays of Lake District lakes, so it seems unlikely that sea water was present in the loch during the formation of these clays (see appendix 2).

Loch Oich (4 km × 0.25 km, max. depth 51 m, altitude 32 m (105 ft).

This narrow loch lies above Loch Ness in the course of the Great Glen, with a conspicuous moraine ridge at Fort Augustus between the two lakes. The large River Garry enters Loch Oich in a delta about half-way along its length; a core was obtained from the middle of the loch above this delta.

The core resembled those from Lake District lakes in its 5 m thickness of organic mud (fine-detritus gyttja) above mineral sediment. At its base this organic mud passed gradually into increasingly minerogenic deposit. The lowest part of this was a grey sediment containing some clay and some sand, but composed mainly of silt, which flowed slowly when extruded from the corer – contrasting strongly with the plastic glacial clay of Loch Ness and all Lake District lakes. No alternation of more and less organic layers suggestive of a late-glacial oscillation was present in this core.

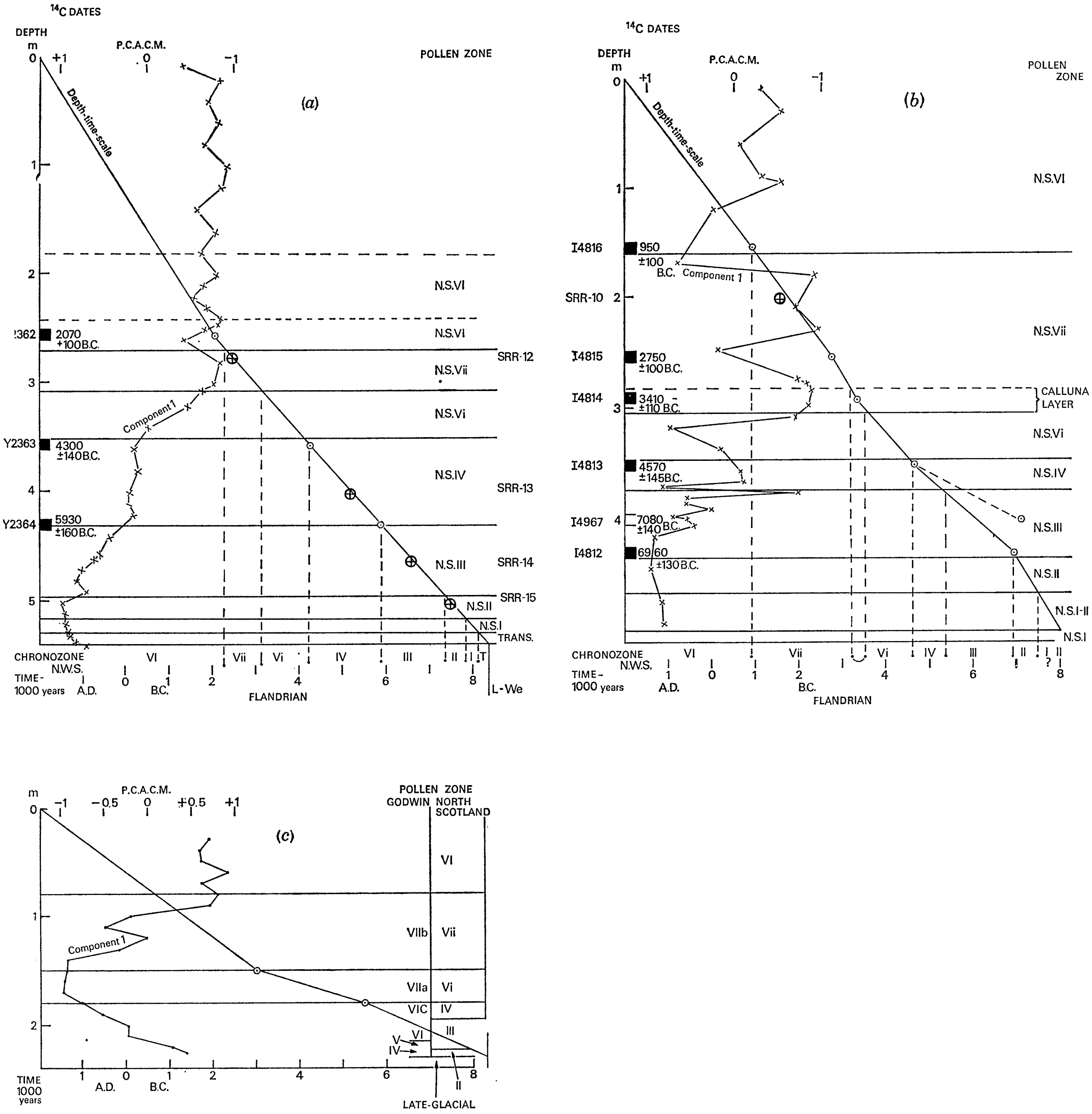


Figure 18. Depth–time scales, pollen zones, and changes in sediment composition as shown by the first component of a Principal Components Analysis of the chemical data: (*a*) Loch Sionascaig, (*b*) Loch Clair, (*c*) Loch Tarff (*a*) and (*b*) based on ^{14}C dates, (*c*) on regional dates for Godwin zone-boundaries VIc/VIIa and VIIa/b. Laboratory numbers of ^{14}C dates from Yale University and Isotopes Inc. are given on the figure. Additional radiocarbon dates, as yet unpublished, from the Scottish Research Reactor Centre, are indicated on the depth–time scales and by the SRR-number under which they will be published in *Radiocarbon*.

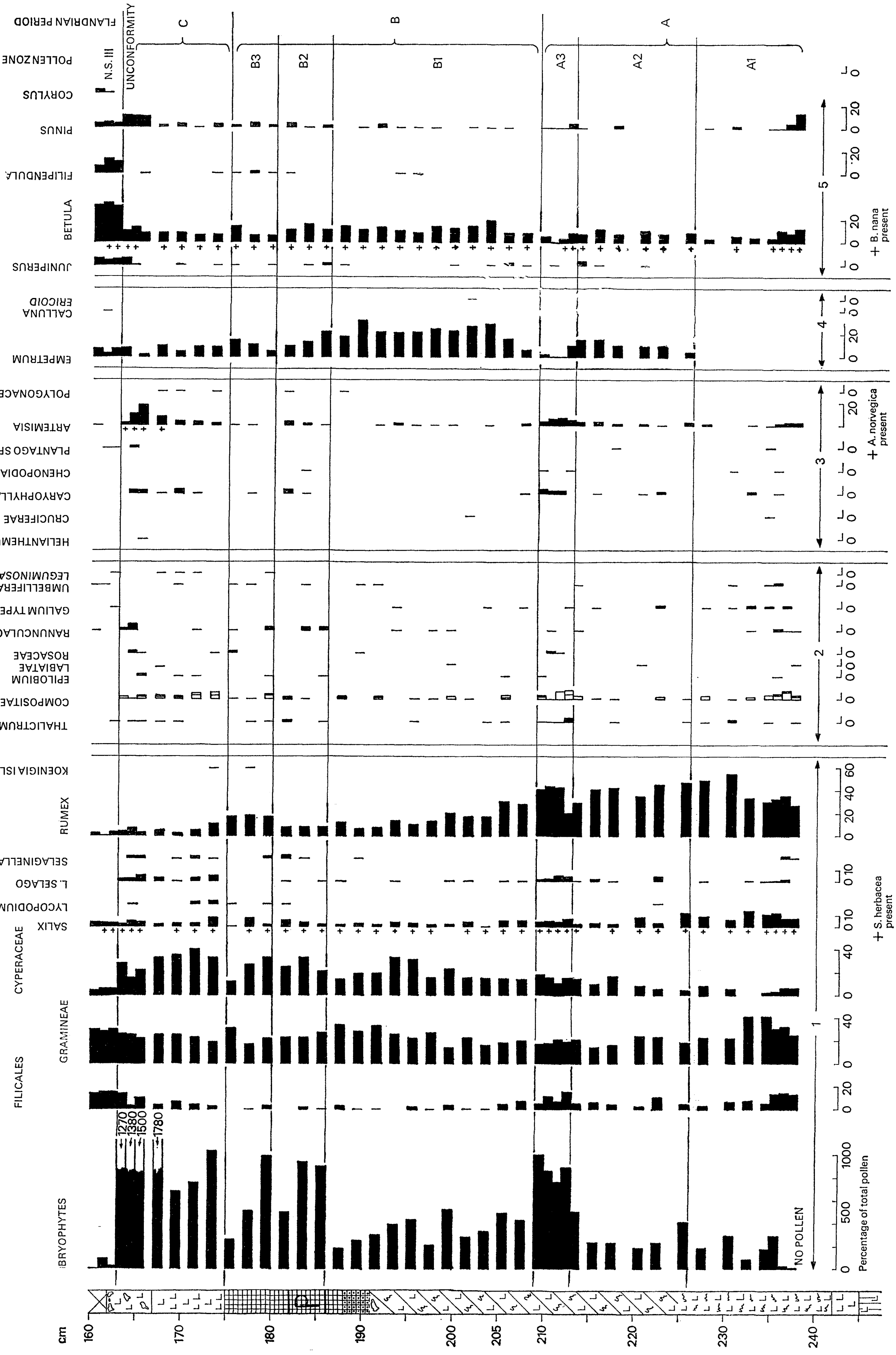


FIGURE 19. Loch Borralan: late-glacial pollen diagram; for arrangement of taxa see figure 3.

