UNIVERSITY OF SOUTHAMPTON
Faculty of Science
Department of Geography

ORIGINS AND DEVELOPMENT OF THE FLOW COUNTRY BLANKET MIRE, NORTHERN SCOTLAND, WITH PARTICULAR REFERENCE TO PATTERNED FENS.

A thesis submitted for the degree of
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ABSTRACT

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The blanket mire of Sutherland and Caithness ('The Flow Country') comprises 400,000ha, the largest area of such peatland in Europe, yet there is incomplete knowledge of its present ecology and almost nothing is known of its palaeoecology. This study examines the status and development of patterned fens, a mire type only recently discovered in Scotland, and relates this to the more extensive surrounding ombrotrophic blanket mire.

A total of 141 vegetation and water chemistry samples were taken from eighteen sites, and analysed using multivariate ordination and classification techniques. A total of nine noda are described and compared with other British and European mire types. The development of patterned fens is elucidated using stratigraphic data and macrofossil analysis of selected cores from four sites. Most of these show a successional development from early fen peats to later ombrotrophic mire growth (ca.6500-6000bp). There is a reversion to poor fen peat after this (ca.2850bp at one site), which persists to the present day. A radiocarbon dated pollen chronology is described and is used as a basis for more detailed work in the Cross Lochs area. Data from a deep ombrotrophic peat shows similar early development to the fens but at ca.2700bp shows a change to a *Sphagnum* rich community, a response consistent with increased surface wetness. It is suggested that this stratigraphic change and the development of patterned fens was a response to climatic change. Development of surface pools on the fens is demonstrated to be a recent event, probably occurring via biological processes. Present process observations indicate that the surface patterning is probably ultimately unstable.

Investigations into the initiation of ombrotrophic peats are fraught with methodological problems; information on the sample context, macrofossil and loss on ignition data is required to establish the conditions under which peat has formed. A comparison of adjacent deep and shallow ombrotrophic peats indicates a primarily climatic origin for peat development in non-basin situations in this area, although anthropogenic burning may have speeded this process later.

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND TO THE STUDY

This research project was formulated as the result of previous work carried out on the peatland of Sutherland and Caithness, in which the author was involved for a short time (Lindsay *et al*, 1988). Although at the time of publication of the Nature Conservation Review (Ratcliffe, 1977), a range of peatland Sites of Special Scientific Interest (SSSI's) had been established, it was appreciated by the Nature Conservancy Council (NCC) that there was inadequate basic knowledge of this habitat to select a truly representative series of the best sites in Britain. This was especially true in the case of blanket mire, particularly in the far north of Scotland, where although there had been some early generalised descriptions (Crampton, 1911; Ratcliffe, 1964) and a little research (Pearsall, 1956), the extent and nature of most of the peatland was unknown. A series of surveys, carried out by the NCC, began in 1977 and continued and expanded in the early 1980's. The results of this work are reported in Lindsay *et al* (1988).

This produced an abundance of new data concerning the nature of the peatlands of Sutherland and Caithness, particularly the present vegetation. It also directed attention to several unusual mire features. One of these, 'Ladder fens' (Lindsay *et al*, 1988, p72), had a combination of attributes previously unreported from British mires but reminiscent of northern boreal patterned fens. These were; vegetation indicative of poor fen conditions; location in a water collecting area; flat, sloping morphology; long, narrow pools and ridges running across the slope. Speculations concerning their present status were made on the basis of these observations, and it was suggested that they were most similar to the 'ladder fens' of the oceanic wetlands of Atlantic Canada (Tarnocai *et al*, 1988; Wells

and Hirvonen, 1988), hence the given name. However, this seems premature, given the paucity of data and lack of comparative study and these sites are therefore referred to as 'patterned fens' in this thesis. This term merely suggests that the mires generally display fen vegetation and have pool and ridge surface microtopography, rather than implying affinity with specific mire types elsewhere in the world. A hypothesis regarding the origins and development of the mires was even more speculative, being based on no empirical data (Lindsay *et al*, 1988, p72).

The present status, origins and development of these mires were therefore enigmatic and this study aimed to investigate this fully. However, although NCC survey work had significantly improved understanding of present mire vegetation and characteristics, there was a complete absence of data concerning the origins and development of the blanket mire systems in general, apart from some incidental information from other work (eg. Durno, 1958; Smart, 1982), and few modern studies of the general palaeoecology of the region. Although, the palaeoecology and mire development of such a large area was too broad a remit for a three year doctoral study, it was accepted that in order to place the patterned fen systems within the correct context, some aspects of these subjects would be part of the research and, indeed, they have proven to be some of the most profitable avenues of investigation. Particularly in need of research were thought to be the early growth of ombrotrophic peats, in relation to the wider questions of anthropogenic influence on blanket mire growth (Moore *et al*, 1984), and the differences between the development of ombrotrophic blanket mire and patterned fens.

It is hoped that this thesis answers at least some of the questions it has set out to tackle, but that, more importantly, it also provides a springboard for further research into some of the questions it raises. The remoteness and inaccessibility of the peatland of

Sutherland and Caithness should not be a deterrent to potential researchers. So little is known of this immense blanket mire region, yet there are opportunities for palaeoecological research, unrivalled elsewhere in Britain.

1.2 THESIS STRUCTURE

Some of the terminology and classificatory vocabulary in mire ecology can be confusing and unfamiliar to ecologists and palaeoecologists from somewhat different backgrounds, particularly some foreign terms which have only gained credence relatively recently. Therefore, the first part of Chapter 2 briefly reviews literature for northern temperate mires and covers some of the main expressions used. The second part of this chapter defines the extent and describes the main features of the study area. Other brief literature reviews are given within other chapters, where appropriate, as the subjects concerned are diverse. It is hoped that this provides a more readable account of the research and permits most of the other chapters to be read in isolation from the rest of the text. Chapters 3-8 form the bulk of the text and describe the aims, methodology, results and implications of the research carried out.

Chapter 3 investigates the present vegetation and water chemistry of the patterned fens, and the relationships with existing phytosociological classifications and ombrotrophic mire communities. The remaining chapters are palaeoecological, and Chapter 4 describes the basic methods employed for this work. Chapter 5 examines the evidence for broad scale environmental change in the region, from the Devensian Lateglacial to the present day, concentrating particularly on the central, inland Flow Country, for which there is least existing data. The application of existing hypotheses for peat development to patterned fens is explored in Chapter 6, and new ideas are put forward. This is followed by data concerning the origin and development of surface patterning on the fens (Chapter 7). Chapter 8

reports the results of a study of ombrotrophic mire development and relates this to patterned fen stratigraphy. The study of the deeper peats is shown to reveal initial peat growth by hydroseral succession, but the initiation of ombrotrophic peats directly over mineral ground is more difficult to explain. This is examined in the second part of Chapter 8.

The concluding chapter (Chapter 9) discusses the wider implications of the work carried out, including the position of Scottish patterned fens in world mire classification, anthropogenic impacts on mire growth in northern Scotland and the possibility for establishing a model of mire initiation and development for the region.

CHAPTER 2: MIRE TERMINOLOGY AND THE STUDY AREA

2.1 MIRE ECOSYSTEMS: TERMINOLOGY AND CLASSIFICATION

Since this study is concerned primarily with peatland ecosystems and particularly with the properties of a specific mire type, it is necessary to outline the characteristics used in the discussion and classification of this habitat. This is especially important because mires have a number of distinctive properties which do not apply to other, perhaps more familiar, ecosystems. Moore (1984a) outlines seven main criteria used in mire classification, and of these, morphology, hydrology, stratigraphy and peat characteristics are unique to mires. It is also important to appreciate the range of mire systems in order to place the blanket mire of the Flow Country within a national and international context, and to understand later discussions, for example when comparing the attributes of patterned fens with those of adjacent mire types.

The idiosyncrasies of peatlands have resulted in extensive discussion and descriptions of different taxonomies in the literature (eg International Peat Society, 1973; 1976; Goode and Ratcliffe, 1977; Gore, 1983b; Moore, 1984b), and the problems of a complex ecosystem are amplified by the different objectives of the various authors. For example, economic exploitation of peat requires only generalisations on peat composition (eg.Puustjarvi, 1973), while ecologists are concerned with more complex classifications. What follows is a summary of the more widely used terms, particularly those which are of most use for this study. Some of the terms have been used in slightly different ways in the past, and this discussion indicates the way in which they will be used throughout this thesis. It is restricted to temperate peatlands and biased towards those found in more oceanic areas. The criteria are interdependent to a certain extent, so that resulting mire types are defined by combinations of these attributes.

2.1.1 Hydromorphology

Because peatlands are organic accumulations, which may still be extending laterally and vertically, there are variable mire forms, characteristic of different hydrological and chemical conditions. This operates at several different scales. Aario (1932) distinguished 'Grossform' as the overall shape of a mire, and 'Kleinform' as the attributes of the surface topography, which may be separated into hummocks and hollows or pools. Ivanov (1981) discusses 'mesotopes' and 'microtopes', which are roughly equivalent, but also mentions 'macrotopes', which consist of a number of different mires combined to form a 'mire complex'. This concept is particularly useful when applied to British blanket mire, where there are no clear limits to the peatland, but within a large area there may be several different mire types.

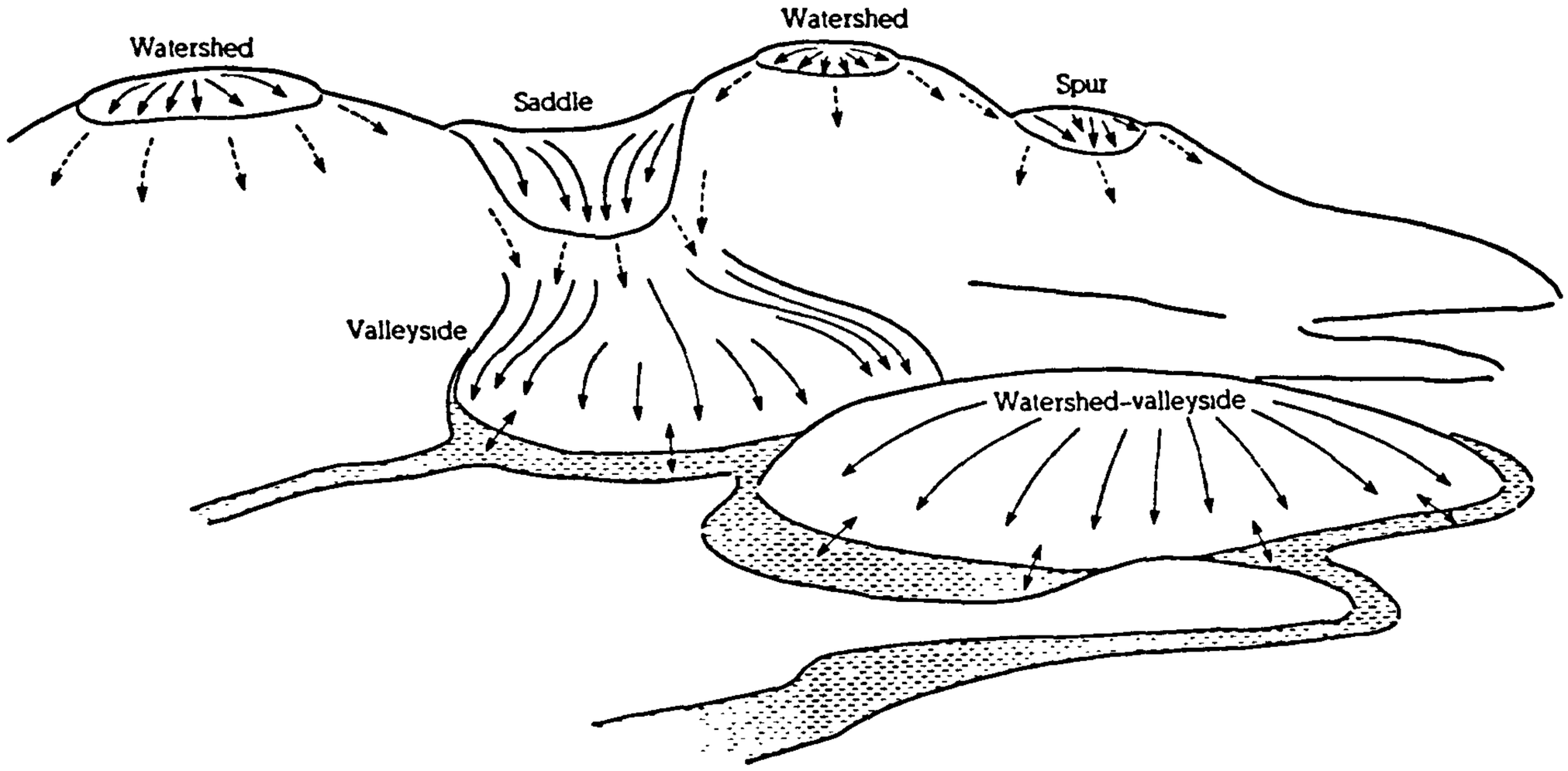
Clearly, the shape of a mire system influences the source area and surface flow of water, and this in turn affects the growth rate and therefore the shape of the peat body. This leads to the separation of 'minerotrophic' mires (fens), influenced by nutrient enrichment, and 'ombrotrophic' mires (bogs), whose water supply is limited to precipitation. The use of trophic status is generally attributed to Du Reitz (1954), as previously the suffix 'genous', implying that the mode of origin of the mire was known, had been used (eg.Tansley, 1939). The terms 'bog' and 'fen' are misused occasionally, for example in some marginal situations such as the valley 'bogs' (sic) (Newbould, 1960) in the New Forest, which are strictly fen systems although their nutrient status is very low.

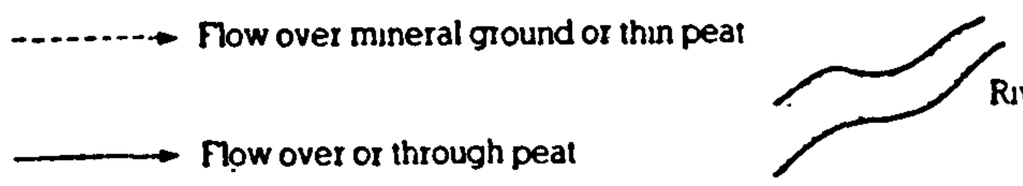
Further subdivisions of the two main categories are also on the basis of the mire form. Minerotrophic systems occur in a variety of situations, obtaining their nutrients and moisture from either standing water, as a result of local topography, or due to an excess of flowing water. The generic terms are generally accepted here, the former are

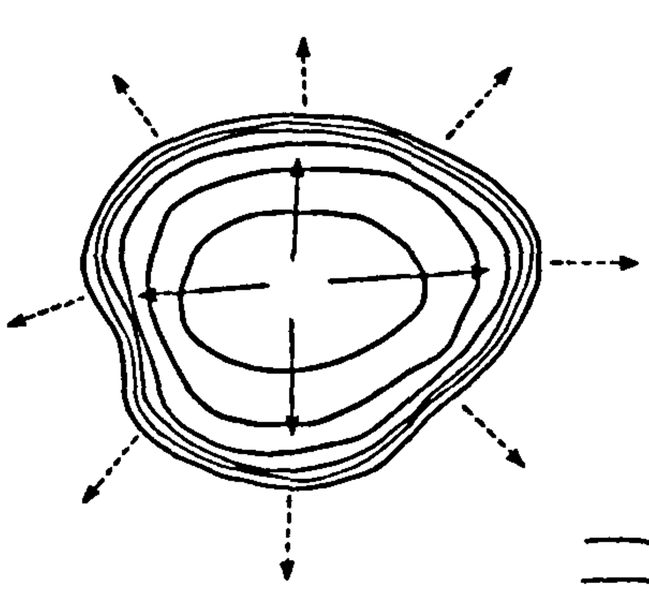
referred to as 'topogenous' and the latter are 'soligenous' mires or 'rheotrophic' systems (Kulzynski, 1949). Topogenous mires are flood plain fens, as in much of the East Anglian fenland, basin fens and lake margin fens. Soligenous mires are valley fens (described for southern England by Rose, 1953), spring fens and flush fens, often occurring within or around ombrotrophic mires.

For British mires, Tansley (1939) is largely responsible for establishing the terms 'raised' and 'blanket' bogs, the two main types of ombrotrophic mires. These broadly correspond to the 'confined' and 'unconfined' mires of Hulme (1980), which have not gained wide recognition. Raised mires usually form initially in basin situations, developing from basin fen communities which grow to a point where they become independent of groundwater influence and become dominated by Sphagnum mosses and higher plants tolerant of extremely acid conditions (Walker, 1970). Blanket mires, as the term implies, cover large areas of landscape with peat of variable depth which forms on all but the steepest and most exposed ground.

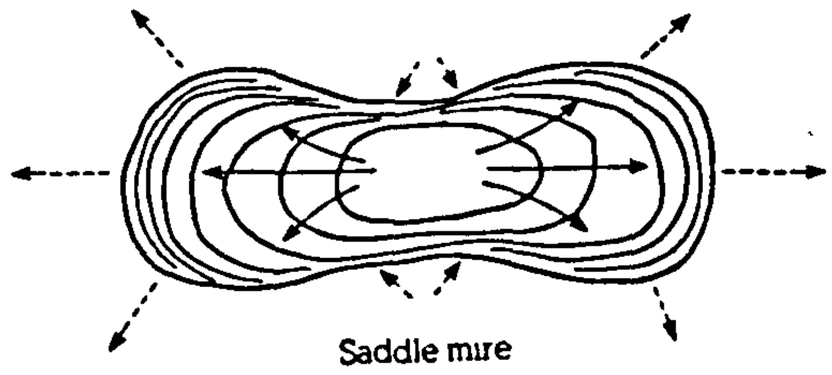
The classification of blanket mire has received little attention apart from that of Goode (1972, 1973) and Goode and Lindsay (1979) who recognise mires forming on watersheds and valleysides as distinctly different. Goode (1972) also recognises saddle mires, formed between two summits as a morphological type. During NCC survey it was found necessary to develop a classification of blanket mire elements which was easily applicable in the field. Hence the following broad categories can be used:- watershed, valleyside, watershed/valleyside, spur and saddle, depending on their topographic position and resulting morphology (Lindsay et al, 1988). Each type has a different flow of surface water and therefore has a different nutrient distribution pattern and forms different surface patterns of pools and ridges. These are shown in Figure 2.1.



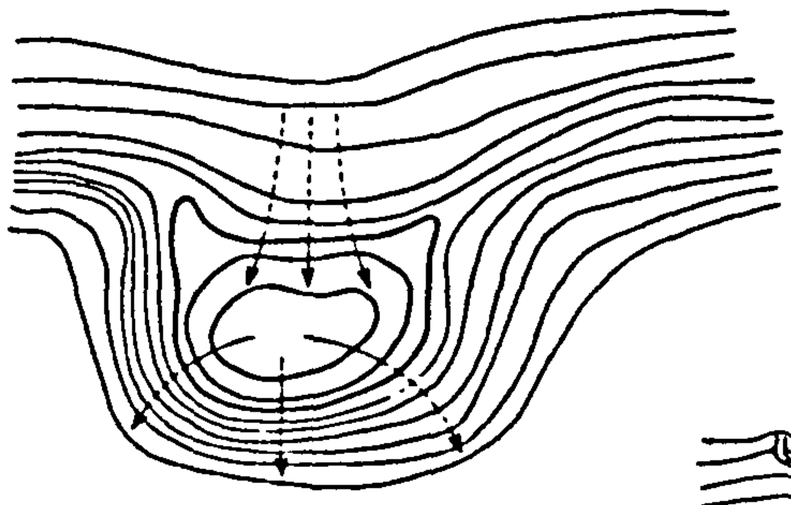




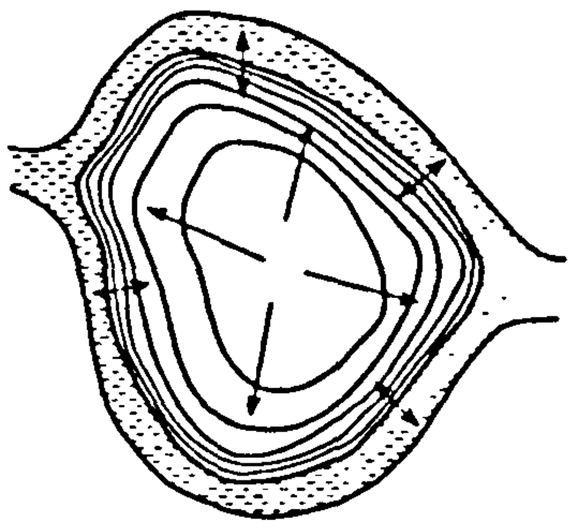
Watershed mire



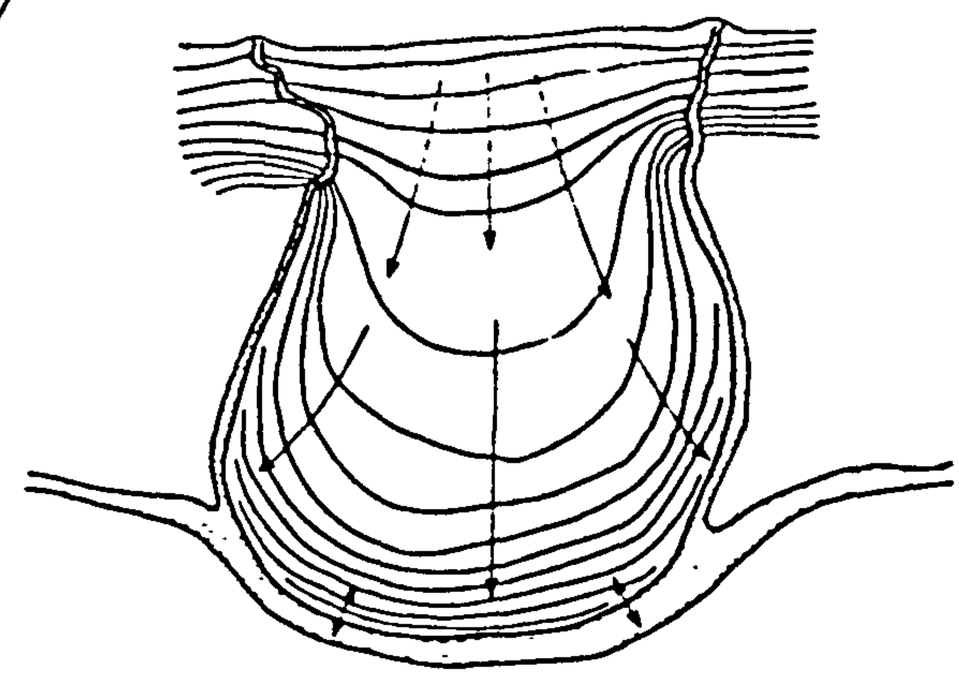
Saddle mire



Spur mire



Watershed-valleyside mire



Valleyside mire

Figure 2.1: Hydromorphological classification of blanket mire according to Lindsay *et al* (1988).

The oceanic position of the British Isles has led to large areas of blanket mire (of which the Flow Country is part), which occurs in few other European locations. However, raised mires and a variety of fens are broadly similar in overall development and morphology across the northern temperate region. The mire formations closer to the pole are similar in North America and northern Eurasia with permafrost influence expressed in 'palsa' mires and 'pounikkos', but northern Britain is too oceanic to possess such features. The major mire type which Britain is believed to lack but which occurs in abundance in the intermediate climatic range is that of patterned fens (Finnish 'aapa moors', sometimes 'ribbed fens' or 'patterned fens' in North America). These are characterised by low gradients and long pools and ridges (Swedish/ north American 'flarks' and 'strings', Finnish 'rimpis' and 'kermis') with species indicative of fen conditions. It is this range of features which has recently been reported to occur in northern Scotland (Lindsay *et al*, 1988).

2.1.2 Stratigraphy and development

Stratigraphic examination of mires indicates the sequence of changes in vegetation, and often hydromorphology, that have taken place, leading to present conditions. Moore (1984a, p4) asserts it would be the "most natural and theoretically satisfying system of mire classification", but the time consuming nature of such investigations preclude its use in most situations. Where the origins and development of mire systems are of concern, however, it is an essential aspect to consider. A tripartite classification of 'templates' of peat formation has been proposed (Bellamy, 1972; Moore and Bellamy, 1974), dividing peatlands into 'primary', 'secondary' and 'tertiary' peats. Primary peatlands form in depressions, secondary peats extend beyond the physical confines of the basin due to the existing peat acting as a reservoir, and tertiary systems are those which develop above the limits of the groundwater. However, these can be difficult to distinguish

in practice.

2.1.3 Vegetation

While hydromorphological criteria form the basis for a primary classification of mires, vegetation is also important as an indicator of environmental conditions and as a variable in its own right. It should be emphasised that it is a classification on a different level to hydromorphology, to be superimposed on that system. A vegetation type may occur on a number of different hydromorphological mire types or be restricted to a single mire type, with specialised conditions prevailing. It must therefore be used in combination with hydromorphological attributes, to characterise a peatland.

There is no universally accepted scheme of vegetation classification for mires in Britain and generally research has concentrated on restricted types. Daniels (1978) produced a classification covering the whole of Britain but did not relate it to other mire classifications. Wheeler (1984) summarises British fen vegetation, although with a bias towards mesotrophic and eutrophic systems. Wheeler (1980a, 1980b, 1980c) has covered rich fens comprehensively but poor fens have received much less attention although there is some data for Wales (Slater, 1984). Further north there are some summaries for a restricted range of vegetation types (Burnett, 1964, and especially Ratcliffe, 1964; McVean and Ratcliffe, 1962). Bog vegetation is also included in the last two accounts. Recently Birse (1980 and 1984) has produced a more comprehensive treatment of Scottish vegetation using classical phytosociological methods and Dierssen (1982) has provided a comparison with other north west European mire vegetation.

Finally, the ongoing work of John Rodwell and Mike Proctor on the National Vegetation Classification (Proctor and Rodwell, 1986) has produced the most comprehensive accounts of mire vegetation in Britain across most of the range of

variation and this will probably become the standard work for mire vegetation types for the UK.

Vegetation studies in Britain have evolved largely in isolation from those in Europe so that comparisons of vegetation with that elsewhere is difficult (see Chapter 3). In mire ecology there is a vast, but often inaccessible, literature for Scandinavia and the USSR, recently summarised by Ruuhijarvi (1983) and Eurola *et al* (1984) for Finland, Sjors (1983) for Sweden, and Botch and Masing (1983) for the USSR. North American publications are reviewed by Zoltai and Pollett (1983) and National Wetlands Working Group (1988) for Canada, and Hofstetter (1983) for the USA. Vegetation in these areas differs in possessing greater structural diversity, so that classifications incorporate a vertical component.

2.1.4 Water chemistry

Although the classification schemes commonly refer to trophic status, mires are not often strictly defined by measured chemical attributes. Instead, the vegetation is used as an indicator of prevailing conditions and is more easily defined and recorded. The ecological effect of water quality is also altered by water flow rate and total supply, and its measurement is complicated by a variety of factors such as seasonal and spatial variability (see Chapter 3), so that its use is normally limited to one of support for floristic studies.

Nutrient levels in mires are therefore often assumed from hydromorphology and vegetation. Information specifically on chemical status has, however, been published for a variety of mire types in northern Britain (Gorham, 1950; Gorham and Pearsall, 1956; Pearsall, 1956 and Boatman et al, 1975), and many vegetation accounts also include some basic water chemistry measurements (eg. Boatman and Armstrong, 1968; Daniels, 1978). Much early work in Scandinavia also concerned chemical attributes (Witting, 1947; 1948; 1949;

Sjors, 1950), but more recent accounts by Comeau and Bellamy (1986) and Malmer (1986), concentrate on international comparisons of these qualities.

In summary, there are a variety of different characteristics used in the classification of mire systems and various authors emphasise particular aspects of these. A hydromorphological classification is most appropriate as a primary classification, combined with vegetation and water chemistry to distinguish different types within these main mire types. Discussions throughout the thesis will use this as a basis.

2.2 THE STUDY AREA: THE FLOW COUNTRY

In this section the definition and characteristics of the general study area will be discussed. Specific site attributes will be discussed at the beginning of each relevant chapter.

2.2.1 Geographical extent

The region under consideration is that comprising the northern peatlands of Scotland. This is a rather nebulous term as although the main deep peat body in northern Scotland lies in eastern Sutherland and Caithness, the precise limits of its boundaries are difficult to define. The Royal Society for the Protection of Birds (RSPB, 1985) defined the 'Flow Country' in rather narrow terms as being the deep, flat expanse of peat between Strath Naver and the River Thurso, extending north almost to the coast and south to Kinbrace (see Figure 2.2 for place names referred to in text). However, Lindsay et al (1988) have shown peatlands extend well beyond this definition, becoming more fragmentary towards the south and west but having a total area in excess of 400 000 ha in the two counties. Figure 2.3 shows the distribution of this peat.

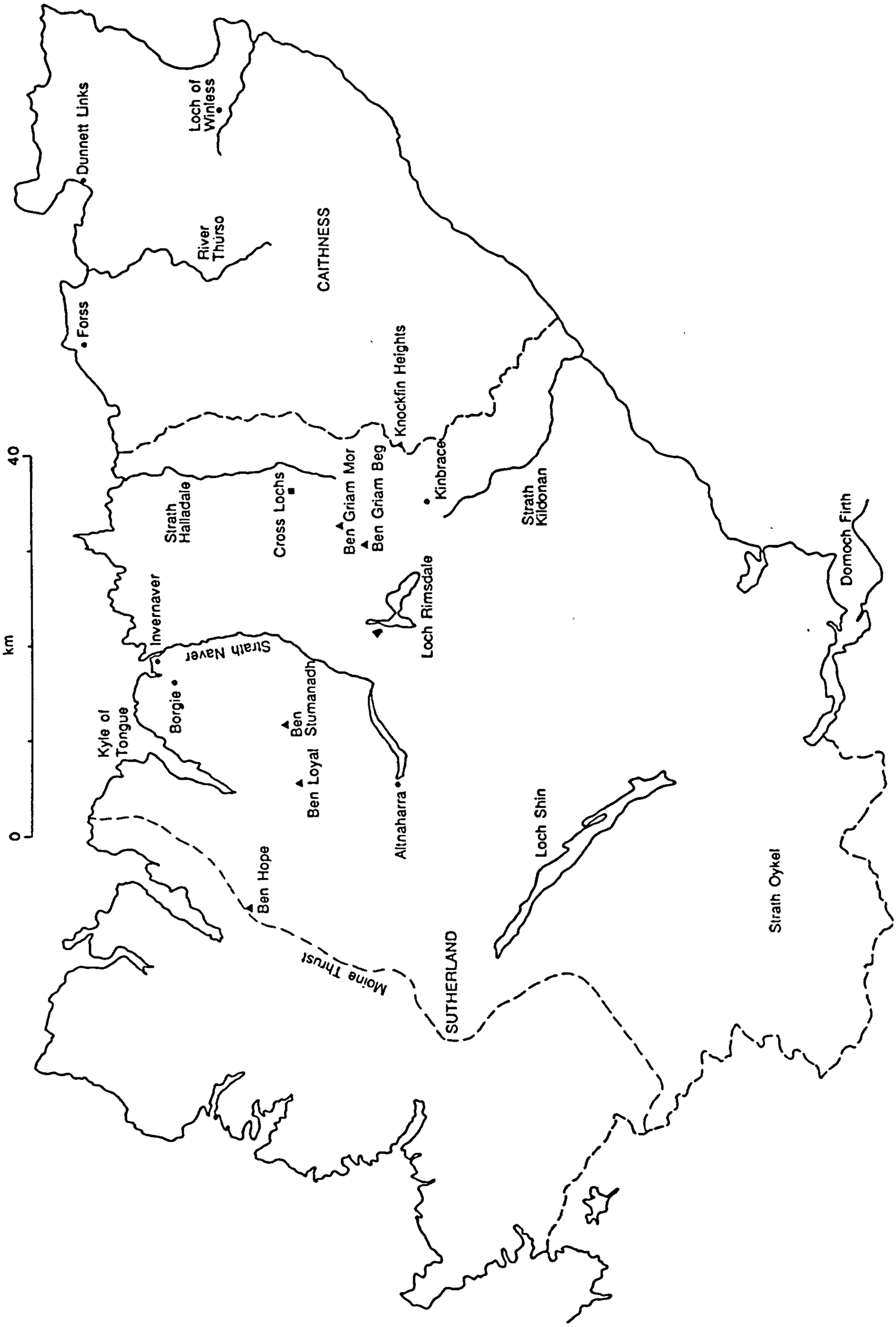
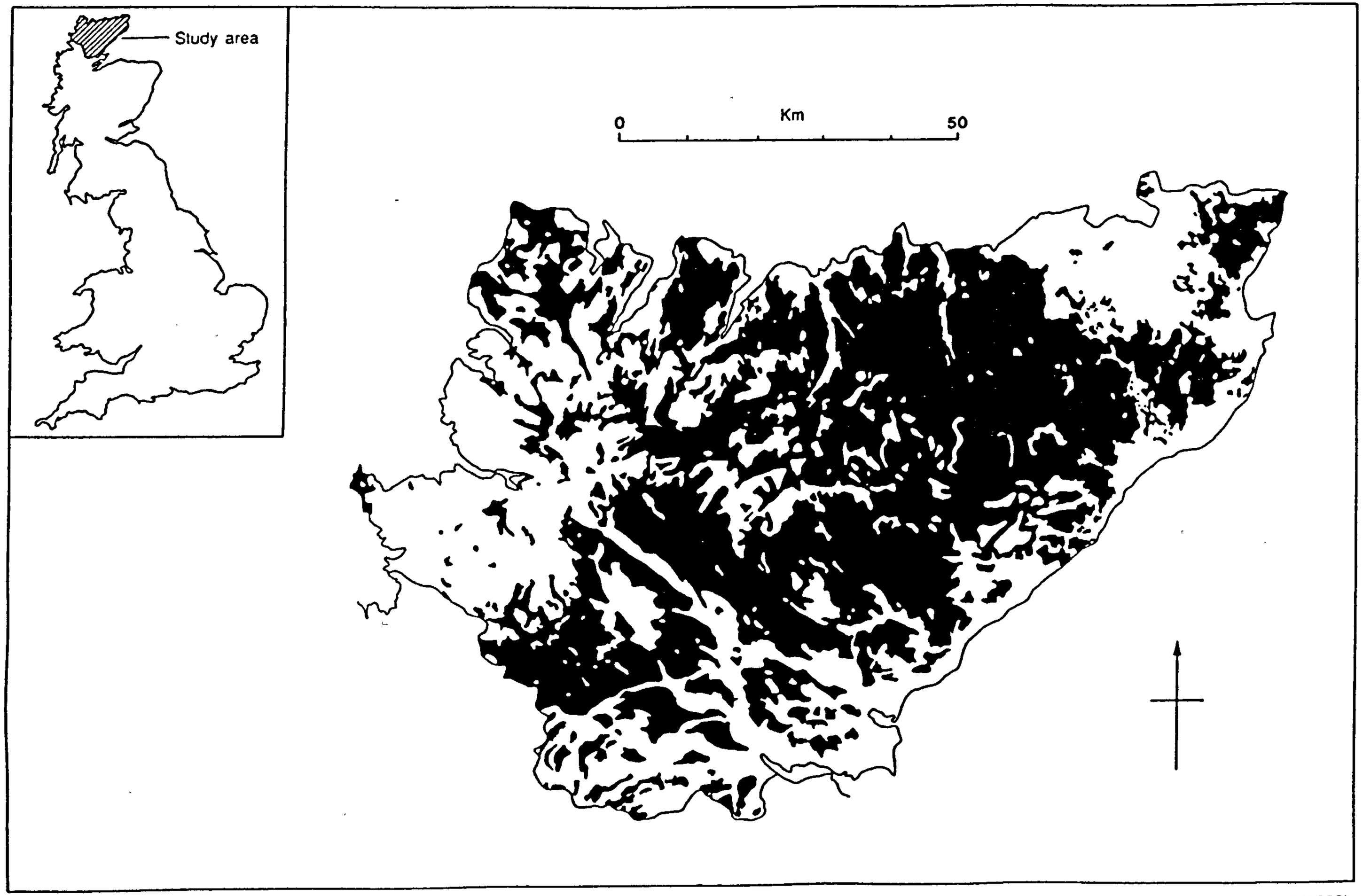


Figure 2.2: Northern Scotland, indicating place names referred to in text.



Source: Lindsay *et al* (1988)

Figure 2.3: Peatland distribution in Sutherland and Caithness.

2.2.2 Geology and relief

These two factors are closely allied within the region and are important in the initiation and growth of peat. Simplifying the geology, the region splits into three main distinct units. The area west of the Moine thrust consists mostly of Lewissian Gneiss, forming undulating, rocky landscape with numerous small lochs and peat basins. The quartzite capped peaks of the mountains around the Moine thrust have steep, often unstable slopes, unsuitable for peat formation. The central and eastern part of Sutherland is made up mostly of schists of the Moinian series. Low summits, with gentle slopes are more frequent here so that peat is more continuous, although rocky outcrops are still common. Peaks such as Ben Loyal and the Ben Griams interrupt this general pattern. Caithness is mostly underlain by Old Red Sandstone, forming a largely flat landscape where topography is ideal for mire development. Much of this area in north eastern Caithness is under agriculture. Additionally there are some granitic intrusions in the area, forming uplands on which watershed mire, like that at Knockfin Heights has formed.

2.2.3 Climate

Clearly, climatic 'wetness' must be important for the initiation and development of an actively growing mire surface. The relationship between climate and mire types and distribution for this region has been examined in detail by Lindsay et al (1988) from data presented by Birse and Dry (1970), Birse and Robertson (1970) and Birse (1971), and a summary of this is given here. There is a steep west-east rainfall gradient, varying between 2500mm pa in some of the western mountain areas and <1000mm pa in the east. Much of the deep peat is subject to only 650-1000mm pa. However, while the rainfall is comparable to much of southern England, the number of 'wet days' (>1mm rain in a 24 hour period) is high at 160-220 compared with <120 in central and southern England. In addition to this

temperatures are low (<8°C daily average) so that evapotranspiration is less. Hence, six monthly water surpluses (April to September) are in excess of 200mm over most of the region. Surpluses may be marginally greater further west and south in Scotland but often the slope gradients there reduce waterlogging through rapid runoff, and prevent peat formation. The geological and topographical characteristics of Sutherland and Caithness, however, are favourable for such a process.

2.2.4 Vegetation

The texts dealing with Scottish vegetation in general but including this region are Burnett (1964) and McVean and Ratcliffe (1962). More recent texts, restricted to phytosociology, are Birse (1980;1984). Species records are given in Kenworthy (1976) and Bullard (1977), but there is no regional synthesis.

Where peatland grades into higher altitude or steeper land, *Calluna* heath is often the dominant vegetation. This may be *Calluna-Arctuous*, *Racomitrium-Calluna* or more rarely lichen rich *Calluna* heath (McVean, 1964). *Vaccinium-Calluna* communities are present on steep and unburnt slopes. *Racomitrium* heaths occur at higher altitudes, with a range of arctic-alpine communities. The unusual climatic conditions of the north coast result in some of these mountain vegetation types descending almost to sea level, as in the case of the *Dryas* heath at Invernaver, Sutherland. For much of the coastline, heath and bog communities extend to the cliff edge, but there are areas of shingle and saltmarsh with sand dunes in many places (eg Dunnett Links). Improved agricultural land is restricted to valley bottoms but is more extensive in north east Caithness, where large areas are under a mixed pastoral/arable land use.

The region is largely treeless, apart from recent plantations, but there are fragmentary woodlands dominated

by *Betula pubescens subsp odorata*. This is mainly in Strath Naver, with scattered remnants elsewhere such as Strath Kildonan, Kyle of Tongue and the lower slopes of Ben Hope, Ben Loyal and Ben Stumanadh. Other arboreal species such as *Sorbus aucuparia*, and *Populus tremula* are also present and *Alnus glutinosa* occurs along some water courses. *Alnus* becomes more frequent in the south east and *Quercus petraea* is fairly common around the Dornoch Firth. Most of the present forest is planted, however, some broadleaved as at Forss, Caithness but the majority is coniferous, mostly of *Pinus contorta* and *Picea sitchensis*, but also *Pinus sylvestris* and occasionally *Larix* spp. Some Forestry Commission plantations have been established for some time, for example around Loch Shin, Strath Oykel, Loch Rimsdale and Borgie. More recent planting by the F.C. and private forestry companies has increased these plantations but has also extended to the flatter peatlands between Strath Naver and the River Thurso (Lindsay *et al*, 1988 and Figure 2.4).

Peatland vegetation is not covered in detail in 'classic' accounts of Scottish vegetation (Burnett, 1964; McVean and Ratcliffe, 1962). Lindsay *et al* (1988) give a full regional account for Sutherland and Caithness and define thirty five communities in twelve vegetation 'groups'. The majority of these are from ombrotrophic blanket mire but a few oligotrophic flush communities are also described. Their relationships with other communities elsewhere in Britain (Proctor and Rodwell, 1986) and Europe (Dierssen, 1982) is discussed. Vegetation and surface microtopography are combined to produce fifteen 'site types', to categorise whole sites rather than vegetation types within sites. The simple division of bog types presented by Ratcliffe (1964) based on the relative dominance of *Calluna vulgaris*, *Eriophorum* spp, *Tricophorum cespitosum* and *Molinia caerulea* is thus considerably refined for this area.

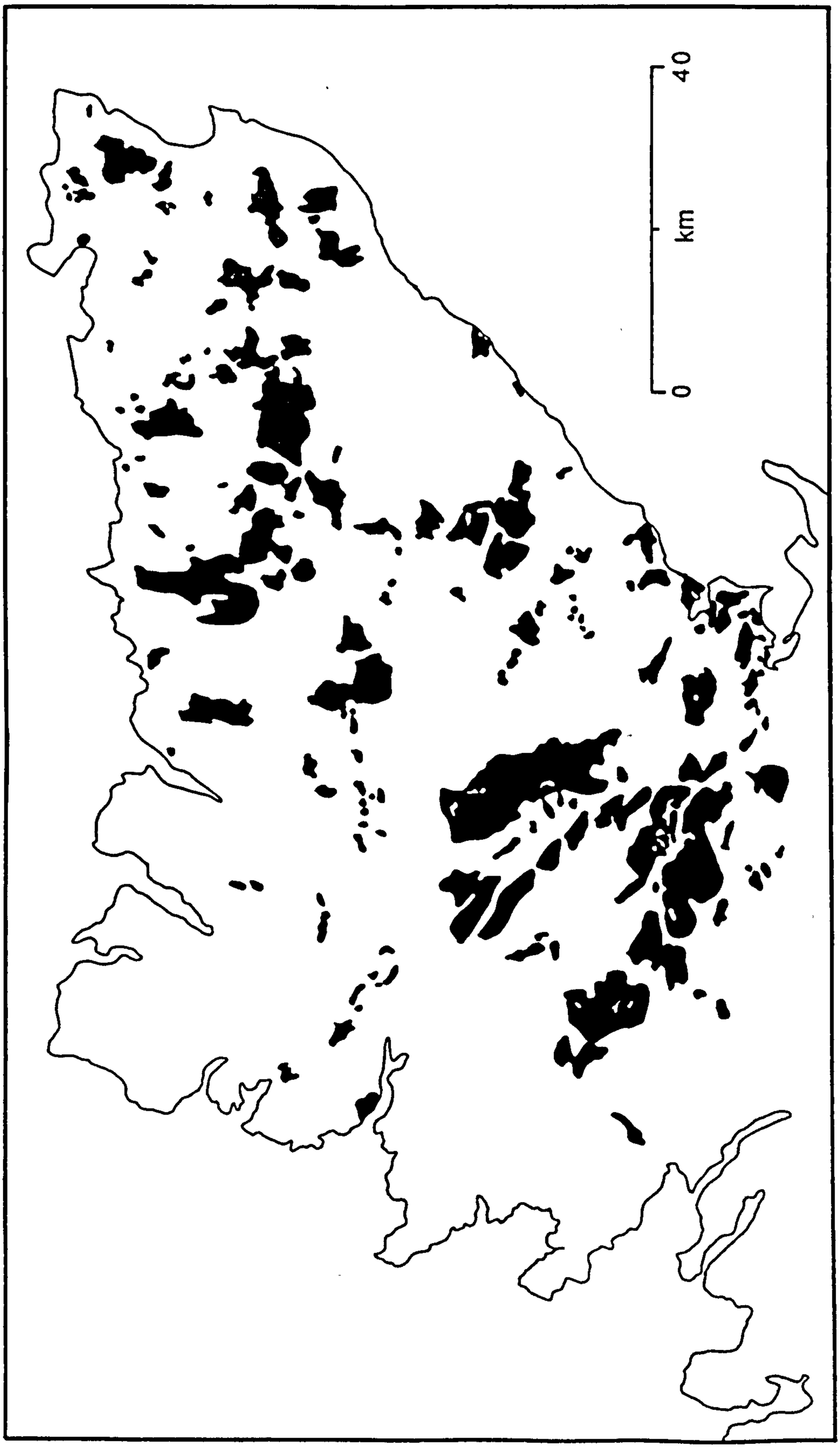


Figure 2.4: The extent of plantation forestry in Sutherland and Caithness (as in 1988).

2.2.5 Conservation value

Major changes have been made to the ecology of Sutherland and Caithness over the last ten years, and some mention of this is an important part of the background information of the area.

The conservation importance of the peatlands and associated habitats has been emphasised by both Government (NCC, 1986; Stroud *et al*, 1987; Lindsay *et al*, 1988) and voluntary bodies (RSPB, 1985; Bainbridge *et al*, 1987; Scottish Wildlife Trust, 1987). In all these reports, afforestation has been identified as the major impact on and threat to the ecology. The major importance to wildlife conservation is summarised by Ratcliffe (1988, p143) as eight nationally and seven internationally valuable features and in summing up he states:

'In essence, the outstanding importance of these peatlands, both nationally and internationally, lies in their total extent, continuity and diversity as mire forms and vegetation complexes and in the total size and range of species composition of their bird populations.'

Of most relevance to this study, is how little we actually know about the palaeoecology and certain aspects of the present vegetation of such a vast mire area. The opportunities for palaeoecological research are enormous but are being rapidly lost with ploughing and planting of large tracts of the peat holding the sedimentary record. Furthermore, there are arguments in the conservation versus forestry debate concerning the vegetational and anthropological history of the area which can only be resolved by such research.

CHAPTER 3: PRESENT ECOLOGY OF PATTERNED FENS

3.1 INTRODUCTION

There has probably been more data collected regarding the vegetation of mire ecosystems, than for all other aspects of their functioning. The importance of vegetation lies not only in the inherent interest of its communities, populations and interactions, but in its role as an indicator for, and influence on, many other aspects of mire ecology. In particular it is used as an indicator of environmental conditions on the mire surface, and by inference, of the regional environment. This is of importance in the present day classification of mire systems and in the use of palaeovegetational records for environmental reconstruction. This chapter considers the main trends and relationships of vegetation and water chemistry on patterned fens in northern Scotland.

3.2 AIMS AND OBJECTIVES

Given the lack of existing data from patterned fen systems in northern Scotland and the relatively recent "discovery" of these features (Lindsay et al, 1988), there is a primary need simply to describe them in terms of the relevant characteristics used for comparison and classification of peatland types (see Chapter 2). Once formally described they can either be assigned to an existing mire type or a new category can be proposed to accommodate them. The characteristics outlined in Chapter 2, used for the majority of ecological classifications are hydromorphology (and ontogeny), vegetation and floristics and soil and water chemistry. Extensive palaeoecological research deals with the ontogeny and hydromorphology of the systems (Chapter 6), so that in this chapter the broad aims are to describe the other features to enable comparisons to be drawn with other mire types both within Britain and throughout the world.

Although the patterned fens in northern Scotland can be considered as a single group and their relationships with other generalised mire types can be examined, a further aim of this part of the research is to assess the degree of variation between and within sites.

This basic classification and establishment of range of variation, is important for two main reasons. Firstly, for further ecological research, it is a basic requirement that the variability of any ecosystem is known, and secondly for the purposes of site selection for conservation. The conservation policies of many countries include an assessment of the range of variation of potential sites (Ratcliffe, 1977; 1986; Pearsall *et al*, 1986; Van der Ploeg, 1986) so that "representative" sites can be selected. This approach has been used in the selection of existing peatland Sites of Special Scientific Interest (SSSI's) and National Nature Reserves (NNR's) (Goode, 1972; Goode and Ratcliffe, 1977; Ratcliffe, 1977; 1986). Clearly, where "new" types of site are discovered, there is a need to set them within a national context and to select sites which fully reflect the perceived differences between these and other sites.

Summarised, the main aims of this chapter are:

1. To describe the character of the patterned fens in northern Scotland with respect to:
   ii) Vegetation
   ii) Water chemistry
2. To classify the vegetation of the sites according to existing national and international classification systems.
3. To assess inter-site variability of vegetation and water chemistry with a view to describing the range of variation within patterned fen systems in northern Scotland and investigating the most likely environmental gradients determining this.

3.3 METHODOLOGY

3.3.1 Site selection and location

The stated aims require that as many sites are used for data collection as is practically possible in the limited time available. However, a major problem existed initially as there were (and still are) many patterned fen sites still awaiting recognition. Although survey work by the Nature Conservancy Council's North of Scotland Peatland Survey had revealed a number of sites (Lindsay et al, 1988), these were very few in number. However, a number of other possible site locations were available from talking to NCC staff with field experience in Sutherland and Caithness, in particular Dr TH Keatinge (ARO, Sutherland) and Mr RA Lindsay (Peatland Specialist, CSD). Most NCC peatland survey sites were initially noted from aerial photographs but most patterning on fen sites is too small scale to be visible on the 1:25,000 scale photographs which formed the only complete air photo cover for northern Scotland at the time, so that a complete search of the likely area was impossible. A four stage site selection system (Figure 3.1) aimed to obtain the maximum number and range of sites for each stage of analysis, while remaining economical in terms of data collection time.

Initially, as many site locations as possible were obtained from NCC records and from verbal reports. The first phase of fieldwork involved visiting all of these locations to gain some basic information on their suitability for more detailed vegetation and water chemistry work. Records were made of surface patterning, topographic situation, obvious surface water flow, vegetation types and notable plant species, together with a photographic record. Sites were excluded from further work where there was extensive damage by forestry or drainage or where they did not possess the following features:

i) Some expression of fen development, with signs of nutrient enrichment and/or water movement, with vegetation

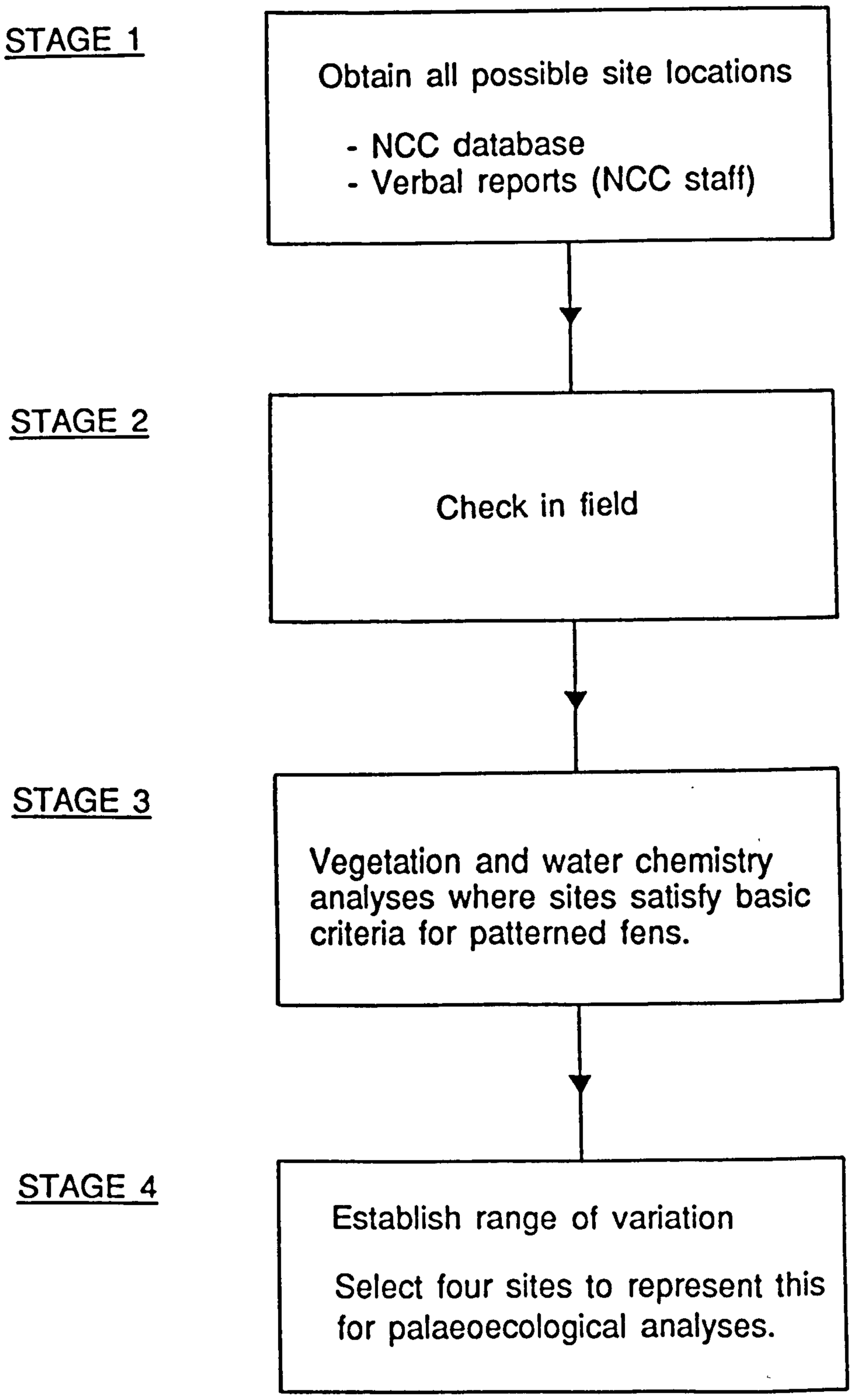


Figure 3.1: Selection procedure for patterned fen sites.

appreciably different to surrounding blanket mire vegetation.

ii) Transverse, linear pools or hollows and ridges in an approximately regular arrangement.

Other microtopography noted was a system of runnels and anastomosing pools, more usual in some valley fen systems, particularly in the west of Scotland and the Hebrides (eg.Goode and Lindsay, 1979) and zones of water movement within otherwise uniform blanket mire displaying no microtopographical variation.

In addition to this first checklist of sites, a number of others were recorded while traversing the sometimes considerable distances to and from sites. Different routes were used where possible in order to maximise the numbers of extra sites noted in this way. It is recognised that these methods will by no means identify all sites within Sutherland and Caithness but they will at least give the best results within the limitations of time. Since this work was completed, a more comprehensive field survey effort of large parts of Sutherland and Caithness peatlands is being undertaken by a team based at NCC's Golspie office, Sutherland which should yield more accurate information on the distribution of patterned fens in the area.

Seventeen sites resulted from the above procedures and some data was collected from all of them (see Table 3.1). The distribution of sites for vegetation and water chemistry analyses is shown by Figure 3.2. Ongoing survey work by NCC has shown that there are likely to be a much larger total number of sites. Survey of a relatively small (approx.70km^2) area north of Altnaharra (the proposed Bad na Gallaig and an as yet nameless SSSIs) has identified 70 separate sites in total (A.Coupar, pers.comm.) compared with only 4 known to the author prior to this survey. However, the NCC work covers sites with similar vegetation but no surface patterning, thereby encompassing far more sites than would have been considered for this study. It is

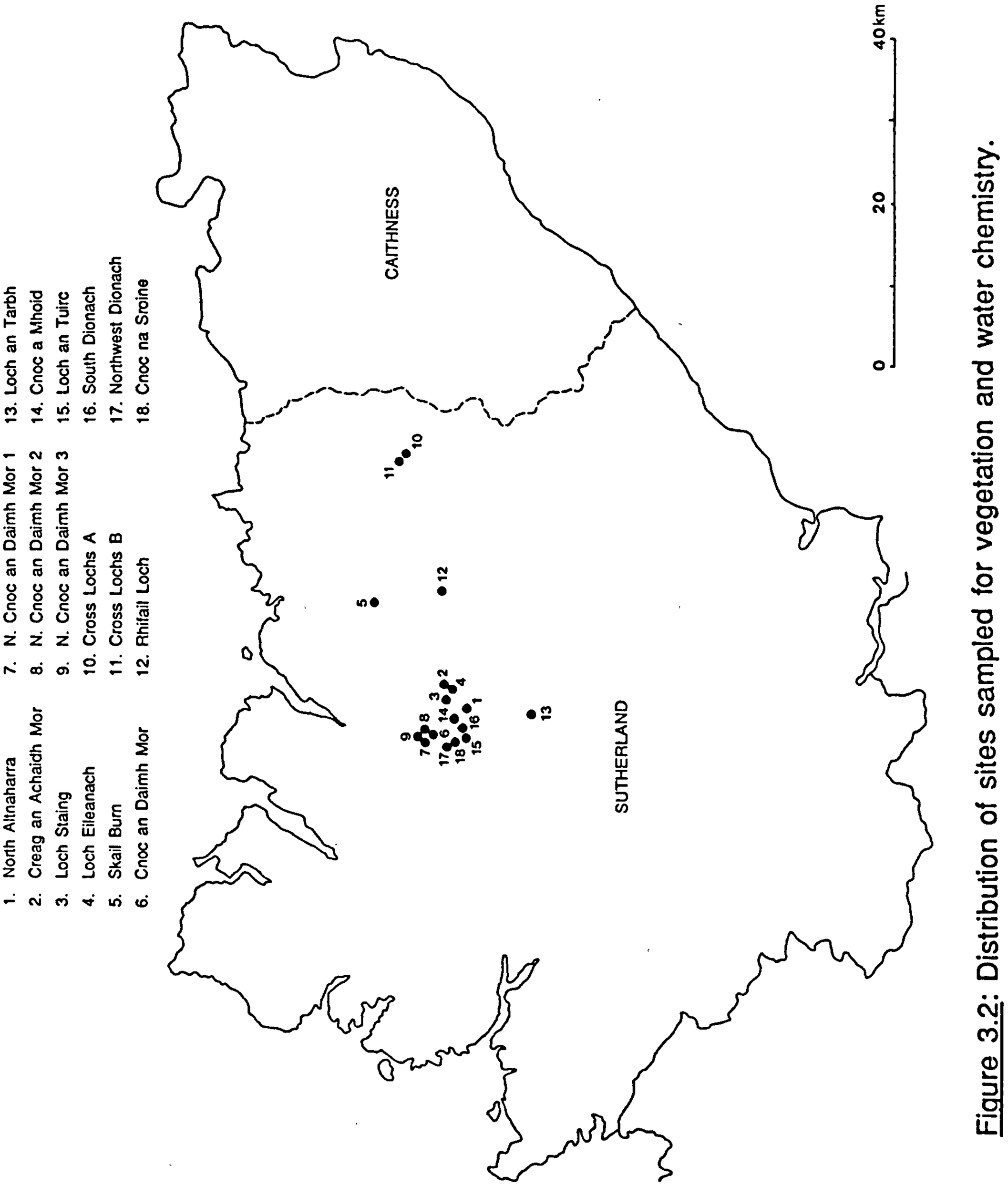


Figure 3.2: Distribution of sites sampled for vegetation and water chemistry.

Table 3.1: Sites where vegetation and water chemistry sampled

No.	Name	National Grid ref.	No. samples
1.	North Altnaharra	NC575385	12
2.	Creag an Achaidh Mor	NC602407	17
3.	Loch Staing	NC586409	7
4.	Loch Eileanach	NC598406	2
5.	Skail Burn	NC707487	20
6.	Cnoc an Daimh Mor	NC542428	11
7.	N. Cnoc an Daimh Mor 1	NC538435	4
8.	N. Cnoc an Daimh Mor 2	NC540435	2
9.	N. Cnoc an Daimh Mor 3	NC540442	9
10.	Cross Lochs A	NC883460	12
11.	Cross Lochs B	NC877467	11
12.	Rhifail Loch	NC717416	11
13.	Loch an Tarbh	NC570313	10
14.	Cnoc a Mhoid	NC563402	9
15.	Loch an Tuirc	NC551398	2
16.	South Dionach	NC558398	2
17.	Northwest Dionach	NC533407	2
18.	Cnoc na Sroine	NC534402	2

also stressed that this particular area probably contains a greater number of likely locations than other parts of the Flow Country. Other areas of NCC survey during 1989 in eastern Caithness and west of Strath Halladale have not located any additional sites. A clearer regional assessment of site distribution must await further results of this work.

The third stage of the sampling strategy is the selection of a limited number of sites for topographic and palaeoecological work. These were chosen to reflect the range of present vegetation and chemical conditions shown by the earlier work (see 3.4.7).

3.3.2 Sampling strategy

3.3.2.1 Review of approaches to vegetation description

There is no truly standard way of describing and recording vegetation data. However, there has traditionally always been a split between the continental school of phytosociology, "Zurich- Montpelier" of Braun-Blanquet (1932) (described by Poore, 1955a; Mueller-Dombois and Ellenberg, 1974; Westhoff and Van der Maarel, 1978, amongst others) and the sometimes more haphazard schemes developed by British vegetation scientists (see Goldsmith *et al*, 1986, for a review of methods). Briefly, the advantages of the Braun-Blanquet methods are that it provides a standard system, within which it is possible to compare plant communities at a pan-European scale in a meaningful way and that once learnt it can provide relatively rapid and complete surveys of vegetation. It suffers from having a somewhat impenetrable system of hierarchical taxonomic units and was originally based on largely subjective organisation and grouping of the releve data collected. Some of the classic British accounts of regional vegetation (Tansley, 1939; McVean and Ratcliffe, 1962; Burnett, 1964, and chapters therein) use similar methods for data collection and organisation but emphasise dominant species rather than the 'constancy' classes of the Zurich-Montpelier school. With the advent of increased computational facilities, British classifications tended to diverge further from continental systems to produce 'objective' classifications of the data examined, while often making little attempt to compare the groups recognised with existing communities described in the literature (eg. Daniels, 1978; Hill, Bunce and Shaw, 1975).

Whereas these two approaches had traditionally been viewed as alternatives (eg.Moore et al, 1970), more recently within British mire ecology, there has been a greater recognition of the value of classical phytosociological methods and a combination of more subjective sampling, objective computer based data analysis, with a final comparison of resulting vegetation types with existing syntaxonomic units has been used (Wheeler, 1980a, 1980b, 1980c; Lindsay et al, 1988). The National Vegetation Classification (NVC) (Proctor and Rodwell, 1986), an attempt to describe and classify the whole range of British seminatural vegetation, uses a similar approach. In addition competent continental phytosociologists have included some British mire vegetation in their work (eg.Dierssen, 1982) and are also using computer programs to sort and classify their data (eg. Moore and O'Sullivan, 1978).

As the main aims of this work are to provide data in order to draw comparisons primarily with the existing classifications of Proctor and Rodwell (1986) at the British scale and Dierssen (1982) within northwest Europe, the approach has been to keep data comparable with these sources. This determines several of the specific sampling techniques used (below).

3.3.2.2 Vegetation recording

A standard quadrat or 'releve' was used to sample vegetation at an individual location within a site. Quadrat size was $4m^2$ in accordance with the NVC (mires) (Proctor and Rodwell, 1986) The effects of sample area on numbers of species recorded within a particular community are well documented (Grieg-Smith, 1983), the number rising with increasing quadrat area to an asymptote at a particular value. Clearly, on a patterned mire surface, there is a large degree of internal vegetational variation, which would not be expressed by a quadrat of 2x2m, when widths of pools and ridges may be as little as 0.5m. Small (10x10cm)

contiguous quadrats have been used on patterned mires to reflect this micro-relief (Lindsay et al, 1985), but this is an extremely time consuming method of recording and would not yield comparable data to that of the NVC. Consequently, irregular 'quadrats', of estimated area $4m^2$, representing ridge and pool microtopes separately were used as sample areas. This separation of pools from ridges for vegetation recording concurs with NVC practice which describes, for example, the type M1 *Sphagnum auriculatum* bog pool community.

Vegetation records include all vascular species, bryophytes and lichens, not including epiphytic species. Species names follow those given in Clapham, Tutin and Moore, (1987) for vascular species, Smith (1978) for mosses, except *Sphagnum* species which follow Daniels and Eddy (1985), Paton (1965) for hepatics and Duncan (1970) for lichens. The Domin scale of cover abundance was adopted for recording abundance cover classes, again for the sake of consistency with the NVC. Cover classes have often been criticised for their inaccuracy and vulnerability to observer and systematic errors (Floyd and Anderson, 1987; Kennedy and Addison, 1987), but they have been used successfully in many studies and are certainly a much more rapid measure of abundance than point interception or frequency measures. Certainly it is adequate for assessing major vegetational differences, particularly where placing of a sample in a particular class often depends on the presence or absence of several species rather than minor differences in single species abundance.

3.3.2.3 Mire chemistry

There are several possible levels of complexity with which the chemical characteristics of mires can be recorded, depending on the objectives of the research concerned. In this case, the intention is not to provide data at the elemental level, but is merely to obtain supporting data for the vegetation analyses, as part of a wide ranging

examination of patterned fen ecology and palaeoecology. Therefore, only those characteristics which would be most helpful when comparing different data sources and which could be measured rapidly and reasonably accurately in the field were assessed. The inorganic geochemistry of peatlands has been most recently reviewed by Shotyk (1988), who mentions a total of 19 elements plus compounds and complexes, in addition to pH (and "acidity") and redox potential. For measurement of peatland chemistry, it is possible to perform analyses on either mire water (pools where the water table is above the surface or pore water where it is at or below the surface) or the peat itself. Most analyses are performed on the mire water, as this is most convenient, but there are also studies using peat chemistry. Although some studies have found soil and water pH values to be similar (Newbould and Gorham, 1956), soil pH is generally below water pH by as much as 0.5 units (Shotyk, 1988).

pH and acidity

One of the most widely quoted chemical characteristics is the pH of mire waters and it is therefore one of the most useful measures for comparative purposes. Simple field measurements of pH are possible with reasonable accuracy from modern field pH meters. However, it is also one of the most misunderstood and problematical of measurements for a number of reasons (Shotyk, 1988). pH expresses the "activity of H^+ ions in aqueous solution" compared with "acidity" which is the "equivalent sum of the acids that are titratable with strong base" (ibid.). Another important point is that

$$pH = -\log (\text{Activity of } H^+ \text{ ions})$$

so that small changes in pH at low values represent far greater changes in H^+ activity than similar changes at high pH. Besides differences in soil and water pH values, there are problems with sampling methodology, which are often not addressed in published accounts. pH varies with season, depending on surface wetness, may be affected by colloidal

material, and changes over relatively small horizontal and vertical distances. These problems make exact comparison of different data problematical, but errors can be held at a minimum within individual studies by careful sampling procedure. For the purpose of this research, water samples were taken from the upper 5cm of standing water in pool quadrats and from shallow depressions in the centre of ridges allowed to fill with water and clear. Samples were taken in a 400ml polypropylene beaker, which was rinsed twice in sample mire water first. pH was measured immediately with a Gallenkamp stick pH meter, with a quoted accuracy of +/-0.1 units. Measurements were possible at all pool locations but could not be performed within some ridges due to a low water table or particularly resistant surface. All data was collected between 20.8.88 and 4.9.88, normally at the same time as vegetation data.

Conductivity

"Differences in the conductivity of water samples are mainly a result of differences in the concentration of charged solutes and to a lesser extent in the nature of the solutes and temperature" (Golterman et al, 1978, p49). When corrected for temperature they are therefore a rough measure of the concentration of the charged solutes, including, however, the H^+ ions. This problem of hydrogen ions is obviously much worse at low pH, so that in addition to temperature corrections, a further adjustment to measured conductivity has to be made. Equations for these corrections are given by Sjors, (1950).
For temperature correction to 20°C standard

$$1)\ k_{20} = (C/R_t)1.02^{20-t}$$

Where R is the measured resistance (ohms) in the cell with the constant C (normally 1) at the temperature t°C and k_{20} is the conductivity at standard 20°C.

For pH correction:

$$2)\ (k_{H+})_{20} = 0.325.a_{H+}$$

Where $(K_{H+})_{20}$ is the conductivity corrected for pH and a_{H+} is the activity of hydrogen ions. In fact pH is only an estimate of the activity of H^+ ions because of the problems mentioned earlier (Shotyk, 1988).

Conductivity is not as widely recorded as pH, but still provides a useful comparative indication of the overall ionic status of mire waters. Sources of error are less well documented than for pH, but higher conductivities were recorded by Summerfield (1974) in June than in January or March for blanket, raised mire and fen sites and it would appear that this is a function of surface wetness. Spatial variability was also found to be significant. Seasonal differences were greatest in bog sites and spatial differences most acute in soligenous fen sites. Ideally the ionic composition of mire waters would be measured but this requires a high input of time and effort and is not justified for this study. Conductivities were measured with a WPA 135 conductivity meter, in the field using the same samples as for pH measurements. Temperature to the nearest 0.5°C was also measured.

3.3.3 Location of vegetation and chemistry samples

For the purposes of vegetation description and classification, sample location is normally determined by subjective assessment of the major plant communities present, taking samples from apparently homogenous vegetation and avoiding obvious transition zones between two types (Goldsmith et al, 1986). This was the primary method of sample location used here, the approximate range of variation on each site being established initially by a brief survey, with at least one sample from each vegetation type. There is a flushed zone at the top and bottom of most sites, often clearly identifiable due to distinct

vegetation changes and particular attention was paid to sampling these locations. In addition, if an obvious water course emerged at the bottom of a patterned fen area then this was sampled for pH and conductivity. The number of samples per site was determined by site size and vegetation variability. In the absence of clear vegetation variation, samples were spaced approximately every 60m apart. Within patterned areas of mire, adjacent pool and ridge samples were taken at each location.

3.4 DATA ANALYSIS AND RESULTS

3.4.1 Methods of ordination and classification of vegetation

As has been mentioned in section 3.2.2, most of the early work on vegetation communities was done by subjective grouping of releve data, whether or not the principles of the Zurich-Montpelier school were applied. This was due to the multivariate nature of the data sets which could not be easily manipulated until more powerful computation was available. Since the early seventies there has been enormous interest in the use of advanced multivariate approaches to handle such large data sets (see Digby and Kempton, 1987; Jongman *et al*, 1987; for reviews).

Before discussing the different approaches to the analysis of vegetation, it is necessary to mention the concept of vegetational and environmental gradients. Inherent in the principle of classification of vegetation is the belief that discrete communities occur and can be recognised as such. However, variation in communities may be continuous and vary along an environmental gradient. This was the concept embodied in Whittaker's (1967) gradient analysis. The predictions of each idea are shown by Shipley and Keddy (1987), who test both hypotheses and demonstrate that neither concept is wholly satisfactory but that a "multiple working hypothesis of community structure" should be considered. This concept has in fact been recognised by

ecologists developing some of the software to deal with vegetation data and it is now generally accepted that vegetational variation occurs along often complex, environmental gradients but that more or less discrete communities can usually be recognised within this and that certain "break points" in the continuum usually occur.

Association analysis (Williams and Lambert, 1959) was an early attempt to synthesise vegetational variation in an objective way, but ordination methods soon became the main focus of attention. There are many different techniques which have been tried and different methods work better in different situations. Digby and Kempton (1987) and Jongman et al (1987) give comprehensive reviews and Ter Braak (1987) concentrates on the detail of some of the most recent developments. Earlier techniques are better covered in Gauch (1982), Greig-Smith (1983) and Kershaw and Looney (1985). Only a few of the more relevant techniques are mentioned here.

Ordination techniques fall into two groups. Direct ordination requires independent environmental data and uses this data in the construction of species and site ordinations. Indirect ordination uses only species and sample data to organize the data (Digby and Kempton, 1987). Principal Components Analysis (PCA), used at an early stage by ecologists (eg Goodall, 1954) but reciprocal averaging and correspondence analysis (Hill, 1973; Hill, 1974) came to be commonly used later, particularly with the availability of a relatively user friendly program for the improved Detrended Correspondence Analysis (DECORANA - Hill, 1979a). The latter method was claimed to be more suitable for ecological data, and the detrending of successive axes largely deals with the problem of the 'arch effect', so called because it results in compression of the ends of axes, giving a horseshoe shape to an artificial data set which should form a straight line (Hill, 1979a). The method has, however, been criticised because of the lack of mathematical justification (Ter Braak, 1987),

appearing 'rather arbitrary' (Digby and Kempton, 1987, p97). It has also been shown to compare unfavourably when compared with other, little known methods such as 'Local Non Metric MultiDimensional Scaling' (LNMDS) (Minchin, 1987). However, once the mathematics have been worked through, it is accepted as an improvement in many situations (Ter Braak, 1985; Dargie, 1986)) and has been incorporated into other recent computer packages with improved algorithms for rescaling by polynomials rather than by segments (Ter Braak 1987). A major development for ecologists looking for improved techniques has been the work of Ter Braak (1986; 1987; 1988a; 1988b; Ter Braak and Prentice, 1988) on Canonical Correspondence Analysis, especially with the production of a program to perform the computing necessary (CANOCO - Ter Braak, 1988b). This is a direct ordination method which allows environmental data variables associated with individual samples to be used to constrain ordination axes to be linear combinations of those variables. This allows community variation to be directly related to environmental variability, rather than relying on indirect interpretation as was previously the case with existing techniques.

Classification techniques have developed parallel with changes in ordination methodologies, to a certain extent. The differences in approach to data collection and organisation (section 3.3.2) are obviously important here but this part of the discussion is restricted to analytical techniques. Again the major texts dealing with ordination cover classification analyses (eg.Kershaw and Looney, 1985; Digby and Kempton, 1987). There are a series of different approaches in classification, summarised as hierarchical or non-hierarchical and agglomerative or divisive. Most classifications are hierarchical, linkages existing not only between members of individual groups, but between the groups themselves at different levels of importance. Non hierarchical methods merely assign each member to separate groups. Hierarchical methods are either agglomerative or divisive. Agglomerative analyses ('Cluster analyses')

operate on a matrix of similarities, initially joining the most similar individuals, then recalculating similarities and joining together the next most similar, which may be groups or individual items. This proceeds until there are only two large groups of items, which are finally joined together in a group containing the entire data set. Divisive techniques start with the whole data set and divide this into two smaller groups on the basis of their dissimilarity. This is repeated until a number of smaller groups are derived or the data is split into its component items. Divisions may be based on a single species ('monothetic') or on a number of species ('polythetic'). The most widely used classification method in vegetation analysis has become a divisive polythetic method which initially used five species for each division (Hill, Bunce and Shaw, 1975) but could use up to fifteen in its later, fully documented form, Two Way Indicator Species Analysis, TWINSPAN (Hill, 1979b). This is based on ordination by detrended correspondence analysis (Hill, 1979a) and is therefore particularly useful when the two methods are used together. More recently Malloch (1988) has used these two programs as a basis for a suite of further programs to provide a more complete system of data entry, preparation, analysis and display in tabular and map form.

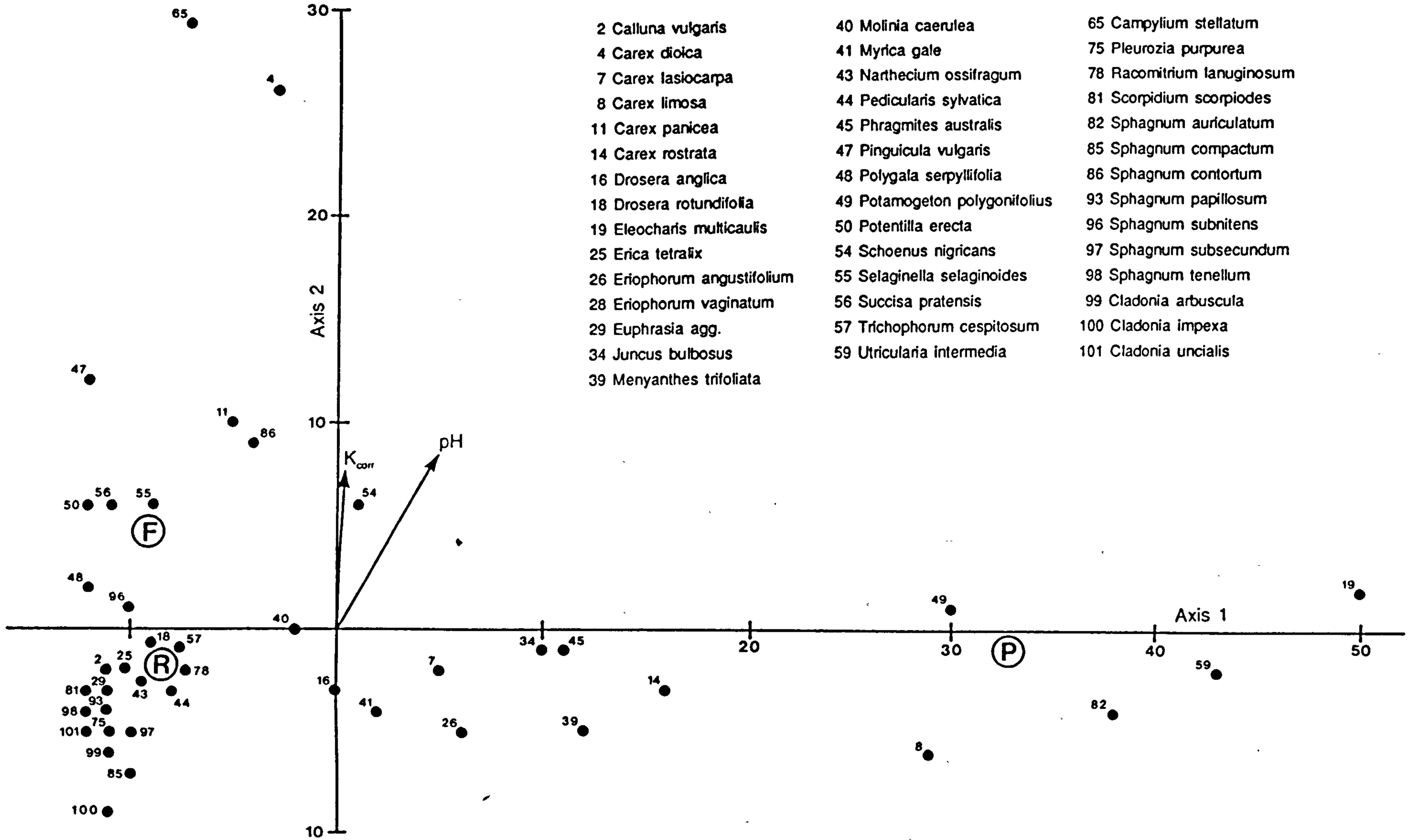
The methods used for this study are TWINSPAN (Hill, 1979b), together with the programs TWINTAB and TABLE (Malloch, 1988) for tabular presentation of data. The programs actually operate using 'pseudospecies' in order to use quantitative data from samples. Each species has a number of possible pseudospecies representing different abundances, defined at the beginning of the analysis. In this case Domin values of 0-10 are grouped into four pseudospecies of 1-2, 3-4, 5-7 and 8-10. This also has the benefit of removing possible errors due to observer bias and inconsistency when recording data. Other parameters entered at this stage are minimum size of a group to be divided (5), maximum number of indicator species (7) and maximum number of divisions (5). No differential weights

were given to pseudospecies, no potential indicators were omitted and the analysis successfully classified all samples without data omission.

3.4.2 Ordination of patterned fen samples

3.4.2.1 Indirect ordination - Detrended Correspondence Analysis (DCA)

DCA (Ter Braak, 1987) was used in the first instance to investigate the major lines of variation in the data. The resulting species ordination (Figure 3.3), is the most meaningful output, where a general assessment of data trends is required. The analysis produces 'eigenvalues' for each axis, always between 0 and 1, which express the importance of the axes and multiplied by 100 they give the percentage variance accounted for (Ter Braak, 1988(b)). Axis 1 is the main gradient of variation in the data with an eigenvalue of 0.466, and appears to reflect a change from species which occur on ridges at low scores to those which are predominantly found in aquatic habitats at the top of the axis. For example *Eleocharis multicaulis*, *Utricularia intermedia* and *Sphagnum auriculatum*, at the extreme right hand side, are always found in pools on the patterned fens. Conversely, within the rather crowded zone below 0.5 on axis 1, the species are those found solely above the water table, and particularly on the drier areas, such as *Calluna vulgaris*, *Erica tetralix*, *Trichophorum cespitosum*, *Sphagnum capillifolium*, *S.papillosum* and some of the *Cladonia* species of lichens. There is an area on the ordination between these two zones where species occur which either have a wide tolerance of water levels or which tend to be found only around the average water table. *Eriophorum angustifolium*, *Carex lasiocarpa* and *Myrica gale* are examples of the former type while *Drosera anglica* is of the latter type. *Juncus bulbosus* is also located within this area but this is complicated by the fact that there are two different life forms of this species, an aquatic form (sometimes referred to as *var. fluitans*) which grows



2 Calluna vulgaris
4 Carex dioica
7 Carex lasiocarpa
8 Carex limosa
11 Carex panicea
14 Carex rostrata
16 Drosera anglica
18 Drosera rotundifolia
19 Eleocharis multicaulis
25 Erica tetralix
26 Eriophorum angustifolium
28 Eriophorum vaginatum
29 Euphrasia agg.
34 Juncus bulbosus
39 Menyanthes trifoliata
40 Molinia caerulea
41 Myrica gale
43 Narthecium ossifragum
44 Pedicularis sylvatica
45 Phragmites australis
47 Pinguicula vulgaris
48 Polygala serpyllifolia
49 Potamogeton polygonifolius
50 Potentilla erecta
54 Schoenus nigricans
55 Selaginella selaginoides
56 Succisa pratensis
57 Trichophorum cespitosum
59 Utricularia intermedia
65 Campylium stellatum
75 Pleurozia purpurea
78 Racomitrium lanuginosum
81 Scorpidium scorpiodes
82 Sphagnum auriculatum
85 Sphagnum compactum
86 Sphagnum contortum
93 Sphagnum papillosum
96 Sphagnum subnitens
97 Sphagnum subsecundum
98 Sphagnum tenellum
99 Cladonia arbuscula
100 Cladonia impexa
101 Cladonia uncialis

Figure 3.3: Species - environment biplot from DCA.

floating in relatively deep water up to 2m in depth (Haslam et al, 1975), and a terrestrial upright form growing in low ridge situations.

While this is the main gradient suggested by DCA, a secondary line of variation is picked out by Axis 2 (eigenvalue 0.298), which appears to be roughly related to nutrient supply. For example, most of the ridge species already mentioned are also commonly found on ombrotrophic bogs and require only low levels of pH and nutrient supply and these occur low on axis 2. Species which occur higher on this axis are those which tend to require higher levels of pH and base status, such as *Schoenus nigricans*, *Sphagnum contortum*, *Scorpidium scorpiodes* and *Carex dioica*. Again there are particular problems of interpretation for some species. *Carex panicea* is generally considered as a plant of 'fens and flushes' (Clapham *et al*, 1981), but it is also found on damaged ombrotrophic blanket mire elsewhere in the Flow Country (see community 21 of Lindsay et al, 1988). Any interpretations such as this only describe rather vague relationships but they are nevertheless useful when we come to consider the ordination of sites.

Because the major split in the data is between aquatic and terrestrial habitats and both these always occur on all sites, a plot of the mean positions of sites tells us very little about the differences in inferred conditions between those sites. It is more useful to plot the mean positions of pool and ridge data for each site, (Figure 3.4). From this diagram, several points become obvious. Firstly, the ridge/pool split in the data is confirmed. Secondly, the pool vegetation is much more variable than the ridge vegetation, covering a much greater range on axis 1. Thirdly, the majority of the sites are remarkably similar, especially in terms of ridge vegetation, with the only exception being the North Altnaharra site, which has both ridge and pool vegetation with apparently rather higher base status than any other site. Also expressing some degree of enrichment is Rhifail, although this shows

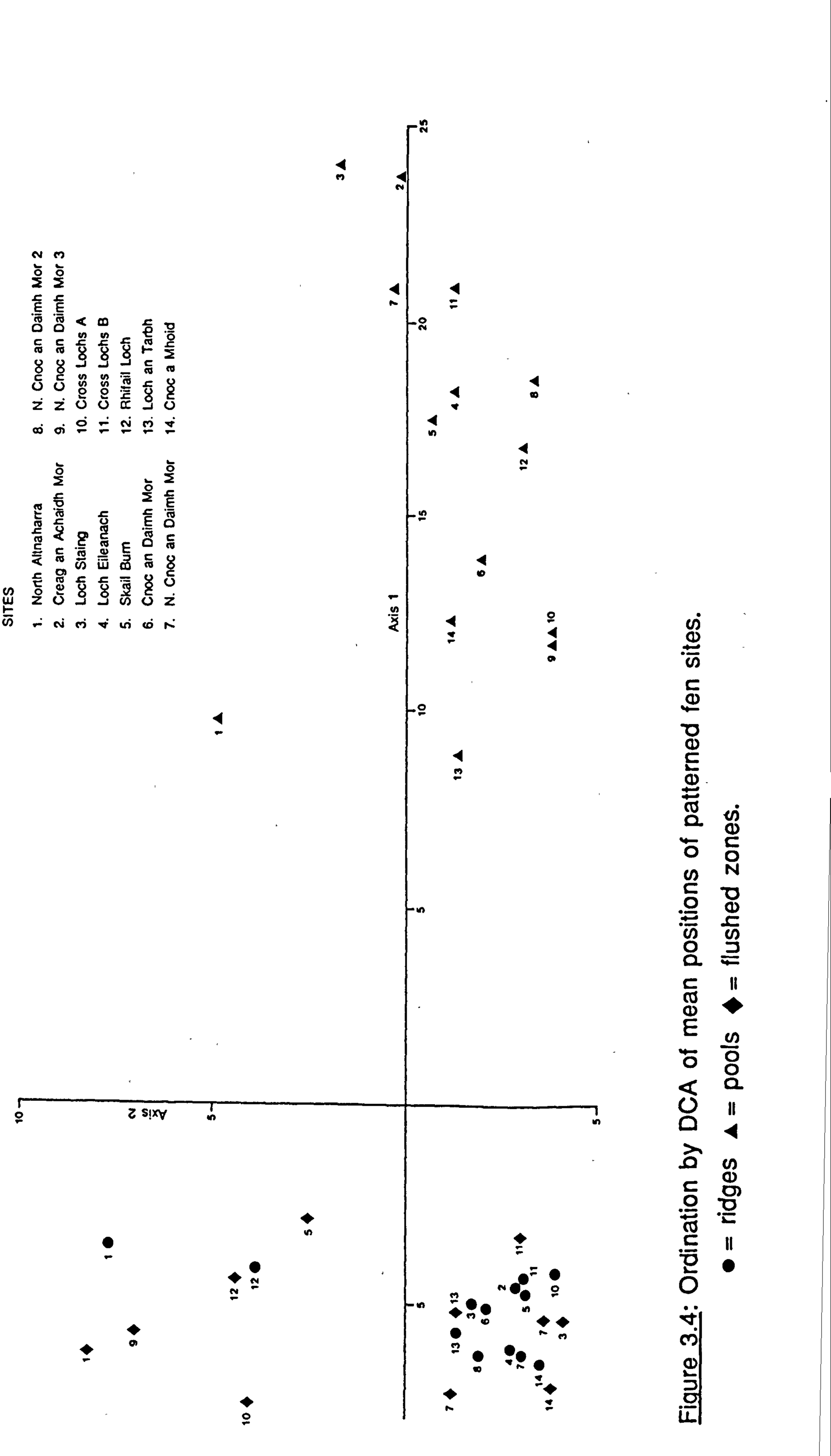


Figure 3.4: Ordination by DCA of mean positions of patterned fen sites.
● = ridges ▲ = pools ◆ = flushed zones.

considerable variations.

CANOCO (Ter Braak, 1988(b)) allows the environmental data to be used as covariables and ordinated on the same axes of variation as the species and sample data, without influencing them. These are also shown on the species ordination (Figure 3.3), where the earlier interpretation of the axes is largely confirmed. The qualitative variables of ridge and pool are placed at opposite ends of axis 1, confirming the dry - wet gradient. The 'flush' data is at the bottom end of axis 1, slightly elevated on axis 2, and corrected conductivity is high on axis 2, confirming the general nutrient gradient of that axis. pH is placed in a slightly ambiguous position, not clearly associated with either axis, but positively associated with both. This is probably a result of dual gradients within the data. Ridge and flush quadrats seem to vary with pH and base status, as do pool quadrats to a lesser extent. However, in general, pool quadrats have higher pH values than adjacent ridges (mean 5.51 and 5.12 respectively) and as a result the coordinates of pH are skewed towards the pool data (ie. to high positive values on axis 1).

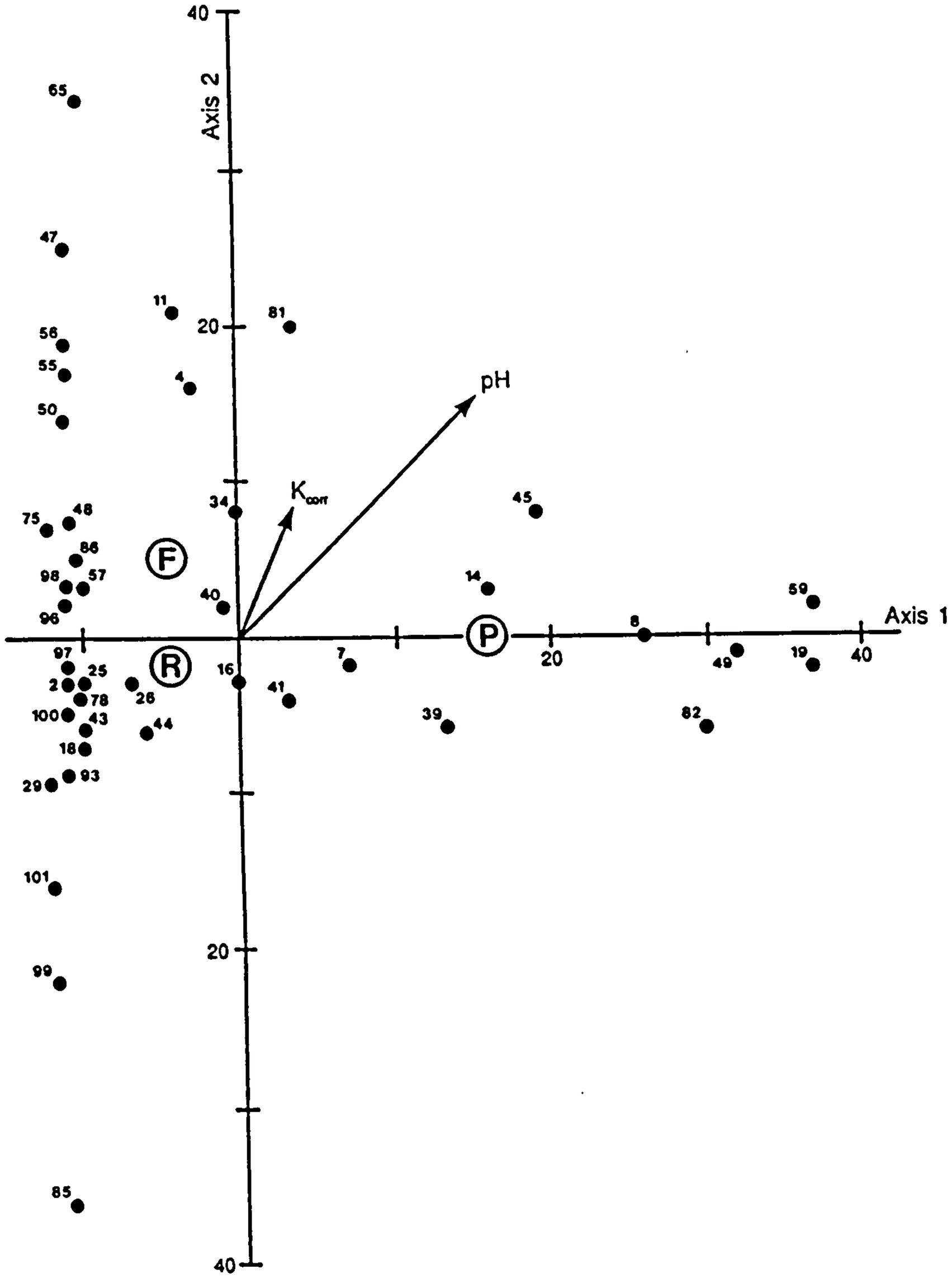
3.4.2.2 Direct ordination - Detrended Canonical Correspondence Analysis

A further step in the analysis is the use of CANOCO for direct gradient analyses. The data presented here are a result of Detrended Canonical Correspondence Analysis (DCCA), in order to remain consistent with the earlier ordination methodology. The main purpose of direct ordination methods is to study the variation in community composition that can be explained by a particular set of environmental variables (Ter Braak, 1988(b)). It is therefore a way of testing hypotheses which may have been generated as a result of earlier indirect ordination. The purpose of the following analyses is therefore to test the hypothesis that community variation is mainly attributable to the microtopographical location and nutrient status of

samples. Monte Carlo permutation tests randomise species and environment data separately between samples and calculate the first eigenvalue for each permutation. This allows a level of significance to be assigned to the constrained axes.

Figure 3.5 shows the resulting species ordination. For axis 1, the species-environment relationships are very similar, with the same separation of pool, ridge and flush species. A Monte Carlo permutation test of the eigenvalue of axis 1 gives a significance value of $p<0.01$. This is also the outcome of an overall test of significance of axes 1 and 2 combined. The results of these tests show that the observed differences in vegetation are indeed associated with microtopographical location.

The relationship between vegetation and microtopographical location comes as no surprise, but what is more significant is that it is the most important factor associated with variations in vegetation composition. A restricted permutation test, using the microtopographical location as a covariable, tests whether chemical characteristics have an independent significant relationship with community variation, by randomising the data within restricted blocks, in this case within pool, ridge and flush releves. When these microtopographical effects are excluded, pH and conductivity show only a relatively weak relationship with community variability (eigenvalue = 0.063) and this is statistically insignificant ($p<0.12$). pH alone shows a similarly low explanatory power and is just outside the 5% significance level ($p<0.06$). This data supports the null hypothesis and suggests that there is no correlation between community variability and pH and conductivity of mire water on patterned fens in Scotland.



2 Calluna vulgaris
4 Carex dioica
7 Carex lasiocarpa
8 Carex limosa
11 Carex panicea
14 Carex rostrata
16 Drosera anglica
18 Drosera rotundifolia
19 Eleocharis multicaulis
25 Erica tetralix
26 Eriophorum angustifolium
28 Eriophorum vaginatum
29 Euphrasia agg.
34 Juncus bulbosus
39 Menyanthes trifoliata
40 Molinia caerulea
41 Myrica gale
43 Narthecium ossifragum
44 Pedicularis sylvatica
45 Phragmites australis
47 Pinguicula vulgaris
48 Polygala serpyllifolia
49 Potamogeton polygonifolius
50 Potentilla erecta
54 Schoenus nigricans
55 Selaginella selaginoides
56 Succisa pratensis
57 Trichophorum cespitosum
59 Utricularia intermedia
65 Campylium stellatum
75 Pleurozia purpurea
78 Racomitrium lanuginosum
81 Scorpidium scorpioides
82 Sphagnum auriculatum
85 Sphagnum compactum
86 Sphagnum contortum
93 Sphagnum papillosum
96 Sphagnum subnitens
97 Sphagnum subsecundum
98 Sphagnum tenellum
99 Cladonia arbuscula
100 Cladonia impexa
101 Cladonia uncialis

Figure 3.5: Species - environment biplot by DCCA

3.4.3 Classification of patterned fen data

The classification produced by TWINSPAN is shown in dendrogram form by Figure 3.6, which illustrates the relationships between the individual 'end groups' as a hierarchy. Indicator species are not shown but for each major group there is a brief description of its apparent ecological characteristics. The program keeps dividing the data until either the maximum number of divisions is reached or a minimum size of group for division is achieved. This results in a number of small groups which are meaningless in vegetation terms, because they are separated on the basis of criteria which may not be within the error margin of the data and/or may not be sufficient to be recognisable in the field. Therefore, the analyst is left with the final responsibility for deciding which groups are ecologically meaningful and are worthwhile maintaining. It is at this stage that it is quite possible to obtain slightly different classifications from different analysts, depending on their interpretation of the significance of the groupings. However, it is felt that the groups given here are recognisable in the field and represent distinct communities. The individual communities derived are from now on referred to as 'noda', indicating they have been separated but not yet assigned to any formal phytosociological association. Poore (1955b) uses this as a term for communities which show "relative uniformity" within the data set considered.

Some indication of the similarities between the different noda is shown by Figure 3.7, showing mean and standard errors for their locations on the ordination axes used by TWINSPAN. Most are clearly separable on axes 1 and 2, with the more similar noda differentiated on axis 3. The summary table of vegetation noda (Table 3.2) gives comparative data for species occurring with a constancy equal to or greater than III (40%) within any one noda and the complete ordered data set is given in Appendix I. Data on the pH and conductivity of each of the vegetation groups is given in

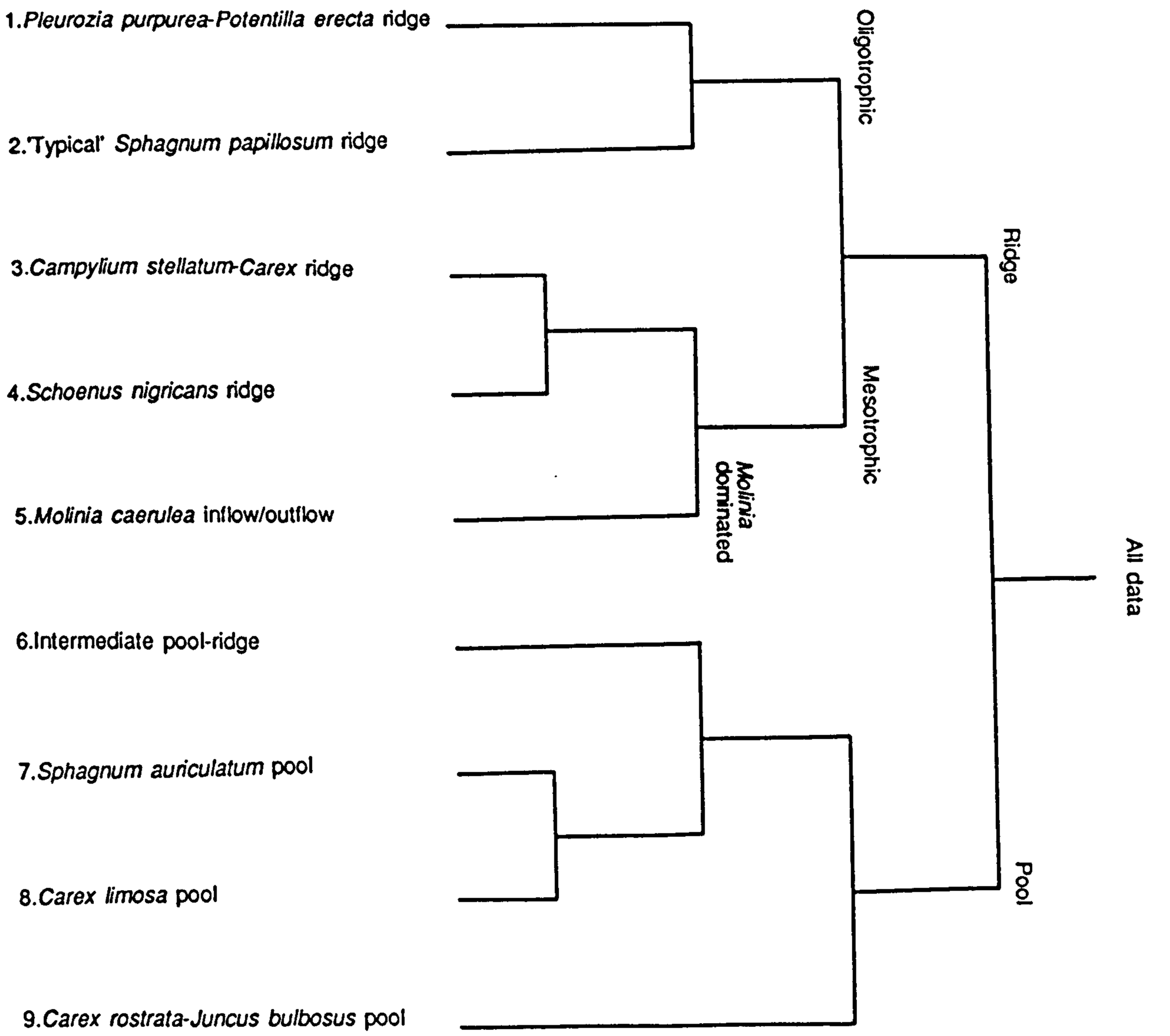


Figure 3.6: Dendrogram of classification by TWINSPAN of patterned fen vegetation.