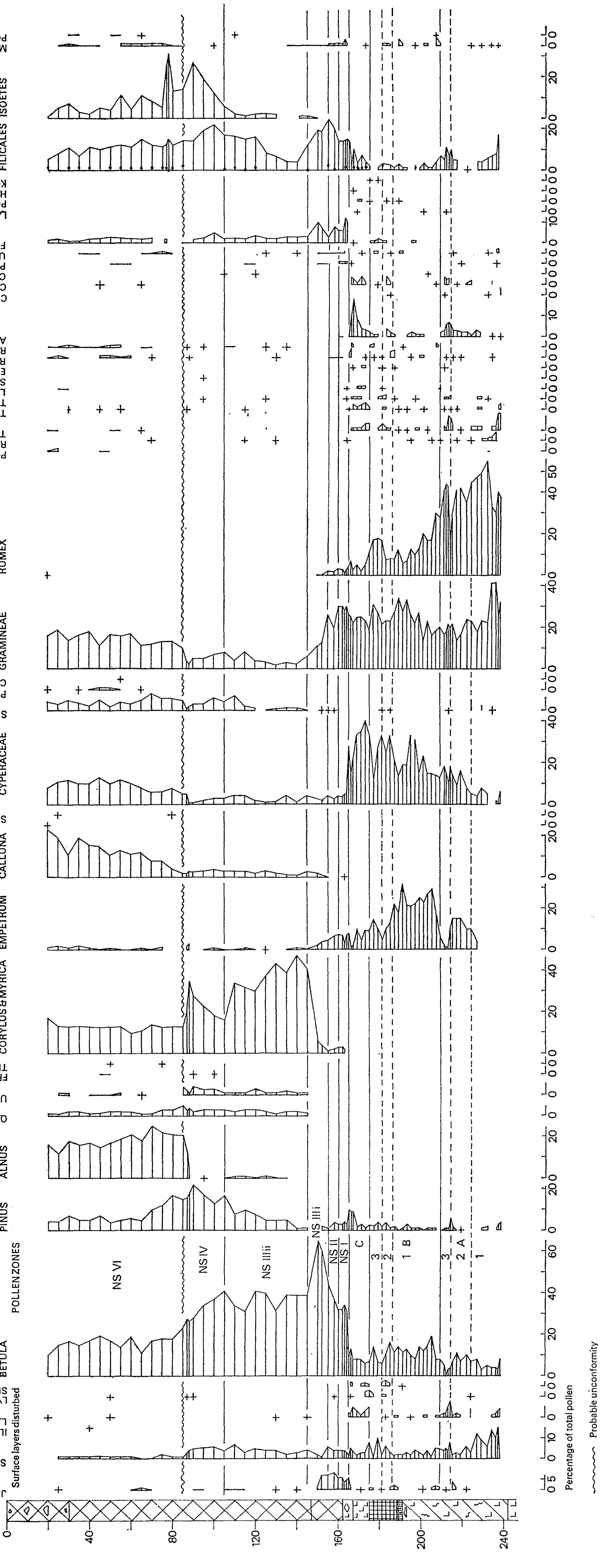


FIGURE 20. Loch Borralan: full pollen diagram, showing unconformity.

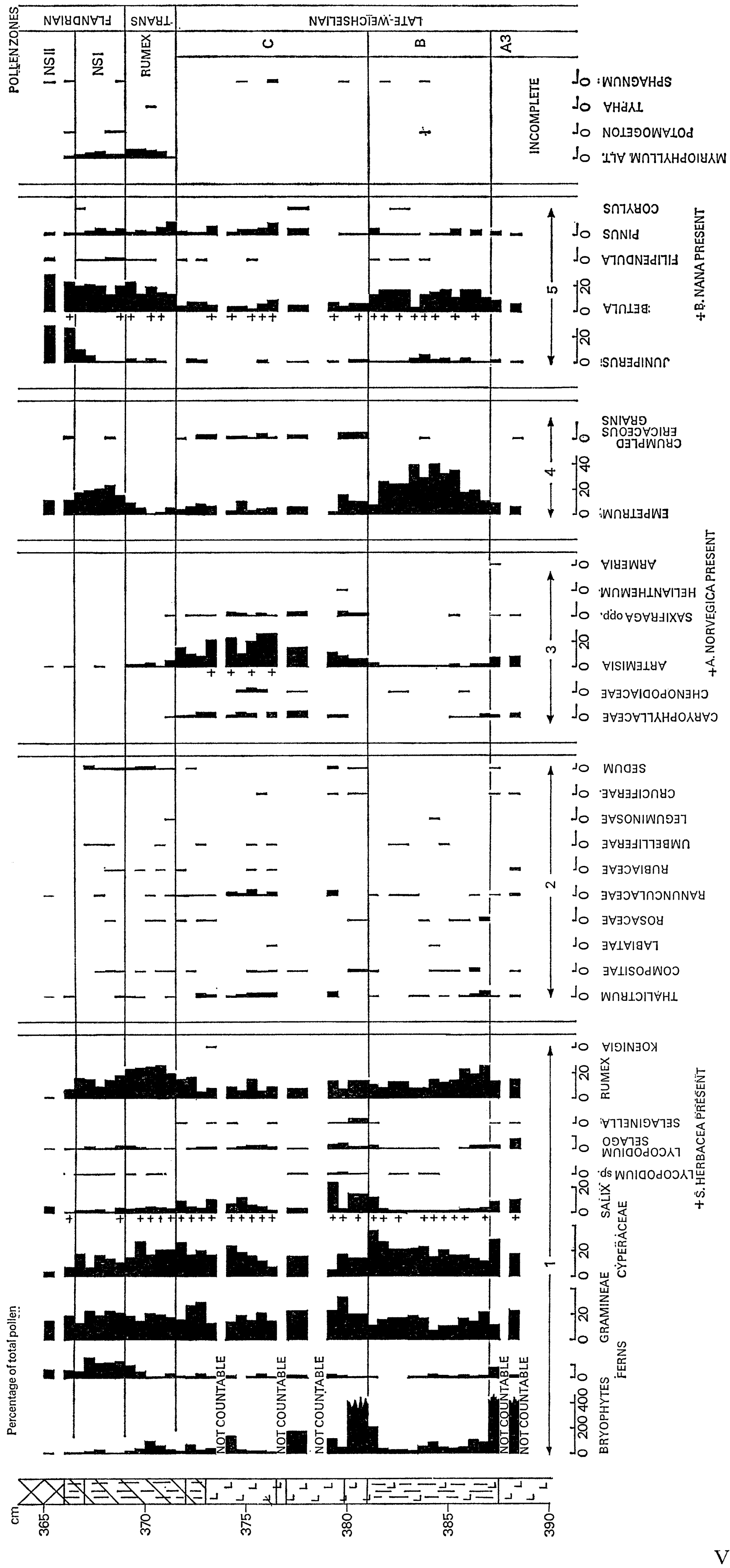


FIGURE 21. Loch Craggie: late-glacial pollen diagram; for arrangement of taxa see figure 3.

TABLE 7. CORRELATION OF LATE-WEICHSELIAN POLLEN ZONES FROM SITES IN REGION 1 AND REGION 2 WITH A DATED LATE WEICHSELIAN SITE IN NORTH-WEST ENGLAND

Heavy broken lines indicate chronostratigraphic correlations. In 'Climate' column, c = colder, t = more temperate, but no estimate of temperatures can be made from these data.

CLIMATE (based on chemical data)	REGION 1				REGION 2	NORTH-WEST ENGLAND BLELHAM BOG (P. & B. 1970)		POLLEN INFLUX
	LOCH SIONASCAIG	LOCH BORRALAN	(K. & G. 1963) LOCH DROMA	LOCH CRAGGIE	LOCH TARFF	LITHOLOGY	POLLEN ZONE	
t	NS I *Empetrum* *ca.* 300 yrs	NS I *Empetrum*		NS I *Empetrum*	NS I *Empetrum*	organic mud	Bh juniper *ca.* 260 yrs	RISING RAPIDLY
t	transition *Rumex–Lycopodium selago*–sedge–ferns *ca.* 300 yrs	NOT PRESENT unconformity	?	transition *Rumex*-sedge	NOT PRESENT		*ca.* 160 yrs Bg *Rumex–Thalictrum–Empetrum*	
c very cold (solifluction)	C *Artemisia–Lycopodium selago*–Compositae–Caryophyllaceae–*Salix herbacea*–bryophytes (+*Empetrum*)	C *Artemisia* (low)–sedge–Compositae–Caryophyllaceae–*Lycopodium selago*–bryophytes	C *Artemisia–Lycopodium selago*	C *Artemisia* (high)–*Salix herbacea*–Caryophyllaceae–*Saxifraga–Lycopodium selago*	C *Artemisia* (high)–Caryophyllaceae–*Thalictrum* bryophytes	clay	Bf *Artemisia*–fern	LOW
							Be *Artemisia–Rumex*–fern	FALLING
t	B3 *Empetrum*–juniper–sedge	B3 *Empetrum–Rumex*	?		B3 *Empetrum*–juniper	organic mud	Bd birch–juniper	HIGH
c slight vegetation recession	B2 *Empetrum*–sedge–bryophytes	B2 *Empetrum*–sedge–bryophytes	B2 *Empetrum–Lyc. selago*–Compositae	B *Empetrum*–sedge	B2 *Empetrum*–sedge–bryophytes			
t	B1 *Empetrum*	B1 *Empetrum*	B1 *Empetrum* 10870 ± 155 B.C.		B1 *Empetrum*	10750 ± 190 B.C. (mean)	Bc birch Bb juniper	
c slightly increased erosion rate	A3 *Rumex–Artemisia*–bryophytes	A3 *Rumex–Artemisia*–bryophytes–*Lyc. selago*	A3 *Rumex–Lyc. selago*–sedge	A3 *Rumex–Lyc. selago*–bryophytes	A3 *Rumex*–bryophytes	silt	Ba *Rumex*–grass	VERY LOW
t	A2 *Rumex–Empetrum*–juniper	A2 *Rumex–Empetrum*	A2 *Rumex–Empetrum*	NO POLLEN	A2 *Rumex–Empetrum*	organic mud slightly raised percentages of birch and juniper		
c	A1 *Rumex–Lycopodium selago*–ferns	A1 *Rumex*–grass–*Salix*	A1 *Rumex–Lycopodium selago*		A1 *Rumex–Salix*–ferns	clay		

FULL GLACIAL (BARREN)

The pollen was found to be so poorly preserved that the organic mud of this core was not suitable for pollen analysis. In shape and in the rapid through-put of water from the Garry, Loch Oich resembles a river rather than a lake, and this is the probable reason for the preponderance of worn and unrecognizable pollen grains.

This single core did however provide the information that the most recent mineral sediment of Loch Oich, which would be supposed to date from the melting of the last ice to occupy the Great Glen, is very different lithologically from the thick deposit of laminated clay which forms the surface deposits of much of Loch Ness.

Region 3. *Summary*

Conclusions reached from study of Region 3 were therefore as follows:

(i) There is a great difference in the sequence of late-glacial lake sediments found in lakes on the course of the Great Glen compared with Loch Tarff on the moorlands above the Glen. As yet it is not possible to assign to a date or a pollen zone the thick deposit of laminated clay in Loch Ness or the basal unsorted minerogenic sediment of Loch Oich. In Loch Tarff the late-glacial sequence of pollen zones resembled that of Region 1.

(ii) The absence of post-glacial organic sediment from much of Loch Ness has been correlated with the depth to which wind-induced water movements disturb the process of deposition in this lake.

(iii) The post-glacial series of pollen zones found in Loch Tarff showed a pattern intermediate between that found in Regions 1 and 2 (north-west Scotland) and the Godwin zonation applicable to sites farther south, consistent with the position of this site on the margin of present areas of distinct forest types (pine–birch and mixed–oak forest).

(iv) Chemical changes in composition of Loch Tarff sediments showed the same correlation as that found in northern England between evidence for accelerated erosion of mineral soils and pollen evidence for the anthropogenic clearance of forests on hill slopes.

(v) No evidence for formation of blanket peat on the catchment was found in the sediments of Loch Tarff; this agrees with present observation of the catchment.

5. General summary and discussion

(*a*) *Regional soil, vegetational and environmental history*

(i) *Full-glacial*

The barren silts and clay-silts of distinct (unleached) chemical composition present at the base of cores from Lochs Sionascaig, Tarff and Borralan are interpreted as the products of fluvio-glacial redeposition at the close of the last glacial episode, under conditions when no biota were present in the lakes because of turbidity and very low temperatures.

(ii) *Late-glacial*

The presence in Lochs Sionascaig, Tarff and Borralan of late-glacial profiles, complete from the lower boundary with barren sediment to the top of the *Artemisia* pollen zone, indicates the absence of ice or active snowbeds from all these sites throughout the late-glacial period. The lower boundary of late-glacial sediment is the same on both biostratigraphic and chemistratigraphic evidence – pollen grains and diatom frustules appear simultaneously, at the same horizon as that at which chemical changes indicate the beginning of maturation of stabilizing skeletal soils – accumulation of humus, leaching of soluble bases, and the formation of potassium and magnesium-rich clay minerals which results from chemical weathering. At these sites no date for this horizon is available. Both biological and chemical evidence indicates the continuity of soil maturation through pre-interstadial and interstadial sediments, demonstrating the absence of intense solifluction from the catchments during these periods. By contrast, in post-interstadial sediment both biological and chemical evidence indicate a severe environmental change with complete disruption of the communities of land plants, and movement into lake basins of mineral soils with contained micro-fossils – *Empetrum* pollen grains, bryophyte spores and subaerial diatoms. The continued presence in post-interstadial sediments of aquatic diatoms, pollen grains and weathered soil mineral matter show that both aquatic and terrestrial plants (though different assemblages) continued to flourish through this period, and that there was no glacial or peri-glacial erosion into fresh unweathered drift on these catchments.

In Loch Craggie the lowest deposit to enter the sampler is dated by its pollen content to the uppermost part of pre-interstadial sediment, and lithologically resembles full-glacial sediment in Lochs Sionascaig and Borralan. Deposition may therefore have begun later in Loch Craggie than at sites west of the present watershed in that latitude (though it would be unwise to conclude this on the basis of one core). The Loch Craggie profile also differs from the other in its thin (6 cm) layer of interstadial sediment and in the very distinctive pollen assemblage of post-interstadial sediment, which includes several plants of arctic-alpine affinities (p. 242). Possibly these differences indicate persistence of ice into the late-glacial period at some place nearer to Loch Craggie than the western sites, with different local post-interstadial conditions due to the nearer presence of ice.

At Lochs Clair and Maree the lowest deposit penetrated by the sampler was a barren micro-laminated sediment which we correlate with the upper varved clay of Windermere (= Godwin zone III) – a post-interstadial sediment formed by ice or active snow-beds in the catchment. The absence of micro-fossils from this type of lake sediment can be compared with the composition of sediment accumulating in the Norwegian lake Vågåvatn which receives drainage from glaciers; this sediment is similarly laminated and poor in micro-fossils including pollen grains, though pine forests surround this lake. It appears that where the water is turbid and the through-put of water from glacier rivers very rapid (short retention time) few micro-fossils are incorporated into lake deposits, and we suppose that during post-interstadial times, Lochs Maree and Clair and Windermere resembled the present state of Vågåvatn, though without trees.

In Loch Ness there is a great thickness of micro-laminated clay (6 m) and the total number of varves present must be much greater than the 400 to 500 varves in post-interstadial sediments in the Lake District (Pennington 1970). In the North Basin of Windermere there is a similarly inorganic late-glacial profile – that is, there is no organic facies of the interstadial sediment in deep water there (Pennington 1947) – and it may be that the micro-laminated clay of Loch Ness also represents much of the late-glacial period though with no organic facies. The Loch Ness deposits cannot as yet provide evidence for the time during which the Great Glen was occupied by ice.

In Loch Tarff the presence of a complete late-glacial profile indicates that the site was free from ice throughout late-glacial time, which agrees with evidence from high tarns in the Lake District (Pennington 1970) that the presence or absence of a complete late-glacial profile is not related to altitude (i.e. snow-line) but to geomorphology – the presence or absence of sites of ice accumulation.

At Lochs Sionascaig, Borralan, Craggie and Tarff the same pollen zones are very consistently present (table 6). The *Rumex* zone (pre-interstadial) is interpreted as indicative of a pioneer vegetation on skeletal soils, with a low annual pollen production and no trees present locally (compare zone Ba at Blelham Bog (Pennington & Bonny 1970)). Diatom evidence shows how rich in bases were the local waters, and so presumably soils, at this time; some of the diatom species are now found near glaciers. The pollen assemblage gives little direct clue to temperatures; it suggests comparison with either a high-altitude alpine or subalpine grass or sedge heath with *Rumex acetosa*, accompanied by *Lycopodium selago* on stony substrata and screes (cf. McVean & Ratcliffe 1962, pp. 61–4), or the assemblage of taxa found today in south-west Norway on ground exposed by the retreat since the eighteenth century of both valley tongues of the Jostedalsbre plateau ice-cap and of the mountain glaciers of Jotunheim (that is, this assemblage is present at altitudes ranging from *ca.* 300 to 1600 m, and therefore over a considerable temperature range). It is not therefore certain whether the *Rumex* pollen zone represents primarily a period of low temperatures or one of colonization of immature soils. The different percentages of *Rumex* and *Lycopodium selago* at the various sites are interpreted as the effects of different substrata, since percentages of *Lycopodium selago* increase with the amount of scree and bare rock in the immediate catchment of the lake.

Subdivision of the *Rumex* zone is quite consistent at the three sites of ours where it is fully represented and at Loch Droma (Kirk & Godwin 1963, Fig. 7); see table 7. Until a site in northern Scotland suitable for a series of late-glacial radiocarbon dates (which would permit absolute pollen counts) is found, it must remain an open question whether the small percentage increases in woody plants which define subzone A 2 represent a real change in annual pollen deposition, or only a small percentage fluctuation (a 'statistical artefact' (Davis & Deevey 1964)) as at Blelham Bog: see table 7. The minor lithological change found in pollen A 3 could most easily be explained as the result of a slight increase in the rate of soil erosion (comparable with examples in the post-glacial period, e.g. those described in Tutin 1969) *not* involving solifluction. The pollen assemblages of subzone A 3 (table 7) provide no certain evidence for a fall in temperature because of the possibility that the small percentage decline in the woody plants (*Empetrum* and juniper) could be a statistical artefact.

The characteristic micro-fossils of zone A 3 are the objects identified here as bryophyte spores: see p. 201. These have been found in surface samples from a small lake at 1400 m in the Jotunheim mountains where the surrounding catchment carries open plant communities of the middle alpine zone which include many bryophytes; the spores appear to enter the lake with soil material from the only partially stabilized soils. Hence the micro-fossils in subzone A 3 could be explained by somewhat increased erosion of the surface soils, and the chemical evidence is against solifluction.

The *Empetrum* zone (interstadial) includes pollen spectra in which *Empetrum* (cf. *nigrum*), grasses and sedges make up most of the total; it appears that these spectra must derive from a type of heath not now found in Scottish vegetation. The absence of *Calluna* and *Vaccinium* distinguishes the spectra from any species list for Scottish dwarf shrub heath today (McVean & Ratcliffe 1962). Since these pollen spectra are not directly comparable with any known existing vegetation type, no estimate of the change in temperature from the time of the *Rumex* pollen assemblages can be made. Both chemical analyses and diatom assemblages show that there must have been a fairly rapid diminution in the base-status of soils and waters during the interstadial, and that acid conditions must have been present by the end of it, suggesting more rapid leaching of stable soils.

Subdivision of the *Empetrum* zone is consistent at Lochs Sionascaig, Borralan and Tarff. An *Empetrum* maximum in subzone B 1 is followed by indications of slight recession in B 2, and in B 3 there is a juniper maximum at Lochs Sionascaig and Tarff. This succession could be explained as the result of a temperature fluctuation during the later part of the interstadial, comparable with the division of the Alleröd sediments of Denmark into subzones II a, b and c (Iversen 1954; Krog 1954). B 3 is interpreted as a second mild period during which juniper flowered more freely at sites where it was present (cf. Iversen 1960).

The *Artemisia* pollen zone, C, is defined by an assemblage not found in any other zone, though present at some sites together with *Rumex* in subzone A 3. *Artemisia*, other Compositae, Caryophyllaceae and bryophyte spores are characteristic of C; percentages of *Artemisia* are higher at Loch Tarff and Loch Craggie, east of the main watershed. Iversen (1954) pointed out that in European late-glacial pollen spectra, amounts of *Artemisia* increase from west to east and from north to south; subsequently published late-glacial pollen diagrams from Spain, with high percentages of *Artemisia*, support this generalization (Amor & Florschütz 1961; Amor 1968). Assemblages of plants resembling the taxa found in pollen zone C in parts of Britain, including these sites from northern Scotland, can be found on the mountains of central Spain (Sierra de Gredos, northern slopes) just below the winter snow-line. This is in contrast to the pollen spectra of zone A, in which, apart from the presence of the *Artemisia* assemblage at some sites in A 3, the *Rumex* assemblages with *Lycopodium selago* and *Salix herbacea* most resemble associations of species found today on the mountains of Scotland and Scandinavia. The differences between zone C pollen spectra at our various sites in northern Scotland (particularly the distinctive spectra at Loch Craggie) indicate a regional differentiation of vegetation types in post-interstadial time.

The profiles from Region 1 do not provide evidence as to the position of active ice in post-interstadial time. Kirk & Godwin (1963) suggested the high frontal moraine below Loch Gharbhrain as the probable limit of ice in the Glascarnoch catchment during this period. Loch Ailsh occupies exactly the same position relative to a moraine of this type in the Oykell catchment, but our attempt to compare the base of its profile with that of Loch Craggie, lower down the catchment, was frustrated by the silty nature of Loch Ailsh sediment (p. 212).

This study of late-glacial lake sediments in northern Scotland has fully confirmed that here, as in the Lake District, parallel changes in micro-fossils and sediment composition indicate environmental changes on the catchments, directly related to those in the lakes. Deposits of the late-glacial interstadial (pollen zone B) at these sites resemble most closely in lithology and sediment composition those of the Lake District site where the pollen spectra approach nearest to the *Empetrum*-dominated Scottish interstadial pollen spectra – e.g. Blea Tarn at 189 m (620 ft) (Pennington & Lishman 1971). These facts suggest that edaphic factors may have played a part in the differentiation of late-glacial vegetation and the nature of the climax vegetation of the interstadial – i.e. that in the delimitation of that area in which birch woodland developed during the interstadial, edaphic factors may have been operative as well as the climatic factors involved in increasing altitude and latitude. It is not, however, clear from our data just what edaphic factor must have been involved in the distribution of interstadial *Empetrum* heath, since the diatom results show conclusively that the Sionascaig catchment must have been comparatively base-rich during the earlier part of the interstadial. All the evidence from Scotland reinforces previous conclusions as to universal soil movements and incomplete plant cover (open communities) during the post-interstadial period, when outwash from active ice entered Lochs Clair and Maree but not the northern lochs of Region 1 or Loch Tarff.