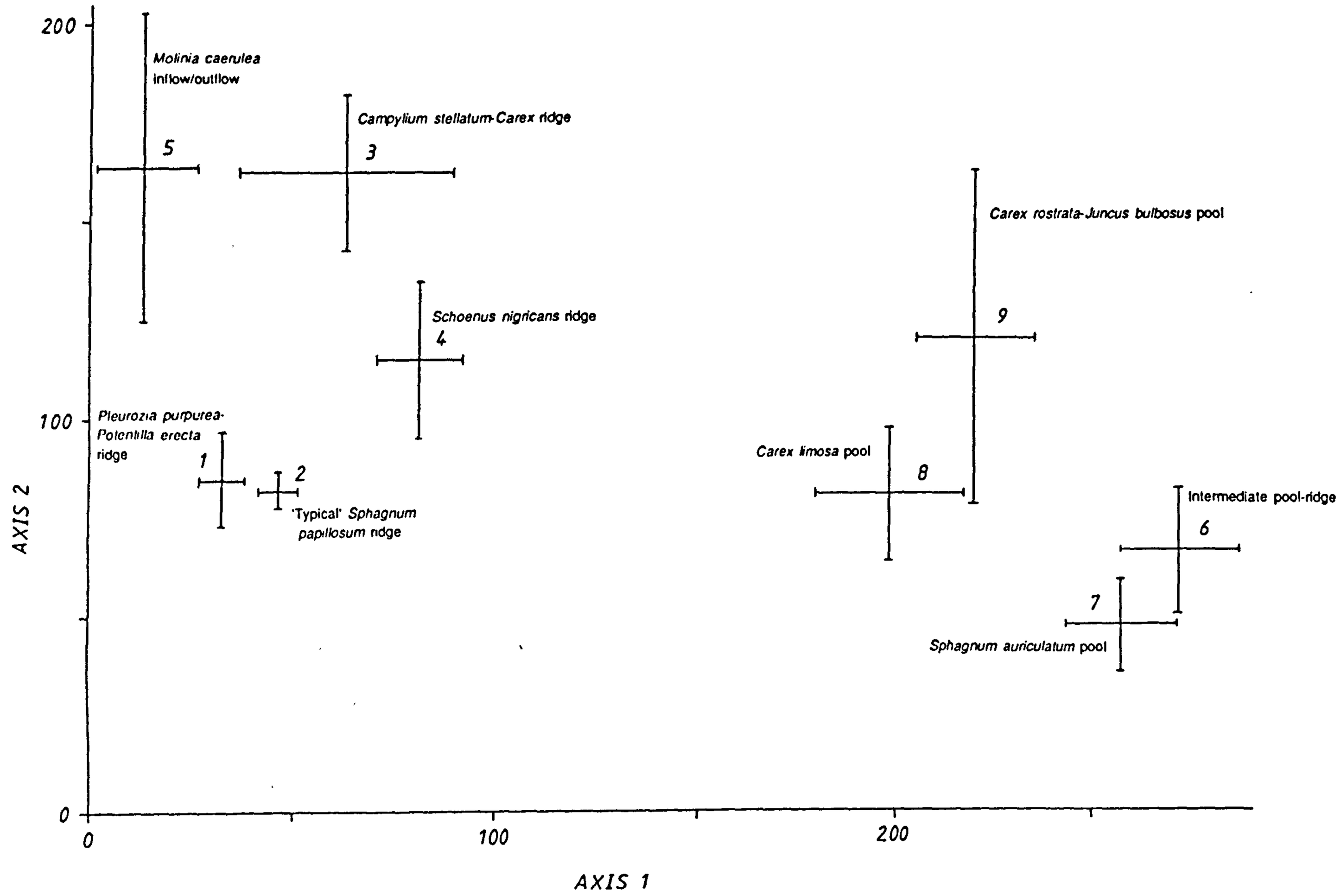


Figure 3.7: Ordination of mean positions of vegetation noda from TWINSPAN. Error bars indicate ± 2 standard errors.

Table 3.2: Constancy table (major species only) for patterned fen noda

Nodum		1	2	3	4	5	6	7	8	9
No. releves		24	42	6	6	5	12	14	22	10
Carex dioica	I	I	III	II	I	I	-	-	-	
C.lepidocarpa		-	-	I	III	I	-	-	-	-
Campylium stellatum		-	-	IV	III	I	-	-	-	-
Sphagnum contortum	-	-	III	-	-	-	-	-	-	
Selaginella selaginoides	III	II	V	V	I	-	-	-	-	
Succisa pratensis		I	II	I	II	III	I	-	-	-
Carex panicea		I	I	IV	III	V	II	-	I	-
Pinguicula vulgaris		III	I	II	-	II	-	-	-	-
Potentilla erecta		V	I	III	IV	V	-	-	-	-
Carex echinata		III	III	III	I	III	I	-	-	III
Erica tetralix		V	V	IV	V	IV	I	-	-	-
Narthecium ossifragum		V	V	IV	V	IV	I	-	-	-
Trichophorum cespitosum		V	IV	V	IV	II	II	I	-	-
Sphagnum subnitens	III	III	IV	I	-	-	-	-	-	
Drosera rotundifolia		V	V	IV	II	I	-	I	-	-
Racomitrium lanuginosum		V	III	II	III	-	-	-	-	-
Calluna vulgaris		V	V	V	I	III	-	-	-	-
Euphrasia agg.		II	III	III	-	I	-	-	-	-
Pleurozia purpurea	V	I	-	-	I	-	-	-	-	
Sphagnum capillifolium		IV	V	III	-	-	-	-	-	-
S.papillosum	V	V	III	-	I	-	-	-	-	
S.subsecundum		III	II	I	-	I	-	-	-	-
Cladonia impexa		III	II	-	II	-	-	-	-	-
C.uncialis		III	II	-	-	-	-	-	-	-
Drosera anglica		IV	IV	V	IV	-	IV	II	II	-
Molinia caerulea		V	V	V	V	V	V	III	III	II
Schoenus nigricans	I	-	III	V	-	II	-	-	I	
Myrica gale		II	V	III	V	II	V	I	IV	-
Carex lasiocarpa		V	IV	V	V	-	IV	V	IV	IV
C.rostrata		III	II	III	-	-	-	II	IV	V
Scorpidium scorpiodes		-	-	III	III	-	I	-	-	-
Eriophorum angustifolium	IV	V	IV	V	II	II	IV	IV	IV	
Menyanthes trifoliata		III	IV	III	IV	I	II	IV	V	III
Potamogeton polygonifolius		I	I	III	II	-	IV	IV	IV	IV
Utricularia intermedia		-	-	-	-	-	II	I	III	-
Sphagnum auriculatum		-	1	-	-	-	II	V	II	-
Carex limosa	I	II	I	I	-	I	II	V	II	
Juncus bulbosus		III	III	III	III	-	II	II	II	V

Table 3.3, and the position of each sample in each group with respect to these two variables is shown in Figures 3.8 and 3.9. The following section describes each major group of communities in turn and draws comparisons with others described elsewhere.

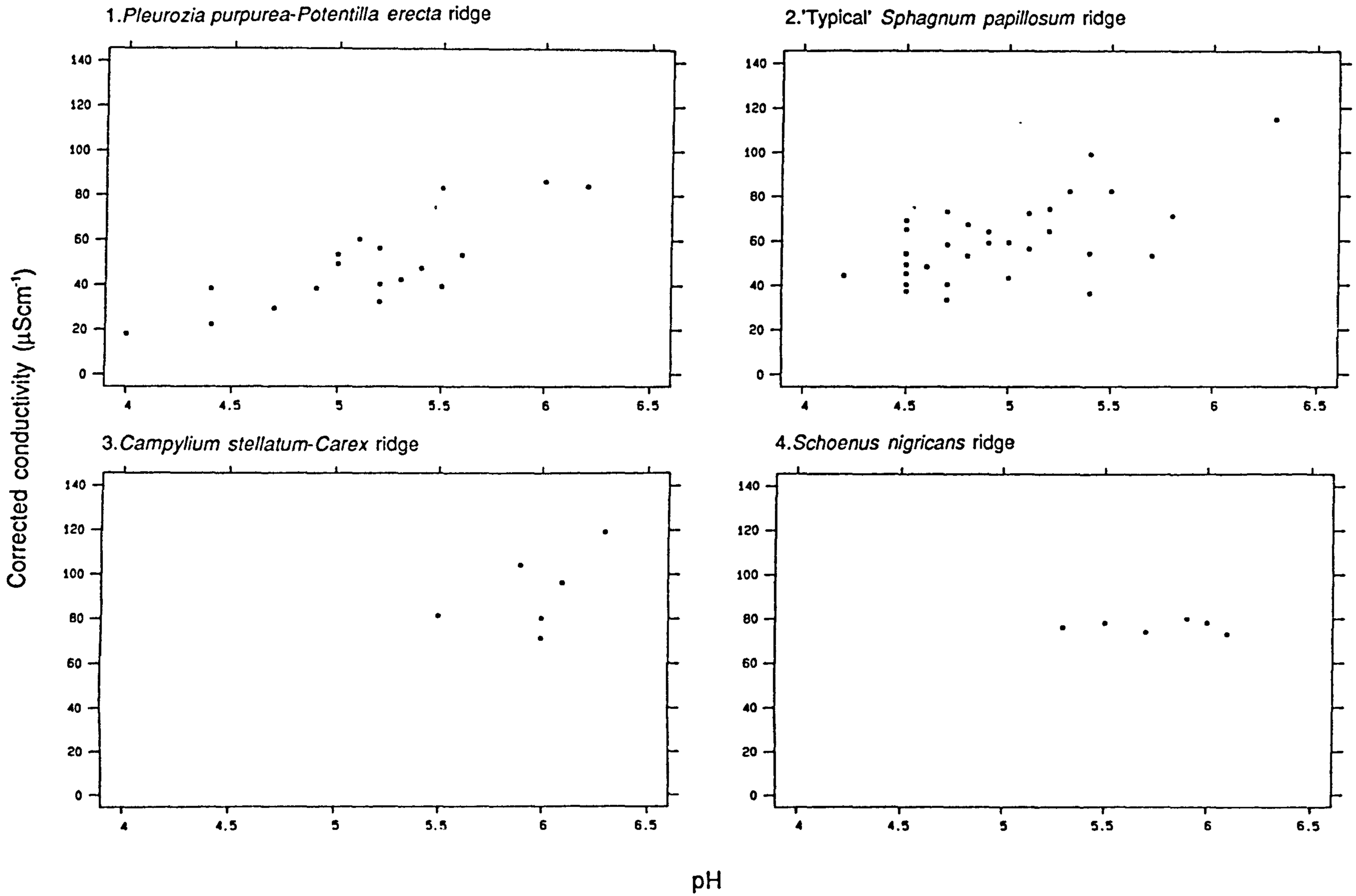


Figure 3.8: Scatterplots of ridge vegetation noda with respect to pH and conductivity.

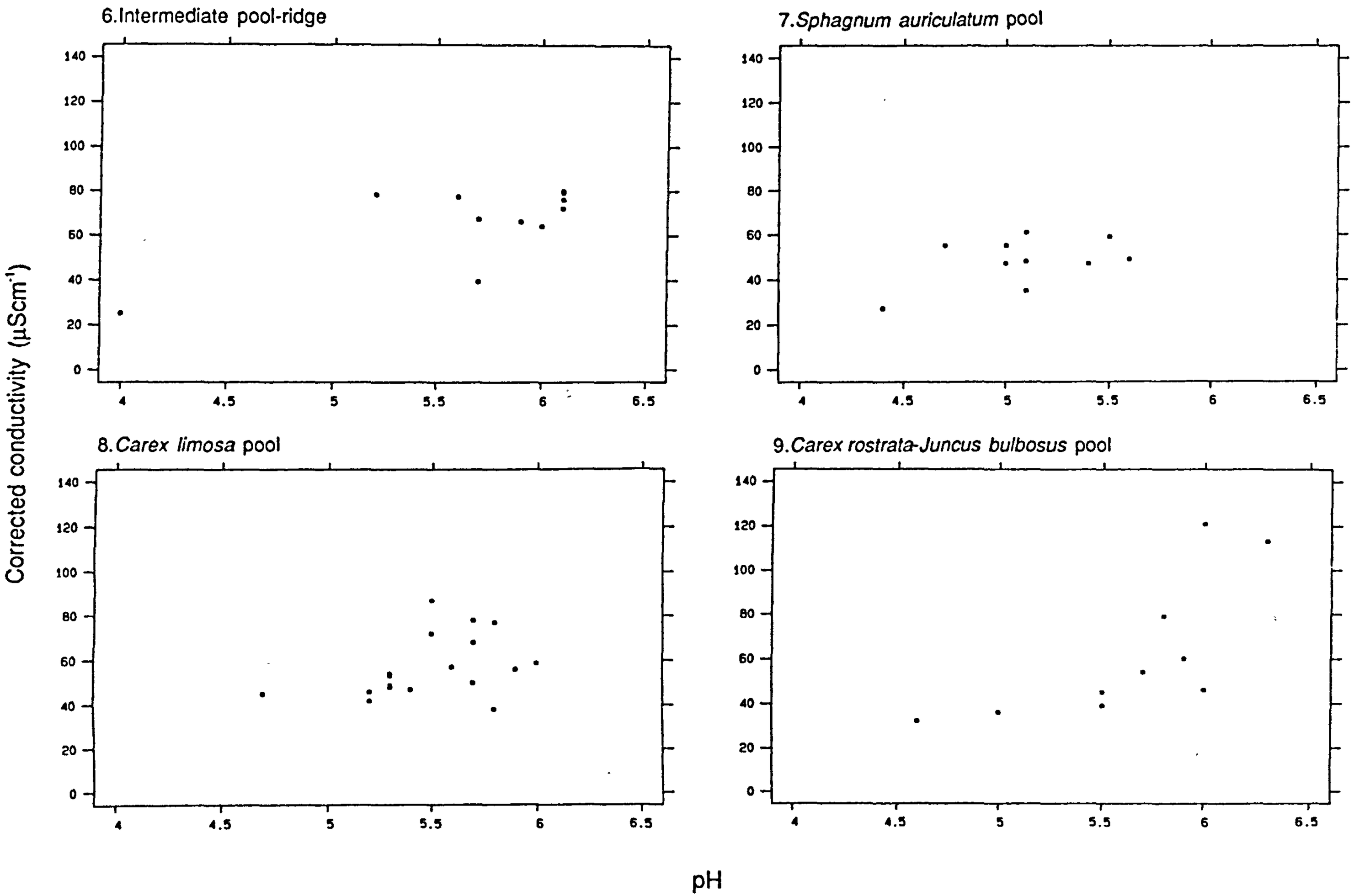


Figure 3.9: Scatterplots of pool vegetation noda with respect to pH and conductivity.

Table 3.3: pH and conductivity data for vegetation noda

Nodum	No.	pH			Conductivity ($uScm^{-1}$)		
		Range	mean	2se	Range	mean	2se
1.Pleurozia-Potentilla ridge	18	4.4-6.2	5.14	0.26	18- 86	48.3	9.4
2.'Typical' ridge	35	3.5-6.3	4.87	0.18	0-115	56.4	7.0
3.Campylium-Carex ridge	6	5.5-6.3	5.97	0.22	71-119	91.3	14.3
4.Schoenus ridge	6	5.5-6.1	5.75	0.25	73- 80	76.5	2.2
5.Molinia inflow/outflow	4	4.4-6.4	5.40	0.80	60- 84	68.5	10.4
6.Intermediate ridge/pool	11	4.0-6.1	5.68	0.37	25- 80	65.7	10.5
7.Sphagnum auriculatum pool	10	4.4-5.6	5.09	0.22	27- 61	48.3	6.5
8.Carex limosa pool	21	4.7-6.6	5.55	0.16	38- 87	59.0	6.6
9.C.rostrata-Juncus bulbosus pool	10	4.6-6.0	5.63	0.32	32-121	62.5	19.7
All data	121	3.5-6.6	5.30	0.11	0-121	59.5	3.8

3.4.4 Community descriptions and comparisons

3.4.4.1 Some generalisations on community composition

The variety of methods for characterisation and comparison of vegetation data has already been mentioned. The intention in this section is to set out the main characteristics of the vegetation of patterned fens as a whole and then to describe the different communities present within this group and the relationships between them as shown by the dendrogram (Figure 3.6). The main characteristics used to compare communities are constancy (I-V scale, corresponding with percentages of 20% increments) and dominance of different species. The syntaxonomic summary Table 3.4 attempts to show where similar communities to those found on patterned fens in Scotland have been described from elsewhere, by other workers.

The majority of data collected is from the patterned mire surface, but there are also releves from inflow and outflow areas of mire where these occur. Sometimes these zones were little different from ridge vegetation on the mire expanse,

Noda	Braun-Blanquet system			NVC (Proctor and Rodwell, 1986)	Other communities	
	Class	Dierssen (1982)	Birse (1980)		Lindsay et al (1988)	
5	OXYCOCCO SPHAGNETEA			M25 Molinia/Potentilla erecta		
1		Pleurozio-Ericetum tetralicis - Racomitrium subassociation	Caricetum lasiocarpae - subassociation with Molinia caerulea	? M15 Trichophorum cespitosum/ Erica tetralix (? subcomm. a - Carex panicea)	(34) Molinia - Myrica ridges	
2		Narthecio-Sphagnum papillosi - typical subassociation		M17 Trichophorum cespitosum - Eriophorum vaginatum blanket mire		
3	SCHEUCHZERIO-CARICETEA NIGRAE	Caricetum lasiocarpae: - Subass Campylium stellatum (or subass Scorpidium scorpiodes)		M18 Erica tetralix - Sphagnum papillosum raised and blanket mire M21 Narthecium ossifragum - Sphagnum papillosum valley mire		
4		- Schoenetum nigricantis				
6		- typical subassociation	Caricetum lasiocarpae - typical subassociation inc. facies with Carex limosa	No near equivalent	(35) Carex lasiocarpa - C.rostrata mud bottom	'Water track' (Goode and Lindsay, 1979) 'Poor fen' (Hulme, 1985)
7		- subass S.auriculatum		M1 S.auriculatum pool - no suitable sub-type		
8		Caricetum limosae		No near equivalent		
9		Caricetum rostratae		No near equivalent		

Table 3.4: Syntaxonomy of patterned fen communities

but communities dominated by *Molinia caerulea* were recorded which are clearly different to the other communities. This nodum is clearly referable to the *Molinia caerulea* - *Potentilla erecta* community (M25) of Proctor and Rodwell (1986) but, as mentioned by these authors, is difficult to place within the formal phytosociological structure. It is not covered by Dierssen (1982) in his review of mire communities of north west Europe. This community is excluded from discussion in the following short section. Within the main data set there are some species which occur with constancy IV or V in all vegetation groups. These are characteristic of patterned fen vegetation as a whole. *Carex lasiocarpa* is typical, with *Eriophorum angustifolium* and *Menyanthes trifoliata* showing similar tendencies and *Molinia caerulea* constancy V on ridges and II to V in pool communities. Within these generalisations, the vegetation is clearly divided into pool and ridge communities, as has already been shown. These two major groups and the variations within them are now described and comparisons made with existing published data, in particular the work of Dierssen (1982), the most comprehensive review of mire communities in north west Europe, and the NVC (Proctor and Rodwell, 1986).

3.4.4.2 Ridge communities

Within ridge communities there are also several species which occur as constants. These are *Erica tetralix*, *Narthecium ossifragum*, *Trichophorum cespitosum* and *Drosera anglica*. The next major division within this group is between mesotrophic and oligotrophic communities.

The majority of ridge vegetation falls into the latter group, characterised by constant *Sphagnum papillosum* and *S.capillifolium*, although the last named species is rarely abundant, typically 3-4 on the Domin scale. These are further split on the basis of the presence, often in moderate abundance, of *Racomitrium lanuginosum*, *Pleurozia purpurea* and *Potentilla erecta* within one group, the

Pleurozia purpurea/Potentilla erecta nodum, which also has a tendency to have more abundant *Molinia caerulea*. The occurrence of the oligotrophic species with high constancy suggests that the vegetation falls into the Oxycocco - Sphagnetea phytosociological class, especially with the only reliable character species, *Drosera rotundifolia* (Moore, 1968). The *Pleurozia/Potentilla* nodum is closely allied with the *Racomitrium* sub-association of the Pleurozio - Ericetum tetralicis, and with a similar subassociation of the Narthecio - Sphagnum papillosi, both within the alliance Oxycocco - Ericion, order Erico - Sphagnetalia (Dierssen, 1982). The 'typical' nodum has affinities with the typical subassociation of the Narthecio - Sphagnum papillosi. However, the constancy of *Carex lasiocarpa* casts doubt on this otherwise clear cut comparison, and these noda may have to be considered within the Caricetum lasiocarpae association, possibly of the *Sphagnum papillosum* subassociation, but within a different class, the Scheuchzerio-Caricetea nigrae. These groups are similarly difficult to place within the NVC, because of the mix of 'bog' and 'poor fen' species. M15 (*Scirpus cespitosus - Erica tetralix; Scirpus = Trichophorum*) is perhaps the nearest, especially as it allows for constant *Molinia caerulea*, with sometimes high pH levels (up to 7.4!), although it does not allow for the occurrence of such abundant and constant poor fen species of other kinds. Although mainly a community of thinner, better drained peats, it does extend into soligenous areas (Proctor and Rodwell, 1986, p214). The *Pleurozia/Potentilla* nodum is closest here as *Potentilla erecta* is a constant of M15. The *Narthecium ossifragum - Sphagnum papillosum* valley mire community (M21) probably best reflects the weakly flushed nature of the vegetation (pH 3.2-5.2) combined with abundant *Sphagnum*, but still does not contain *Carex lasiocarpa* and is restricted to southern Britain.

These oligotrophic ridges are those described in Lindsay *et al* (1988) as Community 34, *Molinia - Myrica* ridges. Wheeler (1984) notes a similar problem in classifying mixed *Carex* -

Sphagnum communities of poor basin fens, noting a poor variant of the Acrocladio - Caricetum diandrae, and suggests there are affinities with the *Trichophorum cespitosum* - *Carex panicea* association of McVean and Ratcliffe (1962) and Birks (1973). Probably the closest communities are the *Carex lasiocarpa* - *Sphagnum* zone described by Spence (1964) between loch edge and surrounding blanket mire and some of the releves in Birse (1980; 1984) placed within the Caricetum lasiocarpae.

The mesotrophic group includes the *Molinia* dominated flush vegetation, but otherwise includes only 12 releves, characterised by the lack of oligotrophic Sphagna, and the presence of a variety of poor fen species, including *Selaginella selaginoides* in particular. Two groups are tentatively separated here, one interpreted as being characteristic of 'high ridge', with some of the more oligotrophic species, such as *Calluna vulgaris* and *Drosera rotundifolia*, but also possessing *Campylium stellatum*, *Sphagnum subnitens* and *Carex panicea*. The second mesotrophic group (*Schoenus nigricans/ Myrica gale* nodum) has fewer bryophyte species and has both *Schoenus nigricans* and *Myrica gale* with constancy V. Both these noda are more clearly allied with the alliance Caricion lasiocarpae of Dierssen (1982), order Scheuchzeretalia palustris, class Scheuchzerio - Caricetea nigrae. Both noda appear to fit into the Caricetum lasiocarpae association, subassociation with *Campylium stellatum* or perhaps sometimes sub-ass. *Scorpidium scorpiodes*. However, the *Schoenus nigricans/Molinia* nodum may also be placed in the Schoenetum nigricantis association of the order Caricetalia davallianae. There is less possibility of fitting these noda within existing NVC groups, the *Scirpus cespitosus* - *Erica tetralix* community (M15) again being the most similar, especially the more mesotrophic *Carex panicea* sub-community (pH 4.2-7.4), with a number of poor fen species although still lacking *Carex lasiocarpa*.

Some additional data (10 quadrats) from Sutherland

patterned fens has been fitted to M17a, M15b, M21b and even M16 (*Erica tetralix-Sphagnum compactum* wet heath), (A.Coupar, pers.comm.), although this appears to be a somewhat uncomfortable classification. Indeed, the selection of four separate communities suggests that the data does not fit properly into any of these types. M15 is favoured by Dr.Wanda Fojt (pers.comm.), mainly on the basis of its allowance for species indicative of nutrient enrichment. Somewhat similar vegetation at Rannoch Moor (Coupar, 1983) can be assigned to M17a (A.Coupar, pers.comm.), but *Eriophorum vaginatum* is a constant (100%) and abundant (Domin 4-7) species here, yet occurs only rarely in the Sutherland data. The direct comparison of this and the additional Sutherland data (above) data is also complicated by the inclusion of both ridges and pools in the releves.

3.4.4.3 Pool communities

Within pool vegetation only *Potamogeton polygonifolius* is constant throughout all groups and there is no meaningful hierarchy of types. A transitional ridge-pool noda has a mix of pool and ridge species, in which *Potamogeton polygonifolius* is found with *Drosera anglica*, *Myrica gale* and *Molinia*. There are then three other communities characterised by different constant species. Two of these (*Carex limosa* and *Juncus bulbosus/ Carex rostrata* noda) have *Carex rostrata* but each has different associates. Finally there are *Sphagnum auriculatum* pools, the only *Sphagnum* dominated pool community, often with a high percentage cover of this more oligotrophic species.

This last community is the only one of the pool communities with a similar NVC type. M1 *Sphagnum auriculatum* pools clearly have the dominant species in common with this noda, but there are none of the poor fen species, such as *Potamogeton polygonifolius* (constant), *Carex lasiocarpa* and *C.rostrata*, and maximum pH values are between 3.2 and 5.1, much lower than the range of 4.4 and 5.6 for patterned

fens. The other pool noda have no near NVC equivalents due to the constancy and dominance of *Potamogeton polygonifolius* and *Carex lasiocarpa*, with the codominants mentioned above. This is not unexpected, as natural patterned zones, separable into pool and ridge microtopes (*sensu* Ivanov, 1981), have only previously been reported from ombrotrophic systems in this country. Although similar vegetation probably occurs in Britain, it may be only in restricted areas of vegetation and therefore remain unrecorded by a large scale investigation. The community 35 of Lindsay *et al* (1988) (*Carex rostrata - C.lasiocarpa* mud bottom hollows) is based on a few samples of similar vegetation and is synonymous with the general pool community described. Water track vegetation on valley mires on Lewis appears very similar, especially the 'mud bottom' community described by Goode and Lindsay (1979) and the 'poor fen' type of Hulme and Blyth (1984) and Hulme (1985). Clearer and more detailed relationships exist with the data of Dierssen (1982), with most pool releves probably falling into the Caricetum lasiocarpae association. The pool-ridge transition nodum perhaps falls within the typical subassociation, while the *Sphagnum auriculatum* nodum has clear similarities with the subassociation of the same name. The *Carex rostrata/ Juncus bulbosus* nodum may however lie in the Caricetum rostratae association, the differentiation between this and Caricetum lasiocarpae being unclear from the data available. It is also possible that the *Carex limosa* nodum fits into the Caricetum limosae for similar reasons. The range of pH conditions recorded for these subassociations is also similar to that in patterned fens, around a mean of 5.5 but ranging from about 4.3 to 6.7, compared with 4.0 to 6.6 (mean 5.48) for patterned fen pools.

3.4.5 Comparisons with blanket mire communities

The patterned fens of Sutherland occur within a blanket mire landscape, largely dominated by ombrotrophic mire vegetation. There is now a large amount of data regarding

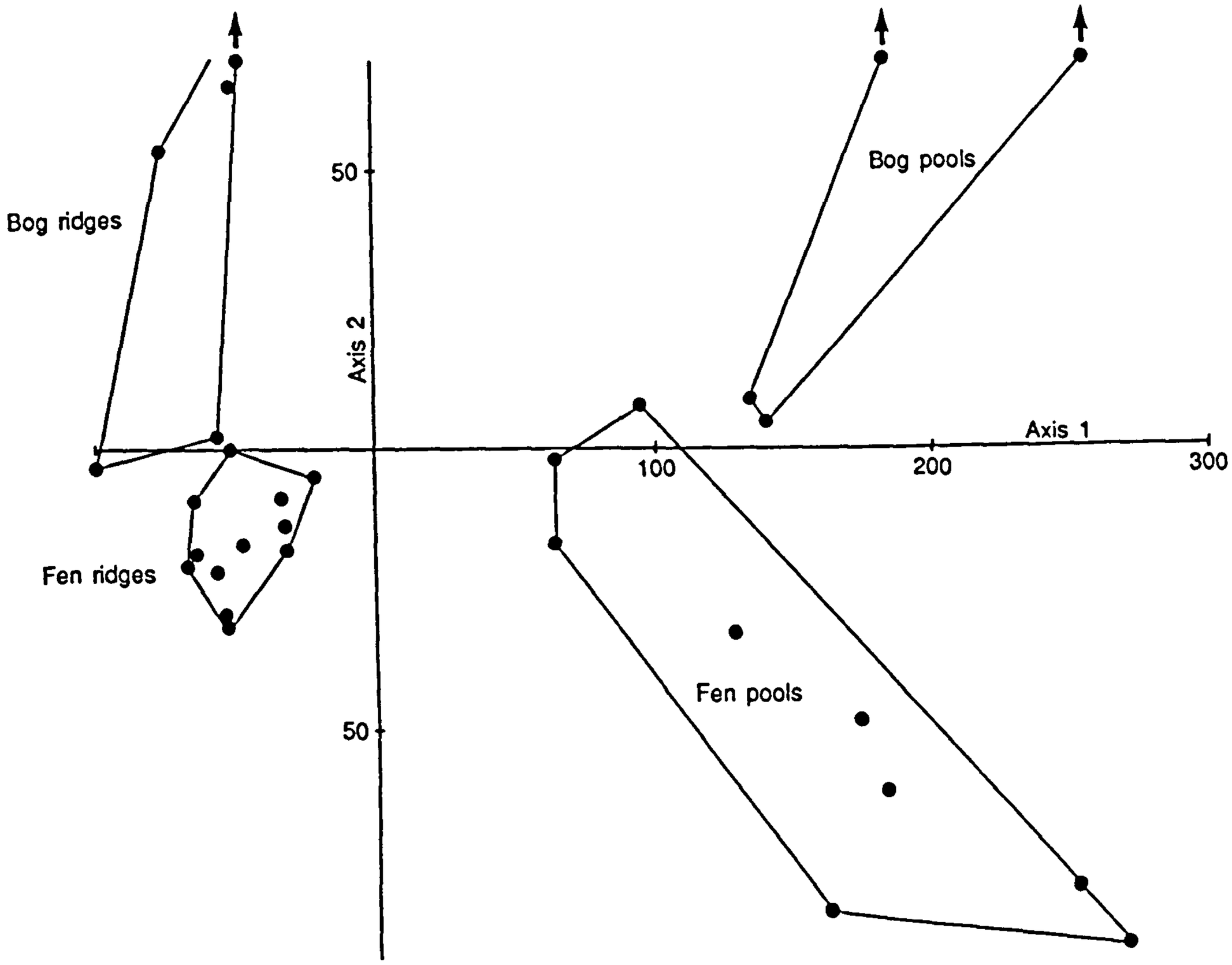


Figure 3.10: Ordination by DCA of ombrotrophic mire and patterned fen vegetation data.

this vegetation (Lindsay et al, 1988) and that of other blanket mire throughout Britain (Proctor and Rodwell, 1986 for a summary). The comparisons made above with NVC types mostly concern blanket mire communities which include much data from other parts of Britain. Despite the obvious oceanic influence in much of the Flow Country blanket mire, which may allow species normally found in poor fens to grow, there are no comparable communities to those described from patterned fens. The more oceanic of the terrestrial communities described by Lindsay et al (1988) have similarities, but differ mainly by their lack of *Carex* species. Some of the closest communities are the *Racomitrium-Pleurozia purpurea* and *S.papillosum-Molinia* ridges of Lindsay et al (1988). An extreme oceanic influence on apparently ombrotrophic blanket mire is the occurrence of *Schoenus nigricans*, widely recorded in Ireland (Bellamy, 1959; Sparling, 1962; Moore, 1968), with records from Islay (Lindsay et al, 1983) and a site at Laxford Bridge, Sutherland (Lindsay et al, 1988). However, on the Scottish sites this is attributed to weak surface water movement and it therefore seems unlikely that oceanicity is the cause of its occurrence in patterned fens from further east and inland. Although there are several pool communities in oceanic blanket mire which lack *Sphagnum* species ('mud bottom hollows'), these are characterised by *Rhynchospora alba*, *R.fusca* or *Eleocharis multicaulis* (Lindsay et al, 1988).

To directly compare the vegetation from patterned fens and the adjacent blanket mire, a small number of releves were taken from an ombrotrophic site next to the Cross Lochs patterned fens. Cross Lochs A site is a 'typical' patterned fen, in terms of vegetation and water chemistry (see section 3.4.7, below), and Cross Lochs B has generally rather lower nutrient status, reflected in its vegetation. The data from these three sites was analysed by DCA, to gain a comparison between the two mire types (Figure 3.10). The diagram shows that the main axes of variation in this data are moisture and nutrient status, with discrete areas

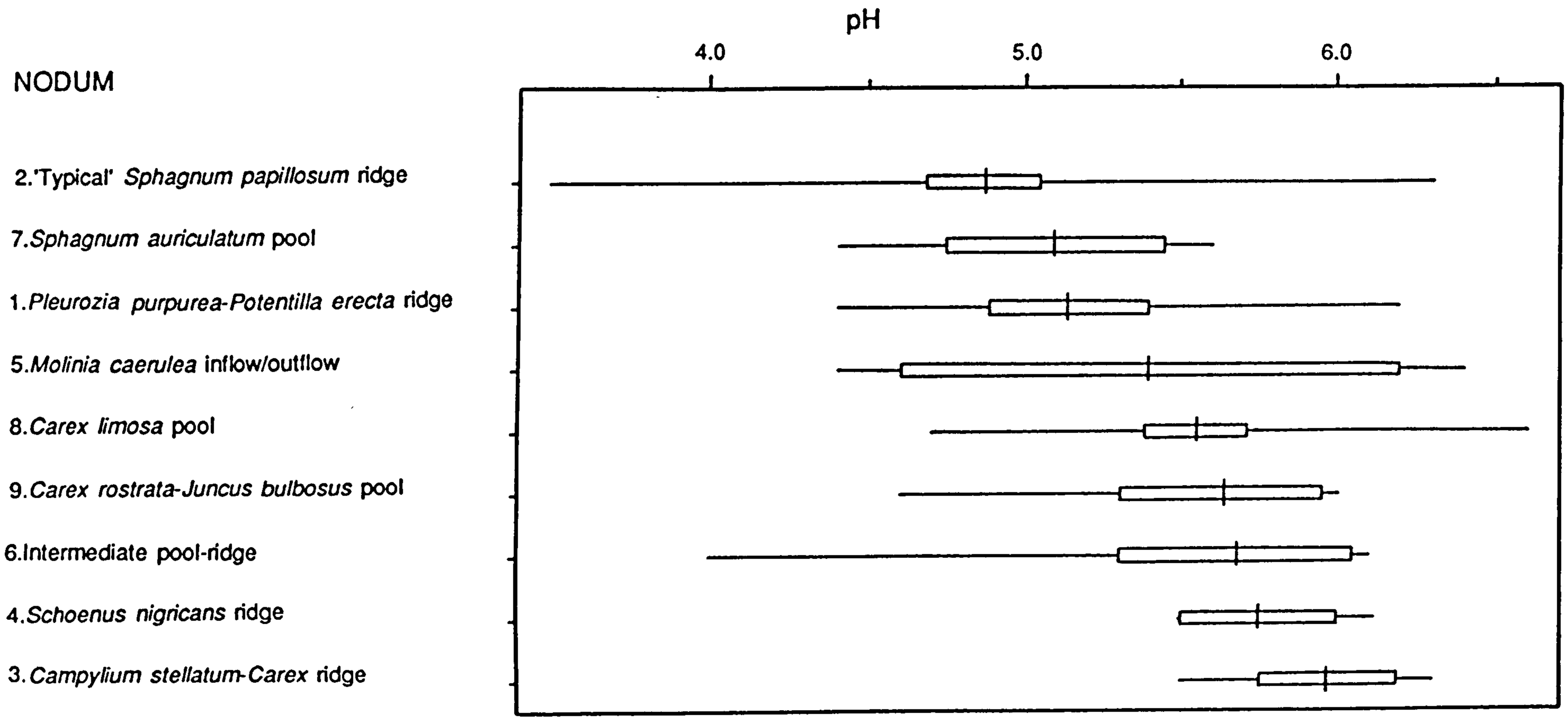


Figure 3.11: Summarised pH characteristics of vegetation noda.

of ordination space occupied by the data sets for fen ridge, fen pool, bog ridge and bog pool. The distribution of these sets and of the individual data points within them suggest several conclusions. Although the ombrotrophic and fen releves are clearly separable, the degree of variation appears to be larger between microtopographical zones than between mire types. This is probably attributable to the much lower plant density of pools, as well as qualitative differences between pool and ridge vegetation, which would have a major effect on the sample ordination. In addition, while the ridge vegetation occupies a relatively small ordination space, the pool data is extremely variable. This is probably because the species diversity of pool communities is low, and consequently they tend to have fewer species in common than ridge communities, and this is especially true for the bog communities. Although pH and conductivity of mire water was measured at each releve, this was done during July 1989. Unfortunately, this was during a particularly dry period throughout Britain, and recorded values are unlikely to be comparable with those for patterned fens, and so are not discussed here.

3.4.6 Chemical characteristics of the mires and vegetation

In the direct ordination of data, above, it was shown that the expected relationship between vegetation and water chemistry was not statistically significant ($p<0.12$). However, it is still useful to compare some of the chemical characteristics of different communities, particularly as several communities can be shown not to overlap at the 95% confidence interval (Figure 3.11), although their total recorded ranges all overlap to some extent. This internal variability of pH values is the factor that makes statements of statistical surety difficult, but is perhaps unsurprising, given the vagaries of pH measurement discussed in section 3.3.2. However, within the limitations of the data, several points become clear. The lowest pH values are reached by the *S.papillosum* (typical) ridge (mean pH 4.87, lowest value 3.5), but also one of the

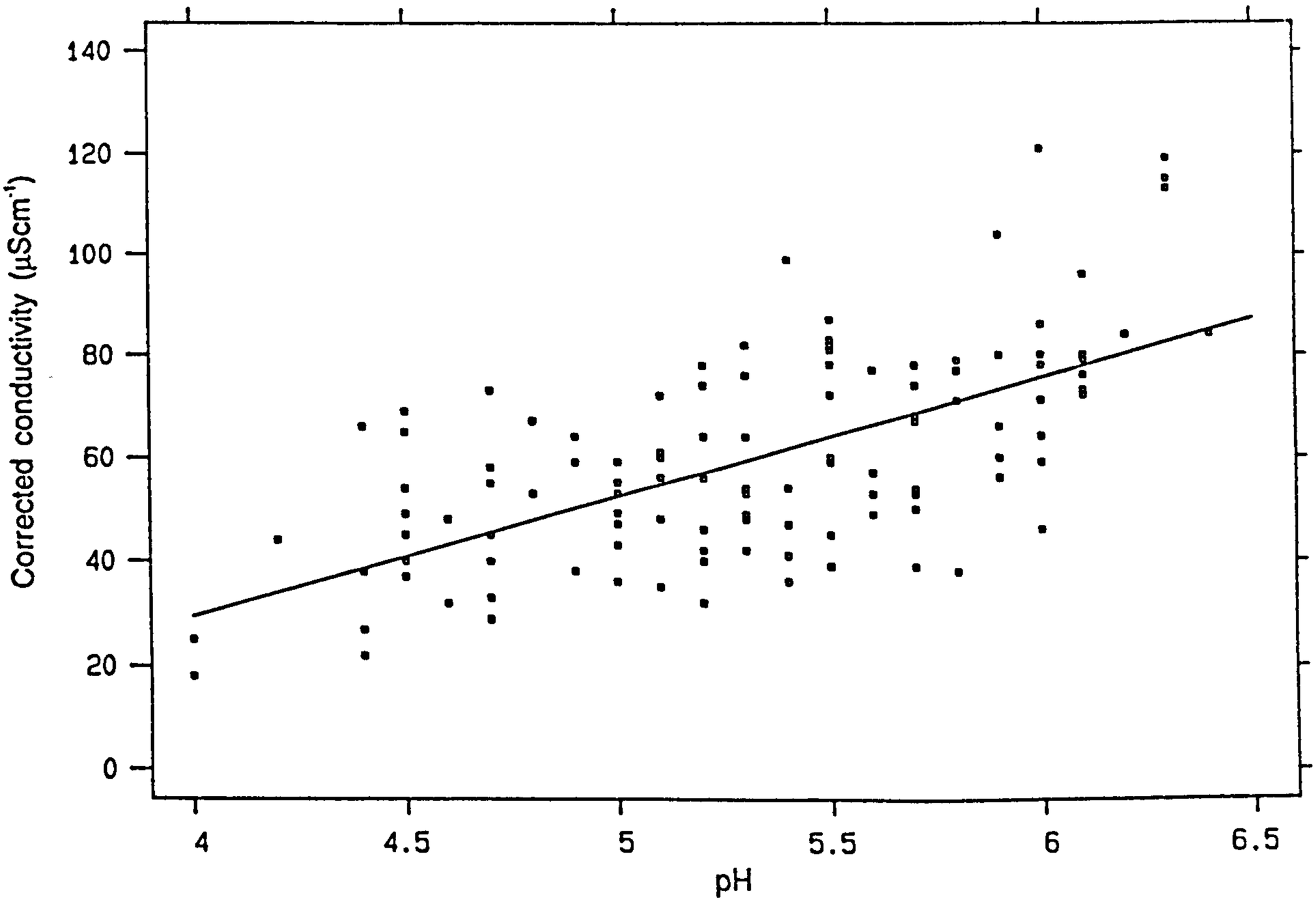


Figure 3.12: pH versus conductivity for patterned fens. r = 0.652p<0.01

Table 3.5: pH data for various mire types of low nutrient statu in different geographical regions. Range and mean values in parentheses.

Source and area	Mire Type Ombrotrophic ‹----------› Mesotrophic				
1.Britain	Inland blanket 2.9-4.4 (3.4)	Raised 3.1-5.1 (3.9)	Oceanic blanket 3.5-5.6 (4.7)	Mixed valley 3.0-6.3 (4.4)	Mesotroph.valley 3.8-7.3 (5.5) --›
2.Sutherland a) b)	Blanket 4.17-4.78 (4.51) 4.42-4.88 (4.61)				
3.Rannoch Moor	Blanket (4.50)				
4.Pennines a) b)	Blanket (3.90) (3.91)				
5.New Forest				'General bog' 4.43-4.73	'Schoenetum' 4.82-5.66
6.Western Europe	Ombrotrophic (3.8)			Transitional (4.5)	Minerotrophic (6.6)
7.Scandinavia	Ombrotrophic (3.8)			Transitional (4.2)	Minerotrophic (6.0)
8.Scandinavia	Ombrotrophic 3.7-4.2			Extreme poor fen 3.8-5.0	Transit. poor fen 4.8-5.7
					Intermediate fen 5.2-6.4
9.Eastern Canada	Ombrotrophic (3.9)			Transitional (4.3)	Minerotrophic (5.5)
10.Minnesota	Ombrotrophic ‹4.2			Poor fen 4.2-5.7	Intermed.rich fen 5.7-6.8
11.Alberta 12.Minnesota 13.Labrador 14.Labrador/Quebec				Patterned fens 4.1-5.3 4.8-4.9 4.7-6.1 ----› 4.4-6.4 ----›	
This study -Ridges -Inflow -Pools -All data			‹------ ‹------	3.5-6.3 (5.12) 4.4-6.4 (5.19) ---› 4.0-6.6 (5.51) -----› 3.5-6.6 (5.30) -----›	

Data sources:

1. Daniels (1978)
2. Pearsall (1956)
3. Gorham (1957)
4. a) Gorham (1958)
   b) Gorham (1956)
5. Newbould (1960)
6. Bellamy (1968)
7. Sjors (1948)
8. Sjors (1950)
9. Comeau and Bellamy (1986)
10. Glaser (1987)
11. Vitt et al (1975)
12. Glaser (1983)
13. Foster and King (1984)
14. Foster et al (1988a)

highest (pH6.6) occurs here. The *Pleurozia-Potentilla* nodum is somewhat richer on average (mean pH5.14), and has a narrower range (4.4-6.2). The *Sphagnum auriculatum* nodum is the most oligotrophic of the pool communities (pH5.09, max 5.6), followed by the *Carex limosa* nodum (pH 5.55). The *Juncus bulbosus - Carex rostrata* and the transitional *Molinia - Myrica* nodum have almost inseparable pH values, although the latter group has a much more acid lower pH range. The only constantly high pH values are recorded in the mesotrophic ridges, with all measurements over 5.5 and means of 5.75 for the *Schoenus - Myrica* nodum and 5.97 for the *S.subnitens* high ridge nodum. These are the only two groups for which there are clearly defined pH ranges, but this may be at least in part due to the fact that there are also fewer records for each. However, even within the small (n=4) data set for the *Molinia* dominated flushes, there is a great degree of variability (pH 4.4-6.4). The distribution of the entire data set with respect to pH and corrected conductivity is shown by Figure 3.12. Clearly the two are correlated ($r=0.652$, $p<0.01$), not unexpected since high base status is normally associated with higher pH values.

Although it is difficult to make meaningful detailed comparisons of water chemistry data for peatlands, if a wider spectrum of data is examined, then the problems of consistency of measurement are less significant. Table 3.5 summarises pH data a range of mire types, from ombrotrophic to mesotrophic fen, excluding eutrophic systems, throughout Europe and North America. The main problem when comparing such wide ranging data is differing terminology. However, an attempt has been made to place each figure in approximately comparable mire type classes.

Within Britain, the most complete published pH gradient is that of Daniels (1978). Within this, patterned fen sites have average pH values somewhere between mixed valley mires and mesotrophic valley mires, although in range they overlap with oceanic blanket and raised mires. Other data

from oceanic blanket mire, in Scotland and Ireland (Pearsall, 1956; Gorham, 1957) suggests that pH data in this study is much higher (ca. 0.5 units) than most of these ombrotrophic systems. The Schoenetum of Cranesmoor, a New Forest valley mire (Newbould, 1960) has comparable values. Comeau and Bellamy (1986) give data summarising the chemical differences between mire types in eastern Canada, Scandinavia and western Europe, showing the generally higher nutrient levels in western European mires, probably due to the oceanic nature of the climate, which is particularly important in ombrotrophic and oligotrophic sites. Within the western European data (Bellamy, 1968), patterned fens would be placed between 'transitional' and 'minerotrophic' mires. Therefore, pH data from patterned fens appears to be consistent with poor fens from Britain and western Europe in general.

The patterned fens in Scotland have been likened to patterned minerotrophic mire elsewhere in the world (Chapter 2; Lindsay et al, 1988) and a general comparison will be made later in this thesis (Chapter 9). The pH of mire waters from such sites is comparable with Scottish data, although average values may be somewhat lower (Comeau and Bellamy, 1986).

3.4.7 Inter-site comparisons and selection of sites for topographic and palaeoecological analysis.

The aim of this section is to assess the range of variation in the present day vegetation and water chemistry between individual patterned fens, in order to justify the selection of sites for further research. For the largely inductive palaeoecological study, it is desirable to select sites which represent, as far as possible, the full range of variation. The ordination of site data by species assemblages (Figure 3.4), gives some insight into the differences between sites, but in order assess this properly, it is necessary to consider additional data, including water chemistry and the character and diversity

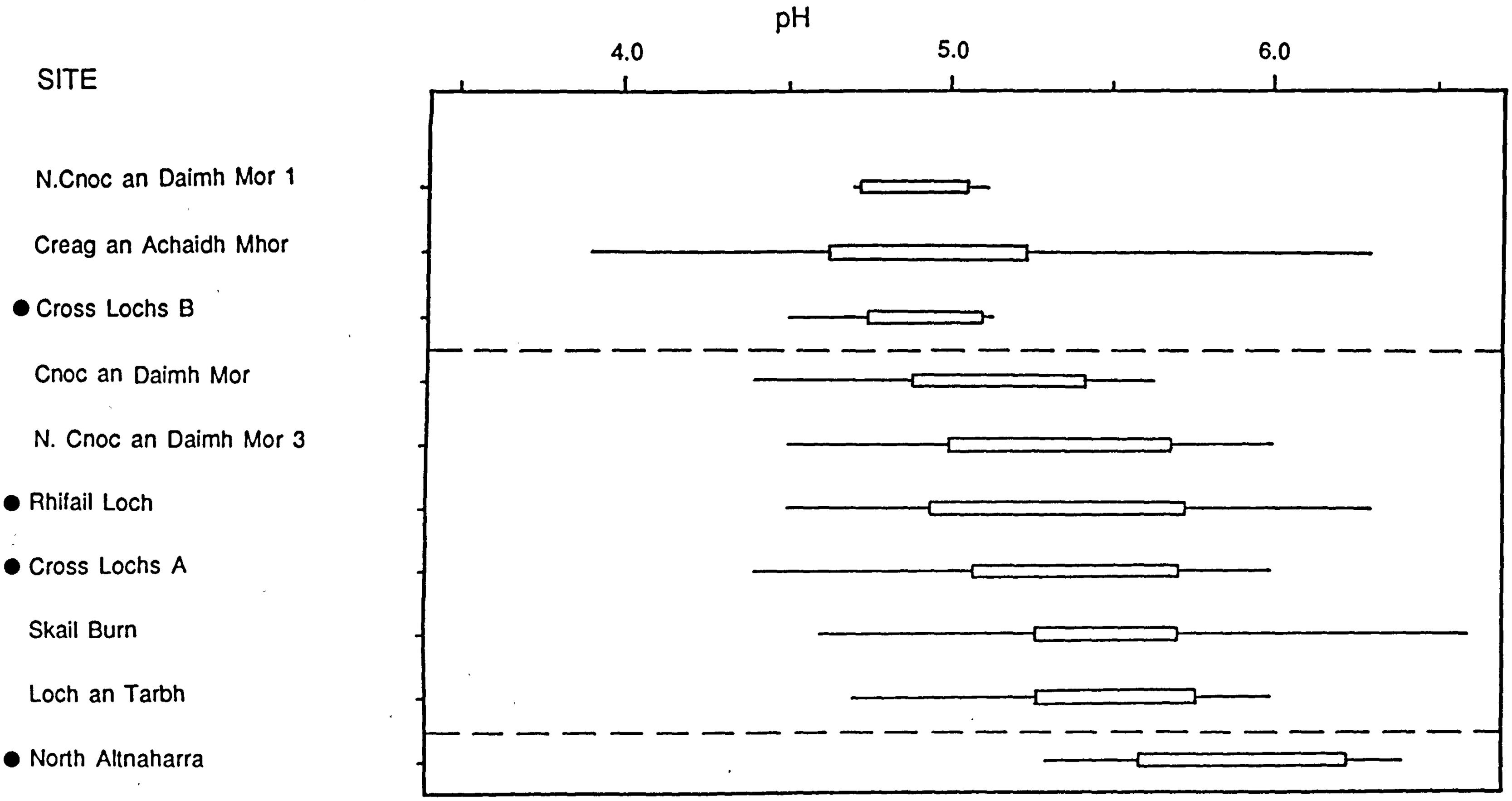


Figure 3.13: Summarised pH characteristics of patterned fen sites. ● - site used for palaeoecological research

of plant communities. This is summarised in Table 3.6, with a graphical representation of pH data distribution in Figure 3.13.

The site data for pH show a similar degree of variability and overlap to the plant communities, but are divisible into three main groups, on the basis of pH data. Most of

Table 3.6: Summary of site characteristics, excluding those where no. releves<5. Sites are ranked according to pH data and scores on axis 1 of ordination using vegetation noda as attributes.

Site	Rank (pH)	No. rel.	pH Range	pH mean	pH 2se	Conductivity ($uScm^{-1}$) Range	Conductivity mean	Conductivity 2se	Ordination Score	Ordination Rank
North Altnaharra	1	12	5.3-6.4	5.91	0.18	72- 84	77.3	1.9	355	1
Loch an Tarbh	2	10	4.7-6.0	5.52	0.25	32- 86	48.4	10.6	103	2
Skail Burn	3	20	4.6-6.6	5.49	0.22	45- 96	67.9	6.8	0	8
Cross Lochs A	4	11	4.4-6.0	5.39	0.32	53-121	74.5	11.6	85	3
Rhifail Loch	5	11	4.5-6.3	5.38	0.45	45-119	68.2	15.3	52	5
N.Cnoc an Daimh Mor 3	6	9	4.5-6.0	5.34	0.35	32-104	55.3	15.0	50	6
Cnoc an Daimh Mor	7	11	4.4-5.6	5.15	0.27	22- 83	47.5	11.6	70	4
Cross Lochs B	8	11	4.5-5.1	4.93	0.19	54- 73	61.9	4.2	0	8
Creag an Achadh Mhoir	9	15	3.9-6.3	4.93	0.31	18-115	46.2	10.6	3	7

the sites occur within the middle of this spectrum, but there are three with noticeably lower pH levels and a single site with generally much higher pH levels. Detrended correspondence analysis of site data with vegetation types as attributes is a convenient way of summarising vegetation variability and scores on axis 1 of this analysis is given as part of Table 3.6. A similar ranking of sites can be achieved in this way, although there are some slight differences in the placing of some sites. The four sites selected are positioned along these gradients, so that a range of sites is studied. Two 'typical' patterned fen sites occur in the middle of the data set (Cross Lochs A and Rhifail) and North Altnaharra appears to be an unusually nutrient rich site. An area being used for other

palaeoecological work contains the Cross Lochs B site, representing the more oligotrophic sites. The palaeoecological research is described in Chapter 6.

3.5 SUMMARY

This chapter has concentrated on the vegetation and simple water chemistry of patterned fens, with the intention of describing these basic features of a 'new' mire type and establishing their variability. Approaches to vegetation description and classification are briefly reviewed and the advantages of different methods for data collection and analysis are discussed. Problems of chemical characterisation of mire systems are outlined. The methodology used for survey and analysis of patterned fens in Scotland is described.

It is clear that the majority of patterned fens in Sutherland are remarkably similar in the plant communities they possess, as shown by the occurrence of a number of constants in the plant communities, particularly Carex lasiocarpa. The major variation in community composition is within sites, associated with microtopographical niches, similar to those described for ombrotrophic mire systems. Although intuitive interpretation of remaining variation in data shown by indirect ordination was in terms of pH and base status, direct ordination and testing by Monte Carlo simulation could not substantiate this hypothesis statistically.

However, classification of releves by TWINSPAN (Hill, 1979a) also appeared to divide data approximately in relation to inferred chemical criteria. A series of nine noda are recognised, four ridge and four pool communities with a separate and quite different *Molinia* dominated vegetation, restricted to inflow and outflow zones of patterned fens. Although within these two major classes there is some evidence to suggest variation along a pH and base status gradient, this cannot be strictly statistically

supported for all divisions. However, the major division between oligotrophic and mesotrophic ridges is significant at the 95% level.

The major characteristics of the nine noda are outlined, in terms of constants and dominants and they are compared with existing data from Britain and north west Europe. The current National Vegetation Classification (Proctor and Rodwell, 1986) does not include similar communities to those derived from the patterned mire data, although the vegetation of the inflow zones is included within the *Molinia - Potentilla erecta* community (M25). The pools are particularly poorly catered for, although some of the ridge vegetation could perhaps be considered as an undescribed variant of Scirpus cespitosus - Erica tetralix wet heath (M15). North west European phytosociological data from mires (Dierssen, 1982) has closer similarities, most releves probably occurring within the alliance Caricion lasiocarpae, although some of the oligotrophic vegetation could be assigned to the alliance Oxycocco - Ericion, within the Oxycocco - Sphagnetea. The occurrence of species normally characteristic of different major groups is problematic.

The vegetation and water chemistry data is used as a basis for justification of site selection for palaeoecological analyses, and it is shown that the sites chosen reflect the present range of ecological variation. The results of these analyses will be the subject of Chapters 6 and 7, and the implications of all the patterned fen research will be discussed in Chapter 9.

CHAPTER 4: PALAEOECOLOGICAL METHODS

4.1 INTRODUCTION

The majority of this thesis is concerned with palaeoecological aspects of the Flow Country blanket mire, with particular attention to patterned fens and their relationship with the ombrotrophic mires. Following chapters investigate regional vegetation history in the Flow Country (5), the development of patterned fens (6), surface pattern development on fens (7) and ombrotrophic mire development (8). While these separate chapters all have differing specific aims and as a result, methodologies, there are a number of basic analytical techniques that are used throughout. In this chapter, the intention is to mention some of the more relevant variations of these methods, to describe those used for the purposes of this study and to set out the reasons for choosing particular analyses. Although the majority of the analyses were performed in exactly the same way, there may be several minor deviations from this generalisation. These are covered in individual chapters, together with specific coring and sampling strategies which are too variable to be covered here.

4.2 STRATIGRAPHY

Stratigraphic records of all cores and monoliths were taken in the field according to the system of Troels-Smith (1955), as recommended by Aaby and Berglund (1986). Further descriptive notes were also made on the general appearance of sediments and any recognisable remains, such as seeds of *Menyanthes trifoliata*. Cores and monoliths were taken in half sections of plastic tube or aluminium tins, labelled, wrapped in aluminium foil and sealed in polythene bags, before being transported back to the laboratory where they were stored at approximately 4°C until analysis. Before commencing laboratory work, the cores were checked against

the field stratigraphy. Specific strategies used for selection of core locations in field work are described in later chapters.

4.3 POLLEN ANALYSIS

Pollen analysis is probably the most widely used and standardised procedure in palaeoenvironmental reconstruction. Reviews of uses, preparation and identification are widespread (Barber, 1976; Berglund and Ralska-Jasiewiczowa, 1986; Birks and Birks, 1980; Faegri and Iversen, 1975; Moore, 1986a; Moore and Webb, 1978). The intention here is merely to describe and justify the methods used and to outline some of the problems encountered.

4.3.1 Sample preparation

As mentioned above field sampling techniques vary, but samples for pollen analysis were always removed from the cleaned surface of either Russian pattern corers or monoliths. The preparation procedure is outlined in Figure 4.1. Sample intervals vary widely with specific aims (see Chapters 5-8). Samples of $1cm^3$ were removed using a calibrated brass sampler, of square section and in most cases it was necessary to cut around the edges with a scalpel first to avoid distortion and compression, especially in the less humified peats. This size of sample usually yielded enough pollen for counting but some problems of low pollen concentration were encountered in some of the topmost peats, where sample sizes were increased.

Lycopodium spores were used as an exotic marker in preparations, for the calculation of palynomorph concentrations (Stockmarr, 1971). Initial preparations showed that the addition of three of the tablets supplied (36,231$\pm$3.1%, Anon., 1984) was appropriate to obtain the recommended ratio of 1:1 exotic to pollen ratio (Berglund

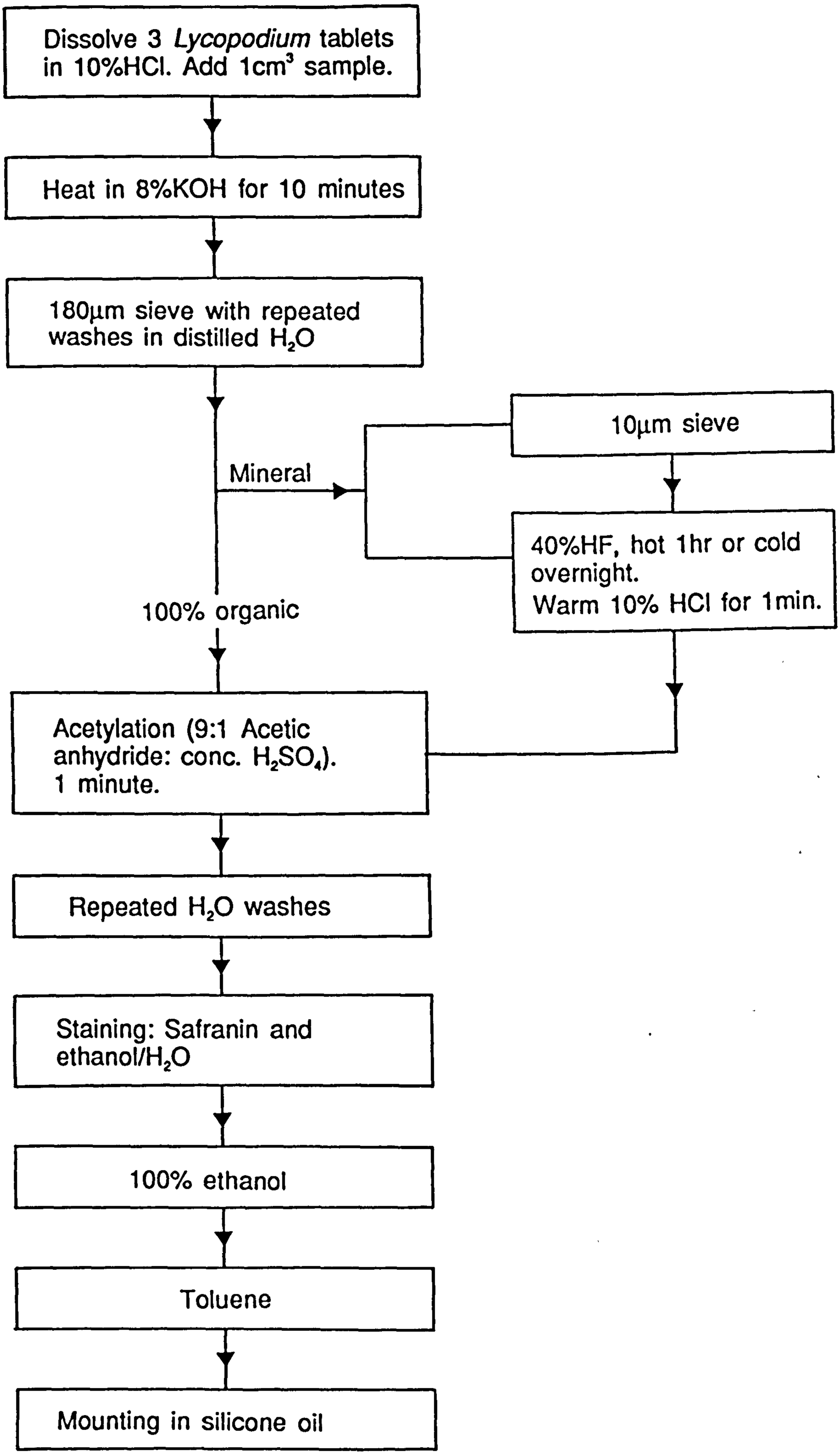


Figure 4.1: Procedure for preparation of pollen samples.

and Ralska-Jasiewiczowa, 1986). However, pollen concentration proved to be extremely variable, even within single cores and monoliths, so that the actual ratios varied between 36:1 and 1:69 (!), the highest concentrations occurring in basal peats and the lowest in peats close to the surface. Concentrations were also difficult to predict, for example some basal peats yielded as little as 1713 grains per cm^3, while others had up to 2.5 million grains per cm^3, so that it was simpler to maintain a constant level of added *Lycopodium* spores. Tipping (1987a) has found an increase in deteriorated pollen when using high concentrations of *Lycopodium* spores (ie. when using 6 tablets for 0.2 to 0.6cm^3 sediment), and although no such effects were obvious here, the possibility of it occurring needs to be considered in interpretation. The tablets were always dissolved in 10%HCl before the addition of the sample, to avoid clumping (Francis and Hall, 1985). The other method of adding a known volume of suspended exotic pollen (Benninghoff, 1962) was not used, mainly because of the ease of use of the pre-prepared tablets. De Vernal *et al* (1987) have expressed some doubts about loss of pollen during the aliquot method, although there is generally good comparability between the different techniques. Errors in the marker grain techniques are more easily assigned statistical significance.

Treatment with hot 8%KOH for 10 minutes to disperse the sediment and to remove humic acids was found to be adequate only when large (50cm^3) test tubes were used, particularly with some of the more compact and highly humified basal peats. These large tubes were subsequently used throughout the preparation until acetylation. A 180µm sieve removed the larger fragments and was followed by repeated washes in distilled water.

Most samples were entirely organic and therefore did not require treatment to remove silicates. This was, however, necessary for some basal peats, sub-peat soils and lake sediments and was achieved using hot 40%HF for one hour or

cold 40 or 60%HF overnight. 60%HF was necessary only for sandy soils underlying peat. Fine mineral material in lake sediments was removed by micromesh sieving (10µm).

After some early problems (see section 4.3.2), a standard acetylation procedure of a double washing in glacial acetic acid, followed by 1 minute in hot acetic anhydride/ concentrated sulphuric acid (9:1) and further washes in glacial acetic acid was used. This was used even on some of the samples with low organic content, to retain consistency between samples, as acetylation can be particularly destructive of certain pollen and spore types (see section 4.3.2).

Repeated washes in distilled water were followed by staining with safranin, dehydration in 100% ethanol and mounting in silicone oil (Andersen, 1960), now widely used in preference to glycerine.

4.3.2 Some problems with acetylation

'Standard' preparation procedures vary widely in specific recommendations, even within a single process, such as acetylation. Barber (1976) has been used as the basis for laboratory preparations at Southampton and the recommended time for acetylation is 1-3 minutes, although a later laboratory note suggests 5-10 minutes for highly organic samples. Faegri and Iversen (1975), also state, in relation to KOH treatment and acetylation that, "unless used to excess, (they will) not appreciably affect the morphology of exines" and in an earlier edition of the same text (1950, in Brown, 1960), "acetolysis was comparatively safe". Dimbleby (1985) merely recommends a continuation of the process "until the mixture turns brown." Godwin (in Brown, 1960), suggests 30 minutes, although this is with a mixture of glacial acetic and concentrated sulphuric acids, rather than the standard acetylation mixture. Brown (1983) also uses an acetylation time of 30 minutes plus.

Initial preparations, from core CRL1 (see Chapters 5 and 6), used extended acetylation times of about 10 minutes, because there appeared to be a high cellulose content. However, this was discontinued for a second batch of samples (1 minute acetylation) when it was found that using larger test tubes for KOH treatment dealt effectively with much of the problem and that the increased acetylation had the effect of blackening many remaining plant fragments, making them opaque and therefore more likely to obscure pollen grains. There thus resulted two sets of counts from CRL1; 23 samples at 16cm intervals and a further 23 samples at intervening points, equidistant from adjacent initial counts. Together, these should have formed a 46 sample pollen stratigraphy.

However, on examination of the resulting pollen diagram, it was noted that a previously smooth curve for *Sphagnum* now fluctuated markedly, with the counts from short acetylation times generally yielding much higher counts of spores. A more minor effect also appeared in the *Pinus* curve. Some of the first slides were recounted to check accuracy of results, but recounts were all within 1% of initial values. The only obvious difference remaining was therefore in terms of preparation, specifically acetylation. The levels which had been subject to prolonged acetylation were resampled and prepared using only 1 minute acetylation. A comparison of the counts of *Sphagnum* spores and *Pinus* pollen resulting from the different preparation procedures is shown in Figures 4.2 and 4.3, respectively. 95% confidence intervals are based on formulae given by Maher (1972).

There is clear evidence for destruction of *Sphagnum* spores by prolonged acetylation, all counts being lower, with most showing clear statistically significant differences. Moreover, the effect was not consistent throughout the core, with the greatest declines between 0 and 200cm. This may, however, be an artefact of the expression of counts in terms of percentages. No clear conclusions can be drawn

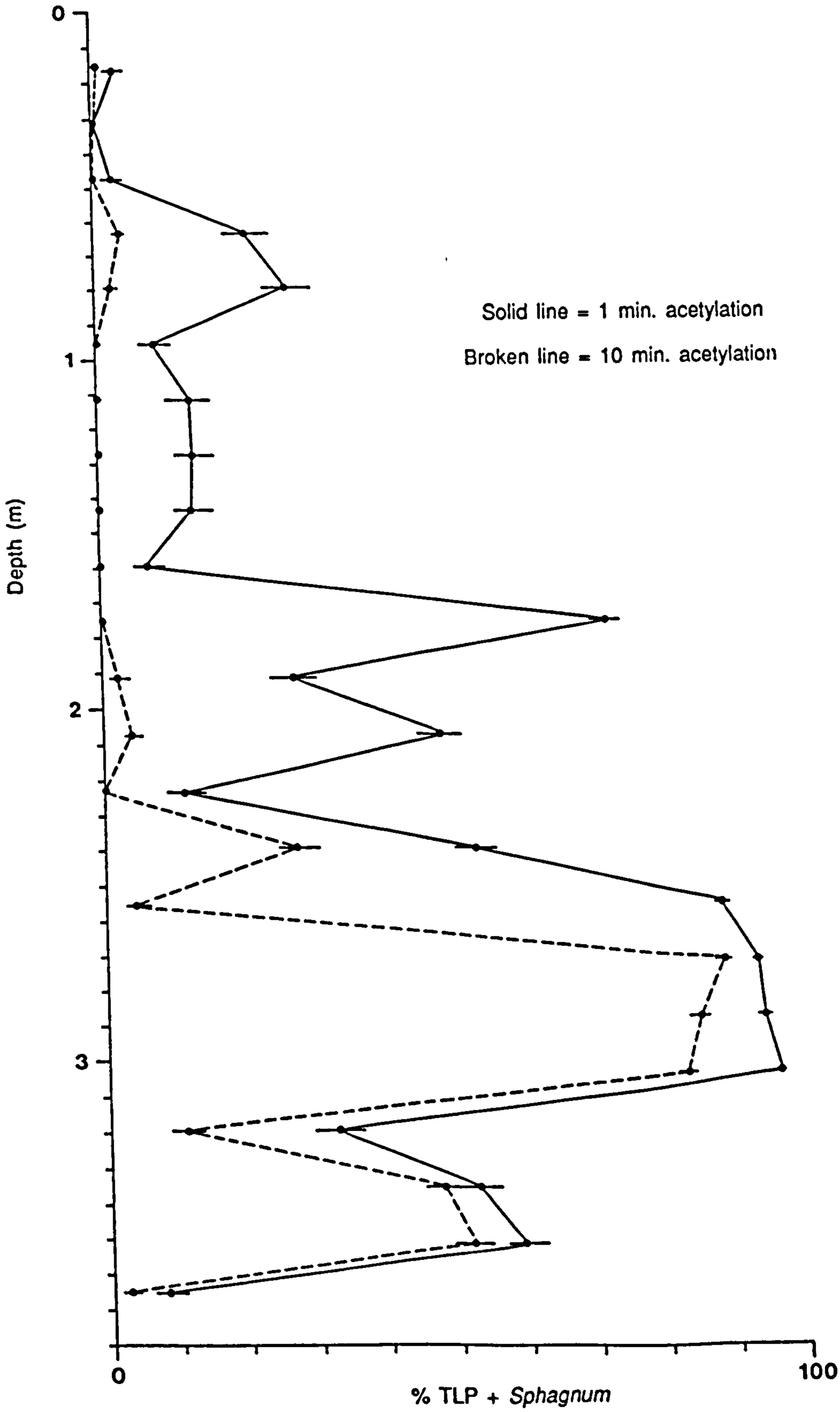


Figure 4.2: *Sphagnum* spore curves resulting from acetylation times of 1 and 10 minutes. 95% confidence limits (Maher, 1972) shown.

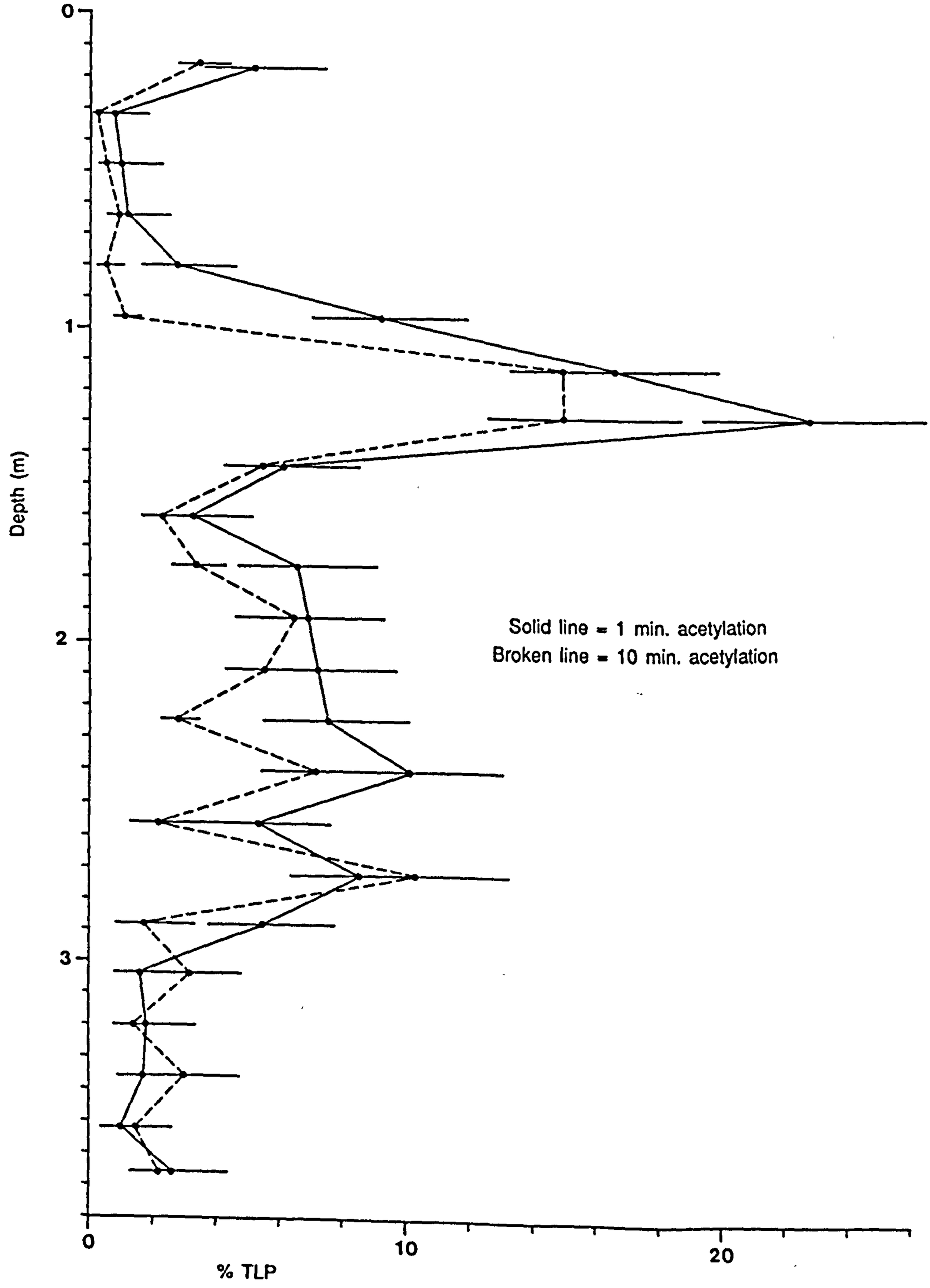


Figure 4.3: *Pinus* pollen curves resulting from acetylation times of 1 and 10 minutes. 95% confidence limits (Maher, 1972) shown.

from the *Pinus* data, however. Although there appears to be a general decline with increased acetylation, counts are not statistically separable. However, the unidirectional nature of the variation, except where counts are low, would argue against a hypothesis of random variation from sampling and counting errors. Some of the more significant differences may be at least partly explained by sampling error rather than preparation treatment, particularly around the large peak at ca.120cm depth, where these are much more likely to occur with such rapid changes in the abundance of this pollen type (see also Chapter 5). It therefore appears that *Sphagnum* spores are selectively destroyed by increased acetylation times, but that effects on *Pinus* pollen cannot be proven to occur.

Supporting evidence for such effects was sought in the literature, but there appears to be little experimental work on the effects of preparation procedures on pollen and spore morphology and representation in counts. Faegri and Deuse (1960) and Reitsma (1969) examine treatment effects on grain size and suggest only an enlargement of grains with increased acetylation times. Praglowski (1970) looks at shape in relation to pretreatment and mounting media, finding acetylation to cause less grain collapse than KOH treatment. The work of Tipping (1987a) regarding the use of *Lycopodium* spores has already been mentioned. Some texts do not mention (Brown, 1960; Barber, 1976; Birks and Birks, 1980; Berglund and Ralska-Jasiewiczowa, 1986) or appear to dismiss (Faegri and Iversen, 1975) possible problems with acetylation. This is despite recommendations for boiling for one minute, and simply bringing to the boil from Erdtman (1934 and 1954, respectively), the original proposer of the method. However, Moore and Webb (1978) suggest 3 minutes as a time limit for the process and state that, "prolonged treatment (>3min) may damage certain spores, especially *Sphagnum*."

This quotation supports the contention that different lengths of time for acetylation are responsible for the

differences noted in *Sphagnum* spore counts. Although there is no conclusive data of adverse effects on pine pollen, it is possible that this and other pollen types are affected to a lesser degree. The lack of basic information on the effects of treatment on pollen and spore representation in most 'standard' texts is a critical omission, but perhaps reflects the neglect of methodological research in palaeoecology in general. This is an avenue of apparently rather tedious work that is in need of exploration.

4.3.3 Counting and identification

Counting was performed on a Nikon Optiphot, fitted with Plan-chromatic x40 objective and x10 eyepiece lenses, approximately equally spaced traverses being made across the whole width of the slide to avoid bias due to edge effects (Brookes and Thomas, 1967). A x60 dry or x100 oil immersion objective was used occasionally for critical determinations. The pollen sum to be used was problematical, given the nature of the deposits and the treelessness of the terrain, a condition that had apparently persisted for some time (Peglar, 1979). To obtain regional pollen spectra from peat deposits, some authors have excluded mire pollen from the sum (eg Barber, 1981). However, since most of the species recorded from the sites in northern Scotland have been growing at some time on the mire surface (including *Betula* and *Pinus*), this would leave only a few regionally present taxa and the long distance element of the pollen spectra represented. Therefore, a total of 500 total land pollen was generally counted for each level and the interpretation of this is considered for each individual profile as appropriate (Chapters 5-8). This appears to satisfy the 'diversity saturation' criteria of Rull (1987) and is the sum most often used by other authors in recent years. Lower counts were used in some instances where extra local vegetation only was of interest or approximate counts were acceptable.

A number of different texts were used in determination of

pollen types, the most useful being Moore and Webb (1978), Faegri and Iversen (1975), Erdtman *et al* (1961) and the Pollen Flora of North West Europe (Punt, 1976-1984). Reference slides, held at the University of Southampton, were used to check determinations made from these texts. Nomenclature generally follows that of Moore and Webb (1978). Separation of *Corylus* and *Myrica* was attempted, using the criteria of protruding aspides (generally >2.5u), thinning nexine within aspides with crowded, upstanding echinae to distinguish *Myrica*. It is recognised that there are considerable problems with this separation and that it is unlikely to be entirely consistent (Edwards, 1981), and therefore 'Coryloid' curves are presented in the main pollen diagrams, with curves for the two tentatively separated types on separate diagrams, where this is felt to be informative. It is stressed that these should be cautiously interpreted. However, the timing of significant rises in the two taxa and macrofossil evidence for *Myrica* would support the contention that separation has been generally successful. Occasionally, and particularly in sub-peat soils, triporate grains were encountered which could not reliably assigned to *Betula* or Coryloid types. These are shown as 'triporate' on the diagrams. The classification of corroded and indeterminable types as recommended by Birks (1973) has been used to advantage by several authors since (eg. Hall, 1981; Lowe, 1982; Tipping, 1987b) in reconstructing catchment environmental history of lakes. Applications in pollen analysis from peats are rather limited and separation of corroded and indeterminable types was not therefore attempted here. Total counts and the figures for 'triporate' grains give some impression of the relative degree of pollen corrosion.

4.3.4 Data analysis and display

Counts were entered into a programme written for the BBC Master microcomputer by Dr JA Milne at the Department of Geography, University of Southampton. This enables calculation of percentage and concentration pollen

statistics, by a variety of pollen sums, with plotting on screen or direct to a Quest plotter. Stratigraphic, pollen assemblage zones and radiocarbon dates can also be plotted. These form the basis of the diagrams showing pollen percentage and concentration data. Influx diagrams are not given, as it is felt there is probably highly variable accumulation rates of most peats and therefore that these cannot be reliably extrapolated between radiocarbon samples. Diagrams have been zoned by careful consideration of fluctuations in the most significant taxa, exact criteria are given later. The advantages of zonation using the methods of Birks and Gordon (1985) were not felt to outweigh the time penalty involved.

4.4 OTHER MICROFOSSILS

Non pollen microfossils are frequently encountered on slides prepared for pollen analysis, but few have been recorded in the past, apart from some lake dwelling organisms such as *Pediastrum* and *Botrycoccus*. Although some remains have been mentioned in the past (eg fungal spores; Graham, 1962), it is only relatively recently that the work of Bas Van Geel and colleagues at the Hugo de Vries Laboratory in Amsterdam have shown the full potential of examination and recording of these remains. The work is summarised by Van Geel (1986), with detailed analyses and microfossil descriptions given in Van Geel (1972, 1976, 1978, 1979a, 1979b), Van Geel *et al* (1981, 1982, 1984), Van Geel and Van der Hammen (1978), Kuhry (1985), Bakker and Van Smeerdijk (1982), Ellis and Van Geel (1978), Pals *et al* (1980) and Van der Wiel (1982).

The identification and interpretation of these microfossils is still in its infancy, and many of the types recorded are still unidentified. All new types recorded are photographed, described and given a type number. Attempts are then made to identify the type by consultation of keys for modern material and with advice from experts in zoology, mycology and algology. Illustrations of most of

the microfossil types are kept in a microfossil reference collection at the Palaeoecology Laboratory, University of Southampton and these were frequently referred to for identification of types encountered while counting pollen.

The effects of sample preparation on different types is, not surprisingly, imperfectly known, although Van Geel (1986) claims no difference in samples treated with HF compared to those prepared using bromoform-alcohol. Certainly HF will destroy any diatoms present and standard chemical treatments for pollen analysis damages most rhizopods (Tolonen, 1986a). A number of rhizopod species were encountered in the uppermost layers of peats sampled for pollen analysis in this study, but their use is limited because of the unknown selectivity of the effects of preparation treatment. Tolonen (1966; 1986a) and Tolonen *et al* (1985) have realised the use of rhizopods and they have recently been used in North American palaeoecological research (Warner, 1987, 1988). Some descriptions from Britain have been published (Corbet, 1973). Rhizopod analyses may have been of use in the reconstruction of on site environmental conditions in this study, but the need for separate preparation and the acquisition of further expertise in identification precluded this.

Data presentation is often in terms of % pollen sum, but may also be as concentrations or absolute counts. Concentrations are presented here, as it is felt that the use of pollen data merely complicates the interpretation of microfossil diagrams, particularly because of likely changes in pollen influx. Full species names and descriptions of unidentified types are given in Appendix II. Counts of microfossils were extremely variable, some levels containing hardly any while in others there was such a high density, they were difficult to count. As in pollen analysis, production and preservation of microfossils is presumably variable with species, although this is likely to be more extreme as several different major groups of organism are being dealt with.

Interpretation of data is problematical given the current lack of data on the ecological requirements of species, even once identified. However, the references mentioned above give some guidelines and the usefulness of the types discovered is discussed, where appropriate, in the following chapters.

4.5 MACROFOSSIL ANALYSIS

There are no accepted standard methods for the sampling, preparation and identification of macrofossil remains, despite the technique predating that of pollen analysis. In order to construct a procedure for analysis, the aims must be clear. In this case the aim was to use macrofossils to provide:

i) a reconstruction of vegetation change through time at the community level.

ii) Data on local plant growth to combine with pollen and microfossil evidence to determine local site conditions.

iii) Data on local plant growth to aid separation of regional and local components of the pollen spectra.

iv) Information on stratigraphic changes, as cursory visual inspection generally proved inadequate, or sometimes misleading, beyond major differences in peat composition.

Plant macrofossils can be defined as "everything that cannot be considered a microfossil" (!) (Grosse-Brauckmann, 1986) but are separable into two major categories; reproductive and vegetative. In addition to this there are zoological remains and charred particles, the latter is discussed in section 4.6.

4.5.1 Preparation

4.5.1.1 Vegetative macrofossils

Work on vegetative macrofossils includes all non-reproductive plant material from bryophytes through to trees and shrubs. In mire sediments where the aim is only

to assess the composition of the peat, it is normally only necessary to look at small samples of 2-10cm^3 (eg Middeldorp, 1984; Dupont, 1987) although Grosse-Brauckmann (1986) has suggested 50cm^3. Smaller samples are easier to cope with and given a reasonably fine matrix should be an adequate representation of peat composition. Dispersal of the sediment may be achieved by the use of chemicals (dilute KOH or HNO_3) or merely with plain tap water (Barber, 1981). Chemicals may damage plant tissues. Dispersion is normally followed by sieving to remove fine highly humified material, retaining the larger, identifiable fragments. Nests of sieves of different mesh sizes can be used but generally two are adequate, 500µm and 120-180µm (Grosse-Brauckmann, 1986). Identification and estimation of relative proportions of peat components are then made under a stereo microscope.

Estimation of abundance is normally on a percentage basis by eye (Grosse-Brauckmann, 1986) or by an ordinal 5 point scale (Barber, 1981). However, Clarke (1988) and Haslam (1988) used a semi-quantitative method in an attempt to produce more reliable estimates of percentage abundances. This involves scanning sieved residue at x10 magnification and performing a number of percentage assessments using an gridded eyepiece graticule as a "quadrat". Standard errors are then attached to estimates of percentage cover, where n = no. of quadrats. *Sphagnum* species composition is obtained by identification and counting of 30-120 individual leaves. This method works particularly well on ombrotrophic peats (Haslam, 1988). Other, more comprehensive, counting methods such as those of Janssens (1983) have been used, but are extremely time consuming.

4.5.1.2 Reproductive macrofossils

One of the disadvantages of reproductive macrofossil analysis is that it requires a relatively large sediment volume in order to obtain enough examples to make meaningful statements about fossil plant communities. Birks

and Birks (1980) recommend 100cm^3 and Wasylikowa (1986) states that at least 10 macrofossils per 100cm^3 are required. Clearly this may place restrictions on the temporal resolution of the data, particularly where core samples of limited volume per unit depth are being used. There is a similar range of methods for sediment dispersal and sieving to those used for vegetative macrofossils. Counts are made on all reproductive remains recovered, and often on some vegetative remains that are easily counted, such as leaves of dwarf shrubs. Greatrex (1983) shows that most peat macrofossils reflect only extra local (<1m) communities, with some additional air and water borne sub-fossils.

4.5.1.3 Study methods

The aim in this study was not only to identify and assess the relative abundance of major peat forming constituents, but also to gain more detailed knowledge of plant communities, requiring data on seeds and fruits. Therefore, a combined methodology was used, detailed in Figure 4.4.

Large samples were required for seeds and fruits and samples were required to correlate with pollen data. Macrofossil samples of between 40 and 50cm^3 were removed from the core or monolith, straddling each pollen sample. In many cases, pollen samples were spaced 8cm apart and a section of 5cm diameter Russian core of 8cm length provided an appropriate sample size. Exact sample volume was established by displacement in a 250ml measuring cylinder, to the nearest 1cm^3.

Trials showed that while dispersal of the less humified peats was possible with plain tap water, more humified sections would not break up adequately. HNO_3 was also tried but although sediment dispersal was efficient, a large amount of unidentifiable organic matter remained, making the 125-500µm fraction difficult to examine. Use of warm, approximately 6%KOH, for 10 minutes, with occasional

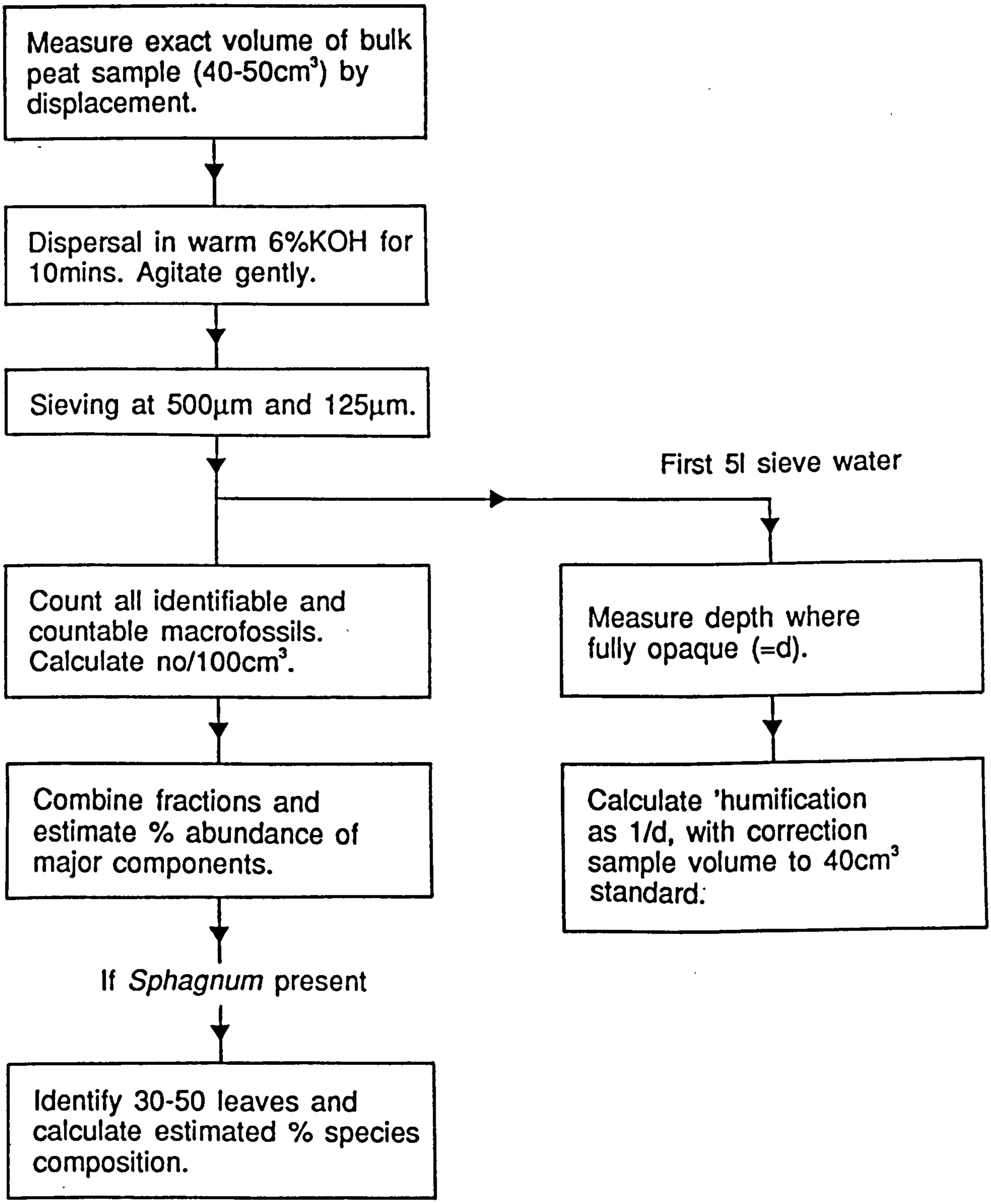


Figure 4.4: Procedure for preparation and counting of macrofossil samples.

agitation achieved both dispersal and removal of much unidentifiable organic matter. Preservation of macrofossils was diminished slightly by this chemical treatment, but this was not found to be a major problem in identification and was preferable to investing large amounts of time sifting through quantities of fine humic material to find smaller macrofossils such as seeds of *Juncus* and *Erica tetralix*. Mucilaginous residue on subfossil material was also not a significant problem, given the use of sufficient quantities of water during sieving (at least 5 litres).

Sieving utilised 500 and 125µm sieves, yielding two fractions. All 'countable' macrofossils in the >500µm fraction were counted. This included remains such as leaves of ericaceous species and shoot bases of Carices, as well as reproductive macrofossils. The 125-500µm fraction did not generally contain many macrofossils, and where present these were often abundant (>1000), so that estimates were made of total numbers from counting approximately 1/3rd (by volume) of the fraction. Estimates of percentage composition of total peat were made by scanning the 500µm fraction and if this contained any *Sphagnum* remains then a sample of 30-50 leaves was extracted, stained, identified and counted, to give estimates of the species composition. While the methods of Clarke (1988) and Haslam (1988) give some sense of strictly quantitative data, this is in some ways spurious. Quoted standard errors, do not give true confidence intervals of the population means, but of the estimated means. They still do not account for the effect of observer bias, which in any scheme using estimates of abundance is likely to be considerable. No attempt was therefore made to obtain multiple estimates of peat composition.

Humification assessments have classically been done according to the Von Post scale (Grosse-Brauckmann, 1986). However, this requires a certain volume of peat to squeeze, if it is to be properly applied and the five point scale of Troels-Smith (1955) is often rather inaccurate. Estimates

of humification can be made from the relative darkness of the water passing through the sieve (Barber, 1981; Clarke, 1988) or more accurate data can be obtained by humic acid extraction and measurement of light transmission (Bahnson, 1968). A compromise method was used here, whereby the first 5l of water passing through the sieve was well mixed and slowly poured into a glass beaker, resting on a white tile, with a black cross drawn on it. When sufficient water had been poured to entirely obscure the cross when viewed vertically, the depth of water was measured to the nearest mm. Corrections were made for variable sample volumes, and the reciprocal of the water depth plotted on diagrams, so that higher values correspond to increased humification. Measured values (in cm^{-1}) are therefore shown on diagrams. An approximate relationship between the measured values and the Von Post scale has been established from estimates made on some samples:

Measured value cm^{-1}	Von Post	Measured value cm^{-1}	Von Post
<0.1	0	0.6-0.7	6
0.1-0.2	1	0.7-0.8	7
0.2-0.3	2	0.8-0.9	8
0.3-0.4	3	0.9-1.0	9
0.4-0.5	4	>1.0	10
0.5-0.6	5		

4.5.2 Macrofossil identification

4.5.2.1 Vegetative

The identification of vegetative macrofossils has never received much attention in the literature and there are few keys or guides available. This is perhaps due to the difficulty of determination of most peat material which is often predominantly root material. Grosse-Brauckmann (1986,

p602) emphasises the variability of cellular structures within individual plants and recommends that histological characters be used only in conjunction with macromorphology for the majority of species. However, cellular characteristics can be used for wood remains (Schweingruber, 1978). There is quite a large amount of German literature from the late nineteenth and early twentieth century relating to vegetative macrofossils (Grosse-Brauckmann, 1986, p591), but the most useful information was found to be Grosse-Brauckmann (1972, 1974, 1986) and Katz *et al* (1977). Comparisons with reference material were also frequently made.

Much of the material examined from patterned fen sites was monocotyledonous root material, which may be referable to Molinia, where an epidermis is preserved. This is not often the case and few identifications have been made of such remains. Most is presented as 'Monocot' in the diagrams. Leaf material of ericaceous species is readily identifiable, as are both the fibres and sclerenchymatous spindles of Eriophorum vaginatum. Some woody material is identifiable to species level, where axial scars remain (Erica tetralix), or where bark is preserved (Betula), but most of the rootlets from dwarf shrubs are indistinguishable beyond the group level. The problems of identification of most vegetative remains preclude the presentation of detailed data. Percentage estimates divide the peat into the following categories:

i) Monocotyledonous roots: all Cyperaceae and gramineae roots not identifiable to species level.
ii) Wood peat: broken fibrous material, thought to be remains of highly decomposed woody species.
iii) Wood: identifiable fragments of shoots from dwarf shrubs and/or Betula.
iv) Ericaceae roots.
v) Eriophorum vaginatum fibres.
vi) Major bryophyte components by species and genus (see below).

vii) Mineral matter: particularly important for basal peat samples.

A series of notes on the diagrams record the presence of any of the above material identified to genus or species level, although this is cannot necessarily be regarded as representative of the total category.

4.5.2.2 Bryophytes

This group is discussed separately, as the problems of identification are rather different to those for the vegetative remains of vascular plants. In theory it includes mosses and liverworts, although remains of the latter are rarely recovered (Dickson, 1973). The main difference between vegetative vascular and bryophyte remains is that bryophytes retain virtually all their diagnostic characters in the sub-fossil state and therefore modern keys can be used to identify them to species level. The most useful keys to the group in general were found to be Watson (1981) and Smith (1978), with some useful additional drawings and photographs in Katz *et al* (1977) and Grosse-Brauckmann (1974).

Sphagnum is the most common genus of ombrotrophic mires, and although the surface vegetation of both ombrotrophic mire and poor fens in the Flow Country contains abundant *Sphagnum*, remains of this genus are not so widely found in a sub-fossil condition. Much of the attention from palaeoecologists has concentrated on its role as an indicator of surface wetness, reflecting climatic shifts in raised mire stratigraphy (Barber, 1981, 1982). Assumptions can be made regarding the probable specific identity of some groups of *Sphagna* found in ombrotrophic mires, because of the restricted range of species. This is not possible in this study, where ombrotrophic conditions cannot be proven to have existed when most of the sub-fossil communities were living. Identifications in subfossil material rely on branch leaf characters as often these are the most abundant remains. The sample of leaves extracted (30-50) were

stained with methyl blue and mounted in Hydramount. Identifications were carried out at x100 to x400 magnification. There have been many keys to this group published, the most useful were those of Hill (1978) and Daniels and Eddy (1985). Also consulted was Klinger (1976), translated in Clarke (1988), for the section cuspidata. Nomenclature follows that of Daniels and Eddy (1985). Reference slides of modern material were also consulted to confirm identifications from keys and drawings.