(iii) *Post-glacial*

Regions 1 *and* 2. The sequence of pollen zones at Lochs Sionascaig, Borralan, Craggie and Clair indicates a prevailing vegetation of shrubby heath for about 1000 years between the end of solifluction in the lowlands (the top of the *Artemisia* pollen zone) and the local rise of the birch pollen curve, which is dated to 6960 ± 130 B.C. at Loch Clair and to approximately the same date on the Loch Sionascaig depth-time-scale. Precise dating of the local absolute increase in tree birch pollen, indicative of the local expansion of birch woodland, must await quantitative pollen analysis, because the course of the percentage curve for birch at any site must be determined by the pollen production of other plants present, and the late-glacial distribution of juniper (the other large pollen producer in these assemblages) appears to have been patchy and local. On comparison of percentage curves the development of birch woodland at these northern Scottish sites appears to have been delayed for more than 1000 years after its arrival at Scaleby Moss.

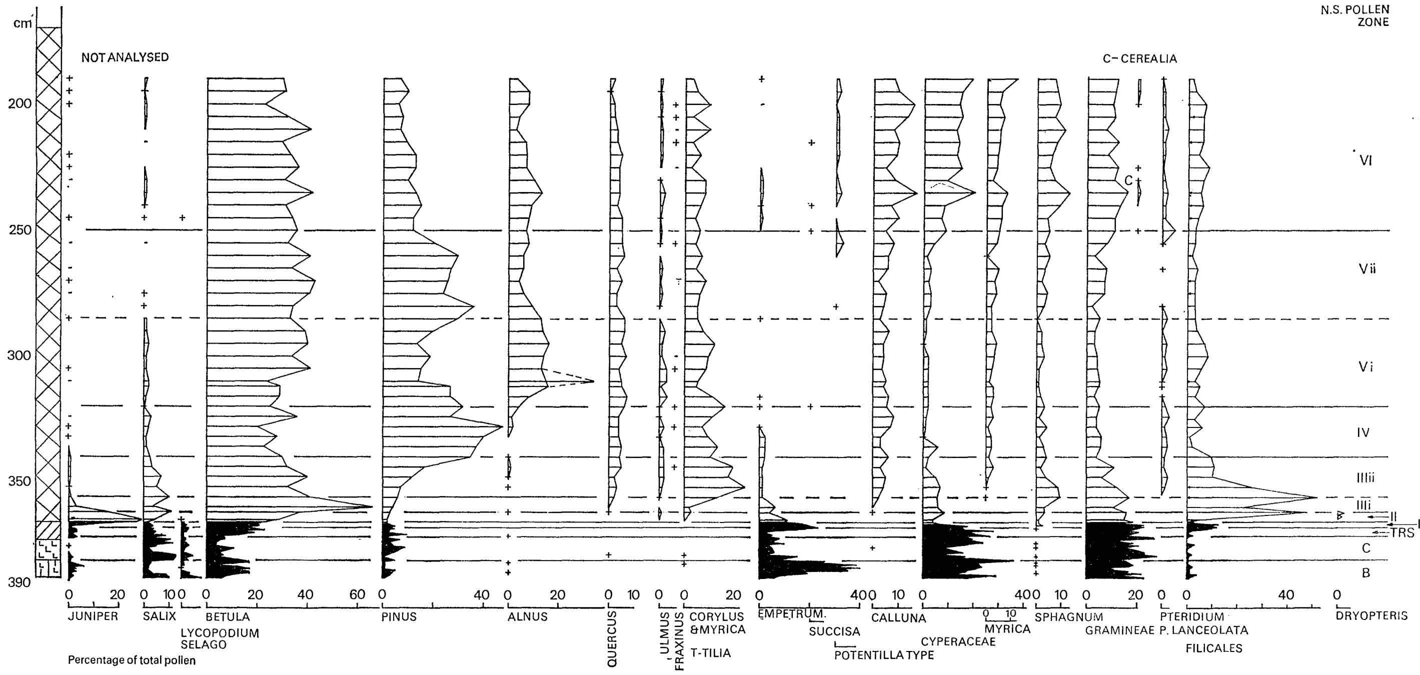


Figure 22. Loch Craggie: full pollen diagram up to horizon of peat inwash.

Table 7 compares the sequence of pollen zones with that from a kettlehole site in northern England, and shows the similarity – above the top of the *Artemisia* zone comes first a *Rumex* zone, then an *Empetrum* zone, then a juniper zone – a repetition of the pre-interstadial–interstadial succession. By comparison of depth-time-scales at dated sites it can be seen that this pollen sequence occupied a longer period of time in northern Scotland than at the English site (Blelham Bog). Yet the changes in sediment composition (increased carbon and decreased base content) and appearance (colour change to brown mud and flocculation) are not similarly retarded at the Scottish sites, so that the chemical and physical changes in the sediment at the base of the post-glacial profiles are complete or nearly so *before* the rise of the percentage birch pollen curve. It seems certain that irreversible changes in soil and water, consequent on normal leaching of newly stabilized soils, had taken place in this part of northern Scotland before the arrival of birch trees, which had been delayed by the time involved in dispersal from those regions where they had been present during the late-glacial period. The effect on subsequent soil history of more than a thousand years of post-glacial leaching under a vegetation which did not recycle nutrients, as does a deciduous forest, may have been important in determining the subsequent vegetation history of both catchments and lakes.

Evidence for early acidification of soils is present in both Loch Sionascaig and Loch Clair.

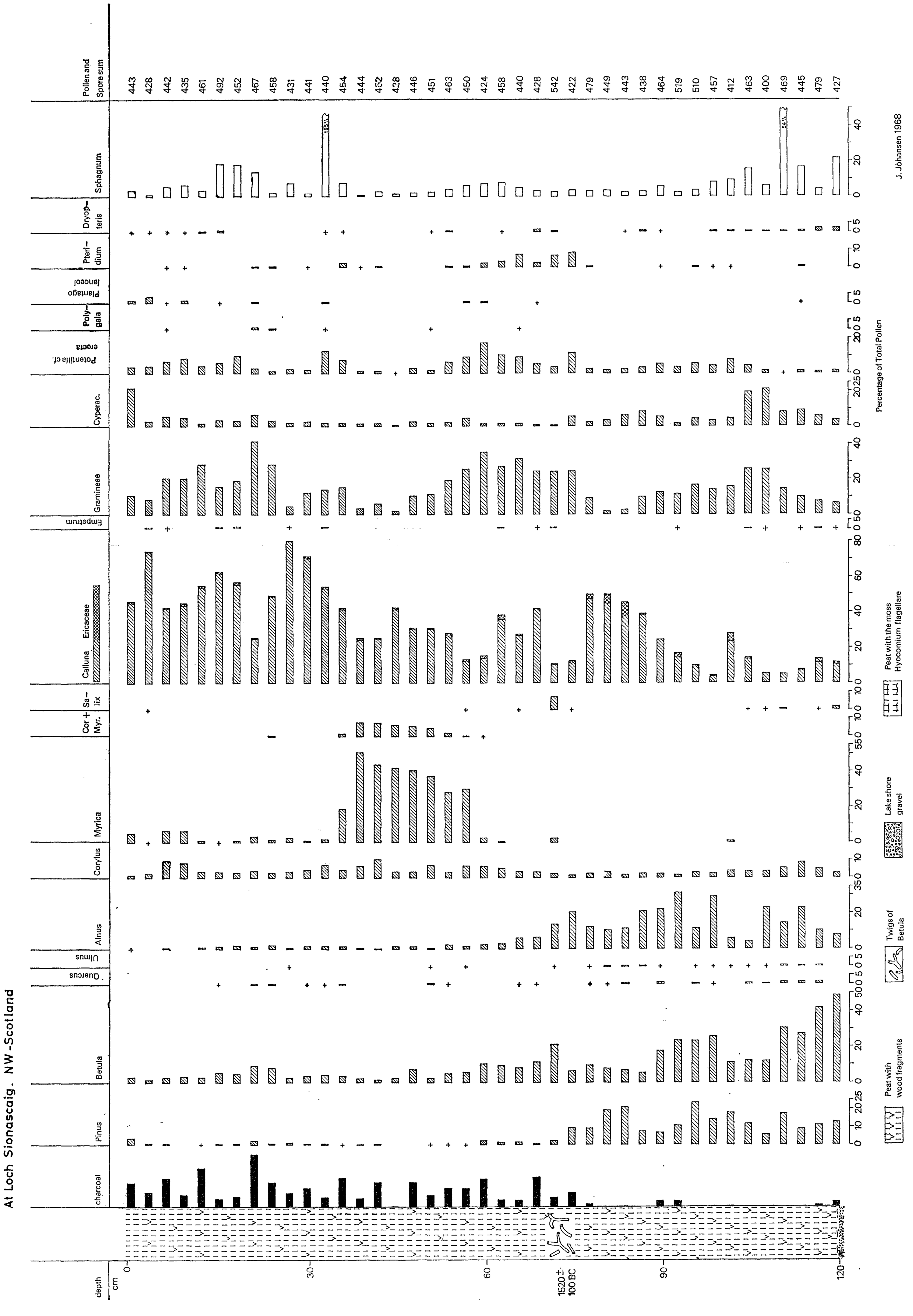


FIGURE 23. Loch Sionascaig peat profile: pollen diagram.