The section *Sphagnum* (also known as cymbifolia) was identified to species level, but most others can only confidently be assigned to group level, apart from *S.cuspidata*, distinguished by leaf and cell shape. Those identified include sections acutifolia, cuspidata, subsecunda and squarrosa. The likely specific identity of some leaves is possible using size criteria and inferred surface conditions from other palaeoecological evidence. All examples of section Squarrosa are probably referable to *S.teres*, because of the lack of markedly squarrose leaves, which distinguishes *S.squarrosa*. It is likely that many of the leaves of section Subsecunda are *S.subsecundum* or *S.subsecundum subsp.inundatum*, as they are too small (<1.4mm long) to be the larger *S.auriculatum*. These possibilities are discussed where necessary in later chapters.

Total *Sphagnum* is expressed as a percentage estimate of total peat, in a similar way to the other major peat forming constituents. Estimates of the relative contributions of particular groups within this are also expressed as % total peat, avoiding the misleading representation of abundance as %total *Sphagnum* (Clarke, 1988; Haslam, 1988).

4.5.2.3 Reproductive macrofossils

Most well preserved seeds can be identified to species level with the use of keys, illustrations and a reference collection. This was possible in many cases here, but particular problems were encountered with some problems of poor preservation, particularly within the Cyperaceae and the Juncaceae. Specific identification of the latter was impossible as testae were absent from all subfossil seeds recovered (Ḳorbe-Grohne, 1964). There are a large number of taxonomic guides for seeds and fruits (see eg.Delcourt *et al*, 1979, for a bibliography), but those found to be most useful in this study were those of Beijerinck (1947), Bertsch (1941), Katz *et al* (1965), Berggren (1969, 1981), Godwin (1975), with specific guides such as Swarbrick (1970) to Scottish aquatic herbs, Korbe-Grohne (1964) to the Juncaceae and Aalto (1970) to the Potamogetonaceae. In addition to this a reference collection, built up at Southampton was used for comparison with modern material. Fossil reference material was also built up as the analyses proceeded and examples of all types preserved in alcohol.

4.5.2.4 Zoological remains

Microscopic zoological remains can form a considerable portion of the microfossils occurring on pollen slides (section 4.4). There are also a number of more obvious remains that occur as macrofossils. These consisted mainly of coleoptera elytra and mites (Acarina). While beetle remains have been proven extremely useful in reconstructing Quaternary climates (eg. Atkinson *et al*, 1987), they do not occur in abundance in small volumes of peat, require specialist study and were not identified for this study, although total numbers were counted. Mites have received less attention although some potential for their use has been shown by Schelvis and Van Geel (1989). They were extremely numerous in the 125-500µm fraction and were not identified or counted, as even total numbers are unlikely to reveal much about contemporary conditions.

4.6 CHARCOAL

An additional source of information concerning human impact on the mire systems and the surrounding area is that of charred particles. For full reconstruction of fire history and frequency, contiguous sampling of sediments with good temporal resolution and control (such as varved sediments) is necessary (Clarke, 1988a). However, in this case, the intention is to gain supporting information for pollen and macrofossil analyses, mainly in order to assess levels of human impact.

Tolonen (1986b) and Patterson *et al* (1987) review charred particle analysis, but the emphasis is on microscopic counting methods. Winkler (1985) suggests a chemical assay method, but Robinson (1984) finds this does not correspond with microscopic counting and macroscopic estimation methods, recommending the two latter analyses. Microscopic analyses typically use the point count methods of Clark (1982), whereby slides prepared for pollen analyses are scanned for charred particles and results are expressed as μm^2 charcoal per unit volume of sediment. Recent work by Clark (1988a) shows, by consideration of theoretical particle motion, that pollen slide charcoal, representing particle sizes of 5-80µm, reflects fire at the subcontinental to global scales. He suggests that thin section charcoal (50-10,000µm) is more likely to reflect catchment fire regimes and demonstrates this by comparison with fire scars on red pine in Minnesota (Clark, 1988b).

In this study, macroscopic charcoal, comparable in size to Clark's thin section material, is of particular interest as an indication of on site and local fire. Early human impact, during the mesolithic, rarely leaves abundant archaeological evidence and can be difficult to detect in pollen spectra, but charcoal curves have been used as evidence of such disturbance (eg.Robinson, 1983). Charcoal abundance has been assessed on a five point ordinal scale, separated into the two size fractions (>500µm and 125-

500µm) in the case of basal peat monoliths. Clearly this has drawbacks in terms of precision, but it was found to work well as a rapid general assessment of charcoal abundance and although minor fluctuations may be beyond the resolution of the method, the most important variations were unmistakable.

Some successful trials were undertaken with thin section preparation by freeze drying and impregnation with resin, but this work was not carried through, due to time limitations. It is clearly a useful method, as charred remains are examined *in situ* and are not subject to breakage in the process of preparation for other analyses, a particular problem with microscopic counts.

4.7 LOSS ON IGNITION

Loss on ignition (%LOI) measurements were used as an indicator of approximate organic content of peats and soils when studying the soil-peat interface and early blanket peat deposits (Chapter 8). The determination of %LOI was carried out according to the schedule in Figure 4.5, modified from Brown (1983) and Allen *et al* (1974).

4.8 RADIOCARBON DATING

Radiocarbon dating was carried out at the NERC Radiocarbon Laboratory at East Kilbride. Specific details of sample pretreatment and dates are given in the appropriate sections of later chapters.

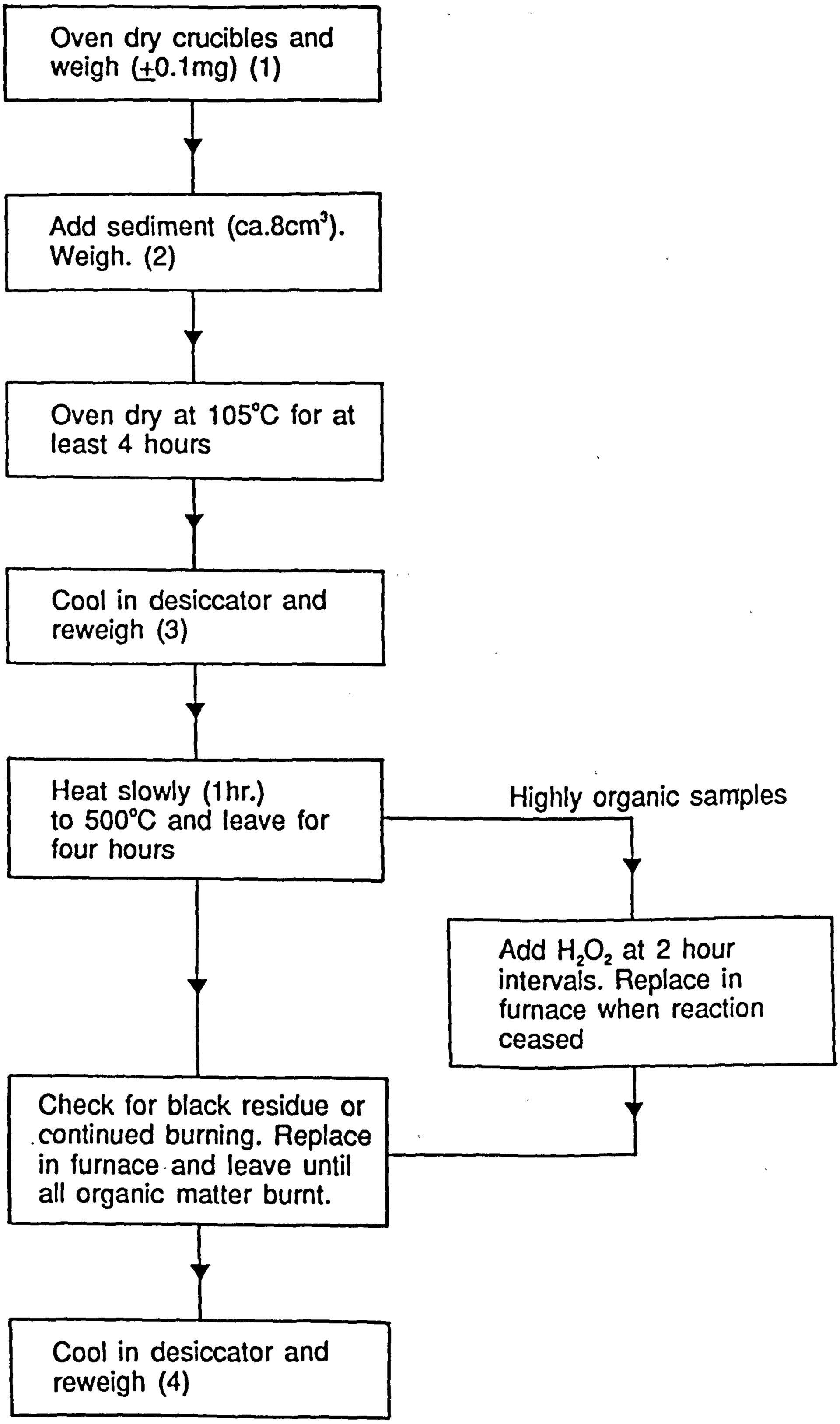


Figure 4.5: Procedure for loss on ignition.

CHAPTER 5: - VEGETATIONAL HISTORY

5.1 INTRODUCTION

As previously mentioned in Chapter 4, the remainder of this thesis is primarily concerned with the development of the mire systems in the Flow Country. An essential part of such research is an understanding of the broader scale environmental changes taking place during the same time period. However, although the peat and numerous small lochs in the region provide ample opportunity for palaeoecological research, there are few modern accounts available. The east of Caithness has a good chronology established from lateglacial times (Peglar, 1979), with additional data from 8000bp-present (Robinson, 1987) and there is published data from western Sutherland (Moar, 1969a; Pennington *et al*, 1972; Pennington, 1975). Data concerning the Lateglacial on the central northern coast has also been published (Birks, 1984). The unpublished information for the Holocene from that core is unavailable (Gear, pers comm.). The only pollen data available for the central Flow Country region is that of Durno (1958), but there are no radiocarbon dates, counts are low and expressed in terms of AP, and temporal resolution is poor. Gear (1989) gives some pollen data but is mostly concerned with the history of *Pinus sylvestris*. It was therefore necessary to construct a pollen chronology for the central part of the deep peat area, within which the main study sites for peatland development research are sited. However, while the provision of a secure chronological framework was the primary objective, the results are also of intrinsic interest in relation to other research concerning vegetational history in Scotland.

This chapter consists of the results from two closely spaced sites, one representing the Devensian Lateglacial and the other covering the Holocene, the latter being most relevant to the large scale peat development in the area. Additional information relating to the two sites is

contained in Chapter 6, where their morphology and development is described and discussed.

5.2 METHODOLOGY

5.2.1 Site selection: The Cross Lochs area

The choice of location was constrained by the need to use sites as close as possible to the main study area for peatland development, which is the large expanse of varied blanket mire centred on the Cross Lochs in eastern Sutherland, close to the Caithness border and almost centrally placed within the 'Flow Country' (Figure 2.2). The site (Figure 5.1) consists of a large watershed area (ca.3.km^2) with a complex of patterned mire systems and lochs and no mineral ground apart from a few isolated rock outcrops. The site is on the Forsinard Estate, now owned by Fountain Forestry, who have planted extensive coniferous plantations to the north and west, mostly of *Picea sitchensis* and *Pinus contorta*. The river Dyke flows north west on the western side, within the plantation, and joins the river Halladale, which also flows north in the major valley of Strath Halladale to the east. Within the plantation there are several forest tracks, the cutting of which has exposed extensive basal peat deposits (see Chapter 8). There are two patterned fen sites and a number of ombrotrophic mire mesotopes.

Early investigations into peat stratigraphy of the patterned fen site Cross Lochs 'A', resulted in a core of 3.7m (CLA1), which was to be analysed for macrofossil content. This was the deepest peat discovered in the immediate area of the Cross Lochs at the time and therefore was used for pollen analytical work, from which it was found to cover most of the Holocene.

Subsequent to this initial analysis, a further stratigraphic survey of another patterned fen site (Cross

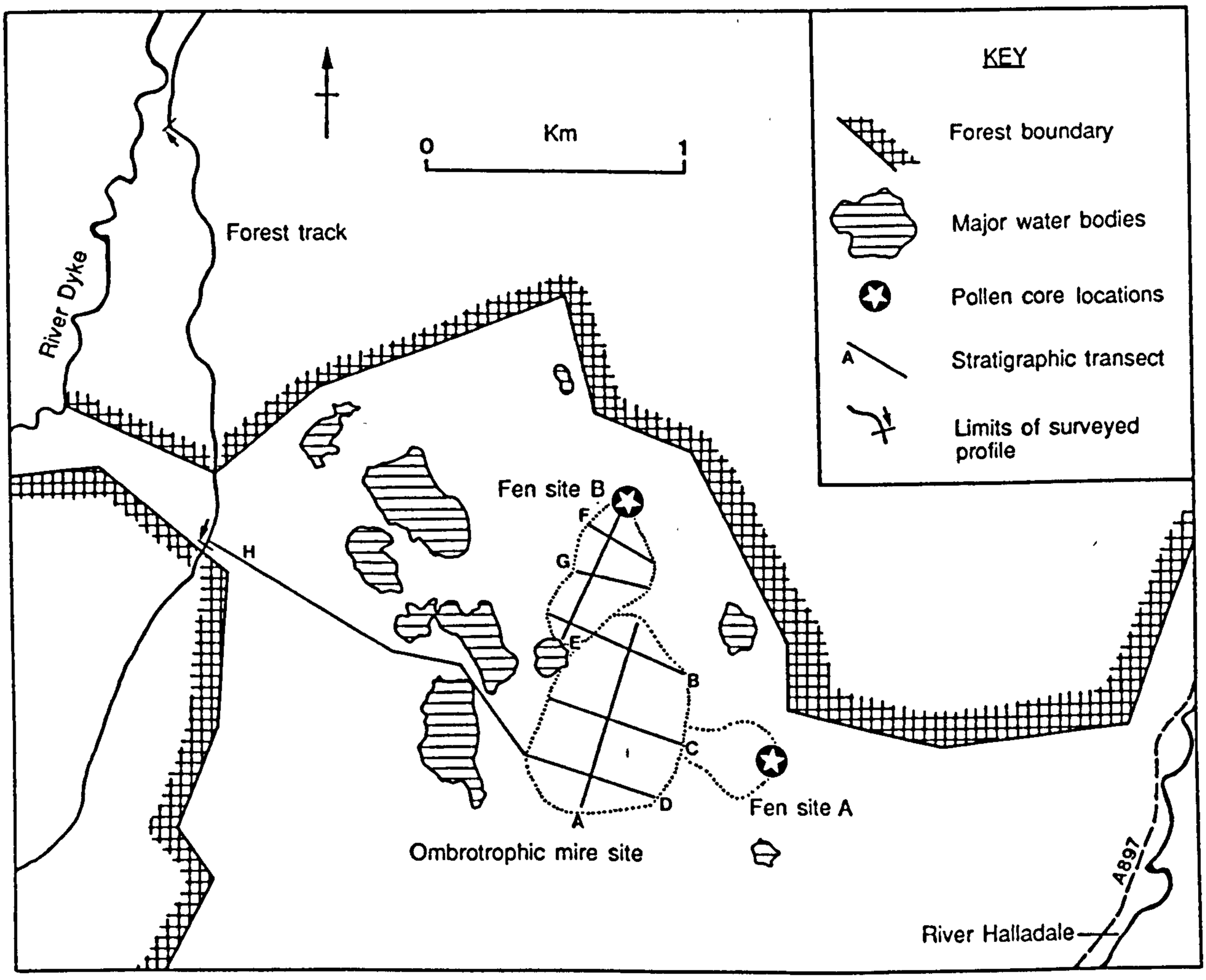


Figure 5.1: The Cross Lochs area, indicating main study sites.

Lochs 'B') was carried out and deposits of over 7.8m were discovered consisting of a variety of peats underlain by 3.9m of lacustrine sediment, the basal part of which was thought to be of Lateglacial age. This second site was only 1km from CLA1, and therefore could be correlated with that core in the upper sediments and only the lower portion of the core was used for detailed pollen analysis, covering the Devensian Lateglacial and early Holocene. The exact location of these two cores and their relationship to each other and the wider study area is also shown in Figure 5.1.

5.2.2 Sample collection and analysis

At both sites, sample collection was by a 50x5cm Russian pattern corer (Barber, 1976) and stratigraphy was described in the field and checked on return to the laboratory, immediately prior to sampling for pollen analysis. Samples for radiocarbon dating were taken using a larger (30x9cm) Russian pattern corer (Barber, 1984), immediately adjacent to the core used for pollen analysis.

Samples from Cross Lochs 'A' were collected in November 1987 and analysed during 1988-89 and Cross Lochs 'B' was sampled during August 1989, with analysis during 1989-90. Sample storage was at 4°C, in plastic half drainpipes, wrapped in aluminium foil and sealed in plastic bags. Samples were of $1cm^3$, normally at 8cm intervals with more closely spaced samples where changes in pollen stratigraphy were of particular interest. Laboratory procedure was as described in Chapter 4. Pollen sums were 500 Total Land Pollen for the Holocene sequence from peats in CLA1 and 300 TLP for the Lateglacial and early Holocene samples from lake sediments in CLB1, although there are several samples where it was not possible to count this number of pollen grains. Pollen sums are shown for each level on the diagrams.

5.2.3 Radiocarbon dating

A total of eight radiocarbon dates have been obtained from the two cores. However, the results of two of these (from the Lateglacial section) have not yet been received, but will be included in any future publications. The other six dates are all from CLA1 and are shown in Table 5.1. Prior to ^{14}C measurement, each sample was digested in 2M HCl at 80°C for 24 hours, washed acid free and dried to a constant weight.

Table 5.1: Radiocarbon dates from Cross Lochs 'A'.

Depth (cm)	Lab.code	Date (bp)	^{13}C (‰)
48-56	SRR-3707	1470 ± 45	-28.0
118-126	SRR-3708	3920 ± 45	-28.1
134-142	SRR-3709	4250 ± 45	-27.7
192-200	SRR-3710	5880 ± 45	-27.9
280-288	SRR-3711	7575 ± 45	-27.6
344-352	SRR-3712	8995 ± 50	-28.0

Dates are uncalibrated and errors are quoted as ± one standard error.

Radiocarbon age is plotted against depth in Figure 5.2, for the Cross Lochs A core. These Holocene dates are all from terrestrial peats and are a conformable sequence, with no reversals or suspected errors of large magnitude. The laboratory standard errors are all 50 years or less and none of the dates overlap, even when two standard errors on closely spaced samples (SRR-3708 and SRR-3709) are considered. They are therefore considered to be a reliable estimate of the age of the peat samples. Variations in the rate of peat accumulation are discussed in Chapter 6.

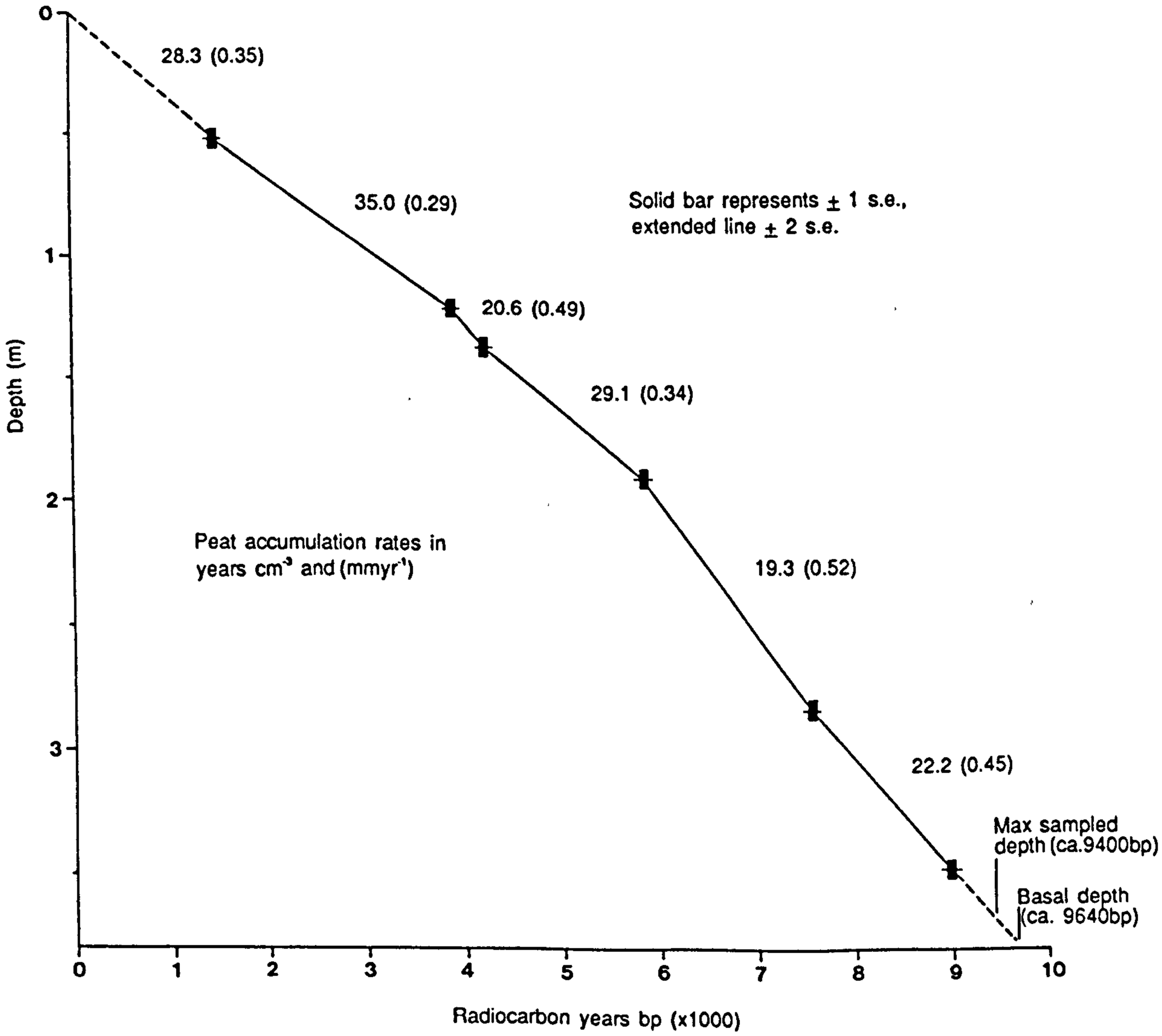


Figure 5.2: Radiocarbon age - depth curve for Cross Lochs Fen A, core 1.

There are a number of problems in dating of Lateglacial sediments; contamination by mineral carbon, recycling of older carbon, and stratigraphic resolution, given the low carbon content and relatively thin layers of sediment (Sutherland, 1980; Lowe and Walker, 1980). 'Younging' of dates has also been experienced, probably due to mobile humic acids (Lowe and Walker, 1981). More recently, some of the problems of radiometric radiocarbon dating have been overcome by accelerator mass spectroscopy measurements of radioactivity either by dating different fractions of sediment (Lowe et al, 1988), macrofossils (Cwynar and Watts, 1989) or the pollen itself (Brown et al, 1989). Within the constraints of the more easily obtainable radiometric dates, approximate chronologies are best reached by using dates from a number of sites, from differing sediments (Walker and Lowe, 1982). The two dates for this study are primarily to confirm the Lateglacial age of the sediments and the approximate correlations with other data, discussed below, and they will be subject to many of these problems, although at least should not suffer from severe 'hard water' error.

5.3 SITE DESCRIPTION

5.3.1 Cross Lochs 'B'

The coring site lies within a shallow valley, at the foot of the patterned fen site Cross Lochs 'B', National Grid Reference NC 877467. The core is within an infilled basin, around which peatland has subsequently spread (see Chapter 6). There are several large swallow holes in the peat, close to the coring point, which presumably help drain the peatland higher up the valley and these subsequently develop into a water course draining the basin. The vegetation of the patterned fen has been described in detail earlier (Chapter 3), and the community at the core location is similar to ridge vegetation within the patterned area, although there is a greater dominance of *Molinia caerulea* in particular, *with Narthecium ossifragum*,

Tricophorum cespitosum and generally less abundant *Sphagnum* species (mostly *S.papillosum*). The stratigraphy of the core was as follows:

Cross Lochs 'B' - Stratigraphy of Lateglacial-Early Holocene section.

485-497cm Brown, banded lake mud
nig.3, strf.3, elas.1, sicc.2, Ld4

497-504cm Darker lake mud
nig.3-4, strf.0, elas.1, sicc.2, Ld4

504-538cm Dark brown lake mud with monocotyledonous remains
nig.3, strf.0, elas.2, sicc.1, Ld3, Th1

538-540cm Pale grey clay with sand
nig.1, strf.0, elas.0, sicc.3, Ag3, Gs1

540-629cm Green-brown lake mud
nig.2-3, strf.0, elas.1, sicc.2, Ld4

629-657cm Sandy, green-brown mud/clay
nig.2-3, strf.0, elas.1, sicc.2, Gs2, Ld1, Ag1

657-670cm Green-brown mud, with bands of brown organics and sand.
nig.3, strf.2, elas.1, sicc.2, Ld3, Gs1.

670-689cm Green-brown mud with silt and sand
nig.3, strf.0, elas.1, sicc.2, Ld3, Gs+, Ag1

689-709cm Grey, sandy mud/clay
nig.2, strf.1, elas.0, sicc.2, Gs2, Ag1, Ld1

709-744cm Green-brown lake mud
nig.3, strf.0, elas.1, sicc.2, Ld4

744-772cm Grey-brown, lake mud with sandy clay.
nig.2-3, strf.0, elas.1, sicc.2, Ld2, Ag1, Gs1.

772-783cm Grey, sandy clay
nig.2, strf.1, elas.0, sicc.2, Gs3, Ag1, Ld+

5.3.2 Cross Lochs 'A'

This is another patterned fen site, where the core for pollen analysis was taken from the lower part of the mire, outside the patterned mire expanse. It also has a number of swallow holes nearby, which emerge as a small stream about

30m away. The deposits have developed in a much shallower depression than those at CLB1, apparently in the northern arm of a bifurcating valley, now completely obscured by subsequent peat growth (see Chapter 6). However, there are no stratigraphic indications of lake formation and all the samples were taken from terrestrial peats. The present vegetation is very similar to that at CLB1, with *Molinia caerulea*, *Narthecium ossifragum* and *Tricophorum cespitosum*, although there is also some *Carex lasiocarpa*. The stratigraphy of the core was as follows:

Cross Lochs 'A' - Stratigraphy

0-20cm Loose, unconsolidated *Sphagnum papillosum* and *Carex* and *Molinia* roots.

20-59cm Pale brown monocot. with occasional *Selaginella* megaspores and *Myrica* twigs.
nig.2, strf.0, elas.3, sicc.1, humo.1, Th3., Dh.1, Dl+.

59-92cm Darker monocot. with gradual lower transition.
nig.2-3, strf.0, elas.2, sicc.1, humo.2, Th3, Sh1

92-124cm *Calluna-Eriophorum*.
nig.3, strf.0, elas.2, sicc.1, humo.2-3, Tl2, Th1, Sh1

124-142cm Highly humified (*Calluna-Eriophorum* ?)
nig.3-4, strf.0, elas.1, sicc.1, humo.3-4, Sh3, Tl1

142-210cm *Calluna-Eriophorum*, with gradual lower transition
nig.3, strf.0, elas.2, sicc.1, humo.2-3, Tl2, Th1, Sh1.

210-340cm Monocot. with occasional *Betula* twigs.
nig.2, strf.0, elas.2, sicc.1, humo.2, Th4, Dl+

340-356cm Monocot.
nig.2, strf.0, elas.2, sicc.1, humo.2, Th4

356-367cm Monocot. with bryophytes.
nig.3, strf.0, elas.2, sicc.1, humo.3, Th2, Tb1, Sh1

5.4 POLLEN ASSEMBLAGE ZONES

The results of pollen analysis are shown as percentage diagrams in Figure 5.3 and 5.4, with concentration data in Figures 5.5 and 5.6, for Cross Lochs 'B' and Cross Lochs 'A', respectively. Pollen concentration analyses give relatively smooth data curves in the lake sediment, but trends are much less clear in the peat samples. This is probably due to the irregular occurrence of larger plant fragments in the $1cm^3$ samples from these deposits, which may result in artificially fluctuating values, especially in the less humified peats. However, there are some general trends which can probably be regarded as being reliable indexes of changes in accumulation rates and pollen influxes. The following zones have been recognised in the percentage diagrams:

5.4.1 Cross Lochs 'B'

CLB1: 783-720cm

This zone has high values of *Empetrum* and Cyperaceae throughout, with generally very low levels of arboreal pollen of about 10%, most of this due to *Betula*. *Rumex/Oxyria* occurs at low levels (3-9%) and there are scattered occurrences of other herb types, especially *Artemisia* and Compositae (Liguliflorae). The two lowest samples are somewhat different in composition, having values of *Rumex/Oxyria* at 8-10%, with slightly higher quantities of other herb pollen. Although there is also some sedimentary change here, the *Betula* curve is unchanged and therefore this is not described as a separate zone.

CLB2: 720-704cm

Although this zone only covers two samples, there is a pronounced rise in the *Betula* and *Juniperus* curves, with a decline in Cyperaceae and some decrease in *Empetrum*. Small amounts of *Calluna* are also present. The sediment changes during this zone, having a significant mineral content above 709cm.

Original Contains Pullouts

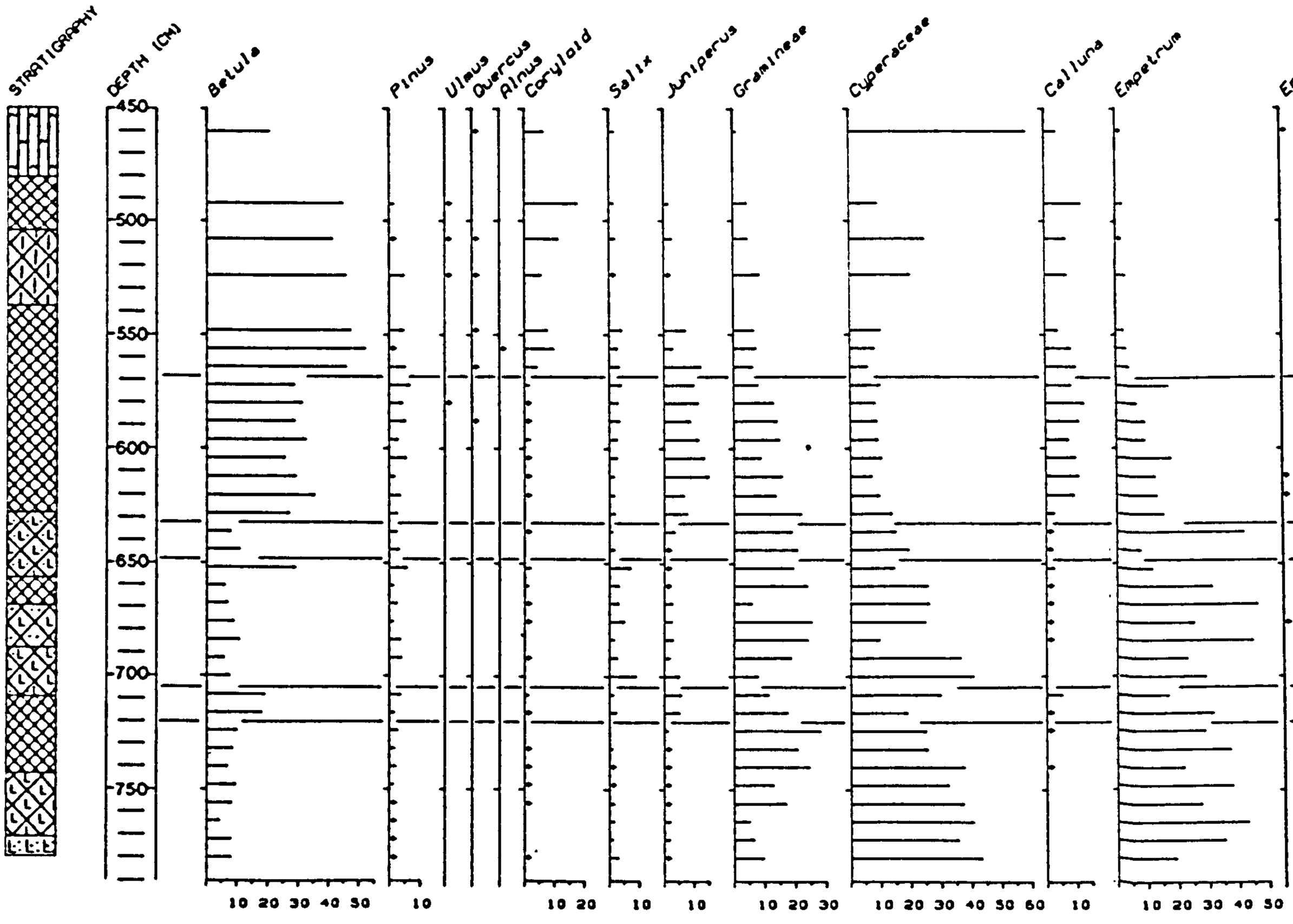
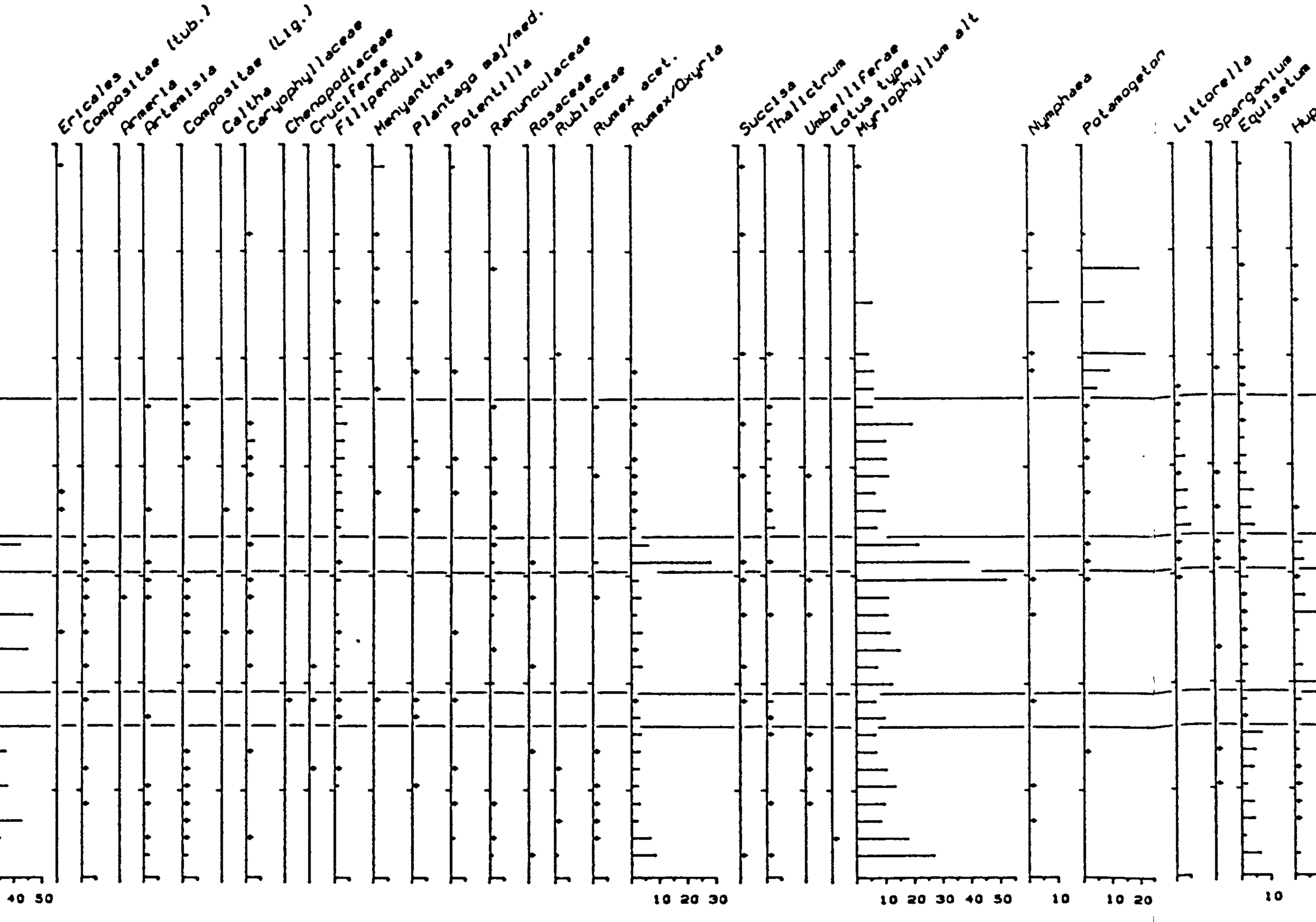


Figure 5.3: Percentage pollen diagram for Cross Lochs Fen B, core E13.

CROSS LOCHS FEN B : LATE DEVENSIAN - EARLY HOLOCENE



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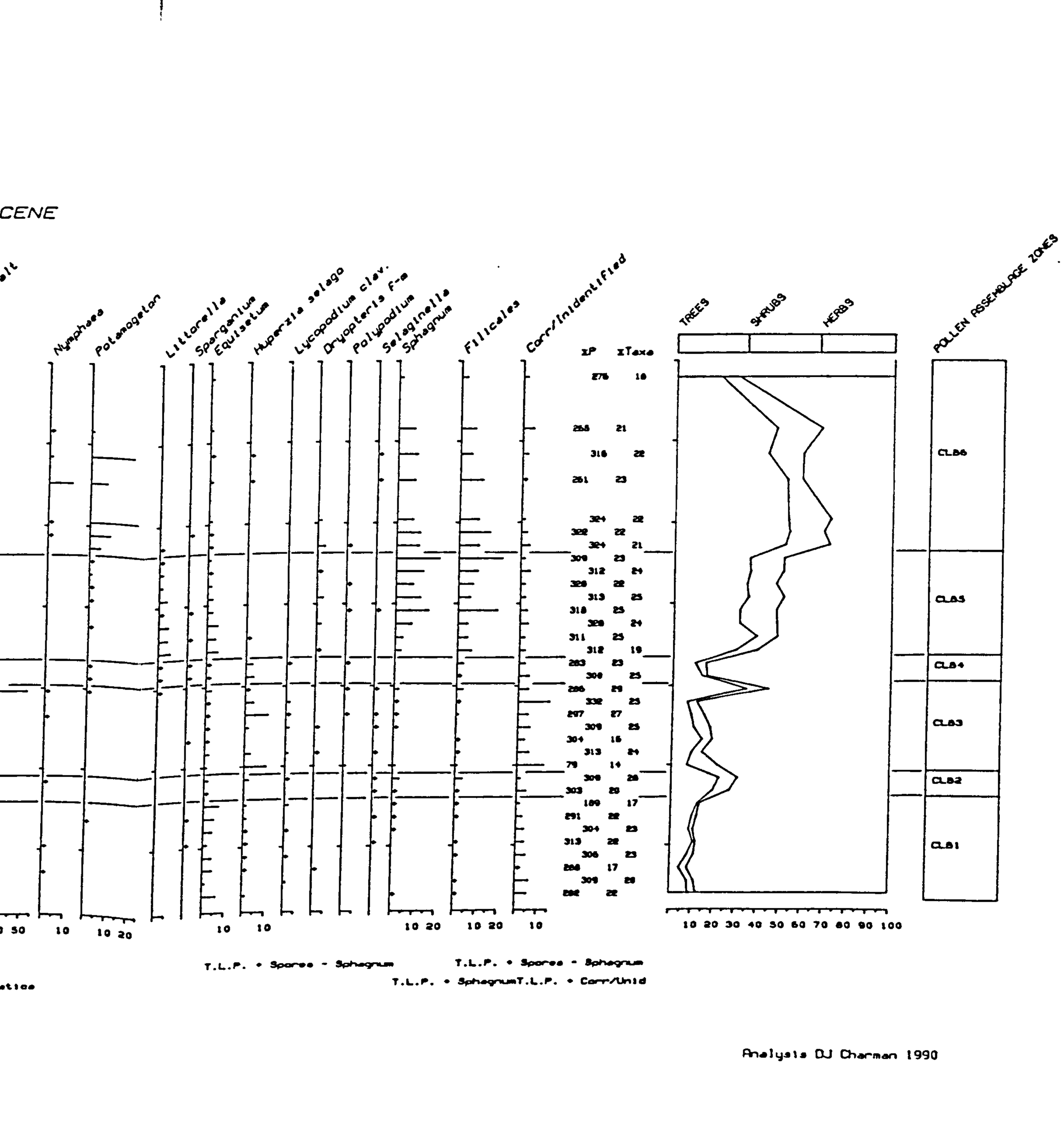

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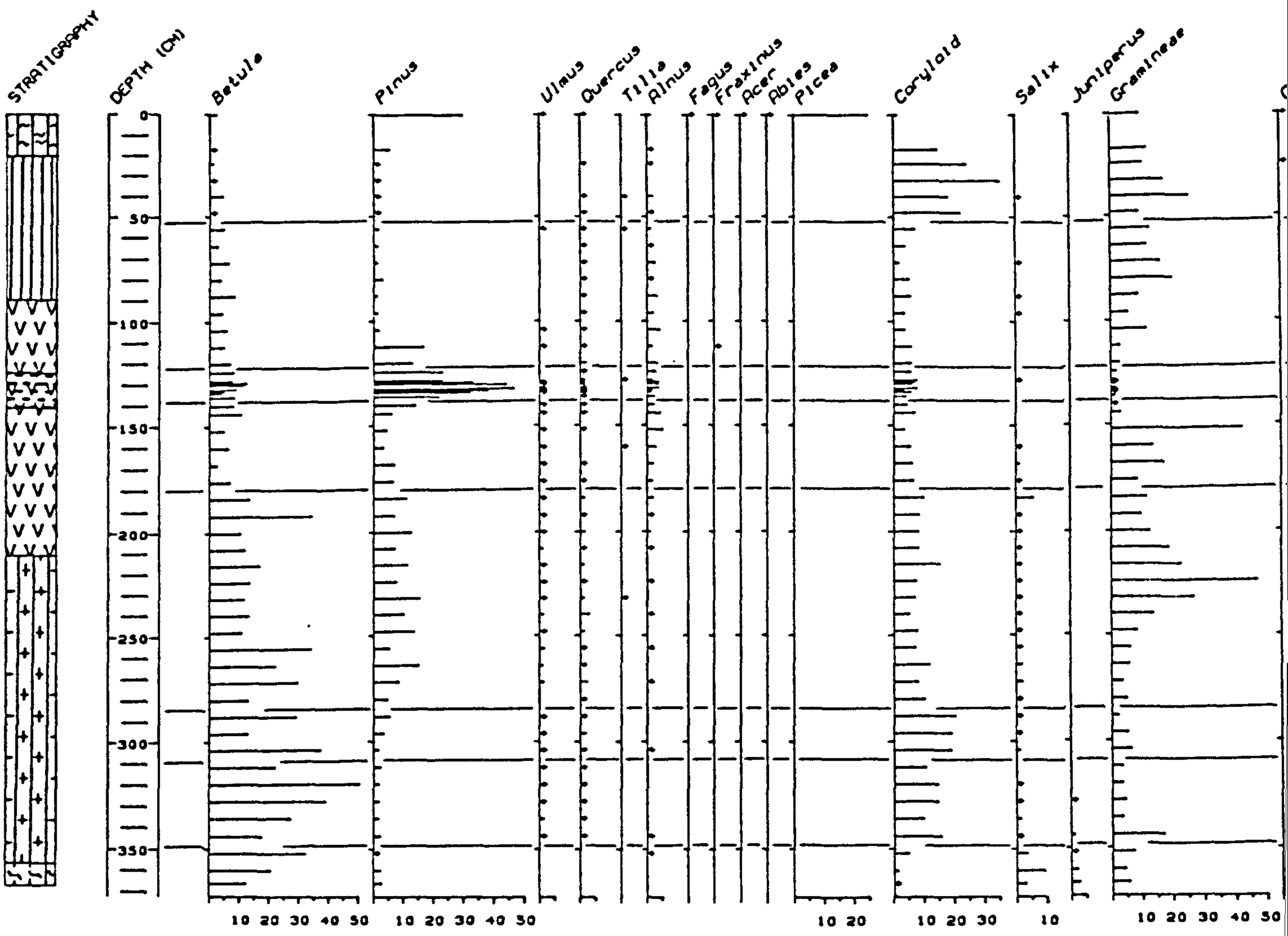
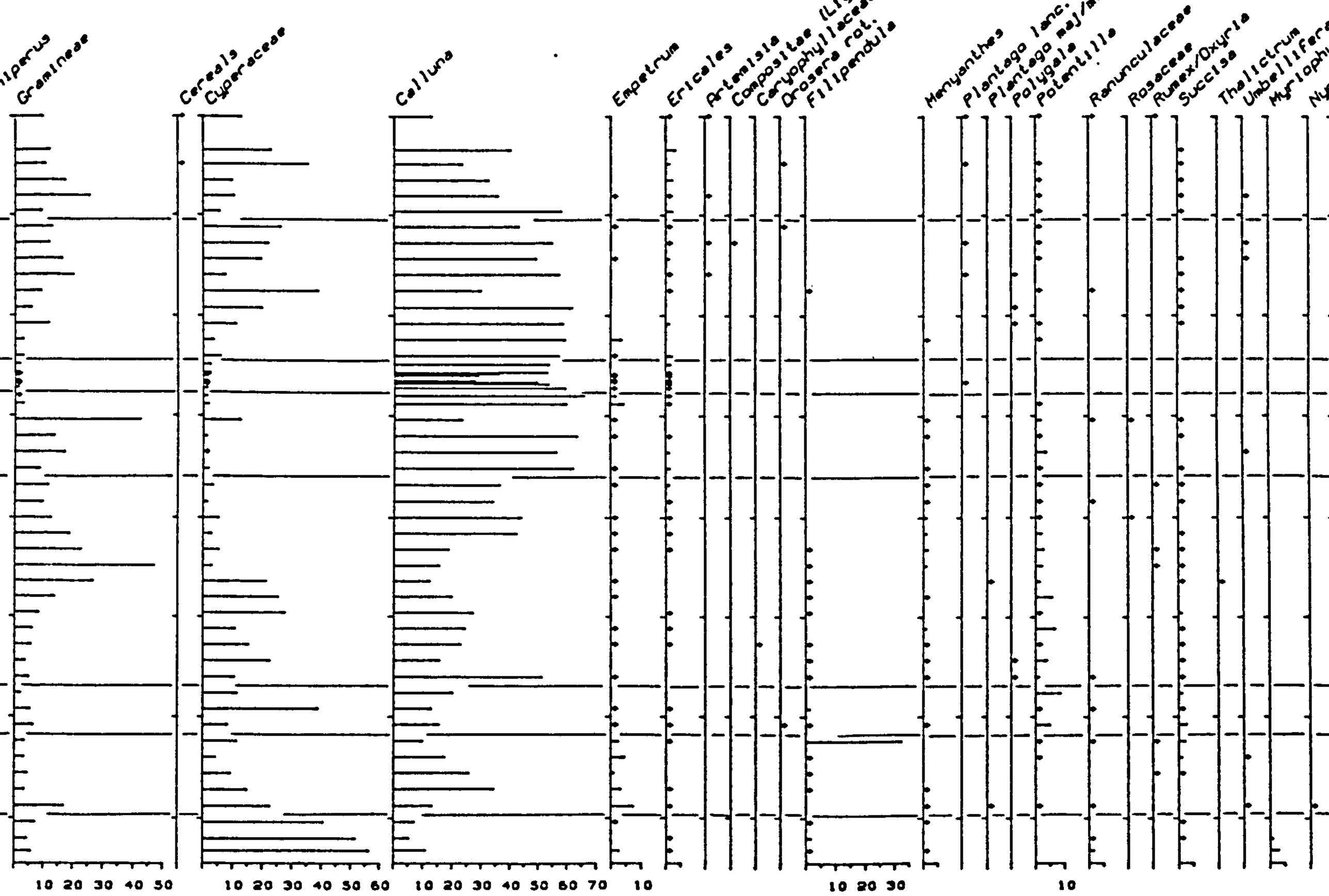


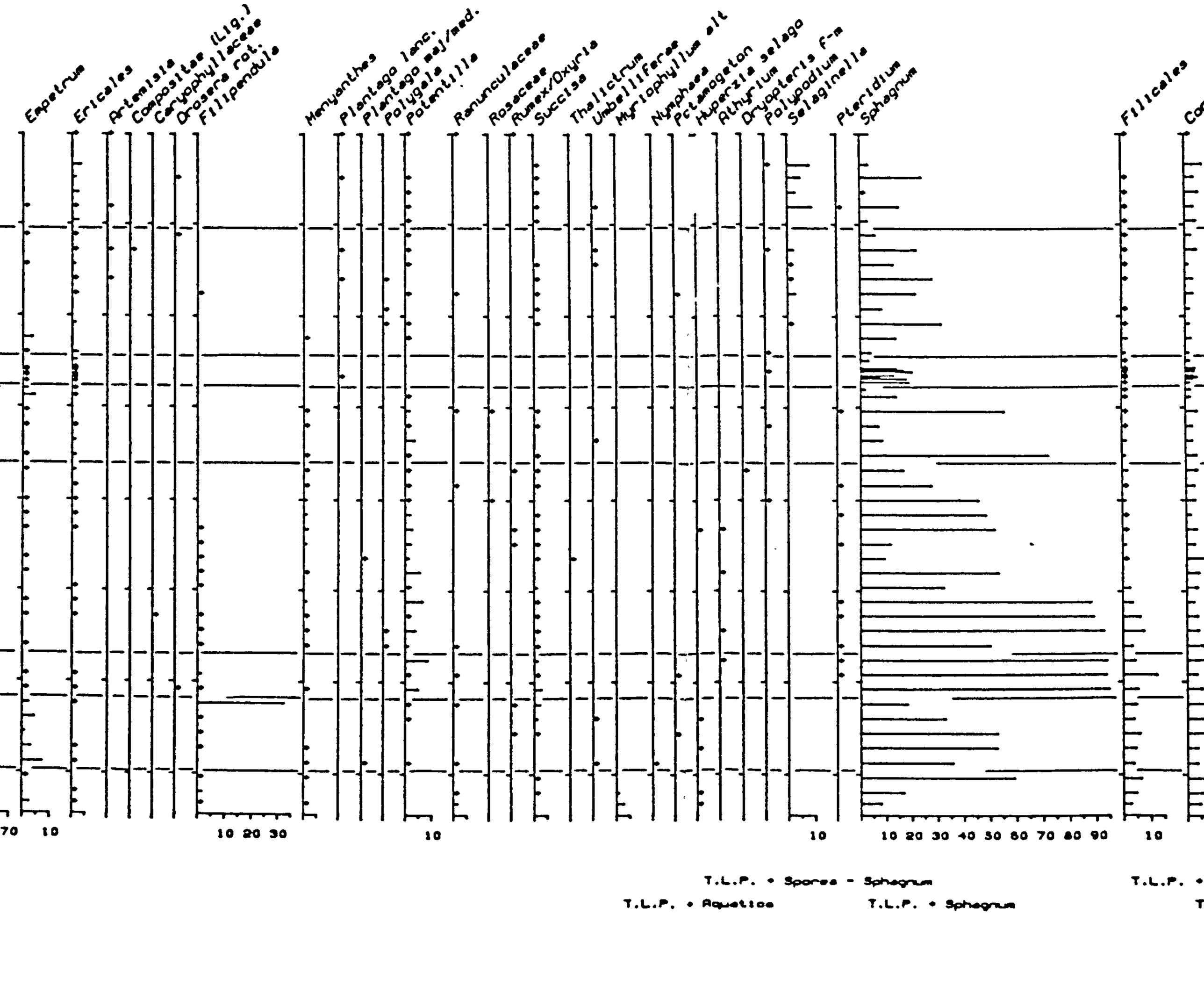
Figure 5.4: Percentage pollen diagram for Cross Lochs Fen A, core 1.

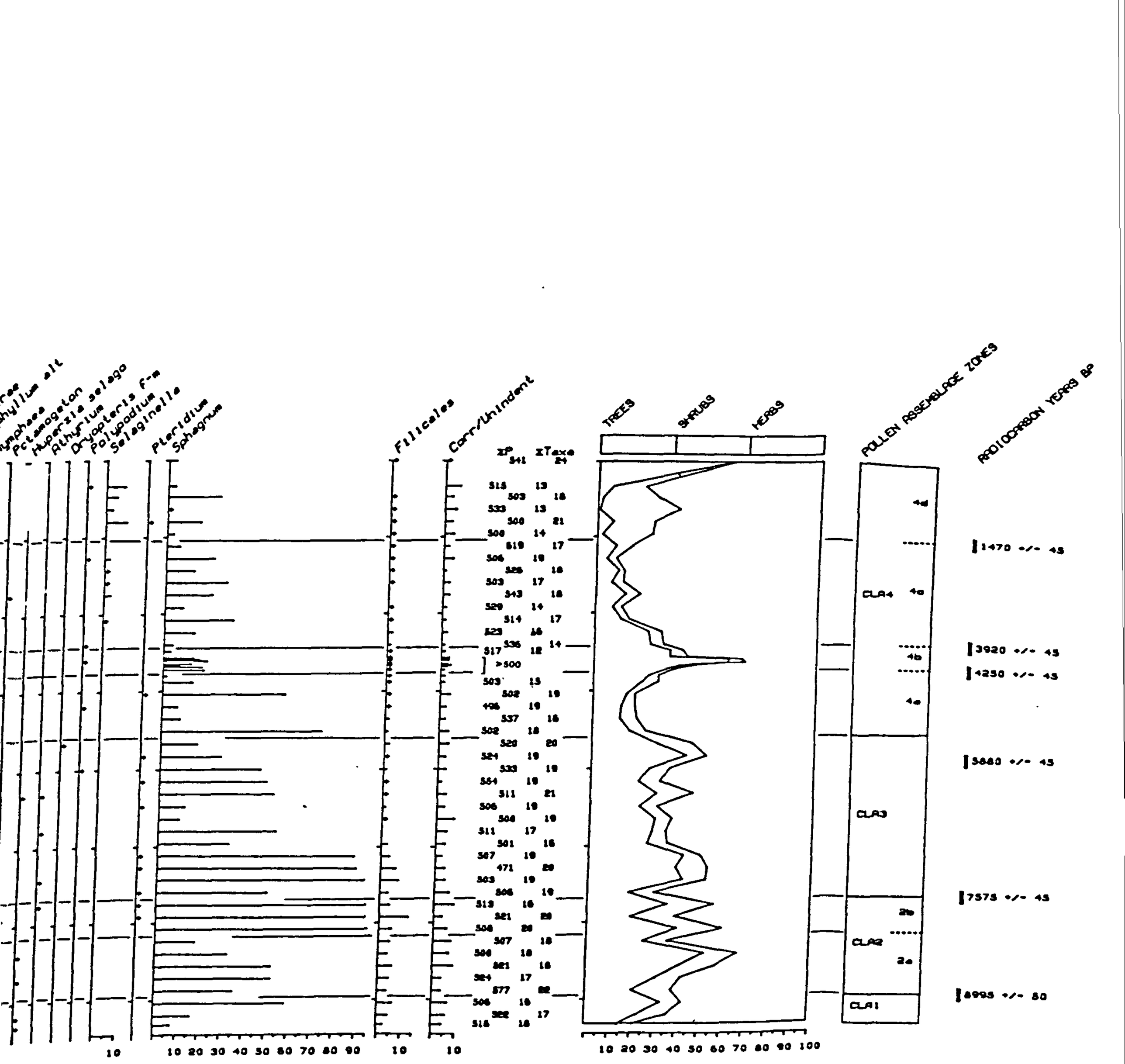
CROSS LOCHS FEN A : HOLOCENE



T.L.P

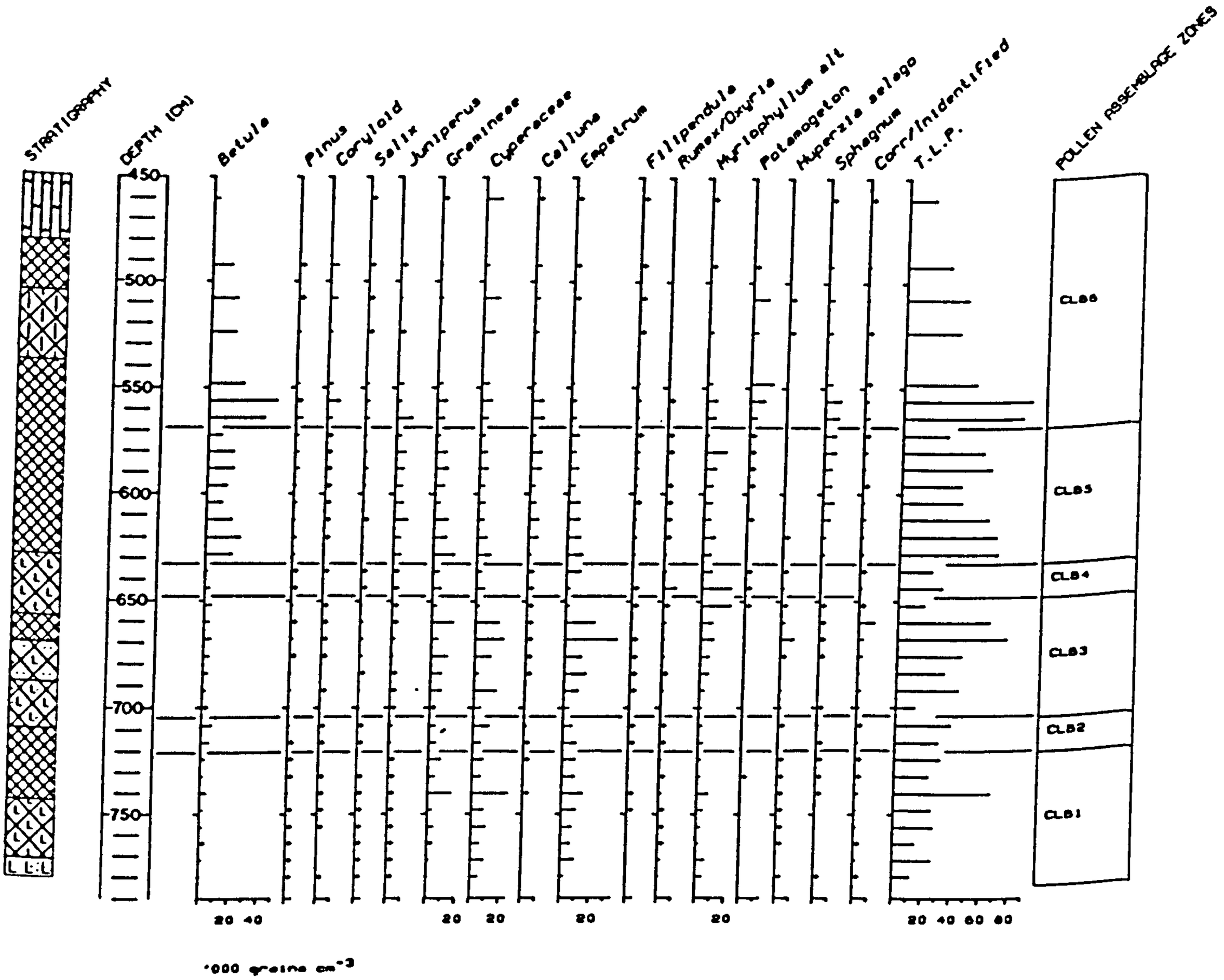
OSS LOCHS FEN A : HOLOCENE





Analysis DJ Charman 1989

CROSS LOCHS FEN B : LATE DEVENSIAN - EARLY HOLOCENE



Analysis DJ Charman 1990

Figure 5.5: Pollen concentration diagram for Cross Lochs Fen B, core E13.

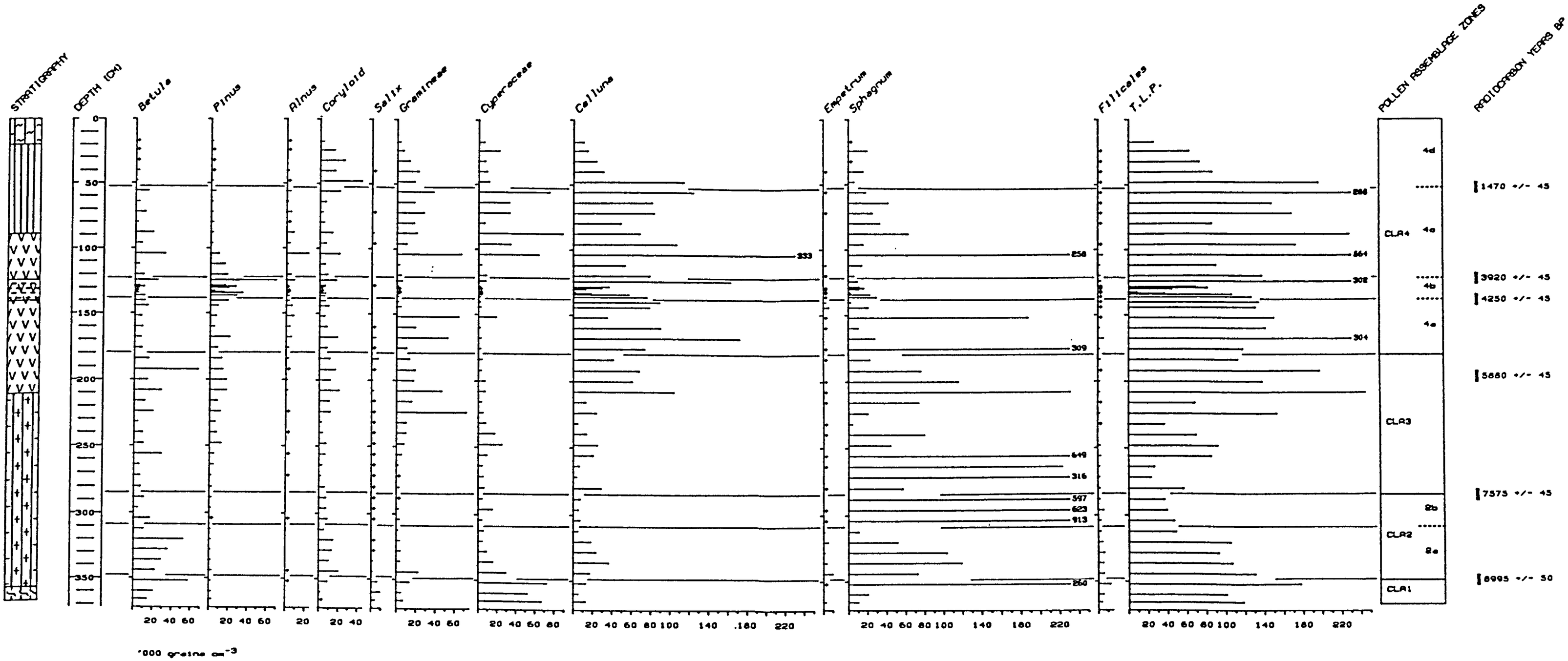


Figure 5.6: Pollen concentration diagram for Cross Lochs Fen A, core 1.

CLB3 704-648cm

This period shows a return to an assemblage similar to that found in CLB1, although *Juniper* maintains low levels (ca.3%) and *Salix* is a constant feature, resulting generally elevated levels of total shrub counts. There is a double peak of *Huperzia selago* at the beginning and end of this zone. At the end of this zone there is a sharp increase in *Betula*, which then falls rapidly as CLB4 begins. The sediment appears predominantly organic, but is at least partially composed of sand.

CLB4: 648-632cm *Rumex/Oxyria*

The large (30%) peak in *Rumex/Oxyria* type clearly marks this narrow zone, which is accompanied by a temporary decline in *Empetrum* and low levels of tree and shrub types. A sharp increase in *Myriophyllum alterniflora* occurs immediately before and during this zone. Sand forms much of the sediment.

CLB5: 632-568cm *Betula - Juniperus*

The beginning of this zone is clearly marked by the rise in *Betula* to >25%, *Juniperus* to >10% and *Calluna to >10%*. *Empetrum*, Gramineae and Cyperaceae are still present in moderate amounts but have declined significantly. *Filipendula* shows continuous values of 2-4% as does *Littorella, amongst the aquatics*. *Potamogeton* expands at the end of the zone. *Sphagnum* and Filicales spores are frequent. A clear change to organic lake muds is evident at the beginning of the zone.

CLB6: Above 568cm *Betula - Corylus*

Corylus and *Myrica* types begin to occur throughout CLB4, but it is not until now that a true expansion occurs. In addition, *Betula* shows a further increase to ca.45%. *Empetrum* and Gramineae show further declines. *Juniperus*, *Salix* and *Filipendula* almost disappear by 492cm. *Potamogeton* and *Nymphaea* reach peaks early in this zone.

5.4.2 Cross Lochs 'A'

CLA1: 367-348cm Cyperaceae - *Salix*

The earliest pollen spectra at this site are dominated by Cyperaceae, with small, but relatively high amounts of *Salix*. Tree pollen is low (12-32%), rising throughout the zone, due to increased *Betula*. There are minor quantities of *Empetrum*, *Juniperus*, *Filipendula* and *Myriophyllum alterniflora*. *Sphagnum* rises to 60% TLP+Sphagnum and Filicales shows continuous levels of ca.5%.

CLA2 348-284cm *Betula* - *Corylus*

Rising values of Coryloid type mark the beginning of this zone, and *Betula* is generally high, but fluctuating, throughout. Most of the Coryloid pollen is probably attributable to *Corylus*, although *Myrica* was probably present (Figure 5.7). Cyperaceae falls to below 20%. There are low (generally <1%), but constant, records of *Ulmus* and *Quercus*. The zone is split into two sub-zones; **CLA2a** (348-308cm) is characterised by continuing low levels of *Empetrum*, which virtually disappears in **CLA2b** (308-284cm). *Potentilla* rises in **CLA2b** and *Pinus* shows a slight increase towards the end of the sub-zone.

CLA3 284-180cm *Betula* - *Pinus*

Betula shows fluctuating, somewhat decreased values throughout the zone but maintains a presence at 10-15%. *Pinus* rises to ca.15% and Coryloid remains, but at much reduced levels. Cyperaceae declines during the zone, when a large peak in Gramineae occurs and *Calluna* rises at the end of the zone. *Alnus* has a continuous, low presence from 208cm upwards.

CLA4: 180-0cm *Calluna*

The remainder of the pollen record is dominated by high levels of *Calluna*, although there are large fluctuations in other pollen types, which are the basis for the following sub-zones.

CLA4a: 180-140cm

Pinus and *Betula* both decline during this zone and, apart from *Calluna*, Gramineae is the only other major contributor to the pollen sum.

CLA4b: 140-122cm *Pinus*

Pinus is the main differentiating taxa here, rising rapidly to a peak of 48%, with all values over 20%. Calluna declines as this occurs, to around 25%, with all other taxa showing only low levels.

CLA4c: 122-52cm

Pinus declines to <20% and finally to levels of <2%. There is a general decline in arboreal pollen throughout the zone. Cyperaceae shows an irregular increase and Gramineae returns to previous moderate, fluctuating levels.

CLA4d: 52-0cm *Myrica*(?)

Coryloid pollen rises to over 20% during this zone and most of this is probably referable to *Myrica* (Figure 5.7). Tree pollen decreases further, to 2% at 32cm. The rise in Coryloid type is accompanied by a rise in *Selaginella* and a small increase in Ericales.

5.5 CORRELATION OF THE POLLEN RECORDS

The intention of this chapter is to reconstruct vegetational history for the main study area of the Cross Lochs, from the two cores for which pollen analysis has been carried out. To do this, it is necessary to correlate and combine the two sequences described briefly above to produce a pollen chronology covering the whole of the Holocene and as much as possible of the Lateglacial. Table 5.2 indicates a tentative correlation of the two cores, and the basis upon which this was made.

The correlation is mainly based on the rise in *Corylus/Myrica* which clearly marks the beginning of CLB6

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and CLA2 (8995±50bp) and percentage values for other pollen types (*Betula*, *Empetrum*, *Juniperus*, *Filipendula*) which are similar, but generally somewhat lower in CLA1, due to the dominance of Cyperaceae. Macrofossil analysis (Chapter 6) and stratigraphy show that this is due to extra local sources, with species of *Carex* growing on the coring site.

Table 5.2: Correlation of cores from Cross Lochs Fen A and Fen B.

Cross Lochs A	Cross Lochs B
CLA4d	
1470±45	
CLA4c	
3920±45	
CLA4b	
4250±45	
CLA4a	
5500	ca.250cm
CLA3	
7575±45	ca.364cm
CLA2b	
8100	
CLA2a	CLB6
8995±50	
CLA1	CLB5
?	
	CLB4
	CLB3
	CLB2
	CLB1

Correlations during the later Holocene are based on less precise data from Cross Lochs 'B', with more widely spaced pollen samples. However, this is unimportant for the following discussion, which utilises the more detailed record from Cross Lochs 'A' from the Coryloid rise onwards.

5.6 INFERRED VEGETATIONAL HISTORY

5.6.1 The Lateglacial Interstadial

The earliest pollen spectra recorded at Cross Lochs 'B' (CLB1) suggest the close of a period dominated by open habitat taxa often described from Interstadial sediments in other Late Devensian Scottish pollen sites (Walker, 1984). The pollen spectra of the two basal sediments is not greatly different qualitatively from the later part of the zone, but there are several minor quantitative changes and these are associated with the lithostratigraphic change from grey, sandy clay to more organic deposits. The decreasing values of *Rumex/Oxyria*, *Artemisia* and *Compositae*, with increasing *Empetrum* imply that the colonists of bare ground were being replaced by a mix of dwarf shrub *Empetrum* heath and areas of sedges and grasses from 768cm upwards. This represents a period of stabilising soil conditions, although the maintenance of *Rumex/Oxyria* and minerogenic input to the basin suggests that there was still a degree of soil movement. Pollen concentrations are relatively low throughout CLB1, apart from an exceptional sample at 740cm.

The pollen spectra vary little until the start of CLB2, where the minor rises in *Betula* and *Juniper* and the occurrence of *Calluna*, suggest a diversification of the local communities and possibly a further climatic amelioration. Increases in *Juniperus* may be due to an increase in the abundance of the species or increased flowering under warmer temperatures.

Following this period, there is a decrease in these particular woody species and an increase in *Salix at the start of CLB3*. Also at this time, *Huperzia selago* and the corroded/ unidentifiable category show a significant increase and more minerogenic sediment replaces the predominantly organic deposits below. No attempt was made to identify *Salix herbacea* type grains separately, but the other features of this zone suggest less stable conditions on the surrounding slopes, a habitat which would favour the growth of the creeping *S.herbacea* rather than shrub *Salix*. *Empetrum* is still abundant here but may be partly derived from inwashed sediments rather than contemporary vegetation, as has been shown to occur by detailed analyses in other similar sediments (Walker and Lowe, 1990). It would therefore appear that there was a general climatic deterioration during this zone, presumably representing the Interstadial-Stadial transition.

5.6.2 The Stadial and Lateglacial - Holocene transition

By the end of CLB3, Stadial conditions must have prevailed. The pollen spectra following this, between the end of CLB3 and the expansion of juniper and birch at the start of CLB5 are rather variable over a small number of samples. It is likely that more detailed analysis of this part of the core would yield a clearer and more detailed picture of the closing stages of the Lateglacial and the transition to the Holocene. However, this has not been possible for this study, within the time available. The following reconstruction is tentatively made within the limitations of the data.

At the close of zone CLB3 and the transition to CLB4, *Empetrum* declines markedly with a single high value of *Betula*, then there a sharp peak of *Rumex/Oxyria*, rapidly succeeded by a single sample resurgence of *Empetrum*. This complex sequence is difficult to interpret, although the *Rumex/Oxyria* peak suggests there was abundant bare ground for this species to colonise and the stratigraphy indicates

increased inwash of mineral material to the basin. The *Betula* peak may represent *B.nana*, rather than tree birch, benefiting slightly from the recession of *Empetrum*, at the onset of markedly colder conditions in the Loch Lomond Stadial. The *Empetrum* peak, following the *Rumex* maximum, may be a response to stabilisation and warming at the close of the Stadial, before the rapid rise in *Betula* and *Juniperus at the start of CLB5*. The beginnings of gradual infill of the basin, with much shallower water, is indicated during CLB4, by a large increase in *Myriophyllum alterniflora*, followed by the occurrence of *Littorella* and then *Potamogeton* and *Nymphaea* much higher up the core.

5.6.3 The early Holocene

CLB5 indicates clear climatic warming, with a rapid response from both *Betula* and *Juniperus*, probably as open woodland, with *Calluna* and *Empetrum* in the herb layer. *Salix* also persists and probably occurred as part of this woodland community. Grasses and sedges may also have occurred here but the low percentages recorded are more likely to represent a fringing fen community which probably also contained *Filipendula* and *Equisetum* with *Sphagnum*, indicated by the rise in spores from the base of this zone, with no obvious stratigraphic indication of its presence at the core location. Filicales begin to occur at 5-15% TLP+Spores and while most have lost their outer coating, some were recognisable as *Dryopteris felix-mas* type and *Polypodium*, suggesting that there were ferns both in the ground flora and growing as epiphytes. Organic sedimentation begins at the start of this zone and despite a probable increase in sedimentation rates, the pollen concentration shows a resurgence to pre-CLB5 levels, reflecting the greatly increased pollen influx.

It is sometime during this period that sediment accumulation begins at Cross Lochs 'A', around 9600bp, extrapolating from radiocarbon dates. The pollen spectra for CLA1 suggest a comparable vegetation to that shown

during late CLB5, of open *Betula* woodland with shrubs and dwarf shrubs, although there is less *Juniperus* and *Empetrum* and more *Salix*. The more advanced stage of terrestrialisation in this site is likely to produce such differences in the pollen record, with a greater influence of extra local pollen sources, as mentioned in section 5.5.

Following the period of establishment and persistence of a relatively stable community composition during CLB5, at 568cm in Cross Lochs 'B' (CLB6) the increase in *Betula*, and rise in Coryloid type suggests a change in the vegetation to a more closed *Betula* woodland with some *Corylus*. Similar indications are present in CLA2, where the rise in Coryloid is dated to 8995±50bp. The increase in pollen concentration with no change in the sediment type, also suggests that pollen influx increased at this stage. Attempts to separate *Corylus* and *Myrica* (Figure 5.7) suggest that the majority of this pollen can be assigned to the former species (presumably *C.avellana*), although *Myrica* may well have been present. As this mixed woodland developed, *Juniperus* disappears but *Empetrum* persists for some time, until 308cm (ca.8100bp) in Cross Lochs 'A', at the close of CLA2a. *Calluna* remains an important component of the vegetation throughout the rest of the Holocene. Increases in Cyperaceae in CLB6 are probably a reflection of the continuing terrestrialisation of the basin, and encroaching monocotyledonous communities, reflected in the stratigraphic change here. A narrow band of clay at 538-540cm in Cross Lochs 'B' suggests there may well still have been some localised instability of the basin sides, with slumping, and a return to pure lake sediment above 504cm indicates a renewed deepening of the water at the core location. The last sample indicated on the Cross Lochs 'B' diagram is comparable to pollen spectra found during zone CLA2a and therefore from here on the discussion refers only to the Cross Lochs 'A' core.

Fluctuating values of birch pollen in CLA2 and early CLA3, are probably due to occasional growth of this species

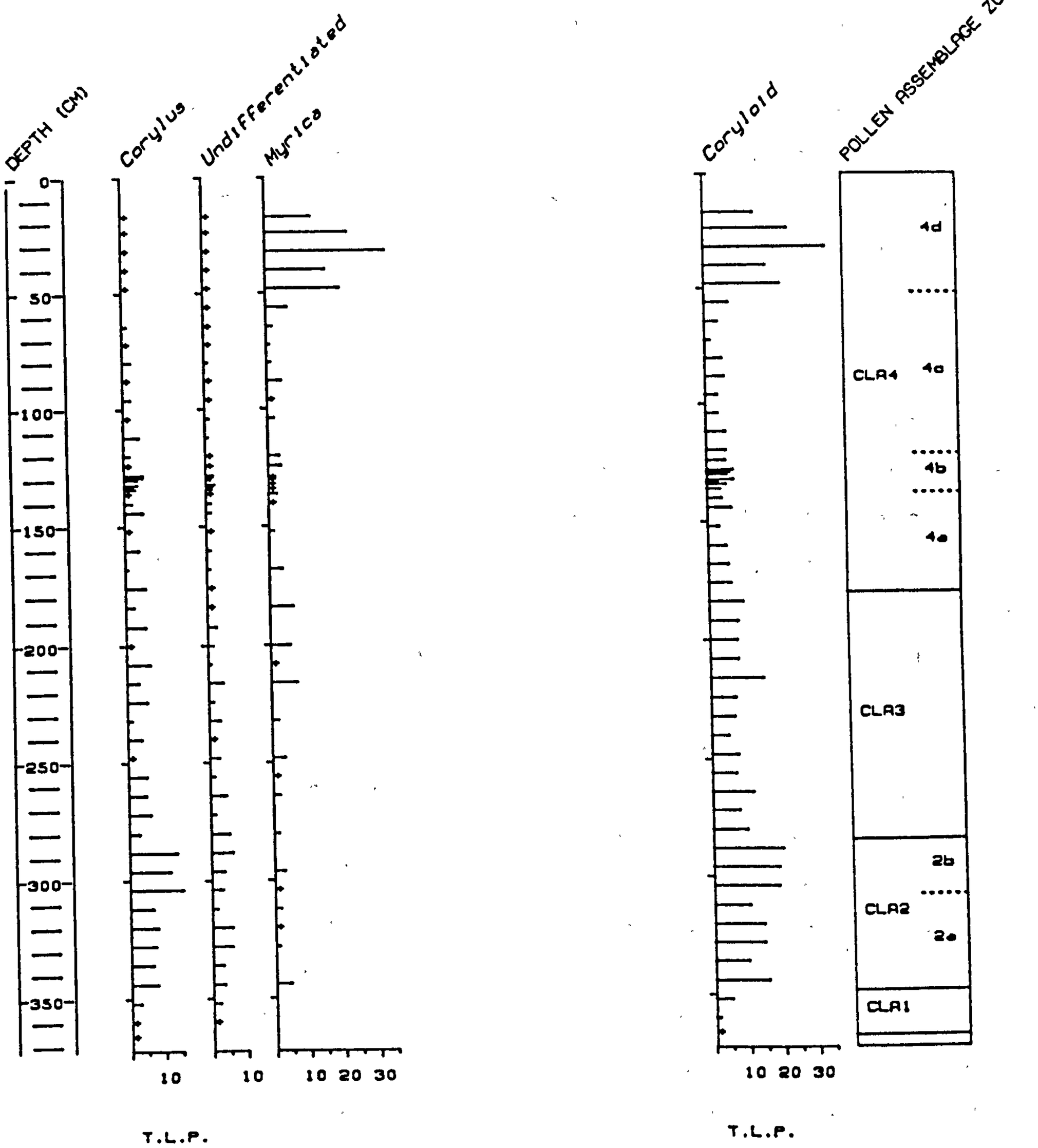


Figure 5.7: Attempted separation of *Corylus* and *Myrica* pollen.

actually at the core location, indicated by macrofossil analysis (Chapter 6). Peat accumulation was generally high during this minerotrophic phase of mire development, as indicated by the generally low pollen concentrations, despite a relatively high proportion of arboreal pollen. Extrapolating from radiocarbon dates, accumulation rates were around 0.5mmyr^{-1}. The small quantities of *Ulmus* and *Quercus* pollen probably reflect the establishment of mixed deciduous woodland further south, or they may represent isolated occurrences of these species closer to the site. The rise in *Potentilla* is due to growth of this species on the mire surface and the peak in *Filipendula* may have a similar origin, although no macrofossil evidence was found to support this contention.

The rise of *Pinus* during CLA3 to a maximum of ca.15% is not sufficient to meet the threshold of 20%TLP proposed as an indicator of local pine growth (Bennett, 1984). However, the species was present in south west Sutherland from 7880±160 radiocarbon years bp (Pennington *et al*, 1972), and from 6980±100bp further south, close to the Sutherland border Ross and Cromarty, at Coire bog (Birks, 1975). These sites are approximately 80 and 65 km from Cross Lochs, respectively. A similar rise at Loch of Winless, Caithness (Peglar, 1979) is attributed to long distance transport from pine stumps recorded by Lewis (1906). Certainly long distance transport from the south and west seems likely, given the widespread occurrence of these records and the date of 7575±45bp for the start of this low level pine rise in CLA3. Over 15% of modern TLP, from moss polsters, is of long distance arboreal pollen on Shetland (Birnie, 1984), and those islands are more distant from source areas, being approximately 200km from the Scottish mainland and 300km from the Norwegian coast.

The *Betula* decline during this zone reflects its disappearance from the macrofossil record but is possibly also a more widespread decline. The stratigraphic change to ericaceous peat at 210cm (ca.6200bp) is reflected by the

pollen percentage data, with decreased Cyperaceae and an increase in *Calluna*, separated by a short lived gramineae peak. Pollen concentrations also increase at this time, as a result of both increased influx, due to the change in local species, and the probable compounding effect of decreased peat accumulation rates. This is not clearly evident from the radiocarbon dates, as there is no date at this boundary. However, the accumulation rate after 196cm within a similar peat type is 0.34mmyr^{-1}, a decrease of 33%. The spread of elm and oak to the south is reflected in their somewhat increased pollen percentages. However, while these species probably never grew locally, *Alnus* was a minor element in the landscape from around 196cm (5880±45bp), possibly in the valleys of the rivers Dyke and Halladale, to the west and east respectively.

5.6.4 Middle and late Holocene

High percentages of *Calluna* from the beginning of CLA4 are likely to be due in part to the local peat forming vegetation, but probably also reflect more widespread decline of the open birch scrub, that was present during the latter part of CLA3, as this species declines to around 5-6% TLP. Depression of the *Pinus* curve is a real reflection of decreased abundance extra-regionally, as concentration also declines, at a time of decreased peat accumulation.

The transition to zone CLA4b shows a startling increase in *Pinus* pollen, from ca.5% at 144cm to 23% at 136cm and up to 48% at the peak at 132cm. The lower zone boundary is the point at which 20% TLP is exceeded, 138cm, and this is dated to 4250±45bp. This is clearly indicating a short lived local presence of open pine forest and is almost certainly contemporary with the widespread pine stumps in the deeper peat deposits. It is difficult to define the period of time for which 'local' pine forest can be said to have been present, but taking Bennett's (1984) figure of 20%TLP, this is estimated at 330 radiocarbon years.

However, only a slight shift in this limit to 25%TLP, gives a much lower estimate of 134 radiocarbon years, perhaps only a single generation of trees.

Associated with the percentage peak, is a dramatic decline in concentration. Deposits are highly humified but have also accumulated relatively rapidly (0.49mmyr^{-1}). Even allowing for this, decreased influx is implied if a constant peat accumulation rate is assumed. This could be explained by increased shading, reducing flowering of *Calluna*, the only other taxa present in significant amounts. Pollen produced by the pine trees themselves may not have easily penetrated to the ground layer and fallen to the peat surface. Oxidative destruction of pollen grains is also more likely to have occurred during this time.

However, it is more likely that the decreased concentrations reflect a phase of very rapid accumulation during the period of on site pine growth, perhaps as a result of the deposition of needles and wood. Relatively rapid decay rates, although capable of rendering this material unrecognisable, may not have been sufficient to exceed the rate of deposition. If this is the case, then the period of local pine growth may have been even shorter than that estimated above.

The reasons for the sudden growth of pine are unclear from the pollen data. Towards the end of CLA4a, there is a minor rise in *Empetrum* pollen. It may be an early indication that the mire surface was drying out, immediately before the local occurrence of pine, as its growth is encouraged by decreased waterlogging (Bell and Tallis, 1974).

The decline of *Pinus* is just as sudden as its appearance, initially dropping to ca.15%TLP in early CLA4c then only occurring at around 2% or less. This indicates that local pine growth (<20%TLP) ceased at around 126cm, dated to 3920±45bp. Over a much wider area, pine rapidly disappeared almost completely at around 108cm depth (ca.3400bp). Total

arboreal pollen continues to decline from this time onwards, and the landscape becomes almost treeless, particularly after 52cm (1470±bp) at the start of CLA4d. At this time there is a large expansion of Coryloid pollen, the majority of which is thought to be *Myrica*, both on the grounds of pollen morphology and because macrofossil remains were recovered from this section. This may not be very meaningful in terms of the wider vegetation history of the locality, but it could be indicative of increased oceanicity, as this is a species which grows best in oligotrophic or oceanic ombrotrophic mires. Supporting this change in nutrient status of the mire is the occurrence of *Selaginella*.

5.7 COMPARISONS AND DISCUSSION

A tentative comparison between the results of the Cross Lochs data and that from elsewhere in northern Scotland has been drawn up in Table 5.3 for the Lateglacial/ early Holocene and in Table 5.4 for the complete Holocene. These comparisons are made on the basis of a combination of criteria, including radiocarbon dating, pollen assemblages (particularly where there are reasonable 'marker' horizons, during the Holocene) and the interpretations of the authors.

5.7.1 The Lateglacial

The base of the core was reached where sediments too stiff to be sampled with the equipment and personnel available were encountered, rather than being those just above base rock. In contrast to many other early Scottish Lateglacial sediments, pollen concentrations remained reasonably high (10-30,000 grains cm^{-3}). Therefore, it is not likely that the pollen spectra recorded are the earliest deposited at the site. Earlier data from this region would be of great interest in view of the limited extent of ice during the Devensian, proposed by Sutherland (1984) and Nesje and Sejrup (1988), on the basis of marine limits and local till

CROSS LOCHS B This study	YESNABY, ORKNEY (Moar,1969b)	LOCH OF WINLESS (Peglar,1979)	LOCHAN AN DRUIM (Birks,1984)	N.SCOTLAND-5sites (Pennington et al 1972)	LOCH ETTERIDGE (Walker,1975a)	
CLB6 Betula-Corylus	Betula-Corylus	LW3 Betula-Corylus	AD5 Betula-Corylus	NS3 Betula-Corylus	LE7 Betula-Corylus	HOLOCENE
CLB5 Betula-Juniperus (Empetrum)	Betula (Empetrum -Juniperus)	LW2c Juniperus- Empetrum	AD4b Betula-Juniperus	NS2 Juniperus-Betula	LE6 Betula-Juniperus -Empetrum	
			AD4a Betula-Empetrum	NS1 Empetrum		
CLB4 Rumex/Oxyria	Rumex	LW2b Cyperaceae-Salix	AD3 Ericales-(Salix)	Transition Rumex-Lyc.selago	LE5 Artemisia	LOCH LOMOND STADIAL
	Artemisia (Compositae)			C Artemisia		
CLB3 Empetrum-Salix- Juniperus-Huperzia	Empetrum- Gramineae- Cyperaceae	LW2a Empetrum-Ericales	AD2 Empetrum- Gramineae- Cyperaceae	B Empetrum- Gramineae- (Cyperaceae- Juniperus-Betula)	LE4 Betula-Empetrum	LATE-GLACIAL INTERSTADIAL
CLB2 Empetrum-Betula- Juniperus					LE3 Betula-Juniperus	
					LE2 Empetrum	
CLB1 Empetrum ?	Gramineae- Cyperaceae-Rumex	LW1 Rumex-Salix	AD1 Salix-Rumex- Gramineae- Cyperaceae	A Gramineae- Cyperaceae-Rumex	LE1 Rumex-Salix	

Table 5.3: Suggested correlation of Lateglacial - Early Holocene pollen zones from selected sites in northern Scotland

APPROXIMATE DATE (Radio carbon yrs bp)	CROSS LOCHS A This study	YESNABY, ORKNEY (Moar, 1969b)	GLIMS MOSS, ORKNEY Keatinge and Dickson, 1979)	AUKHORN, CAITHNESS (Robinson,1987)	LOCH OF WINLESS CAITHNESS (Peglar, 1979)	LOCH SIONASCAIG NW SCOTLAND (Pennington et al, 1972)
0	CLA4d Calluna-Myrica	Gramineae-Cyperaceae	Calluna	AK5 Calluna	LW5 Calluna	NSVI Calluna-grass sedge-Myrica
	1470±45					
2000	CLA4c Calluna		Gramineae-Cyperaceae			
	3920±45					Non-synchronous
4000	CLA4b Pinus-Calluna		Plantago lanc. - herbs	AK4 Corylus-Betula -Alnus	LW4 Betula-Coryloid	NSVii Pinus-Betula-Alnus
	4250±45			Ulmus	Ulmus	
	CLA4a - Calluna			AK3 Calluna-Corylus -Alnus-Betula		NSVi Pinus-Betula-Alnus -Ulmus
	5500					
6000	CLA3 Betula-Pinus	Betula-Corylus	Betula-Corylus	AK2 Corylus-Betula	Alnus Pinus	NSIV Pinus-Betula-Corylus
	7575±45			AK1 Calluna-Gramineae -Peat initiation		
	CLA2b Betula-Corylus					
8000	8100					NSIII Betula-Corylus
	CLA2a Betula-Corylus-Empetrum					
	8995±50					
	CLA1 Cyperaceae-Salix -Betula	Betula-Empetrum -Juniperus			LW3 Betula-Corylus	

Table 5.4: Suggested correlation of Holocene pollen zones from selected sites in northern Scotland

stratigraphy, but more recently contested by Hall and Bent (1990), using drift mapping and dated organic deposits from south east Caithness (Hall and Whittington, 1989).

The deepest deposits for which data are available from Cross Lochs are comparable with the earliest pollen records from most of the sites in northern Scotland. *Rumex* is a consistent component, often with *Salix*, usually referred to *S.herbacea*, with Cyperaceae and Gramineae sometimes named as important taxa. Other herbs (*Artemisia*, Caryophyllaceae, Chenopodiaceae) are present in small amounts, but do not often contribute a large proportion of total pollen. This type of assemblage was often strictly separated from subsequent assemblages as a 'pre-interstadial' (Pennington *et al*, 1972), but more recently it has been regarded simply as the earliest part of the Interstadial, following the wastage of the Devensian ice sheet (eg. Walker *et al*, 1988), within the two stage chronology of the Scottish (Gray and Lowe, 1977) and Europoean Lateglacial (Lowe and Gray, 1980). The deepest pollen spectra of Zone CLB1 probably represent the latter part of this kind of pollen assemblage, at the start of the *Empetrum* rise, which is again a common feature of most chronologies in the region. This species seems to have formed extensive heaths across the whole of northern Scotland, from Caithness and Orkney (Peglar, 1979; Moar, 1969b) to northern and western Sutherland (Birks, 1984; Pennington et al, 1972; Pennington 1977b). It was certainly important during the whole of the interstadial at Cross Lochs, especially in view of its low representation in pollen spectra (Birks, 1973).

Although the Interstadial is a clearly recognisable feature throughout Scotland (Walker, 1984), there is some uncertainty about the detail of climatic and vegetational changes which occurred during this time. Published data from northern Sutherland, Caithness and Orkney suggests few obvious changes in vegetation (Birks, 1984; Peglar, 1979; Moar, 1969b), but a three stage division of the period,

corresponding to the Bolling - Older Dryas - Allerod of Mangerud *et al* (1974), has been suggested by Pennington (1975) in a pollen concentration diagram from Cam Loch, west Sutherland, and subsequently in three other profiles from the same region (Pennington, 1977a). However, the percentage data was originally thought to "provide no certain evidence for a fall in temperature" (Pennington *et al*, 1972). If this kind of feature is to be detected in the future, it may be only be by closely spaced, absolute pollen counts, in more rapidly accumulating sediments.

The spectra from Cross Lochs suggest some variability of Interstadial vegetation, in many ways comparable with those reported from the central Grampians, at Loch Etteridge (Walker, 1975a), where an initial *Empetrum* zone (LE2) is followed by *Betula-Juniperus* (LE3) and then a return to *Empetrum (LE4)*. Although the *Betula* rise is not so marked at Cross Lochs, the CLB1-CLB2-CLB3 sequence is very similar, including a rise in *Salix* and *Lycopodium* in CLB3/LE4. At least some of the *Betula* pollen is referred to *B.nana* at Loch Etteridge and this may also be true for Cross Lochs, although no attempt was made to separate this from tree birch. Rather than a colder intervening period, corresponding to the Older Dryas, this change perhaps suggests that birch and juniper were just beginning to respond to the warmer conditions, when they began to be affected by the deteriorating conditions leading to the Lateglacial Stadial. Coope *et al* (1971) suggest slower response rates for plants than insects under rapid climatic improvement, which would explain the initial slow response, and a steadily declining temperature during the Interstadial from 13,000bp, similar to that indicated for south Scotland (Bishop and Coope, 1977), would account for their subsequent decline before the main Stadial period. Thermophilous plant species decline would be in phase with a deteriorating climate.

The transition to the Loch Lomond Stadial is perhaps less clear at Cross Lochs than at some other sites in northern

Scotland and for this reason the correlation of CLB4 with other Lateglacial pollen zones has proved problematic. The potential for clarification of this, and later, periods by further analysis has been mentioned above. However, while the pollen spectra are difficult to interpret, the sedimentary changes suggest a transition to increased mineral inwash and Stadial conditions at 657cm, just prior to the start of CLB4.

Most sites in western Scotland, from Mull (Lowe and Walker, 1986) north to Loch an Smuraich (Pennington, 1977b) and those in the Grampians (eg. Walker, 1975a; 1975b) show a rise in *Artemisia to at least 5%*TLP during the Stadial. However, this does not occur at Cross Lochs or at Lochan an Druim and Loch of Winless. Pennington (1980) shows a negative correlation between this taxa and snow cover in modern Greenland. Macpherson (1980) plotted the distribution of pollen spectra at the *Artemisia* maximum for a number of Scottish sites, not including any in the far north east, linking percentages of this species to snow cover and precipitation variations in the Stadial. The data from the three sites in the north and east of Sutherland and Caithness suggests that this region may have had extensive snow cover at this time. Conditions were not suitable for snow and ice accumulation, however, as there is no glaciological evidence for glacierisation nearby and firn lines were much higher than the land surface during the Loch Lomond Stadial (Sissons, 1980).

There are also other contrasts in pollen spectra at this time. The sites in east Sutherland and Caithness have much more variable vegetation than other sites in northern Scotland. At Loch of Winless, a Cyperaceae-*Salix* zone indicates 'fell field' vegetation (Peglar, 1979), while at Lochan an Druim, although a zone dominated by undifferentiated Ericaceae occurs, this is interpreted as inwashed, corroded *Empetrum* pollen, with a landscape largely of open ground with *Saxifraga oppositifolia*, *Huperzia selago* and other open habitat species. Although

the amount of data for Cross Lochs is low, there was clearly a recession of the *Empetrum* communities which previously occurred and an expansion of bare ground suitable for colonisation by *Rumex* species and/or *Oxyria*. There is no indication that conditions were severe enough to make the waters of the small loch barren, as was suggested for Lochan an Druim (Birks, 1984), *Myriophyllum alterniflora* persisting and increasing throughout this period.

Although CLB4 is tentatively suggested as being approximately equivalent to the Loch Lomond Stadial, it is likely that the *Rumex/Oxyria* maxima represents a period shortly after the coldest temperatures, and therefore contemporary with some of the transitional zones after the *Artemisia* maxima in other regions, such as the Cyperaceae-*Rumex* zone in eastern Skye (Walker *et al*, 1988) or the *Rumex* zone at Yesnaby (Moar, 1969b).

The end of CLB4 is marked by a temporary increase in *Empetrum*, and given more detailed analysis this may warrant a further zonation. This would perhaps reveal a further Lateglacial - early Holocene transition zone similar to those recorded in west Sutherland (Pennington *et al*, 1972), with a brief *Empetrum* or *Empetrum-Juniperus* zone. This type of feature also occurs at Cam Loch and Loch an Smuraich, as well as being recorded at sites in Skye (Walker *et al*, 1988; Walker and Lowe, 1990). There is no noticeable rise in *Pinus* at the transition from Stadial to early Holocene pollen spectra, such as that suggested by Tipping (1989). However, as Tipping suggests, this may be due to problems of temporal resolution.

Clearly there were some rapid changes occurring at this time at many locations in northern Scotland, but in order to be documented accurately for inland Sutherland and Caithness, further work would be required on the Cross Lochs profile.

5.7.2 The early Holocene

The rapidly changing vegetation during the Inter-Stadial was succeeded by longer lived communities in the early Holocene. The establishment of a mixed birch - juniper community is the most striking change at the Cross Lochs and this is parallelled by similar rises, particularly in the latter taxa, across the whole of northern Scotland and the British Isles, although this may not have occurred synchronously (Tipping 1987c). Although the two taxa increased at the same time at Cross Lochs, this is not the case in other areas. Brief phases of juniper growth are recorded before large rises in *Betula* at Loch of Winless, Yesnaby, Cam Loch, Loch an Smuraich, Loch Ashik and other Skye sites. Synchronous rises appear at Lochan an Druim and Loch Etteridge, although juniper rapidly declines under the growing cover of birch trees. The often more rapid expansion of juniper is probably attributable to it being present throughout the Lateglacial, at least in its low growing form (*Juniperus communis* subsp.*alpina*). Tree birch may well have been generally absent from most of Scotland during the Lateglacial (Gray and Lowe, 1977), but local nuclei (eg. Peglar, 1979) must have allowed it to expand almost immediately as temperatures increased. This seems the most likely scenario at Cross Lochs.

The continued warmer conditions led to the arrival of *Corylus* and/or *Myrica* shortly afterwards, apparently at every site under consideration. The timing of the rise of this taxa is dated to before 9500bp along the west coast, with slightly later arrivals eastward and inland (Birks, 1989). The rise at Cross Lochs is relatively late at 8995±45bp, and the pre-9550bp date at Loch of Winless may be affected by hard water error (Peglar, 1979), so that the early spread across northern Scotland suggested by Birks (1989) seems doubtful.

Corylus seems to have formed a mixed woodland with *Betula*,

although the proportions of these two species varies, as does the apparent density of the woodland. During CLB6 and CLA2, *Betula* reaches around 45%TLP, with *Corylus/Myrica* at about 10-15%. Similar values are recorded at Loch of Winless, but cover of both species was more dense around Loch an Druim, to the north west and in the Cairngorms and Grampians (Birks, 1970), before the arrival of *Pinus*. In the south west of Sutherland there was probably never a woodland dominated by these two species, as pine followed shortly after juniper had declined (Pennington *et al*, 1972). The persistence of *Empetrum* in the early post-glacial vegetation at Cross Lochs is another indication that the eastern part of Sutherland and Caithness was probably a rather open birch woodland with abundant dwarf shrubs.

A major event in the early Holocene throughout most of northern Scotland was the spread of pine, which seems to have replaced the early birch-hazel woodland. This is evident from throughout the Grampians, Wester Ross and western Sutherland (Bennett, 1984; Birks, 1989). That it did not reach further east in any quantity until much later, is indicated by this study, Peglar (1979) and Birks (unpublished, in Birks, 1989), any pollen recovered being attributed to long distance transport from the abundant sources south and west. This lack of pine from this time onwards distinguishes the vegetation of the north eastern part of northern Scotland from that to the south and west.

6.7.3 The middle and late Holocene.

The vegetation of the mid- and late-Holocene in northern Scotland was far more variable than in earlier times. This is shown by Table 5.4, where difficulty is experienced in finding comparable pollen zones. This emphasises the need for further radiocarbon dating of pollen diagrams from this period of time. Recently Dugmore (1989) has reported the presence of a volcanic ash layer in peats from Altnabreac, Caithness, thought to correspond with the 'Hekla 4'

eruption in Iceland, at ca.4000bp. This would certainly provide an excellent marker for correlation of pollen records.

A generally open landscape is indicated at Cross Lochs from at least as early as 180cm (ca.5500bp) and perhaps as early as 252cm (ca.7000bp), where total tree pollen declines to around 10% and less than 25%TLP, respectively. Apart from some early growth of *Betula* and *Corylus* scrub on Shetland (Johansen, 1975) and Orkney (Moar, 1969b; Davidson *et al*, 1976; Keatinge and Dickson, 1979), there was no growth of woodland in the northern isles and this is similar to the pollen record at Loch of Winless (Peglar, 1979). This has been attributed to adverse environmental conditions, including wind exposure, low temperatures and insolation, storms, short growing season and salt spray (Peglar, 1979). Although these factors will clearly retard growth of some species, they seem unlikely to account entirely for the lack of tree growth, particularly considering the mature and healthy growth of a variety of deciduous trees in the area today (albeit often as planted woodland). There is no unambiguous pollen analytical evidence for anthropogenic impact on vegetation at Loch of Winless until much later (ca.2500bp) but charcoal data from elsewhere suggests that there was likely to have been burning of existing vegetation from as early as 7895±105bp and continuing erratically throughout the rest of the postglacial (Robinson, 1987). Regular occurrence of macrofossil charcoal occurs above 292cm (ca.7750bp) at Cross Lochs and increases at 212cm (ca.6250bp) (Chapter 6). Similar early indications of anthropogenic impact have appeared from south west Scotland (Robinson, 1983; Affleck *et al*, 1988), apparently in the absence of unequivocal pollen analytical evidence, and work on early blanket peat growth (Chapter 8) indicates that anthropogenic impact by burning was occurring in eastern Sutherland from well before the arrival of alder. Earlier work has also shown the presence of charcoal in putative Mesolithic peats from Nairn (Knox, 1954) and Ben Eighe (Durno and McVean, 1959). Even

relatively infrequent burning, and later grazing of stock, would be sufficient to prevent the establishment and spread of tree species already at the limits of their range. As Robinson (1987) points out, it is "virtually impossible to employ the interpretive methods which can be applied to pollen diagrams from forested areas" in these sparsely wooded environments. It is suggested here that this sort of anthropogenic impact occurs widely in the mid-Holocene, and that if charcoal analyses were carried out more regularly, it would be detected more frequently. Edwards and Ralston (1984), suggest there is limited evidence for widespread mesolithic impact, and this conclusion is not necessarily altered in the light of evidence which suggests much earlier occupation than had hitherto been realised (Morrison and Bonsall, 1985).

The alder rise at Cross Lochs is difficult to pinpoint precisely, as early constant values are only 1-2% with a rise to a peak of 4% at 152cm, the latter part of zone CLA4a. The early rise is dated to 5880±45bp with the later increase beginning at ca.4800bp. This compares with an initial rise dated to 6920±70bp at Loch of Winless, rising to a similar levels initially, but eventually reaching a maximum of ca.6% at around 2500bp. The map of Birks (1989), showing isochrones for the rational limit of alder, inexplicably indicates a date of less than 5500bp for Loch of Winless. However, with such low percentage values, it is difficult to accurately delimit the occurrence of this species. Slightly later dates are indicated in western Sutherland (6250±140bp, Pennington *et al*, 1972), where it formed a significant component of the woodland. The nature and ecology of the alder expansion has received considerable attention recently (Brown, 1988; Chambers and Elliott, 1989) and several reasons have been suggested for its increased abundance in the mid-post glacial. The pollen data from Cross Lochs, Loch of Winless and Orkney suggest that although it may have been present from as early as ca.6920bp, it never formed more than a minor element of the vegetation, despite the lack of competition from other tree

species.

A very minor 'elm decline' has been detected at Loch of Winless and on Orkney (Keatinge and Dickson, 1979). This is attributed to long distance transport. However, there is no such clear cut feature at the Cross Lochs (most values <1%TLP), and this is probably due to a greater dominance of local taxa. This well dated, synchronous feature of British pollen diagrams (Smith and Pilcher, 1973) is therefore of limited use in the far north of Scotland.

The reduction in tree pollen at the CLA3/CLA4 transition lasts from ca.5500 to 4250±45bp and may reflect an early increase in human impact, approximately coincident with the beginnings of the neolithic culture, for which there is abundant archaeological evidence in the form of chambered tombs (Hunt, 1987). This is a temporary decline, however, as subsequently the expansion of pine occurs.

The occurrence of local pine in the pollen diagram is an unusual feature for the far north east of Scotland. Pine maintained a consistent major presence in the north west of Scotland from 7-8000 bp to 4-4500 bp (Birks, 1975), but has not been noted as occurring locally in the pollen record from further east in the far north (Peglar, 1979; Robinson, 1987), despite widespread occurrences in peat deposits. A complete doctoral study has recently been directed at the problem of the palaeoecology of pine in northern Scotland (Gear, 1989), where it is demonstrated that most of the macrofossil pine remains date to around 4000bp, and similarly short lived peaks (around 1.5cm in depth) of pine pollen are found in the stump bearing horizons of peat (Gear, pers. comm.). Underwood (1989), however, found a pine dominated zone at Altnaharra, mid-Sutherland covering approximately 40cm depth of peat with a maximum of almost 80% TLP, although this probably results from rapid peat accumulation at this site. It was only by looking at closely spaced samples that this short lived event was discovered in the Cross Lochs core, although clearly it was

of major significance in terms of the appearance and ecology of the landscape. Table 5.5 shows the time periods between pollen samples for the published diagrams from the east of Caithness and the estimated time for which pine was present locally at Cross Lochs, probably between 134 and 330 years, but possibly less if the hypothesis of much faster peat accumulation at the pine maximum is accepted (section 5.6.4). Clearly it would be possible for pine to have had a short lived occurrence in the east but to remain undetected in the pollen stratigraphy due to it falling between samples.

Table 5.5: Pollen sample spacing and temporal resolution for 4500 to 4000 years bp from sites in Caithness and east Sutherland.

Site and Author	Loch of Winless Peglar (1979)	Aukhorn Robinson (1987)	Cross Lochs This study
Radiocarbon years for period	1425	3310	330
Peat depth (cm)	42.5	64.0	16.0
Accumulation rate Years/cm	33.5	51.7	20.6
Sample spacing	5	8	1
RC years between samples (ie.record 'missing')*	168	414	20.6
Pinus %TLP at approx. 4000bp	5	5	48 (4125bp)

*Compare with estimated period of local *Pinus* occupation at Cross Lochs of 134 years (>25%TLP) or 330 years (>20%TLP), assuming constant accumulation rates between 4250 and 3920bp.

This apparent inconsistency between pollen and macrofossil

evidence is parallelled by data from the Outer Hebrides. Birks and Madsen (1979) found no evidence of any forest development at Little Loch Roag, Lewis, but subsequent investigations by Wilkins (1984) indicated the presence of relatively extensive *Pinus* dominated woodlands, from macrofossil evidence. Bohncke (1988), in pollen diagrams from peat at Callanish, Lewis, indicates some localised growth of *Betula*, but again fails to detect the presence of *Pinus*. A possible explanation is that prolonged westerly winds removed much of the anemophilous pollen from the local pollen rain (Wilkins, 1984). This seems unlikely in view of the relatively high frequencies of tree pollen found at Loch Lang on South Uist (Bennett *et al*, 1990), for although the Uists are south of Lewis, they would probably be exposed to similar winds. Limited extent of pine and/or low pollen production of trees under stress has been suggested to explain the presence of pine stumps with low *Pinus* pollen counts, on Mull (Walker and Lowe, 1985). An additional explanation for these discrepancies would be that the macrofossil remains represent short lived occurrences of pine forest, unresolved in spectra of existing pollen diagrams. A very short pine phase, coincident with that at Cross Lochs (approx. 4250-3900bp) occurs in a pollen diagram from Loch Ashik, eastern Skye (Birks and Williams, 1983) so that this kind of event is not unique to the north east.

While similar short lived occurrences of pine are not often represented in published pollen diagrams from elsewhere in northern Scotland, the decline of pine at around 122cm (3920±45bp) is coincident with the widespread decline to the south and south west (Birks, 1975; Pennington *et al*, 1972). This decline is possibly associated with a climatic deterioration, with increased oceanicity (Pennington *et al*, 1972) perhaps combined with problems of soil leaching and podsolisation on mineral soils (Birks, 1972a). However, while there was probably some climatic change, it would be unreasonable to exclude human impact from consideration, particularly in eastern Sutherland and Caithness, as

archaeological evidence of neolithic peoples is widespread (Hunt, 1987). There were certainly large numbers of people, living in advanced groups, on the Orkney Islands at this time (Hedges, 1984). Charcoal remains increase appreciably in macrofossil samples from Cross Lochs at 124cm (ca.3950bp) (Chapter 6) which supports this hypothesis. However, burning would have to be very widespread and frequent to be the main agent of destruction as single fires, where a seed source remains, appear to encourage *Pinus* on mire surfaces (O'Connell, 1990).

The expansion of open habitats, probably mostly blanket mire, following the decline in pine, does not appear to have been so extensive in the west, with a certain amount of mixed woodland persisting. However, from this time on, the far north east mainland and Orkney was undoubtedly almost entirely treeless, with expansions in *Calluna*, gramineae and cyperaceae (Peglar, 1979; Robinson, 1987; Moar, 1969b; Davidson *et al*, 1976; Keatinge and Dickson, 1979). This is also reflected in the Cross Lochs diagram. There do not appear to have been any major fluctuations in the general appearance of the landscape from this time onwards, although there may have been some intensification of human impact in Caithness at around 2500bp; with increased cultivation (including the growth of cereals) (Peglar, 1979). This may also be seen in the archaeological record with large numbers of 'brochs' found throughout Sutherland and Caithness, including a number in Strath Halladale, close to the Cross Lochs. There is little evidence of cultivation in the Cross Lochs area, however, with a few grains of *Plantago lanceolata* and Cerealia, perhaps reflecting agricultural activities in northern Strath Halladale, where there is a limited amount of flat, cultivable land.

The quite dramatic changes occurring at the start of zone CLA4d (1470±45bp) are thought to reflect changing conditions on the mire surface itself, with a return to mesotrophic fen conditions. The site development, aspects of

this are further discussed in Chapter 6, where it becomes clear that the change in surface conditions to poor fen actually occurs rather earlier at 92cm (ca.2850bp), but this is not reflected in the pollen record until the increase in *Myrica* and *Selaginella* occurs. It is suggested that the return to this state is possibly a result of generally increased surface wetness on the mires in the region as a result of climatic deterioration. Although this does not seem to be parallelled in other Scottish pollen diagrams, any effects on regional pollen rain may well be minimal and easily confused with anthropogenic impact.

5.8 SUMMARY AND CONCLUSIONS

This chapter has described the results of pollen analysis from two cores, from separate sites within the same area of blanket mire, close to the Cross Lochs, eastern Sutherland. However, the sites are relatively close to each other (ca.1km) and the resulting pollen diagrams can be correlated, and considered as a complete Lateglacial and Holocene record of vegetational change in the area.

It is suggested that the 'basal' sediments recovered from the Lateglacial site may have further deposits underlying them and that these and other similar sediments may shed further light on early Lateglacial environments and the problem of ice extent during the Devensian glacial maximum. The earliest Lateglacial pollen spectra recovered suggest a transition from open habitat to more stable communities, dominated by *Empetrum* heath. This Interstadial vegetation shows some variability, with a phase of increased growth of juniper and birch, followed the deteriorating climate and less stable soil conditions in the transition to the Stadial, with *Huperzia selago* and *Salix*. There is a poorly defined Stadial and Stadial - Holocene transition period, characterised by *Rumex/Oxyria*, after which much warmer, post glacial conditions occur, with a succession of birch-juniper and birch-hazel woodland. Birch persists in small

amounts locally, but the presence of other arboreal pollen is thought to be mostly due to long distance pollen transport. From ca.5500bp, the landscape is largely treeless, apart from a brief phase of local pine forest ca.4500-4000bp.

These changes are compared with other pollen records for northern Scotland. The trends in the Lateglacial vegetation are broadly similar to those displayed by other sites, although many of the changes appear to be less extreme than for areas to the south and west. The lack of *Artemisia* during the Loch Lomond Stadial in the east Sutherland and Caithness area is particularly noteworthy. This may imply more extensive snow cover. The early postglacial is similar to the rest of northern Scotland, but invasion of *Betula* was more rapid and the later growth of this species and hazel was not so dense. The lack of pine in the early postglacial allies the site with eastern Caithness and the Northern Isles, rather than the north west Scotland and the Grampians. It is suggested that the effects of early human populations on such marginal forest areas may have been underestimated in the past. The paradoxical existence of pine macrofossils with no pollen evidence in several areas of Scotland is explained, at least in part, by the lack of temporal precision of pollen diagrams rather than by low pollen productivity, extremely localised occurrences of the species or strong prevailing winds. The reasons for such an event remain unexplained.

The pollen evidence described provides a pollen chronology with which to correlate, and thereby assign approximate dates to, other peat cores and samples used in the reconstruction of peatland history. It also serves as a background chronicle of change, against which the events of peatland development are set, in the next three chapters.

CHAPTER 6: PATTERNED FEN DEVELOPMENT

6.1 INTRODUCTION

The present status of Scottish patterned fens in terms of their vegetation and water chemistry has been examined in Chapter 3, and it is clear that these mire systems represent a unique and previously undescribed peatland environment in Britain. The purpose of the next three chapters is to investigate past mire environments in the Flow Country. Areas of particular interest are the timing and causes of early peat growth, community succession, differentiation of existing mire types and pattern development.

This chapter is concerned specifically with the development of the patterned fen systems, as defined in Chapter 3. This is the timing and nature of early peat growth at these sites, the changes in site hydromorphology and mire conditions, and the longevity and origins of the existing mire type and plant communities. The characteristics and origins of surface patterning are discussed in Chapter 7. In Chapter 3, comparisons of patterned fen vegetation were made with that of similar mire systems elsewhere in the world, and also with the rather different, but adjacent, ombrotrophic blanket mire communities. If the development of patterned fens could be characterised, then a further line of enquiry would concern the contrasts and similarities between them and other related mire systems.

The overall approach to the research is outlined in 6.2, and the methods used to carry this out are covered in 6.3. Section 6.4 relates the results of an investigation based on a single site and summarises the implications of this for hypotheses of patterned fen development. Results of work on three further sites are described in 6.5 to 6.7. In the concluding section (6.8), comparisons between sites and some generalisations on patterned fen development are made.

6.2 RESEARCH APPROACH

The initial task in this part of the research was to generate hypotheses of patterned fen development. Existing data concerning Scottish patterned fens was limited to speculation (Lindsay *et al*, 1988), while there were a number of plausible scenarios relating to similar mire systems elsewhere in the world (see below). Lindsay *et al* (1988) suggest that peat accumulation begins in an existing valley, with a central watercourse, and that this initial peat nucleus reduces the hydrological competence of the valley and results in further waterlogging and peat build up. This implies fen peat throughout the profile, with an earlier or more rapid peat accumulation at the base of the slope.

Boreal patterned fens elsewhere in the world are also generally 'primary' peats. Poor fen peats occur throughout some mire profiles in Sweden, indicative of apparently similar conditions since mire inception from 6500 to 3000bp (Sjors, 1983, p76). Other sites, such as Krackelbacken Fen, Sweden (Foster and Fritz, 1987), have an initial nucleus of peat growth in a waterlogged hollow, spreading outwards by paludification of forest, upslope, initially forming woody peat and then a mixture of sedge-*Sphagnum*-shrub peats, similar to contemporary communities. North American patterned fens appear to develop in a similar way, although the initial nucleus is often a result of ponding behind ice-push ridges at lake margins (Foster and King, 1984; Foster *et al*, 1988a). Work on patterned fens in Minnesota (Glaser *et al*, 1981; Glaser, 1983; Glaser, 1987) shows simple stratigraphy, with basal humified wood peat overlain by sedge peats. In some situations, mire waters may in fact still be in contact with mineral ground (Wells, 1981), with only a thin covering of sedge and *Sphagnum* peat underlying the ridges.

Existing data and ideas on patterned fen development can be formalised into a series of hypotheses, from which

palaeoecological predictions follow (Table 6.1). These hypotheses can then be tested for their application to Scottish patterned fens.

The research investigation had two stages. The first was concerned with the testing of these existing hypotheses of development, with the generation of alternatives, if these were falsified. This was based on data from a single site (Cross Lochs 'A'), which has been shown to represent a 'typical' patterned fen, determined by its median position in a range of variation based on vegetation and water chemistry of the present vegetation (Section 3.4.7). Secondly, support for the remaining hypotheses was sought from similar, but less intensive, investigations of further sites, representing a wider range of patterned fens. The range of variation and the selection of these sites has been described in section 3.4.7, and the three further sites are Cross Lochs 'B', Rhifail Loch and North Altnaharra.

6.3. METHODS

Stratigraphic studies at each site involved levelling of the mire surface, using an electronic 'Total Station' (Hewlett Packard 8100A). One of the main problems encountered in levelling of a mire surface is maintaining the survey instrument in a stable position on a wet and spongy surface. A 'total station' can be set up on adjacent rock outcrops or thin peat, which avoids this difficulty. Surface heights were measured to the nearest 10cm, with the survey prism placed consistently in the same microtopographical position, approximately 10cm above the water table on 'low hummock' or 'lawn' features. Peat depths were measured at each survey point and stratigraphy was recorded at suitable locations.

Early work on Cross Lochs 'A' used random survey points, increasing where surface topography was highly variable.

Hypothesis	Expected palaeoecological evidence	Source
'Primary' peatland type formed directly on mineral substrate.	Uniform poor fen peats in contact with mineral substrate.	Lindsay et al (1988) Sjors (1983)
Second stage in succession, formed after initial paludif ication of dry ground.	Poor fen peat throughout profile except basal deposit which may show wood remains.	Foster and Fritz (1987) Glaser (1987)
Peat growth from initial nucleus upslope via 'back paludification'	Peat gradually thinner towards head of mire. Successively later dates in this direction	Foster and King (1984) Foster and Fritz 1987)
Development within valley, enclosed by mineral ground.	Valley evident from sub peat contours	Lindsay et al (1988)
Development within valley, between adjacent peat masses.	Poor fen peats in centre of mire, with fen peats overlying peat at the periphery.	Lindsay et al (1988)

Table 6.1: Hypotheses for patterned fen development and expected palaeoecological evidence

This allowed the production of a contour map for this site. Time was more limited in subsequent studies and a series of transects was used instead, normally five per site, with depth measurements at 10-20m intervals. Data for these sites is presented as transects, rather than contour maps, although a three dimensional representation of the relationships between transects and generalised sub-peat topography is also shown.

Stratigraphy was described in the field, using a 5x50cm Russian pattern corer, sub-samples being removed for checking in the laboratory later, where necessary. Checking of peat composition in the laboratory showed that the major stratigraphic divisions were adequately and accurately detected, although it was often difficult to assess proportions of different components where mixed peats occurred, so that boundaries between peat types were often difficult to determine. Surface pattern characteristics and major vegetation boundaries were also recorded, and a map of these features drawn on site and later transferred to a scale map, using the survey data.

For more detailed reconstruction of plant community change on the mires, the deepest core, which included most stratigraphic changes recorded, was brought back to the laboratory for macrofossil analysis by the methods described in Chapter 4. In the case of Cross Lochs 'A', this was the same core used for pollen and microfossil analysis, providing additional sources of information for the reconstruction of past mire conditions.

6.4 CROSS LOCHS 'A'

6.4.1 Site description

The Cross Lochs area has already been described generally in Chapter 5 (see Figure 5.1), as it is the location for much of the research described in this thesis. However, it is appropriate to describe the setting and vegetation of this particular poor fen in a little more detail. Plate 6.1 shows a low level oblique aerial photograph, taken from the south and the morphology of the mire surface is described in section 6.4.2. It was shown in section 3.4.7 that this site is 'typical' in terms of vegetation and water chemistry. Ridge vegetation in the patterned zone is of the 'typical' nodum, a *Molinia*-tall sedge-*Sphagnum papillosum* community, with pools of *Carex rostrata-Juncus bulbosus*, and *Carex limosa*. At the top and bottom of the mire, are *Molinia* flushes. The steeper surrounding slopes, particularly the rock outcrop to the north and the ground to the west leading to the summit of the hill, are dominated by *Calluna vulgaris*, while *Calluna-Trichophorum* associations occur on most of the rest of the surrounding blanket mire. The forestry plantation to the north east is only around 100m from the mire, but is outside the hydrological catchment. Further down the slope, there are a number of drainage channels or 'moor grips'.

6.4.2 Mire morphology and hydrology

Contour maps for surface and pre-peat topographies are shown in Figures 6.1 and 6.2, respectively. Also indicated are the main lines of water flow and existing patterned zones.

The present mire surface slopes gently from west to east, with a steeper area at the head of the mire, after which the slope decreases and the main patterned zone occurs. A seepage spring occurs at the base of this slope, where the vegetation is sparse and there is a bare mud area, stained

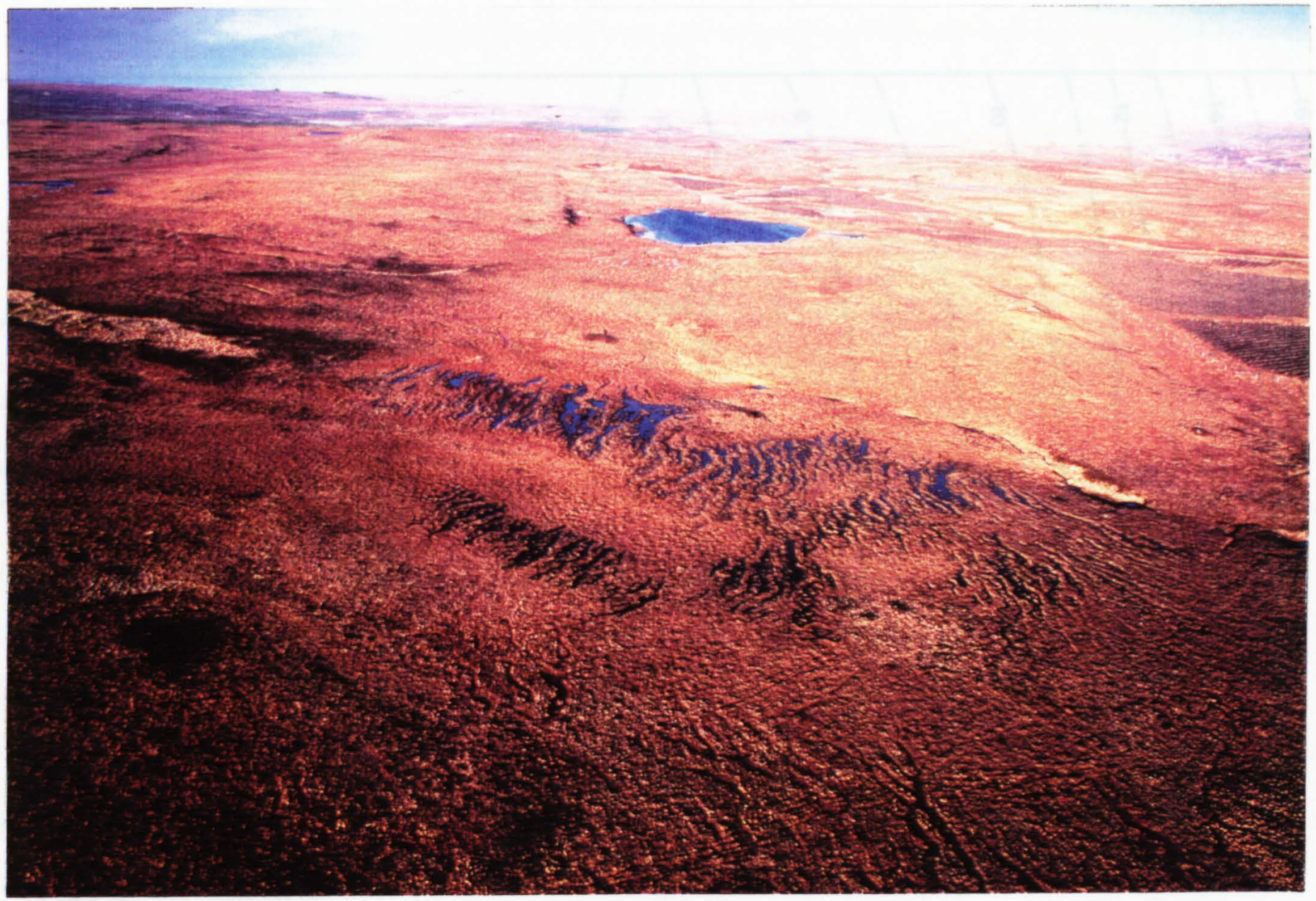


Plate 6.1: Oblique aerial photograph of Cross Lochs Fen A from the south.

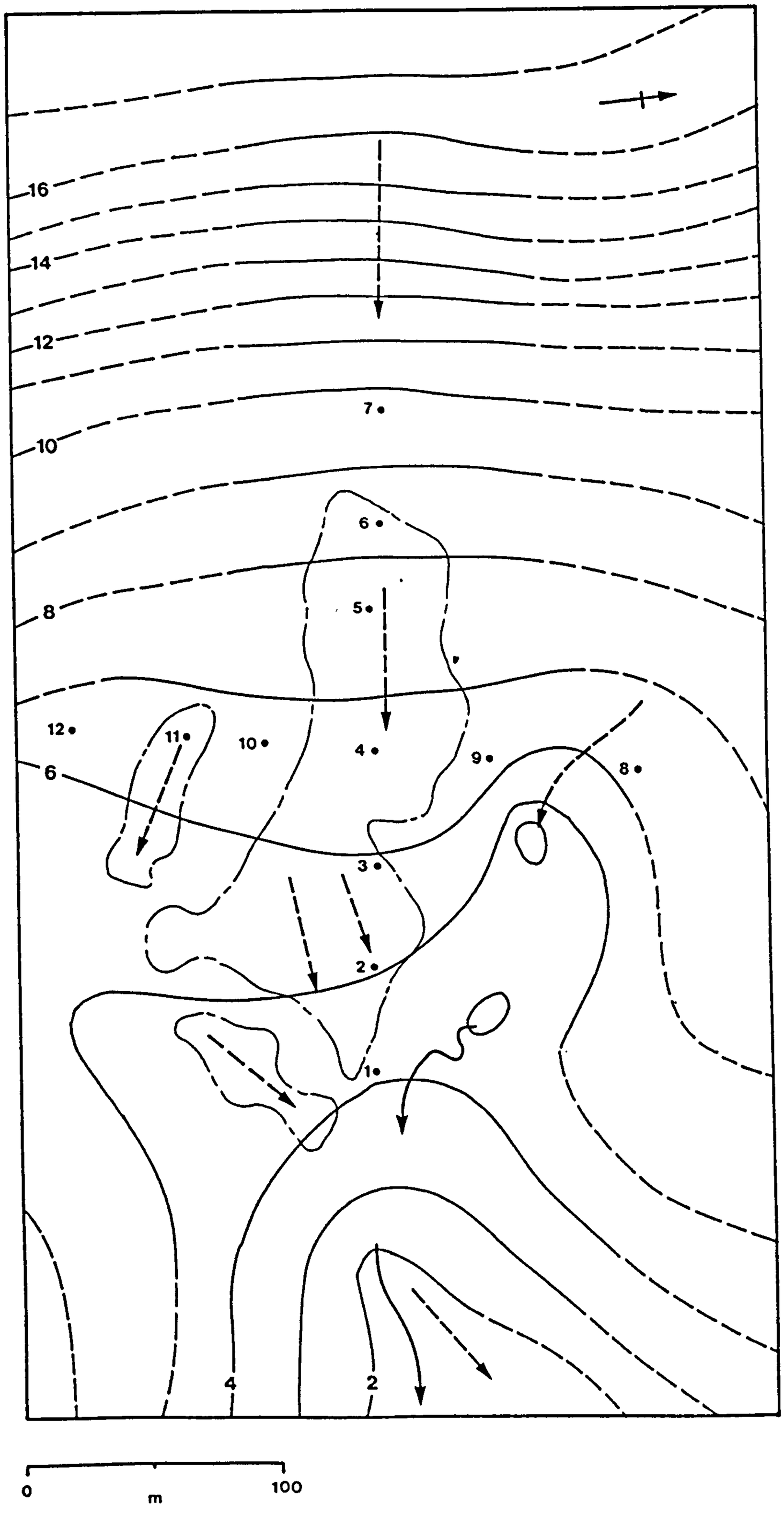


Figure 6.1: Surface contour map of Cross Lochs Fen A. Contours are at 1m intervals above lowest point recorded. Irregularly broken line indicates main zones of surface patterning. Main zones of water flow indicated by arrows; solid = channel, broken = diffuse seepage. ● = core location.

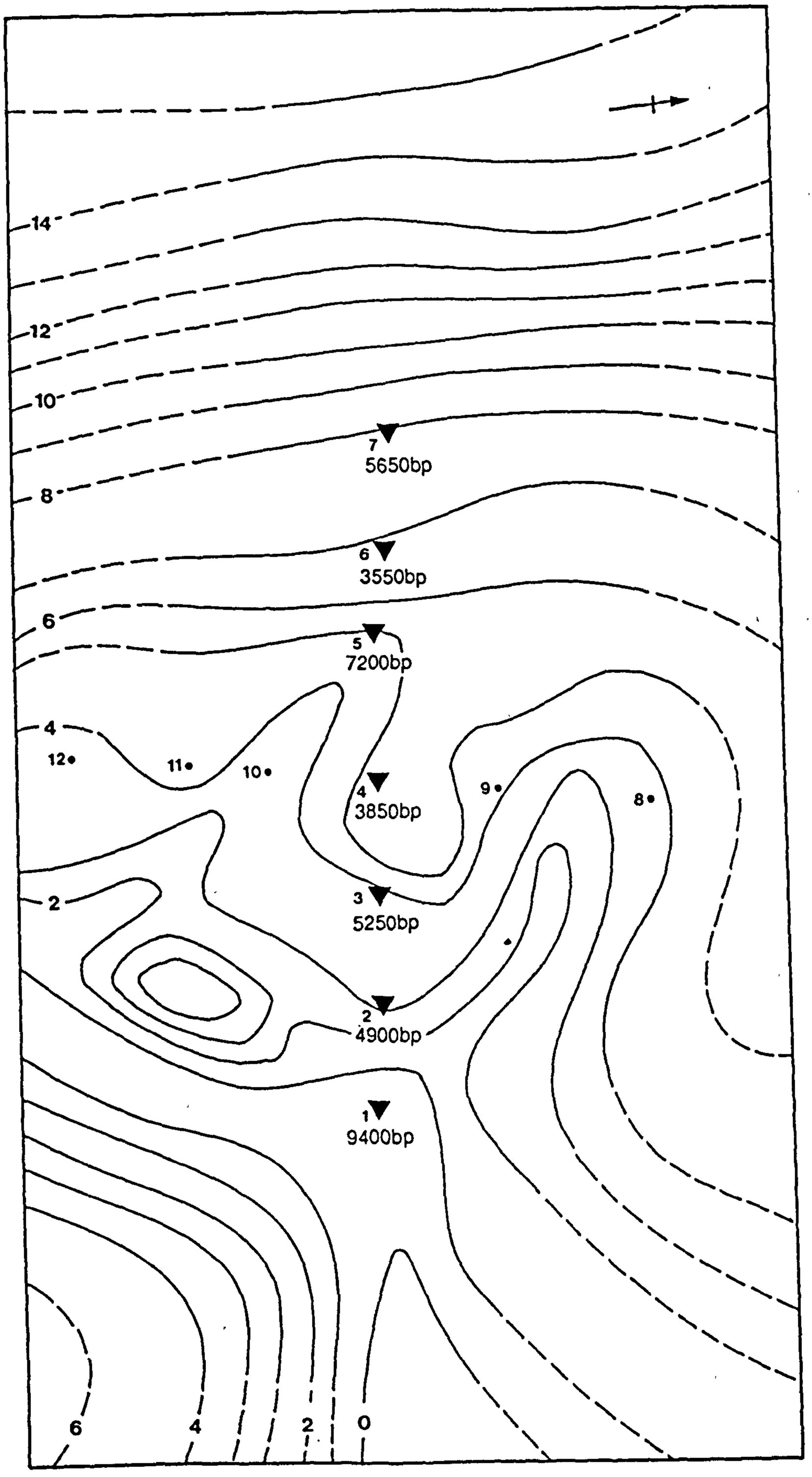


Figure 6.2: Sub-peat contour map of Cross Lochs Fen A. Contours are at 1m intervals above lowest point recorded. ▼ = estimated basal peat age (radiocarbon years bp).

red-brown, possibly as a result of iron enrichment. There is a slight depression to the north, which appears to drain the area to the north of the patterned fen. This drainage appears as surface seepage and also as a permanent channel, with swallow holes indicating the presence of sub-surface flow. This does not, however, appear to drain the patterned fen directly, and there is probably some coalescence of drainage systems just below the location of core 1. There is also a very slight depression to the south east of the fen, in which a smaller patterned zone lies. The main area of patterning, covering most of the mire surface lies on a slight convexity, if anything.

Sub peat topography shows that the site is far more complex than was initially supposed from the surface. The upper slopes show similar morphology, although the gradient is somewhat steeper, but the lower part of the site varies greatly. There was a spur running down the centre of the site, with a shallow gulley to the south and a much deeper gully to the north. The ridge dipped in the centre and terminated in a small, steep knoll. The two gulleys came together in a single valley at the base of the site, perhaps with localised deeper depressions, and then the valley probably ran away eastward, towards Strath Halladale. The drainage pattern would have been sheet flow over the top of the site, separating into more channelised flow in each gulley, forming a stream flowing eastward. The northern gulley probably drained the wider valley, with the loch, to the north (see Figure 5.1).

It is notable that the wettest mire area today, with best developed surface patterning, does not correspond with areas of water collection in the pre-peat landscape. This is contrast to the findings of other authors, working on raised mires, such as Boatman *et al* (1981). Although certain features of the hydrological network are retained, such as the gulley (now a depression) to the north, most of the patterns of water flow and water collection are completely altered.

6.4.3 Site stratigraphy

The stratigraphy of this site is shown by the two transects of cores in Figures 6.3 and 6.5. The location of the cores was intended to sample the main area of patterned fen and its periphery, and coring took place in November 1987, early on in the project. The transects were unfortunately determined before a full peat depth survey was performed, and the highly variable nature of the sub-peat surface fully appreciated. However, although the location of cores would probably have been altered with this hindsight, the existing data adequately demonstrates the main features of peat growth.

Estimates of basal dates for the cores on the longitudinal transect were produced by pollen analysis of several samples from the lower regions of each of the cores 2-7 and comparison with the fully dated, more detailed data from the main core (no.1). Data for the main species used for correlation is shown in Figures 6.6 to 6.11 and the estimated dates are given on the stratigraphic diagrams. This was an attempt to provide some indication of the timing of the spread of the peat deposit and provides only the crudest approximation of this. Clearly, it is difficult to use most of the herb types to estimate the ages of pollen spectra as local vegetation is likely to vary. The main indicator species used were the tree taxa and total arboreal pollen.

Peat growth appears to have started with a flush community in the main valley, indicated by the mixed bryophyte and monocot. peat at the base of core 1. This changed to a pure monocot. fen and then birch appears to have colonised the site and small twigs are evident in the peat until a depth of 210cm. The lateral extent of this particular peat deposit is unknown, similar material is found at the base of cores 5, 9, 10 and 12, with some difficult to determine, more highly humified peat in core 8. These are all areas of deeper peat, deposited in the gulley areas of the site.

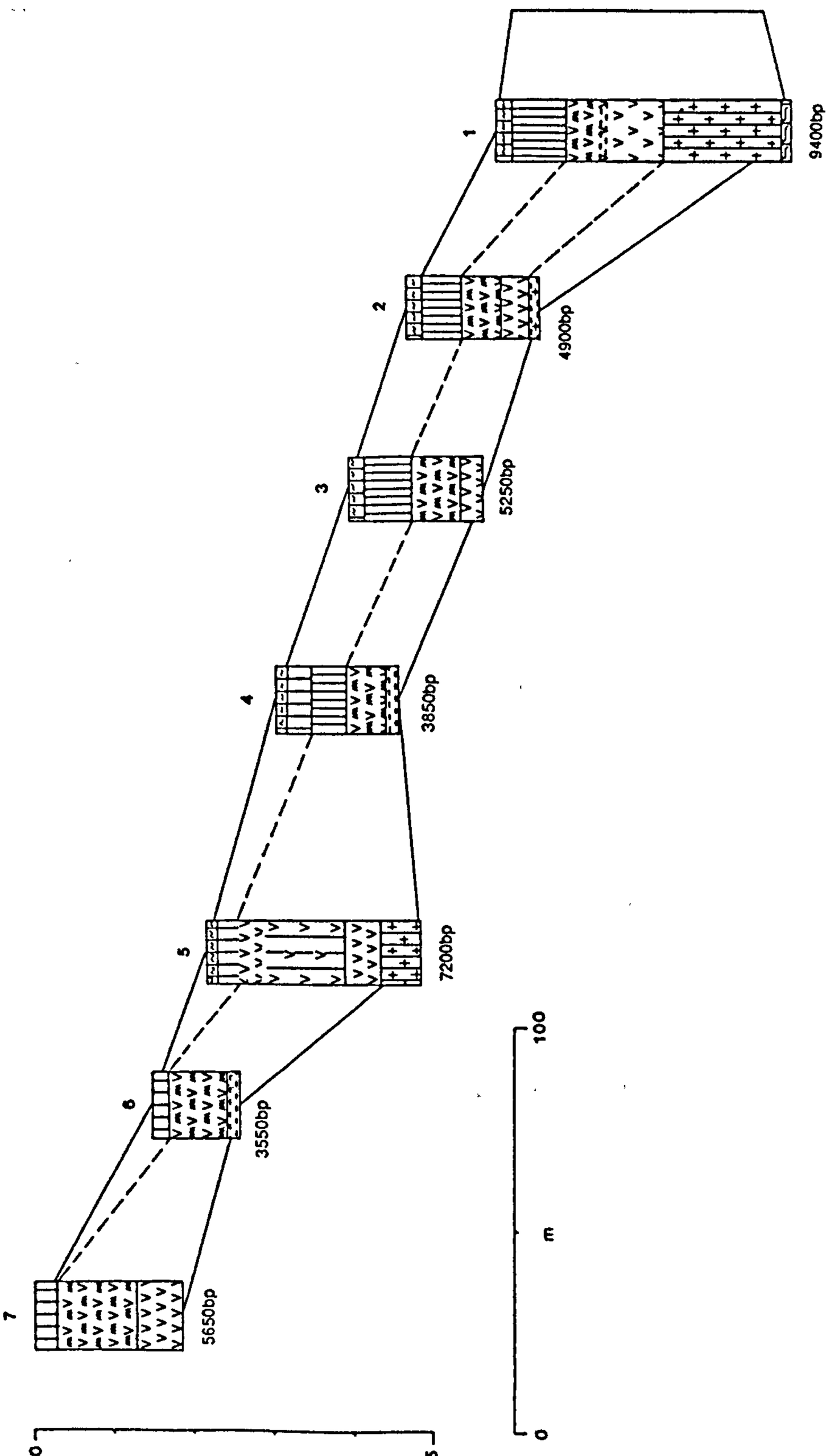
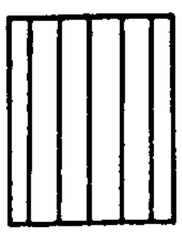
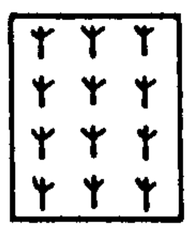


Figure 6.3: Stratigraphy of longitudinal transect at Crossloch Fen A, with estimated age of basal peats (radiocarbon years bp). See Figure 6.4 for key to symbols.

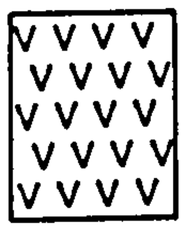
KEY TO STRATIGRAPHIC SYMBOLS



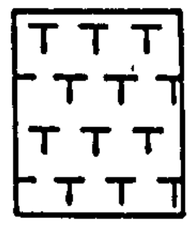
Monocotyledonous peat



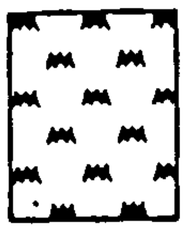
Menyanthes trifoliata



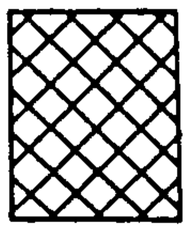
Ericaceous peat



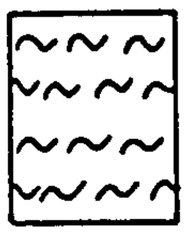
Trichophorum cespitosum roots



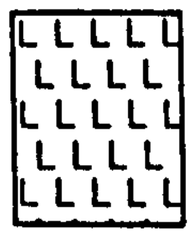
Eriophorum peat



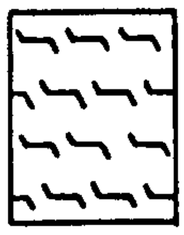
Organic lake mud



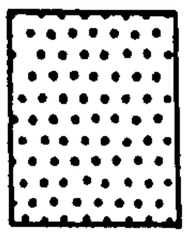
Sphagnum peat



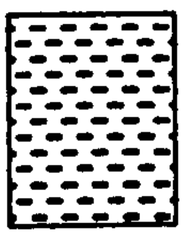
Lake clay



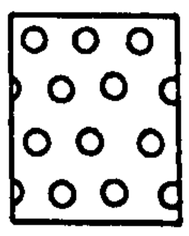
Bryophyte (non-*Sphagnum*) peat



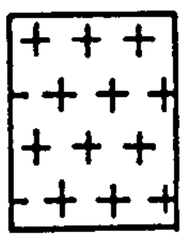
Sand



Highly humified peat
(Substantia humosa)



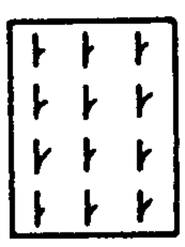
Gravel



Betula wood



Pinus sylvestris stump



Phragmites australis

Symbols based on Troels-Smith (1955)
Only major components detectable from field examination shown
Denser shading indicates higher humification

Figure 6.4: Key to stratigraphic symbols used throughout thesis.

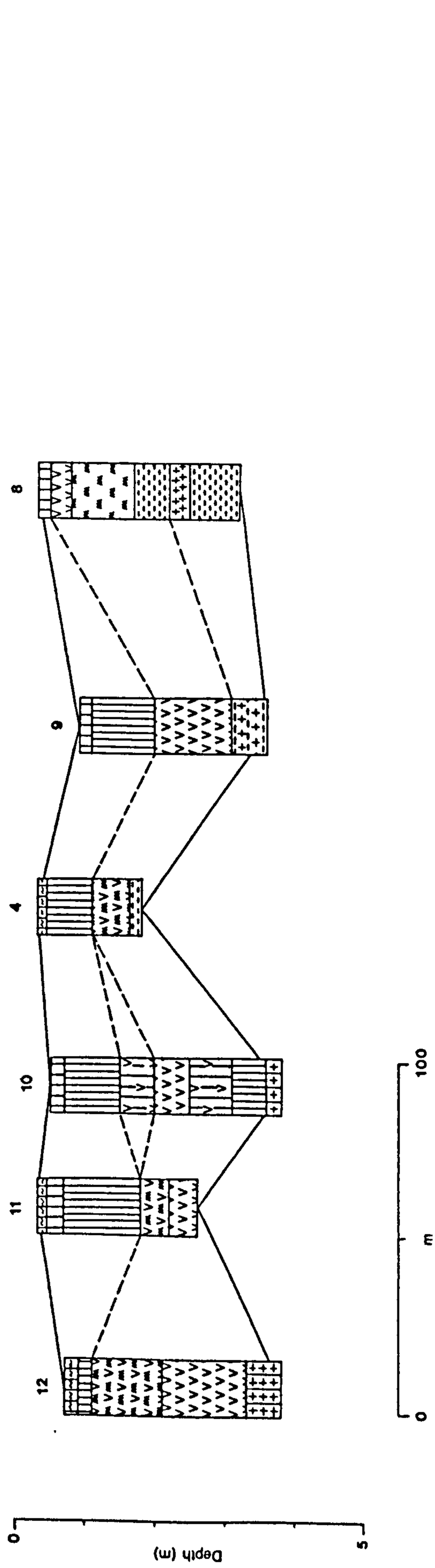


Figure 6.5: Stratigraphy of transverse transect at Cross Lochs Fen A. See Figure 6.4 for key to symbols.

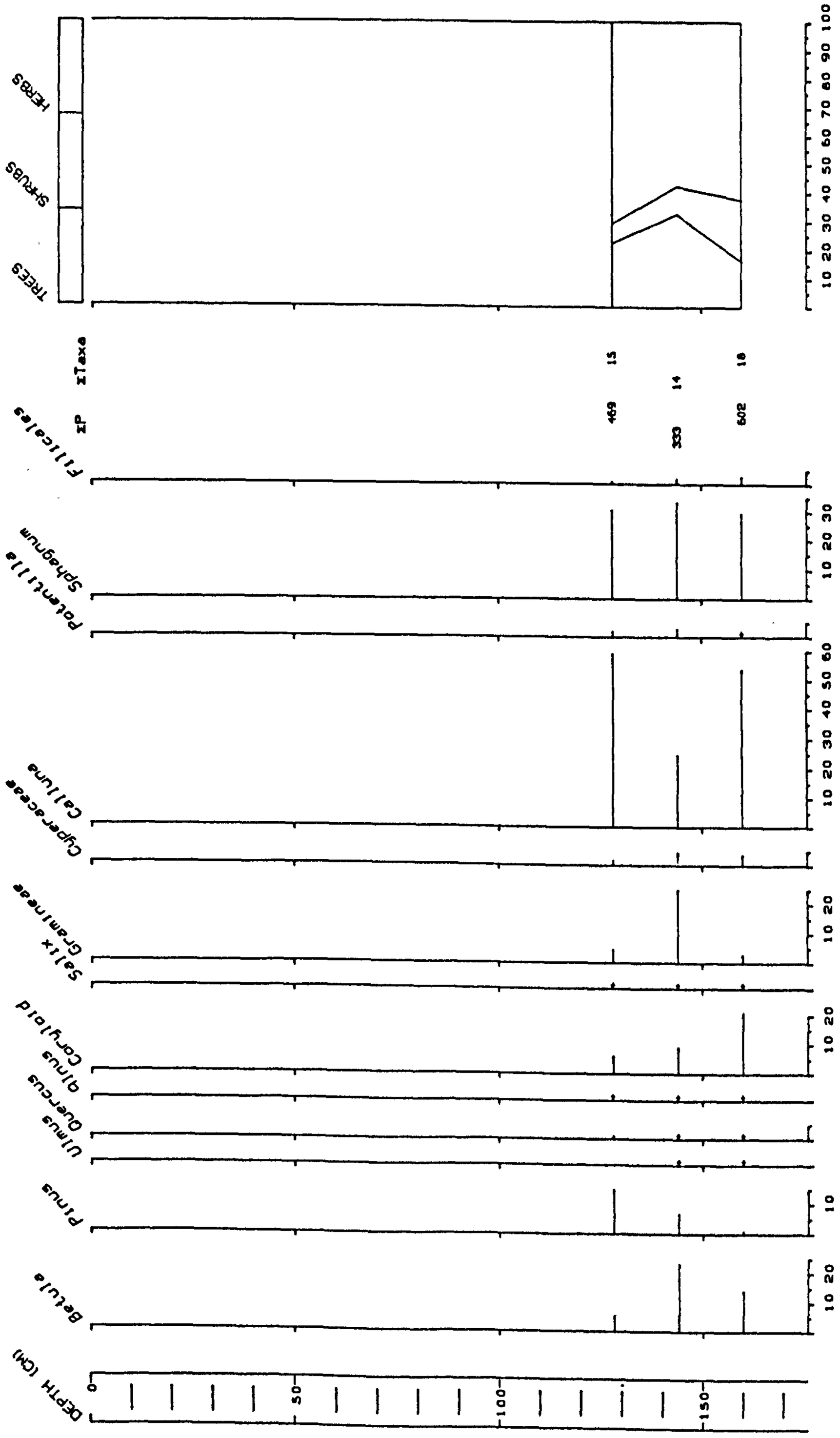


Figure 6.6: Skeletal pollen diagram for the base of Cross Lochs Fen A, core 2.

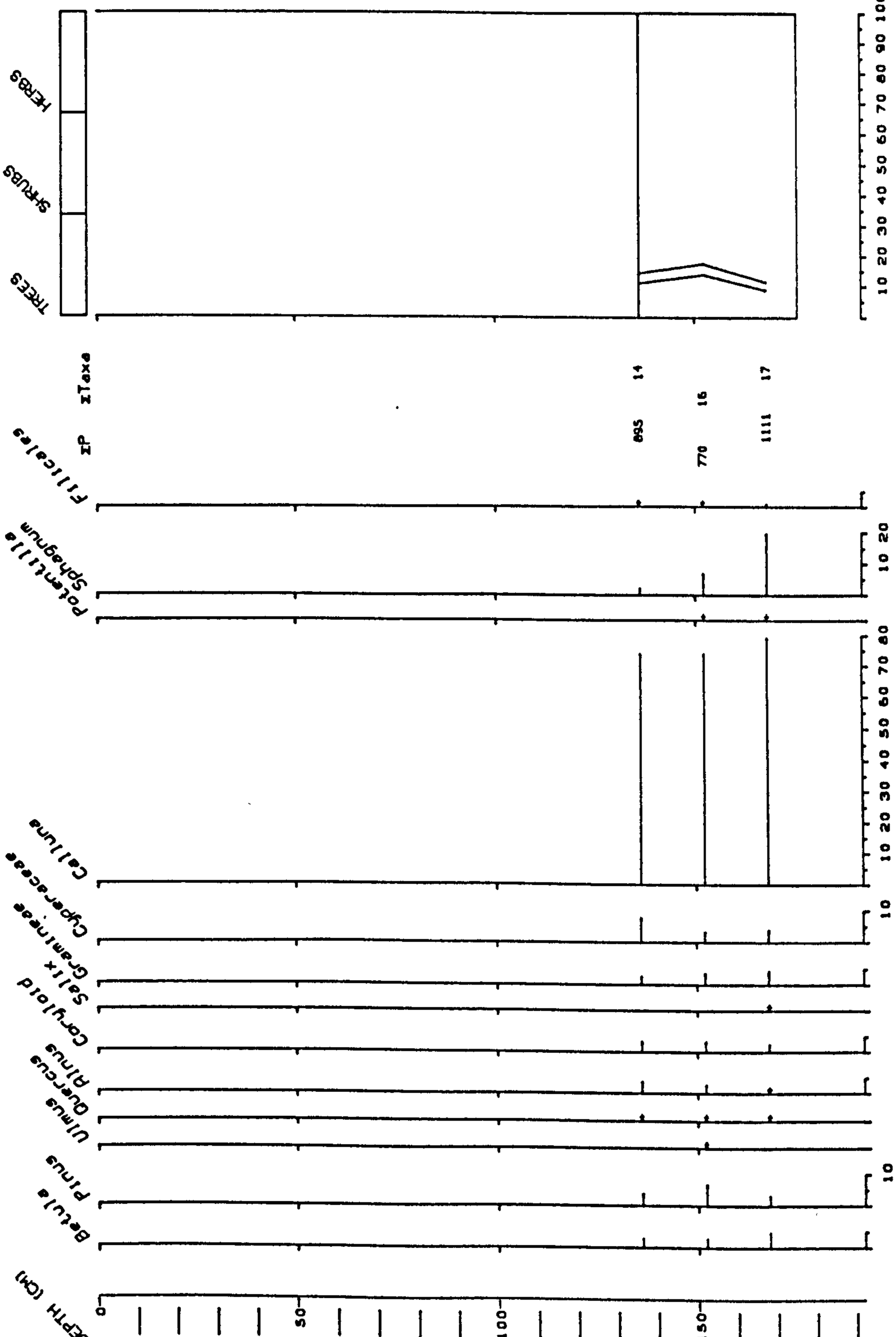


Figure 6.7: Skeletal pollen diagram for the base of Cross Lochs Fen A, core 3.

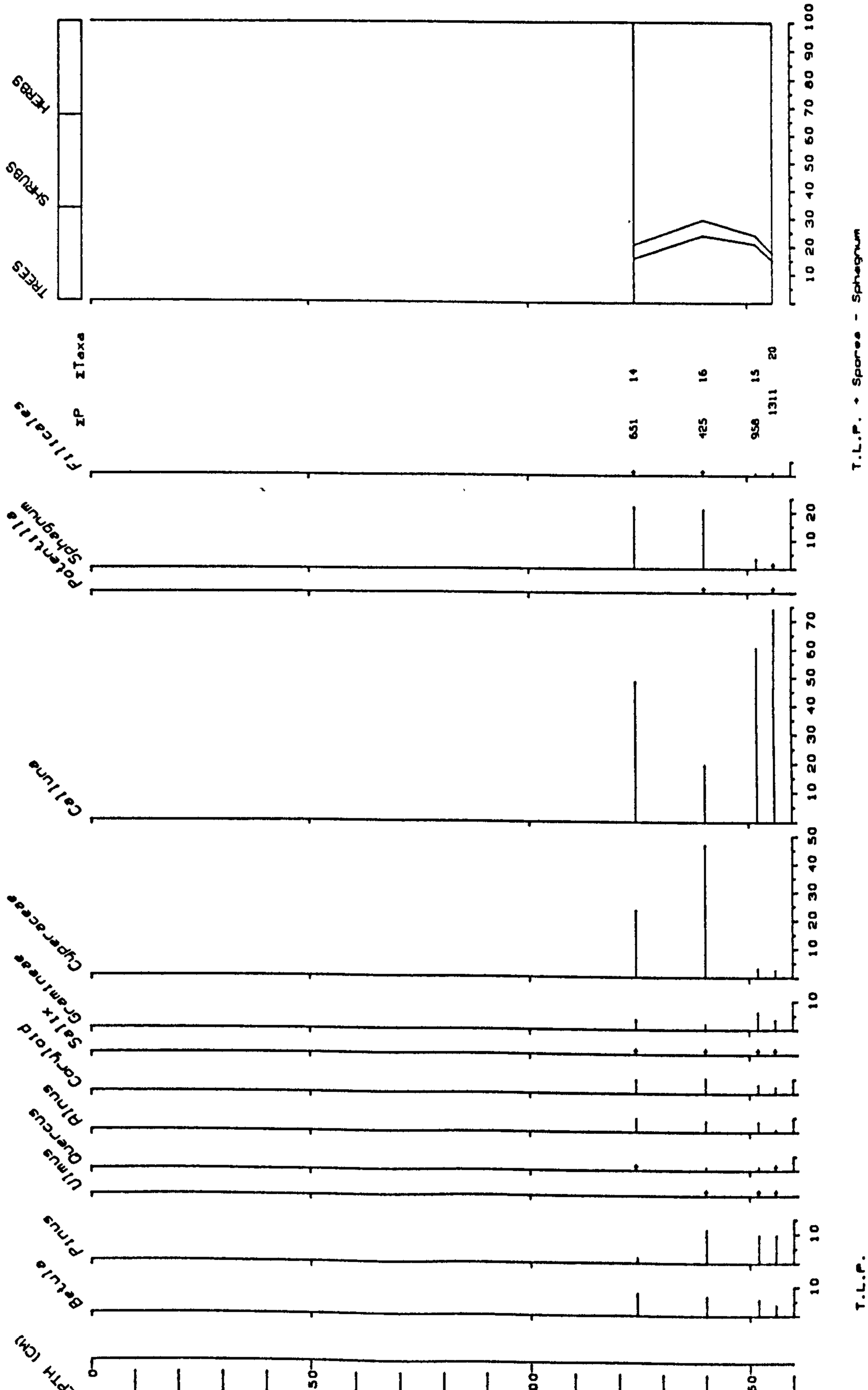


Figure 6.8: Skeletal pollen diagram for the base of Cross Lochs Fen A, core 4.

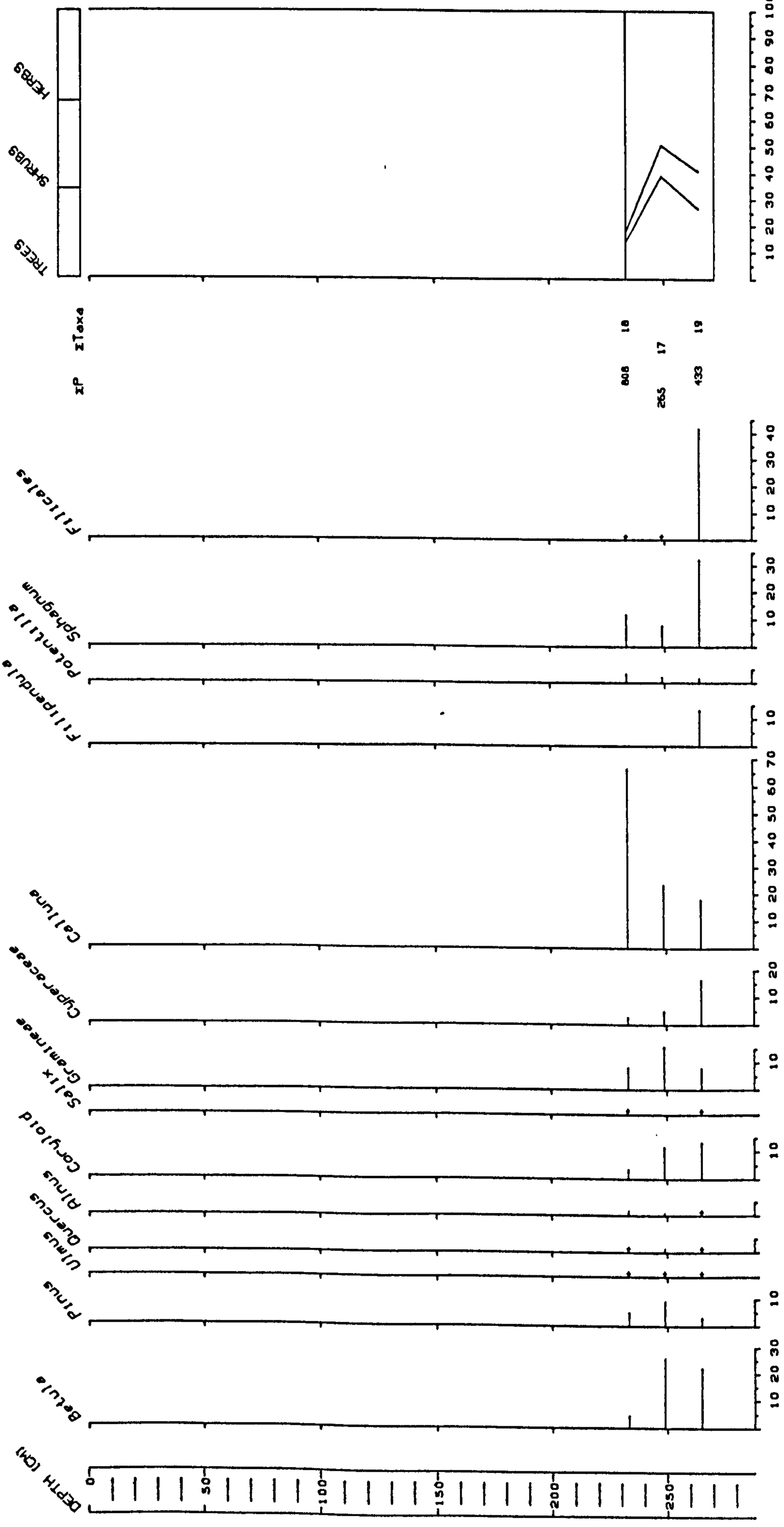


Figure 6.9: Skeletal pollen diagram for the base of Cross Lochs Fen A, core 5.

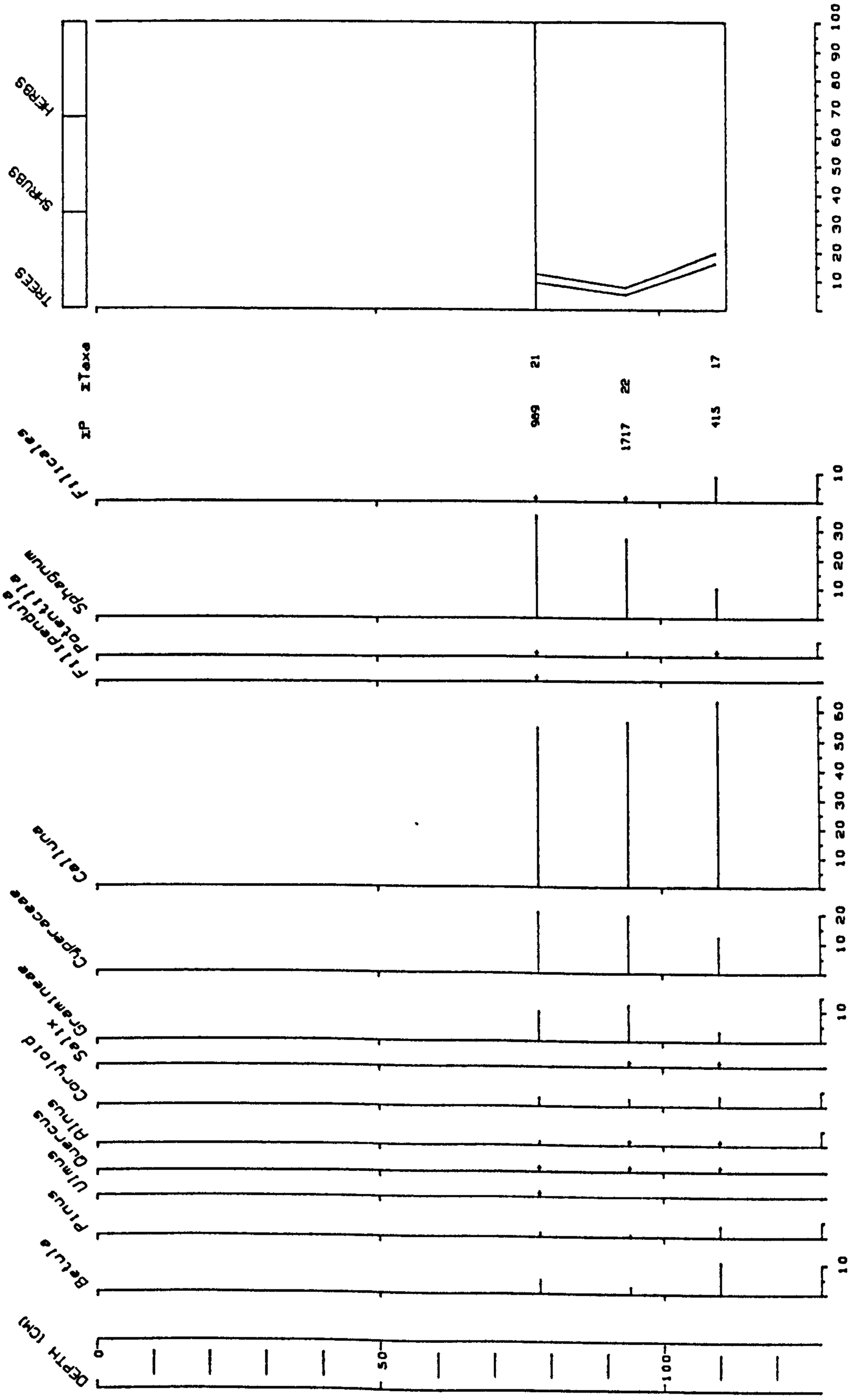


Figure 6.10: Skeletal pollen diagram for the base of Cross Lochs Fen A, core 6.

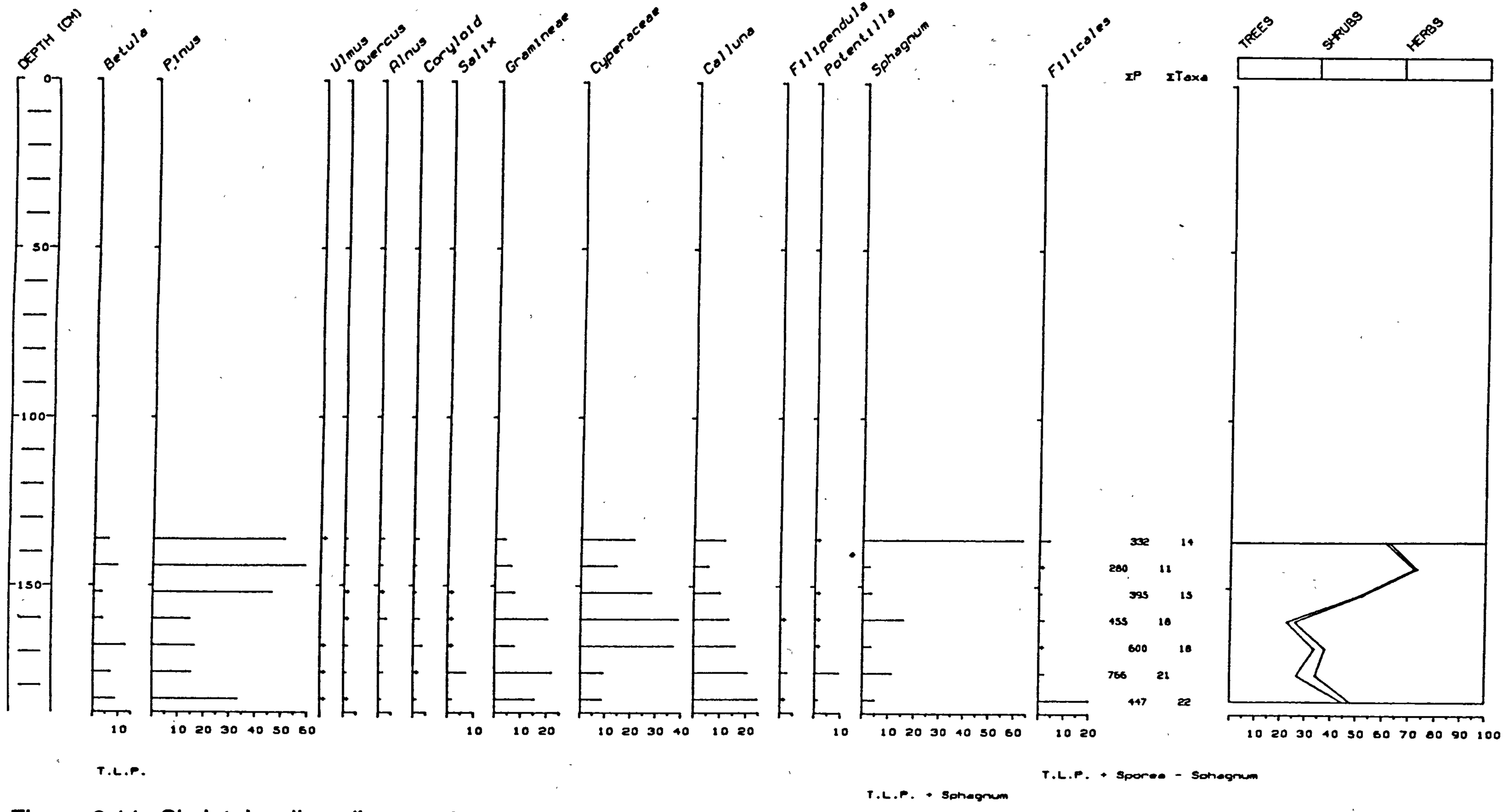


Figure 6.11: Skeletal pollen diagram for the base of Cross Lochs Fen A, core 7.

These deeper peats are therefore probably contemporary, and infill of both gulleys was probably taking place between ca.9400 and 6200bp, although it is not possible to tell whether or not this was a spread from a single nucleus, or occurred simultaneously across all the locations with suitably impeded drainage. There is no indication of peat formation on the spur area or upper slopes at this time.

The remains of birch cease to be found above this stratum and the monocot fen peats are replaced by ericaceous and *Eriophorum* peats of variable composition, representing an ombrotrophic stage of mire development. This is therefore the first time at which true 'blanket mire' formation could be said to occur. The transition is not so clear in cores 5 and 10, located within the original southern gulley, where peats continue to contain a proportion of poor fen monocot. peat. This probably indicates that this area remained a seepage zone for some time after the main change to an ericaceous/*Eriophorum* mire. The same is true, to a lesser extent for the northern gulley, as core 9 shows some monocot. remains in the peat above the birch.

These ombrotrophic peat forming communities spread to the surrounding area between about 5300 and 3500bp, the youngest basal peat being at core 6, with an estimated date of 3550bp, although the basal deposit of highly humified peat and sand indicates that there may have been a podsolised soil forming a slow accumulation of 'mor' humus before this time.

Over most of the present patterned fen surface, a uniform change back to poor fen monocot. peats occurs at between 70 and 90cm depth and the peat above this boundary often contains obvious megaspores of *Selaginella selaginoides*. This occurs at approximately 2850bp in core 1. At the periphery of the mire (cores 8 and 12), this occurs only in the top 20-30cm, within the rooting zone, and is therefore difficult to compare directly with the sub-fossil peats. At the top of the mire, the monocot. peat is also much

shallower, and contains bands of mineral, orange stained (iron rich?) deposits. Both these cores are located just downslope of the seepage spring obvious today. Core 7 lacks the mineral staining, but the monocot. peat is also very shallow here.

This stage of mire growth represents a reversion to slightly enriched conditions. The relative timing of changes in peat stratigraphy is not known, but it is probable that the relatively shallow depth of monocot. peat with mineral staining has accumulated only slowly, as the peat is humified and existing plant density (and therefore probably productivity) is low in areas affected by similar deposits today. The transition may therefore be contemporary with the change to deeper monocot. peat further downslope. If this is so then it may be that the emergence of a sub peat pipe/ seepage spring, which had contact with mineral ground, increased the supply of nutrients and raised the pH of the mire waters around core 5 and 6. The position of this spring and the slope of the mire would result in an enrichment of the mire waters generally. Certainly the present mire appears to derive most of its moisture from this source and from surface flow from the *Molinia* flush above it (which is probably a related feature), as it is only below the spring that surface patterning occurs, and similar slopes nearby lack patterned mires.

6.4.4 Changes in plant communities and mire conditions

Core 1 has been shown to be one of the deepest peat deposits on this site and also to represent the major changes in mire development indicated from the stratigraphy of the rest of the site. In this section, the intention is to investigate in greater detail the changes in plant communities and mire conditions that took place, mainly by the use of macrofossil analysis, but also by referring to the results of pollen analysis (Chapter 5) and non-pollen microfossils.

6.4.4.1 Macrofossil analysis

The macrofossil data (Figure 6.12) has been divided into six main zones with a total of eight sub-zones. The characteristics of these are described below.

CLA1 366-356cm. Brown moss/base tolerant Sphagna peat
Cyperaceae/*Ranunculus flammula*.

The composition of the peat of this basal sediment is very different to any other stage of the mire's development. *Bryum pseudotriquetrum* is the dominant constituent with *Sphagnum* of sections subsecunda, squarrosa and some acutifolia, particularly at the top of the zone. Monocotyledonous peat forms a maximum of 50% peat. Humification is low. The small trigonous cyperaceae (Type 4) and *Ranunculus flammula* are restricted to this zone and *Potentilla palustris* is most common here. *Carex nigra* type, *Carex* cf.*rostrata* and *Juncus* are all abundant in the basal sediment.

CLA2 356-340cm Base tolerant *Sphagna*/Monocot. peat
Carex nigra/Juncus

Peat composition changes during CLA2 and humification rises slightly. *Sphagnum* is present at between 10 and 25% and the zone appears to straddle the middle of a succession from the lower sect.subsecundum/sect. squarrosa to the upper *S.palustre*/ sect acutifolia, containing a little of both the last two types. The reproductive macrofossils of *Juncus* and *Carex nigra* type are abundant but there are no herbaceous species present. Several unidentified types were recovered.

CLA3 340-220cm Monocot. peat
Viola palustris/Potentilla erecta/Carices

Initially, *S.palustre* is an important peat constituent but monocotyledon remains soon become dominant and subsequent

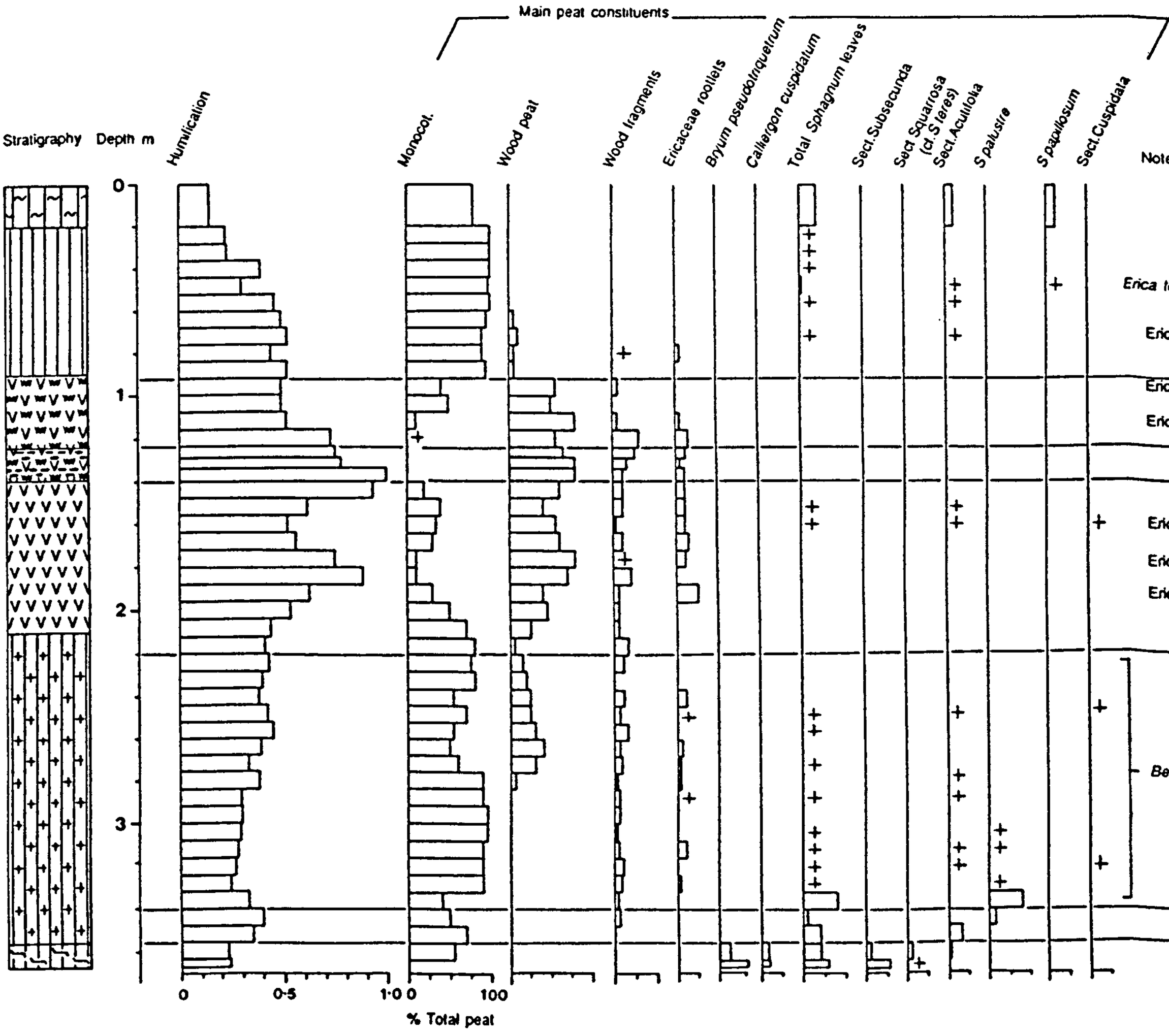


Figure 6.12: Macrofossil diagram for Cross Lochs Fen A, core 1.

Charred remains

Other macrofossils

Notes

Charcoal

Charred *Erica tetralix* leaves

Charred *Calluna vulgaris* leaves

Trigonous Carex

Ranunculus flammula

Potentilla palustris

Carex cf.rostrata

Carex nigra type

Juncus

Viola palustris

Potentilla erecta

Erica tetralix twig

Ericaceae

Encaceae

Ericaceae

Ericaceae

Ericaceae

Ericaceae

Ericaceae

Betula

1340

940

200

0 1 2 3 4

0 200

0 20

0 500

0 10

No./100cm³

Other macrofossils

Carex nigra type

Juncus

Viola palustris

Potentilla erecta

Cenococcum geophilum sclerotia

Eriophorum vaginatum 'spindles'

Enca tetralix

Selaginella selaginoides megaspores

Acanna

Coleoptera elytra

Macrofossil Assemblage Zones

Radiocarbon years bp

CLA6c

CLA6b — 1470±45

CLA6a — 3920±45

CLA5 — 4250±45

CLA4 — 5880±45

CLA3 — 7575±45

CLA2 — 8995±50

CLA1

1340

940

5·6

4·7

5·9

200

0 500

0 10

0 1k 2k 3k

0 400

0 200

0 20

to 284cm woody peat occurs at low %. Wood fragments, mostly of *Betula*, are present throughout the zone. Other *Sphagna* are scattered; sections acutifolia, cuspidata, squarrosa and *S.palustre*. Trigonous Carices (cf. *C.rostrata*) are most abundant during this zone and *Carex nigra* type is of reduced but almost constant occurrence. *Viola palustris* and *Potentilla erecta* are found throughout the zone and *P.palustris* also occurs. *Calliergon cuspidatum* leaves are abundant.

CLA4 220-140cm Fibrous/ woody peat
Erica tetralix/Cenococcum/Juncus/C.nigra

Peat composition during this phase becomes progressively more woody, with little contribution from monocotyledons. The only identifiable fragments were from ericaceae and *Betula* remains were not recovered. Humification peaks in the middle of the zone and then drops again. *Erica tetralix* seeds are abundant until the end of the zone and *Cenococcum geophilum* attains numbers in excess of 5000/100cm^3, coinciding with the peak in humification. *Carex nigra* type and *Juncus* reappear.

CLA5 140-124cm Highly humified peat
Eriophorum vaginatum

The most striking aspect of MAZ CLA5 is the lack of reproductive macrofossils. Humification is very high, especially at the beginning of the zone and the peat is fibrous and woody. The sclerenchymatous spindles of *Eriophorum vaginatum* are the only identifiable macrofossils here. This is not an uncommon occurrence in highly humified peats as they are extremely resistant to decay (Godwin, 1975).

CLA6 124-0cm Charred remains.

This zone is defined by the common occurrence of charcoal and charred leaves of *Erica tetralix* and *Calluna vulgaris*.

There are also infrequent occurrences of charred *Calluna* flowers. It is split into three subzones:

CLA6a 124-92cm Ericaceous peat
Cenococcum geophilum/ Erica tetralix

Humification falls during this zone and this is accompanied by a gradual rise in the % monocotyledonous peat. Wood and ericaceous rootlets are also present and *Sphagnum* is absent. *Erica tetralix* seeds reappear at lower frequencies and *Cenococcum geophilum* reaches numbers in excess of 5000/100cm^3. *Potentilla erecta* and *Eriophorum vaginatum* spindles are present.

CLA6b 92-20cm Monocot. peat
Selaginella selaginoides/Juncus

Monocotyledonous remains form almost 100% of peat during this zone and humification falls gradually towards the surface. Some *Sphagnum* is present, mostly sect. acutifolia with some *S.papillosum*. The main characterising feature of the zone is the high number of *Selaginella selaginoides* megaspores (up to 350/100cm^3) throughout its duration. *Juncus* seeds are also abundant at up to 1300/100cm^3 and charred *E.tetralix* leaves show a marked increase here.

CLA6c 20-0cm Monocot./*Sphagnum* peat
S.papillosum/sect acutifolia

This is a tentative zonation only as it is uncertain exactly what time span this active surface layer (acrotelm) represents and whether its macrofossil composition would change significantly once it had been incorporated into the inert catotelm below. However, the main characteristics are a reappearance of *Sphagnum* peat at 20% and a decrease in *Juncus* and the disappearance of *Selaginella*. The *Sphagna* is of Sect.acutifolia and *S.papillosum*.

6.4.4.2 Non-pollen microfossils

As has been mentioned previously (Chapter 4), the study of microfossils other than pollen is still in its infancy and there are severe limitations on the use of such data in reconstructing past conditions. In addition to the problem of interpretation, there are considerable problems with recognition and identification of some types. However, they are used here as additional information to macrofossil and pollen data.

Figure 6.13 includes all the microfossil types recorded. However, some of the microfossils for which there is appropriate information, can be used as indicator species. Two main groups are recognised in the Cross Lochs A core, those tending to occur in drier conditions and those restricted to mesotrophic conditions, although these categories are not necessarily mutually exclusive. Figure 6.14 illustrates the abundance of total "dry" and "mesotrophic" indicators selected from the microfossil types with the help of Van Geel (1978). The summarised microfossil data (Table 6.2) shows some clear trends which are outlined below.

The lowest part of the profile 366-352cm shows high total numbers of microfossils and those which can be assigned to the major groups are all mesotrophic indicators. From 352 to 304cm total numbers fall but the number of mesotrophic indicators remains high. At 304cm the total number rises and subsequent to this there is a period where mesotrophic and total numbers remain at moderate levels. Dry indicators maintain a constant low presence from 224 to 160cm when numbers suddenly increase as do those of mesotrophic conditions, but these decline suddenly after 144cm. Total numbers and dry indicators continue to rise to a peak at 128cm, with some fluctuations of the latter. Totals and dry indicators then both decline to 104cm after which mesotrophic types reappear at moderate levels. The totals are low and dry indicators have a sporadic occurrence until

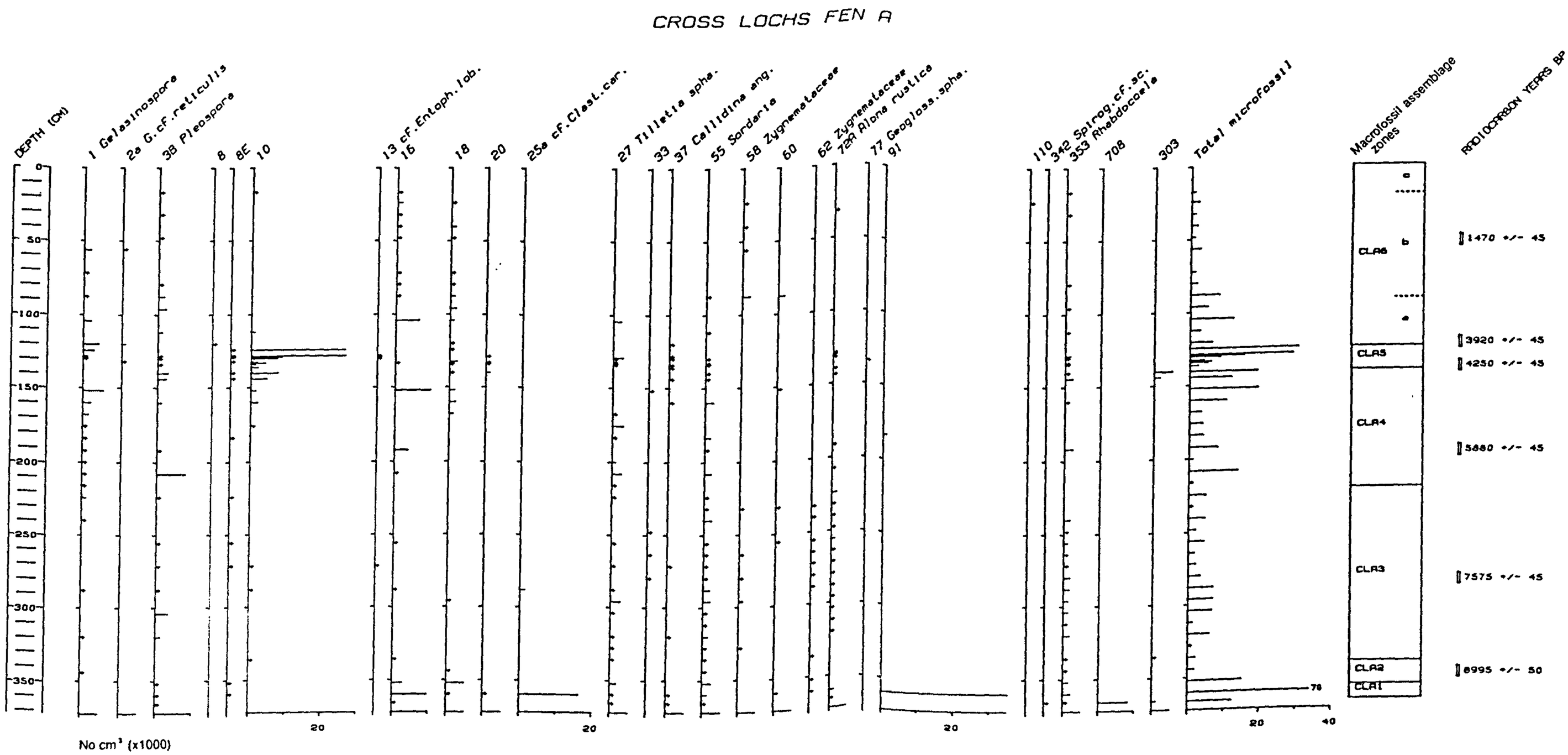


Figure 6.13: Non-pollen microfossil diagram for Cross Lochs Fen A, core 1.

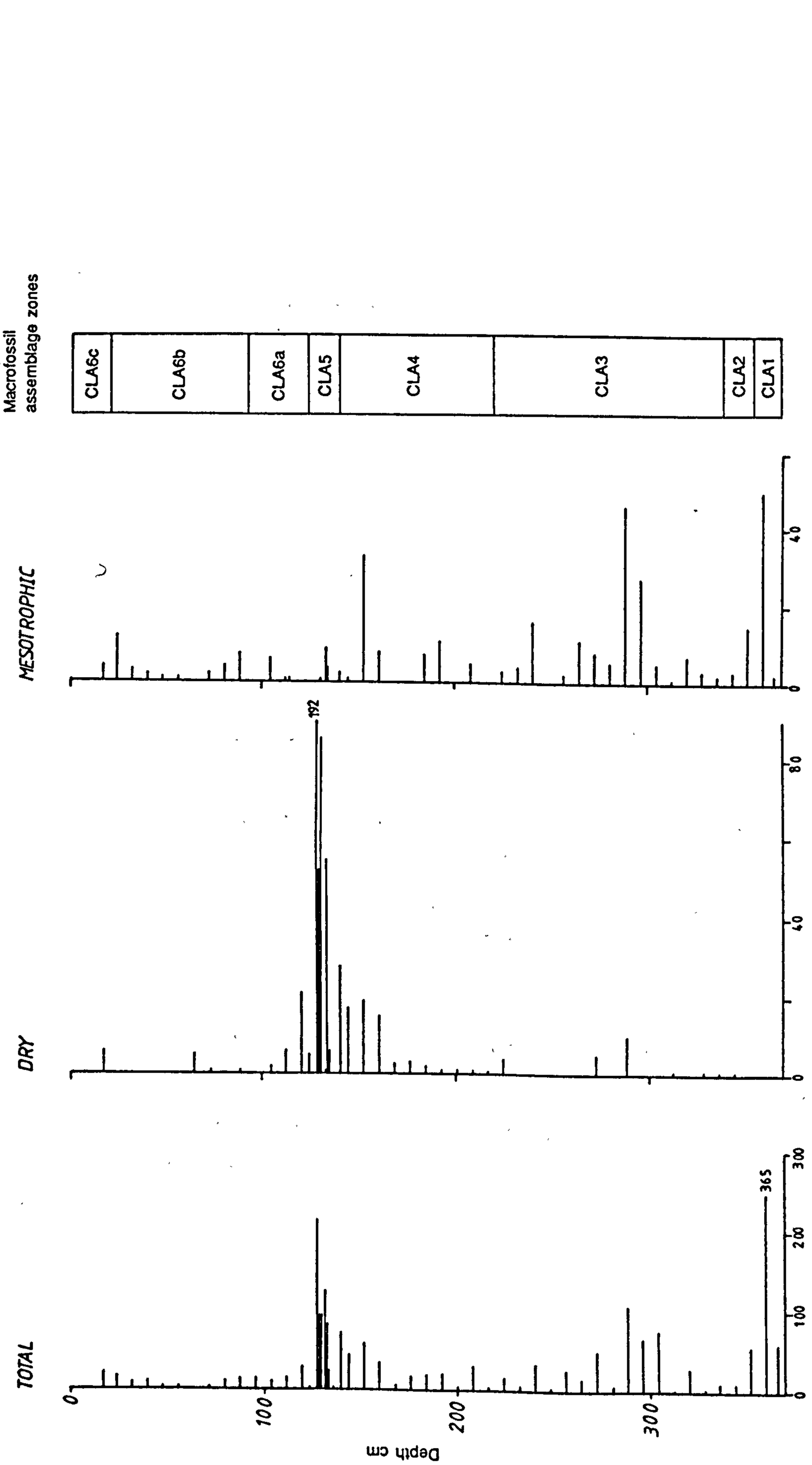


Figure 6.14: Summary of microfossils indicating dry and mesotrophic conditions from Cross Lochs Fen A, core 1.
Dry indicators include Types 16, 25, 55 and 58 (Van Geel, 1978). Mesotrophic indicators include Types 1, 2 and 10,

the present day.

Table 6.2: Summary of trends in microfossil data, using 'dry' and 'mesotrophic' indicators.

Depth(cm)	Characteristics
366-352cm	High numbers mesotrophic indicators and totals.
352-304cm	Low totals - most mesotrophic.
304-224cm	Initial rise and then fall in total numbers but most are mesotrophic types.
224-160cm	Low totals of mixed dry and mesotrophic types.
160-144cm	Rise in totals and of both dry and mesotrophic types.
144-128cm	Large rise in totals - mostly dry indicators.
128-104cm	Decline in total numbers and dry indicators. Low mesotrophic types.
104-0cm	Low total numbers of mostly mesotrophic with some dry types.

The individual types recorded can sometimes provide additional and more detailed information than these generalised patterns. For example, Type 25 (*Clasterosporium caricinum*) is known to grow on the leaves of Carex species, often subject to periodic flooding (Van Geel, 1978). This kind of information will be referred to in the discussion of past mire conditions.

6.4.4.3 Reconstruction of past mire conditions

The three main sources of evidence for past mire conditions and plant communities in the core from Cross Lochs have been described (including pollen - Chapter 5). This section aims to combine all this evidence and suggest how the mire has changed since its inception ca.9400 years ago. For convenience, the macrofossil assemblage zones are used as a basis for this, although it is emphasised that changes are often gradual and so will cross the zone boundaries. Date estimates are based on the radiocarbon chronology.

CLA1 366-356cm ca.9400-9150bp

The earliest sediment has an estimated age, by extrapolation of the radiocarbon dating curve (Figure 5.2), of around 9400bp. However, since the nose of the corer is 10cm long and early accumulation may have been slow, peat was probably forming from the early tenth millennium before present. The macrofossil evidence indicates that the early mire community included a moss carpet composed of species such as *Bryum pseudotriquetrum*, *Calliergon cuspidatum* and *Sphagnum* sect subsecunda, squarrosa and to a lesser extent, acutifolia. *B.pseudotriquetrum* is a common species of fens and flushes with a wide present geographic range (Smith, 1978) Dickson (1973) lists it as having many fossil records in the highland zone and regards it as a possible per-glacial survivor, especially as it is now found well into the holarctic. Of the *Sphagna* branch leaves, sect squarrosa are most likely to refer to *S.teres*, as they are relatively small (<2.2mm) and lack the strongly squarrose habit of the only other member of this group, *S.squarrosa*. In any case, these species differ little in habitat requirements, both occurring in meso- to eutrophic conditions with *Juncus*, *Molinia* or Carices (Daniels and Eddy, 1985). Sect. subsecunda includes five species, several of which are highly variable so that the group is difficult to separate by branch leaf anatomy alone. *S.platyphyllum* is unlikely given its present restricted

range and *S.auriculatum* is excluded on the basis of leaf size. The habitats of the remaining species, *S.subsecundum* and *S.subsecundum* subsp.*inundatum* are generally mesotrophic flushes and *S.contortum* favours eutrophic habitats, subject to considerable enrichment (Daniels and Eddy, 1985). Sect. acutifolia is often assumed to equate with *S.capillifolium* or *S.fuscum* in raised mire peats, all other species being excluded on the basis of habitat preferences (eg Barber,1981). Daniels and Eddy (1985) list eleven European species within this group, none of which can confidently be excluded from consideration here. They vary from mesotrophic fen species to bog hummock formers which could occur as isolated hummocks within fen communities. The occurrence of this group is therefore inconclusive in determining past mire conditions.

The reproductive macrofossils here - seeds of *Ranunculus flammula*, *Potentilla palustris*, *Carex nigra* type, *Carex* cf.*rostrata* and *Juncus*, indicate that the mosses grew underneath a mesotrophic mixed herb and sedge/rush community. The identity of the small trigonous cyperaceae seed, Type 4, remains unknown. The abundance of this and the other carices is reflected in the high values attained by cyperaceae pollen, although this is likely to be partly a function of the regional pollen rain. There may have been some open water for *Myriophyllum alterniflora* to survive with the above species, although perhaps these pollen grains were water transported from a stream or loch further upslope, both habitats being suitable (Haslam et al, 1975). Godwin (1975) gives this species as an example of a late-glacial to early post glacial species. *Betula* extended on to the mire surface towards the end of this zone as vegetative macrofossils were recovered from 360cm (ca.9250bp). Pollen of this genus rises to >20% at this point.

Numbers of non-pollen microfossils are high during this early phase and many of these types are mesotrophic indicators. In addition to those types, Type 708 of Bakker

and Van Smeerdijk (1982), and associated with eu- to mesotrophic helophyte marshes, is found in abundance at 366cm. Type 25a, included in the mesotrophic total, is *Clasterosporium caricinum* a fungi of sedge leaves, often subject to periodic flooding (Van Geel, 1978). Cocoons of flatworms of the order Rhabdocoela (Type 353D) are abundant at 360cm but this is difficult to interpret without specific identification (Van Geel et al, 1981).

The mire community during CLA1 would have been a mesotrophic sedge fen with some herbaceous content and a bryophyte layer of *Bryum pseudotriquetrum, Calliergon cuspidatum* and a number of *Sphagnum* species tolerant of such conditions. Shallow standing water may have been present or the site may have been subject to periodic flooding.

CLA2 356-340cm ca.9150-8800bp

The *Sphagnum* remains during this phase are of sect acutifolia, the limitations of which has been described, and also of *S.palustre* at the end of the zone. The latter is a species of mesotrophic fens and wet woodland or other habitats where there is some, but not excessive, enrichment (Hill, 1978). This, combined with the disappearance of the more nutrient demanding *Sphagna* and other bryophyte species may represent a decline in nutrient status. This would be supported by the demise of the herbs which were present in CLA1. The dominant seed types are *Juncus, Carex nigra* type and *Carex* cf.*rostrata*. The lowered levels of cyperaceae pollen here (20-40%) may be attributable to the loss of Type 4, compounded with a regional decline. Grasses may have briefly been a mire component when gramineae pollen rises from 5 to 15% at 344cm. *Myriophyllum alterniflora* has disappeared from the pollen record which may indicate a succession from aquatic or periodically flooded ground to a drier community which would, however, still have maintained a high water table. Although no macrofossils were recovered from the zone, *Betula* pollen percentages remain as high or

higher than in CLA1. This may be attributable to increases in its abundance around the site. The microfossils during CLA2 are mainly mesotrophic indicators but apart from this generalisation they contribute no further information.

During this zone, then, the habitat became slightly drier and less nutrient rich, perhaps relying more on surface flow rather than ground water. Plant communities would still have been sedge and rush dominated with a ground cover of mesotrophic *Sphagna*, including *S.palustre*, although there would have been few herbaceous plants. Grasses perhaps occupied the site but the status of *Betula* is unclear.

CLA3 340-220cm ca.8800-6400bp

Although *Sphagna* are found throughout the zone, these are of minor importance, apart from an early dominance by *S.palustre*. Other species are scattered and of sections acutifolia, squarrosa (cf *S.teres*) and cuspidata. *Sphagnum* spores are still abundant but this may be a result of differential spore production by different species or to decay of the less resistant vegetative material. Certainly biological differences between species in the timing of spore production occur (Clymo and Hayward, 1982), and capsules from some species have only rarely been recorded (Hill, 1988). The emergence of a rather different mire community is clear here with the disappearance of *Juncus*, but a continuation of *Carex rostrata* and *C.nigra* types. Cyperaceae pollen continues at >10%. Herbs such as *Viola palustris*, *Menyanthes trifoliata*, *Potentilla palustris* and *P.erecta* present in macrofossil and pollen records (except *Viola*) indicate a shift to a more herbaceous community. These generalisations on this zone conceal some minor fluctuations in other species. The pollen record shows that *Succisa pratensis* was present and was especially abundant at the beginning of CLA3. Another addition to the herbaceous flora, this is a species of meso to oligotrophic mire and wet peat soils and is common in the area today.

There is an isolated peak in *Filipendula* pollen (assumed to be *F.ulmaria*) at 312cm (ca.8200bp). No seeds of this species were recovered but with pollen of >35%, it is difficult to imagine that it did not grow very close to, if not actually on the coring site. Although it is most often associated with lateglacial sediments (Godwin, 1975), it occurs commonly today in northern Scotland in peat fens and other wet habitats such as meadows and ditch sides (eg. Valeriano-Filipendulion of Birse, 1980). It would not therefore be an unexpected component of the herb/sedge community described so far, although the reasons for its sudden appearance and subsequent decline, are not clear. Low levels of Gramineae pollen suggest that this group may either have been present in small amounts on the mire or occurred nearby as a component of the regional pollen. Towards the end of the zone (224cm), a large peak of this type (47%) presumably reflects a local increase. Although most of the peat consists of monocotyledonous remains and is probably attributable to the Carices and to Gramineae at the end of the zone, some woody peat and identifiable wood fragments are present from 280cm (ca.7500bp) upwards. These are *Betula* and Ericaceae but with many fragments lacking sufficient features for confident identification. Although pollen counts are relatively low, ericaceae must have occurred on the mire surface for at least the latter part of the zone. The data for *Betula* is difficult to interpret as high percentage pollen figures do not always coincide with macrofossil remains. Macrofossil remains were recovered from depths with as little as 10% TLP. Most of the twigs recovered are small, the largest measuring only 10mm in diameter. Microfossil evidence is inconclusive for this period, but most types can be considered mesotrophic indicators, with some indications of drier conditions at 288 and 256cm in particular.