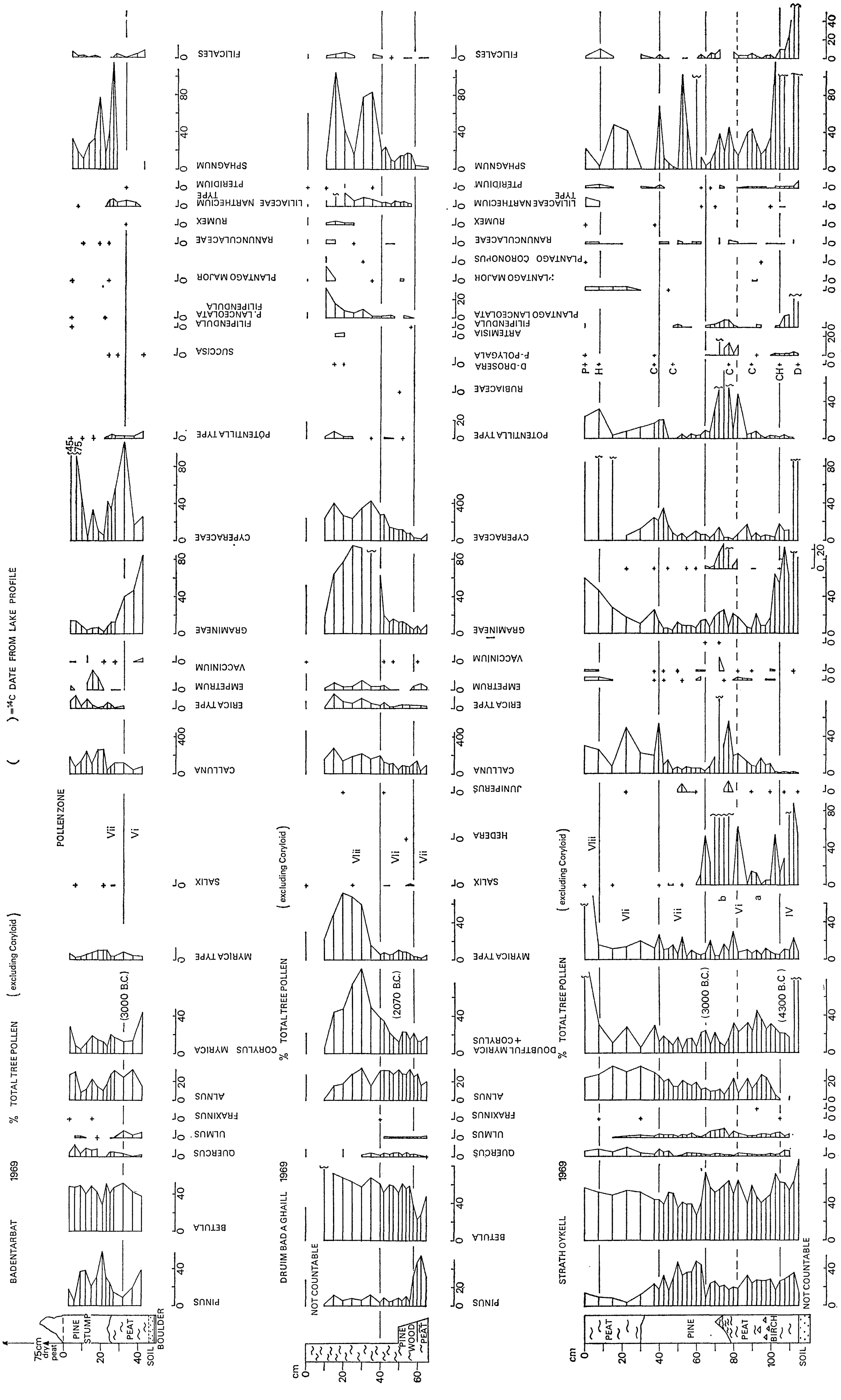


FIGURE 24. Pollen diagrams from three peat profiles in Region 1.

Round Loch Sionascaig the prevailing type of inwashed humus had changed to acid (Class I ESR spectra) within the *Empetrum* pollen zone. The Loch Clair sediment contains evidence showing that the *Empetrum* of the lowest pollen zone (NS I) was growing on soils so full of fungal hyphae and containing such dark organic matter that acid mor must be envisaged. In these two regions, therefore, delay in arrival of deciduous forest must have combined with the general poverty of sandstone (Torridonian) and quartzite (Cambrian) source rocks to produce areas of soil which could never thereafter have been expected to have supported either hazel or mixed-oak forest. In the soil mosaic of Regions 1 and 2, however, more base-rich parent material exists, in more basic gneisses (especially where maintained by dry flushes on slopes), Moine schists, and the limited outcrops of Durness Limestone, as well as on drifts derived from these rocks. In the remainder of this discussion we will show how it is possible to explain the subsequent sequence of pollen zones in Regions 1 and 2 as the result of a history of differentiation of vegetation types on a soil mosaic, as post-glacial leaching and soil impoverishment proceeded.

Within pollen zone NS III the percentage curves for birch and hazel expand simultaneously at the western sites, Lochs Sionascaig and Clair, whereas farther east at Lochs Borralan and Craggie, where there was less juniper, birch percentages expand before hazel, as happens also at Loch Tarff. At Lochs Sionascaig and Clair pollen zone NS III contains an assemblage of taxa suggestive of herb- and fern-rich birchwoods, with much willow, and low percentages of hazel pollen. These low values for hazel in the sites from north-west Scotland indicate a regional difference during the time of the birch–hazel pollen zone; at Loch Tarff the pollen spectra of this zone are more like those of Godwin zone VI c in the rest of Britain.

At Loch Sionascaig the lower limit of the pine–birch zone, NS IV, falls at *ca.* 5900 B.C.; there is a sudden expansion of pine percentages to *ca.* 40 % of the total at this horizon at this site, with a corresponding fall in the birch–hazel–willow–fern assemblage. From the Loch Clair pollen diagram and time-scale (figures 11, 18) it appears that this change began somewhat later there and took place more slowly. The pine maximum of Godwin zone VI c in northern England dates from the period just before 5500 B.C. (Pennington 1970) and the base of the pine assemblage zone in the Cairngorms has been dated to *ca.* 5000 B.C. (Birks 1970). We interpret this as indicative of a gradual and non-synchronous replacement by pine–birch of birch–hazel woods on both upland and poorer soils in northern England and in Scotland, as these soils deteriorated, between *ca.* 6000 and 5000 B.C.

Within the period dated to between *ca.* 6000 and 4400 B.C. at Lochs Sionascaig and Clair, there is no evidence for any environmental change comparable with that found at the Boreal/Atlantic transition (Godwin zone VI c/VII a) in northern England, where the Scaleby Moss time-scale dates this horizon to 5475 ± *ca.* 350 B.C. (Godwin *et al.* 1957; Pennington 1970; Pennington & Lishman 1971). The apparent absence of any detectable change in the vegetation of the far north-west of Scotland at the Boreal/Atlantic transition merits further investigation, but these two profiles indicate a pattern of climatic and vegetation history different from that of the rest of Britain.

Both the expansion of the percentage curve for alder pollen, and chemical evidence for the rise in water-tables which is found at the Boreal/Atlantic transition at some English sites, are dated to a horizon nearly a thousand years later in north-west Scotland – the zone boundary NS IV/V i, dated to 4300 ± 140 B.C. at Loch Sionascaig and 4570 ± 145 B.C. at Loch Clair. At both these sites percentages of alder remain low, suggesting that in the region of western pine forest the alder did not become established as a stream-side and lake-side tree, but was confined to wet carr woodland where at this date it largely replaced willow – cf. *Alnus* and *Salix* curves, and the higher *Alnus* percentages at Lochs Borralan and Craggie, near sites of carr.

Within pollen zones NS IV and V i the percentages of oak and elm remain very low. There is no certain evidence from these profiles as to whether these pollens came from the extra-local or the regional pollen component, but there can never have been more than very small areas of oak–elm woodland within Regions 1 and 2. The first break in the elm curve is used to define the upper boundary of pollen zone NS V i; it is interpreted as the result of a synchronous fall in the regional (Scottish) pollen rain at *ca.* 3000 B.C., for it falls near this date on the time-scales from both Loch Sionascaig and Loch Clair; the details of the Elm Decline in the Loch Tarff profile suggest an episode comparable with that found in northern England (Pennington 1970) and south-west Scotland (Birks 1972). We have shown how in the Loch Sionascaig profile there is no other change in the pollen taxa beyond the break in the elm curve, but that chemical evidence indicates a pronounced increase in the solutional transport of iron and manganese which we interpret as the result of accelerated peat formation following the spread of waterlogged soils during the preceding period. Peat profiles from Badentarbat and Strath Oykell confirm that peat was forming on flat land outside basins by the time of the Elm Decline. At Loch Clair, by contrast, there is no evidence for any acceleration of peat formation on the steeper slopes of this catchment, but there are pronounced changes in the pollen curves, suggestive of both forest fires and the presence of man, at a horizon dated to 3410 ± 110 B.C., which falls between two breaks in the Loch Clair elm curve. This episode is the earliest trace of anthropogenic influence on vegetation that we found in northern Scotland.

The evidence for acceleration of formation of blanket peat in Region 1 at *ca.* 3000 B.C., at sites showing complete absence of any signs of human influence, agrees with what Conway (1954) found on the Pennine plateau of northern England. It seems possible that at about this date, some climatic fluctuation crossed a significant threshold in those parts of highland Britain where soil degradation (due to rapid leaching) had reached a certain point (see Iversen 1964) where accumulation of a thick layer of mor humus leads to swamping and peat formation. Since the effects of this inferred climatic fluctuation were felt in the Pennines, it must have affected the Lake District hills, though these are in general too steep for blanket peat formation. However, some of the changes in sediment composition noted by Mackereth (1966*b*) at a depth of *ca.* 3 m in the sediment profiles of the larger English Lakes, and interpreted as indicative of increased erosion of soils may possibly be attributed to a temporary climatic change towards more oceanic conditions, acting on soils in the higher parts of the drainage basins. Sediment profiles from the Lake District, which show no qualitative change in organic matter, show an increase in iodine content and iodine:carbon ratios above this horizon which can be interpreted as the results of an increased supply of iodine from rain, but the very high iodine values of Loch Sionascaig and Loch Tarff appear to be related primarily to the acidity of the organic matter formed on their catchments (Pennington & Lishman 1971).

The 3000 B.C. horizon is the latest at which a regional change for the whole of north-west Scotland (Regions 1 and 2) is detectable. Maintained percentages for pine and birch pollen in pollen zone NS V ii show that the spread of blanket peat deduced from chemical evidence in Region 1 did not reduce the pollen production of those trees, so it must be supposed that regeneration continued on a substratum of shallow peat. As the thickness of peat increased, it would be supposed that pines would become increasingly vulnerable to adverse conditions in the form of poor nutrition, poor prospects of regeneration by seedling establishment, and increasing liability to wind throw. These profiles do not provide certain evidence as to the primary cause of the widespread disaster to the pine forests of Region 1 just before 2000 B.C. Forest on growing peat must have been in precarious equilibrium, vulnerable to natural destruction by swamping (see Godwin in Lamb 1964) or the effects of gales on trees rooted in peat. However, the apparently simultaneous destruction of many large pines at Badentarbat, and the general synchroneity of the dates for this episode in Region 1, suggest a more sudden catastrophe than gradual and progressive swamping. The upright position of many stumps still *in situ* in the peat (figure 24) argues against wind overthrow by uprooting. The question is whether the trees were snapped off at ground level by the effects of a gale on trees already partially rotted at that point by encroaching peat, or whether man caused the destruction by either felling or burning the pine forest. Careful assessment of the quantities of charcoal in the Sionascaig peat profile by Mr Johansen (figure 23) suggested to him that the small amount present before 1520 ± 100 B.C. could be explained by natural forest fires, and it was not until this date that evidence for anthropogenic burning was present. No visible charcoal was present in the other peat profiles, and no signs of charring could be seen on the pine stumps, but this may have disappeared with time. Evidence for the presence of man in Region 1 at the time of the disaster to the pine forest can be seen in the presence of cultural pollens, mainly *Plantago lanceolata*, at some sites, but at others there is no sign of cultural pollens at this horizon of the steep fall in pine pollen. At Loch Sionascaig some evidence for inwash of soil material containing *Pteridium* spores (many degraded) and *Calluna* pollen accompanies the fall in pine at the zone boundary V ii/VI i, but chemical analysis revealed no trace of generally accelerated soil erosion. In pollen zone NS VI i pine is replaced in Region 1 by increases in *Calluna*, grass, sedge, and *Sphagnum*; these taxa could all have formed part of the 'field communities of native pinewoods' as given by Steven & Carlisle (1959). It is not until the pollen zone boundary NS VI i/ii that the rise in percentages of *Myrica* pollen, with further increases in the above taxa, indicates the spread of the communities of western blanket bog. From this horizon (corresponding with the date from the Sionascaig peat of 1520 ± 100 B.C.) onwards, it is clear that no regeneration of forest on peat took place in Region 1.

At Loch Clair the pollen diagram shows no sudden fall in pine or birch percentages, but a gradual decline from 2750 ± 100 B.C. to the surface (figure 12) in both trees. The non-synchronous pollen zone boundary V ii/VI, marked by the main increase in *Calluna*, is not drawn here until a level radiocarbon dated to 950 ± 100 B.C., where the curve for *Plantago lanceolata* begins. At this site pine–birch forest has survived on hill slopes, but Steven & Carlisle (1959) emphasize the boggy nature of the ground of this Coulin Forest, and it can be supposed that the efficiency of regeneration of the pine must have diminished through time since the third millennium B.C. At no horizon in the pollen diagram above 3410 B.C. is there any suggestion of a human effect of any magnitude, and it seems that this pine–birch forest on very poor quartz sands can never have attracted settlement by prehistoric man.

We would therefore interpret the present vegetation of the far north-west Highlands as follows. The birch and birch–hazel woods of Region 1 (e.g. of the Inverpolly Nature Reserve) represent the survival on dry flush habitats on the gneiss of a forest type which was widespread between *ca* 7000 and 6000 B.C. The blanket peat of much of the rest of Region 1 covers the remains of a pine–birch forest which succeeded the birch–hazel at about 6000 B.C. on those areas where soils were by that time impoverished. A general rise of water-tables from *ca.* 4400 B.C. was followed by widespread peat formation by *ca.* 3000 B.C. The pine–birch forest on this ground was destroyed by a series of episodes between 2000 and 1500 B.C. which most probably represent a culmination of the effects of natural adverse factors followed by anthropogenic burning. Pollen spectra similar to those of the present have prevailed since just after 1500 B.C. On well-drained slopes and poor soils in Region 2, fragments of pine–birch forest have survived, such as the Coulin Forest by Loch Clair and, presumably, Coille na Glas Leitire on Beinn Eighe.

Region 3. The interest of the series of pollen zones at Loch Tarff is that it can be related both to the northern Scotland (NS) series of pollen zones and to the Godwin zones from III–IV to VII b, though the actual pollen percentages are different both from the sites in Regions 1 and 2 and from more southerly sites.

TABLE 8. COMPOSITION OF BEDROCK IN LAKE DISTRICT AND NORTH-WEST SCOTLAND

(Compared analysis after Ward (1876) and Peach (1907).)

	Borrowdale Volcanic Series (Ward) Base Brown: Lingmell Beck			Lewisian gneiss (Peach)	
				(i)	(ii)
silica	69.673	59.151	SiO_2	54.86	60.39
alumina	19.492	19.212	Al_2O_3	17.3	16.14
lime	2.296	5.208	CaO	7.45	6.36
magnesia	0.324	1.909	MgO	3.97	3.43
potash	4.554	2.933	K_2O	1.06	0.87
soda	3.017	4.217	Na_2O	3.27	3.75
ferrous oxide	2.784	5.192	Fe_2O_3	2.25	3.56
ferric oxide	0.442	0.879	FeO	7.43	3.88
bisulphide of iron	0.410	0.360	—	—	—
phosphoric acid	0.343	0.439	—	—	—
sulphuric acid	0.205	trace	—	—	—
carbonic acid	0.660	trace	—	—	—
loss on ignition	0.800	0.500	loss on ignition	1.76	0.91

The major question, as yet unanswered, at Loch Tarff is the date of the expansion of the alder curve. At this site this horizon resembles lithologically the Boreal/Atlantic transition in certain Lake District profiles, with a stratigraphic change to more organic mud (cf. Windermere (Pennington 1947) and Blea Tarn (Pennington & Lishman 1971)). No stratigraphic change of any kind is found at the expansion of the alder curve in north-west Scotland sites. At Loch Tarff the percentage pollen figures suggest that here, as in the Lake District, there was an absolute fall in pine pollen at the time of expansion of the alder, and this, as first stated by Oldfield (1965) presents an ecological problem if a direct succession from pine to alder is envisaged. In north-west Scotland, where alder percentages remain low, there is no decrease in the percentages of pine within the pine–birch–alder zone (NS V i). Hibbert *et al.* (1971) suggest that late spring frosts, characteristic of an oceanic rather than a continental climate, may have been the reason for the delayed appearance of alder in the west, as compared with the east, of north-west Europe. The contrast between the pollen diagrams from Loch Tarff and from north-west Scotland, at the horizons where alder appears, suggest that northern Scotland, with its climatically contrasted east and west coasts, may include strong contrasts with respect to the date of expansion, and degree of success, of the alder. It seems a promising region within which to investigate this horizon by radiocarbon dating and estimates of absolute pollen frequency.

In summary then our evidence indicates a sequence of late-glacial and post-glacial environmental changes in northern Scotland which can be related by radiocarbon dating to those found in the rest of Britain. The present areas of birch and pine forest in north-west Scotland appear from the pollen record to have had a different post-glacial vegetation history from that of the central part of the Great Glen where apparently native mixed-oak forest is present. In north-west Scotland both regional vegetation history and differences from site to site within the region can be explained in terms of early post-glacial impoverishment of the prevailingly base-deficient soils, and a general tendency towards the formation of blanket peat since *ca.* 3000 B.C. Differentiation of vegetation has (on the evidence of the pollen spectra) taken place in response to different degrees of soil drainage, forest having survived primarily on well-drained slopes. In the absence of mixed-oak forest, birch–hazel survived on the better soils, notably the gneiss, and was replaced by pine–birch forest on poorer siliceous soils. In north-west Scotland, man appears to have played a relatively unimportant part in determining vegetation history until *ca.* 1500 B.C., but at Loch Tarff the evidence suggests a pattern of anthropogenic destruction of hill woodland from *ca.* 3000 B.C., similar to that already found in north-west England.

(*b*) *Paleolimnology – a lake and its catchment*

(i) *The record in sediments*

Detailed analysis of pollen content and chemical composition of the deep-water sediments of these three lakes in northern Scotland has confirmed the close relationship which was found in the Lake District between sediment composition and pollen spectra. Principal Components Analysis of the chemical data has demonstrated how horizons of change in sediment composition always correspond with pollen zone boundaries (figure 18). This close relation must indicate a causal connexion, which is completely explicable if the sediments are derived from the soils of the catchments and the pollen spectra from the vegetation of these soils. Diatom analysis of one core has shown such a close relationship with pollen and chemical analyses (pp. 239–240) that a close relation between aquatic and terrestrial biota must be accepted.

Loch Sionascaig (plate 33) is now as acid, oligotrophic and unproductive as any lake in Highland Britain. Yet its late-glacial lake sediments contain diatom species characteristic of eutrophic environments, just as do those of the now unproductive lake Blea Tarn in the Lake District hills (Haworth 1969). These facts demonstrate the role of a glaciation in 'eutrophication' of waters by the results of mechanical pulverization of a country rock (such as the Borrowdale Volcanics or the Lewisian gneiss) which is fundamentally a reasonably rich source of mineral nutrients, though too hard and resistant to subaerial weathering to maintain base-rich waters during an interglacial cycle. The richness of the late-glacial aquatic flora of such lakes demonstrates the importance of mineral nutrients, as well as of nitrogen and phosphorus, in the ecology of 'eutrophic' species, and gives rise to speculation about the nitrogen and phosphorus budgets of the soils and eutrophic lakes of the British uplands during the late-glacial period. The rapidly maturing soils indicated by the chemical analyses were, on the evidence of the pollen spectra, carrying some form of high-altitude or high-latitude grassland which changed to ericaceous heath during the more favourable climate of the interstadial period.

Iversen (1958, 1964) and Andersen (1964) have emphasized the importance in each interglacial cycle in north-west Europe of the trend towards poorer and more acid soils as leaching progressively removes bases. The history of Loch Sionascaig, as recorded in its sediments, demonstrates how rapidly this process went on in this catchment at the opening of the post-glacial period, by comparison with changes during the late-glacial period; see table 7 for time-scales. Until recently it was generally considered that the late-glacial period began not very long before 10 000 B.C., and that temperate conditions were limited to the interval between just after 10 000 and *ca.* 8800 B.C. – the Alleröd oscillation (Van der Hammen, Maarleveld, Vogel & Zagwijn 1967). Recent radiocarbon dates and other evidence from sites in the west of Britain (Coope (1970) from Wales and the Isle of Man, and Pennington & Bonny (1970) from Blelham Bog in the Lake District) have confirmed the evidence first suggested by Kirk and Godwin's radiocarbon date of *ca.* 10 870 B.C. from Loch Droma, that there have been vigorous biota since a much earlier date than had previously been supposed, and that a major environmental change towards more favourable conditions took place at about 11 000 B.C. in western Britain. From that date onwards, deposits were more organic, biota were richer (shown by a great increase in pollen production per year) and there was a change in species; woody plants increased, and the beetle assemblage changed to one of climatic conditions at least as warm as at present (Coope 1970). This means that the temperate period which we have termed the 'interstadial' must have lasted for at least 2000 years (11 000 to 8800 B.C.) and was preceded by a period we have called 'pre-interstadial', which was well established by *ca.* 12 350 B.C. at Blelham Bog, during which biota were rich and varied, but included species and assemblages now found in higher latitudes. In all there must have been a late-glacial period of at least 4000 years during which soil maturation was proceeding under a plant cover.

By the end of the interstadial – i.e. at the close of this period of *ca.* 4000 years, the rich phase with alkaliphilous diatoms in Loch Sionascaig was beginning to change to a more acid phase – that is, leaching was taking effect. The universal disruption of soil profiles by the final very cold phase of the late-glacial (post-interstadial, from *ca.* 8800 to 8300 B.C.) renewed the base content of the water of Loch Sionascaig and restored the alkaliphilous diatom flora; humus washed into the lake at this time was mild and circumneutral. But within a few hundred years the environment changed rapidly to acid poverty, with inwash of acid humus; this happened before the local arrival of post-glacial forest. It is of course possible to explain this rapid post-glacial soil change by postulating that, since there was no actual glaciation locally during the post-interstadial period, the brief return to base-rich conditions was only a minor fluctuation in the inevitable progress of leaching. It is however of considerable interest to speculate on why lakes continued to support some 'eutrophic' species for most of the 4000 to 5000 years of the late-glacial period.