This zone represents a continuation of a mesotrophic fen community with a return to a significant herbaceous content, albeit a different and more diverse range of species. Peat accumulation was relatively rapid (22.2-

19.3mmyr^{-1}). Dwarf shrubs and *Betula* were present, particularly towards the end of the zone, but were probably of sparse and rather variable occurrence. The plant species and microfossils suggest that the mire may have been slightly drier during this phase.

CLA4 220-140cm ca.6400-4300bp

Major changes are apparent during this phase of mire development. Most of the herbs and sedges encountered during CLA3 disappear except for low amounts of *Potentilla erecta* and *Menyanthes trifoliata* seeds. Cyperaceae pollen falls to negligible values but Gramineae probably occurred on the mire as values are consistently >10%. Increases in *Juncus* and *Carex nigra* type seeds imply a return to conditions similar to those of CLA2 but a number of other factors point to a rather different situation. The monocotyledonous component of the peat declines and wood peat and fragments are more abundant. The woody component is thought to be derived from ericaceous dwarf shrubs, as no remains of *Betula* were found. *Erica tetralix* seeds are present in large numbers and Ericaceae pollen is recorded at low levels at the same time. Records of ericaceous twigs and rootlets are also frequent. Pollen values for *Calluna* show a large increase at this time but may not necessarily be attributable to on site growth. Clearly the ericaceous dwarf shrubs increased over a wide area during this zone with *Erica tetralix* actually on the mire surface. This is reasonable in view of its greater tolerance of waterlogged conditions (Bannister, 1964).

During this zone accumulation rates decrease to an estimated 0.34mmyr^{-1} and humification rises to a peak at 180-188cm (ca.5500-5750bp), shortly after a peak in *Cenococcum geophilum*. The black sclerotia of this species are more often found in soils (Van Geel, 1978) although they have been recorded in raised mire peats (Van Geel, 1972) under dry, ombrotrophic conditions. It is known to be a facultative mycorrhiza of a number of tree species in

various soils. Its occurrence here is suggestive of much drier conditions and its tree host may have been *Betula* or ericaceous shrubs. Although no reference can be found to dwarf shrub hosts, it seems likely that this is possible as it is also found later in the profile when there were certainly no trees species present. Sclerenchymatous spindles of *Eriophorum vaginatum* occur towards the top of the zone. Microfossil evidence largely confirms these indications of macrofossils and pollen with increasing frequency of dry indicator types. An interesting feature of the microfossils here is the occurrence of type1 (*Gelasinospora*) which increases steadily up to 152cm and then disappears from the microfossil record. While this is generally regarded as a "dry" indicator (Van Geel, 1978) it may be possible for the mire to be too dry for it to survive so that in this case the optimum conditions are reached at 152cm (ca.4550bp).

CLA4 was a drier phase of mire development, with perhaps some acidification of the peat and mire water. A community containing *Erica tetralix*, *Juncus* and *Carex nigra* type sedge developed and conditions became suitable for species such as *Eriophorum vaginatum* and *Empetrum nigrum*. *Betula* continued to grow on the mire surface.

CLA5 140-124cm ca.4300-3950bp

Macrofossil evidence is sparse here but the ericaceous peat and *Eriophorum vaginatum* spindles suggest that a community of this species and ericaceous dwarf shrubs and forming highly humified peat was present. Possibly the dwarf shrubs included small amounts of *Empetrum nigrum* as pollen of this genus occurs here. The pollen evidence also suggests that *Pinus sylvestris* grew locally (48% TLP max) and it may have grown actually on the mire surface, although there is no macrofossil evidence for this. As discussed in Chapter 5, decay rates may have been too rapid to allow preservation of *Pinus* macrofossils, and the relatively rapid peat accumulation ($0.49 mm yr^{-1}$) is probably a result of high

input of dead organic material. However, macrofossil remains, including cones, have been recovered from elsewhere in the district (AJ Gear, pers.comm), but these may be from locally favourable conditions, as they do not appear to be widespread. It seems unlikely that other tree species, such as *Betula*, were present, despite their % pollen figures being depressed by the overwhelming abundance of *Pinus*.

Microfossils show that the surface would have been even drier during this phase than in CLA4. Dry indicators, and particularly Type 10 dominate this zone and achieve very high levels. Type 10 is a fungus of *Calluna vulgaris* and so perhaps reflects abundance of this species which in turn reflects dry, more acid conditions on mires. Type 18, which occurs here, has been found to correlate with remains of *Eriophorum vaginatum* (Van Geel, 1978). This is supported in this case as it occurs abundantly at the same levels as the sclerenchymatous spindles of that species.

This zone represents an extreme drying out of the mire surface and the immigration and increase of plant species associated with dry, ombrotrophic mires. This is accompanied by the invasion of pine close to, or actually on, the mire surface.

CLA6 124-0cm ca.3950-0bp

The abundance of charcoal and charred fragments of ericaceous species in this phase suggests burning on the mire surface. Charcoal was also found in CLA4 in slightly smaller amounts and also occasionally in CLA2 and CLA3. This increase in burning may be attributable to man but whether or not he was responsible for the demise of pine is another problem. Unfortunately it is impossible to know the frequency of fires from the data available but it seems unlikely that natural fires from lightning strikes would produce this quantity of charcoal. A full discussion of anthropogenic influences on the area will be covered in

later discussion (Chapter 8). Peat accumulation is low (0.29-0.35mmyr^{-1}), and this includes the acrotelm, suggesting a long term figure below this. This may be in part also due to burning, reducing the total biomass input to the peat body.

CLA6a 124-92cm ca.3950-2850bp

This is a transition zone between the shrub dominated, dry mire which formed highly humified peat during CLA5 and monocotyledonous peat and wetter surface conditions of CLA6b. *Cenococcum geophilum* reappears with very high numbers (>5000/100cm^3) as does *Erica tetralix*, reflecting a return to wetter, but not very wet, conditions. Peat composition changes gradually from highly humified wood peat and fragments to moderately humified monocotyledonous with little or no fibrous or wood content. Pollen data suggests there may have been a minor element of *Empetrum nigrum* in the vegetation and that Gramineae and Cyperaceae returned to the mire. *Calluna* pollen remains high but there is no macrofossil evidence for its occurrence on the mire except ericaceous wood which may be attributable to *Erica tetralix*, which certainly was present. Perhaps *Calluna* was dominant in the surrounding vegetation as the contribution to the pollen sum from other sources is very small as *Pinus* finally declines to <5% as do all tree taxa. Microfossil evidence confirms the trend of increasing wetness as dry indicators decline almost to zero and mesotrophic indicators increase slightly.

CLA6b 92-20cm ca.2850-?600bp

Clearly marked in pollen and macrofossil diagrams at the beginning of the zone is the occurrence of *Selaginella* on the mire surface. Godwin (1975) notes this species as abundant in lateglacial deposits but it is also present in a wide range of habitats in the north today. In mires it prefers meso- to eutrophic conditions. *Cenococcum geophilum* is largely absent from this zone and *Erica tetralix* is much

reduced. This indicates greater surface wetness and this is supported by increases in pollen of Cyperaceae and Gramineae and almost 100% monocotyledonous peat. Reproductive macrofossils of these groups are rare or absent at all levels. Perhaps this is indicative of the establishment of a grass and sedge community similar to that of today. In this, *Carex lasiocarpa* and *Molinia caerulea* appear to only rarely produce seeds and so are unlikely to be represented in the fossil record. Some indications of a decline in nutrient status are apparent from the lack of herbaceous species, only *Potentilla erecta* is present in the pollen record. In addition to this *Sphagnum* sect. acutifolia and *S.papillosum* occur here. From 56cm upwards Coryloid pollen is abundant (up to 35%). Much of this was referred to *Myrica* (Figure 5.7), and some vegetative remains were found so that this probably indicates the localised spread of this species onto the site. Although *Myrica* occurs on oceanic ombrotrophic blanket mires, it is not normally abundant and its occurrence here again indicates an oligo-mesotrophic community. This coincides with a large increase in *Juncus* seeds which continues to the present day. The only species of *Juncus* on the mire today is *J.bulbosus* although *J.effusus* grows about 400m upslope. The former seems the most likely source of seeds.

It seems that grasses and sedges became the dominant peat formers during this zone although *Erica tetralix* maintained a presence. *Selaginella selaginoides* indicates slight enrichment of the mire waters and *Juncus* (probably *J.bulbosus*) and *Myrica gale* became important after 56cm confirming this oligo-mesotrophic mire status.

CLA6c 20-0cm ca.?600-0bp

The extrapolated date for the start of this zone is almost certainly too early. This is because almost the whole of the zone is within the acrotelm, and has therefore not been subject to the same decay processes as the catotelm below,

from which the dating estimate is based by extrapolation. It is likely that it represents only the last 200 years growth.

The tentative zonation is marked by decreases in *Selaginella* which is present in the pollen record but not as macrofossils and *Juncus*. *Selaginella* has not been noted from the site in recent survey work. *Sphagnum papillosum* is a significant peat former and this may indicate the start of a drop in nutrient status as although this species is tolerant of slightly raised nutrient levels, it is also associated with more oligotrophic habitats in Britain.

The reconstructed changes in mire conditions indicate the changes occurring at a single location within the mire. Early changes must be considered extremely localised, probably applicable to only a small area metres or tens of metres across at the most. Later changes to drier, more acid conditions from 6400 to 2850bp are probably applicable to wider areas. Existing fen communities only seem to have developed since ca.2850bp when peat cover was complete and these changes are likely to have been more widespread across the area of the present mire surface. Present directions of water flow would probably have developed by this time.

6.4.5 Implications and discussion

The investigation into development of Cross Lochs 'A' provides a basis for examining the application of the original ideas on patterned fen development generally, shown in Table 6.1, to Scottish patterned fens in particular. The Cross Lochs patterned fen is clearly not a primary peatland formed directly on mineral ground, nor has it formed after a brief period of paludification of drier, soils, bearing woodland. It does appear that peat spread from at least one initial nucleus in a water collecting area, but this does not seem to be critical to the later extent of the poor fen. There is evidence to suggest that

the extension of the peat body proceeded gradually upslope, presumably by the process of 'back-paludification', but this is again not critical to the much later growth of the present poor fen community. Equally, although there are two underlying gulleys, these run in different directions to the present water flow and the existing features of the mire are unrelated to the underlying topography, so it appears that patterned fens do not necessarily develop within enclosed mineral based valleys. The development of patterned fens between already established peat masses is more plausible, but the implication of Lindsay *et al* (1988) was that it would still develop over mineral ground, at least at the deepest point, where the original watercourse ran. It therefore appears that while some of the ideas demonstrated to be the case in other similar mire systems, or derived from speculation, may have occurred earlier in the initiation and extension of the peat body, they are not important in the subsequent formation of the patterned fen system as seen today.

Instead, the results of this initial investigation allow a set of suggestions for the major developmental characteristics of Scottish patterned fens to be put forward. These are:

i) Mire growth may begin with an initial peat nucleus and extend outwards from this, but this is not necessarily related to the occurrence or characteristics of a contemporary patterned fen.

ii) A recognisable hydroseral succession may follow from this, with a progression to fen and then bog peats, but this is also unrelated to subsequent patterned fen development.

iii) The poor fen systems are recent (ca.2850bp) developments, which may overlie extensive earlier peat deposits of an ombrotrophic character.

iv) The sites have developed as a result of localised hydrological changes within the underlying peat body and mineral base, resulting in increased volume and quality of the water supply. This is probably by the development and emergence of sub-peat pipes at the head of a suitable slope.

In order to test the wider applicability of these suggestions, much simplified investigations were undertaken on three additional sites. The emphasis is on stratigraphic description of gross changes, with macrofossil analysis to provide further detail on the nature of changes in vegetation and to confirm the stratigraphically deduced changes.

6.5 CROSS LOCHS 'B'

6.5.1 Site description

This site is part of the mire complex around the Cross Lochs, and its general position is shown on Figure 5.1. It is situated only 1km to the north west of Cross Lochs 'A', still on the eastern side of the summit area. Figure 6.15 is a more detailed map of the site and its environs. The poor fen lies in a shallow valley, sloping approximately south to north, with a short, steep slope to the west and sloping ombrotrophic blanket mire to the east. The southern and eastern blanket mire becomes part of the patterned ombrotrophic mire studied in Chapter 8, and the two sites, considered separately here, are strictly part of the same 'macrotope' (*sensu* Ivanov, 1981). At the head of the mire, there is a small loch, from which descends a diffuse flushed zone. There is no obvious spring like that found at Cross Lochs 'A', but there are other, more minor seepage zones along the base of the western slope. A series of swallow holes occurs at the foot of the poor fen area, and further down the valley, this underground water course emerges as a small stream, eventually reaching the river

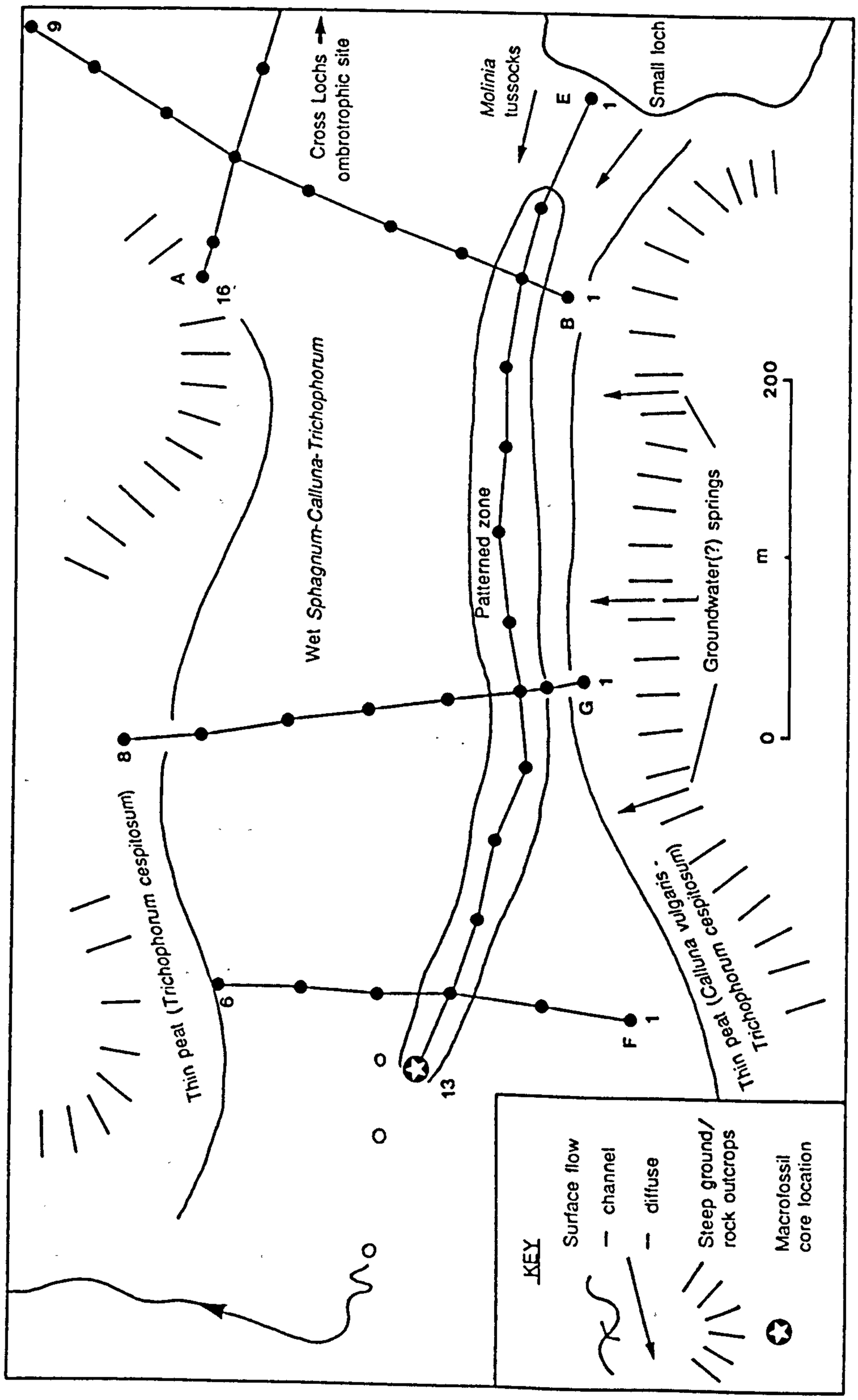


Figure 6.15: Main site features and location of core transects at Cross Lochs Fen B.

Halladale. As demonstrated in Chapter 3, the vegetation of the main patterned area is relatively nutrient poor in comparison with other patterned fen sites. This is displayed particularly by the pool vegetation, which is generally of the *Sphagnum auriculatum* nodum. Ridge vegetation is mostly of the 'typical' nodum, but often possesses relatively sparse tall sedge growth, particularly in the lower mire area. The flushed zone at the head of the mire contains *Carex rostrata* and merges into a tussocky *Molinia* dominated community close to the loch edge. The steeper ground to the west is mainly *Trichophorum cespitosum*, with occasional patches of *Calluna vulgaris*, while the bog to the east is a *Calluna-Trichophorum* mire with *Eriophorum angustifolium*.

6.5.2 Mire morphological development

The location of the four transects of peat depths and cores is also shown in relation to the other features in Figure 6.15, and a three dimensional scale diagram, gives an indication of the overall site surface and sub-peat topography (Figure 6.16). The stratigraphy of some of the cores on these transects is shown in Figures 6.17, 6.18 and 6.19.

The present longitudinal profile is as envisaged from fairly cursory examination and description, with an almost uniform, low overall gradient, increasing slightly at the top and bottom of the site, where patterning ceases to occur. The transverse sections however, reveal that the patterned fen area is not within the lowest part of the valley, but is at the same or slightly higher altitude than adjacent blanket mire of a more ombrotrophic nature.

Sub-peat topography indicates that there were several localised depressions on the periphery of the present mire area (B4, E13 and E1 to a lesser extent), and that there is a deeper area of peat to the east, in the main valley. The existing site has developed over the sloping sides of the

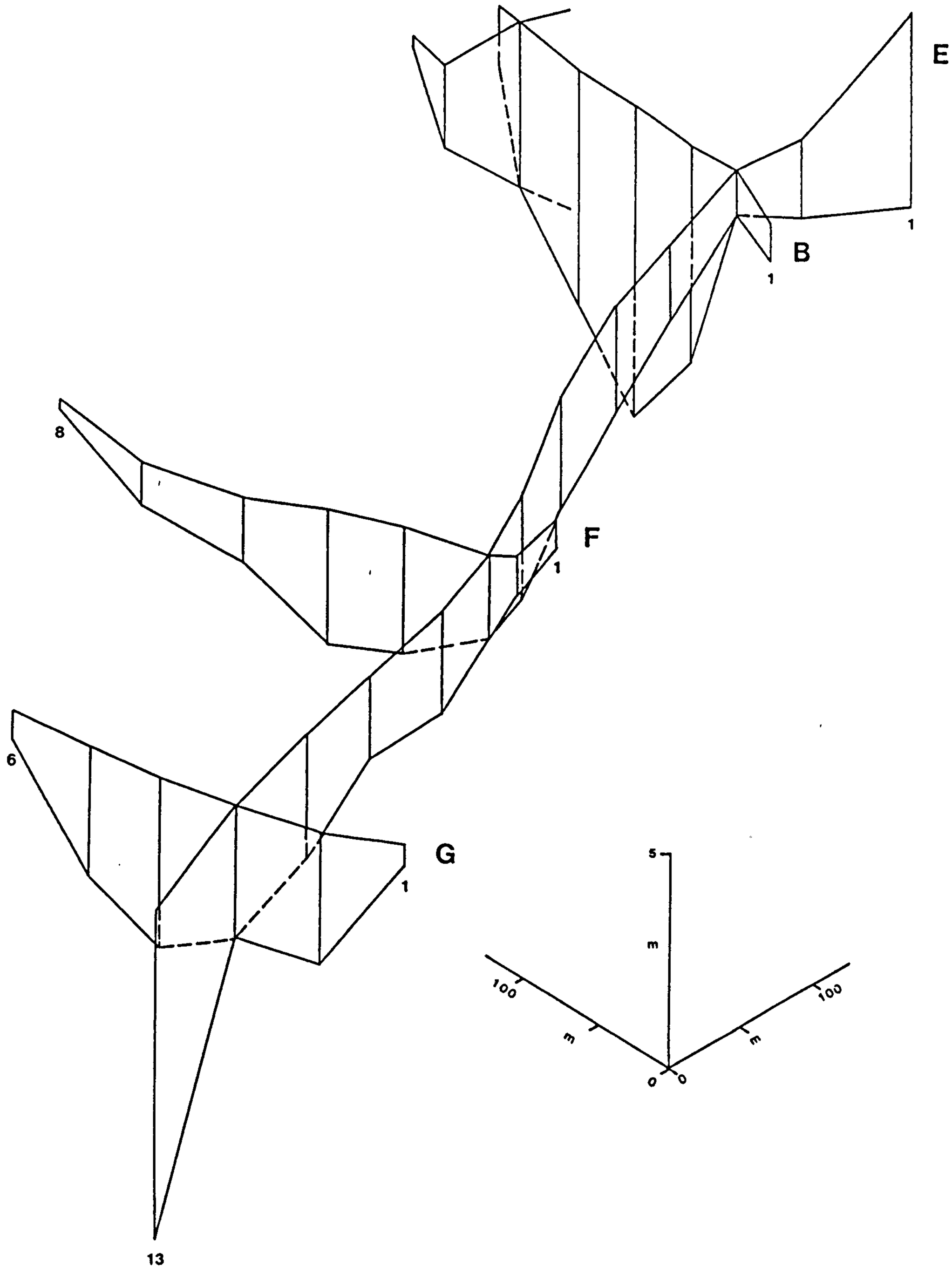


Figure 6.16: Three dimensional plot of peat depths for Cross Lochs Fen B.

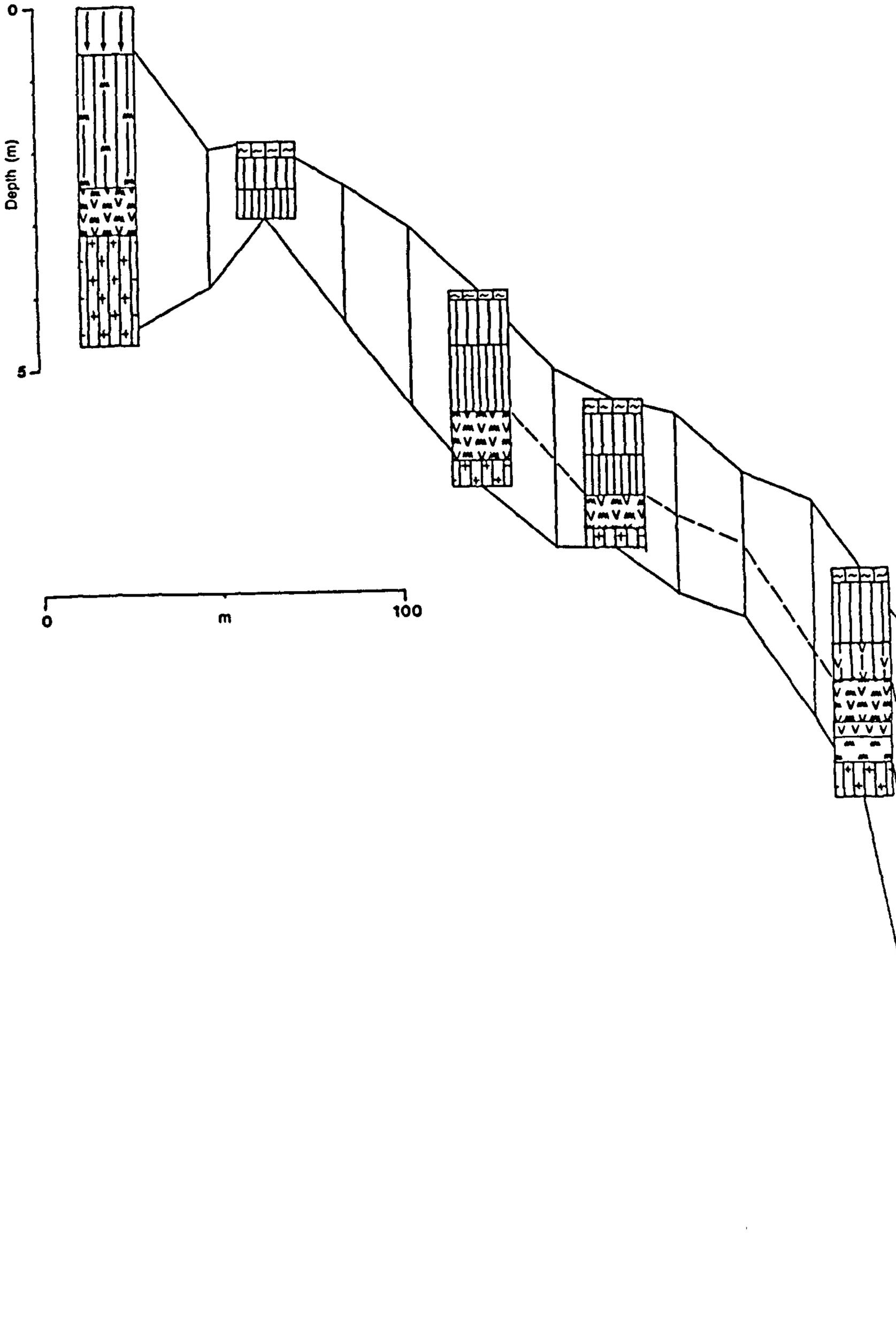


Figure 6.17: Stratigraphy of transect E at Cross Lochs Fen B.

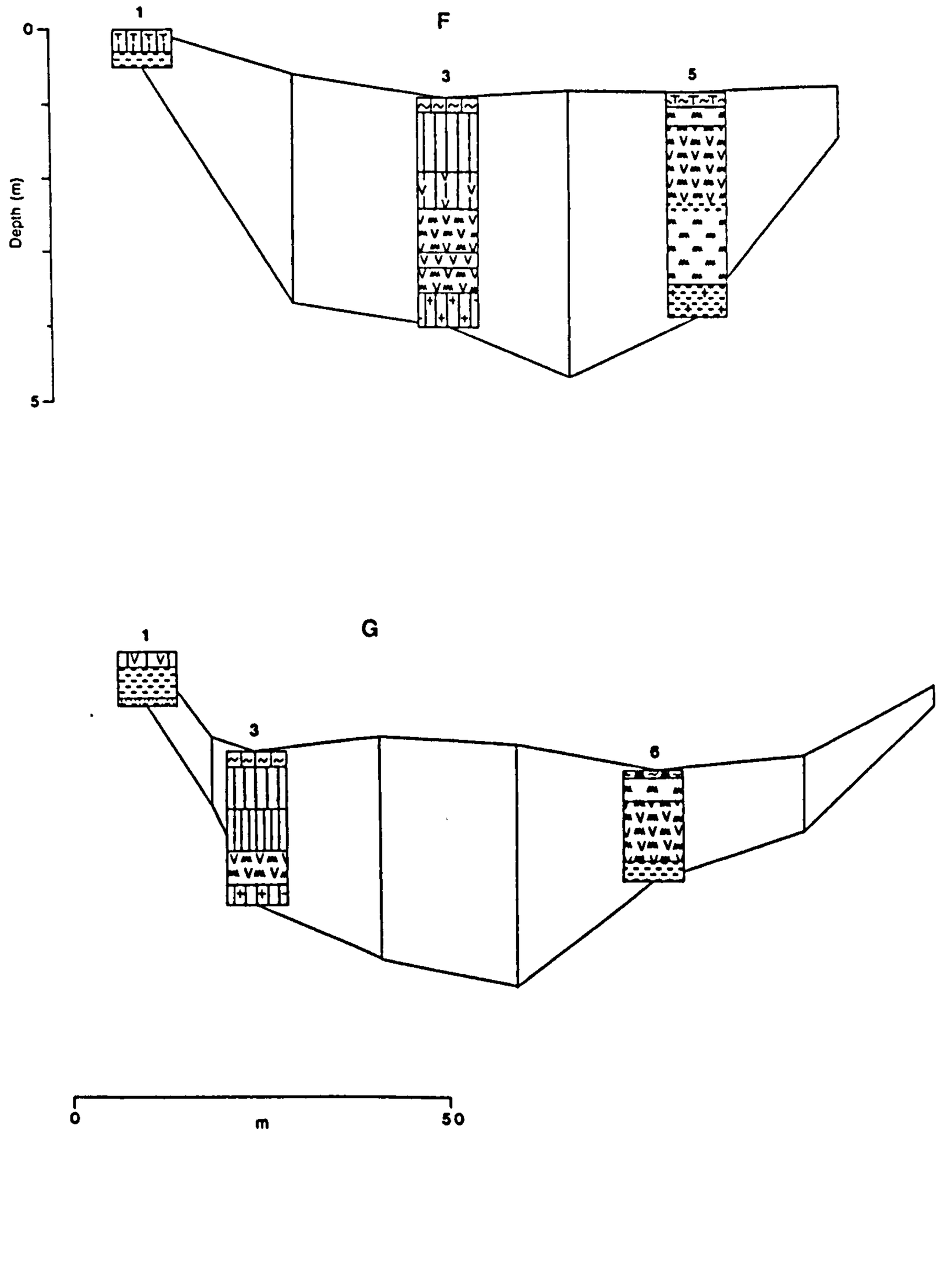


Figure 6.18: Stratigraphy of transects F and G at Cross Lochs Fen B.

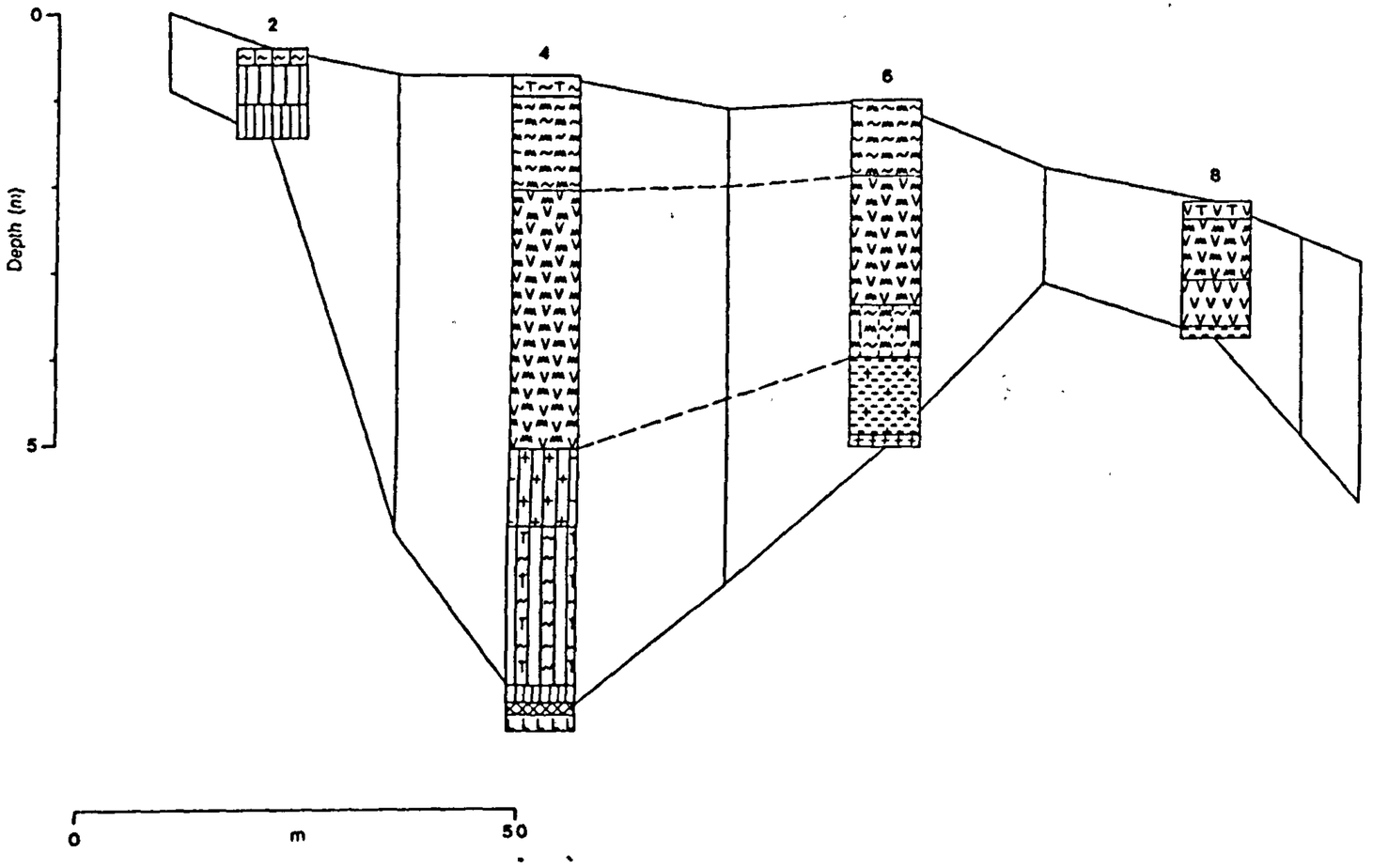


Figure 6.19: Stratigraphy of transect B, covering part of Cross Lochs Fen B and part of the ombrotrophic mire site (see Chapter 8).

pre-peat valley, and peat depths over the main site area are shallow.

In the deepest depressions there were water bodies, sedimentation occurring throughout the Lateglacial (Chapter 5), and once these had infilled, they were replaced with monocot. communities, with birch. These communities also occurred within other, shallower depressions underlying the patterned fen site, sometimes forming dense, impenetrable peat, dominated by quite large birch remains (E10). This is overlain by *Eriophorum* and ericaceous peats in many places, but this is not quite so clear as at Cross Lochs 'A', and monocot remains are still abundant at several locations. The relationship of the basal *Eriophorum*/ericaceae peats further east is not clear but these appear to have started growth after the birch/monocot. peat. Subsequent to this there is an increase in monocot., in all poor fen cores examined, which continues to the present day. Such a change is not evident in the peats underlying existing blanket mire vegetation, although the deep core at B4 contains monocot. material throughout its length.

6.5.3 Community change

The core used for macrofossil analysis is E13, at the foot of the mire, where a deep depression is found. This holds the longest record of change and appears from the stratigraphy to be representative of changes on the rest of the mire, although much of the peat elsewhere probably did not begin growth until the upper levels of E13. For this reason, only the top 5m of the core have been sampled for macrofossil analyses. Pollen analysis, as part of the work described in Chapter 5, involved counting some samples from these levels, but this is inadequate for dating control of most of the top 5m of deposits. However, some approximate dates are referred to below. The macrofossil diagram (Figure 6.20) has been divided into six macrofossil assemblage zones, from which plant community change has been inferred.

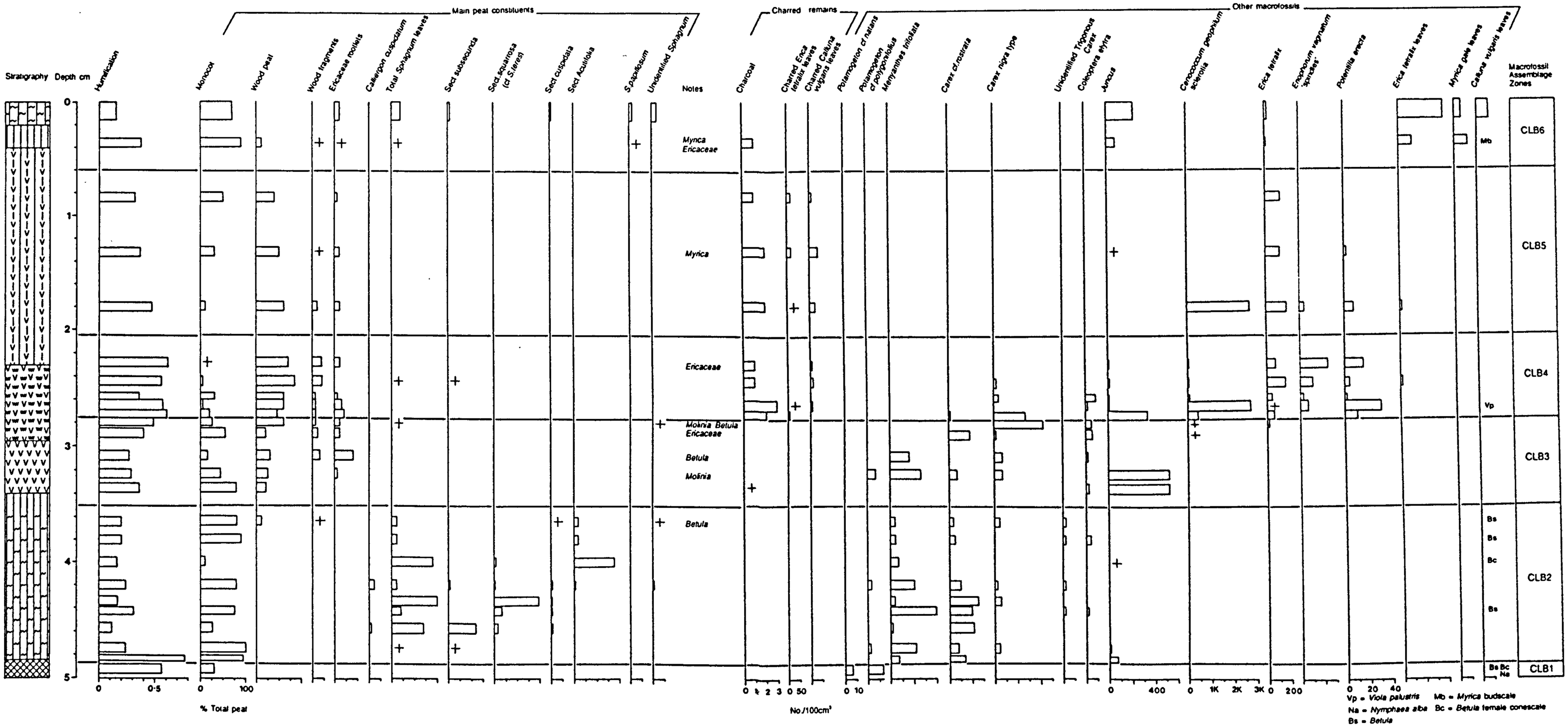


Figure 6.20: Macrofossil diagram for Cross Lochs Fen B, core E13.

CLB1 500-480cm

This represents the closing stages of lake infill, where there is still lacustrine mud, mixed with monocot. remains and with seeds of *Potamogeton* cf.*natans* and *P.polygonifolius*. There are also some unidentifiable fragments of dicotyledons and a seed and scale of *Betula* (cf.*pubescens*). This was probably a shallow water community of sedge and pondweed swamp, with birch growing close by. This occurred sometime during the early part of the *Betula-Corylus* pollen zone, probably between 9000 and 8000bp.

CLB2 480-350cm

Stratigraphically, this is a complex section of the core, but this variability is shown to represent only fluctuations in the quantities and species of *Sphagnum* present. All samples are indicative of various *Sphagnum*-monocot. communities. After the initial transition sample at the base of the zone, humification values are low and accumulation rates were probably high, 130cm peat in around 1000-1500 years, a rate of around 10 years per cm. The peat is dominated by monocot. roots, but this is replaced by narrow bands of almost pure *Sphagnum* peat in some places. These include species of section subsecunda, squarrosa, acutifolia and cuspidata. The possible specific identities of the first three of these groups have been discussed in 6.4.4 and the same reasoning applies here, Sect.squarrosa is probably *S.teres*, on the basis of leaf size and morphology and sect. subsecunda may be one of a variety of mesotrophic species. Theoretically, sect.acutifolia could refer to any one of eleven species, with varying habitat requirements. However, the dominance of this type in the three uppermost samples, immediately before CLB3, an assemblage indicative of somewhat drier conditions, suggests that it may be one of the hummock forming species, such as *S.subnitens* or *S.russowii*. *S.capillifolium* and *S.fuscum* could occur as isolated hummocks, but would be unlikely in a generally mesotrophic fen, as they are essentially species of ombrotrophic mires. *Menyanthes trifoliata* and carices occur constantly throughout this

zone, the latter representing species of the *Carex nigra* group and *Carex.cf.rostrata*.

This zone is comparable with CLA3, but lacks evidence of local growth of *Betula*, although several seeds and scales were recovered. However, the other macrofossils indicate that the area was probably too wet for *Betula* to grow at the core location, although it must have been present outside of the immediate depression. It is likely that birch wood found in the lower parts of other cores on the site is contemporary with this zone. This would imply that sediment accumulation was beginning outside of the major aquatic hollows at this time (up to ca.7000bp).

CLB3 350-276cm

This zone retains some of the characteristics of CLB2, but *Sphagnum* disappears and more fibrous, woody peat is encountered. This is derived from *Betula* and ericaceous species; larger, identifiable fragments of both being recovered from the same samples. *Juncus* shows a marked peak at the beginning of the zone and there are frequent *Carex nigra* type seeds towards the end of the zone.

This indicates a drying of the mire surface with the invasion of birch and ericaceous species, a not unsurprising hydroseral succession. These drier surface conditions were probably present at other better drained locations on the mire surface already. At E13 this occurred between about 7000 and 6000bp.

CLB4 276-204cm

At the beginning of this zone, the fen species decline severely and the monocot. component of the peat is reduced to negligible levels, being replaced by amorphous ericaceous peat, roots and twigs. *Erica tetralix* seeds and sclerenchymatous 'spindles' of *Eriophorum vaginatum* occur indicating the ombrotrophic nature of the mire and *Cenococcum geophilum* occurs at high levels early on, indicating drier conditions. *Potentilla erecta* seeds are

common and this must have been a frequent associated species. Charcoal is found abundantly and constantly above 276cm indicating local burning and this may be associated with the change in community composition and the decline of *Betula* in particular.

This change occurs in most places across the mire, although it does not appear to be quite as clear cut at all locations.

CLB5 204-60cm

The division between CLB4 and CLB5 is indistinct and therefore it is indicated as a gradual transition. This makes this change difficult to detect in stratigraphic examination, particularly as it occurs over such a long section of core, covering several individual 50cm sections. However, there is a clear change back to monocot. peat over this zone, with a corresponding decline in ombrotrophic indicators of all kinds. There are generally few reproductive macrofossils, but charcoal remains common, with charred leaves of *Calluna vulgaris* and *Erica tetralix*. This represents the gradual establishment of a poor fen community, replacing the ombrotrophic mire vegetation which had colonised the site and is a change that is found in all the cores from the main poor fen area.

CLB6 60-0cm

Ultimately, the surface peats are almost entirely monocot., but there is also a return of *Sphagnum* species (*S.papillosum*, sects. cuspidata and subsecunda), with *Juncus*, *Selaginella* and a number of leaves of dwarf shrubs; *Erica tetralix*, *Calluna* and *Myrica gale*. Again there are obviously problems in interpreting surface peats, but this does seem to indicate rather different, possibly slightly more acid, conditions than existed previously. Certainly *Sphagnum papillosum* occurs over most of the fen ridges today.

6.5.4 Conclusions

Stratigraphic and macrofossil data suggests early peat growth began in the early Holocene in water collecting locations, as an apparently natural hydroseral process. A fen flora with birch occupied such locations, where the water table was sufficiently low. Ombrotrophic peat is found above this and further peat spread takes place as this type of mire spreads laterally, although probably not over the whole of the mire surface. Poor fen peats then spread again and the existing area of this mire type develops. Recently, there may have been a reversion to somewhat more acid conditions.

The findings show good agreement with those from Cross Lochs 'A', indicating that poor fen development is a relatively recent occurrence, and that the peatland has also undergone many earlier changes. Although there is no obvious source of groundwater at the head of the mire, there is clearly some flushing effect from the loch, possibly from surface water runoff at times of high water. There are, however, several possible groundwater sources at the base of the steep western slope and the proximity of the site to this feature, rather than simply occurring in the lowest part of the valley, suggests that such springs may be important in the maintenance of the fen system.

6.6 RHIFAIL LOCH

6.6.1 Site description

Rhifail Loch lies approximately 15km WSW of the Cross Lochs study area, about 1km from the B871 Kinbrace to Syre road. At the southern end of this small loch is a small patterned fen. The main features are shown in Figure 6.21, with the positions of the survey transects and core locations. It measures about 300m by 180m, having a total area of around 5ha. In terms of general appearance, the mire is surrounded by either quite steeply sloping blanket peatland or rock

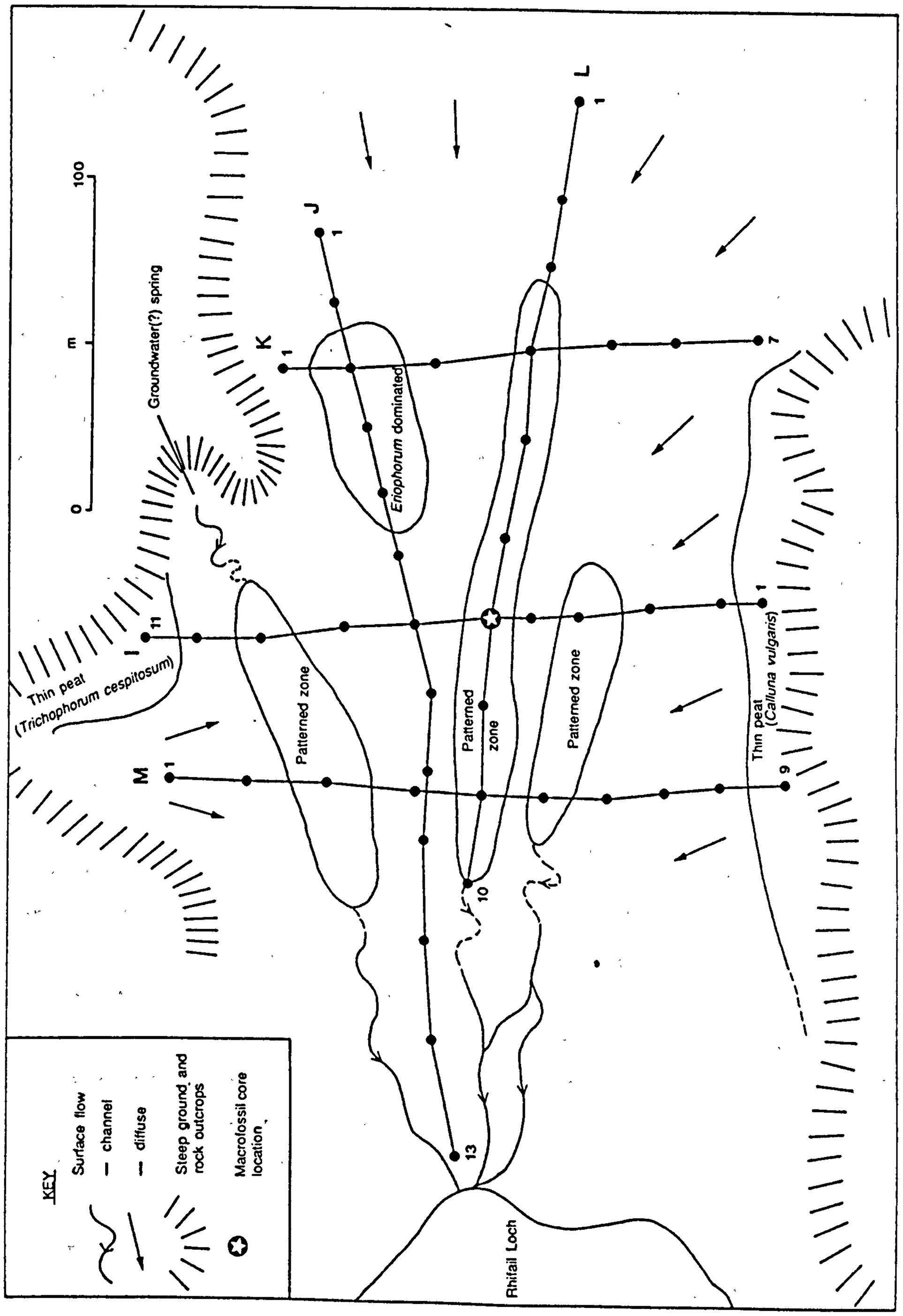


Figure 6.21: Main site features and location of core transects at Rhifail Loch Fen.

outcrops, particularly to the west, with Loch Rhifail at the northern end. The site is therefore within a present day basin, and slopes approximately south to north. The most striking feature of the mire is the arrangement of surface pattern, which occurs as three distinct areas of pools and ridges. These form long, thin patterned zones running down the main slope and almost converging towards the bottom of the mire. All these patterned zones merge into permanent (?) channels lower down the slope, eventually draining into Rhifail Loch itself. There appears to be a spring at the top of the most easterly of the patterned zones, but the only indication of inflow into the other two, are small areas of flushed vegetation, shown by the occurrence of abundant *Carex rostrata* and *Molinia caerulea*. Present vegetation of the patterned zones is mostly within the *Pleurozia-Potentilla* nodum, with several pool communities, generally lacking *Sphagnum auriculatum*. The vegetation is approximately centrally placed in the inter-site range of variation (See 3.4.7). The surrounding slopes are dominated by *Trichophorum cespitosum* or *Calluna vulgaris* on the western, rocky areas.

6.6.2 Mire morphological development

The sub-peat topography was investigated by means of five transects, shown in Figure 6.21. Only three of these were used for stratigraphic work, as these appeared to sample most of the variability of the present vegetation and included the deepest (and probably therefore oldest) parts of the site. The two longitudinal transects were intended to represent a central patterned zone and one of the intervening areas showing weakly flushed, otherwise ombrotrophic, blanket mire vegetation. The sub-peat topography is shown in Figure 6.22 and the stratigraphic data is shown for each transect in Figures 6.23, 6.24 and 6.25.

The pre-peat site consisted of a basin, sloping approximately south to north towards Rhifail Loch. While

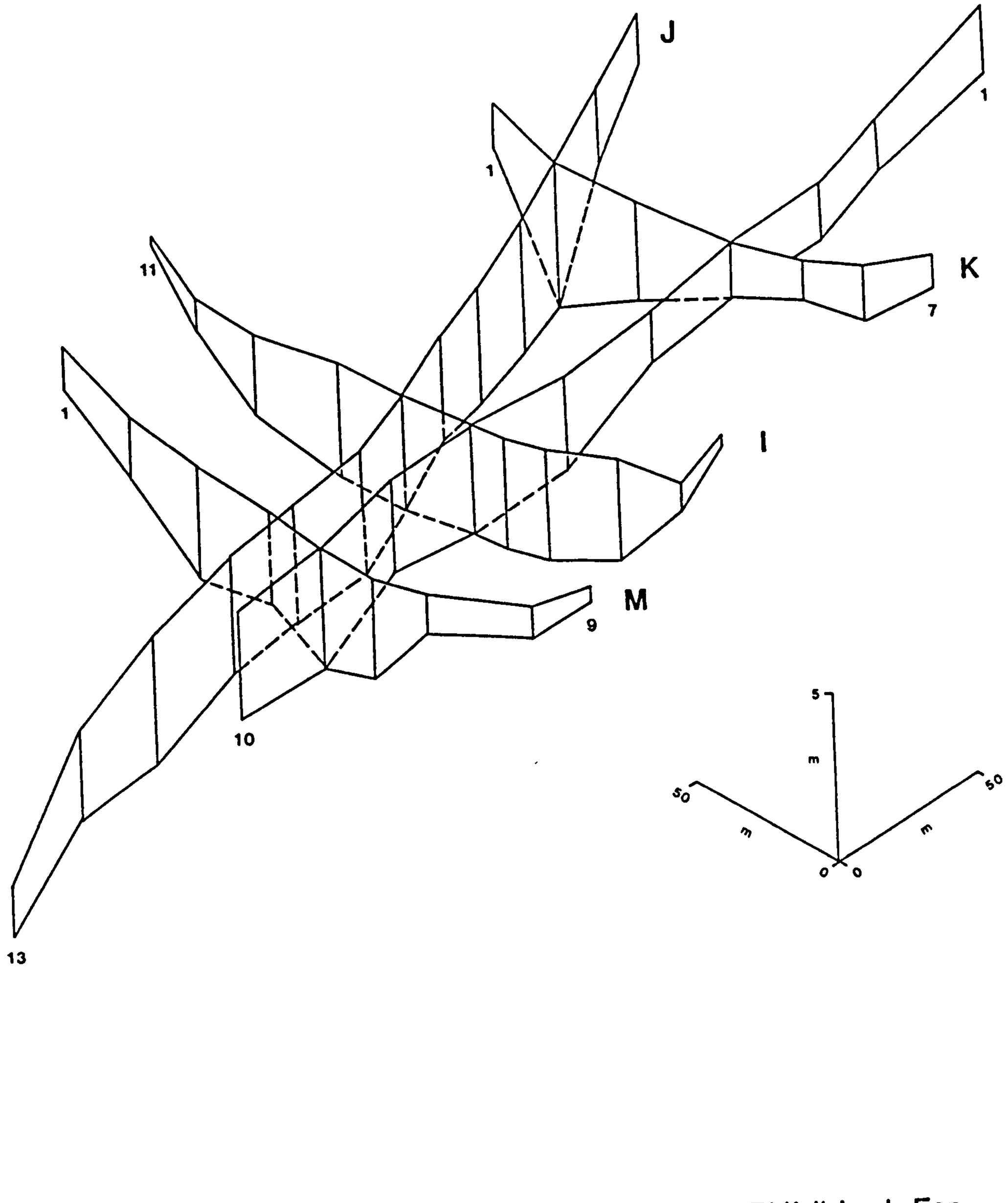


Figure 6.22: Three dimensional plot of peat depths for Rhifail Loch Fen.

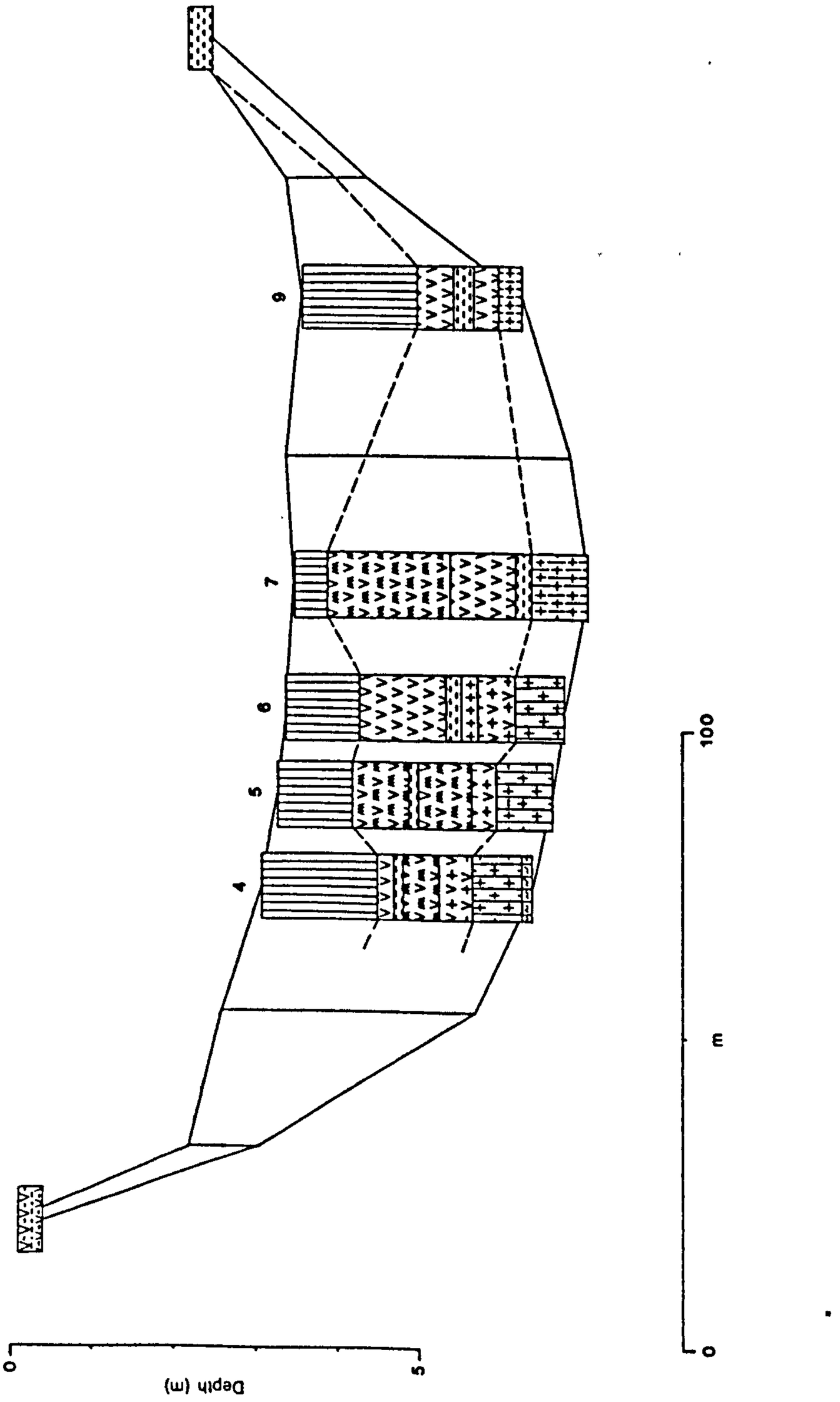


Figure 6.23: Stratigraphy of transect I at Rhifail Loch Fen.

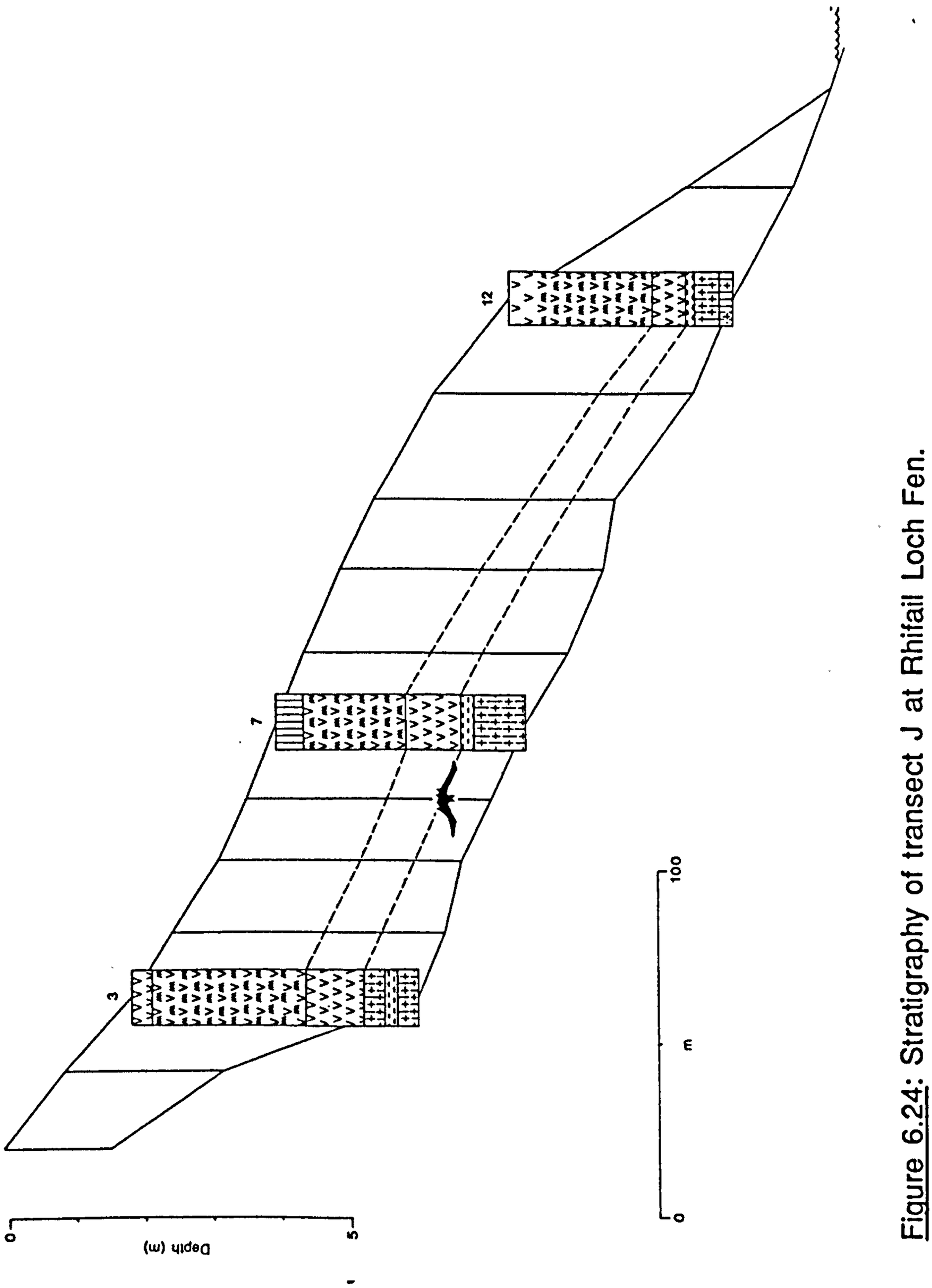


Figure 6.24: Stratigraphy of transect J at Rhifail Loch Fen.

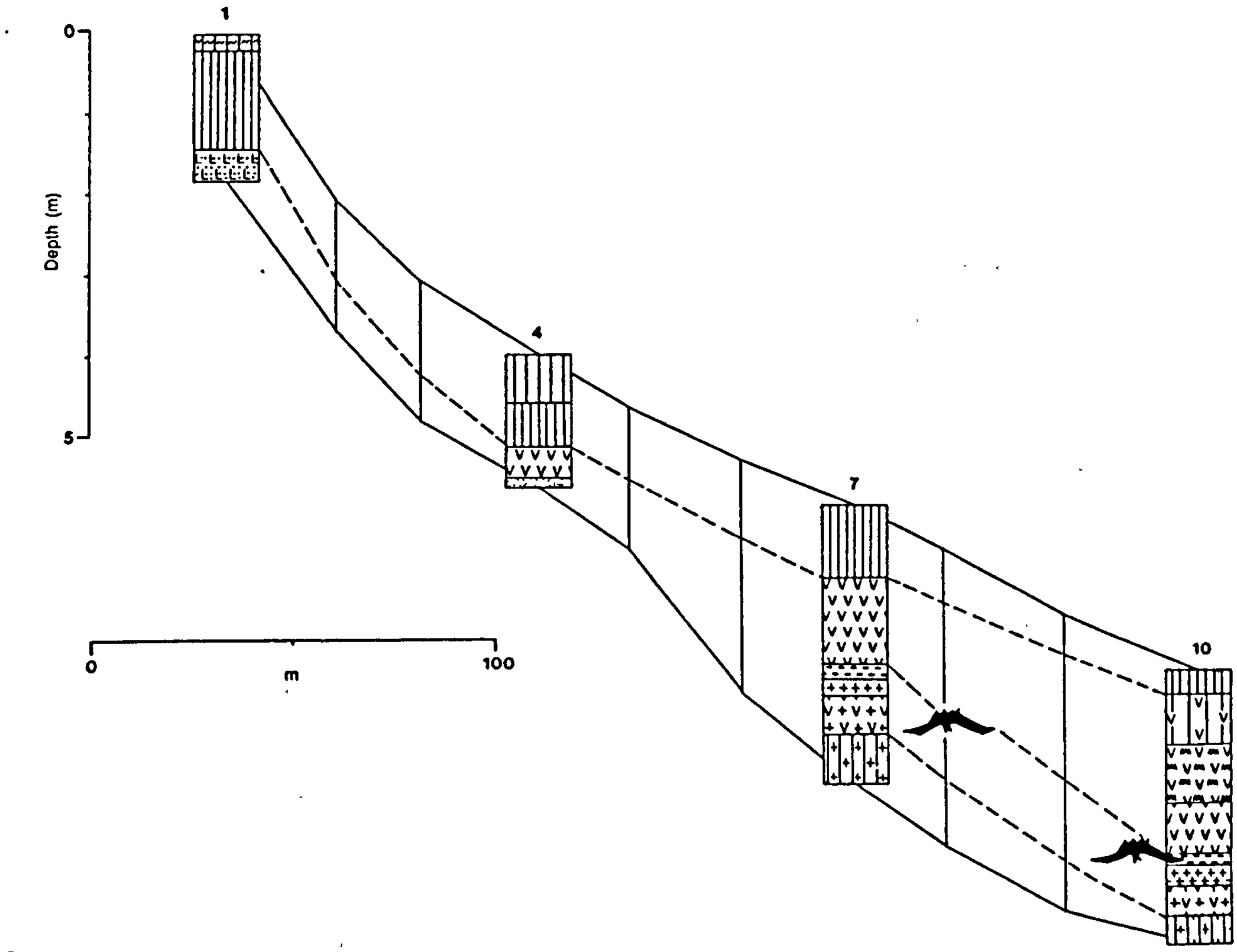


Figure 6.25: Stratigraphy of transect L at Rhifail Loch Fen.

there was apparently a slightly deeper area of the upper valley at K2, there does not seem to be any obvious area of water collection. The deeper peats all have basal deposits rich in remains of birch, usually twigs of no more than 2cm in diameter. This is normally within a matrix of monocot. root material, but it was not always possible to confidently identify the more highly humified remainder of the peat constituents.

The peat changes to ericaceous and/or *Eriophorum* peat above this, and birch ceases to occur. Some of this peat type is found at the base of the shallower peat cores, usually underlain by highly humified material. Two of the cores (L8 and J6) were initially thought to be relatively shallow, when the corer hit an impenetrable obstruction. However, when the stratigraphic profiles were drawn up, these appeared to be anomalously shallow and if the data were accepted, would represent localised steep sided 'bumps' in the sub-peat surface. However, they occur approximately at a level where large pieces of *Pinus* wood and roots were recovered and it seems likely that at these two locations, larger, impenetrable pine stumps occurred. This suspected pine layer occurs across the whole of the site, apart from in the shallow marginal peats.

The site then shows some divergence of development. The peat at the top of transect L (core 1) shows some evidence of pine at the very base but this is overlain by pure monocot. peat, as is the pine zone in the next core downslope (L4). This is also occurring at I4, representing the furthest west of the three patterned zones. Other cores all have some growth of ombrotrophic type peat above the pine zone. This appears to represent the start of the growth of the present poor fen complex. Poor fen peats occur in the top metre of all other cores located within present patterned zones with well developed poor fen vegetation. Transect J is largely composed of *Eriophorum* peat above the pine layer, although this is beginning to show some change in the surface peats and *Molinia caerulea*

(an indicator of water movement where it occurs in increased abundance) occurs throughout this area today. It would appear that the area of poor fen is spreading to these intervening remnants of ombrotrophic mire and that the patterned areas occur where poor fen has existed for longest, so that these may also spread in the future. The relationship of the main deep peat area to the extremely shallow (ca.30cm) marginal peats is enigmatic.

6.6.3 Community change

The core used for macrofossil analysis was located at the intersections of transects I and J. The results of the analysis are shown in Figure 6.26. The diagram has been split into six zones, RHI1 - RHI6. These are described below, together with the inferred changes they indicate.

RHI1 333-312cm

The peat from the base of the core is composed largely of *Sphagnum* stems, with a small proportion of leaves of the same genus. This was mostly of Section acutifolia, with some *S.papillosum*. There is small amount of monocotyledonous and wood peat also. The only other vegetative remains were a few leaves of *Calliergon cuspidatum*. A relatively small number of *Juncus*, *Viola palustris* and trigonous *Carex* seeds were present with a megaspores of *Selaginella selaginoides*.

This assemblage probably represents an early bryophyte flush, dominated by *Sphagnum* species, with *C.cuspidatum*, and a herb layer containing a variety of poor fen species, including those already named. Although in ombrotrophic mires *Sphagnum* sect.acutifolia is normally referred to *S.capillifolium* or *S.fuscum*, the stratigraphic position and associated species make these unlikely. There are a number of poor fen species within this group that are more plausible, such as *S.subnitens*, *S.russowii*, *S.warnstorfii*, *S.fimbriatum* and *S.girgensohnii*, all of which can be found in mesotrophic fen habitats (Smith, 1978). Quite large

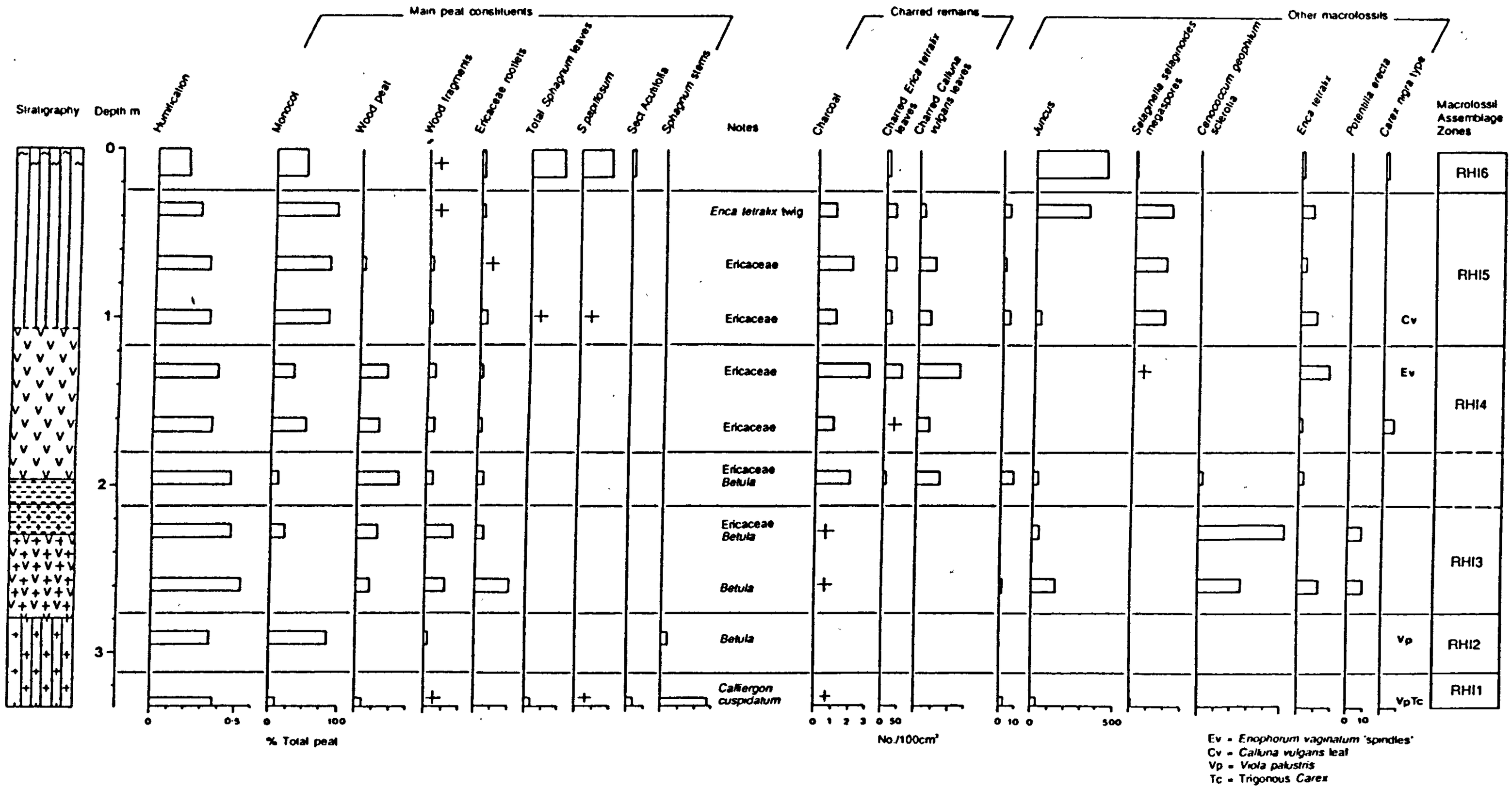


Figure 6.26: Macrofossil diagram for Rhifail Loch Fen.

amounts of decayed *Sphagnum* leaves were found in the 125um fraction and this, combined with the relatively high frequency of stem material suggests that much of the *Sphagnum* peat has decayed.

RHI2 312-276cm

This zone shows a change to the sort of conditions indicated by the stratigraphy, with peat dominated by monocotyledonous remains with some *Betula* wood. This probably indicates a sedge and grass fen with birch. *Viola palustris* and *Juncus* remained present.

RHI3 276-212cm

This phase of peat growth indicates a distinct change in the plant communities. The majority of the peat is made up of woody remains, either as fibrous peat or identifiable twigs of ericaceous species or *Betula*. *Erica tetralix* seeds are present indicating that this was one of the ericaceous plants present and suggesting the maintenance of relatively wet conditions, despite the rise in humification and the change to dwarf shrub communities. This may be a hydroseral successional change to more acid, possibly ombrotrophic conditions. There were, however, other plants present, including *Potentilla erecta* and *Juncus*. *Cenococcum geophilum* may have been growing in association with the roots of *Betula* and/or the ericaceae and perhaps it is only absent from other levels because of rather wetter conditions.

RHI4 212-116cm

The main feature here is the occurrence of abundant charcoal remains, which continue to occur almost until the present day, and the disappearance of birch remains. Some of the charcoal is identifiable as leaves of *Calluna* and *E.tetralix*. The transition stage RHI3/RHI4 shows features of both main zones, with abundant charcoal, but also with at least some *Betula*. The plant communities are dominated by ericaceous species (including *E.tetralix*) and monocotyledons (probably *Eriophorum angustifolium* and some

E.vaginatum). Humification values are slightly decreased. The more diverse herbaceous flora of RHI3 disappears, possibly associated with the burning or a change to more acid conditions.

It seems likely that the onset of local burning affected immediately adjacent, perhaps drier areas of birch scrub and dwarf shrub communities at first (RHI3/RHI4), but that shortly afterwards, the mire at the core location was also burnt and any remaining birch was eliminated.

Although no direct evidence of the suspected pine stratum (ca.170cm) was found during this zone, this perhaps not surprising, as it has already been shown (Chapter 5) that this was probably a short lived event in this region, and the samples have large gaps between them. In addition to this, there was no macrofossil evidence of pine at Cross Lochs 'A' where local presence can be shown from pollen data. It may be that the highly humified transition zone (RHI3-4) represents this period, when it is likely that the mire surface was drier than at any other time.

RHI5 116-24cm

From the beginning of RHI5, the peat is dominated by remains of sedges and grasses and ericaceous plants form only a minor component and again include *Erica tetralix*. Burning continues and the charred remains include *Calluna* and *E.tetralix* leaves. *Selaginella* megaspores are abundant.

This clearly indicates enrichment and possibly increased wetness on the mire surface, with a reversion to poor fen conditions, shown particularly by the occurrence of *Selaginella*.

RHI6 24-0cm

The surface peats are very different to any that are found below, possessing 50% *Sphagnum*, mostly *S.papillosum*, with the remaining peat being sedge and grass (*Molinia*) roots. *Juncus* seeds are abundant and *Selaginella* declines. Despite

problems of interpretation of an assemblage which is not yet fully incorporated into the catotelm, this appears to indicate recent acidification.

6.6.4 Conclusions

The site is relatively simple in terms of sub-peat topography, and there is only a short phase of early fen-moss peat growth in the deepest area. A poor fen with birch was widespread in the basin, but later changed to an ericaceous bog community, apparently by hydroseral succession, as there is no evidence of burning until after this process has begun. A further drying of the mire surface allowed pine to colonise the surface. Poor fen communities similar to the present only develop in the top 1.2m of peat and there is apparently some acidification in the top 20cm. Areas retaining essentially ombrotrophic vegetation do not show this reversion in the top 1.2m, but appear to undergoing similar changes at the moment.

The same general sequence of peat types exists here as occurs for Cross Lochs 'A' and 'B', although the Rhifail stratigraphy is much clearer and less complex. It is particularly interesting because there is evidence that adjacent bog areas are undergoing a change similar to that found in the stratigraphy of all three sites around a metre below the surface. The role of groundwater springs is less clear but the eastern patterned zone is associated with a present day spring and the others have incoming water supplies, indicated by flush vegetation, running off relatively thin peat.

6.7 NORTH ALTNAHARRA

6.7.1 Site description

This site is the furthest west of those sampled, being 30km WSW of the Cross Lochs study area. It is located next to the A836 Lairg to Tongue road about 2.5km north of Altnaharra. The main site features and transect lines are shown in Figure 6.27. The site initially appears to be a small (300x160m) valley mire, sloping approximately north to south, and surrounded by short but steep slopes, with only a thin peat covering and occasional rock outcrops. However, on closer inspection, the vegetation is clearly divided into long, very low ridges and intervening shallow pools, much less obvious than many other patterned fen sites. This patterning is concentrated in the central area of mire but also occurs to some extent in two other places. The water source feeding the mire is clear, there being a stepped channel in the narrow part of the valley at the northern end, which becomes diffuse and finally disappears as it enters the patterned area. There appear to be two drainage outlets, one of which has been straightened and converted to a drainage ditch at the south western end of transect N, and the other a more diffuse seepage running into the ditch next to the road at the south eastern end of transect O. As discussed in Chapter 3, the Altnaharra site displays rather different vegetation to all other sites in that study. The flushed areas at the head and bottom of the mire are dominated by *Molinia caerulea*, but the patterned mire surface is almost uniform in its vegetation, which is the most nutrient rich found in this work (3.4.7). This is mostly *Schoenus* or *Campylium stellatum-Carex* ridge, with rather shallow pools, always with *Utricularia intermedia*.

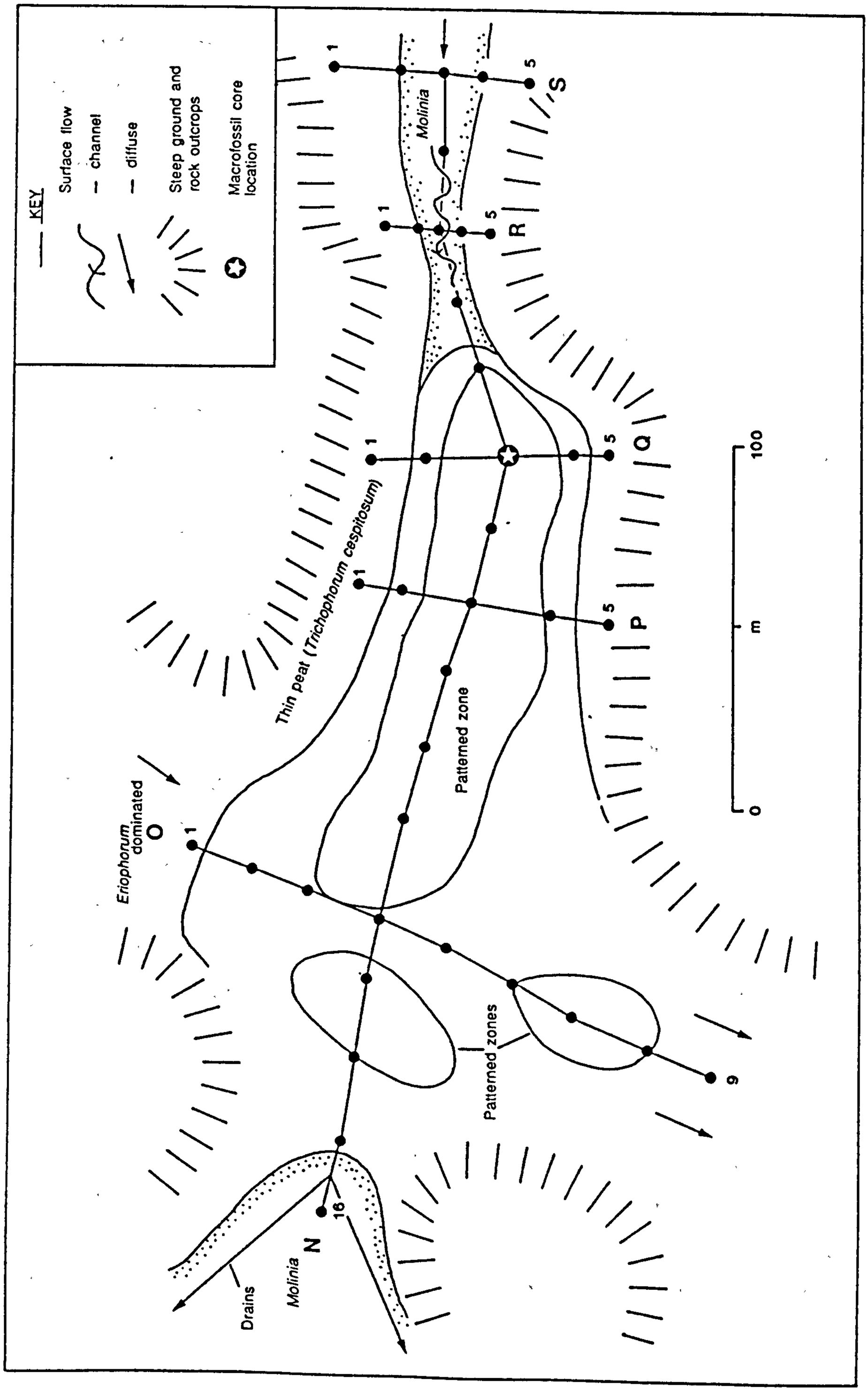


Figure 6.27: Main site features and location of core transects at North Altnaharra Fen.

6.7.2 Mire morphological development

Six transects were used for survey on this site (Figure 6.27), but only three of these were cored for stratigraphic examination. The peat depth data is presented in Figure 6.28 and results of stratigraphic analysis in Figures 6.29 and 6.30.

Prior to peat growth the site consisted of a narrow gulley at the top of the site, underlying the present day, *Molinia* dominated flushed zone at the head of the mire. This widened out below to form a more gently sloping valley, eventually sloping down to the south and south east. There appears to have been a slight depression, or at least a flattening of the contours, around the intersection of transects N and Q.

It is at this point that the earliest peat probably started to form, although there is no easily differentiated peat at the base of this core (but see below). The deeper peats appear to be differentiated by the presence of rhizomes of *Phragmites australis*, although this nowhere forms an appreciable proportion of the total peat composition. The species occurs only at low density on the mire today. Apart from this observation, the peat varies little in gross composition and it appears that the vegetation has been similar throughout the whole of the mire's existence.

6.7.3 Community change

Macrofossil analysis was performed on a core from the intersection of transects N and Q and the results of this are shown in Figure 6.31. The macrofossil diagram, in common with the site stratigraphy as a whole, varies relatively slightly, although it does point to some differences undetected by examination of gross peat composition. The core is divided into three main zones, ALT1 - ALT3.

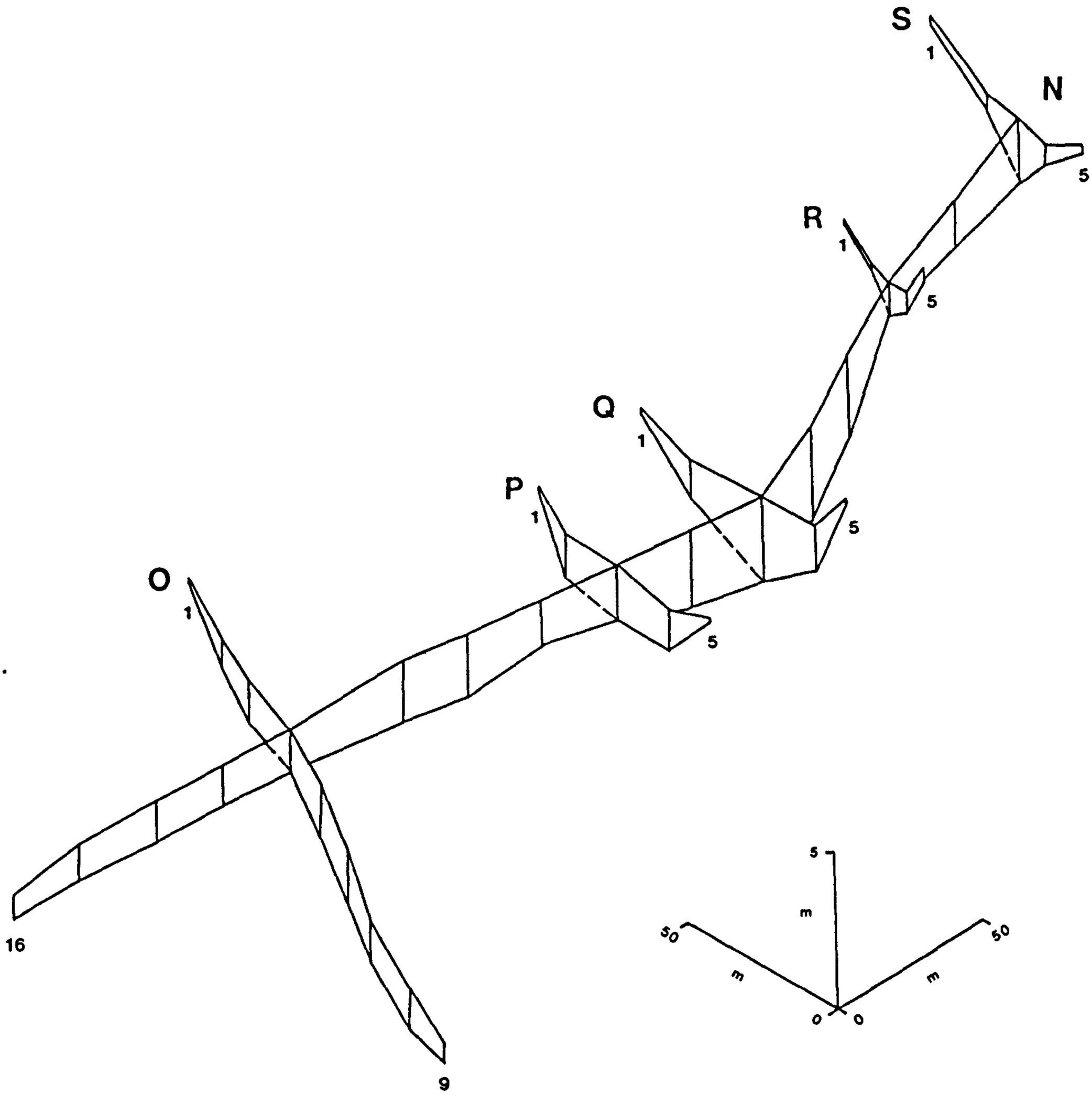


Figure 6.28: Three dimensional plot of peat depths for North Altnaharra Fen.

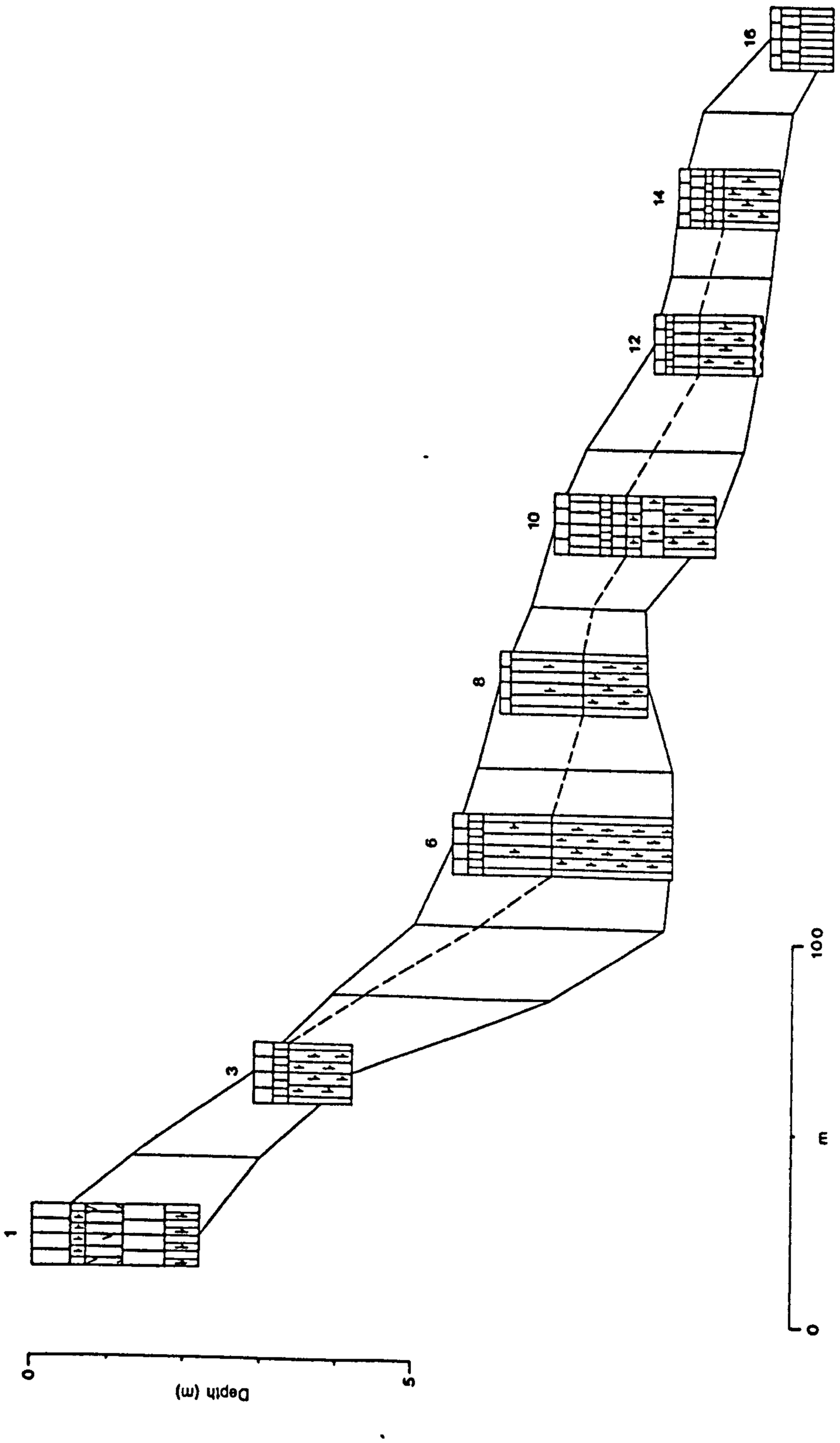


Figure 6.29: Stratigraphy of transect N at North Altnaharra Fen.

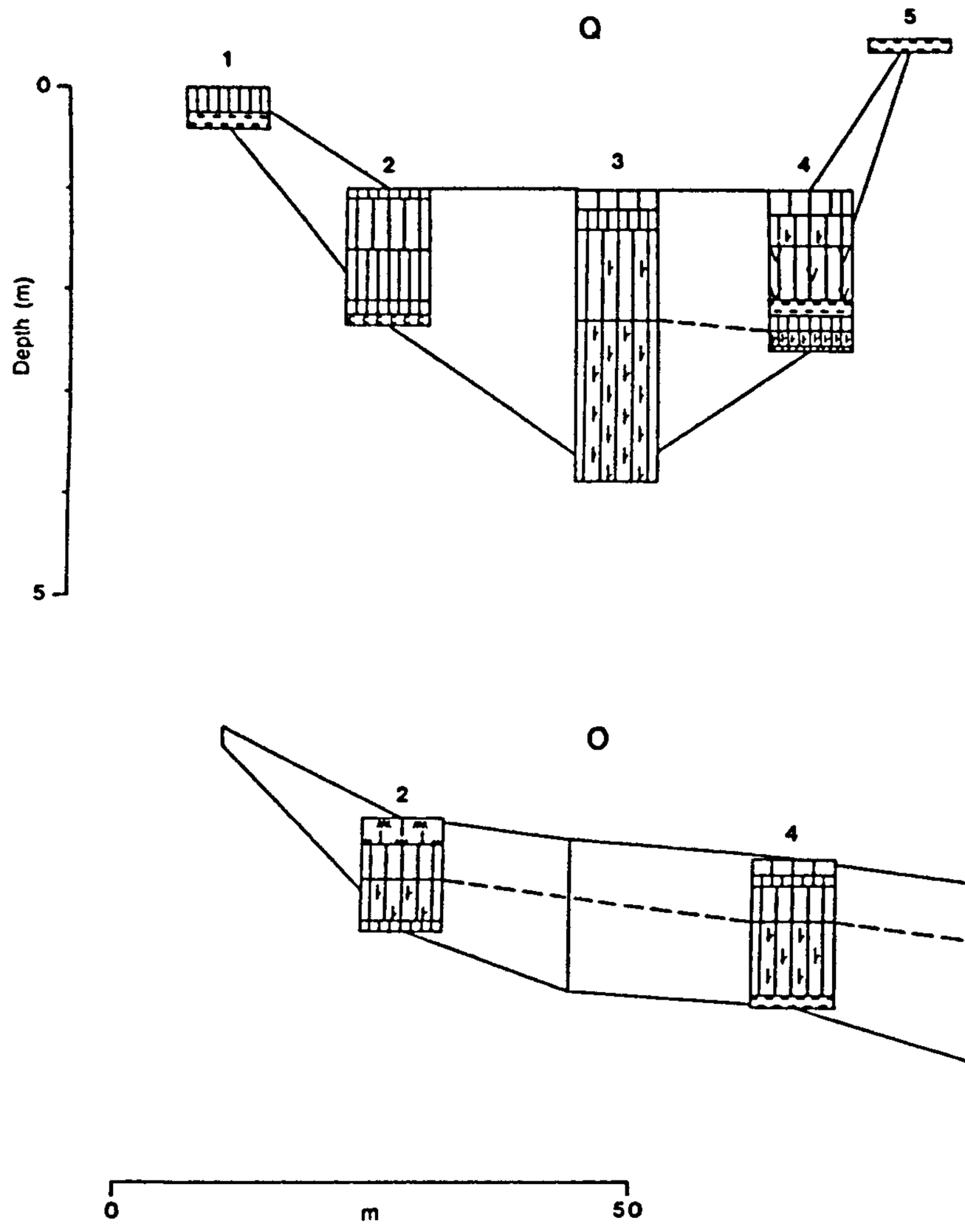


Figure 6.30: Stratigraphy of transects O and Q at North Altnaharra Fen.

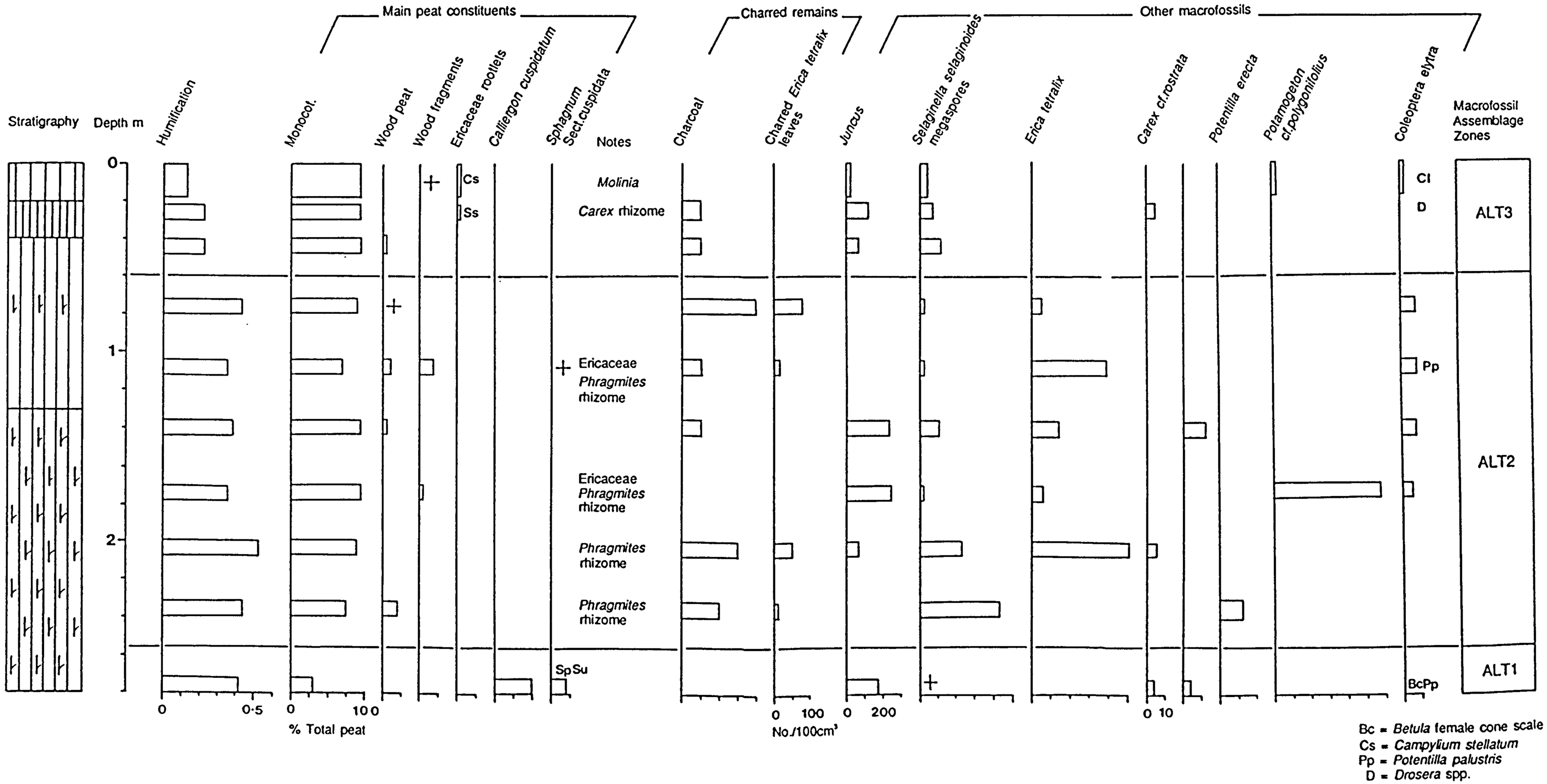


Figure 6.31: Macrofossil diagram for North Altnaharra Fen.

ALT1 280-256cm

The basal sample contains abundant remains of a variety of bryophyte species, including *Calliergon cuspidatum*, and *Sphagnum*, sect.cuspidata, sect.subsecunda and *S.palustre*. *C.cuspidatum* and *S.palustre* are species of mesotrophic fens and are commonly found on substrates other than peat (Smith, 1978; Hill, 1978). Sections cuspidata and subsecunda include a number of mesotrophic species. The other macrofossils present indicate that the moss layer was accompanied by a sedge and herb community including *Potentilla palustris*, *Juncus* and *Carex* (cf.*rostrata*). This community was growing in area of the original valley where the gradient was lower, reducing the velocity of any water flow and thereby allowing the establishment of a more stable community than could colonise the rest of the valley. Once established it would be able to grow laterally and affect the rest of the localised depression in which it was growing.