(ii) *The accumulation of sediment in a lake*

Evidence from these lakes in northern Scotland shows clearly that only under certain conditions does a complete and comformable sequence of lake sediment accumulate in temporal succession. In lakes particularly exposed to strong winds – those of the western seaboard and Loch Ness – the zone of wave erosion within which no sediment comes to permanent rest on the bottom extends down to considerable water depths – 50 to 60 m in parts of these lakes. In such lakes it is of doubtful value to express any variable of sedimentary analysis in terms of deposition per unit area per year, since the *area over which deposition takes place* may well vary from year to year, and constitutes an unknown fraction of the lake area unless a very detailed survey is possible. Nevertheless such exposed lakes may contain, in those parts where sediment does come to permanent rest, a valuable and complete record of environmental history, in complete and conformable sediment profiles (see Loch Sionascaig, ^{14}C-dated profile, figure 18).

In Loch Clair, a sheltered lake where 15 cores along two transects have proved that orderly deposition of sediment has gone on over the whole of the lake bottom, exploratory quantitative pollen analysis has shown that the sediments are unusually rich in pollen. Comparison with

Windermere shows that for the same time-horizon, the mid-post-glacial period at *ca.* 3500 B.C., when the natural forest of both catchments was quite undisturbed by man, the pollen concentration per cm^3 of fresh sediment is 370 600 grains in Loch Clair and 160 400 grains in Windermere. When a depth-time-scale is drawn between radiocarbon dates obtained on these profiles, and these figures are converted to grains per cm^2 per year (pollen influx) the figures are then 21 800 for Loch Clair and 2970 for Windermere. Carbon content of the mud of both lakes is *ca.* 10 %; the Loch Clair sediment has a coarser grade of mineral sediment, which we attribute to the nature of the bedrock and drift of its catchment which both provide mainly sand-sized particles. It would appear that a sheltered lake of the morphometry of Loch Clair (figure 2*b*) provides a situation most favourable for maximum deposition of pollen grains (and possibly other forms of sediment) each year, with little loss down the outflow compared with a lake such as Windermere. This provokes speculation about the effects on lake biota of such favourable conditions for sedimentation, which are possibly related to the shape of Loch Clair, a rounded deep basin from which the outflow leaves from a position only about one quarter of the distance round the shore from the inflow. This may well contrast markedly with the situation in lakes, such as Windermere, where the long axis of the basin lies parallel to the course of inflow and outflow streams, in determining the proportion of particulate matter which is washed through the basin. This raises the interesting question of the possibility of changes in absolute pollen deposition in the past which could be due to climatic changes affecting the through-put of water in lakes of these two types.

In the work described in this paper, pollen analyses have been done by W.P. and A.P.B., diatom analysis by E.Y.H., and chemical analyses by J.P.L. Pages 228 to 238 have been written by E.Y.H. and the rest of the paper by W.P.

Field work in northern Scotland was originally assisted by a grant from Leicester University to W.P. in 1966 and 1967, when W.P., A.P.B. and J.P.L. were supported by a research grant from N.E.R.C. to the University of Leicester. The research project and further field work continued after all authors joined the staff of the Freshwater Biological Association's Quaternary Research Group. We should like to thank the coring team of the Freshwater Biological Association, particularly Mr B. Walker, for the hard work involved in obtaining the cores; the Nature Conservancy for the loan of boats, accommodation at their Anancaun Field Station, and for help by their staff on Loch Sionascaig and Loch Maree, and the various landowners for permission to work on their lochs.

Throughout the progress of the work we have been grateful to Mr F.J.H. Mackereth for discussion of methods and results. For help with specific problems we are indebted to the following; Professor R. D. Haworth, F.R.S., for analysis of humic acid; Professors P. Greig-Smith and P. H. A. Sneath for discussion of multivariate analysis and Mr M. J. Sackin, of the M.R.C. unit for Microbial Systematics in Leicester University, who carried out the computer analysis of the chemical data; Dr H. J. B. Birks, Dr H. H. Birks, and Miss R. Andrew for help with problems of pollen morphology; and Mr R. Ross, Dr P. Fusey and Mr J. R. Carter for help with taxonomic problems of the diatoms.

Appendix 1. Diatom taxonomy

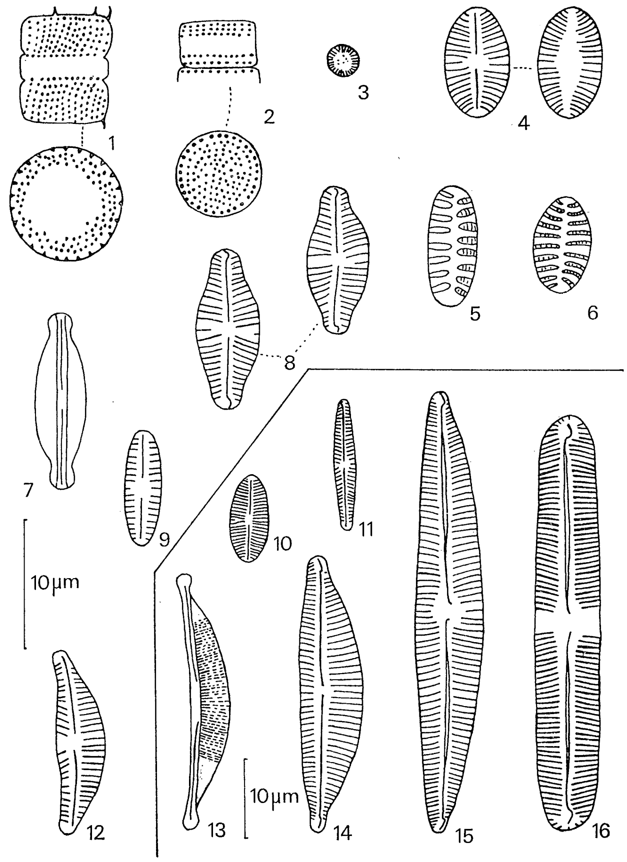


Figure 25. Selected diatom taxa:

1. *Melosira distans* var. *alpigena*
2. *M. tenella*
3. *Cyclotella comensis*
4. *Achnanthes levanderi*
5. *Fragilaria pinnata*
6. *F. elliptica*
7. *Navicula* sp. *S* 80
8. *Navicula* sp. *T*
9. *Navicula* sp. *S* 340
10. *Navicula* sp. *V*
11. *Navicula* sp. *S* 550
12. *Amphora* sp. *B*
13. *Amphora* sp. *A*
14. *Cymbella* sp. *L*20
15. *Cymbella* sp. *S* 10
16. *Pinnularia* sp. C

List of diatom species recognized at Loch Sionascaig

Note. Numbers refer to the position of the taxon on figures 7 and 8. + denotes that the taxon only occurs rarely in the core. Taxa can all be referred to drawings by Hustedt (1930, 1930–66) or the authority cited, unless specified.

Achnanthes affinis Grunow	·
A. atomus Hustedt	+
A. austriaca Hustedt	·
A. calcar Cleve	2
A. clevei Grunow	2
A. depressa (Cleve) Hustedt	101
A. didyma Hustedt	+
A. flexella (Kützing) Brun	·
A. flexella var. *alpestris* Brun	·
A. gracillima Hustedt	62
A. holstii Cleve	·
A. cf. *kryophila* Petersen	+
A. lanceolata (Bréb.) Grunow	·
A. lapponica var. *fennica* A. Cleve	·

A. laterostrata Hustedt	+
A. levanderi Hustedt	49, figure 25, no. 4
A. linearis W. Smith	53
A. marginulata Grunow	74
A. microcephala Kützing	57
A. minutissima Kützing	57
A. östrupii (A. Cleve) Hustedt	51
A. peragallii Brun & Héribaud	.
A. pseudosuchlandtii Manguin	83
A. pseudoswazi Carter	92
A. sublaevis Hustedt	+
A. suchlandtii Hustedt	50
Amphipleura pellucida Kützing	20
Amphora ovalis Kützing	5
A. ovalis var. *libyca* (Ehr.) Cleve	4
A. ovalis var. *pediculus* Kützing	5
Amphora sp. *A*	85, figure 25, no. 13
Amphora sp. *B* *eximia* Carter (unpublished)	78, figure 25, no. 12
Anomoeoneis exilis (Kützing) Cleve	58
A. exilis var. *lanceolata* Mayer	59
A. follis (Ehr.) Cleve	102
A. serians (Bréb.) Cleve	98
A. serians var. *brachysira* (Bréb.) Hustedt	73
A. zellensis (Grunow) Cleve	68
Asterionella formosa Hassall	30
Caloneis bacillum (Grunow) Meresch.	.
C. fasciata var. *fonticola* (Grunow) Petersen	76
C. obtusa (W. Smith) Cleve	+
C. schroederi Hustedt	+
C. silicula (Ehr.) Cleve	10
Campylodiscus noricus var. *hibernica* (Ehr.) Grunow	2
Ceratoneis arcus Kützing	45
Cocconeis diminuta Pant.	+
C. placentula Ehr.	12
C. placentula var. *euglypta* (Ehr.) Cleve	12
C. placentula var. *linearis* (Ehr.) Cleve	12
Cyclotella antiqua W. Smith	63
C. comensis Grunow	56, figure 25, no. 3
C. comta (Ehr.) Kützing	60
C. glomerata Bachmann	105
C. kützingiana Thwaites	55
C. meneghiniana Kützing	+
Cymbella affinis Kützing	.
C. aspera (Ehr.) Cleve	.
C. cesatii (Rabh.) Grunow	.
C. cesatii var. *capitata* Krieger	.
C. cistula (Hemp.) Grunow	.
C. cuspidata Kützing	.
C. gracilis (Rabh.) Cleve	.
C. helvetica Kützing	.
C. leptoceros (Ehr.) Grunow	10
C. microcephala Grunow	.
C. perpusilla A. Cleve	.
C. sinuata Gregory	39
C. subaequalis var. *oblonga* (Fontell) Ross	.
C. turgida (Gregory) Cleve	.
C. ventricosa Kützing	47
Cymbella sp. *S* 10	+, figure 25, no. 15
Cymbella sp. *L* 20	+, figure 25, no. 14
Denticula tenuis Kützing	11
Diatoma elongatum Agardh	15
D. vulgare Bory	+
Didymosphenia geminatum (Lyngbye) Schmidt	36