ALT2 256-60cm

The bryophyte community was relatively short lived and the macrofossil evidence indicates it was superseded by a grass and sedge dominated community. This is probably a natural succession, the more competitive monocotyledons displacing the bryophytes which had established a stable rooting medium for the vascular plants. Initially this is characterised by highly abundant *Selaginella* megaspores and *Potentilla erecta*, and this is followed by *Erica tetralix* and *Juncus*. Also from the start of this zone almost to the present day there are abundant charcoal remains and some of these are identified as leaves of *Erica tetralix*. This probably represents a plant community dominated by grasses and sedges which have left few reproductive macrofossils, but with *E.tetralix* occurring and having a relatively high seed production/preservation. Although this represents a more 'shrubby' community than the present day, it still retains many poor fen characteristics. The burning may have been on site or on the surrounding ground, from where it would easily be blown or washed in to this small site.

There may be more variation in the core than is shown by the small number of samples analysed. There is a sample with a somewhat different macrofossil assemblage at 168-176cm depth, where *Potamogeton* (cf.*polygonifolius*) occurs in abundance and charcoal is not found. This presumably represents a phase of temporary wetness, although its extent and representativeness of the site as a whole is uncertain from the existing evidence.

ALT3 60-0cm

During this zone, there appears to be a slight intensification of the fen conditions, as *E.tetralix* seeds cease to be found and there is an increase in *Selaginella* megaspores and *Juncus* seeds. There is the only occurrence of *Campylium stellatum* and *Scorpidium scorpiodes* in the near surface samples supporting this inference, but this may be due to uncompleted decay at these depths. The decreased humification values probably result from a similar effect.

6.7.4 Conclusion

Although the earliest peat forming community was sedge-bryophyte vegetation, the Altnaharra patterned fen has been dominated by grass-sedge communities throughout its existence. This has infilled a simple valley, where the peat has grown directly on mineral ground.

The site shows similar development to that speculated on by Lindsay *et al* (1988), and that found in patterned fens elsewhere in the world. The mire is a primary peatland, probably spreading from an initial nucleus, although this does not appear to have been from the base of the slope upwards, but merely from the area of the valley with the lowest gradient. The mire is contained by largely mineral ground, with only a thin peat covering in some places (ca.20cm), and it probably obtains nutrients from these slopes in addition to that from the inflow at the top of the mire. This is perhaps the reason for the rather

different plant communities and high nutrient status.

6.8 CONCLUSION

Clearly the actual origins and development of the fen systems are more complex than it was originally thought. There is no one developmental sequence which applies to all Scottish patterned fens. However, it is possible to examine the similarities between the mires (Figure 6.32) and to generalise to a certain extent about the probable origins of the majority of sites.

The figure shows that three of the sites have very similar developmental histories. Early peat growth has occurred in a localised basin or slight depression and is indicative either of early terrestrialisation of an open water environment or of a bryophyte flush community. This is succeeded by peat dominated by monocotyledons, with local growth of birch, either on site where conditions were suitable, or close to the site. There is then a change to ericaceous peats, probably formed under ombrotrophic conditions. This is sometimes apparently a very rapid, clear cut change, but may be more gradual. This may be part of the natural hydroseral succession, but is associated with commencement of burning in some cases, which may have hastened the changes already underway. A general rise in humification is found at this time. The precise composition of the peat during this 'ombrotrophic' phase is variable, but sometimes development of a phase of pine woodland is apparent. However, in all cases, there is a reversion to poor fen peats in the top part of the mire profile, and again this is sometimes sudden or may occur more slowly. Finally, surface peats are indicative of slight acidification, with the commencement of *Sphagnum* growth.

In these three sites, the development of the patterned fen is therefore a recent occurrence and one which has occurred after the establishment of ombrotrophic blanket mire.

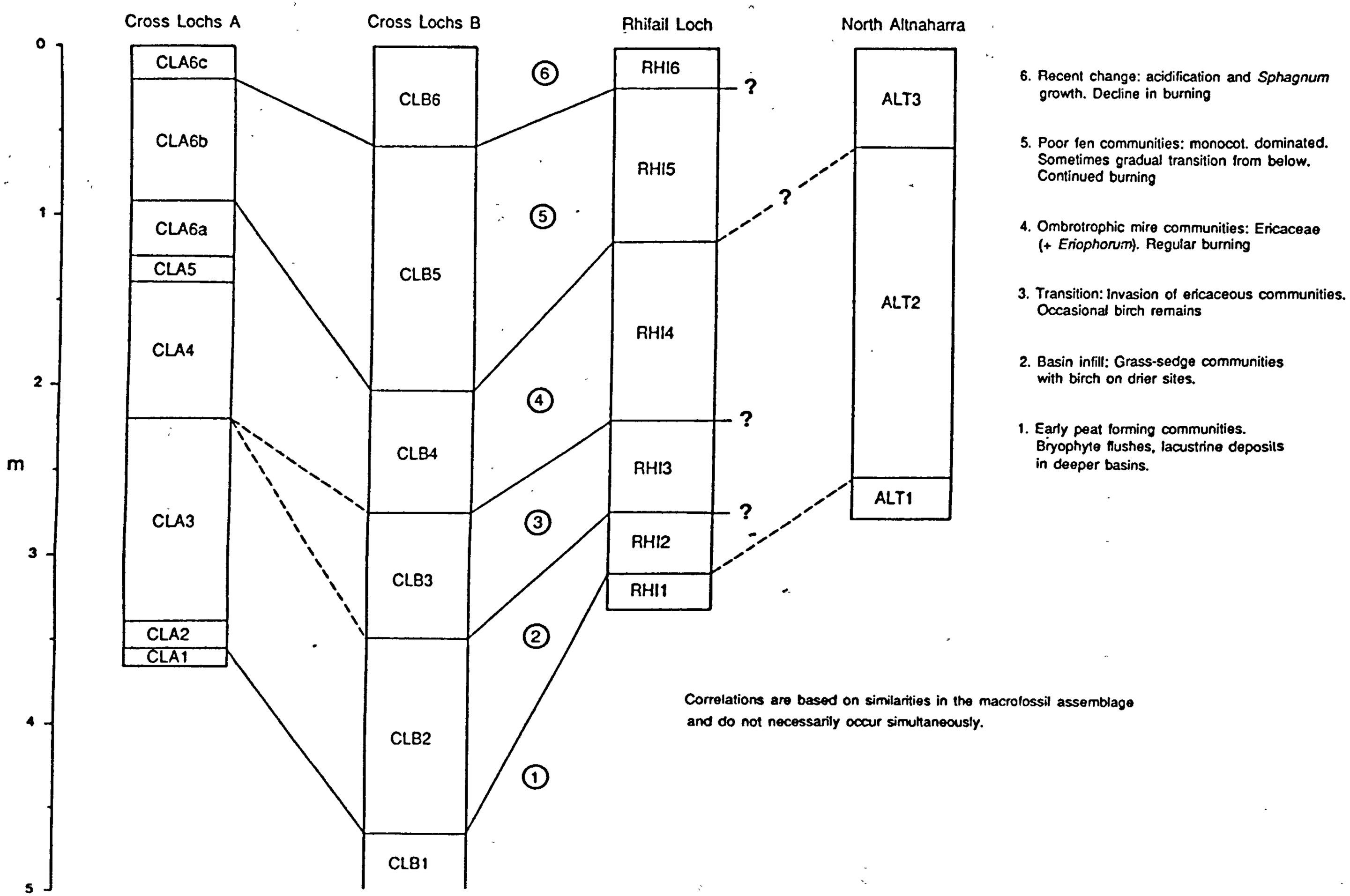


Figure 6.32: Comparison of macrofossil stratigraphy of four patterned fens

Present day occurrence of the fens appears to be governed by the existence of an adequate source of water at the head or sides of the mire, which often has evidence of ground water influence in the form of precipitated ochreous mineral deposits. It is suggested that the original emergence and development of such water supplies has been crucial in the promotion of these poor fen systems. Sites which occur within the main area of well developed ombrotrophic blanket mire are more likely to show this sort of stratigraphy.

Recent work in Minnesota (Glaser, 1987) suggests that there may be similar processes occurring in the development of patterned and unpatterned water tracks within mire complexes. Here, there is a change from a bog forest to water track forming fen peat. It is suggested (Glaser, 1987) that there are two hypotheses to explain this. Surface flow of water draining from the bog would create particularly wet zones where *Sphagnum* communities replace the bog forest. Increased alkalinity occurs where such zones converge and poor fen water tracks develop (Glaser *et al*, 1981). However, it has also been shown that groundwater can influence surface mire chemistry (Siegel, 1981; 1983; Siegel and Glaser, 1987) in areas of groundwater discharge. These provide the enriched water supply from which the water tracks develop downslope. The occurrence of probable groundwater discharge at the head of Scottish patterned fens suggests this process is occurring here as there is no evidence to suggest that large amounts of surface flow are being directed through the mire systems. There is generally an inadequate source area for such discharge and topographic survey shows that the present surface does not have the correct morphology to allow such a surface flow. Further research would be required to test this hypothesis directly by employing piezometer nests, geochemical stratigraphy and detailed surface water chemistry analyses.

The North Altnaharra site appears to be very different, both in terms of present day vegetation and development. In

this case, the hydrology of the mire has remained almost unchanged since peat inception, and the peat body has never grown above the influence of the groundwater flowing on to its surface. It is a primary mire and, in terms of development, it therefore corresponds well with previous ideas on patterned fen development in Scotland and elsewhere in the world. There may be other sites which show similar stratigraphic records where similar topographic situations occur. These are most likely to be in western Sutherland where the development of ombrotrophic mire has not been so complete.

CHAPTER 7: - SURFACE PATTERN DEVELOPMENT ON FENS

7.1 INTRODUCTION

Surface patterns are the differentiation of surface features into aquatic and terrestrial phases - "pools" and "ridges". They occur in north and west Britain and Ireland and across most of the high latitude peatlands of North America and Eurasia. In Britain they are considered to be purely a feature of ombrotrophic peatlands, whereas elsewhere it is clear they occur on minerotrophic mires also. The problem of how patterning is initiated and maintained has received much attention since the early work of Auer (1920), but is still not convincingly explained (Washburn, 1979). There is certainly more than one mode of formation and oceanic and boreal patterning is probably caused differently (Boatman, 1983; Seppala and Koutaniemi, 1985).

"String" patterns in minerotrophic mires have received most attention from Scandinavian and North American researchers and these are reviewed by Seppala and Koutaniemi (1985) and Foster *et al* (1983). Oceanic mires have been most intensively studied by DJ Boatman and coworkers at the University of Hull and the bulk of their work is summarised by Boatman (1983). Moore (1982) briefly reviews the wider situation. The situation on patterned fens in Scotland may be somewhere between these two situations or it may be referable to either one. The different processes that may affect patterning are now briefly reviewed.

7.2 A REVIEW OF PROCESSES

Biotic influences on the mire surface of patterned fens have recently been given greater weight than previously. The hypothesis outlined by Foster *et al* (1983) envisages channel flow changing to sheet flow over a gently inclined, actively growing peat surface, with localised ponding of

water in low spots. Differentials in plant growth rates then accentuate this existing height difference and when water levels are high plant growth rates around the margins of the shallow pools are reduced. A succession of hollow and pool communities with lower and lower accumulation rates then occurs. Adjacent pools at the same level coalesce to form the linear pools. Pools at different levels joining together will drain the upper pool. However, this part of their hypothesis is only supported by observations of present day conditions of localised ponding of water and "incipient" pools (Foster and King, 1984; Foster and Fritz, 1987).

This basic process is largely the same as that described by Boatman (1983) for the Silver Flowe, Galloway, except here the appearance and development of pools is mostly dependent on the balance of growth between *Sphagnum papillosum* and *S.cuspidatum*. The latter grows best at pool margins so that pool edge/centre differences in depth will be accentuated (Boatman, 1984). High decomposition rates of *Sphagnum cuspidatum* are also involved (Clymo, 1965) and hollow species have a longer growing season than "flat" species on the Silver Flowe so that they may be able invade adjacent flats when they are dormant (Hulme and Blythe, 1982). Hulme (1986) invokes differential growth rates within flats of S.papillosum as being responsible for initial depressions, which are later invaded by aquatic Sphagna. Pool systems on the Silver Flowe correspond to sub peat depressions in topography and it is postulated that these are the areas that have the greatest supply of surface water (Boatman *et al*, 1981). Despite the ideas of cyclic change on patterned mires put forward by Osvald (1923) and enshrined in British ecology by Tansley (1939), it seems likely that once established, pools merely contract and expand (Walker and Walker, 1961; Moore, 1977; Barber, 1981).

Following establishment of pools, many authors invoke peat degradation of the bottom and sides of pools as the maintaining and extending process (Foster *et al*, 1983;

Foster and King, 1984; Foster and Fritz, 1987; Seppala and Koutaniemi, 1985). Foster and Fritz (1987) found that pool stratigraphy on a patterned fen in Sweden shows basal peat, similar to adjacent ridge peat, overlain by peat detritus and then gyttja to support this. Radiocarbon dating of the detritus and gyttja shows a 2000 year difference at the interface, showing that the detritus is derived from much older pool side material (Foster and Fritz, 1987). Mets (1982) relates long term changes (17 years) in a pool system which demonstrates the effect of peat degradation with shorelines of pool islets and peninsulas shortening. Pools in ombrotrophic mire may not suffer this to the same extent as oxygen levels may be lower and although there is no reference to this process by Boatman (1983), Hulme (1986) mentions it as a possible mechanism in the later development of pools. Methanogenesis may serve to mix detrital material on the pool bottom and further expose it to decomposition (Foster and King, 1984). Wave action can erode the edges of large pools on blanket mire (Hulme, 1986).

A process which received much attention in early literature is that of frost and ice action. This may affect mire topography in two ways:- by thrusting up of ridges due to the moisture contained within them and ice pressure from adjacent pools pushing against ridges. Evidence for this comes mainly from the climatic zone in which patterned fens occur, their southern boundary being marked by increases in evapotranspiration, temperatures and growing season length. Northern boundaries are marked by decreased temperatures in March and July (Thompson and Worley, 1984). Schenk (1959, 1970) states that permafrost thawing with climatic warming allowed solifluction to form ridges and mounds of peat, which were then accentuated by seasonal freeze/thaw processes, although the role of biological factors is acknowledged (Schenk, 1970). More detailed recent measurements of frost depth and snow cover lead Seppala and Koutaniemi (1985) to regard the influence of frost action, ice expansion and solifluction as over emphasised in the

past.

The deposition of detritus at the spring melt may provide centres for ridge vegetation to establish itself (Thom, 1972), and Sakaguchi (1980) describes an analogous situation during and after heavy rain in a park in Tokyo. He then extends this argument and claims that a similar process may occur in the patterned fens on Ozegahara Moor, Japan. Freeze/thaw or spring melt water processes are regarded as very unlikely in the oceanic climate of the Silver Flowe (Boatman, 1983)

Pearson (1960, 1979) proves quite conclusively that mass movement of peat over a lens of water is occurring at Muckle Moss, causing splitting of peat surfaces to form pools. Downward movements of up to 3.59m are recorded over seven years. However, this is certainly not a typical British mire. Seppala and Koutaniemi (1985) record significant movement of strings but not in a single direction over time and with variations in magnitude and direction between strings. This is attributed to hydrostatic pressure of surface waters. Steeply sloping mires with a series of oriented pools have been recorded in Colorado (Vitek and Rose, 1980) and the Falklands and South Georgia (Weller, 1975). These are thought to be a product of solifluction. The main argument against gravitational theories as a universal explanation for pattern initiation is that many of the best developed patterns occur on flat or very gently sloping peatland rather than on the steepest slopes.

7.3 RESEARCH OBJECTIVES

The research on surface pattern development on mires has been briefly reviewed above. In Britain, this research has been exclusively on ombrotrophic mire systems, and has primarily been concerned with the dynamics of *Sphagnum* communities (eg. Boatman, 1984). Elsewhere in the world, pool development on fens has been researched, mainly in the

boreal regions of Scandinavia and North America, where physical influences are more usually invoked as possible causes of pool formation and persistence (Seppala and Koutaniemi, 1985, for a review). While much of this work may be relevant to patterned fens in Scotland, the intermediate position of this mire type demands further research into the timing and possible causes of pool initiation. The arguments which have been used for the mode of change on ombrotrophic, oceanic mires cannot apply to patterned fens, as *Sphagnum* species are a relatively minor component of the past mire communities (see Chapter 6). Equally, the physical factors at work on patterned minerotrophic mires in the boreal regions are the result of a far more severe climatic regime than that existing in the north of Scotland.

The general purpose of this chapter is to report results of some preliminary palaeoecological investigations into pattern development on Scottish patterned fens and to propose possible mechanisms for the establishment and maintenance of the pool systems. The specific objectives are therefore:

i) To date the onset of pool formation.

ii) To characterise the biostratigraphic changes occurring at this time.

iii) To suggest possible reasons for the sedimentary transition.

iv) To use observational data to suggest mechanisms for the maintenance and likely future development of patterning.

v) To compare the proposed mechanisms with those suggested for oceanic ombrotrophic and boreal minerotrophic mires.

The chapter mainly consists of the results of palaeoecological research; the sampling strategy, present pool - ridge vegetation, stratigraphic change, macrofossils, pollen analysis and other microfossils. This is followed by a discussion of this evidence and a

comparison with other published ideas on pool development on mire systems.

7.4 METHODS

7.4.1 Site selection

The site used for this work is that of Cross Lochs 'A'. This particular site appears from the work on present ecology (Chapter 3) to be a 'typical' patterned fen site and is also within the area where other palaeoecological research has been carried out (Chapters 5 and 6), so that the development of pools can be seen within the context of overall site development. Also, pollen chronology was becoming available for this site and therefore date estimates would be available from this information.

7.4.2 Levelling and sampling

A present day pool - ridge sequence in the centre of the site was selected for levelling and sampling (see Figure 7.1). Levelled transects were taken, using the apparatus shown in Figure 7.2, across the main pool from ridge top to ridge top, and across the top of the pool with heights measured at 10cm intervals. Notes on the vegetation were taken to construct a local vegetation map of the study area (Figure 7.3) based on the vegetation classification derived in Chapter 3.

Four cores were taken from this sample area, representing two adjacent ridges and intervening pool, together with the extreme end of the pool. These were in large (9x30cm) Russian corers (Barber, 1984), to provide enough material for all analyses and radiocarbon dating. Below 90cm depth, where preliminary probing of other pools had shown there were no significant differences in pool and ridge cores, a narrower (50x5cm) Russian corer was used for stratigraphic description only.



Figure 7.1: Surface pattern on Cross Lochs Fen A with location of sample pool shown. Shaded areas are pools visible on 1:2500 aerial photograph taken in 1983.

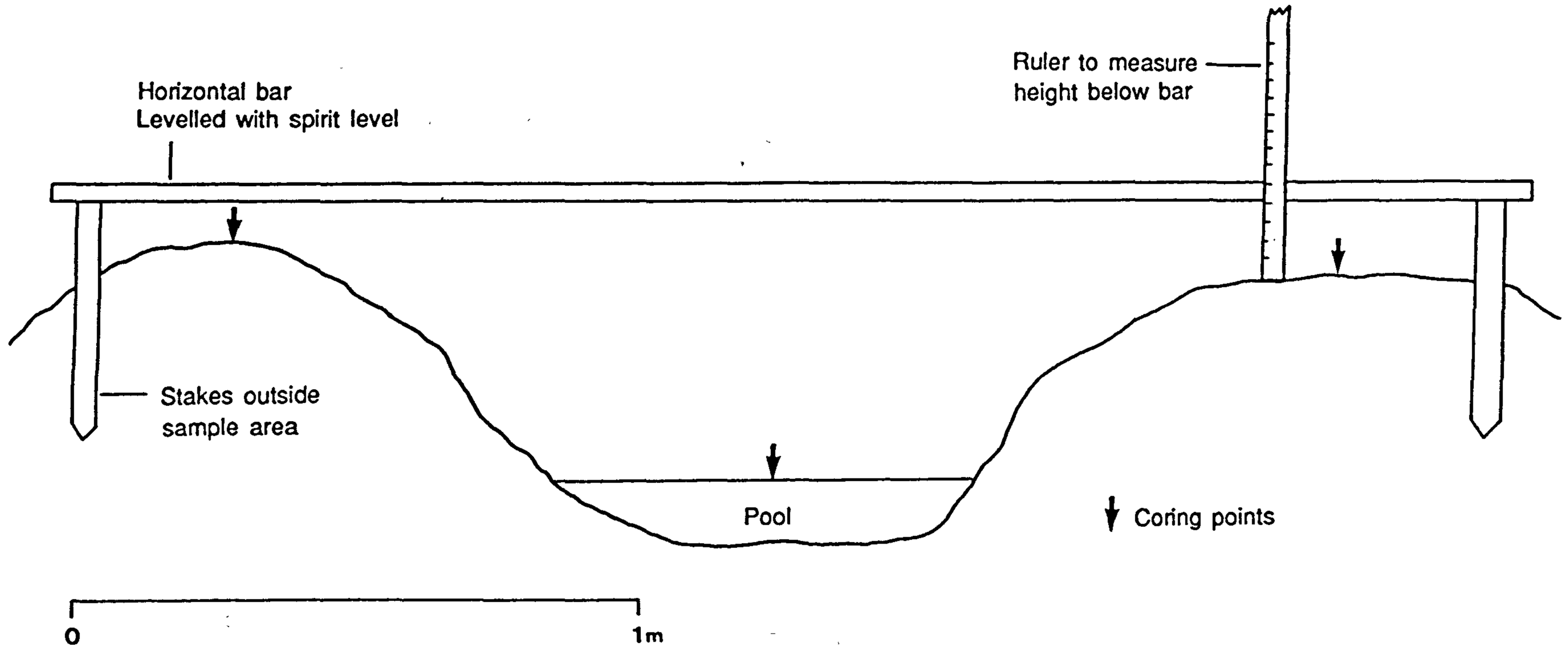


Figure 7.2: Apparatus for levelling and sampling pool - - ridge transition.

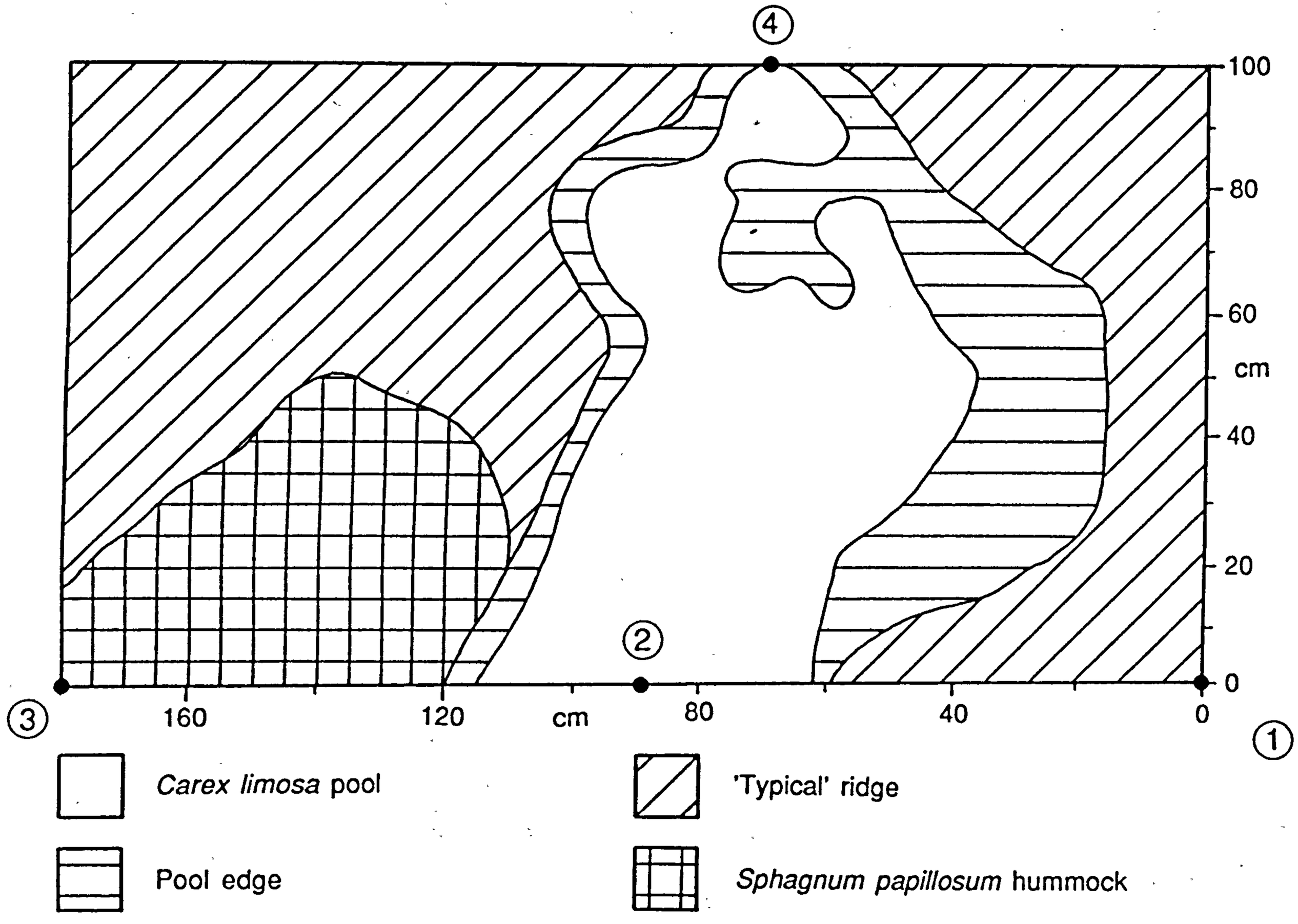


Figure 7.3: Vegetation of surface pattern development study area.

7.5 STRATIGRAPHY

The stratigraphic descriptions of all four cores are given in diagrammatic form in Figure 7.4, showing possible correlations between cores. The stratigraphy of all cores shows a similar sequence to that shown for the rest of the Cross Lochs A site, with basal monocotyledonous peat with *Betula* remains, succeeded by ombrotrophic peat in the form of more humified ericaceous material, *Eriophorum vaginatum* and a then an ericaceae-*Eriophorum* mix up to just over 2m.peat. A gradual transition to more monocotyledonous peat then occurs over the next 1.5m. However, there appear to be several differences in the topmost 0.5m of the cores. These differences are illustrated in relation to the present topography in Figure 7.5. This shows that from 35cm to 19cm in the core from the pool centre (CLP2) there is a layer of darker, looser sediment than the uniform monocotyledonous peat below and that this is overlain by poorly consolidated black, muddy material with detrital leaf remains. This contrasts with the adjacent ridge core (CLP3), which shows a change to slightly less humified monocotyledonous peat, and then in the topmost 28cm, a transition to *Sphagnum* - monocotyledonous peat. The pool edge core (CLP4) has a similar transition to the initial change in CLP2, but the other ridge core does not display any obvious change to *Sphagnum* rich peat.

Below these changes there is clear correlation of all cores with the occurrence of a band (ca. 7cm in depth) of slightly darker (more humified?) peat containing abundant *Selaginella* megaspores. The similarity in stratigraphy below ca.50cm depth suggests that pool development is only a recent phenomenon here, although it could be argued that this is not representative of the other pools on the mire surface. However, the stratigraphy of a number of other pools was found to be very similar, with shallow water, underlain by loose, detrital sediment and then more consolidated but darker, more humified peat before the uniform monocotyledonous peat found all over the mire at

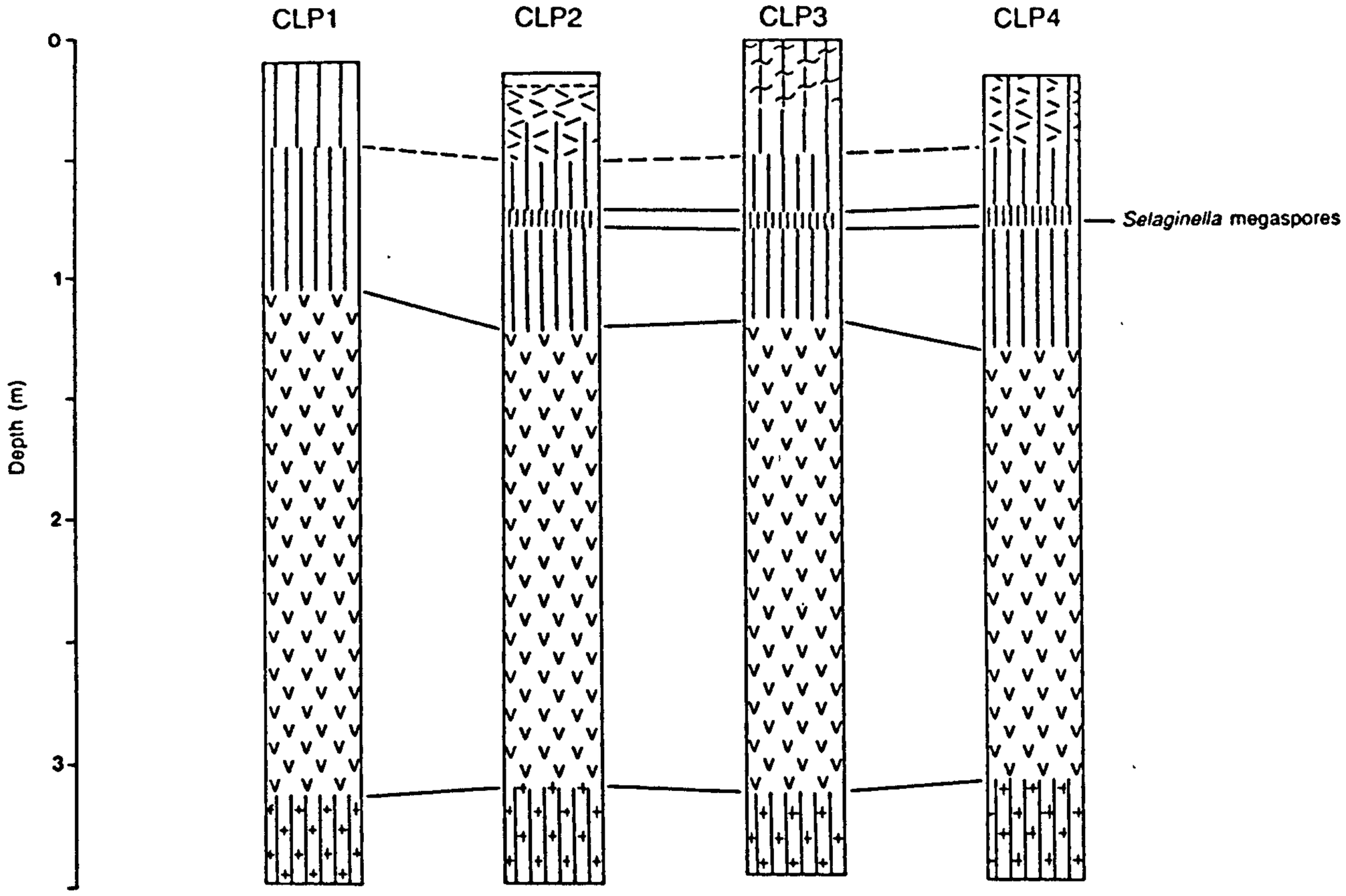


Figure 7.4: Stratigraphy and correlation of pattern development cores (CLP1 - CLP4).

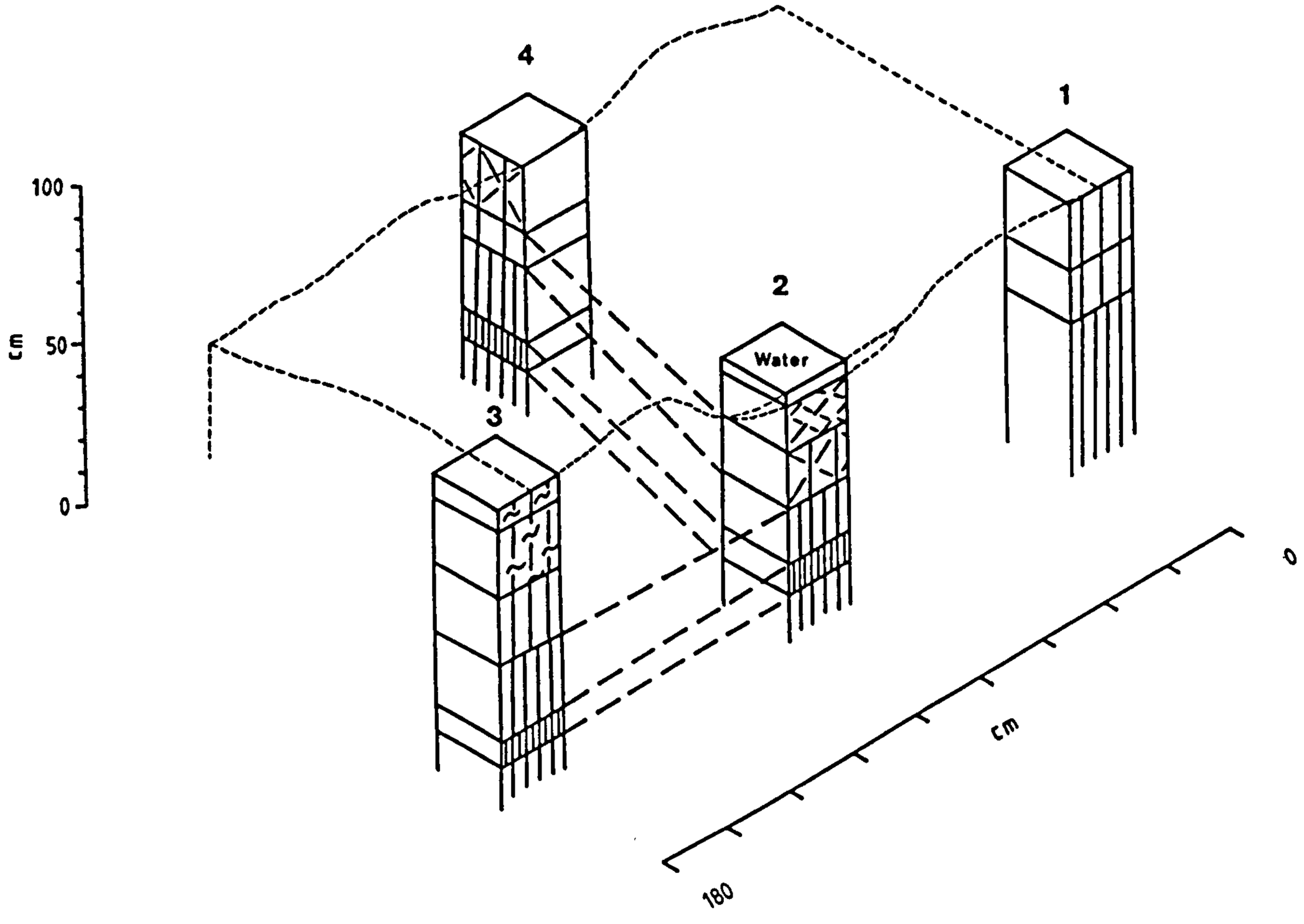


Figure 7.5: Three dimensional portrayal of present topography and near surface stratigraphy of pattern development cores (CLP1 - CLP4).

relatively shallow depths is encountered. The band of darker, *Selaginella* rich peat was also found elsewhere.

Macrofossil analysis was then required to confirm the observed stratigraphic changes observed and to characterise these in more detail. Pollen analysis would also help to assess actual species changes, but also was necessary to provide estimates of dates by comparison with the main dated pollen chronology (Chapter 5).

7.6 MACROFOSSIL ANALYSIS

It was not felt necessary to perform further palaeoecological analyses on all four cores, but rather that it would be more profitable to concentrate on the two cores displaying the most significant changes; the ridge core CLP3 and the pool core CLP2. Only the top 80cm of each core was analysed, as this covers all the main differences in stratigraphy between the cores.

Macrofossil analyses were carried out in the way described in Chapter 4, although some of the sample volumes were rather less than 40cm^3, as measured by displacement, due to the unconsolidated nature of near surface sediments. The diagrams (Figure 7.6) are divided into local macrofossil assemblage zones at the levels which appear to display the most significant changes in composition. The depth of the samples (8cm) causes some problems of inadequate resolution, when attempting to compare the macrofossil data and the stratigraphic changes. The stratigraphic boundaries themselves also cover a depth as they are all gradual, so that it would be unreasonable to expect the two to be exactly coincident, although the major changes should be similar.

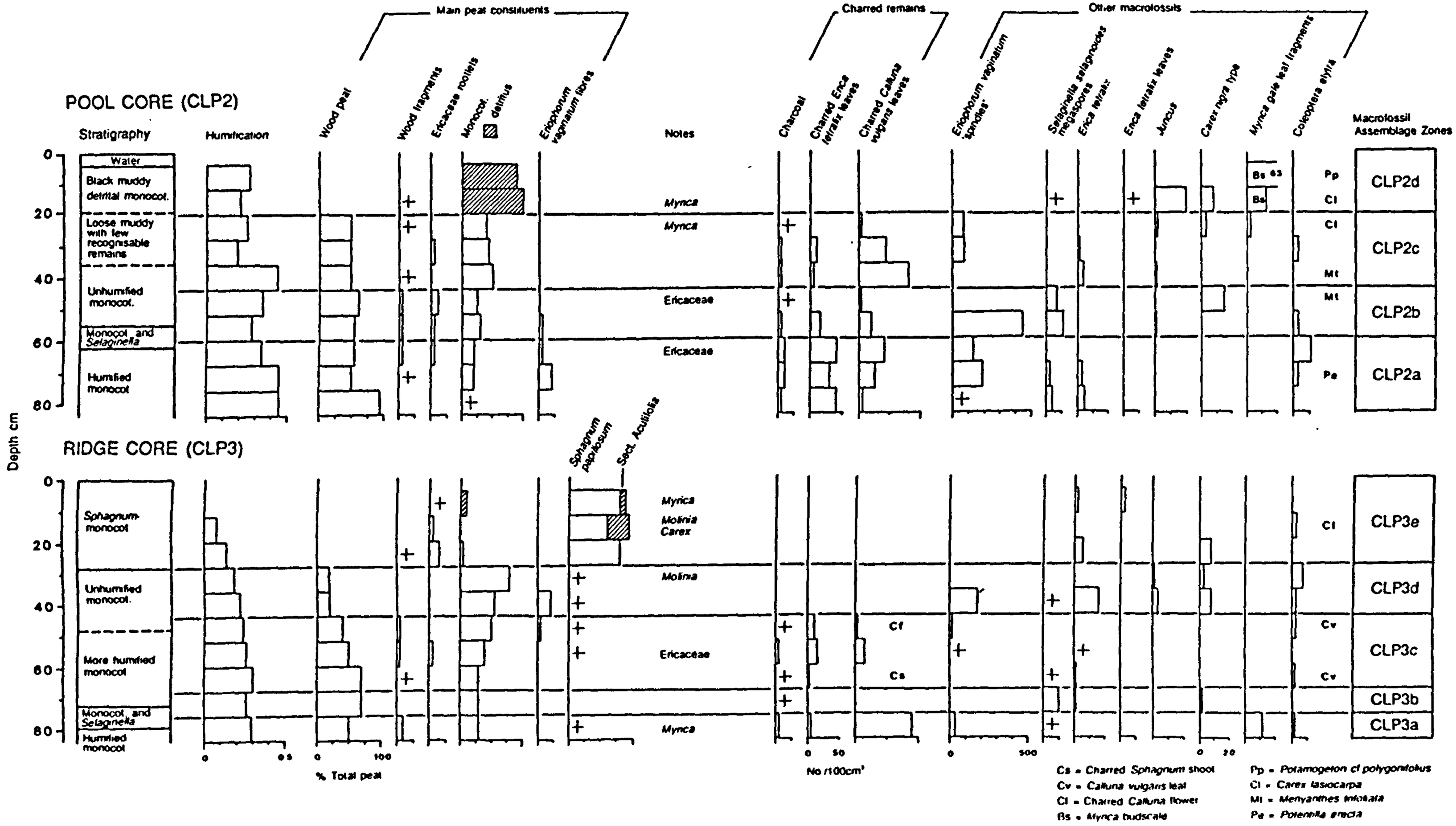


Figure 7.6: Macrofossil diagrams from near surface sediments in pool (CLP2) and ridge (CLP3) cores.

7.6.2 Pool core (CLP2)

The lowest zone here (CLP2a) represents a mixed mire community of ericaceous shrubs, *Eriophorum vaginatum* (sclerenchymatous spindles, fibres) and monocotyledons (possibly *Molinia* and *Carex* species). This differs from the stratigraphic data in showing evidence of species generally associated with more acid conditions than pure monocotyledonous peat, but is other wise in agreement, with the upper boundary approximately coinciding with that of the stratigraphy. This is followed by a CLP2b with increased numbers of *Selaginella* megaspores and other indications of slight enrichment and/or surface wetness in the form of biconvex *Carex*, *Menyanthes trifoliata* and *Juncus* seeds. Also during this phase there is a slight reduction in the quantity of charred remains recorded. This is a much broader zone than that detected in the stratigraphy, but again basically shows similar changes. CLP2c indicates a change to a community more dominated by monocotyledonous plants, with less ericaceous shrubs and *Eriophorum* remains. This shows some discrepancy with the stratigraphic changes described previously, probably due to the diffuse stratigraphic change. The upper sample from this zone is beginning to show some of the characteristics of CLP2d, with leaf fragments of *Myrica* and *Carex lasiocarpa* seeds. However, it is only in CLP2d that the major peat forming constituents appear to change wholly to detrital monocotyledonous remains in the form of *Carex* roots and leaves, which have apparently been subject to little decay. Also during this zone, charcoal remains are completely absent. The macrofossils within this zone are likely to be rather homogenous because of the loose sediment and possible mixing. The looseness of the sediment may also mean that heavier remains such as charcoal are likely to fall through some of the upper layers of sediment and therefore to be deposited in an 'older' sedimentary layer.

7.6.3 Ridge core (CLP3)

The earliest zone in this core (CLP3a) corresponds with CLP2a, being an Ericaceae - *Eriophorum* mix with some monocotyledonous peat. There is also evidence for local *Myrica* growth here. CLP3b is a relatively narrow *Selaginella* zone, followed by an Ericaceous-monocotyledonous peat zone (CLP3c). All these zones also contain some charcoal remains, in common with zones a, b and c of CLP2. CLP3d shows a greater dominance of monocotyledonous remains, some of which is identifiable as *Molinia caerulea*, and a complete cessation of charred remains at the bottom of the zone (44cm). This may be coincident with the CLP2c - CLP2d change in the pool core and appears to be the beginning of the differentiation of the two microtopographical units. CLP3e shows clear differences to preceding zones and to the pool core with peat being dominated by *Sphagnum* remains, mostly *S.papillosum* with some section Acutifolia (probably *S.capillifolium*, from present day evidence). It could be argued that the abundance of *Sphagnum* remains in these upper layers of peat is merely a result of differential decay processes and that once these remains are part of the anoxic catotelm, most the *Sphagnum* remains will have decomposed. However, this seems unlikely given the very large differences in macrofossil composition and the generally well preserved remains of other species in the lower layers. Experiments which show differential weight losses in *Sphagnum* plants of different species (Clymo, 1965) do not suggest that structural features used in identification of subfossil material are necessarily affected.

7.6.4 Correlation and discussion of macrofossil results

There are clear correlations between the macrofossil zones described above and shown in Figure 7.7, especially when combined with the charred remains record for the two cores. The earliest zones (a, b and c) are very similar in both cores, showing a mixed mire community becoming increasingly dominated by monocotyledonous species, interrupted by a phase of increased nutrient availability and/or wetness shown by the rise in *Selaginella* megaspores and other associated minor changes.

Throughout these three zones, charred remains are found, with a slight decrease during the *Selaginella* phase. After these corresponding early phases, the two cores diverge and at the same time charred remains cease to occur. Although this may be associated with depositional processes in the pool environment, the ridge core provides a true record of the deposition of charred remains over time and therefore it is likely that this cessation is real.

The divergence of pool and ridge development consists of an increase in monocotyledonous remains in the ridge core, followed by the more recent development of the surface *Sphagnum* peat. The pool appears almost to cease true peat development at this point, with only poorly consolidated, humified remains and detrital material which may be of relatively recent origin.

Further information on local conditions during this period of time can be provided by pollen analysis, giving information on other vegetational changes, with other microfossil data perhaps allowing more definitive statements on surface wetness in particular. Pollen data will also allow chronological correlation of the cores and tentative dating of the major changes.

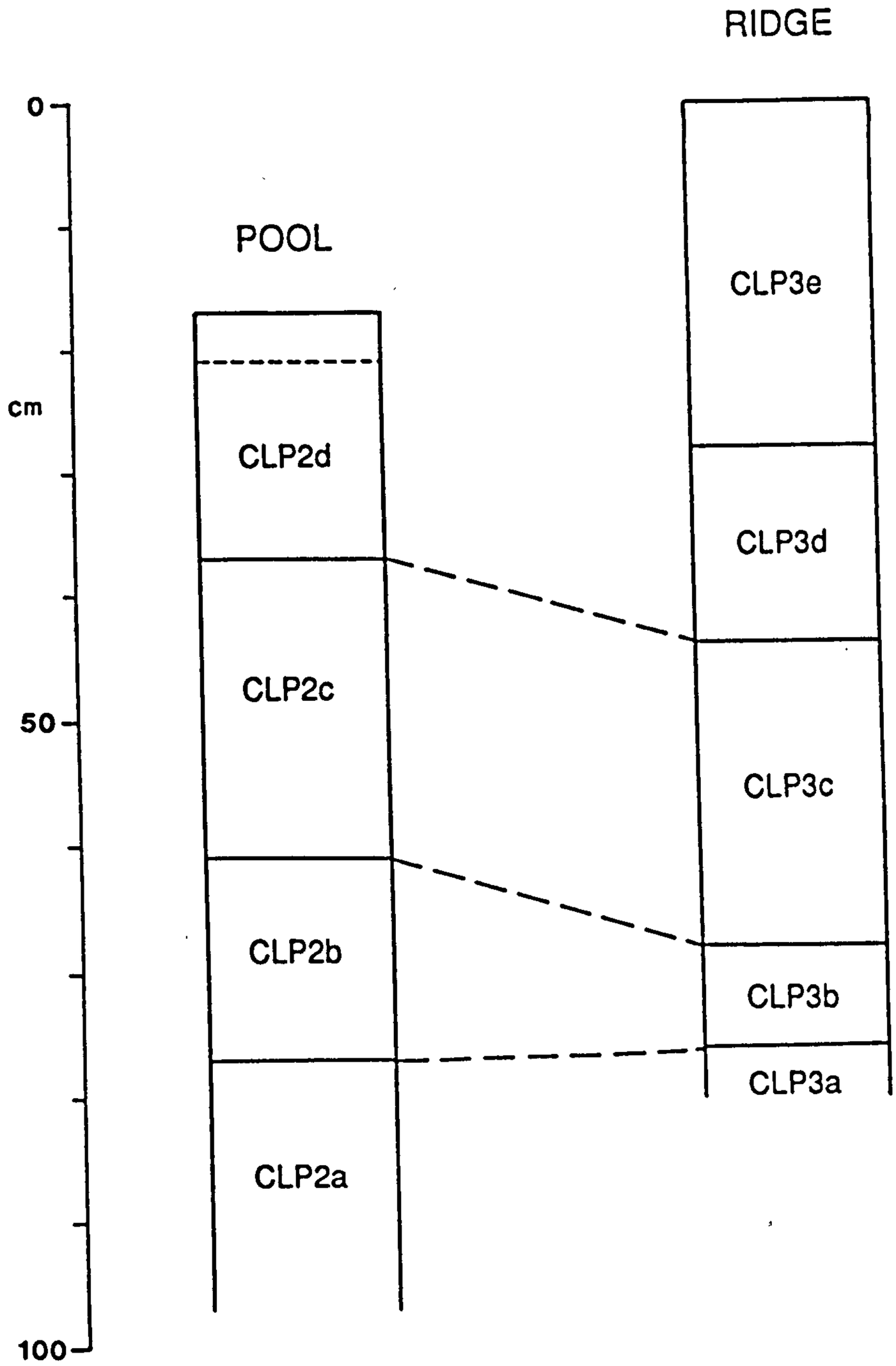


Figure 7.7: Correlation of macrofossil assemblage zones from pool (CLP2) and ridge (CLP3) cores.

7.7 POLLEN ANALYSIS

Pollen samples were taken every 4cm throughout the 80cm top section of each core and prepared and counted according to Chapter 4. However, the minimum pollen sum used was 200 Total Land Pollen as it was felt that this would provide adequate data on local changes and for correlation with the radiocarbon dated core CRL1 (Chapter 5), only 100m away. During these counts, all other microfossil types were recorded and the results of these are presented and discussed in section 7.6. It was necessary to use larger volumes (up to $4cm^3$) of the *Sphagnum* peats near the surface as pollen concentrations were extremely low. Relative pollen diagrams (Figures 7.8 and 7.9) have been zoned by eye and their main features are described below.

7.7.1 Ridge core (CLP3)

CLP3-1a (>78cm)
This zone is characterised by relatively high levels of *Betula* (ca.10%) and low levels of *Calluna* (<20%). Other tree taxa show only low levels of occurrence, (<5%), although this is relatively high compared to some zones.

CLP3-1b (78-66cm)
These three levels are characterised by the occurrence of *Selaginella* microspores, but otherwise the pollen assemblages are similar to those in the zone below.

CLP3-2 (66-38cm)
The beginning of this zone is marked by a fall in *Betula* to below 5%TLP, accompanied by the further decline of other tree species to a point at which occurrences are discontinuous. *Selaginella* disappears and *Calluna* rises to over 35%, reaching a maximum of 55%. *Ericales* show a slight increase to continuous occurrences of ca.2%. *Sphagnum* spores show an increase at the start of this zone, immediately following the *Selaginella* decline, but then fall again towards the end of the zone.

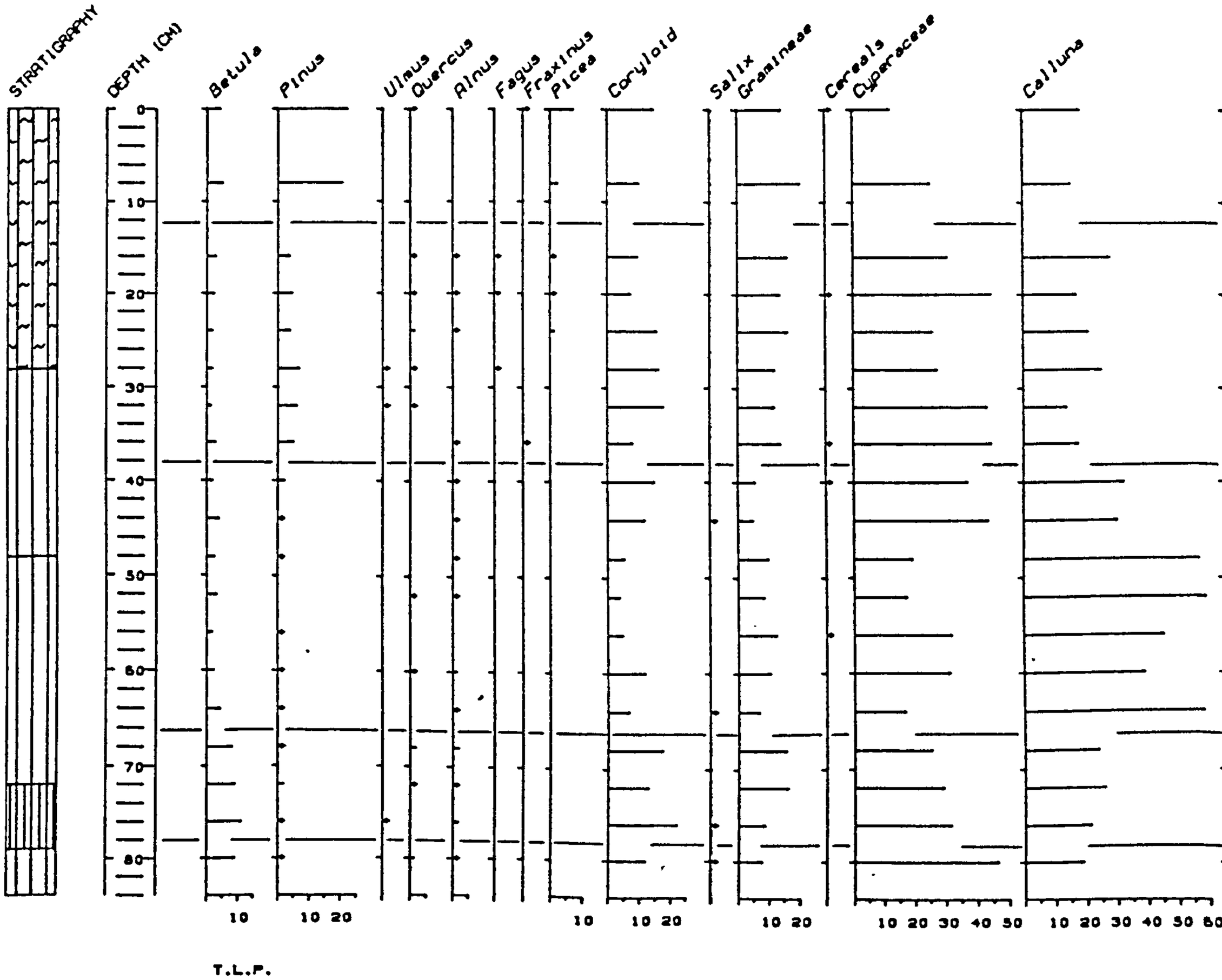
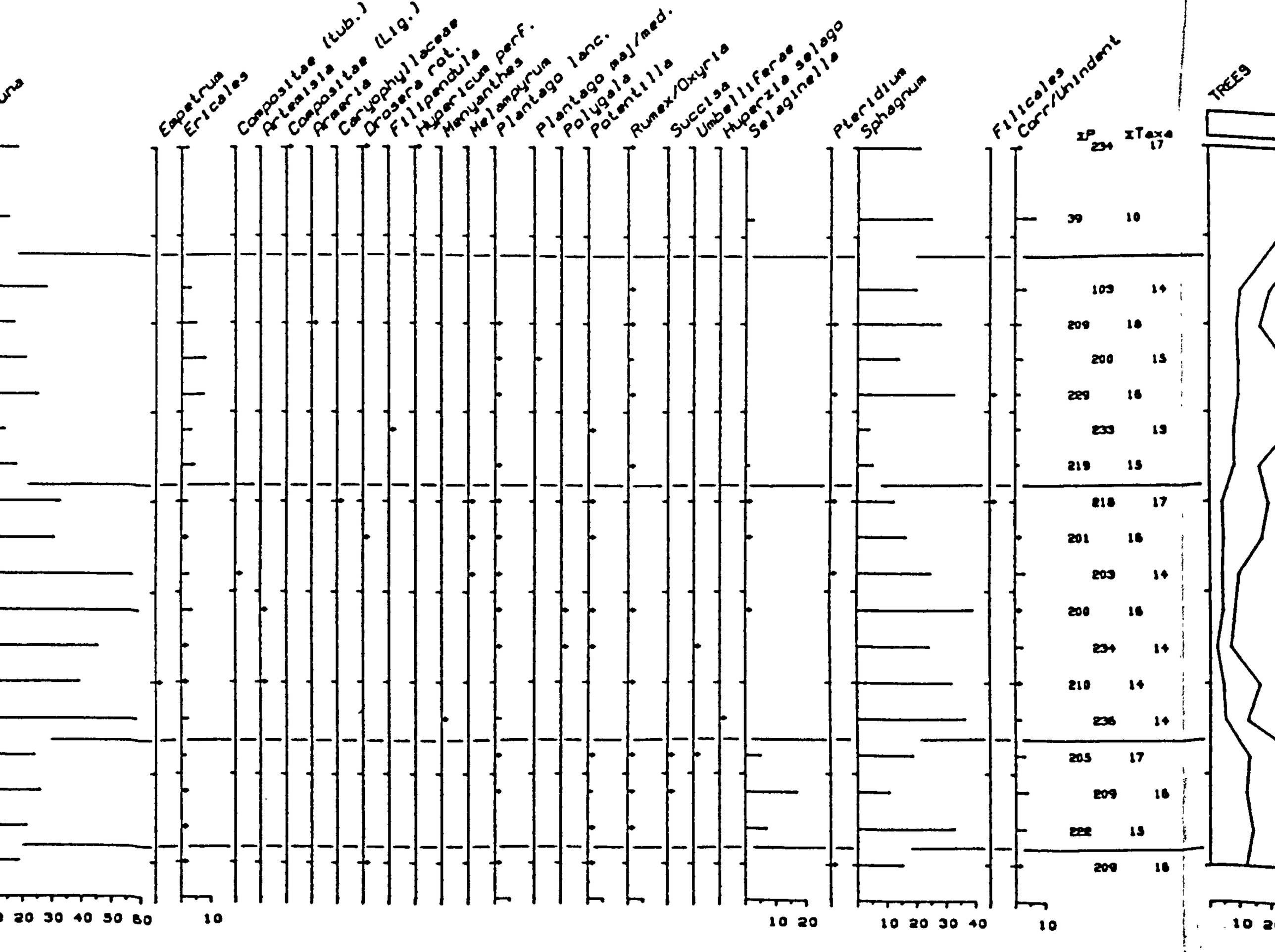


Figure 7.8: Percentage pollen diagram for ridge core (CLP3).

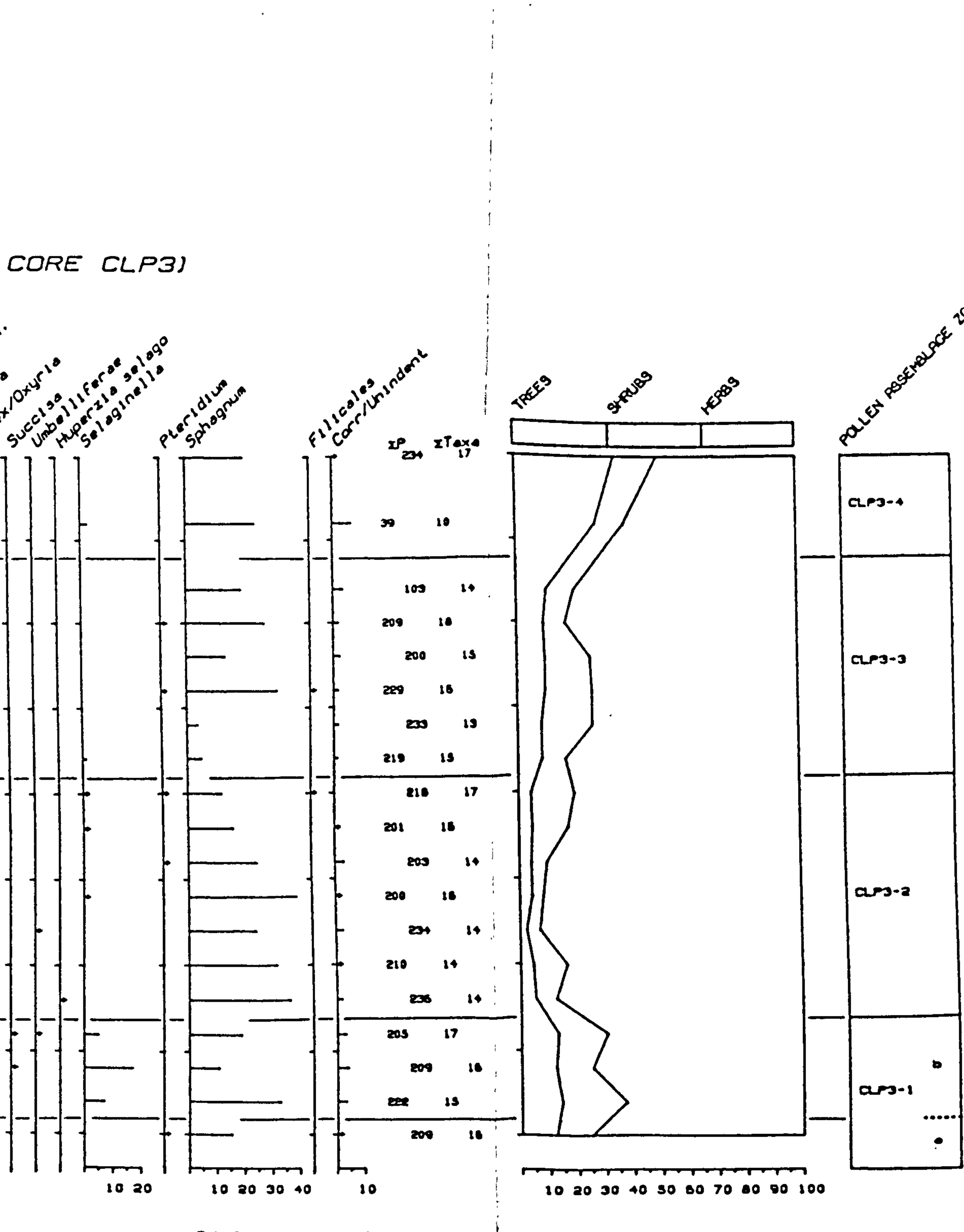
EN A : PATTERN DEVELOPMENT (RIDGE CORE CLP3)



T.L.P. • Sphagnum T.L.P+ Corr/Unid

T.L.P. • Spores - Sphagnum T.L.P. • Spores - Sphagnum

CORE CLP3)



Analysis DJ Charman 1990

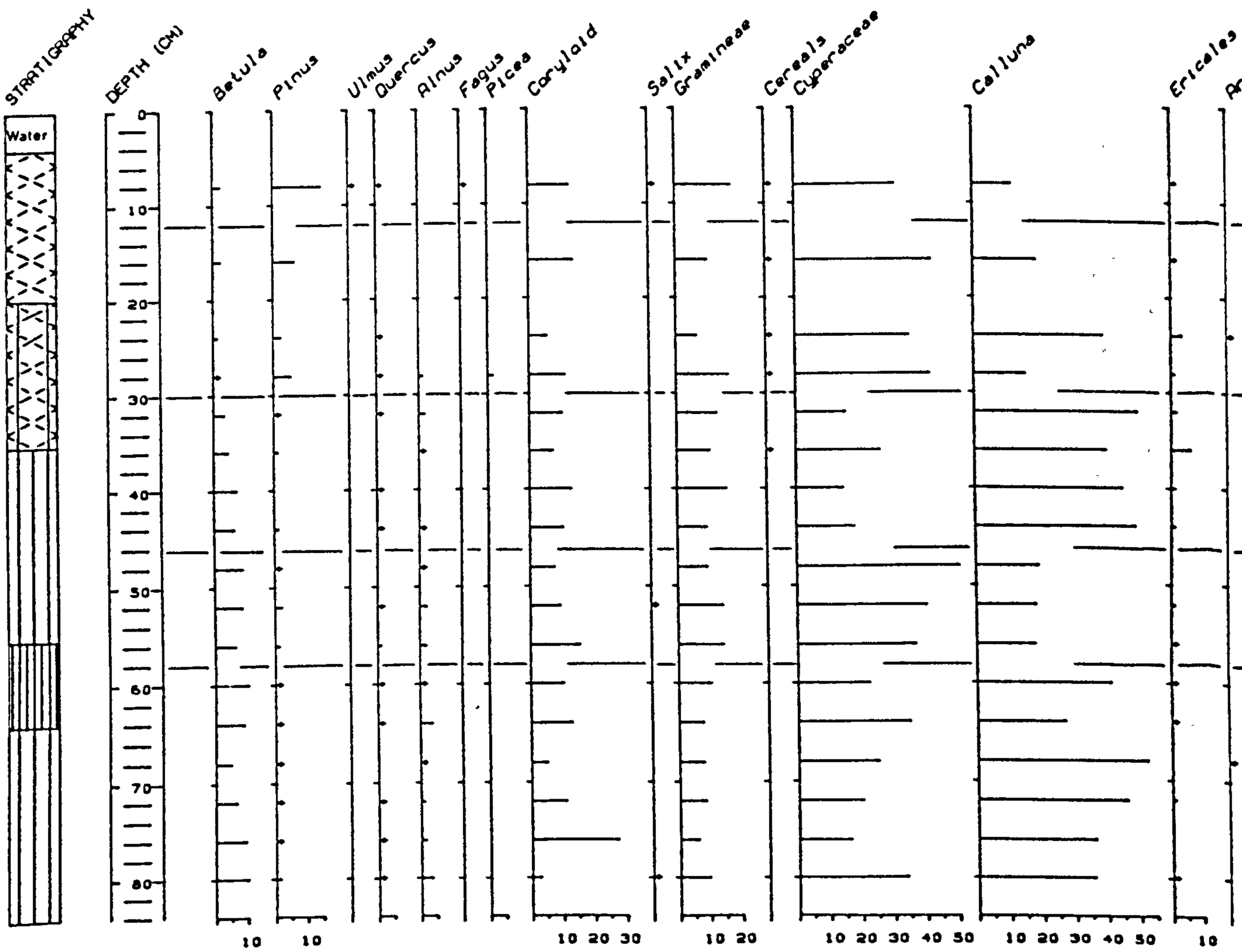
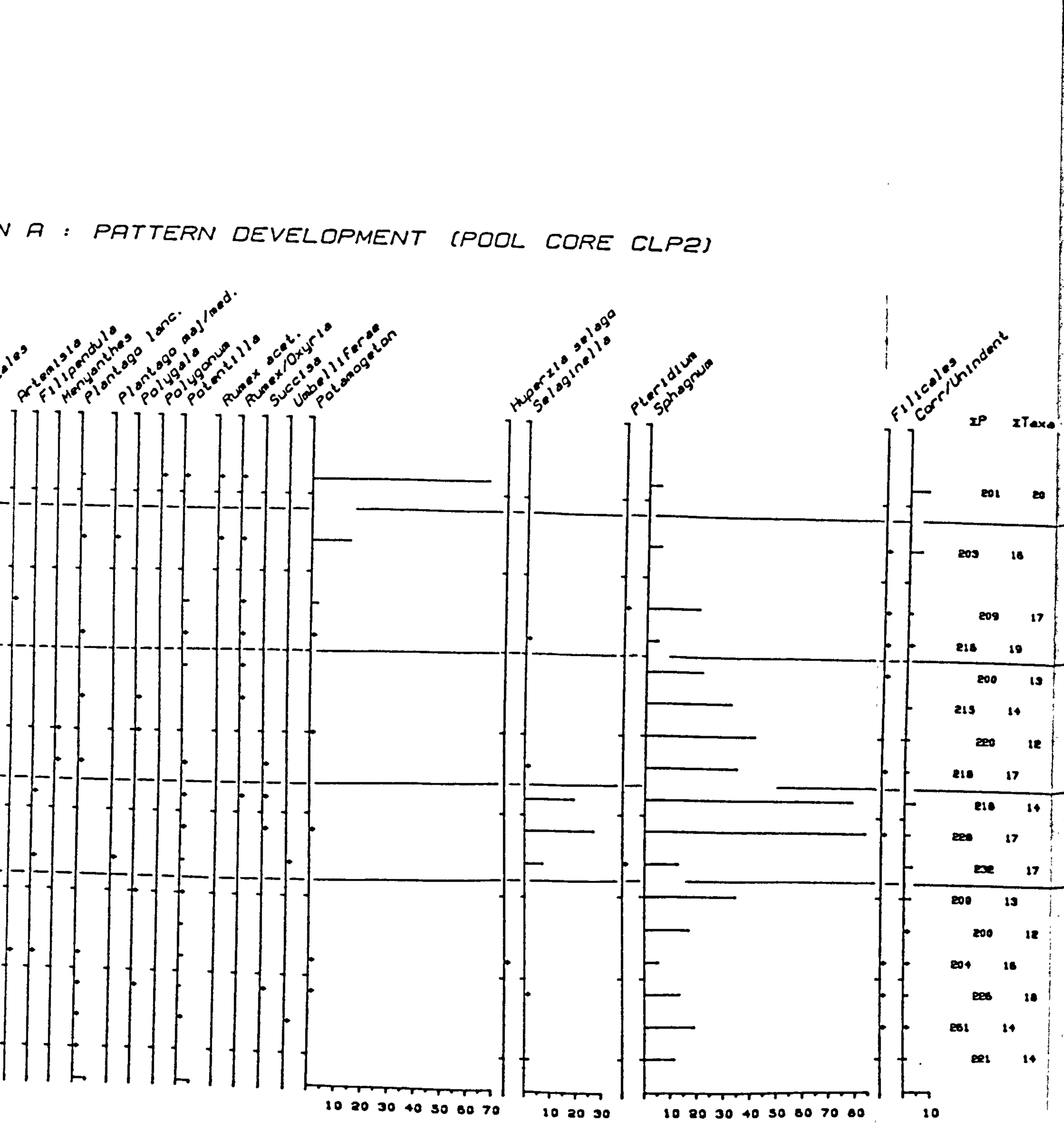


Figure 7.9: Percentage pollen diagram for pool core (CLP2).

N A : PATTERN DEVELOPMENT (POOL CORE CLP2)



T.L.P. + Aquatics

T.L.P. + Spores - Sphagnum

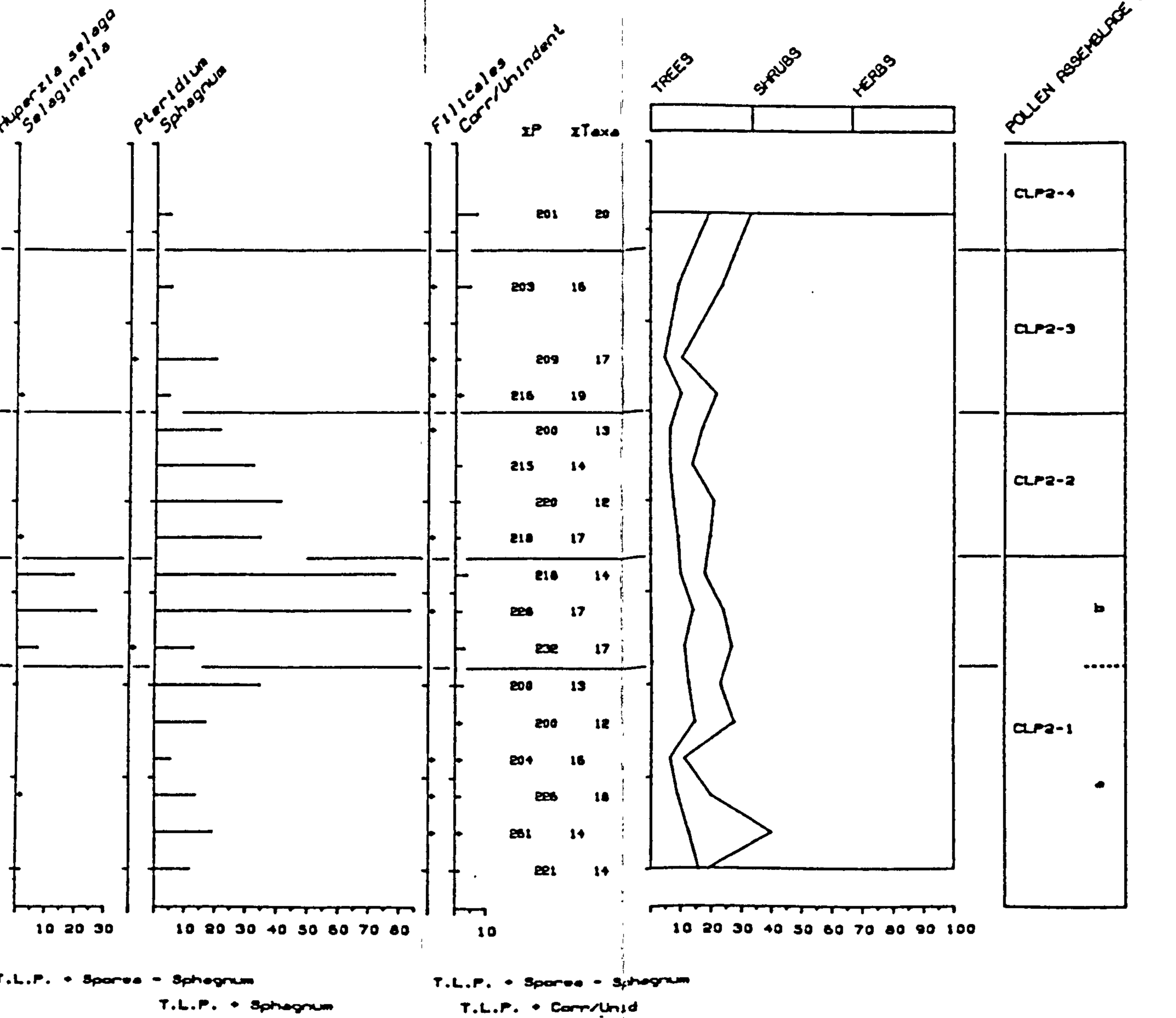
T.L.P. + Sphagnum

T.L.P. + Spores - Sphagnum

T.L.P. + Corr/Unid

A

L CORE CLP2)



Analysis DJ Charman 1988

CLP3-3 (38-12cm)
During this phase, *Pinus* reappears at low values (>5%TLP) after showing discontinuous occurrences of <1% during CLP3-2. *Ericales* rise to over 5% and *Calluna*, already declining at the end of CLP3-2 remains at low levels (ca.20%).

CLP3-4 (12-0cm)
This represents the modern pollen rain, probably with some downward movement of pollen falling on the surface through the loose *Sphagnum* moss. *Pinus* occurs at >20%, implying local presence in plantations established only recently (early 1980's), together with some *Picea*, almost certainly the *Picea sitchensis* planted locally.

7.7.2 Pool core (CLP2)

CLP2-1a (>58cm)
This zone covers a greater depth than that described from CLP3, because it appears to go back further in time. This is unsurprising as the core was removed from a present day surface depression, so that the top 80cm of peat actually goes rather deeper than the equivalent depth from the top of an adjacent hummock. However, the main features are the same as for CLP3-1a, with *Betula*>10% and *Calluna* relatively low, at least at the top of the zone. Separation of older subzones could be on the basis of *Potentilla* type and *Calluna* percentages, but this is not important here, as the main objective is comparison of the contemporary parts of both cores.

CLP2-1b (58-46cm)
Again this zone is clearly comparable with CLP3-1b, with the rise in *Selaginella* microspores.

CLP2-2 (46-30cm)
This zone possesses many of the features of CLP3-2, with decreased arboreal pollen of most types, increased *Calluna* (>35%) and a rise in Ericales during the top of the zone. *Sphagnum* spores also show a rise at the base of the zone,

although in this case they have already risen to high values during the latter part of CLP2-1b. However, *Betula* values do not decrease so significantly here, and the decline is gradual throughout the zone.

CLP2-3 (30-12cm)
Several of the features here are the same as those in CLP3-3. *Pinus* makes some recovery to ca.5-8% and *Calluna* declines to relatively low levels. However Ericales show a decline and the most obvious difference is the beginning of a rise to 15% (TLP+aquatics) in *Potamogeton*. This is the first clear indication of the formation of an aquatic community in this location.

CLP2-4 (12-0cm)
This again represents modern pollen deposition in the pool, characterised by raised levels of *Pinus*. At this time, *Potamogeton* achieves very high percentages of ca.70% of TLP+aquatics. Small amounts of *Fagus* pollen probably represent the few beech trees planted in Strath Halladale near to farms within the last 100 years.

7.7.3 Correlation and dating by comparison with CLA

The pollen stratigraphy described in Chapter 5 can be used to provide approximate date estimates for the two cores CLP2 and CLP3, although this has to be cautious as there are significant differences in local vegetation. The amounts of pollen coming from other sources which can be reliably separated from extra local pollen are extremely low, represented by the arboreal pollen which only achieves levels of 10-15%TLP here, due to the virtually treeless landscape. Other species outside the immediate mire vegetation are likely to be provide the same pollen types (Cyperaceae, *Calluna*) as the species found on the mire itself and these cannot therefore be differentiated from one another in the pollen record.

Figure 7.10 suggests the most likely correlation between cores and the date estimates derived from this. This is based upon the decline in *Betula* and the slight decrease in arboreal pollen generally and suggests that the top of zone CLP-1b may have occurred at around 1500bp. The expansion of *Myrica* and *Selaginella* is not evident in the CLP cores, but they do show a rise in Ericaceae, similar to that at the start of CLA4d. It is stressed that this is a tentative correlation only. A radiocarbon sample selected to provide a date for the time of pool initiation has been sent to the NERC Radiocarbon Laboratory at East Kilbride but the result of this analysis has not yet been received. Clearly there are major problems in attempting to estimate dates in the upper part of the profiles where processes of decay are still continuing relatively rapidly and full compaction has not yet taken place.

7.7.4 Pollen concentration

Pollen concentration data are presented in Figures 7.11 and 7.12. In discussing these data it is necessary to bear in mind the experimental errors inherent in the method, especially when applied to peats, described in Chapter 4.

The TLP concentration for CLP2 is very high (>100,000 grains cm^{-3}) at the lower levels (72-80cm). As the end of CLP2-1a is approached the level begins to fall and reaches a low of 42,500 grains cm^{-3} in the middle of CLP2-1b. Concentrations then rise to peak at the CLP2-1b-CLP2-2 transition at between 70 and 85,000 grains cm^{-3}. A very similar pattern, with almost identical magnitudes, is shown by CLP3, with a double peak either side of the trough centred on CLP3-1b, although the pollen record clearly does not begin as early as in CLP2, so there are no values greater than 100,000 grains cm^{-3}. Subsequent to this, both cores show general declines in pollen concentration, as would be expected towards the top of cores where the sediment becomes less compact, although there is a decline and recovery at the end of zone CLP2-2, also reflected in

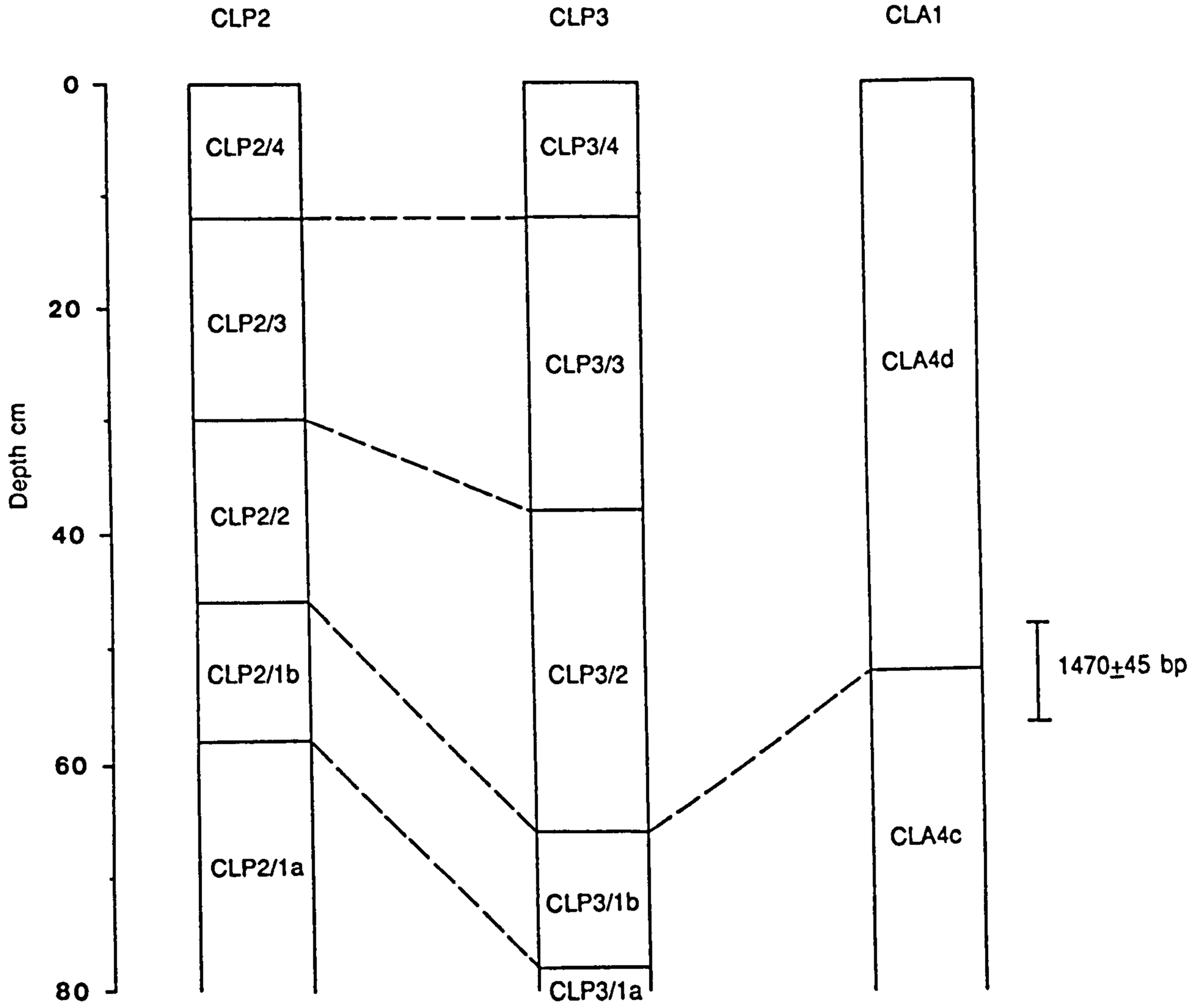


Figure 7.10: Correlation of pollen assemblage zones from pool (CLP2) and ridge (CLP3) cores and core 1.

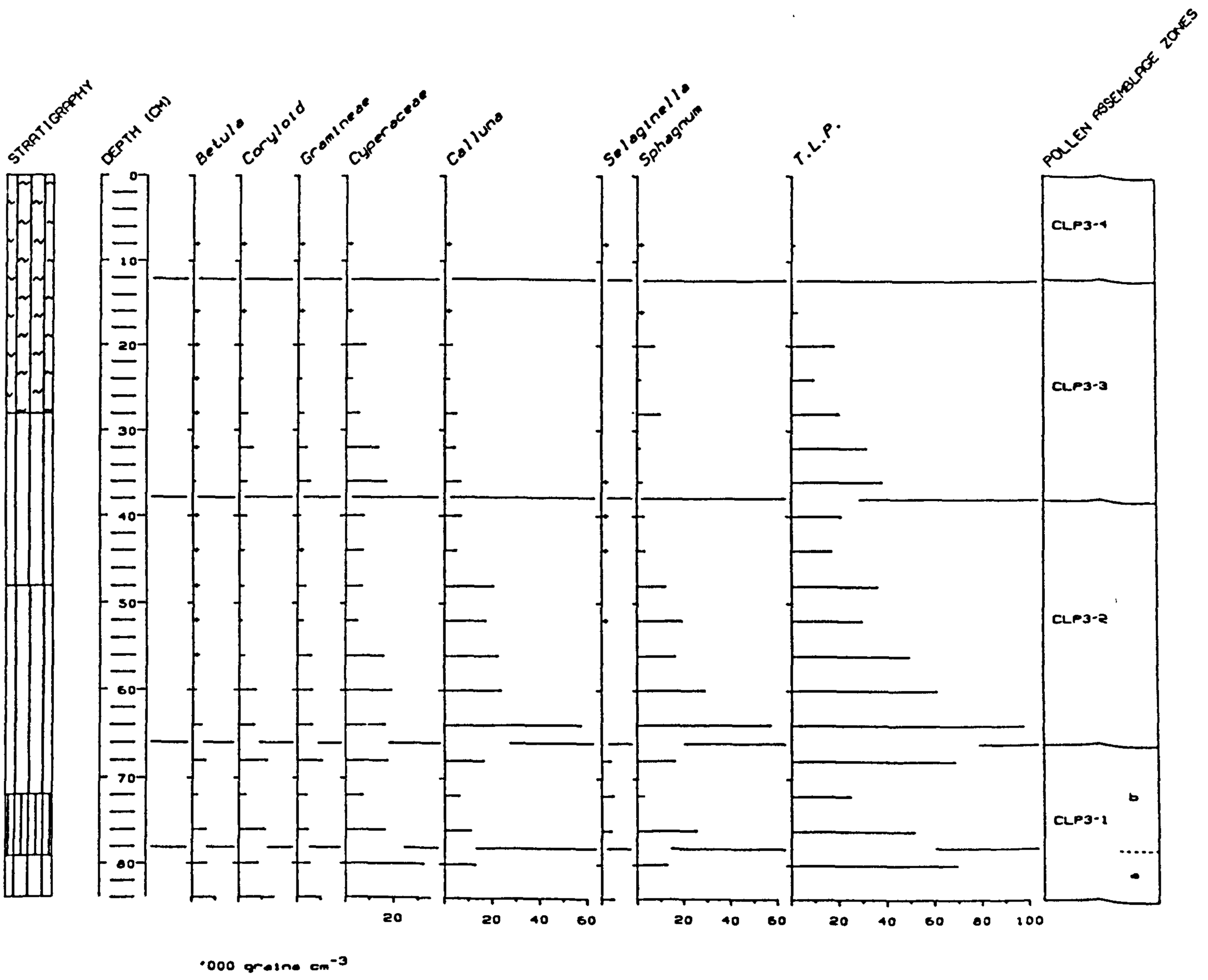


Figure 7.11: Pollen concentration diagram for ridge core (CLP3).

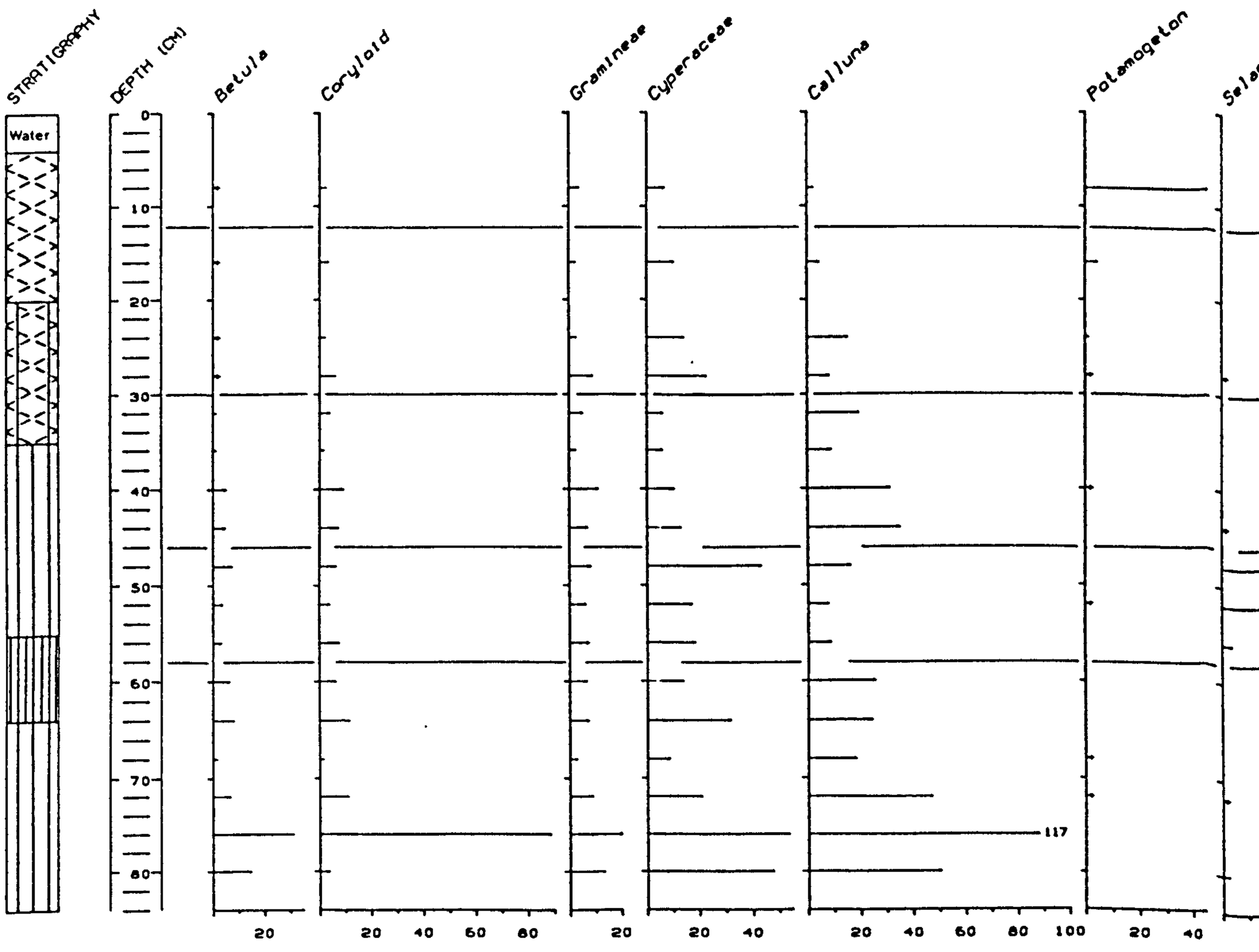
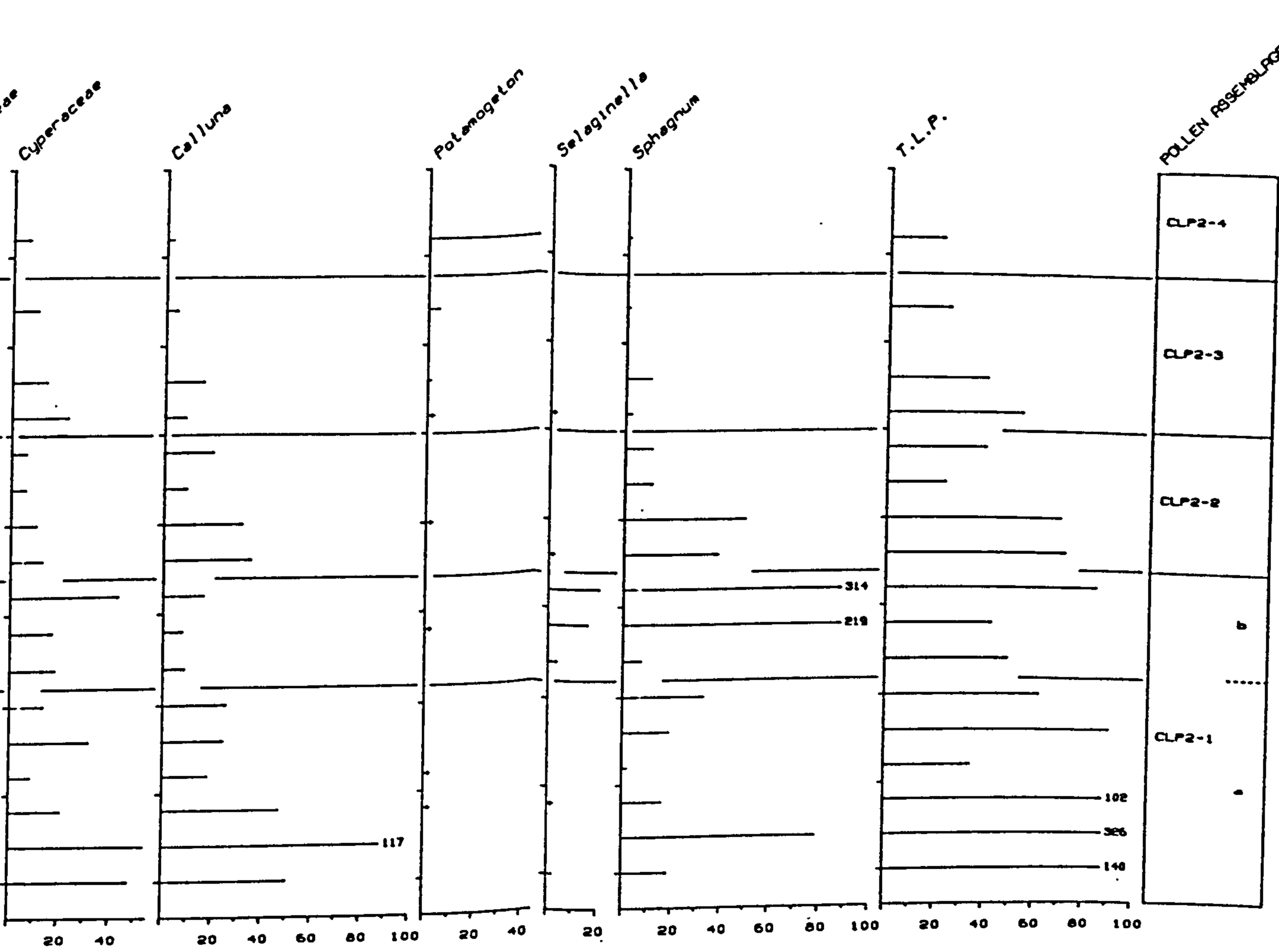


Figure 7.12: Pollen concentration diagram for pool core (CLP2).

FEN A : PATTERN DEVELOPMENT (POOL CORE CLP2)



Analysis DJ Charman 1990

or pool core (CLP2).

CLP3-2, supporting the temporal correlation of these two zones. However, although the two CLP-2 zones both show the same pattern of variation, this occurs over a greater depth in CLP3 (30cm compared with 20cm for CLP2) and concentrations are generally higher in CLP2 compared with CLP3. During zone CLP-3, concentrations in both cores show a general decrease, but those in CLP2 remain above 20,000 grains cm^{-3}, while those in CLP3 fall steadily to below 1,000 grains cm^{-3}. This is clear evidence that peat accumulation rates become much lower in CLP2 during the latter part of pollen zone CLP-2 and CLP-3 and CLP-4.

The higher concentrations in pool sediments contradict the findings of Wilkinson and Huntley (1987), who suggest higher oxygen levels in wet hollows lead to pollen deterioration at these locations. No such effect was recorded at Cross Lochs and pollen was generally well preserved. Therefore the hypothesis does not appear to be generally applicable, although differences in vegetation and hydrology may explain part of the discrepancy.

7.7.5 Conclusions from pollen analysis

The data suggests that during the end of zone 1a (the earliest level for which there is data from both cores) and throughout zone 1b, peat accumulation rates and pollen deposition were similar, and that there was a uniform peat surface in this area of the mire. Subsequently, although the pattern of fluctuations in concentration and the percentage pollen spectra allow temporal correlation of the cores, the concentration values and the greater depth of peat covered by zones CLP3-2 and CLP3-2 imply that there was a differential in peat growth rates during this time. This may therefore be the point at which the differentiation of present microtopographical features began.

In contrast, conclusive evidence of divergence of pool and ridge development does not appear in the taxa recorded

until the start of CLP2-3, with emergence of *Potamogeton*. However, there are other indications of differences in earlier levels. A comparison of the latter part of zone CLP-1b and the start of CLP-2 reveals that in CLP2, the rise in *Sphagnum* spores begins earlier and achieves much higher levels than in CLP3 (ca.75% compared with ca.35%). The cause of this difference may either be related to greater abundance of *Sphagnum* at CLP2 or it could be related to the relative ranges of dispersal of the local species, if localised waterlogging at CLP2 resulted in an inhibition of plant growth and canopy thinning. If *Sphagnum* spores were able to disperse more effectively than the pollen of *Calluna* and other species growing on the area of CLP3, then the observed differences in pollen spectra could occur. No macrofossil evidence of *Sphagnum* was found in CLP2, but there were small amounts of *Sphagnum papillosum* recovered from most of zone CLP3-2. This may indicate the initial nucleus of this species which now dominates the bryophyte layer of the ridge. The hypothesis of a thinning canopy is also supported by the curve for *Betula*, which shows a much less severe decline during CLP2-2 than CLP3-2. A more open canopy would allow more deposition of pollen from greater distances, such as that of *Betula*. Greater levels of *Calluna* and later, *Ericales* in CLP3 may be an indication of greater abundance of these species on this slightly elevated (and therefore drier) area, away from the depression at CLP2. An alternative explanation of the differences in *Sphagnum* spore curves would be that this genus was present at CLP2, and that greater abundance of spores is a result of increased abundance or is due to greater spore production of a different species. In this case it would have to be assumed that macrofossil remains have been entirely decomposed, which seems unlikely.

At the start of zone CLP-3 there is clear evidence of the start of pool development, as the *Potamogeton* rise begins at CLP2. This is the first indication of an aquatic community similar to the one found today. This stage of pool formation is shown in concentration values by the

rapid decline during CLP3-3 compared with the more moderate decline during CLP2-3, due to a greater differentiation of peat growth rates. Modern pollen rain in surface peat and pool sediment is similar but there is no *Picea* in the pool. This may be due to the large, light grains floating on the water surface and being blown to the edge of the pool.

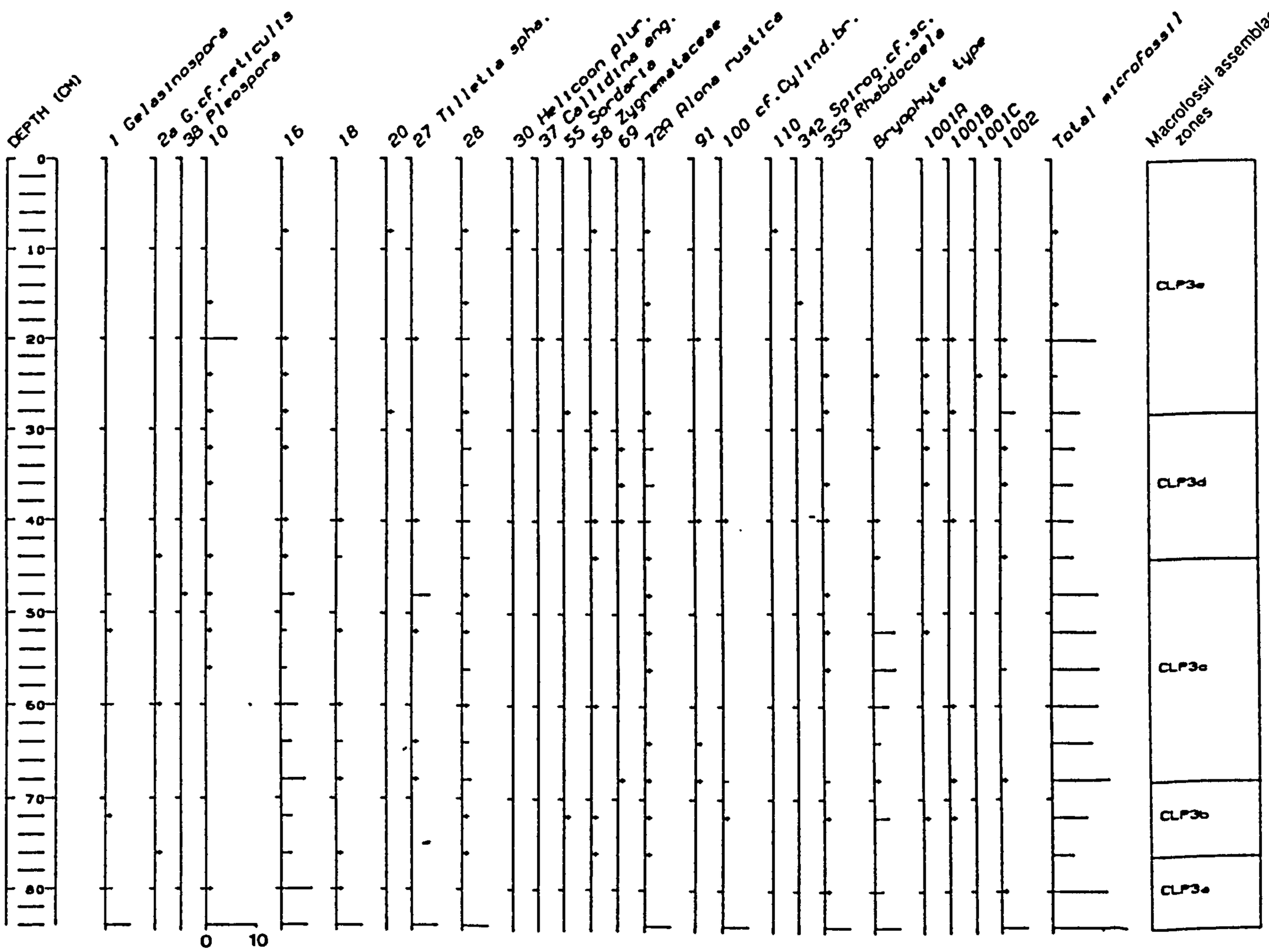
7.8 OTHER MICROFOSSIL DATA

The drawbacks and present limitations of using microfossils other than pollen for palaeoecological inferences have already been discussed in the relevant sections of Chapter 4 and Chapter 5. However, there is useful additional information to be gained from this source, so that some of the microfossil data is briefly discussed in this section. The full diagrams of microfossil occurrences are shown in Figure 7.13 and 7.14, and the pollen assemblage zones are shown on these, as the results are discussed in relation to that data.