Diploneis elliptica (Kützing) Cleve	37
D. interrupta (Kützing) Cleve	+
D. marginestriata Hustedt	38
D. oblongella (Naeg. ex Kützing) Ross	.
Epithemia muelleri Fricke	+
E. sorex Kützing	9
E. turgida (Ehr.) Kützing	10
E. zebra (Ehr.) Kützing	13
Eunotia arcus Ehr.	70
E. bidentula W. Smith	70
E. bigibba Kützing	70
E. diodon Ehr.	70
E. elegans Östrup	70
E. exigua (Bréb.) Rabh.	70
E. faba (Ehr.) Grunow	70
E. faba var. *obtusa* (Grunow) A. Cleve	70
E. gracilis (Ehr.) Rabh.	70
E. lunaris (Ehr.) Grunow	70
E. monodon Ehr.	70
E. monodon var. *bidens* (Gregory) W. Smith	70
E. monodon var. *maior* (W. Smith) Hustedt	+
E. pectinalis var. *minor* (Kützing) Hustedt	70
E. pectinalis var. *minor* forma *impressa* (Ehr.) Hustedt	70
E. pectinalis var. *ventralis* (Ehr.) Hustedt	.
E. polyglyphis Grunow	+
E. praerupta Ehr.	.
E. robusta var. *diadema* (Ehr.) Ralfs	.
E. robusta var. *tetradon* (Ehr.) Ralfs	.
E. valida Hustedt	.
E. veneris (Kützing) O. Müller	.
E. acmocephala Fusey	.
Fragilaria brevistriata Grunow	6
F. constricta Ehr.	+
F. construens (Ehr.) Grunow	7
F. construens var. *binodis* (Ehr.) Grunow	8
F. cf. *elliptica* Schumann	7, Cleve-Euler† 1951–5, figure 348h, figure 25 no. 6
F. leptostauron (Ehr.) Hustedt	+
F. pinnata Ehr.	1, figure 25 no. 5
F. vaucheriae (Kützing) Petersen	27
F. virescens Ralfs	54
Frustulia rhomboides (Ehr.) de Toni	67
F. rhomboides var. *saxonica* (Ehr.) de Toni	66
F. vulgaris Thwaites	24
Gomphonema acuminatum Ehr.	.
G. acuminatum var. *brebissonii* (Kützing) Cleve	+
G. acuminatum var. *coronata* (Ehr.) W. Smith	.
G. angustatum (Kützing) Rabh.	.
G. constrictum Ehr.	.
G. gracile Ehr.	48
G. helveticum var. *tenuis* (Fricke) Hustedt	100
G. intricatum Kützing	+
G. intricatum var. *dichotomum* f. *semipura* Mayer	+
G. intricatum var. *pulvinatum* (Braun) Grunow	+
G. intricatum var. *pumila* Grunow	.
G. lanceolatum Ehr.	.
G. longiceps Ehr.	.
G. olivaceum (Lyngbye) Kützing	17
G. olivaceoides Hustedt	+
G. parvulum Grunow	.
G. subtile Ehr.	+
G. ventricosum Gregory	+
Gyrosigma acuminatum (Kützing) Rabh.	9
Hantzschia amphioxys (Ehr.) Grunow	29

Mastogloia grevillei W. Smith	+
M. smithii var. *lacustris* Grunow	+
Melosira cf. *distans* (Ehr.) Kützing	.
M. distans var. *alpigena* Grunow	72, figure 25, no. 1
M. islandica ssp. *helvetica* O. Müller	22
M. italica (Ehr.) Kützing	33
M. italica var. *valida* Grunow	33
M. tenella Nygaard	104, figure 25, no. 2
M. teres Brun	75
Meridion circulare Agardh	16
Navicula bacillum Ehr.	25
N. bryophila Petersen	89
N. cari var. *angusta* Grunow	.
N. cincta (Ehr.) Kützing	.
N. clementis Grunow	.
N. cocconeiformis Gregory	64
N. contenta var. *parallela* Petersen	82
N. costulata Grunow	3
N. cryptocephala Kützing	15
N. cuspidata Kützing	25
N. elginensis (Gregory) Ralfs	+, Patrick & Reimer‡ 1966, pl. 50, figure 3
N. fracta Hustedt	79
N. gibbula Cleve	+
N. graciloides Mayer	+
N. ignota var. *anglica* Lund	34
N. järnefeltii Hustedt	.
N. minima var. *atomoides* (Grunow) Cleve	.
N. mutica Kützing	40
N. naumannii Hustedt	+
N. perpusilla Grunow	41
N. petersenii (Petersen) Hustedt	95
N. pseudoscutiformis Hustedt	.
N. pupula Kützing	.
N. pusilla W. Smith	+
N. radiosa Kützing	.
N. radiosa var. *tenella* (Breb.) Grunow	.
N. rheinhardtii Grunow	25
N. rhynchocephala Kützing	26
N. rhynchocephala var. *elongata* Mayer	+
N. schassmannii Hustedt	87
N. scutiformis Grunow	93
N. seminulum Grunow	+
N. subtilissima Cleve	98
N. tuscula (Ehr.) Grunow	34
N. vulpina Kützing	+
Navicula sp. *T*	77, figure 25, no. 8
Navicula sp. *V*	+, figure 25, no. 10
Navicula sp. *S* 80 *impexa* Hustedt	91, figure 25, no. 7
Navicula sp. *S* 340	+, figure 25, no. 9
Navicula sp. *S* 550 *tenelloides* Hustedt	+, figure 25, no. 11
Neidium affine var. *amphirhynchus* (Ehr.) Cleve	42
N. affine var. *undulatum* Grunow	+
N. bisulcatum (Lager.) Cleve	46
N. dubium (Ehr.) Cleve	42
N. iridis (Ehr.) Cleve	+
N. iridis var. *ampliata* (Ehr.) Cleve	44
N. ladogense (Cleve) Foged	+
Nitzschia amphibia Grunow	84
N. amphibia forma *abbreviata* Manguin	+
N. angustata var. *acuta* Grunow	.
N. denticula Grunow	2
N. dissipata (Kützing) Grunow	21
N. fonticola Grunow	14

N. frustulum (Kützing) Grunow	28
N. frustulum var. *perminuta* Grunow	.
N. cf. *gracilis* Hantzsch	+
N. ignorata forma *longissima* Manguin	90
N. linearis W. Smith	+
N. palea (Kützing) W. Smith	.
N. recta Hantzsch	.
N. sinuata (W. Smith) Grunow	+
N. sublinearis Hustedt	+
N. cf. *suchlandtii* Hustedt	+
N. thermalis var. *minor* Hilse	18
N. tryblionella var. *debilis* (Arnott) Mayer	+
N. cf. *vivax* var. *tussei* A. Cleve	+
Opephora martyi Héribaud	+
Peronia heribaudi Brun & Peragallo	96
Pinnularia acrosphaeria Bréb.	+
P. alpina W. Smith	99
P. balfouriana Grunow	61
P. borealis Ehr.	+
P. braunii var. *amphicephala* (Mayer) Hustedt	+
P. brebissonii (Kützing) Rabh.	.
P. divergens W. Smith	.
P. divergentissima (Grunow) Cleve	+
P. episcopalis Ehr.	.
P. gentilis (Donkin) Cleve	.
P. gibba Ehr.	.
P. interrupta W. Smith	.
P. lata (Breb.) W. Smith	+
P. legumen Ehr.	.
P. maior Kützing	.
P. mesolepta (Ehr.) W. Smith	36
P. microstauron (Ehr.) Cleve	.
P. nobilis Ehr.	.
P. nodosa Ehr.	43
P. cf. *obscura* Krasske	+
P. platycephala (Ehr.) Cleve	88
P. semicruciata (A.S.) A. Cleve	86
P. silvatica Petersen	97
P. stauroptera (Rabh.) Cleve	.
P. stauroptera var. *minuta* Mayer	.
P. stauroptera var. *recta* (Mayer) A. Cleve	.
P. suchlandtii Hustedt	81
P. stomatophora Grunow	.
P. sudetica Hilse	.
P. tenuis var. *subundata* A. Cleve	+
P. undulata Gregory	.
P. viridis (Nitzsch) Ehr.	.
Pinnularia sp. *C*	80, figure 25, no. 16
Rhopalodia gibba O. Müller	15
R. gibberula (Ehr.) O. Müller	.
Stauroneis acuta W. Smith	.
S. anceps Ehr.	45
S. legumen Ehr.	94
S. phoenicenteron Ehr.	.
S. prominula (Grunow) Hustedt	.
S. smithii Grunow	35
Stenopterobia intermedia (Lewis) Fricke	71
Stephanodiscus astraea var. *minutula* (Kützing) Grunow	19
Surirella angusta Kützing	.
S. elegans Ehr.	52
S. linearis W. Smith	65
S. linearis var. *constricta* (Ehr.) Grunow	+
S. linearis var. *helvetica* (Brun) Meister	+

S. ovata Kützing	23
S. ovata var. *pinnata* W. Smith	23
S. robusta Ehr.	.
S. tenera Gregory	+
S. tenuis Mayer	+
Synedra acus var. *radians* (Kützing) Hustedt	31
S. amphicephala Kützing	.
S. capitata Ehr.	.
S. parasitica (W. Smith) Hustedt	11
S. pulchella Kützing	+
S. rumpens Kützing	+
S. ulna (Nitzsch) Ehr.	32
Tabellaria fenestrata (Lyngbye) Kützing	69
T. flocculosa (Roth.) Kützing	69
T. cf. *quadriseptata* Knudson	69
Tetracyclus lacustris Ralfs	103

† Cleve-Euler, A. 1951–5, *K. svenska Vetensk-Akad. Hanhl.* Fjärde Ser. **2–5**.

‡ Patrick, R. & Reimer, C. W. 1966 *The Diatoms of the United States.* Monographs **13**, A.N.S.P., 688 pp.

APPENDIX 2. LOCH NESS SEDIMENT

Details and analysis for total halide of one core from Dores Bay (21 m water)

(i) *Stratigraphy*

cm	
0–5	Soft brownish-grey clay-mud.
5–55	Brown and grey silty clay, mottled.
55–65	Grey clay with faint colour laminations.
65–90	Grey clay with graded diatactic varves, 2 to 5 mm wide.
90–91	Transitional grey clay.
91–133	Grey clay, consisting of laminations which are alternating bands of fine clay (the bands up to 1 mm wide) and extremely narrow layers of angular particles 10–30 μm in diameter.
133–135	Grey clay with brown sand.
135–157	Grey clay with faintly marked graded bedding laminations, visible only when half dry.
157–162	Grey clay with brown sand.
162	A conspicuous layer of brown sand in the grey clay.
162–166	Grey clay without visible laminations.
166	A conspicuous layer of brown sand in the grey clay.
166–200	Grey clay with faint colour laminations but no visible graded bedding.
200–205	Transitional.
205–219	Grey varved clay with such strong contrast in particle size between summer and winter layers that the coarse layers are mainly silt.
219–225	Grey silty clay without laminations.
225–272	Slumped layers of clay and silt, colour grey smudged black.
272–282	Hard grey silty clay with very fine gravel at base.

(ii) *Halide analysis*

cm	μg/g dry weight	cm	μg/g dry weight
54–55	44	134–135	36
55–56	46	140–141	73
65–66	71	150–151	68
71–2	26	160–161	61
80–81	24	170–171	38
89–90	29	200–201	24
91–92	28	220–221	36
100–101	35	230–231	66
110–111	19	250–251	81
120–121	66	270–271	27
130–131	58	280–281	39
133–133.5	154		

Note. Average total halide content of the varved clays of Windermere and Ennerdale Water is (
(determined by F. J. H. Mackereth).

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Loch Sionascaig. In the foreground is Boat Bay, surrounded by rocky shores of Lewisian gneiss; in the background are mountains of Torridonian sandstone. The sampling site is in the right middle distance, between the rocky point and the small island.