Only some of the taxa are of use here, as some are almost ubiquitous throughout both cores or are recorded at very low values. Also, there are some for which there is no reliable information on identity or ecological requirements. During zones 1a and 1b microfossil assemblages are similar in both cores, supporting the hypothesis of similar conditions at both locations. However, spores of *Tilletia sphagni* increase towards the end of CLP2-1b, presumably associated with the increased level of *Sphagnum* spores mentioned previously.

Differences appear during zone 2, however, with Type 10 and Type 18 both showing more constant and higher levels in CLP3-2 than in CLP2-2. Type 18 is associated with *Eriophorum vaginatum*, and may be the fruit bodies of a leaf fungus growing on this species (Van Geel, 1978). Van Geel (1978) suggested that Type 10 is probably a mycorrhiza of *Calluna vulgaris*, suggesting that this species was more

CROSS LOCHS FEN A : PATTERN DEVELOPMENT (RIDGE CORE - CLP3)



Analysis DJ Charman 1990

Figure 7.13: Non-pollen microfossil diagram for ridge core (CLP3).

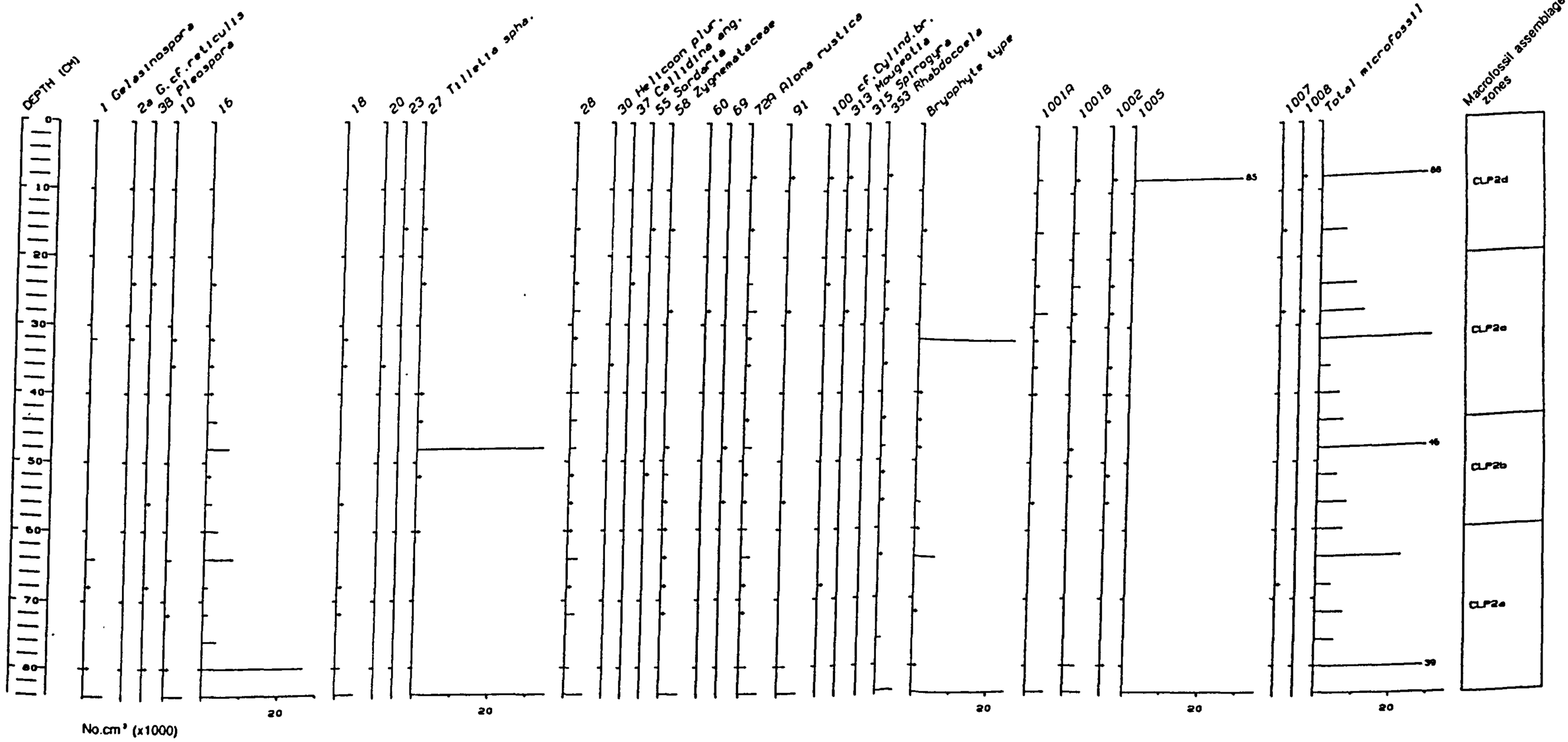


Figure 7.14: Non-pollen microfossil diagram for pool core (CLP2).

abundant on the embryo hummock area. This supports the assertion of locally drier conditions and increased *Calluna vulgaris* at CLP3, made on the basis of pollen evidence. The trend is continued into zone 3 for Type 10, where it disappears from CLP2-3 altogether and reaches a peak in CLP3-3 at 20cm. Higher levels are recorded for the almost ubiquitous Type 28 here, too. Different conditions are most obvious in modern samples, which may be partly a result of incomplete decay processes. Unidentified algal(?) types (1001A, 1001B, 102 and 1005) are particularly abundant in CLP2-4, with Types 32A (*Assulina muscorum*), 32B (*A.seminulum*), 31A (*Amphitrema flavum*) and 354 and being confined to the surface sample of CLP3-4. All these types are generally associated with *Sphagnum* peats, and *A.flavum* is restricted to *S.cf.rubellum* (=Sect.*acutifolia*) (Van Geel, 1978) and has therefore been used as an indicator of relatively dry mire conditions. Although the count of Type 354 is low, its occurrence is interesting as it has been found to be associated with the transition to *Sphagnum* peat growth (Van Geel et al, 1981).

7.9 PALAEOECOLOGICAL CONCLUSIONS

The different components of the palaeoecological evidence described here are in general agreement in relation to pool development. All suggest that there were no significant microtopographical differences until relatively recently. However, there are differences in the depths at which the various techniques used indicate a divergence of pool-ridge development. Stratigraphic data reflect the change at about 35cm in CLP2 and 48cm in CLP3. Macrofossil data show that peat composition cannot be accurately assessed from stratigraphy alone and changes here are not evident before 20cm in CLP2 and 44cm in CLP3. However, there are serious drawbacks with both the techniques, as used here, due to limited resolution and identification of remains.

Conclusive pollen evidence of wetter conditions in CLP2

exists from 28cm, where *Potamogeton* begins a rapid rise. There are also indications that change was occurring before this time, when pollen concentration and estimated peat growth rates are considered in conjunction with fluctuations in curves of *Betula*, *Calluna* and *Sphagnum*. It is suggested that waterlogging at CLP2 led to reduced productivity of the local plant community and therefore to a decrease in peat growth rate. The area around CLP3 remained drier and the growth of dwarf shrubs (especially *Calluna*) was uninhibited. Evidence from other microfossils also supports this assertion. *Sphagnum papillosum* colonised the area around CLP3 and began to form the low, elevated ridge seen today.

7.10 PRESENT PROCESS OBSERVATIONS

During the course of fieldwork, many observations were made on the nature of surface patterning on a variety of sites. There is no way of formally analysing such 'data', but this sort of information is useful in formulating and supporting hypotheses of the way in which pools are likely to form and be maintained. This short section describes some of the main observations and discusses them in connection with the ideas put forward in the previous sections and the possible future development of existing patterned areas.

7.10.1 Pool initiation

Plate 7.1 shows a shallow depression within a uniform Carex lasiocarpa - Molinia community. This kind of feature is quite commonly found in unpatterned areas of mire with vegetation similar to that of patterned fen ridges (Noda 1 and 2 of Chapter 3). Although there is no standing water within the hollow, it would clearly be one of the first areas to be inundated in times of increased surface wetness. While there is little difference in terms of the species present, from the surrounding vegetation, the plants are further apart and less vigorous. This may



Plate 7.1: Shallow depression in *Molinia-Carex lasiocarpa* community, forming suggested incipient pool.



Plate 7.2: Mature linear pool, on intact mire surface.

represent the initial stage of pool formation, where a slight undulation in the surface is enough for water to begin to collect and to inhibit plant growth by providing temporarily anaerobic conditions. Inhibition of growth rates by waterlogging has been shown for several mire plants (Gore and Urquart, 1966) and *Molinia caerulea*, a common patterned fen species, has higher productivity in relatively well aerated mire conditions (Armstrong and Boatman, 1967). This 'incipient pool' surface feature may be an analogue for the early differences in pollen records found at CLP2 and CLP3, where it was proposed that canopy thinning and reduced productivity and growth rates occurred prior to any qualitative species change.

7.10.2 Pool maintenance and expansion

Once this process leading to locally reduced peat growth rates has begun, it is self perpetuating, and depressions become deeper as surrounding peat continues to grow unchecked. In fact, surface depressions are likely to provide a local drainage effect on immediately adjacent areas, perhaps increasing growth rates here, particularly if they were also less susceptible to enrichment from surface seepage, allowing colonisation by *Sphagnum* species. The edges of pools are subject to periodic submergence and are thus in a similar position to the shallow depressions mentioned before, of reduced peat growth rates. Therefore the pool expands outwards.

These more sparsely vegetated pool edges can be seen in Plate 7.2, showing a mature linear pool, typical of most of the intact patterned surfaces.

Sometimes pools of greater width are encountered, and often it appears that this is a result of the breakdown of an intervening ridge, probably by the expansion mechanism described above, but there may also be some effect of erosion by oxidation of the peat and possibly even wave action. Plates 7.3 to 7.5 show several different stages of



Plate 7.3: Early stage of ridge break down on mire with low gradient, with penetration of adjacent pools.



Plate 7.4: Ridge remnants, following further ridge break down.



Plate 7.5: Ridge remnants, with amorphous peat decayed ridge in foreground.

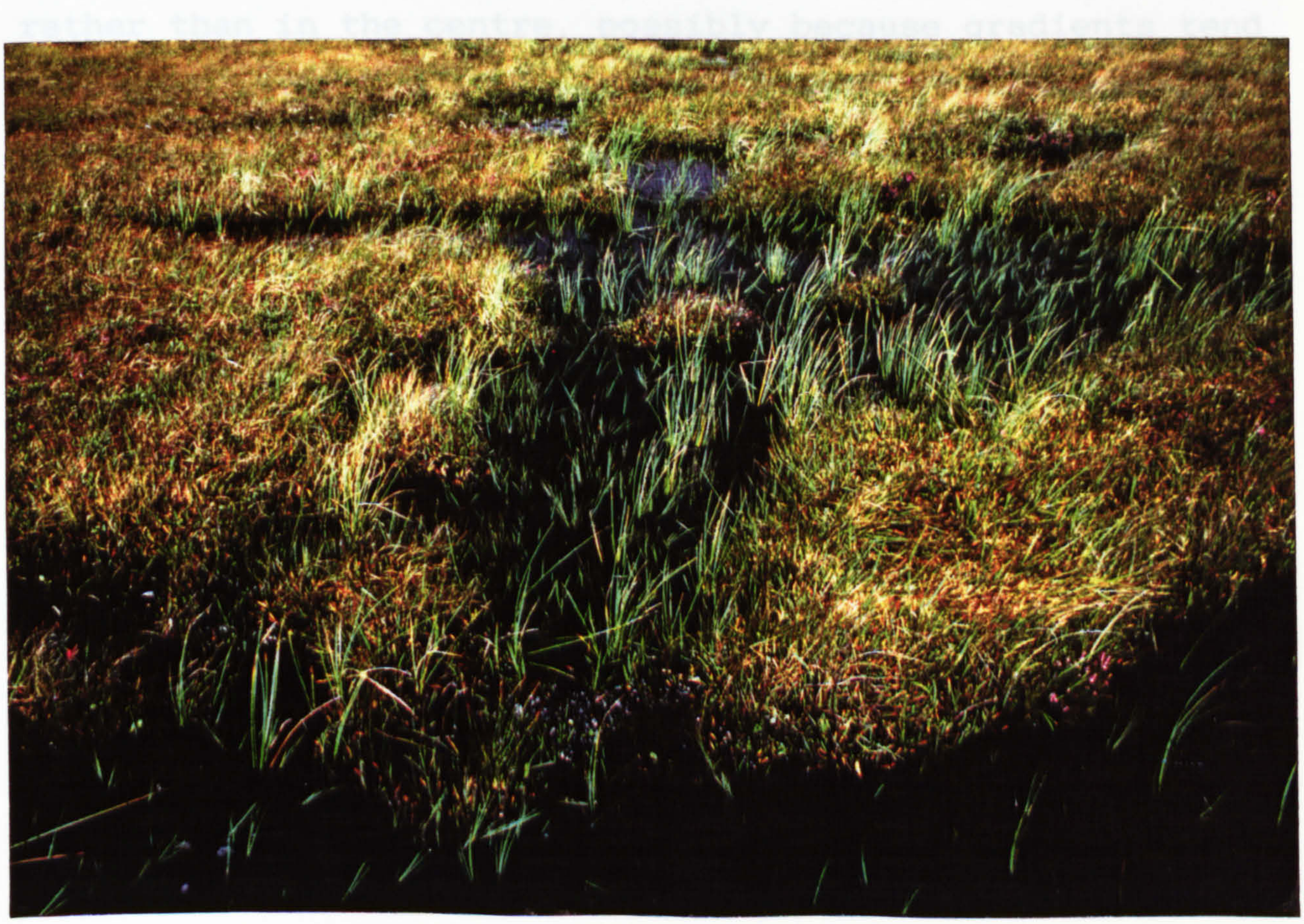


Plate 7.6: Channel cut through ridge on steeply sloping mire

this expansion. Initially, the pool expands along a line of weakness in the ridge and breaks through to the next pool, usually downslope (7.3). This may then happen in several other places and the former ridge becomes a string of small islands (7.4). Finally, some of the islands are unvegetated and form only amorphous peat masses rising to the surface of the pool (7.5).

7.10.3 Pool breakdown and the collapse of patterning

Where there is a large height differential between adjacent pools, this breakdown of intervening ridges can be observed as a channel beginning to cut through the ridge (Plate 7.6). This is often vegetated only by *Narthecium ossifragum*. In some cases this appears to be a gradual process, and where it occurs in a number of different places down the length of the mire, it results in the development of a continuous, meandering channel, formed by the breaks in ridges and existing pools. This appears to be more frequent at the top and bottom of the patterned area rather than in the centre, possibly because gradients tend to be somewhat steeper in these parts. It has been suggested that this is the stage before linear pool formation (Lindsay et al, 1988), but this envisages infill of channels, which seems unlikely given the very slow peat accumulation rates in the aquatic zones.

Clearly, there are a number of possible ways in which gradual ridge breakdown may occur, but occasionally a catastrophic event may occur under the correct conditions. Plate 7.7 shows an area of patterning shortly after such an event, which appears to be similar to the widely recorded 'bog bursts' on ombrotrophic mires (eg.McEwen and Withers, 1989). In this case the ridges seem to have reached a critical weakness for the pressure from the pools they hold back and mass movement of peat has occurred, even to the extent of sections of ridge being found 5m downslope of the photograph.



Plate 7.7: Catastrophic ridge collapse and mass movement of peat.

7.11 GENERAL DISCUSSION

The suggested mode of pool formation discussed above has similarities with several of the mechanisms proposed for pattern development on other mire systems. The initialisation of pools by locally reduced peat accumulation is put forward by a number of workers on a variety of different systems. Various papers from workers on the Silver Flowe, Galloway have suggested that *Sphagnum cuspidatum* can invade *S.papillosum* lawns (Boatman and Tomlinson, 1977), and forms peat less rapidly than surrounding *S.papillosum*, due to reduced growth rates of the living plants (Boatman, 1972, 1977, 1984) and/or increased rates of decay (Hulme, 1986). Workers on patterned fens in North America suggest that differential growth rates of higher plants leads to some topographical variation in the fen surface and that this is accentuated at times of waterlogging, when the anaerobic conditions in the minor depressions lead to reduced productivity and peat accumulation (Foster et al, 1983, Foster and King, 1984; Glaser, 1987). A similar situation probably exists on Scottish patterned fens, although it cannot be conclusively shown that the occurrence of different species was responsible for initial microtopographical variation. The occurrence of patterning at North Altnaharra, a site showing somewhat different morphological development (Chapter 6), is further evidence that the development of surface pools is not limited to particular mire or vegetation types.

Various mechanisms for pool expansion and spread have been proposed. Coalescence of adjacent pools across the slope is suggested as the main cause of linear pool development in North American patterned fens, followed by deepening and widening by cessation of peat accumulation and degradational processes by microbial action and methanogenesis (Foster et al, 1983). This active degradation cannot be occurring in *Sphagnum* filled follows on raised mires as subfossil records of such features are

found (Barber, 1981; Walker and Walker, 1961). However, it is clear that peat accumulation in bog hollows is lower than that on hummocks (Van der Molen and Hoekstra, 1988). It is theoretically possible that there is degradation occurring in Scottish patterned fens, as there is little vegetation and rarely any *Sphagnum* in the pools here. However, the conformable pollen record and (relatively) low pollen concentrations suggest that peat accumulation is merely exceedingly slow. If degradation does occur it may be that it is mainly active on pool sides and is not a major agent of pool deepening at present, particularly as pools are very shallow (ca.5-10cm water). This difference in the balance between peat accumulation and degradation has been shown in a comparison of Swedish and eastern Canadian mires (Foster et al, 1988b), for both bog and fen pools. Pools are deepening by peat degradation in the Canadian sites, while there is slow accumulation in the Swedish sites.

The longer term effects of degradation have been noted by observation of pool systems over a long period of time and it has been shown that on ombrotrophic mires pools and hollows do have a tendency to coalesce and degrade adjacent shorelines progressively (Mets, 1972). Similar effects have been noted by the use of air photographs (Boatman and Tomlinson, 1973). The observation of various stages of ridge degradation (Plates 7.3-7.5), would suggest that similar changes occur on Scottish patterned fens.

There is no evidence that any of the physical influences on pool formation are implicated on the sites under investigation. Freeze-thaw processes are clearly active in boreal mire systems, particularly the more northerly and high altitude sites (Henoch, 1960; Vitek and Rose, 1980), but the importance attached to it by some authors (Auer, 1920; Thom, 1972; Schenk, 1959, 1966) has subsequently been questioned (Forsgren, 1969), and it seems to be agreed that it is responsible for accentuation of patterning rather than its initiation (Moore, 1982; Foster et al, 1983;

Seppala and Koutaniemi, 1985). Although there is correlation between climatic zones and patterned fens (Thompson and Worley, 1984), the occurrence of patterned fens on the margins of the region of severe frost (Grittinger, 1970) and more oceanic areas of North America (Davis et al, 1983; Sorensen, 1986) suggest this is not an essential process here, and the same argument has been used for blanket mire in south west Scotland (Boatman, 1983). No data was collected on frost persistence and penetration on patterned fens in Sutherland but climatic records from nearby weather stations suggest it is unlikely to occur to any great extent. Effects of moving water pressure (Madsen, 1985) are also only likely to be important in boreal regions, where the spring melt provides large amounts of water at one time. Similarly, there is no evidence for 'thatch line' processes (Sakaguchi, 1980; Sakaguchi and Sohma, 1982) or mass movement of peat causing splitting (cf. Pearsall, 1956; Pearson, 1960; 1979). The pools would be expected to be of a different shape if this were occurring, and patterning would be best developed on the sites with the steepest gradients, but this is not the case.

Work on the Silver Flowe, Galloway, shows that the distribution of pools is associated with areas of increased surface wetness, as a result of water flow from man made and natural drainage on to the mire surface (Boatman and Tomlinson, 1973) or due to sub peat basins (Boatman et al, 1981). The sub-peat topography shown in Chapter 6 indicates no correlation between patterning and deeper areas of peat, probably because the hydrology of the site has changed considerably since peat inception. Patterned areas on the Cross Lochs A and other sites may be associated with the emergence of sub-peat pipes at the surface, increasing the supply of water.

The recent development of the pools is in contrast to many other British mire systems, where in a variety of cases they can be shown to be long standing features (Walker and

Walker, 1961; Moore, 1977; Barber, 1981; Smart, 1982), although there are examples from oceanic mires where evidence for pools exists only in the top metre, representing peat growth over the last 900 years (Boatman et al, 1981; Hulme, 1986). Patterned fens in North America and Scandinavia appear to show more comparable stratigraphy, and pools have been shown to have developed at a variety of dates within the last 2,000 years (eg.Seppala and Koutaniemi, 1985; Foster and King, 1984). However, the recent development of fen pools on these mires is unsurprising in view of the relatively recent development of the poor fen vegetation itself (Chapter 6). The primary cause of pool formation remains enigmatic, possibly being locally changing hydrology (emergence of sub-peat pipe) or climatic shift. The latter possibility may become clearer when a radiocarbon date for pool initiation is available.

CHAPTER 8: OMBROTROPHIC MIRE DEVELOPMENT

8.1 INTRODUCTION

Preceding chapters have concentrated on the patterned fen systems of the north of Scotland, investigating the past and present vegetation and development of these unusual mire systems. However, the majority of the Flow Country blanket mire consists of ombrotrophic peatland, and this chapter considers aspects of its development in relation to the patterned fen systems. The first part of this chapter considers the later development of an ombrotrophic system up to the present day, using similar methods to those for the patterned fens, and the second part examines the changes taking place in the transition from mineral substrate to basal peat deposits.

8.2 LATER MIRE DEVELOPMENT

It has already become apparent (Chapter 6) that the poor fens only developed relatively recently from previously ombrotrophic mire systems, the deepest parts of which originated in waterlogged hollows, with some peat of this type developing directly over mineral ground. This raises the question of whether the previous peat growth encouraged the development of poor fens in particular locations, or whether it was occurring in a similar way elsewhere, in places now occupied by ombrotrophic mires. If early peat growth beneath ombrotrophic surfaces is identical to that beneath patterned fens, then it may be possible to propose a general model for early peatland development in the region, and to suggest that patterned fen initiation only took place as a response to some external influence.

The aim of this first part of the research was to compare the development of the two mire types to see whether similar changes did in fact take place on ombrotrophic

mires in the early to mid-Holocene and if so, how subsequent mire development differed from that of the patterned fens.

8.2.1 Site selection and description

Data from two patterned fens in the Cross Lochs area has already been shown in Chapter 6 and has provided a local pollen chronology in Chapter 5. One of the adjacent ombrotrophic mesotopes was close to both sites, appeared to be a 'typical' mire unit of the area and was an appropriate size for a limited study. This was also the site from which quadrats were taken for the ordination comparing ombrotrophic blanket mire and patterned fen vegetation (Section 3.4.5). In addition the pollen chronology already established could be used for approximate dating of deposits. The general location of the site (referred to as Cross Lochs 'ombrotrophic') and its relationship with the two patterned fen sites are shown in Figure 5.1 and the main site features are indicated in Figure 8.1.

The site is a patterned ombrotrophic mire with round to oval pools, conforming to the description of 'central watershed blanket bog' (Lindsay *et al*, 1988). It is located to the east of the Cross Lochs, covering the eastern part of the main summit area. Although this is a watershed mire, it slopes gently approximately south to north, with a flat area at the southern end. The patterned zone merges into the more steeply sloping peatland to the south and east, with a low ridge of mineral ground in along some of the eastern edge, and Cross Lochs 'A' patterned fen beyond this. Cross Lochs 'B' patterned fen lies to the north and there is a mineral outcrop with some thin peat to the south west. The deep oval pools have little vegetation, with sparse growths of *Menyanthes trifoliata*, *Eleocharis multicaulis* and *Sphagnum auriculatum*. Most of the ground between consists of *Tricophorum cespitosum/Calluna/Erica tetralix* mire with scattered, depauperate *Myrica gale*, of variable surface wetness with moderate *Sphagnum* cover of

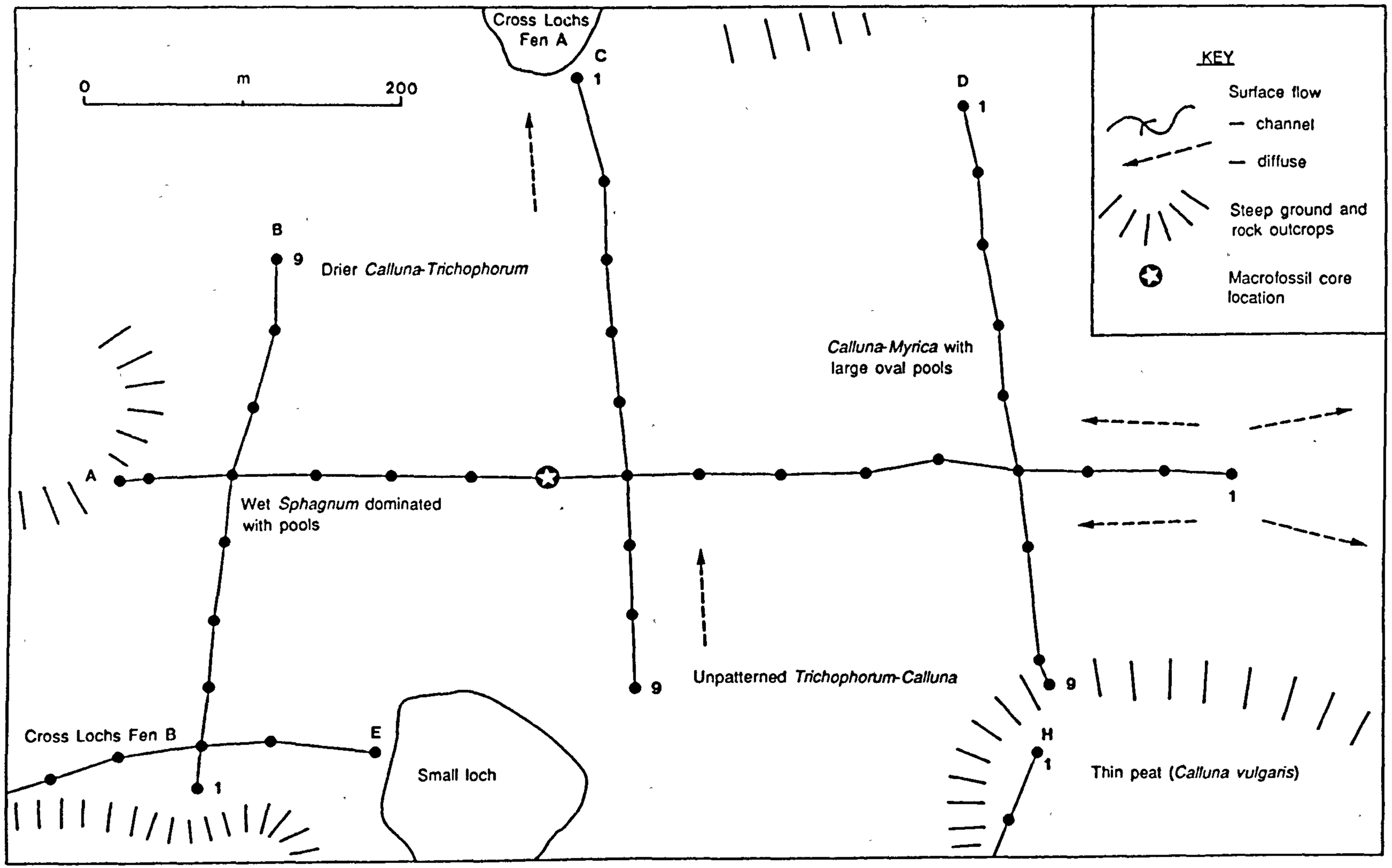


Figure 8.1: Main site features and location of core transects at Cross Lochs Ombrotrophic site.

various species. The northern part of the site is much wetter, with abundant *Sphagnum tenellum*, *S.capillifolium*, *S.papillosum* and *S.cuspidatum*, with a more gradual transition to the shallower pool communities. The shallower peat areas and more steeply sloping ground is dominated by *Calluna* or *Tricophorum cespitosum*.

8.2.2 Mire morphological development

Four transects of peat depth measurements and cores were surveyed by the same methods used for the patterned fen surveys in Chapter 6. The location of these transects is shown in Figure 8.1, with a three dimensional representation of the peat depth data in Figure 8.2. Stratigraphy of selected cores is shown in Figures 8.3 and 8.4, with additional data for transect B contained in Chapter 6, Figure 6.19.

The peat depths reveal that the mire has developed in a valley, running south to north, with the valley sides becoming higher and steeper further downslope. There was probably an enclosed basin within this valley as lacustrine deposits collected at the base of core A10. This valley appears to have run NNW towards the Cross Lochs 'B' patterned fen.

The shallow lacustrine deposit at the base of A10 is overlain by monocotyledonous peat with remains of birch, and this is also found in the deepest parts of several other cores, although B4 has few birch remains amongst the *Sphagnum* and monocotyledonous peats which are found at its base. Seeds of *Menyanthes trifoliata* were particularly abundant here and it may be that conditions were too wet for birch to survive at the core location. It appears that sedge fen with birch colonised the water collecting areas and gradually began to accumulate peat throughout most of the valley.

Birch remains are also present at the base of some of the

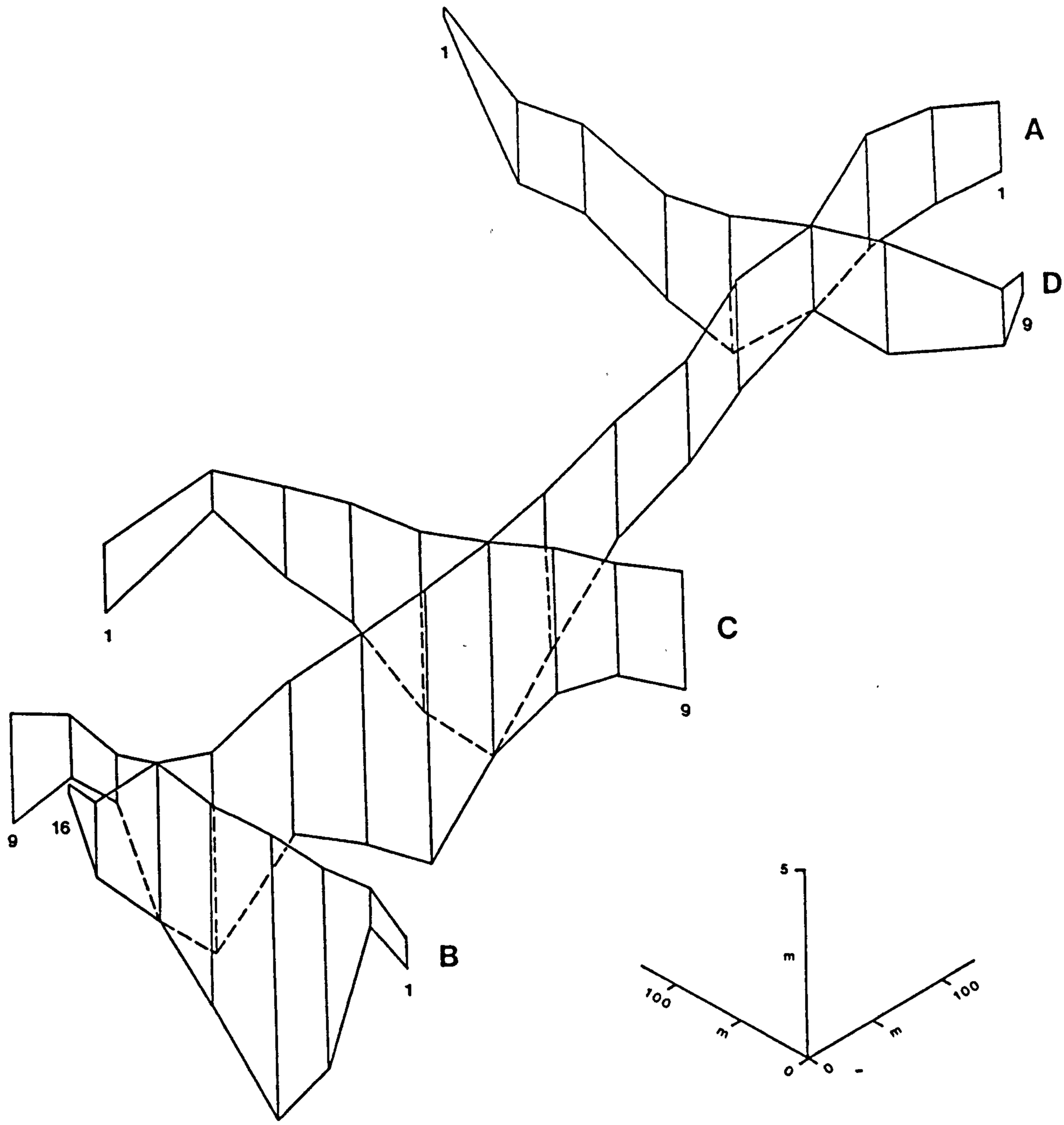


Figure 8.2: Three dimensional plot of peat depths for Cross Lochs Ombrotrophic site.

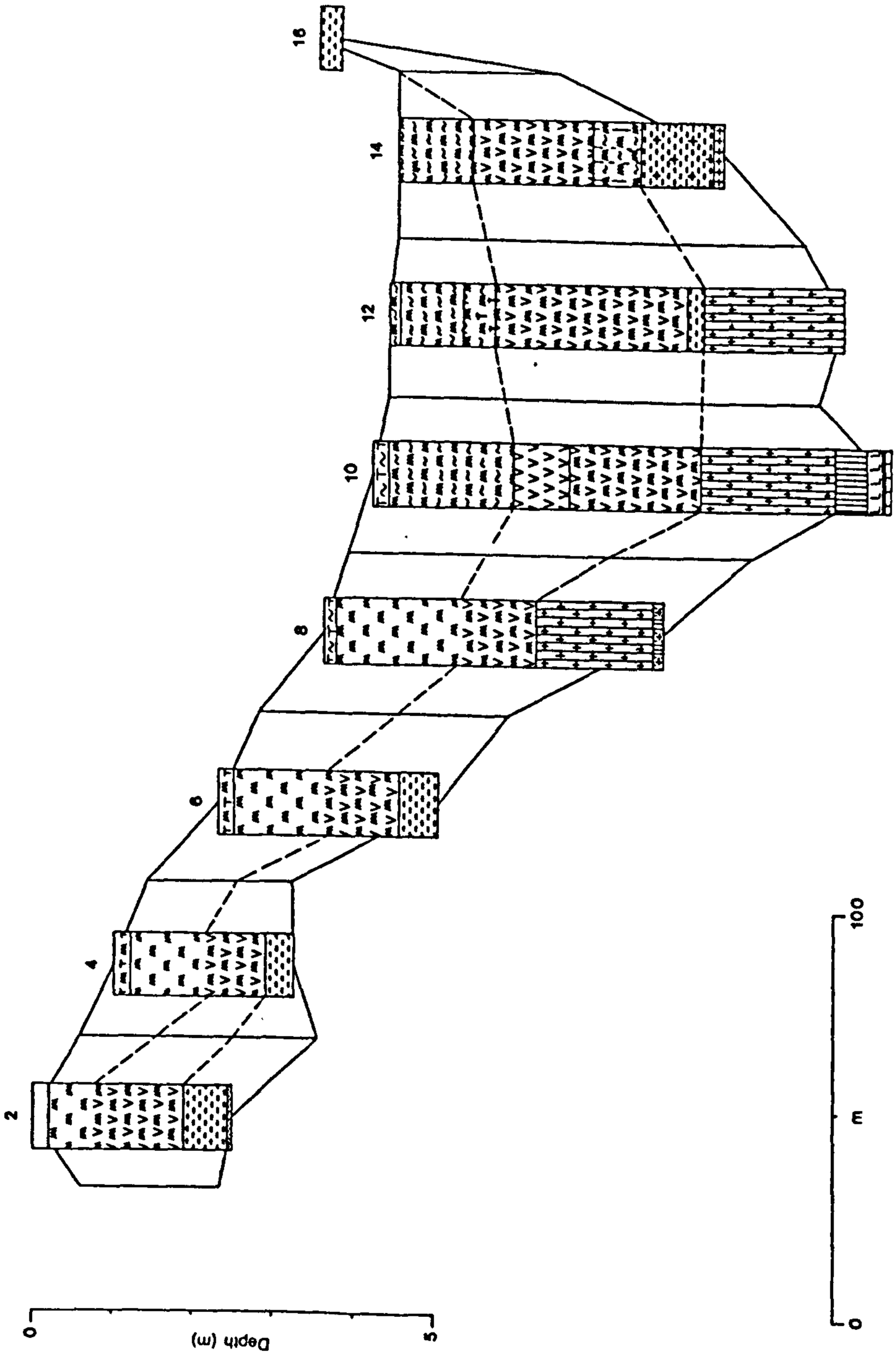
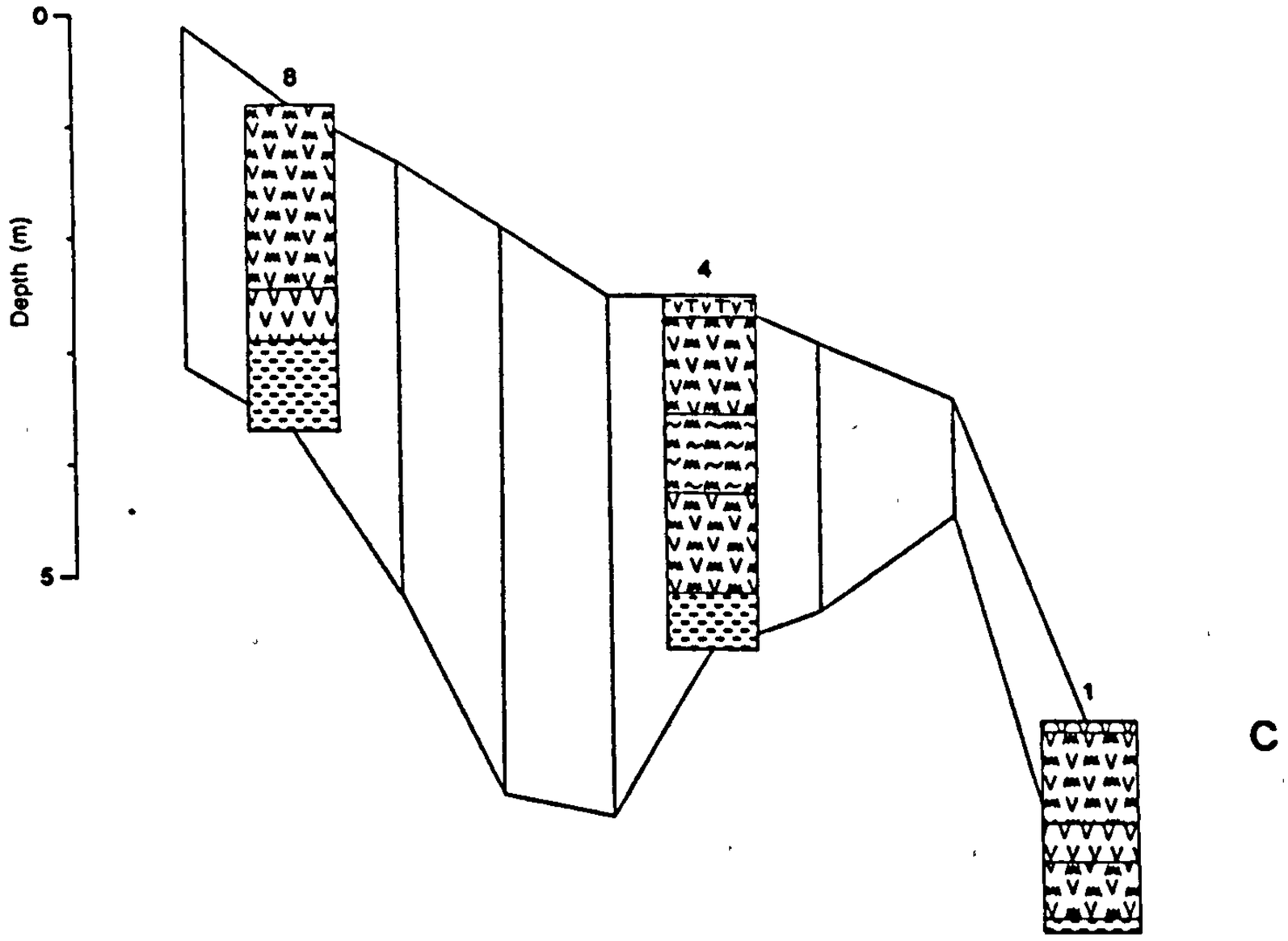
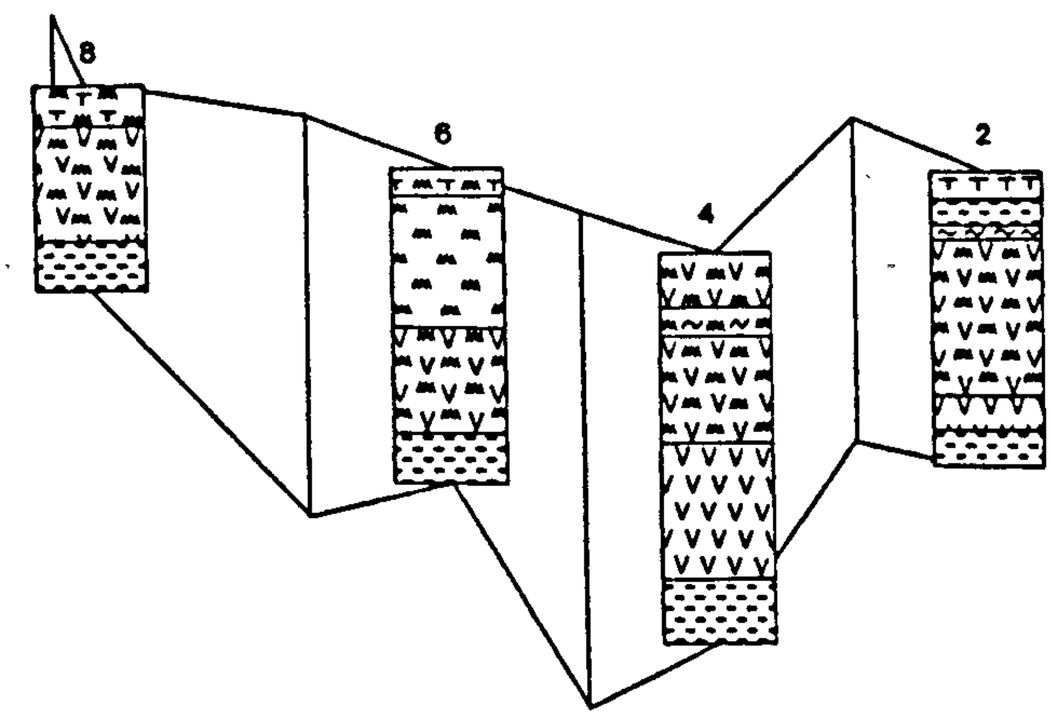


Figure 8.3: Stratigraphy of transect A at Cross Lochs Ombrotrophic site.





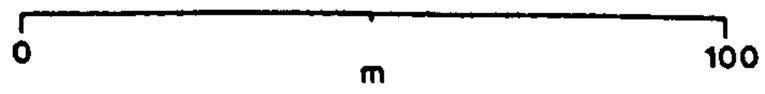


Figure 8.4: Stratigraphy of transects C and D at Cross Lochs Ombrotrophic site.

other cores, although most of the basal material is highly humified and unidentifiable. Above this however, peats dominated by *Eriophorum* remains are ubiquitous, although their humification is variable, with more humified peats on the more steeply sloping areas. There is a detectable component of monocotyledonous remains in peats at the bottom of the valley, with it dominating throughout much of core B4. None of this peat appears to have abundant birch remains so that during this ombrotrophic phase the mire was probably treeless.

There is little change in the peat composition of most cores until the surface, apart from some decrease in humification. Surface peats were generally *Tricophorum* roots with some *Sphagnum* remains. The part of the mire which is the wettest today, around A12 and A14, has rather different stratigraphy in the top 1-2m, with *Sphagnum* peats, some ericaceous remains and large amounts of *Menyanthes* seeds. This may indicate increased surface wetness in this area in more recent times.

The earlier mire development is therefore very similar to that described for three of the patterned fen sites, with basin infill with birch and sedge peat, followed by ombrotrophic mire development. However, there is no subsequent reversion to poor fen peats, although there is some indication in several cores from the wetter part of the site that *Sphagnum* has become increasingly important more recently.

8.2.3 Community change

Although the stratigraphic survey allows changes over a wide area to be investigated, it provides only limited detail on plant community changes. Therefore, macrofossil analysis was undertaken on core A10, using the methods described in Chapter 4. The core A10 was selected because it is the deepest peat within the main ombrotrophic mire, and therefore probably covers the greatest length of time.

The stratigraphic data shows that it is representative of most of the main developmental changes of the mire in general.

8.2.3.1 Dating community change

Approximate dating was obtained by 20 pollen counts, using a pollen sum of 200TLP, to give a 'skeletal' pollen diagram to compare with the radiocarbon dated diagrams in Chapter 5. The pollen diagram (Figure 8.5) has been compared with the Cross Lochs 'A' core, and pollen stratigraphic changes similar to those found at the dated levels in that core have been identified. An approximate age - depth relationship derived from this is shown in Figure 8.6. The base of the core is probably of Lateglacial - early Holocene age, with the lower inorganic lake sediment possibly dating to the Loch Lomond Stadial. There is no zonation and description of the core on its own merits, as it is not intended to make détailed inferences concerning regional vegetational change from this data, although some of the implications for local vegetation change are mentioned below. The pollen spectra are remarkably similar to those found in CLA and the upper part of CLB, particularly those types which are thought to be representative of the wider locality, rather than the individual core location.

The *Betula* rise is clearly marked at 592cm, the base of CLA1 and 632cm in CLB. The extrapolated date for this is prior to 9400bp in CLA. Other taxa also attain similar levels to those in zone CLA1, with high Cyperaceae, low *Calluna*, and low, but significant levels of *Salix* and *Empetrum*. Following this, there is a rise in Coryloid pollen (560cm), placed at 8995±45bp in CLA, at the beginning of zone CLA2a. The differentiation of equivalents to both CLA2a and CLA2b is not possible, there being no clear decline in *Empetrum* pollen, and the pine rise is only tentatively placed at 496cm. This boundary, thought to reflect long distance transport of pine pollen from further

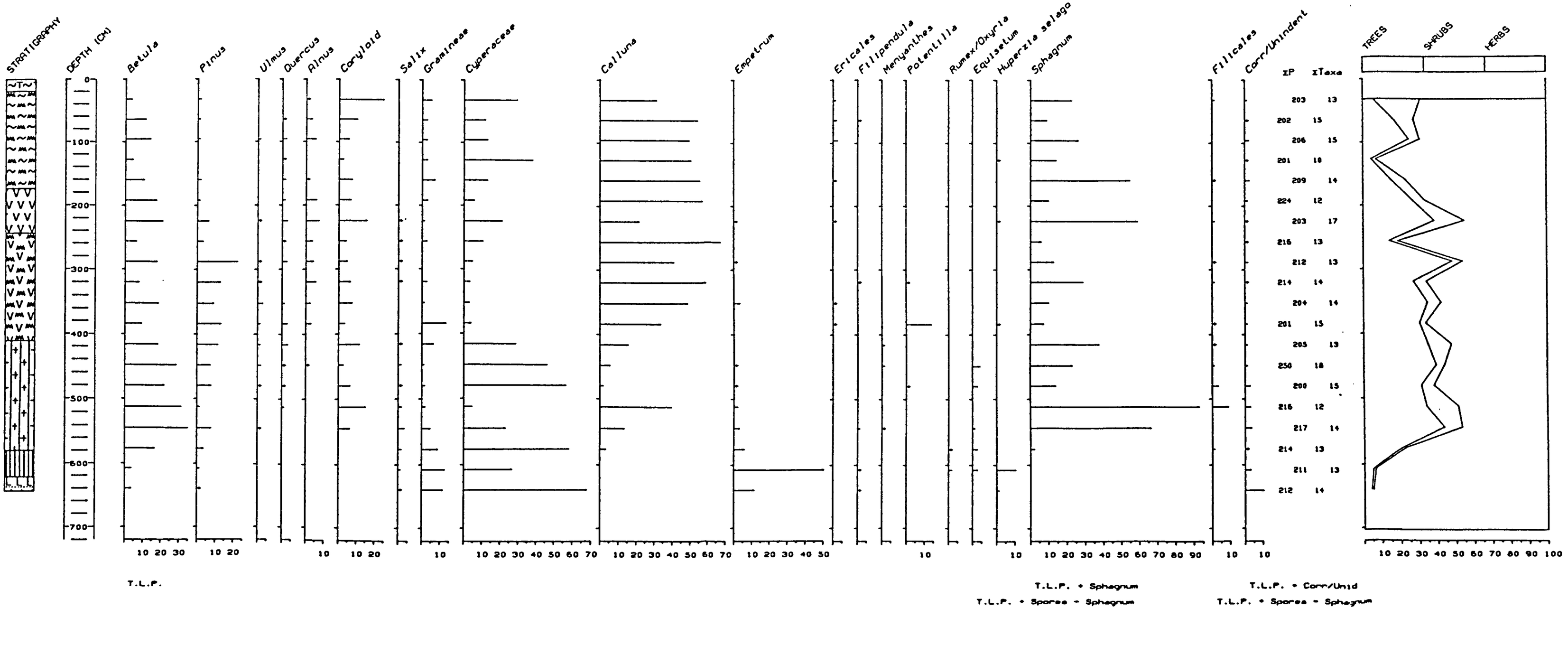


Figure 8.5: Percentage pollen diagram for Cross Lochs Ombrotrophic, core A10.

south and west, is dated to 7575±45bp, at the beginning of zone CLA3. The *Alnus* rise is one of the few consistent features of all the pollen diagrams in this study, although it is often difficult to delimit precisely, and it is dated to 5880±45 at CLA. This also marks the large expansion in *Calluna* at the Cross Lochs ombrotrophic mire site. In this core, in contrast to CLA a clear *Ulmus* decline is shown at 336cm, dated by extrapolation to 4900bp, approximately in line with other British dates (Smith and Pilcher, 1973) and Peglar (1979) at 5300bp.

The problems of detecting the short lived pine expansion and decline with relatively widely spaced samples was noted in Chapter 5. This effect is seen here, with no clear local occurrence of the species. However, the rise to 23% at 288cm is thought to be the close of this period, as it declines to very low levels after this. Thus the decline is placed at 272cm, dated to 3920±45bp at CLA. This is unlikely to be precise. Estimating later dates is difficult because regional pollen (tree and shrub) decreases generally. However, the rise in Coryloid (probably *Myrica*) is well marked and occurs with the rise in Ericales, as at CLA. This is dated to 1470±45bp.

In summary, the skeletal pollen diagram has allowed an approximate chronology to be applied to the core from the ombrotrophic mire site. Although there are some discrepancies between sites, the data is generally in good agreement concerning the major rises and declines of those species most likely to represent the regional pollen rain. The rapid accumulation rate of the ombrotrophic mire core means that the widely spaced pollen samples are 550 years apart, on average, about two and a half times that of the typical spacing in the reference diagram from CLA (227 years), despite a difference in measured separation of a factor of 4 (32cm cf. 8cm). Although this is clearly subject to not insubstantial errors, these are likely to be limited to a relatively small fraction of the total time period under examination. The reasonable accuracy of dating

estimates for the mid-Holocene is shown by the extrapolated date of 4900bp for the elm decline.

8.2.3.2 Macrofossil analysis and inferred community change

The core has been divided into six major zones on the basis of the data in Figure 8.7. The characteristics of these and the changes in plant community they indicate are described below, with additional information from pollen (Figure 8.5) and microfossil (Figure 8.8) analyses, where appropriate. The microfossil data in this case has not been of great use, due to low numbers of microfossils for which there is adequate ecological information available.

CL01 654-624cm Lateglacial?

The stratigraphy indicates a lacustrine environment in the early stages of sedimentation at the core location. The macrofossil sampling was not of sufficient resolution to differentiate the sub-zones within this, but the stratigraphy suggests that the coarse sand stratum at the base of the core may be referable to the end of the Loch Lomond Stadial. Pollen of the earliest lake mud superseding this is dominated by Cyperaceae, perhaps reflecting the transition to early Holocene. There were few macrofossils recovered from this zone and it is difficult to assess the relative contributions of *in situ* and inwashed remains. However, there were obviously a number of fen bryophyte species present, including *Calliergon cuspidatum*, *C.sarmentosum* and *Drepanocladus fluitans*, all of which may have been growing at the edge of the water body in a mixed bryophyte community. Although *C.cuspidatum* is widespread in Britain, *C.sarmentosum* is a species of montane flushes (Smith, 1978). *Pogonatum* cf.*nana/aloides* was also recovered, and was probably inwashed from surrounding slopes.

CL02 624-408cm 10,400?-6050bp

During this zone, the basin is infilled and there is no longer any lacustrine sediment. The peat is dominated by

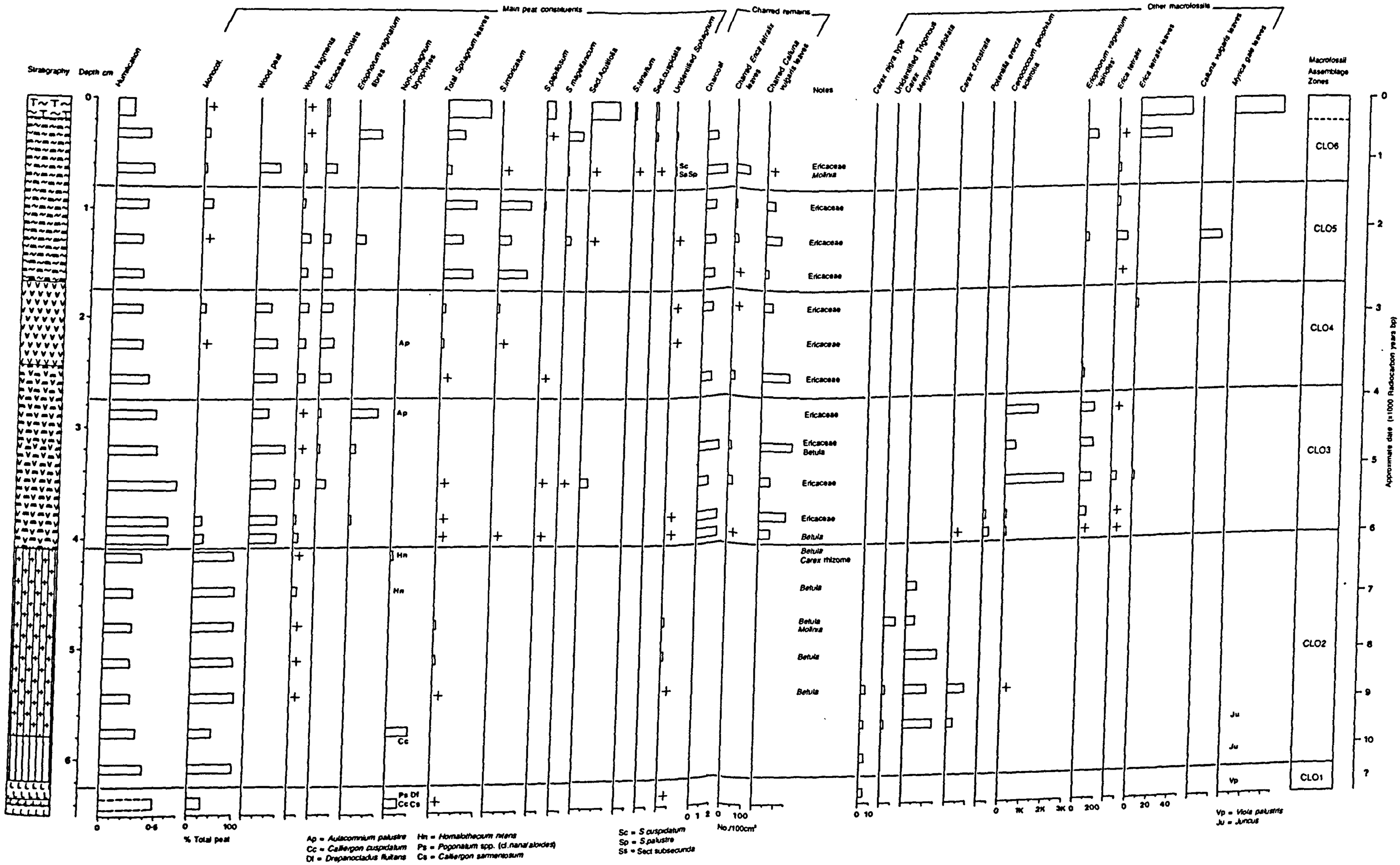


Figure 8.7: Macrofossil diagram for Cross Lochs Ombrotrophic, core A10.

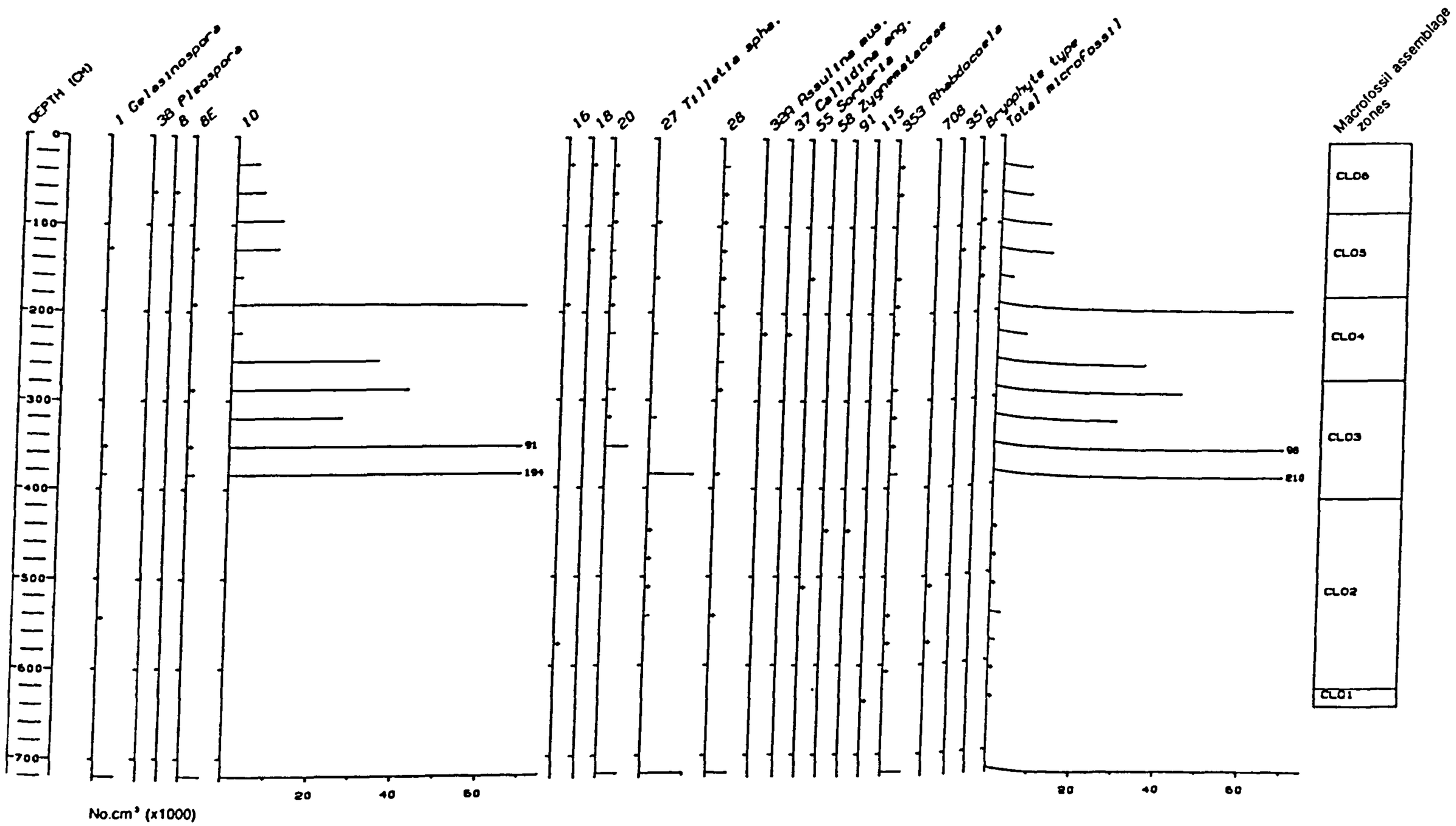


Figure 8.8: Non-pollen microfossils from Cross Lochs ombrotrophic, core A10

monocotyledonous remains, with some wood, some of which was identified as birch. Percentages of birch pollen are only moderately high (ca.25%, but up to 35%) probably indicating scattered, open stands of tree birch, as there is no macrofossil evidence for *B.nana*. The early part of this zone could perhaps be separated as a sub-zone, as no birch remains were found, and this genus does not appear to be present on site until later. Pollen data largely concurs with the dominance of Cyperaceae locally, although *Calluna* may have been present on the mire around 512cm and in the earliest stages, *Empetrum* was generally abundant, although it may not have been growing actually at the core location.

There are occasional bryophyte remains, *Calliergon cuspidatum* contributing 50% peat at 572-580cm and *Homalothecium nitens* occurring in the latter part of the zone. This concurs with existing records for *H.nitens*, which was apparently widespread in the Boreal and now has only a relict distribution (Dickson, 1973).

A similar disagreement in macrofossil and pollen records for *Sphagnum* occurs as that described from zone CLA3 at the Cross Lochs 'A' site. There are very high percentages of spores from 544cm, but few macrofossils. However, in this case, a large amount of highly decayed *Sphagnum* was found in the 125µm fraction here, and it appears that while there was probably abundant *Sphagna* present, much of the vegetative material has decayed. This may be due to conditions of preservation or to greater susceptibility to decay of the species present, which were probably fen species. Reproductive macrofossils present in significant amounts are *Menyanthes trifoliata*, *Carex* cf.*rostrata* and *C.nigra* type. The core site was therefore a mesotrophic sedge fen, with some *Sphagnum* and other bryophytes, dry enough for a sparse growth of small birch shrubs.

CL03 408-272cm ca.6050-3900bp

The start of this zone is clearly defined by stratigraphy, macrofossil content and pollen spectra, as a change from

sedge to Ericaceae-*Eriophorum* peat. Remains of *Eriophorum vaginatum* are particularly abundant, with the characteristic matted fibres and 'spindles', although there is little cyperaceae pollen, which may be due to a low pollen production capability of this species. Birch has not disappeared completely and occasional small twigs were found, but it had certainly decreased in abundance. This is also supported by the decreased pollen percentages. Pollen data also reflects the local, and probably also more widespread, expansion of *Calluna*, and abundant type 10 microfossils, associated with local *Calluna* growth (Van Geel, 1978) occur. This was probably one of the driest phases of mire conditions as sclerotia of *Cenococcum geophilum* are abundant and humification reaches its highest levels. At the end of this zone, there is a rise in the *Pinus* curve. The pollen samples are too widely spaced to resolve the brief, local occurrence of pine found at Cross Lochs 'A', but it probably occurs close to this more minor rise.

These vegetational changes are coincident with the occurrence of the earliest charcoal and charred leaves of *Calluna* and *Erica tetralix*, which are found throughout the rest of the core, except for the surface peats. Also beginning at this time is a rise in the *Alnus* pollen curve, usually taken as indicating the Boreal-Atlantic transition, and somewhat wetter conditions. The change in vegetation could therefore be explained by three possible mechanisms. Firstly, it may represent a natural hydroseral succession in a relatively oceanic climate. Secondly, this process may have been accelerated by a climatic change and increased surface wetness. Thirdly, anthropogenic influence, by burning, may have encouraged a change to a dwarf shrub and cotton grass mire.

CL04 272-176cm ca.3900-2700bp

This zone is similar in many respects to CL03, in that it represents the continuation of an ombrotrophic mire community. *Eriophorum*, however, ceases to occur in such

abundance, and the mire was almost completely dominated by ericaceous dwarf shrubs, with some *Sphagnum*, most of which occurs as unidentifiable stem material, but there is some *S.imbricatum* at the end of the zone. Paradoxically, *Calluna* pollen decreases in the middle of this zone. However, pollen of *Betula*, *Alnus*, and Coryloid shrubs shows some increase, in contrast to a decrease in the Cross Lochs A core. This may be due to a significant spread of the mire at this time so that there is an increasing proportion of regional pollen rain.

CL05 176-80cm ca.2700-1470bp

This zone is marked by an expansion of *Sphagnum* growth, almost all of which is *S.imbricatum*. This is not clearly reflected in the *Sphagnum* spore curve, which shows an increase at the beginning of the zone, followed by a rapid decline. It may be that this reflects a phase of immigration where spread is by reproductive means, followed by vegetative growth once established over a wide area. However, Hill (1988) notes that both subspecies of *S.imbricatum* only rarely produce capsules, with no records for ssp.*austinii* in Britain, the most likely subspecies in this case. Ericaceae continue to occur, probably a mix of *Calluna* and *Erica tetralix*, as there is abundant pollen of the former and seeds of the latter. Burning of the mire surface continues, as charcoal and charred remains continue to be found.

CL06 80-0cm ca.1470-0bp

The final zone of this core indicates that *S.imbricatum* disappeared from the *Sphagnum* community, to be replaced by a more diverse composition, including *S.papillosum*, *S.magellanicum*, *S.tenellum*, *S.cuspidatum*, sects. acutifolia, cuspidata and subsecunda. Initially, total *Sphagnum* was relatively low and ericaceous dwarf shrubs were more abundant. More recently, *Sphagnum* has increased and both macrofossil and pollen evidence suggests that the occurrence of *Myrica gale* on the mire surface is a comparatively modern event. The disappearance of

S.imbricatum is also a feature of a number of raised mires elsewhere in Britain, and Green (1968) has shown that most sub-fossil material is of a phenotype which favours relatively wet conditions, rather than the hummock forming type mostly recorded today. Although Slater and Slater (1978) have shown a decline in the species after fire, this cannot explain its massive decline from the Cross Lochs or other British sites. There is certainly no suggestion from charcoal analyses that there was an increase in the intensity and/or frequency of fire coincident with the disappearance of *S.imbricatum* at Cross Lochs.

8.2.3 A comparison with patterned fen development

At the end of Chapter 6, the development of four patterned fens was compared and some generalisations were made concerning the stratigraphy of patterned fen sites. It was also suggested that development of the poor fen systems was independent of early mire conditions. If this is true, then nearby ombrotrophic systems, such as the one investigated here, are likely to show similar stratigraphy in the deeper peat areas. Figure 8.9 shows the main changes in macrofossil composition on the ombrotrophic mire site, compared with those found in the adjacent patterned fen at Cross Lochs 'A'. There are clear affinities between the profiles from the deep peats. Although peat growth began earlier at the ombrotrophic site, the earliest deposits are of similar composition with mesotrophic bryophyte remains. Following these pioneer communities, there is a deep layer of sedge peat with birch remains, although the wood content is variable. There is then a transition to ombrotrophic or 'bog' communities, dominated by ericaceous dwarf shrubs and *Eriophorum*, in the late seventh millennium bp. This transition is synchronous within the limitations of the dating method used. Around this transition, there is some variation as to the exact sequence of events, but there is some persistence of birch on all sites after ericaceous shrubs have begun growth. All sites also show either the beginning of, or a substantial increase in charcoal and

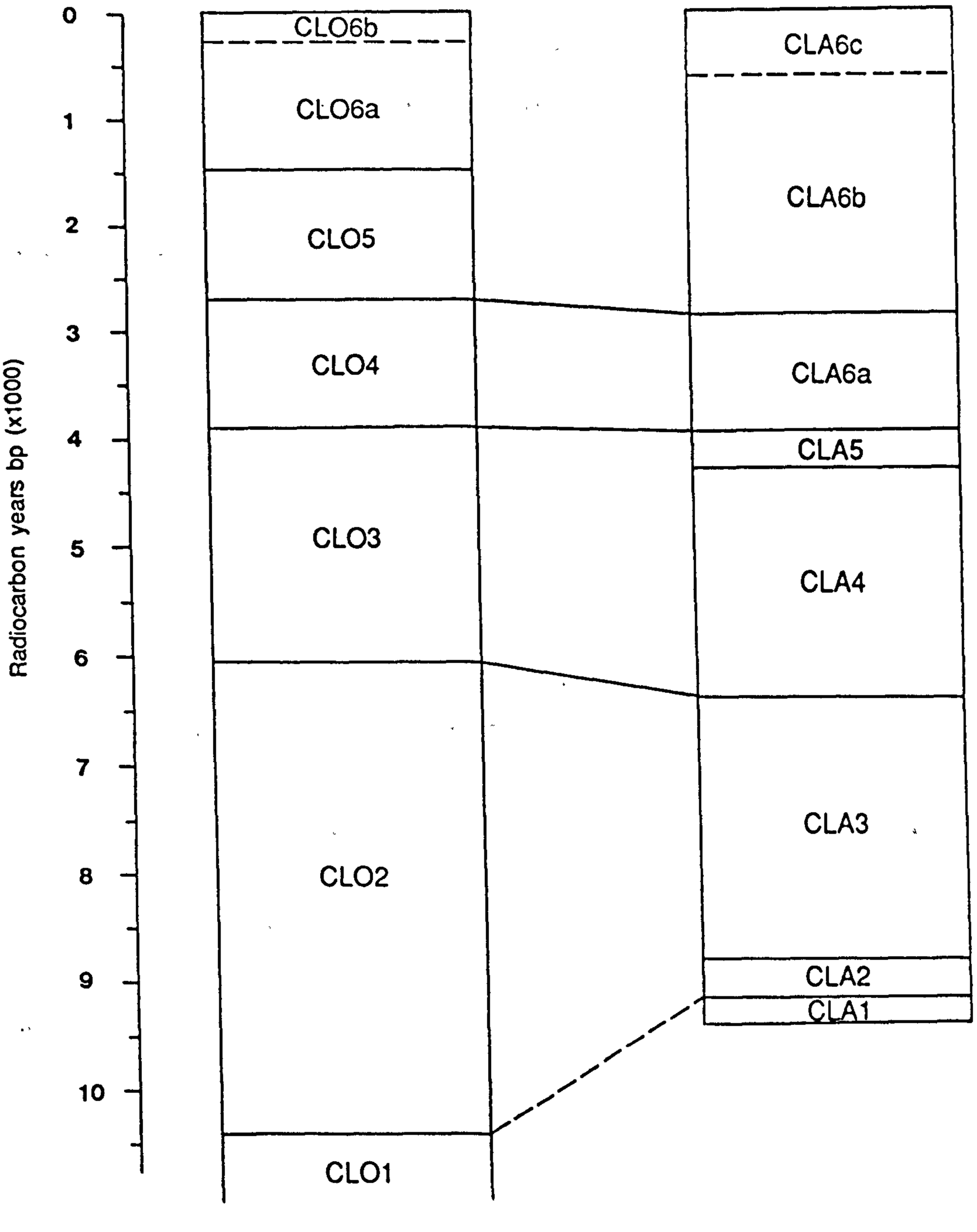


Figure 8.9: Correlation of macrofossil stratigraphy for Cross Lochs Fen A and Cross Lochs Ombrotrophic sites.

charred remains at this transition, although it is only in the ombrotrophic site that all changes are clear cut and occur simultaneously. The burning continues at all sites at least until very recently (top 20cm).

The patterned fens show a rather variable reversion to poor fen peats in the top 1-2m. In the case of Cross Lochs 'A', the transition begins slowly at 3950bp with the development of wetter, but still largely ombrotrophic mire, and is fully developed as poor fen by about 2850bp (the start of CLA6b). The ombrotrophic mire site, however, shows a rather different change, after the shrub dominated CLO4, which also started at around 3900bp. At the start of zone CLO5 (176cm), there is the change to *Sphagnum imbricatum* peat, estimated at 2700bp, from pollen data. This is contemporaneous, within the limitations of the date estimates, with the start of CLA6b, suggesting that although the vegetational change is different, the cause may have been the same.

The nature of the change in the ombrotrophic peats suggests a similar transition to that found in many raised mire stratigraphies throughout north west Europe ('Grenzhorizont'; Weber, 1900) and occurs within the range of dates for this (Haslam, 1988). It is possible that a higher water table on the mire systems throughout the region was not the only change in the mire hydrology, in response to increased precipitation-evaporation ratios. A raised water table will increase the amount of evaporation taking place, and may balance increased precipitation. However, if the increase is too great, then the mire system must develop a routeway for increased runoff. This may be by surface runoff, perhaps leading to gullying and erosion, but it could also be by sub-surface water movement in peat pipes.

Such peat pipes must emerge at some point, and this is especially likely to occur where the slope is relatively steep, as the water in the pipe is likely to have higher

velocity and erosive power at this point. If, in addition to this, the peat is thin, then this increases the likelihood of emergence. If the topography immediately below the point of emergence is suitable, then the piped water will spread over a wide area, without forming an erosive gulley. Water in sufficient quantities or of sufficient quality will lead to a change in vegetation, perhaps to the poor fen communities of patterned fens. This (data) is therefore suggested as the mechanism for the development of the peat pipes which are considered influential in the formation of patterned fens (see Chapter 6).

8.3 INITIATION OF OMBROTROPHIC PEATS

8.3.1 Introduction

The above discussion is largely based upon the deepest peat deposits in each site, as these cover the longest period of time and can also be shown to be representative of many of the main site stratigraphic changes. However, on all sites there are shallower peats, and many of the basal peats from these cores are also similar, being generally highly humified and apparently of an ombrotrophic nature, despite underlying different contemporary mire types. The deeper peats in all the sites investigated appear to have a common origin and have clearly developed initially in basins, as 'primary' peats (*sensu* Moore and Bellamy, 1974). However, the shallower peats (<2.5m), appear to have developed directly on mineral ground, in places unlikely to have been naturally water collecting sites, as 'secondary' peats. This is the type of blanket peatland that is usually implied when 'blanket peat initiation' is under discussion, as by definition this mire type must spread outside the confines of water collecting topographical units. After a brief review of the possible causes of this, this section investigates the palaeoecological evidence at the base of the Flow Country deposits, which are probably typical of a

large part of the area.

8.3.2 The causes of peat initiation

8.3.2.1 Primary causal factors

The basic rules governing whether or not peat formation will occur are relatively simple - if the biomass produced by the extant vegetation exceeds that decomposed then partially decayed organic matter accumulates. Rapid biomass accumulation or low decomposition rates may be the cause of peat growth. These conditions are fulfilled when the water table is at or above the soil surface as shown by Ivanov's (1981) model. The conditions and complex interactions which occur as a result of this initial waterlogging of the soil are dealt with fully in Gore (1983a) and Moore and Bellamy (1974), amongst others. What are not so easily defined are the causes of such a rise in water table which must have preceded the initiation and subsequent growth of blanket mire over large parts of the north and west of the British Isles.

Climate is obviously of importance to water relations in the soil. Conway (1954) was able to state that the blanket peat on all her sites in the South Pennines began to form at or around the Boreal/Atlantic transition, when conditions were thought to have become wetter than during the earlier postglacial. Hence, a primarily climatic origin was attributed to the peat. Although the temperature is also thought to have risen at this time (Lamb,1972) the precipitation-evaporation ratio must still have risen for peat to begin growth, if a climatic origin is accepted. However, this simple sequence of events cannot have occurred in all areas, for all basal deposits cannot be dated to the same climatic transition. The present distribution of blanket mire is strongly correlated with climatic parameters (Mitchell, 1972, for Ireland; Ratcliffe, 1964, for Britain).

However, an anthropogenic cause of peat growth was espoused by Peter Moore in the early seventies (Merryfield and Moore, 1974; Moore 1968; 1972; 1973; 1975). Moore (1975) expresses the arguments for this most clearly. In reviewing a number of sites from England and Wales, he finds the elm decline a good palynological marker for initiation of peat on most sites and regards the south Pennine sites as exceptions. The elm decline has been shown to occur consistently between 5,100 and 5,300 bp (Smith and Pilcher, 1973). This is approximately coincidental with the commencement of the Neolithic period and the introduction of farming into a broadly forested countryside (Smith *et al*, 1981b), although it has recently been shown that the meso-neolithic transition is rather less well defined than has previously been thought (Edwards, 1985; 1988). Moore (1975) claims that forest clearance by man at this time allowed an increase in effective ground wetness and quotes modern clear felling experiments for a number of woodland types in the USA in support of this (eg.Swank and Douglas, 1974; Bormann *et al*, 1968). Increases in catchment discharge vary from 8 to 40 % after felling in US studies. Increases of 10% are viewed as more realistic for the climatic regime of Neolithic Britain. Recently, similar results have been obtained in Britain (Anderson *et al*, 1990), although the increased discharge of 40% or more, applies to clear felled plantation. Some initial clearance of wet woodland, followed by repeated "interference phases" are shown to be associated with peat growth (Moore, 1973). Peat initiation has occurred on abandoned cultivated surfaces, particularly in northern Ireland (eg.Case *et al*, 1969; Mitchell, 1972) and grazing may serve to accelerate or allow peat growth (Smith *et al*, 1981a). Deforestation may have also been important for other mire types, particularly the valley mires in southern England. At Thursley Common, Suffolk, Moore and Wilmott (1976) found basal peats were associated with estimated Bronze Age clearances. However, Clarke (1988) has found basal dates in the New Forest mires which preclude such a cause. There is also evidence from Norway to suggest human activity can be

a primary cause of blanket mire formation on the west coast (Solem, 1989), although this is not always the case (Solem, 1986).

Tallis (1975) puts forward evidence from Pennine peats which suggest that peat growth had already begun before forest clearance as a layer of tree remains occurs sandwiched between two layers of peat, well above the mineral ground. This could represent a later regeneration phase, though. Later work in Wales (Chambers, 1980; 1981; 1982a; 1983; 1984; Price, 1981) also indicates human interference at the time of peat initiation, but shows peat initiation is not synchronous, even within a small area.

The other possibility is that blanket mire represents the final stage of a natural soil maturation on base poor soils in areas of high rainfall. These *in situ* biopedological processes may be particularly important in areas less sensitive to changes of water balance (Smith and Taylor, 1989). Podsolisation, resulting from strong soil leaching occurs in many areas of Britain and leads to the formation of a 'mor' humus, which may ultimately become a deeper organic peat. Taylor and Smith (1972, 1980) term this "pedogenic peat" and distinguish from the overlying "climatic peat" and it is regarded as a useful classification by later authors (eg Chambers, 1982b). Although podsolisation undoubtedly has preceded peat development in some cases (eg.Jaumiainem, 1972; Soulsby, 1976), blanket peats are not always underlain by fully developed podsols (Dimbleby, 1965, quoted in Moore, 1975). This has been shown to be an important process in Alaskan peatlands (Ugolini and Mann, 1979), and in conjunction with climate (with which it is intimately linked) is widely regarded as being responsible for peat growth in Newfoundland (Davis, 1984) and Quebec (Payette, 1984) provinces in Canada.

8.3.2.2 Local site factors and variability

Besides the actual causes of an increase in soil wetness already mentioned - climatic change, pedogenesis or anthropogenic factors, there are a number of local variations which also determine where peat formation is possible. Some of these problems have been touched upon by Edwards and Hirons (1982).

Topographic position is recognised as an influence on peat growth and times of initiation (Moore and Bellamy, 1974; Edwards and Hirons, 1982). Basins are most likely to become waterlogged first and therefore begin peat growth first, followed by flat areas then sloping ground. This has given rise to the terms 'primary', 'secondary' and 'tertiary' (Bellamy, 1972; Moore and Bellamy, 1974). Clearly, if we are to compare basal dates of mire from different locations for correlation with environmental history, we must know the topographic context from which samples are taken (Hafsten and Solem, 1976) and the peat type, indicating the conditions under which it was formed. Blanket peats are not, by definition, primary peats, and basin fen peats should be excluded from consideration, although the implementation of this has some problems (see section 8.3.6).

Slope gradient affects the timing of peat formation. Gentle slopes shed water more slowly than steeper slopes and therefore reach the threshold level of wetness required for peat growth first. Steeper slopes may require several effects compounded (eg increased rainfall and deforestation) while on adjacent flat areas peat forms under the influence of climate alone, possibly at a different time. Peat growth may proceed upslope from a localised source by back-paludification, in the manner shown for patterned fens in North America and Sweden (Foster and King, 1984; Foster and Fritz, 1987).

Altitudinal variation in peat initiation dates, associated

with climatic differences, has been suggested by Durno and Romans (1969) for sites from the Pennine-Cheviot area and the Grampian region. Chambers (1981) found some support for this, with peat formation earlier at higher altitude sites in south Wales.

Most of the work mentioned has been carried out on blanket peats from England, Wales and Ireland, yet paradoxically, some of the best developed systems occur in northern Scotland. Later comments by Moore (Moore *et al*, 1984; Moore, 1985; 1986b) have recognised this and he has suggested that because there is little evidence for extensive post-glacial tree cover in these areas, blanket mire must have developed as a direct result of an extreme oceanic climate (Moore, 1986b, p92). A careful study of basal peats in this area will indicate if this is the case.

The reviewed hypotheses can be used to predict the palaeoecological evidence which should occur (Table 8.1). There are difficulties with some of these predictions, for example in the number of profiles which would have to be studied to test 1(b), that synchronous peat development occurred in similar topographic situations. However, this does at least provide a formal basis on which to base discussions of results.

8.3.2.3 Dates of initiation

The distribution of basal blanket peat dates for 71 samples, distributed throughout Britain, Ireland and western Norway is shown in Figure 8.10. A list of sources is given in Appendix II. The value of such an exercise is limited because of the problems of determining the exact nature and context of samples, as well as the different dating methods employed (radiocarbon and the authors' estimates from pollen stratigraphies), but it does allow some generalisations to be made concerning the timing of blanket peat growth. Dates vary between over 9000 and less than 1750bp, but between these extremes there is a strong

Table 8.1: Hypotheses of mire initiation and predicted palaeoecological results

Hypothesis	Palaeoecological evidence expected
1. Climatic change	a) Peat initiation dates correlate with times of increased climatic wetness indicated from other sources. eg.Raised mire stratigraphy b) Synchronous peat development in similar topographical situations. c) Synchronous with other stratigraphic changes in nearby cores from older mires. eg.Holocene sequence from patterned fen.
2. Pedogenic	a) Evidence of buried soil profiles showing podsol development and impeded drainage by iron pans. b) Evidence of 1(b) may apply but not 1(a)
3. Anthropo-genic	a) Pollen evidence for clearance episodes: decreased AP and occurrence of disturbance indicators. b) Evidence for burning: abundant locally derived (>125µm) charcoal, of greater frequency than would be expected from natural fires. c) Peat initiation synchronous with independent archaeological evidence of human activity in the area.
4. Paludific-ation	a) Gradual spread of peat in direction expected from slope of ground. ie. "back paludification"

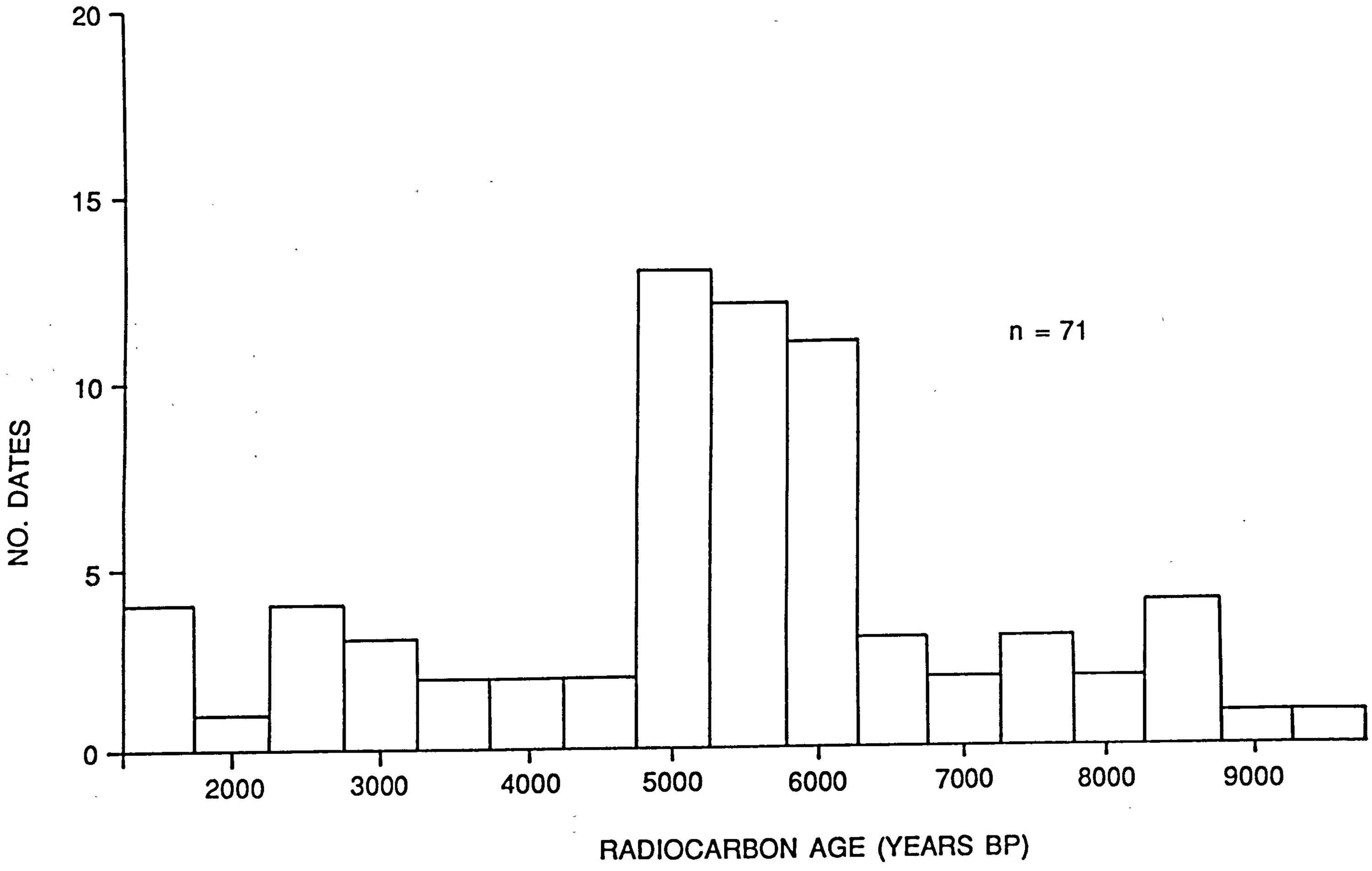


Figure 8.10: Distribution of ages of basal peat deposits

peak between 6250 and 4750bp. This would tend to support the assertion of Moore (1975) of mire initiation occurring at the first major human impact, the start of the neolithic. However, the data have a strong regional bias towards sites in south Wales, so such a conclusion must be regionally restricted. This graph includes several sites where the topographical location and/or peat type are difficult to determine from the published data. Some of the older dates undoubtedly refer to basin fen peats.

8.3.4 The study site: The Dyke peats

The sub-peat deposits are generally too hard for any standard corer to penetrate, augering showing that coarse sands and gravel, often with large stones, are generally present. There are, however, a number of forestry tracks in the Cross Lochs area (see Figure 5.1), and these are normally cut through to the sub-peat material on all but the deepest of peats, providing excellent opportunities for sampling of the peat-soil transition. One of these tracks forms a transect from the River Dyke valley almost up to the summit of the Cross Lochs watershed. This provided the ideal opportunity to study the origins of secondary ombrotrophic peats.

To establish the context of the track exposures in relation to the peat deposits used for the rest of the study, a transect of cores was taken across the whole of the watershed linking the two study areas. Ideally, a complete stratigraphic survey of the whole of the watershed would have been performed but this would have involved over 600 cores, even if a relatively coarse interval of 50m were used, and this would have taken an unacceptably long period of time. The position of this transect in relation to the other sites investigated is shown in Figure 5.1 and the results of the survey are shown in Figures 8.11 and 8.12.

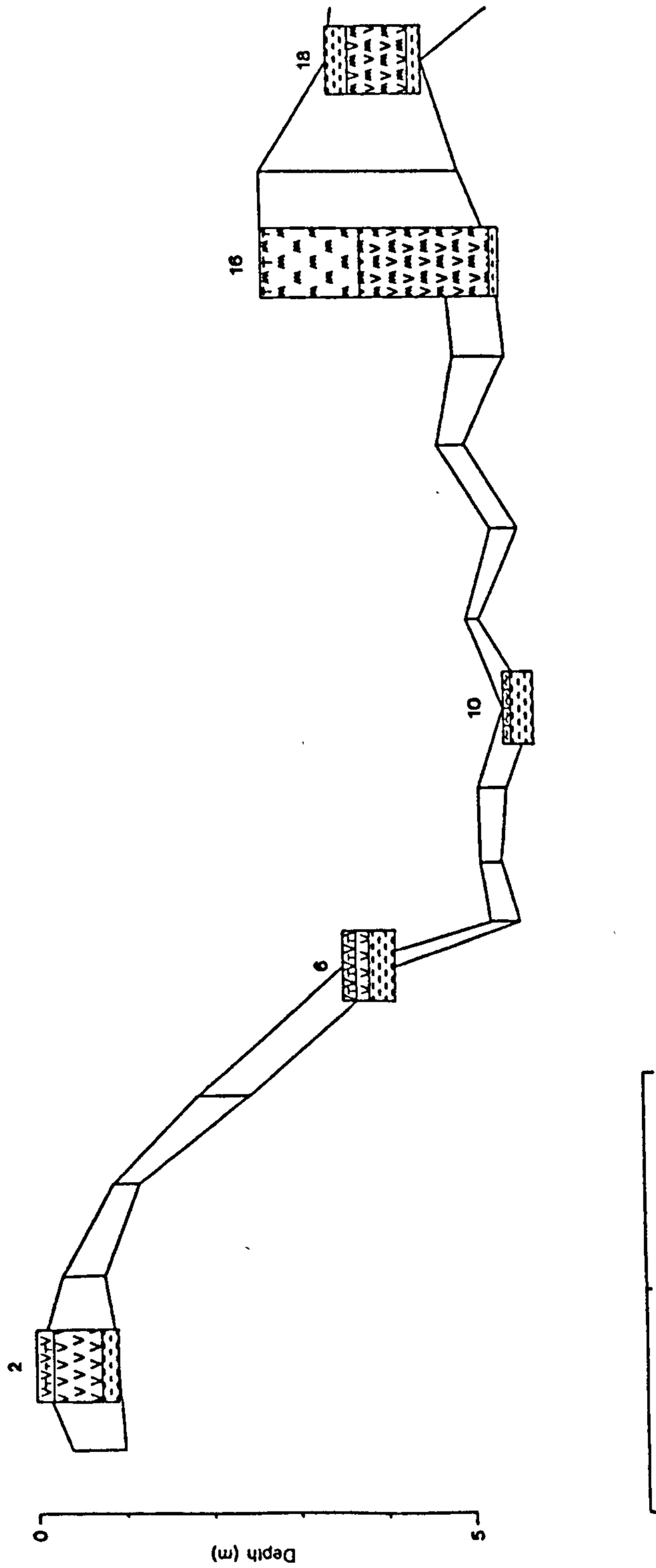


Figure 8.11: Stratigraphy of Cross Lochs watershed (transect H), cores 1 to 18.

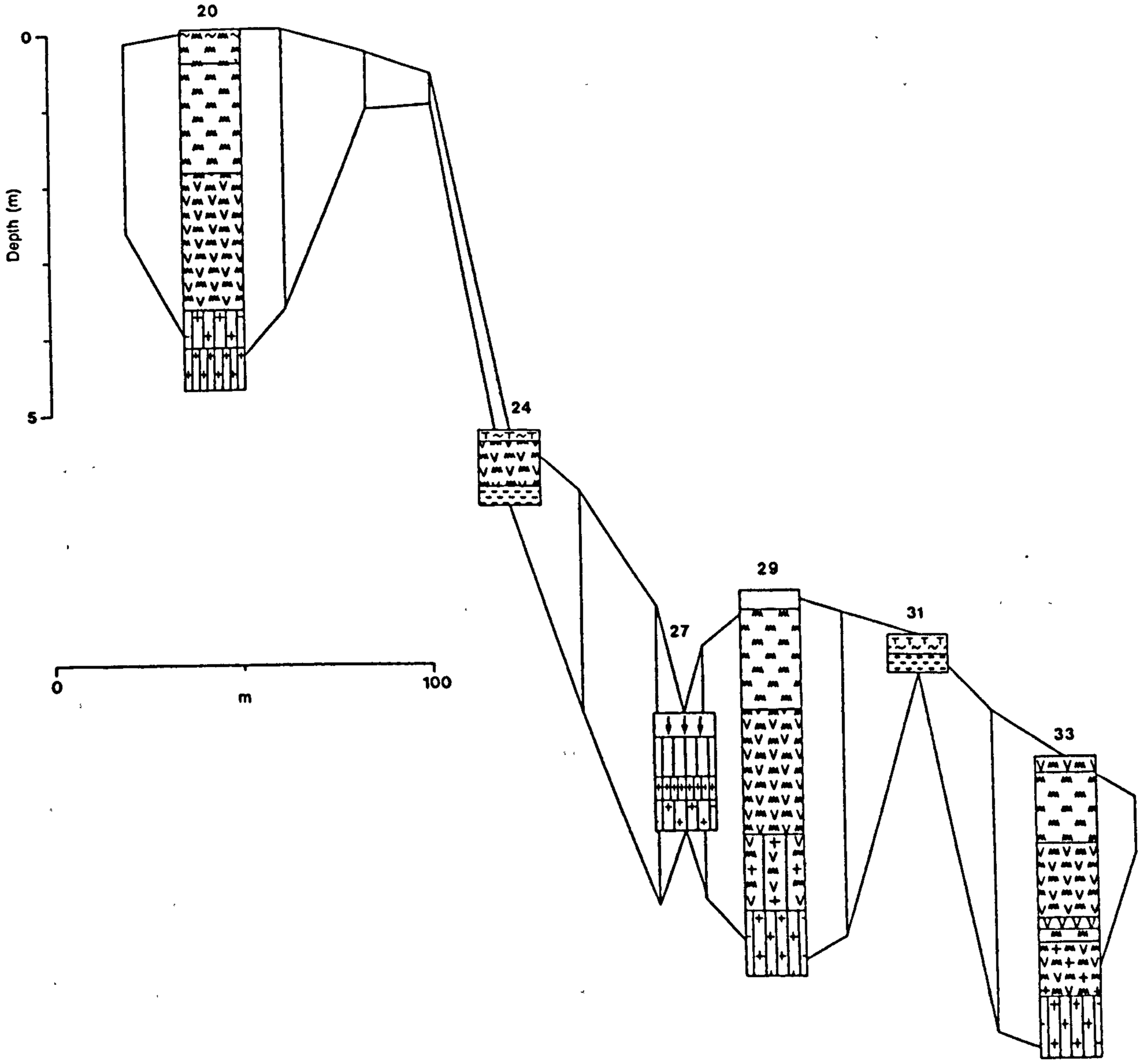


Figure 8.12: Stratigraphy of Cross Lochs watershed (transect H), cores 18 to 34.

Shallow peats only occur over the steeply sloping knoll at the end of transect D, and also over the flat expanse between the two large lochs to the west. Deeper peats occur underneath the patterned bog still further west, and the deepest of these again shows similar stratigraphy to that found in the deep peats of all other sites, being derived from basin sedge and birch fen. There is a double basin closer to the track, again with deep ombrotrophic peat, underlain by basin fen deposits. The trackside profile begins where this transect ends and is shown in Figure 8.13.

8.3.5 Methods

8.3.5.1 Field sampling

The peat depth profile shown in Figure 8.13 was obtained by measuring the peat depths at an interval of approximately 20m, the exact distance depending on the complexity of peat depth changes. The surface profile was reconstructed from the 1:10,000 Ordnance Survey map and is only approximate. Peat depths vary between around 30cm and approximately 3m. However, it is difficult to measure some of the shallow peats accurately because of disturbance by machinery, and deeper peats often disappear beneath the track, so that it is not possible to reliably sample either of these extremes. Four monoliths were removed, each representing a different location type from the sample area. These are detailed in Table 8.2.

The stratigraphy at each profile location was recorded prior to any excavation, paying particular attention to the sub-peat material. Although small differences in organic deposits are normally much easier to observe in the fresh, wet state, soil horizons are often better differentiated when dry, particularly where there may be a podsolised E horizon.

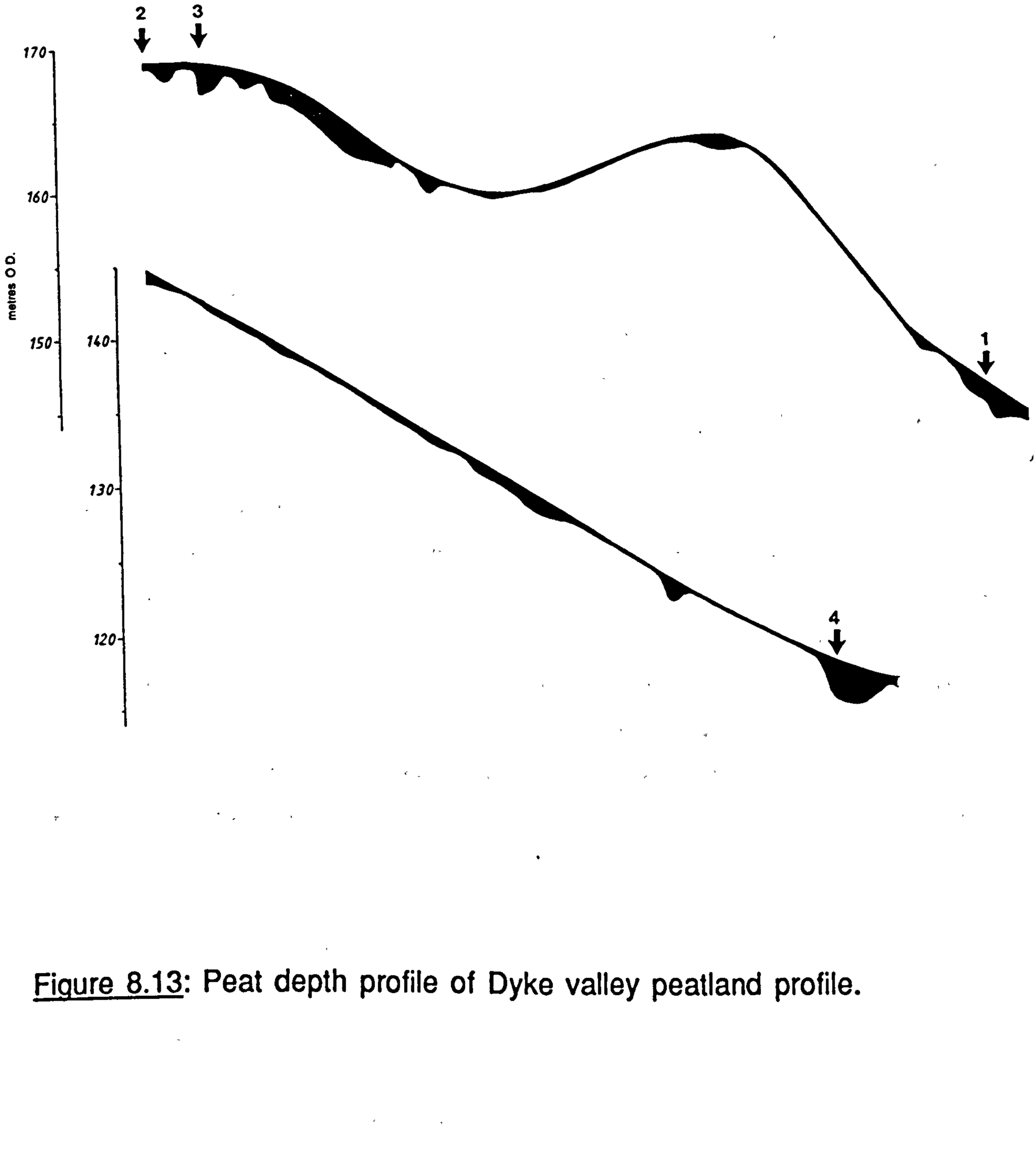


Figure 8.13: Peat depth profile of Dyke valley peatland profile.

Table 8.2: Location characteristics for peat-soil interface samples

Monolith	Depth	Macrotopographic position	Microtopographic position	Altitude
1	138	Slope	Depression	145
2	52	Summit	Hummock	169
3	206	Summit	Depression	169
4	172	Valley	Depression	118

Sampling at each location involved cleaning the face, to expose a vertical section of the basal peat and mineral substrate, unaffected by surface drying and contamination. Any additional stratigraphical details were noted and two monoliths removed. A 10x10x50cm monolith for laboratory analyses, with a 15x15x30cm sample for radiocarbon dating. These were taken immediately adjacent to one another and could therefore be matched together accurately as their exact relationship with one another was known. Both samples spanned the peat-mineral transition. The large sample for radiocarbon dating has the advantage that very thin (1cm, yielding 225cm^3 peat) samples could be used, increasing the stratigraphic resolution (see below). Some difficulty was encountered in removing sub-peat material, as the sands and gravels were compacted and coarse with some large boulders, but tended to disintegrate when extracted. However, it was generally possible to obtain at least 10cm of the mineral substrate.

8.3.5.2 Laboratory methods

The samples were subject to three main analyses. Firstly macrofossil analysis allowed the determination of the basic peat type. Although the highly humified condition of the peat meant that few reproductive macrofossils were retrieved, it was possible to establish whether or not samples were truly ombrotrophic and were not therefore 'primary' peats. It is often not possible to tell this from

field stratigraphy, because of high humification, but despite this, examination of macrofossil remains is rarely undertaken in studies of this kind. However, it is surely a crucial factor when discussing the cause of initial peat growth. Methodology was as described in Chapter 4, but samples were of 1cm thickness, and closely spaced (sometimes contiguous). Assessments of abundance of major sample constituents were made on a five point scale. The charcoal content of each sample was also determined during these analyses, in order to assess the local fire regime. The methods are as detailed in Chapter 4.

The problems of defining the division between organic soil and true peat growth have been mentioned by Chambers (1980; 1982b) and Edwards and Hirons (1982), but there does not seem to have been any acceptable suggestion on the resolution of such terminological difficulties. However, the nature of the organic material can be determined from macrofossil analysis, and loss on ignition (LOI) provides an objective, rapid and repeatable method of assessing the total organic content of the deposit. The %LOI which should be used as the minimum for 'true' peat growth is, however, difficult to define. In this study, it is suggested that there are two reference points which might be used as definitive stages in early peat growth. The first is the lowest organic horizon, where there is a clear departure from a mineral soil, indicated by a stratigraphic change and a rise in the LOI curve. Secondly, the stage at which wholly organic deposits begin to form, defined where the LOI reaches continuous sustained high values, usually around 95%LOI, but probably variable depending on the degree of decomposition. It is only really at this stage that 'true' peat growth can be said to have occurred.

Finally, pollen analysis, following the methods in Chapter 4, was used to assess the nature of vegetational change occurring during the transition in two monoliths, in conjunction with macrofossil evidence. It was also of use in estimating dates. There are difficulties in the

interpretation of soil pollen profiles (Dimbleby, 1985) which would not affect the samples from peat. Differential preservation, faunal mixing and downward movement of pollen must be considered.

8.3.5.3 Dating the deposits

Pollen analytical dating by comparisons with established regional chronologies, such as the Godwin zones, has been widely used to estimate dates of basal deposits (eg.Moore, 1973, 1975; Durno and Romans, 1969) and this may well be a reliable indicator, using consistent boundaries such as the elm decline (Smith and Pilcher, 1973). However, there are problems with this method further north, where the standard zonation is not generally applicable (Walker, 1984).

Radiocarbon dating should provide a more reliable method of assessing the timing of basal peat initiation, although there are a number of additional methodological problems associated with this. Practical problems are presented by radiocarbon dating in terms of the quantity of material required. Chambers (1980) states that it is necessary to have a sample containing at least 2.5g carbon, so that as much as 2-300 $cm3^{\circ}$ of wet peat may be required, where the sample is split into different fractions. A large surface area of peat is then needed to keep the vertical size of the sample to a minimum and hence the time span of accumulation as low as possible. This is particularly important for basal peat samples as accumulation rates may be very slow, for example a basal humus layer from Wales was found to cover an estimated 1000 years (Smith and Taylor, 1969).

Errors in radiocarbon dating are likely to occur from various sources when conducted on untreated peat samples. Mobile humic acids will give younger dates than expected and rootlet penetration introduces younger carbon to older deposits. Dating was carried out on the fine particulate (<500μm) fraction to reduce these effects. Dresser (1970)

and Chambers (1980) recommend a sieve size of 250μm, but this failed to yield adequate material (D. Harkness, pers. comm). Eight radiocarbon dates were obtained from the four samples. Six of these were from the two summit peat sites. The sample details and dates are shown in Table 8.3.

Table 8.3: Radiocarbon dates from peat-soil interface samples

Monolith	Depth (cm)	Lab.code	Date (bp)	^{13}C (‰)
2	51-52	SRR-3726	4035±55	-28.3
2	55-56	SRR-3727	4890±65	-28.0
2	60-66	SRR-3728	4475±55	-27.8
3	206-207	SRR-3729	6805±50	-29.9
3	209-210	SRR-3730	7310±50	-28.7
3	211-212	SRR-3731	6765±55	-29.8
1	137-138	SRR-3725	9170±90	-28.2
4	170-172	SRR-3732	8835±165	-28.0

Dates are uncalibrated and errors are quoted as ± one standard error.

These results will be further discussed throughout this chapter, but there are several general points to be made here. In both cases where there are sequences of dates (ie. monoliths 2 and 3), the basal date is younger than the date above it and in the case of monolith 3 is the youngest of all three dates. There is little likelihood that the upper dates are too old, and therefore it is the deepest samples that are regarded as being too young. This is not an entirely unexpected problem as it has also been reported by Smith and Cloutman (1988) amongst others, although two out four of these profiles have younger than expected basal radiocarbon ages rather than a reversal of dates. This 'younging' of basal peat samples is probably caused by the introduction of later root material, a process which would

be particularly effective in soils of higher mineral content, where younger carbon from this source forms a greater proportion of the total carbon present. Within these types of sediment, accumulation rates may have been lower than in later fully organic sediments, so that penetration of roots may have continued for longer. Also, higher decay rates in the mineral soils result in greater breakdown of organic matter present, so that remaining particles are more likely to be less than the 500μm sieve mesh than in organic sediments, where the smaller size fraction is likely to form only from remains contemporary with the peat surface. The basal dates SRR-3728 and SRR-3731 are therefore regarded as being anomalous and are disregarded in assessing the likely age of these sediments. Although there may be some similar effects on the shallower dates, these are probably of much lower magnitude, and the dates are close to estimates made on the basis of the pollen content of the samples. They are therefore used in the following discussions. The basal dates from monoliths 1 and 4 are both taken from levels at which LOI is comparable with the two upper dates from monoliths 2 and 3 and are also thought to be reasonably reliable, although this is difficult to establish without further dates from higher up the profile.

8.3.6 Preliminary investigations

As the work was intended to examine the changes occurring where ombrotrophic peat directly overlies mineral substrate, preliminary macrofossil and loss on ignition analyses were carried out to confirm the existence of basal ombrotrophic peats, as this was not possible from stratigraphic examination alone.

8.3.6.1 Monolith no.1

This sample was removed from a depression in the underlying topography with moderate peat depth (Figure 8.14). The site is situated about 1km from the summit area at an altitude

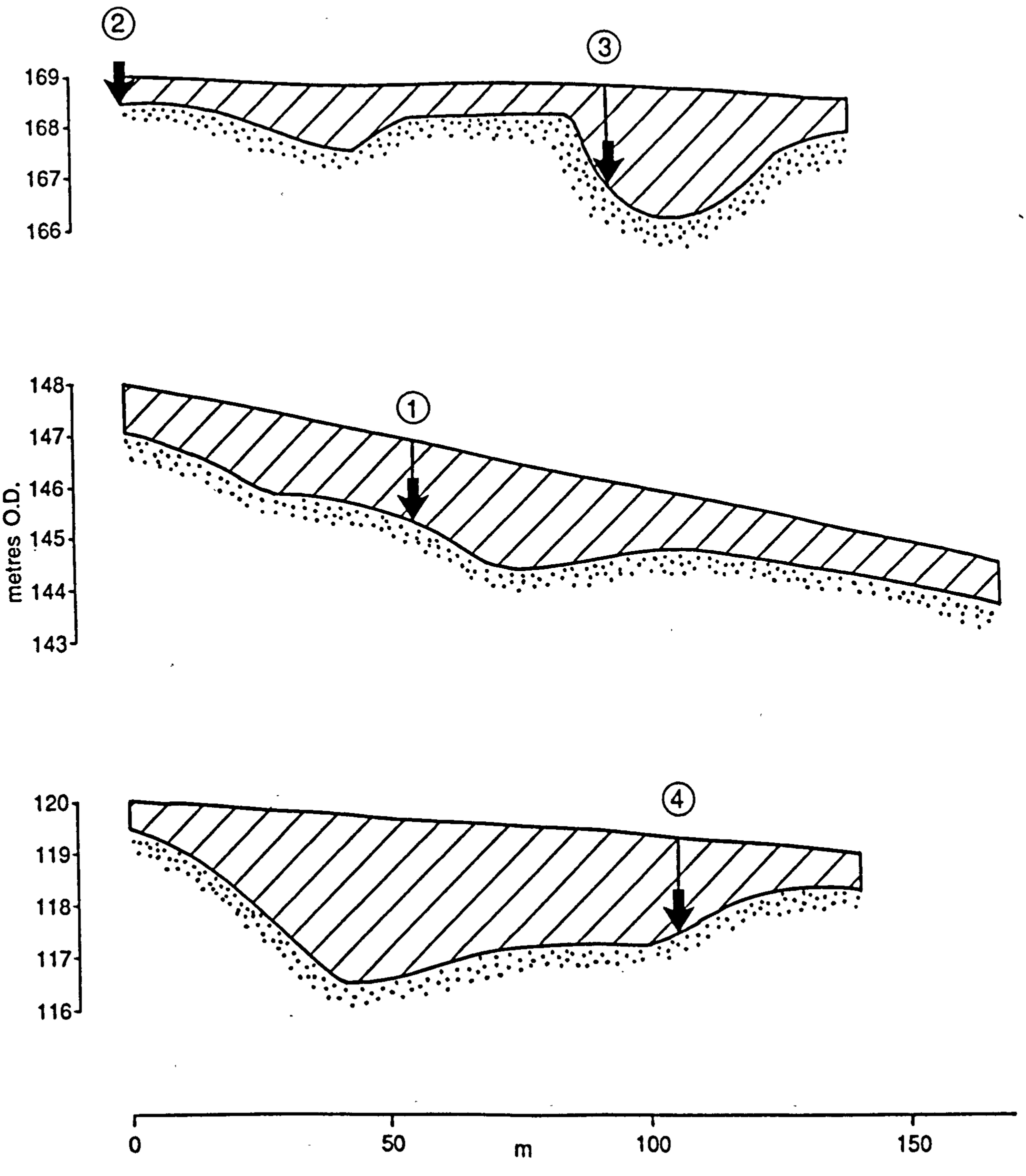


Figure 8.14: Small scale topographic context of peat monolith samples.

of 145m OD. The stratigraphy is as follows.

0cm Surface vegetation: *Calluna*, *Myrica*, *Carex nigra* (probably a consequence of surface disturbance).

0-36cm Pale, fibrous, unhumified *Calluna/Eriophorum* peat with surface roots.
nig.2, strf.0, elas.3, sicc.2, humo.1-2, T12, Th2

36-45cm *Calluna/Sphagnum* peat
nig.2, strf.0, elas.2-3, sicc.2, humo.2, T12, Tb2, Sh1.

45-70cm Humified ericaceous peat
nig.3, strf.0, elas.2, sicc.1, humo.3, T11, Sh3.

70-138cm Highly humified peat
nig.4, strf.0, elas.1, sicc.1, humo.4, Sh4, D1+.

138-140cm Black, highly humified peat with small sand grains.
nig.4, strf.0, elas.0, sicc.2, humo.4, Sh2, Gs2

>140cm Sand and gravel.
nig.2, strf.0, elas.0, Gs3, Gg(min)1, Gg(maj)+.

The macrofossil and LOI data (Figure 8.15) confirms the relatively rapid transition from predominantly mineral material to fully organic deposit, over little more than 4cm depth. This is reflected in the major constituents, dominated initially by mineral matter, and rapidly replaced by woody (ericaceous?) peat. The black peat with sand at the base of the organic deposit is shown to be largely composed of charcoal, which is also found in decreased quantities higher up the profile. There are seeds of *Juncus* and *Carex nigra* type beginning at 138cm, but abundant from 136cm upwards.

Burning seems to have occurred immediately prior to peat initiation and probably aided, or may have been responsible

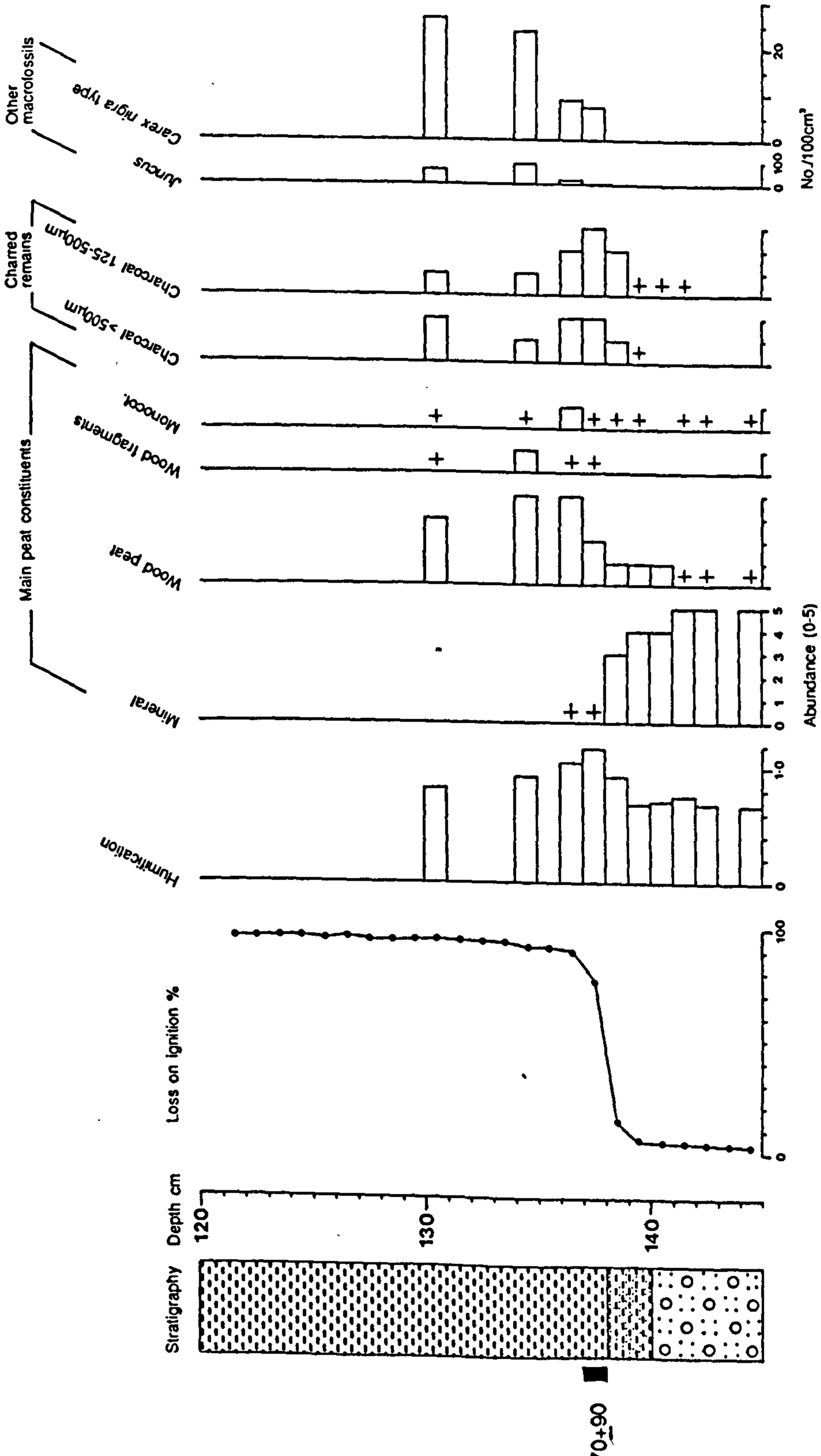


Figure 8.15: Loss on ignition and macrofossil stratigraphy for monolith 1.

for, a change in surface wetness. The single radiocarbon date indicates that this occurred in the early postglacial (9170±90 bp). In this case, although the major vegetative peat formers were woody (probably dwarf shrub) plants, there was probably some surface water movement and flushing, leading to the establishment of a rush and sedge vegetation component. There is therefore some doubt over whether the deposit can be regarded as a secondary ombrotrophic peat.

8.3.6.2 Monolith no.2

This monolith was removed from a shallow (52cm) peat deposit at the top of the exposure. The field stratigraphy was as follows:

0-17cm Surface vegetation and roots. *Calluna/Eriophorum* roots and mid-brown peat.

17-41cm Highly humified, brown, ericaceous (?) peat, with a few roots penetrating from above.
nig.3, strf.0, elas.2, sicc.2, humo.3, Tl1, Sh3.

41-52cm Darker highly humified peat.
nig.3-4, strf.0, elas.1, sicc.2, humo.4, Sh4, Dl+

52-56cm Black, very solid peat
nig.4, strf.0, elas.1, sicc.2, Sh4, Dl+.

56-64cm Black, humified peat with sand. (Mor humus?).
nig.3, strf.0, elas.1, humo.4, Sh2, Gs2.

>64cm Brown sandy soil and gravel with some large stones. Some organics at top. Paler between 64 and 69cm - eluviated A horizon?.
nig.2-3, strf.0, elas.0, Gs3, Gg(min)1, Gg(maj)+, Sh+.

The monolith for laboratory analysis covered the depth 23-

73cm and the adjacent monolith for radiocarbon dating 38-68cm, covering all the basal deposits with a significant organic content.

The macrofossil diagram (Figure 8.16) confirms most of the stratigraphic description of the cleaned face. The peat is generally highly humified, but there does not appear to be as much difference between the different peat strata as had been thought and the intermediate peat/sand deposit proved to be very highly humified.

The assessment of major constituents shows that the mineral content of the deposit gradually declines through the peat/sand stratum, but also persists in the black basal peat. It is confirmed that the earliest organic material is of woody (probably ericaceous) remains and therefore this can be regarded as an ombrotrophic peat. There are few reproductive remains, apart from *Cenococcum geophilum*, which probably grew on the roots of the ericaceae, and a few *Juncus* seeds in the peat/sand.

The charcoal record shows that from 56cm upwards (ca.4890±65 bp) charcoal is present in quite large amounts. Pieces greater than 500µm in size are particularly abundant at the base of this zone and this indicates quite intense local burning. Identifiable charred particles (*Calluna* and *Erica tetralix* leaves) are found higher up the profile.

The loss on ignition data, also shown on Figure 8.16, shows that wholly organic peat does not begin to form until above 52cm depth (ca.4035±55 bp), where the %LOI reaches a level of 96%. It indicates that the transition to the peat/sand horizon from mineral soil is not so clear cut as the stratigraphy would imply and that this phase of soil development was comparatively stable in terms of organic content.

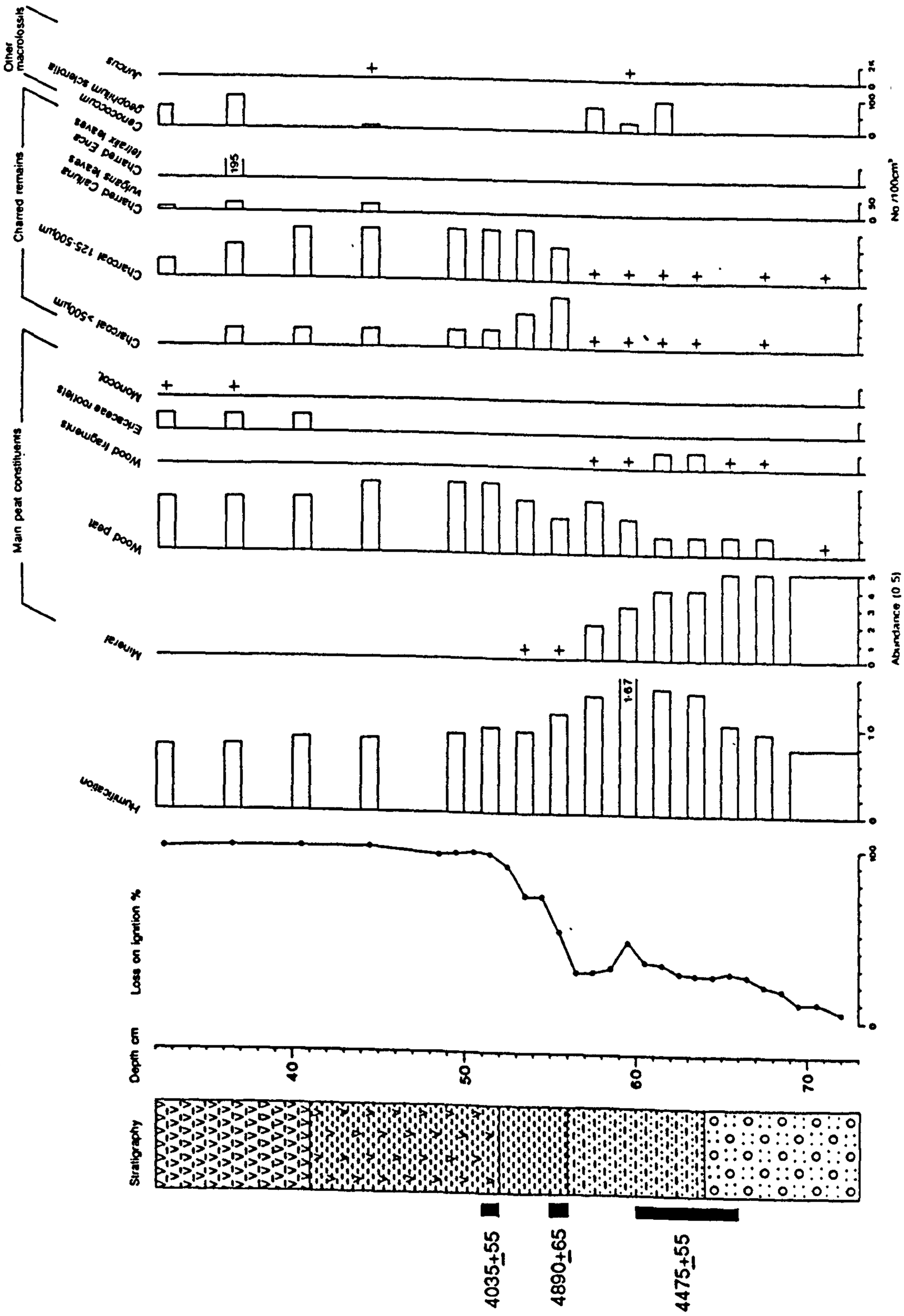


Figure 8.16: Loss on ignition and macrofossil stratigraphy for monolith 2.

8.3.6.3 Monolith no.3

Monolith 3 was taken close to no.2, but in a much deeper peat area, with deposits in excess of 2m. The stratigraphy is as follows.

0-15cm Surface vegetation and roots.
Calluna/Eriophorum angustifolium/Tricophorum cespitosum

15-102cm *Eriophorum/Sphagnum* peat with root penetration from above.
nig.2, strf.0, elas.3, sicc.2, humo.2, Th2, Tb1, Sh1.

102-121cm Humified *Eriophorum* peat.
nig.3, strf.0, elas.2, sicc.2, humo.3, Sh3, Th1.

121-133cm *Betula* wood layer, with *Pinus* in adjacent peats.
nig.2, strf.0, elas.2, sicc.1-2, humo.2, Dl2, Sh2.

133-142cm Highly humified peat, with occasional *Betula* remains.
nig.3,strf.0,elas.2, sicc.1-2, humo.3, Sh3, Dl1.

142-155cm *Betula* wood layer.
nig.2, strf.0, elas.2, sicc.1-2, humo.2, Dl2, Sh2.

155-162cm Humified *Eriophorum*/ericaceous peat.
nig.3, strf.0, elas.1-2, sicc.1-2, humo.3, Sh3, Th1, Tl+.

162-206cm Highly humified ericaceous (?) peat.
nig.3-4, strf.0, elas.1, sicc.1-2, humo.3-4, Sh3, Tl1.

206-210cm Highly humified peat with sand.
nig.3, strf.0, elas.1, humo.3, Sh3, Gs1.

210-212cm Black, highly humified peat.
nig.4, strf.0, elas.1, sicc.2, humo.4, Sh4.

>212cm Brown sand and gravel, merging into coarser gravel with large stones below.
nig.2, strf0. elas.0, sicc.3, Gs3, Gg(min)1, Gg(maj)+

The monolith for laboratory analysis covers 173-223cm.

The macrofossil and loss on ignition data is shown in Figure 8.17. The transition from mineral substrate to peat occurs over a depth of only 6cm and therefore samples were taken contiguously, although they remained 1cm thick.

The major constituents confirm that the basal peat was formed under acidic conditions, being primarily woody, with no sign of monocotyledonous fen peats. There is a little *Sphagnum* in the upper samples of the mineral soil, mostly *S.imbricatum*, but also *S.magellanicum* and sects. acutifolia and subsecunda. This assemblage probably indicates somewhat open, acidic conditions. A few leaves of *Hypnum cupressiforme* were also recovered, again an acidophilous species, although tolerant of shading. The mineral content of the peat, as recorded by macrofossil analysis, and the LOI curve indicate fluctuating organic content. The organic content rises initially in the earliest mineral/organic transition and then falls during a subsequent phase where there are sand sized particles. Fully organic peat is formed from 207cm (ca.6805±50) upwards, where LOI reaches 96%, although there is a small amount of mineral material at 199-200cm depth.

There are again few reproductive remains, *Cenococcum geophilum* sclerotia and a small amount of *Juncus* seeds in the lower samples, as before. Higher up the core, an

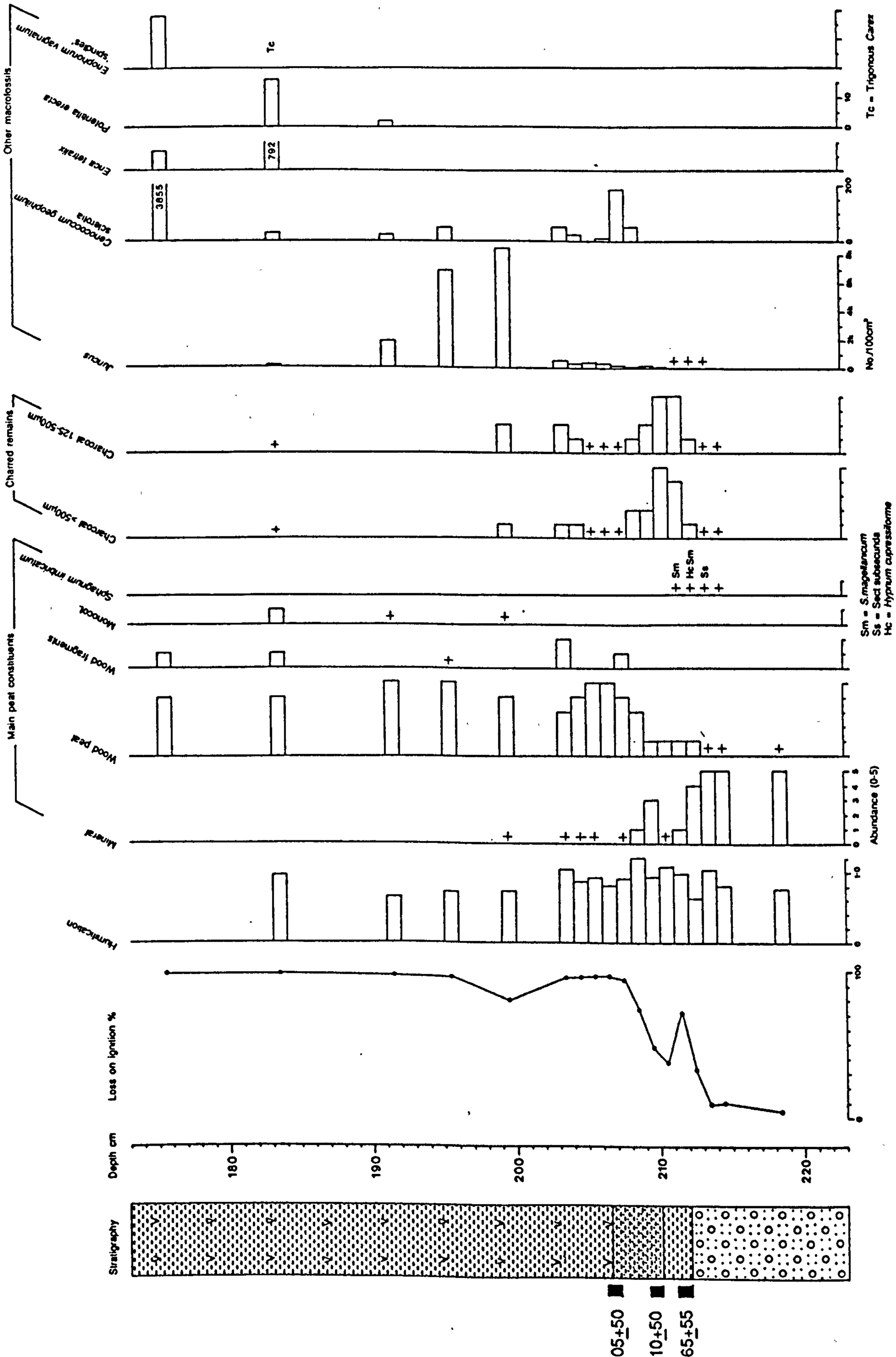


Figure 8.17: Loss on ignition and macrofossil stratigraphy for monolith 3.

expansion of *Juncus* suggests some nutrient enrichment, and the occurrence of seeds of *Potentilla erecta* and *Erica tetralix* perhaps suggests better preservation conditions. However, the peat is predominantly ombrotrophic in the lower peat.

The charcoal record shows that the basal organic deposit is almost entirely charcoal, of both size fractions. This then declines during the sandy peat stratum and almost disappears in the transition to fully organic peat, before reappearing at low levels further up the sample. The fire history is therefore more variable at this site; early, intense burning is followed by a phase of little or no fire, with decreased severity and/or frequency thereafter.

8.3.6.4 Monolith no.4

This sample was removed from another sub-peat depression, close to the valley bottom at an altitude of 118m (Figure 8.18). The stratigraphy is as follows.

0-26cm Unhumified *Eriophorum angustifolium* peat and surface roots.

26-74cm More humified *Eriophorum/Calluna* peat
nig.3, strf.0, elas.2, sicc.1, humo.2, Th1, T11, Sh2

74-130cm Dark, ericaceous peat.
nig.3-4, strf.0, elas.2, sicc.1, humo.3, T11, Sh3

130-140cm Highly humified peat and *Betula* remains
nig.3-4, strf.0, elas.1, sicc.1, humo3, D11, Sh3

140-150cm *Betula* bark and wood, with occasional stump.
nig.2, strf.2, elas.2, sicc.2, humo.1, D13, Sh1

150-172cm Highly humified peat with some *Betula* remains
nig.3-4, strf.0, elas.1, sicc.1, humo.4, Sh4, D1+

172-174cm Black, highly humified peat with sand
nig.3, strf.0, elas.1, sicc.2, humo.4, Sh1, Gs3
Gg(min)+

>174cm Pale brown sand with gravel and larger stones
nig.2, strf.0, elas.0, sicc.3, Gs1, Gg(min)1,
Gg(maj)2

This profile again shows a relatively rapid transition from mineral substrate to organic peat initially, although the LOI curve (Figure 8.18) does not reach stable levels of >95% until 166-165cm depth. A date of 8835±165 bp was recorded from the deepest predominantly organic deposits (ca.70%LOI). Although some of the later peat consists of unidentifiable woody remains, there is a significant component throughout the basal peat of monocot. roots and an unidentified red-brown epidermis. In addition to this there are large numbers of *Juncus* and trigonous *Carex* seeds with some *Selaginella selaginoides* megaspores, and *Carex nigra* type later. This, together with the topographic position of the sample suggests that the basal peat is not ombrotrophic but represents a fen community, forming a primary peat, which may even be a palaeochannel of the nearby river Dyke. No charcoal was found at the base of this profile, although the appearance of the black basal layer was very similar to that at other sites. This highlights the importance of more careful stratigraphic analysis in sediments of this nature.

8.3.7 Further analysis

The preliminary analyses revealed that two of the deeper peats were probably not entirely ombrotrophic in nature, although the evidence for this is much clearer in the case of monolith no.4, than it is for no.1. The much older dates from these samples (8835±165 and 9170±90 bp) also support this contention as such primary peats are likely to be the

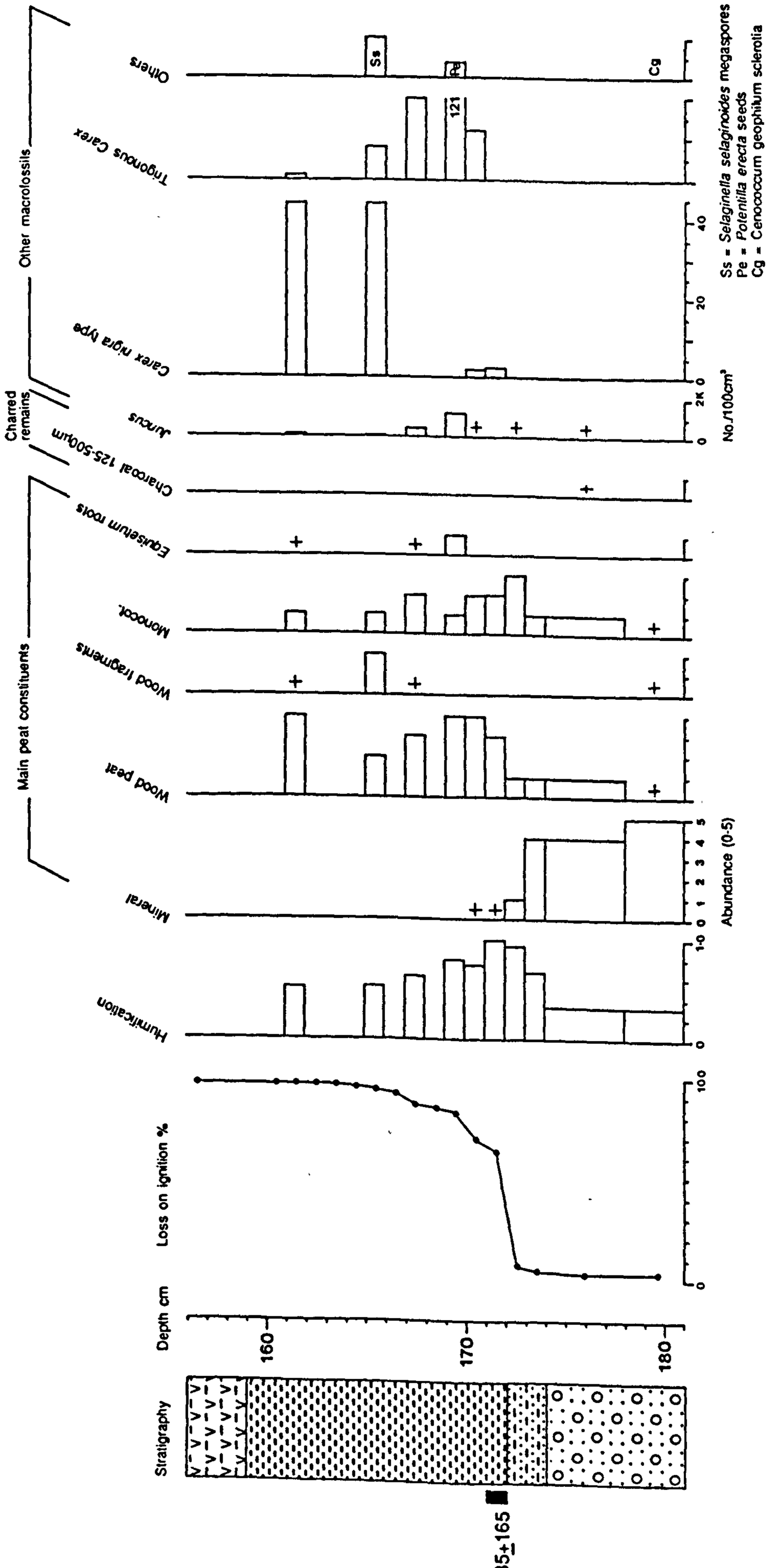


Figure 8.18: Loss on ignition and macrofossil stratigraphy for monolith 4.

earliest peat deposits to form. These were therefore excluded from further analysis. Although only three deeper peat profiles have been examined, the fact that two of these show signs of fen development suggests that many other similar profiles may also have begun to form in this way. The two monoliths from the summit area, however, provided basal ombrotrophic peats formed in close proximity to one another, but occurring in contrasting situations. The results of pollen analysis for these two sites are presented next, together with short discussions of the combined evidence from each site.

8.3.7.1 Monolith no.2

Pollen percentage and concentration data is shown in Figures 8.19 and 8.20, respectively. The diagram covers only the transition period from mineral to organic deposits, and can be split into three major zones.

DYK2a 73-63.5cm

Betula is the dominant pollen type, with 65-85% TLP. There is some *Calluna* (ca.10-20%), with traces of a number of other species, including *Corylus*. The 'triporate' pollen is difficult to interpret but most probably refers to *Betula*. The pollen spectra represent a closed birch woodland, with an understorey dominated by *Calluna*. There may have been ferns growing in the woodland, or these may have been epiphytic on the birch (eg.*Polypodium*). Pollen concentrations are high during this zone, at 2-400,000 grains cm^{-3}. The higher concentrations in the lowest sample may be due to downward movement of small particles (including pollen grains) as part of the pedogenetic processes. The eluviated soil horizon approximately from 64 to 69cm will have been depleted of these more mobile soil constituents. The greater percentage of *Calluna* in this sample may be a result of greater mobility of this pollen type.

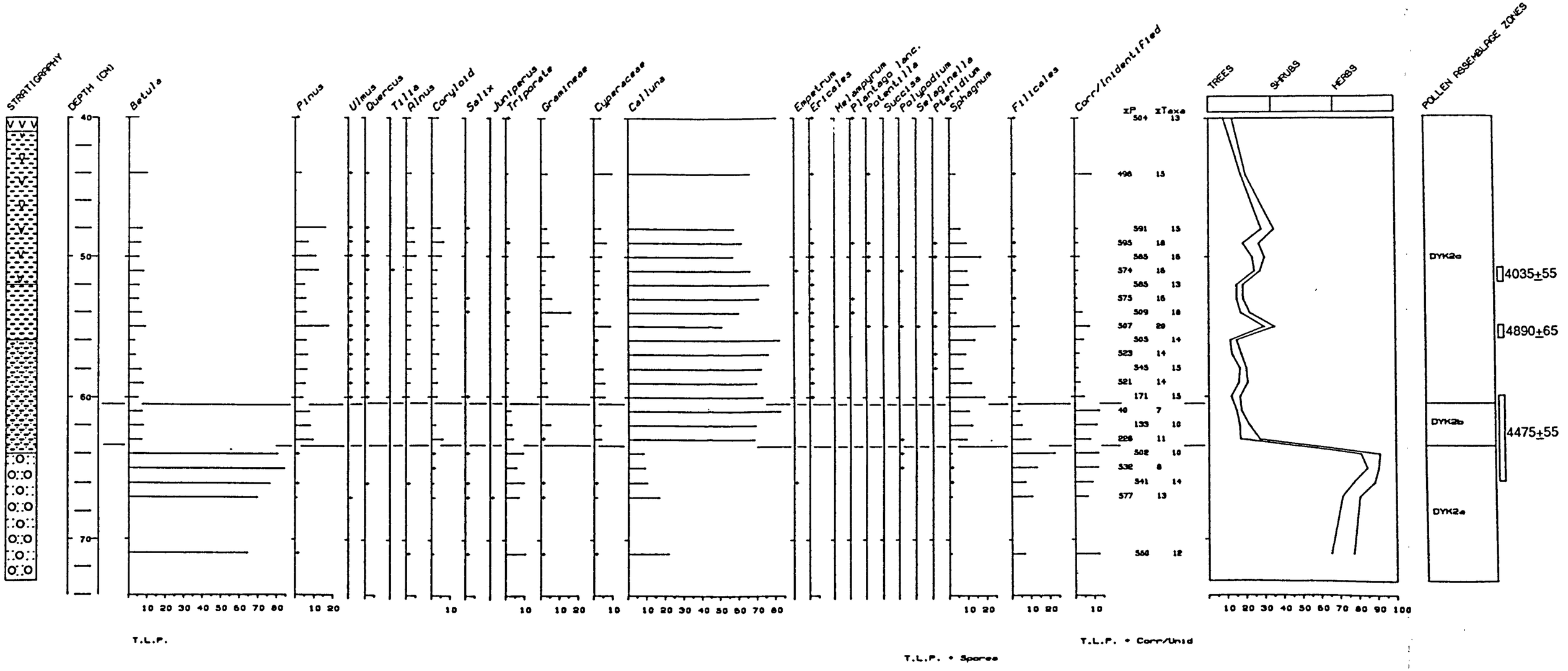


Figure 8.19: Percentage pollen diagram for monolith 2.

Analysis DJ Charman 1990

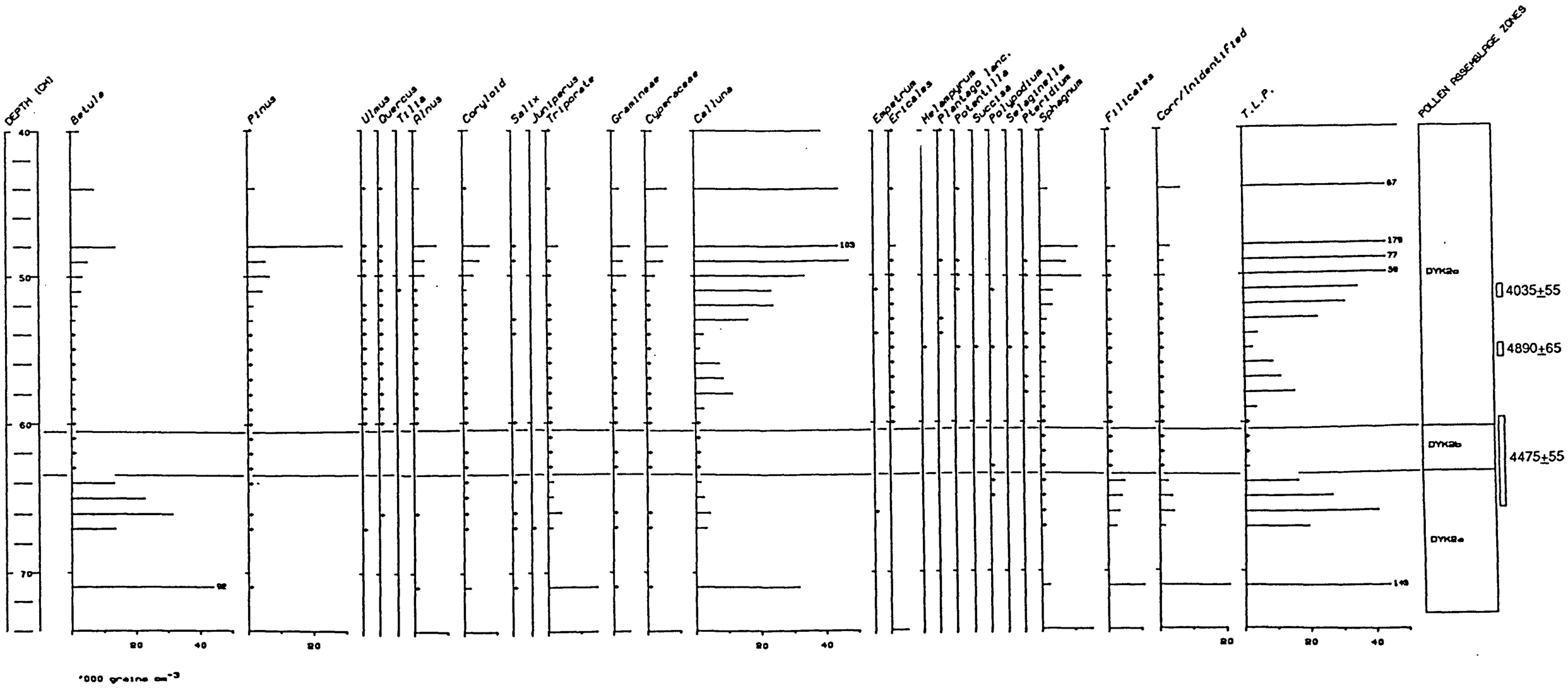


Figure 8.20: Pollen concentration diagram for monolith 2.

DYK2b 63.5-60.5cm

This is dramatically different to the earlier pollen spectra, being dominated by *Calluna* (65-80% TLP). Birch has declined to around 8%TLP, but pine is the only other tree taxa present, although levels of only 7-10% do not indicate local presence. Coryloid shows some increase and gramineae and cyperaceae are present. There is a rise in the *Sphagnum* curve and Filicales decline. Although it is possible that there is some differential pollen preservation, particularly as there are abundant Filicales spores a well known resistant type (Havinga, 1964, 1967, 1984), there is no major decline in total corroded/unidentifiable grains so the effect is thought to be minimal. There may also be a hiatus in the pollen record because of the relatively sharp transitions in most pollen curves. However, this does not alter the nature of the vegetational change.

The spectra represent a replacement of the birch woodland by *Calluna* heathland. The disappearance of the tree canopy probably allowed the long distance element of the pollen rain to become significant, this mainly represented by pine. Pollen concentration drops dramatically at the start of this zone. This may be due to reduced pollen influx or to increased sediment accumulation rate. It is likely that both these factors are operating, as the pollen concentration is extremely low, reaching as little as 1700 grains cm^{-3}.

DYK2c <60.5cm

This zone represents a continuation of DYK2b in the persistence of the *Calluna* dominated spectra. However, there is a further diversification of the pollen assemblage, with the appearance of several other tree taxa, *Alnus* in particular, but also *Ulmus* and *Quercus* at very low levels. Filicales decline further. There is no sedimentary change at this time and this suggests that the beginning of this zone marks the regional alder rise, one of the few reasonable chronological markers in the region, at 5880±45 bp at Cross Lochs Fen A (Chapter 5). This estimate of age

from pollen spectra supports the assertion that the radiocarbon sample 60-66cm is contaminated by younger carbon, and is regarded as being a more reliable estimate of true age on the radiocarbon timescale. Pollen concentration remains low at the start of this zone, indicating that the appearance of alder is a real event rather than an artefact of changing local pollen.

Inferred environmental change

The earliest evidence suggests that there was birch woodland on this site from early in the site history. A shallow mineral soil was developing, but this began to be subject to leaching and there was some podsolisation of the upper mineral soil. It is difficult to tell whether this preceded the change in plant communities to *Calluna* heath, or whether the removal of the tree canopy caused the soil leaching. It seems unlikely that birch would be eliminated by a relatively minor soil deterioration, as it is a rapid coloniser of much better developed podsolic soils elsewhere in Britain today (Webb, 1986, p190-1), can be established from seed in Callunetum (Miles, 1973; 1974) and even has a tendency to reverse the deterioration process (Miles, 1981). Indeed, Cruickshank and Cruickshank (1981) show that podsols formed in the past can eventually be recolonised by species such as *Quercus petraea* and *Q.robur* in the absence of further disturbance. The rise in *Sphagnum* spores suggests that conditions may have become wetter at this time, which may have affected birch growth and promoted soil leaching. Given the problems of radiocarbon dating of these deposits, it is not possible to give a precise date for this early vegetation change, although it must have been well before the alder rise (5880±45bp at Cross Lochs A), possibly by as much as 1000 years assuming an accumulation rate of 250 yearscm^{-1}.

The very low pollen concentrations immediately after the vegetation change suggest that accumulation rates were relatively rapid, despite the high humification and mineral

content of the deposit. Wetter conditions, with decreased rates of decay, would also explain this feature. Pollen percentage data suggests there was little change in the local plant community during this phase and macrofossil and loss on ignition also indicate a relatively stable situation, although there may have been some slow down of accumulation rates as pollen concentration rises slightly. This continues until well after the regional alder rise (ie.5880bp).

The major macrofossil and stratigraphic change at 56cm depth (dated to 4890±90bp), with abundant charcoal indicating the start of local burning, does not register strongly on the pollen percentage curve. There is a temporary depression of the *Calluna* curve and a rise in cyperaceae, then gramineae, together with a few more grains of *Pteridium*. This indicates a relatively minor and short lived response of the local vegetation. The increase in arboreal pollen, particularly in *Pinus*, may be a result of a decreased density of *Calluna*, allowing a greater proportion of longer distance pollen rain to be deposited.

However, the limited response of the plant community to the influence of burning is perhaps unsurprising in view of the use of fire to maintain Callunetum on upland moors today (Gimingham, 1975). Although vegetation does not change very much, the nature of the deposit rapidly alters to develop into wholly organic peat by 52cm depth (ca.4035±55bp). Burning is known to reduce soil porosity by blocking pore space (Mallik *et al*, 1984) and this may have increased waterlogging here, leading to decreased decay and peat initiation.

8.3.7.2 Monolith no.3

The pollen samples were 0.5cm thick at contiguous 0.5cm or 1cm spacing, to gain sufficient detail on changes occurring over a relatively short section of the monolith. Pollen percentage and concentration diagrams are shown in Figures

8.21 and 8.22, respectively. The data has been divided into four zones.

DYK3a 223-211.75cm

Birch occurs at 50-60%TLP, with *Calluna* at 30-40%. There is a small amount of Coryloid pollen (5-6%TLP towards the end of the zone. Filicales are present at 40-60%TLP+spores. The pollen spectra are indicative of an open birch woodland, with *Calluna* dominating the herb layer, with pteridophytes probably growing on the ground and epiphytically, as there are occasional spores of *Polypodium* and *Pteridium*. Pollen concentrations are high, reaching a maximum of over 2,500,000 grains cm^{-3} at the top of the zone. The radiocarbon date of 6765±55bp for the end of the zone is regarded as being too young for reasons already explained. Presumably the DYK3a-3b transition is older than the date of 7310±50bp from 209-210cm (which may itself be slightly affected by younging), but more recent than the local Coryloid rise (dated to 8995±50bp at Cross Lochs A).

DKY3b 211.75-208.5cm

This zone sees a decline in *Betula* to ca.30%, with a corresponding rise in *Calluna* to around 50%. There is also a rise of other open habitat taxa, including Gramineae, Cyperaceae and *Potentilla* and a fall in Filicales. There is a rise in all tree pollen other than birch, but only to very low levels. During this zone, the woodland became more open, although birch was probably still present locally, with *Calluna* dominating the ground layer with some grasses and sedges. The more open canopy allows greater representation of more distant tree taxa in the pollen record.

DYK3c 208.5-205.75cm

There is a recovery of birch from the beginning of this zone (ca.7145bp by interpolation between dates), to former abundance of 65% by 207cm, with a corresponding decline in almost all other types, especially *Calluna*. However, Coryloid remains at ca.5%, and pine at 2%. There is a

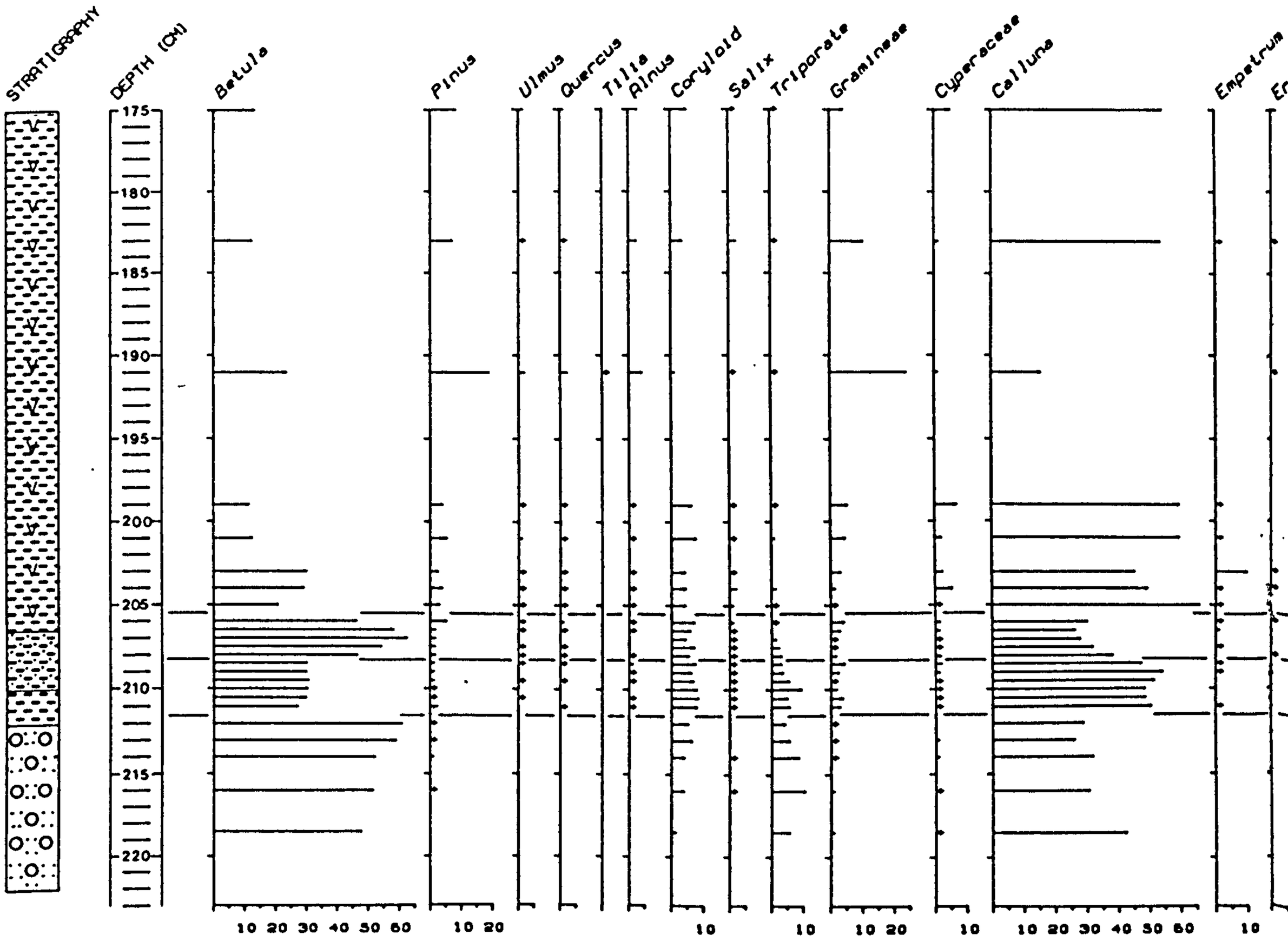
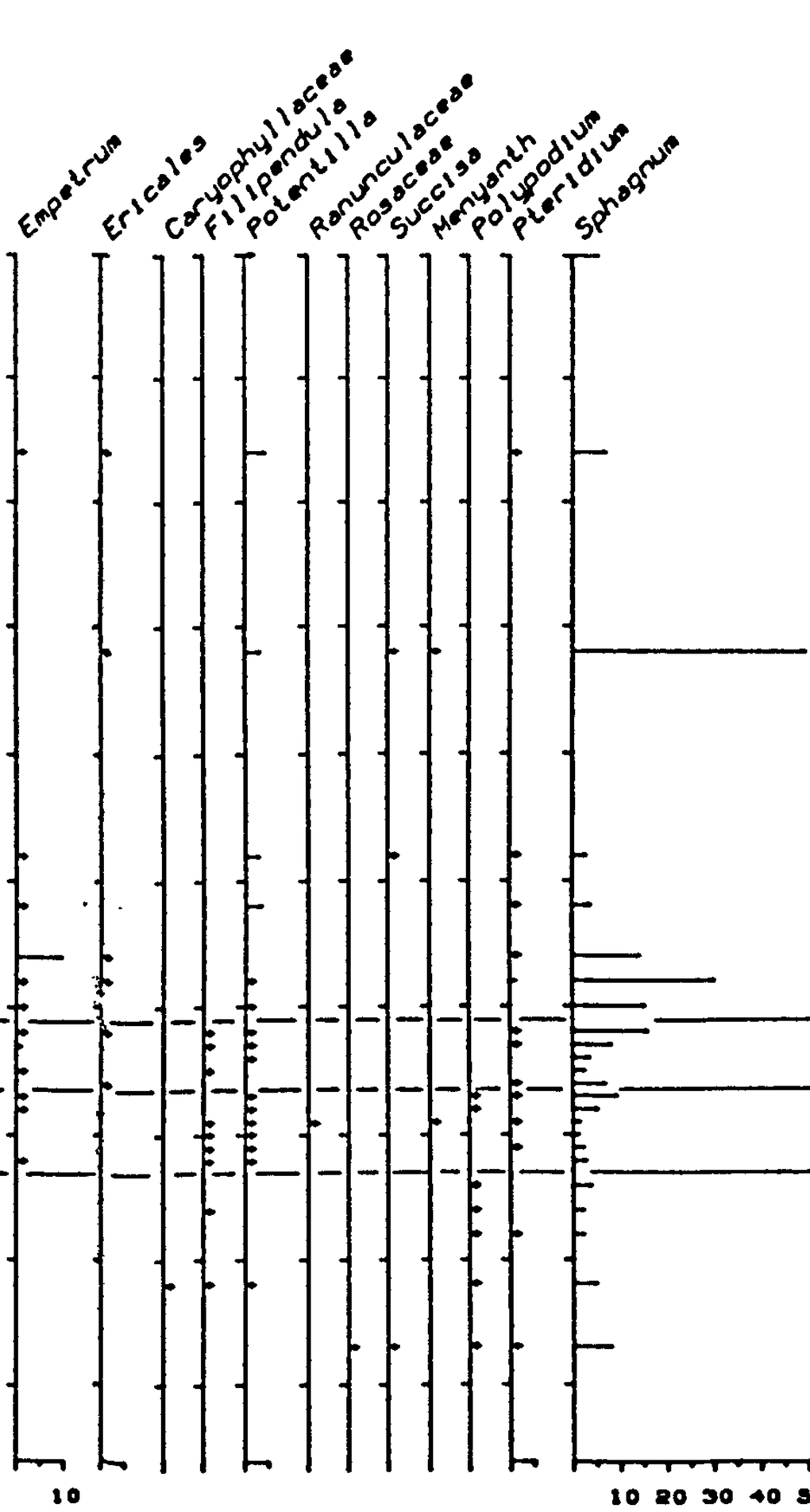


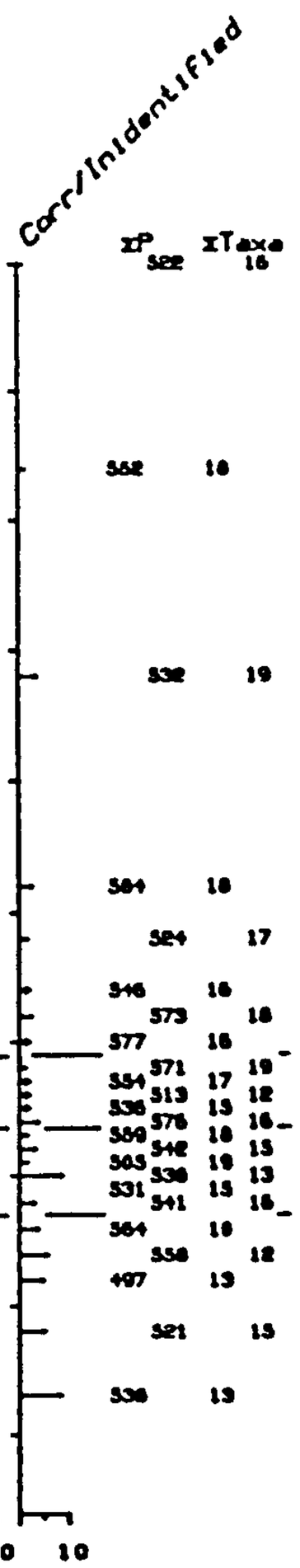
Figure 8.21: Percentage pollen diagram for monolith 3.

BASAL PEATS: NO.3



T.L.P. • Spores

T.L.P. • Aquatics



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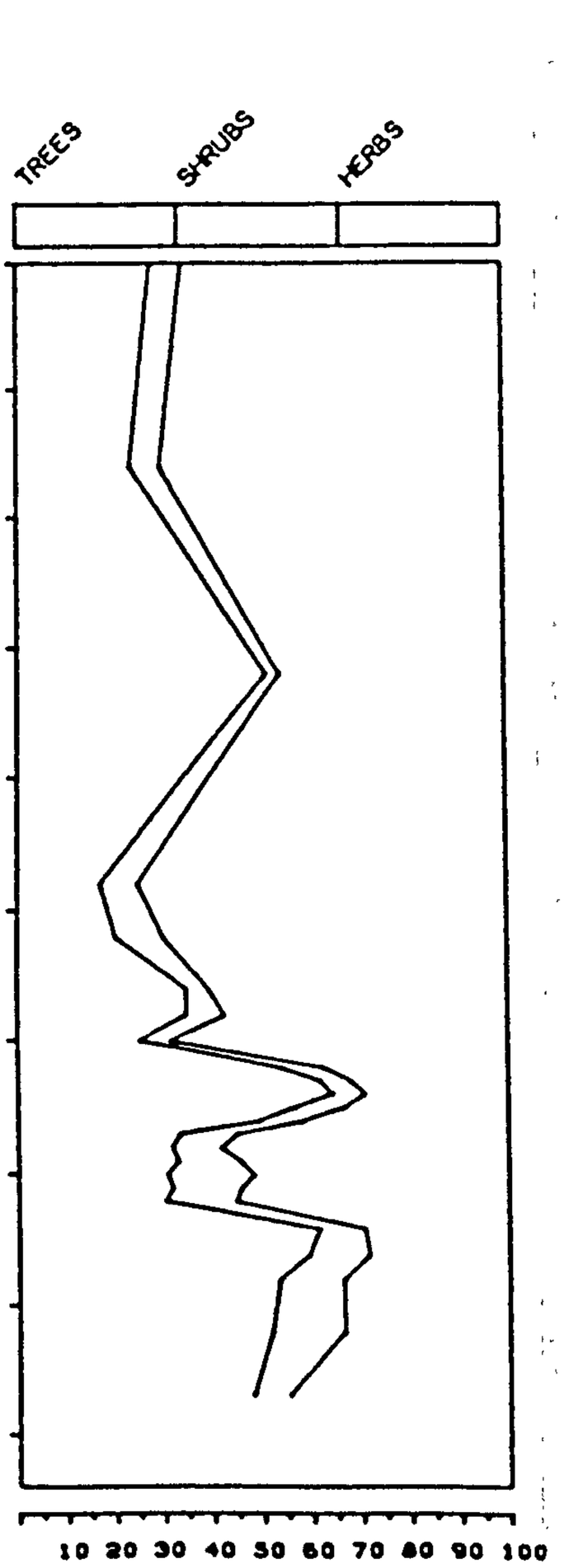

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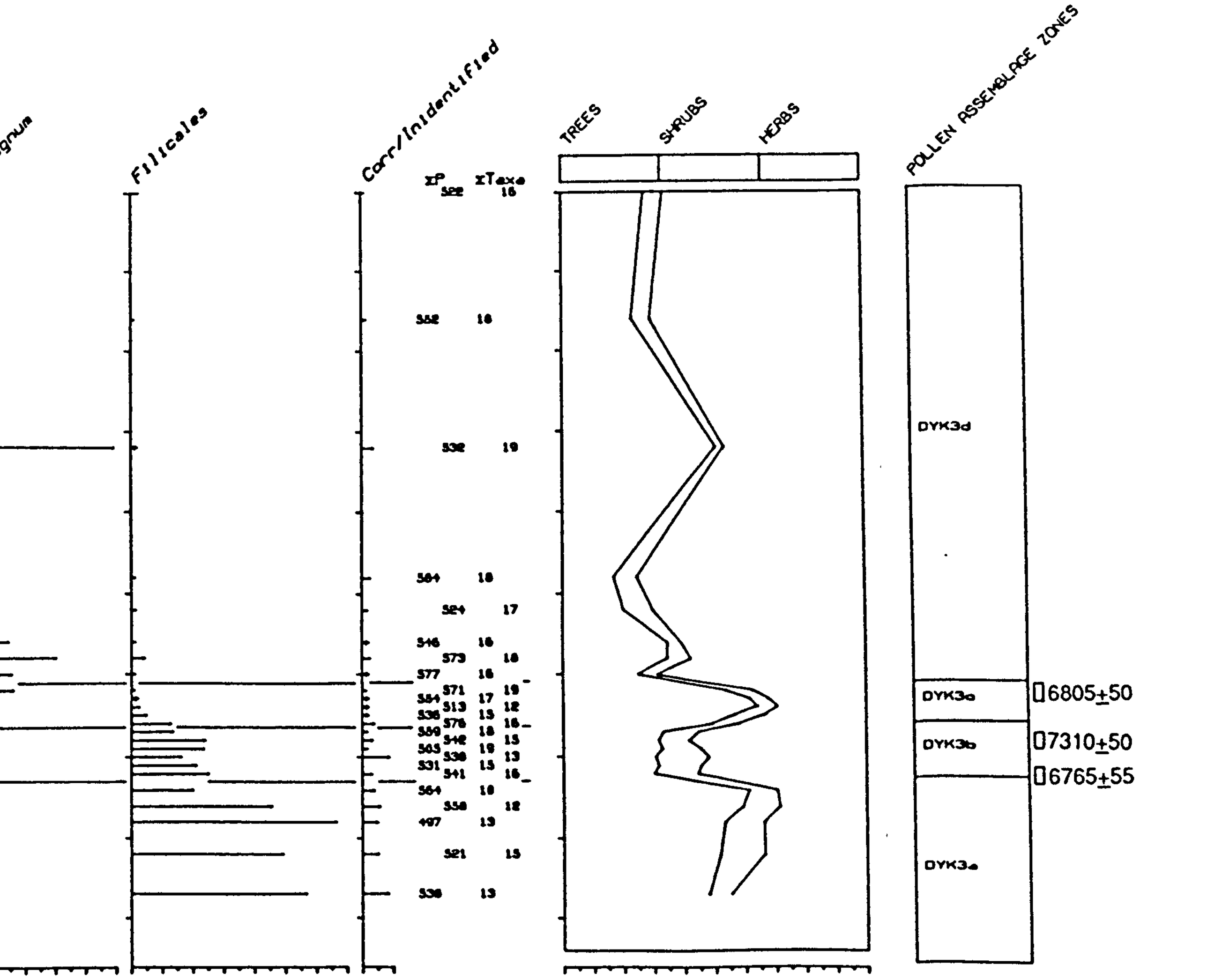
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TREES
SHRUBS
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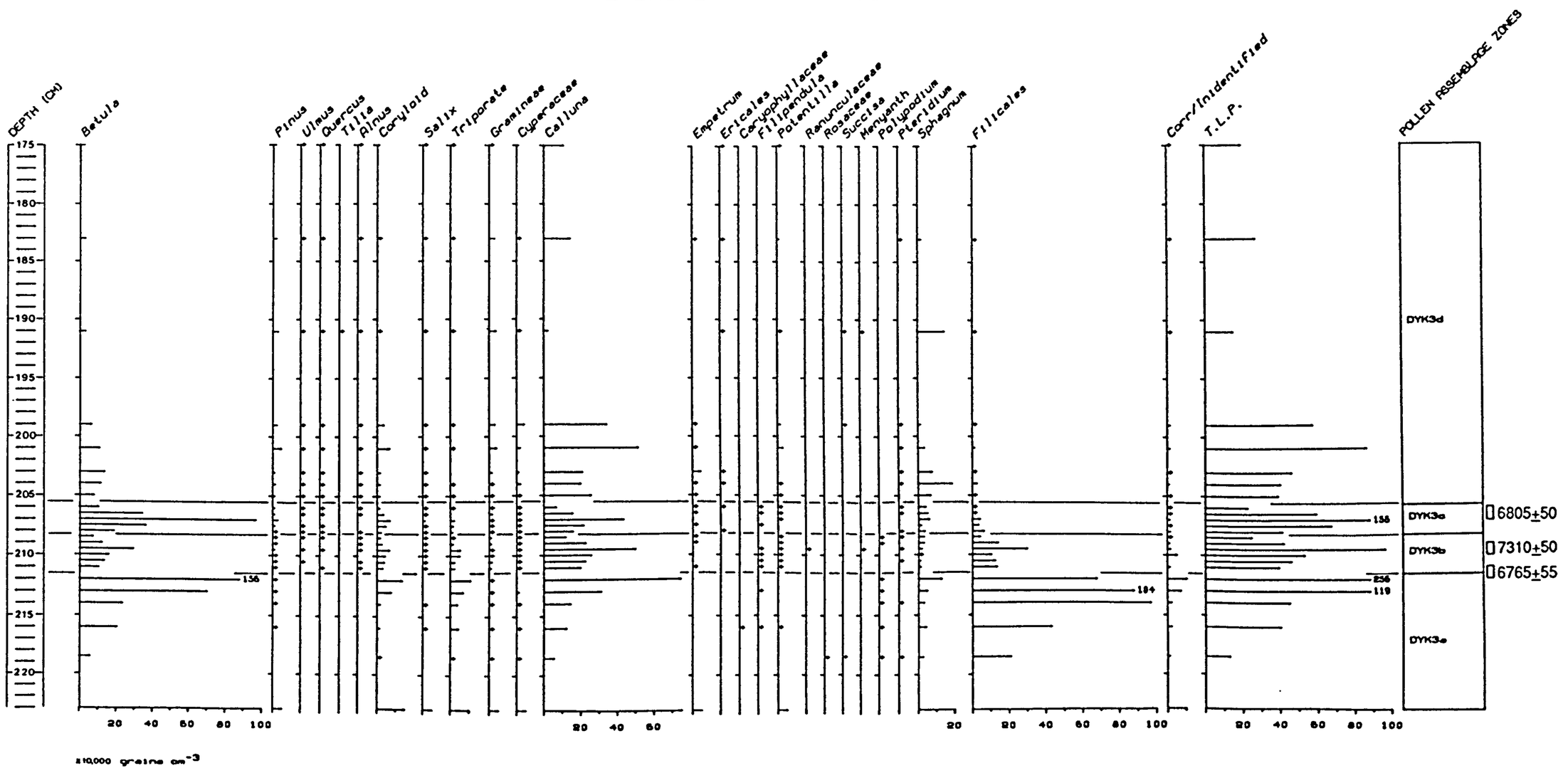

Figure 8.22: Pollen concentration diagram for monolith 3.

Analysis DJ Charman 1990

further decline in Filicales spores. This is the lowest zone where there is a negligible proportion of unidentifiable and 'triporate' grains. Clearly a recovery of birch growth is indicated, with similar vegetation mid-way through the zone to that in zone 1, except for the pteridophyte flora, which suffers a continuing decline.

DYK3d <205.75cm

The changes noted at the DYK3a/DYK3b boundary are initially repeated here, with a decline in birch (30%), a rise in *Calluna* (50-65%), Cyperaceae, Gramineae and *Potentilla*, and small increases in *Pinus* (4%), *Ulmus* and *Quercus* (1% each). This occurs at around 6685bp. Again, the birch canopy has thinned initially and then almost disappears, when levels fall to only 10% above 202cm. The dwarf shrub community, of which *Empetrum* is briefly a significant part, dominates. *Pteridium* also appears briefly at the start of this zone, and for the first time *Sphagnum* spores show a large increase.

Inferred environmental change

The early changes in vegetation are synchronous with the main stratigraphic differences and macrofossil and charcoal curves. There is evidence of severe burning at the same time as the open birch woodland declines at 212cm, so that the circumstantial evidence for regarding these as cause and effect is strong. The clear link between fire history and vegetation change is continued with the regeneration of birch during the phase where little charcoal was found (PAZ 3). It would seem unlikely that quite thick (2cm) deposits of sediment dominated by charcoal would occur as a result of lightning strikes and anthropogenic interference must have been important. The effects on the vegetation were relatively short lived as the woodland cover appears to have regenerated to former levels by the middle of zone 3. The lack of recovery of Filicales may be a result of much slower response times of epiphytic pteridophytes in particular.

It was suggested that burning led to the change from heathland to blanket mire in monolith 2. Although it has been demonstrated experimentally that porosity of heathland soils decreases after burning (Mallik *et al*, 1984), the consensus of opinion in north America is that burning actually reduces the probability of paludification (Heinselmann, 1981; Viereck, 1983), or that it depends on the intensity of burn (Wein, 1983). However, these authors are considering boreal forest ecosystems and the effects on forest soils may well be different to those on heathland. Pore sizes are likely to be much smaller in the upper 'mor' humus horizons of heathlands and therefore more susceptible to blocking by ash. This may account for the different responses found following fire in monoliths 2 and 3, the early event in the latter sample occurring in a woodland ecosystem on a sandy substrate with large pore sizes. In addition to this, the climate was probably drier during this time.

Later on, however, the final decline of birch does not correlate with the slight increase of charcoal at 204-205cm, but begins earlier, at the end of zone DYK3c, with a decline of about 20%, to 45%TLP at 206cm. This correlates much better with the start of the increase in *Sphagnum* spores, indicating increased surface wetness. In addition to this, there is much less charcoal at 204-205cm than occurs during the earlier deforestation episode (DYK3b) yet the decline in birch is much greater. The most likely explanation of the decline in birch is that increased surface wetness resulted in less suitable soil conditions for its growth, and that later burning had a further destructive effect. In addition to this there may have been a more widespread decline in birch, reducing regional birch pollen influx.

Wholly organic peat occurs from 207cm (6805$\pm$50bp) upwards and this must reflect decreased decay rates, again implying increased surface wetness and anaerobic conditions. It is difficult to assess whether this has occurred partly as a

result of the earlier deposition of charcoal. Certainly the charcoal would have reduced soil porosity as described for monolith 2, earlier.

Although the dating of the earlier events is uncertain due to the problems of radiocarbon dating, the early burning events probably date from at least 7500bp and peat growth was undoubtedly established by 6805±50 bp, much earlier than at the shallow peat site.

8.3.8 Discussion and conclusions

8.3.8.1 The combined evidence

The results of the investigations into the two summit peats are summarised and correlated in Figure 8.23. The earliest events on the trackside profile are the initiation of the primary fen peats at sites 1 and 4 around 9000bp. In the case of monolith 1, the oldest sample (9170±90bp), there is some evidence for early burning. The existing data does not allow a full assessment of the effects of this on the vegetation, but it occurs in comparable amounts to later episodes thought to be attributable to anthropogenic causes. There is direct evidence at monolith 3 for the disturbance of early birch woodland by anthropogenic burning from as early as 7500bp, in this case possibly a single severe episode or possibly a longer period of less severe fires. This led to fluctuations in the cover of birch which appears to have been the dominant, possibly the only, tree species of the woodland cover. Sometime prior to the alder rise (ca.5880bp), cover of birch began to decline more generally, not in response to anthropogenic activities, but probably as a result of increased surface wetness. In areas more susceptible to waterlogging (monolith 3) this led to the formation of an organic A horizon and blanket peat growth. In naturally drier locations (monolith 2), the effect was podsolisation of the surface layers of the sandy soil, and replacement of the birch by *Calluna* heathland. The pedogenetic change is

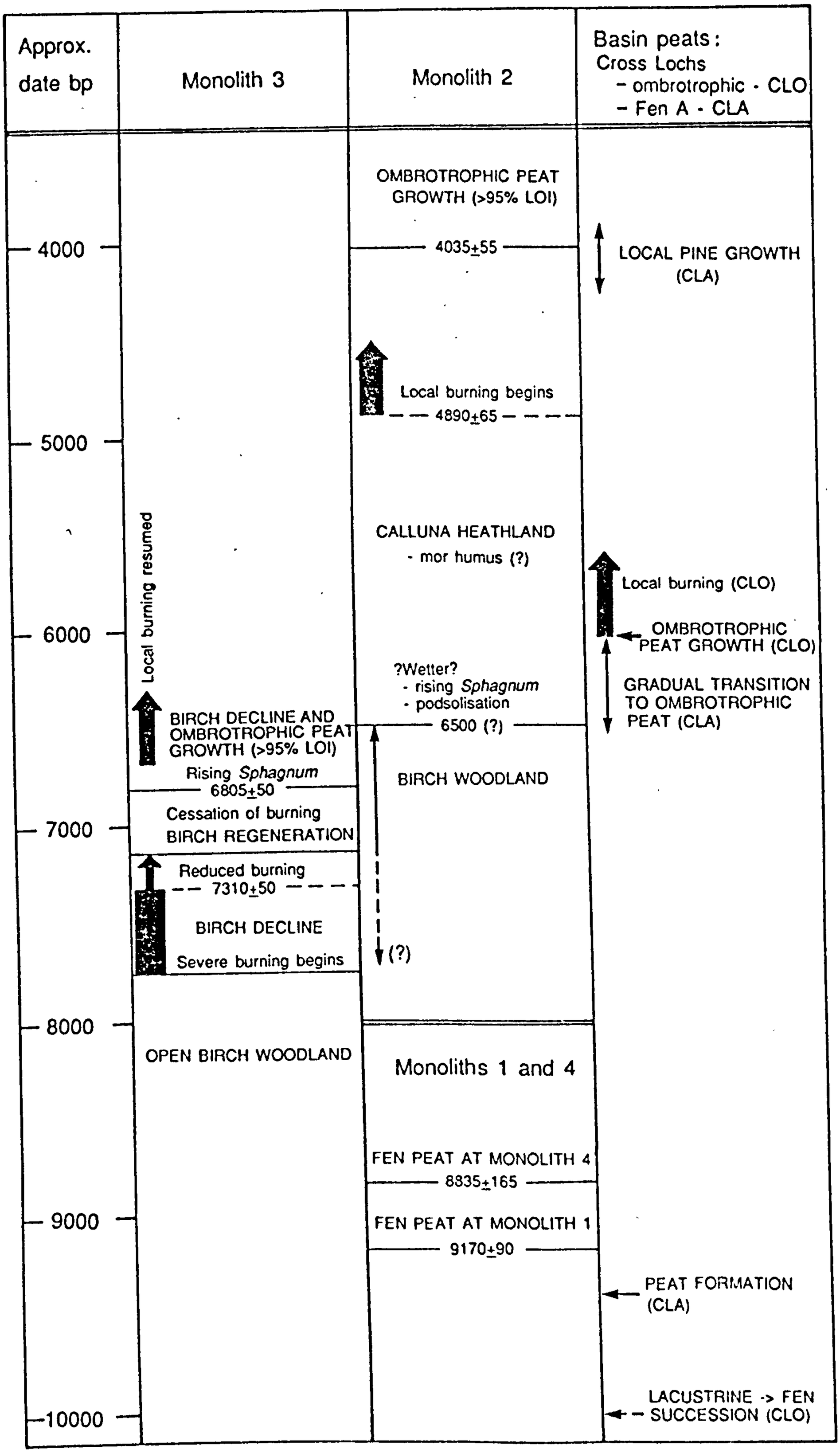

Figure 8.23: Summary of environmental change at monolith sites, compared with two basin peat sites

unlikely to have caused the decline in birch here. The timing of the event is estimated as 6685bp, by interpolation, at monolith 3, but it is not possible to be precise at monolith 2. However, the closest reliable date is 4890±65bp, 8cm above the birch decline, so that the change here may be contemporaneous with that at monolith 3, suggesting that a climatic origin for the change is possible.

Resumed burning after this change, from ca.6640bp probably played a part in further reducing *Betula* and favouring *Calluna* on the deep peat area. *Calluna* heath seems to have persisted at the drier site and was probably encouraged further by burning from 4890±65bp. This burning may have been influential in the subsequent formation of wholly organic deposits from 4035±55bp, by reducing the soil porosity.

8.3.8.2 Methodological implications

It is clear from the preliminary investigations into four samples with apparently similar stratigraphies, that the nature of basal blanket peat deposits is difficult, if not impossible, to determine from careful stratigraphic examination. The high humification of the deposits masks the more subtle differences between deposits which may be crucial in determining the conditions under which they were formed. The peats which developed in deeper, wetter depressions, such as those cored in earlier investigations, accumulated faster as a result of lower decay rates and are thus recognisable in field investigations. However, where conditions were more marginal for primary peat growth, such as at the site of monolith 4, in particular, higher decay rates, possibly as a result of lower or more variable water level, led to the slower accumulation of more humified organic matter. These must still be regarded as primary peats, rather than the start of true ombrotrophic peat growth. This vindicates the use of crude macrofossil analysis to assess the sediment composition.

The charcoal data also shows the difficulty of using examination of such deposits by eye alone to infer the presence or absence of this crucial evidence. All the profiles had a layer of very black, humified material at their base, with the possible presence of charcoal, but in fact, it is entirely absent from monolith 4. Consequently, the validity of interpretations made from stratigraphic descriptions of such profiles must be in serious doubt.

Further analysis of the two monoliths from the summit area gives further insights into the difficulties of interpretation of basal peat deposits, as well as data on the nature and mode of transition at these particular sites. The relative timing of events is crucial if correct inferences are to be made regarding the relationship between soil processes, climate, anthropogenic impact and vegetation. For example, in monolith 3, there is abundant charcoal at the base of the profile which may have been regarded as being the cause of deforestation and blanket peat growth. However, although the early burning is clearly responsible for fluctuations in the abundance of *Betula*, the later decline of this taxa occurs <u>before</u> the second charcoal layer, being connected with increases in *Sphagnum* spores and therefore a probable increase in surface wetness. Likewise, at monolith 2, there is a basal charcoal layer, but woodland cover had disappeared long before this occurs. This again shows that detailed analyses of such transitions are necessary before conclusions are drawn on the origins of such mire systems.

8.3.8.3 <u>The results in relation to causal hypotheses</u>

The results of this work provide some support for several of the hypotheses presented in Table 8.1. Pollen evidence of anthropogenic impact is present, but only suggests temporary forest clearance before peat initiation. There are no 'indicators' of human impact, associated with more intensive land use (Behre, 1981, 1986, 1988), and often found in basal peats elsewhere in Britain (Moore, 1975).

There is no independent archaeological evidence of human occupation in this area at the same time (Mercer, 1980; Mercer and Hill, 1985) but a mesolithic culture would be unlikely to leave major structures and the detection of lithic finds would require extensive and careful survey of the few exposures of mineral-peat transitions. The charcoal curves provide the strongest evidence of human impact, but some of these are difficult to date, although very early dates are possible (9170±90bp at monolith 1) with clear effects on the open birch woodland from ca.7500bp. This latter date estimate is comparable with that of 7895±105bp for abundant charcoal in basal peat in east Caithness (Robinson, 1987). However, Edwards (1988) has urged caution in the interpretation of such charcoal data, presenting several different explanations for individual charcoal curves.

Comparable evidence has been found in Arran, south west Scotland, where charcoal dating to 8665±155bp is thought to indicate the presence of a mesolithic population undetected in the archaeological record at the time (Robinson, 1983; Robinson and Dickson, 1988). Since then, lithic assemblages of mesolithic age have been reported from nearby (Affleck *et al*, 1988). Some of the earliest archaeological remains in Scotland were thought to be those from this south west coast area falling around 8000bp (Edwards and Ralston, 1984). These authors also state (p19) that "hunter-gatherer penetration of Scotland's inland and upland areas ..... is likely to have been too ephemeral to have caused detectable changes to the vegetation cover, in gross terms, at least." However, Edwards (1985) shows that the doubts expressed by pollen analysts in early work from inland Galloway regarding possible mesolithic impact (eg.Birks, 1972b) are unfounded, after further archaeological work. Morrison and Bonsall (1985), review more recent archaeological evidence, and conclude that there were two main phases of human occupation in mesolithic Scotland, pre- and post-9000bp, with strong circumstantial evidence for Lateglacial settlement in Assynt, southwest Sutherland and several

other Scottish sites. It would not be unreasonable to suggest therefore that there was a small population around the time of the early burning at Cross Lochs, but it is not possible to be certain that they were responsible for the ensuing vegetation change. It has been proposed that mesolithic people used fire as a tool for the management of vegetation and animals (Smith, 1970; Jacobi *et al*, 1976; Mellars, 1976; Simmons *et al*, 1981). However, cause and effect may never be firmly established. As pointed out above, although there was vegetational disturbance following fire, this does not appear to be clearly related to the initiation of blanket peat at the deep peat site.

Pedogenic influence appears to be limited to the hummock site (monolith 2), where excess water would have drained away more easily. There is evidence of eluviation in the upper mineral horizons, but there was no illuvial horizon or iron pan in evidence although such features were observed elsewhere along the exposure. The estimated time between loss of forest cover and peat growth (95% LOI) is 2500 years. Podsolisation can occur very rapidly, in 250 years (Andersen, 1979), but Askew *et al* (1985) state that while a bleached E_a horizon may develop within several hundred years, it takes much longer (1-3,000 years) for sufficient translocation of iron oxides to form an iron pan. Accumulation rates during this time are highly variable (Boyd, 1985) being in the range 0.7-38.5 years/mm. The accumulation rate in monolith 2, during the early *Calluna* heathland phase from 63.5-55.5cm, is in the middle of this range, estimated at 20.1 years/mm. Pedogenesis is, however, clearly related to climate, and cause and effect are impossible to separate and it may be unnecessary and confusing to do so (Davis, 1988).

The hypothesis invoking climatic change as a cause of peat initiation also finds some support in the data. Although radiocarbon dating of the deepest sample from monolith 2 was unreliable, the estimated date of ca.6500bp for the birch decline at this site and the interpolated date of

6685bp for the second and final decline at monolith 3, both associated with increases in *Sphagnum* spores, suggest that a synchronous increase in surface wetness may have occurred. The charcoal record does not suggest that either of these declines is directly attributable to human impact, and the lack of a podsolic soil profile at monolith 3 implies that soil processes were also unimportant. It is therefore thought that a predominantly climatic origin can be invoked for the early initiation of peat at monolith 3. On the drier site, later burning, in addition to this climatic influence, may have been required for peat to form. It has been suggested (section 8.2.3 that the transition to ombrotrophic peat at the deep peat sites (Cross Lochs Ombrotrophic and Fen A) is approximately synchronous, occurring in the late seventh millenium bp. This change also appears to be related to the start of, or an increase in, on site burning. Although this is somewhat later than the birch declines at monoliths 2 and 3, it may be significant that all these major transitions occur within 600 radiocarbon years of each other. Further research will be necessary to provide data for an assessment of the synchroneity of peat growth at other sites in similar topographic situations.

In summary, there were a number of environmental pressures leading to the formation of ombrotrophic peats on mineral ground which interact with one another, together with local site factors to produce varied dates of peat initiation. Despite evidence for early anthropogenic impact, this does not appear to be the primary cause of peat development on the deeper peat site, where the earliest fully organic peat is dated to 6805±50bp. Instead, this is more easily explained by an increase in effective climatic wetness. This same climatic change is detectable in another, shallower, basal peat and less clearly in deep cores of successions from primary fen peats. Peat development on the shallow, less suitable site was probably a result of long term soil changes arising from climatic change in addition to burning from 4890±65bp.

CHAPTER 9: CONCLUSION

The preceding chapters have described a range of investigations into the past and present status and ecology of patterned fens in Scotland and the palaeoecology of the Flow Country blanket mire. Each chapter contains a short summary of the results for each part of the research and it is not intended to repeat those conclusions here in full. However, in the short concluding sections below it is necessary to reiterate some of the points made earlier in discussing some of the combined results contained within this thesis. This concluding chapter summarises and draws together the findings of the individual chapters and indicates where further research would be particularly useful and where there is potential for related complementary research.

9.1 Methodological implications

The thesis has used evidence from a variety of palaeoecological and ecological analyses and has attempted to use these in a complementary way to provide a full picture of events associated with particular phases of peatland development. This not only provides the "training element" required of postgraduate students by NERC, but points to the benefits of such an approach. There are a number of recommendations arising from these analyses, which are worth emphasising here.

It became clear in chapter 4 that even within an apparently well established analytical method (pollen analysis) that the effects of the experimental procedure are imperfectly known, without the added complications of source areas, preservation processes and redistribution which are normally considered by pollen analysts. Although at least these effects can be held constant within an investigation, comparisons with other work must bear such influences in mind.

An attempt has been made to use non-pollen microfossils to provide additional data on local conditions in all investigations using pollen analysis. Some potential for more routine usage of such data clearly exists, but the ecology and preservation characteristics of the organisms involved are so poorly known that this is extremely limited at present.

Problems of interpretation and semantics have particularly hampered previous analyses of basal peats (Chapter 8). Here it has been shown that many of these problems can be solved by the use of combined data analyses. Loss on ignition data and crude macrofossil analysis allow a much better definition of basal ombrotrophic peats than has hitherto appeared in the literature and it is hoped that similar methods will be adopted in future investigations of such problems. Likewise it has been emphasised that adequate consideration should be given to topographic control and description at the macro and micro scales. It is only by gathering full data regarding the nature and context of the deposit that pollen and charcoal analyses can be properly interpreted.

9.2 The characterisation and classification of Scottish patterned fens

One of the main aims when commencing this research was to provide data regarding the origins, development and present status of Scottish patterned fens to allow the characterisation and classification of this recently discovered and little known mire type. Knowledge of the distribution of sites is still limited, but chapter 3 has demonstrated the range of variation of known sites and described the main plant communities occurring at these sites. Chapter 6 provided detailed information on the morphology and development of a number of sites. This information can now be combined to properly characterise these peatlands.

In terms of water chemistry and floristics, the mires are clearly best classified as poor fens, rather than being somewhat enriched variants of more widespread ombrotrophic mire communities. Indeed, macrofossil analysis demonstrates that it is probably only relatively recently that *Sphagnum* species have occurred in abundance on the surface of such sites. A comparison of pH data from other mire types throughout the northern hemisphere also supports this general conclusion. Although there are some similar communities occurring elsewhere in Europe (Dierssen, 1982) and Scotland (Birse 1980; 1984), they are not catered for in the existing draft of the National Vegetation Classification (Proctor and Rodwell, 1986). However, there are no previous accounts of such vegetation occurring within patterned mire, differentiated into pool and ridge microtopography. It is clear therefore, that contrary to previous descriptions of UK peatlands, a type of patterned fen does indeed occur in Scotland.

Work on development of these sites (Chapter 6), indicates that they are not strictly comparable to the boreal patterned fens reported from Scandinavia and North America, as they are not primary peatlands, and their occurrence is not governed by the original topography and hydrology of the underlying land surface. Instead they are superficial deposits underlain by peat formed under ombrotrophic conditions. The only published analogy for which there is sufficient data appears to be the 'water track' elements in the mire complexes of northern Minnesota (Glaser, 1987), although there may also be similar seepage fens (the "ladder fens" mentioned by Lindsay *et al*, 1988) in the Atlantic Oceanic wetland region of Canada (Wells and Hirvonen, 1988; Tarnocai *et al*, 1988). It is thought that groundwater discharge by the formation of sub-peat pipes is responsible for the input of increased water quantity and quality, although further hydrological research is necessary to provide empirical data to substantiate this claim. The recent research demonstrating such processes in Minnesota lend support to this hypothesis (Siegel and

Glaser, 1987) and this may be a more important process in mire succession elsewhere than has previously been realised.

Pattern formation has been shown to be a comparatively recent event on Scottish patterned fens (Chapter 7) and biostratigraphic analyses and surface observations suggest that pattern initiation is a biotically rather than physically controlled process. Localised ponding of water led to reduced productivity of existing communities, and therefore to lower peat accumulation rates. Plant growth and peat accumulation in adjacent areas (present day ridges) were not impeded. The colonisation of these raised areas by *Sphagnum papillosum* may have actually increased peat accumulation and exacerbated the differences already existing between the two zones. *Potamogeton* began to grow and expand in the wetter situation. Thus, although there were few qualitative differences in plant communities to begin with, the different hydrological regimes in the two situations encouraged the invasion of several different plant species. Subsequent expansion of the pool may have been by inhibition of growth rates of communities present at the pool edges and coalescence of adjacent pools. The emphasis on biotic control is similar to more recent work in both southern and northern patterned fens in America and Scandinavia (Foster, King and Santelmann, 1988; Glaser, 1987, Seppala and Koutaniemi, 1985), although frost activity is still thought to play a role in boreal mires (Seppala and Koutaniemi, 1985).

It can therefore be concluded from palaeoecological work that the Scottish patterned fens are in many ways similar to the water track mires in the peatland complexes of the northern USA. They show similar developmental trends, both in terms of overall morphology and microtopography. The adoption the concepts of "mire complexes" and/or "macrotopes" for blanket mire systems as in the investigations of workers on Minnesota peatlands and in the USSR (Ivanov, 1981) should be encouraged for future

research into the development and functioning of this peatland.

9.3 Models of peat development in the Flow Country

The work on the development of an ombrotrophic mire at Cross Lochs (Chapter 8) demonstrates that the deeper peats show similar gross stratigraphic changes to those recorded from patterned fens in the succession from basin infill to ombrotrophic mire. The consistency of the records suggests that early peat development may have occurred in a very similar way throughout the region. The landscape following the Devensian glacial maxima was clearly more topographically variable than at present, with numerous basins which became infilled with lake or early fen peat sediments during the close of the Devensian Lateglacial and the early Holocene. Bryophytes of the Amblystegaceae ('brown mosses') were a frequent component of the earliest fen communities, probably reflecting the greater availability of nutrients in the unstable, predominantly mineral terrain at the time. Although composition of these communities was variable, they were replaced by remarkably consistent sedge fen with birch scrub. This type of community is represented in the deeper peats at all sites investigated, although the presence of birch is variable, possibly reflecting the different moisture conditions present on different sites. *Sphagnum* species more tolerant of nutrient enrichment were also a component of the vegetation at the time, particularly sect.squarrosa (cf.*S.teres*) and *S.papillosum*. Occasionally, there are apparent layers of birch remains in basin peats. The pollen and microfossil data suggest however, that although there were local variations in growth of birch on mire surfaces, this was probably not consistent between sites. This may be analogous to the variability of *Pinus* on mire surfaces between approximately 7000 and 4000 years bp (Bridge *et al*, 1990). Ombrotrophic peats begin to form from ca.6000 bp, presumably by natural succession, but possibly encouraged by human induced burning. There were subsequent variations

in the moisture conditions and bog communities present from this time, including a particularly dry period when *Pinus* colonised at least some of the mire surfaces. Ombrotrophic and patterned fen sites developed in similar ways up until the late Holocene and it is proposed that this was the case across the majority of the central Flow Country area.

Divergent development is dated to around 2700bp at the Cross Lochs site. The reasons for this are related to the changing hydrology of the system. Increased surface wetness across the region led to vigorous *Sphagnum* growth in some situations and it is speculated that sub-surface piping also formed in response to this. Emergent pipes, probably after being in contact with groundwater sources, provided increased supplies of nutrient rich water at and below their spring point. Where gradients were suitable this has led to the growth of the present poor fen communities.

Clearly, further work will be necessary to test this tentative model of Flow Country peat development, particularly in other deep ombrotrophic peat areas, especially those found further south and west of the Cross Lochs. This more fragmented peatland may show rather different developmental trends. The site at North Altnaharra suggests that shallow basin peats are relatively recent in origin and some of the thin, *Tricophorum* dominated peat around here is probably even more modern.

9.4 The influence of anthropogenic activity on mire development in the Flow Country

The evaluation of anthropogenic impact was a specific research objective only in investigating the causes of blanket peat initiation (Chapter 8). However, several other areas of research have indicated that the human element of the past environment of the Flow Country cannot be regarded lightly. Charcoal content of sediments from all sites investigated has been high from quite deep down in the cores, suggesting fire has been a frequent event for at

least the last 7000 years, although recent years may have seen a decline. Although fire can be caused naturally in organic terrain (Wein and McLean, 1983), it is unlikely that all the charcoal can be attributed to such events and anthropogenic activity is therefore implicated.

Detailed analysis of the mineral-organic transition (8.3) has shown that the abundance of birch was strongly linked to fire regime before about 7000bp, but that this did not have any long lasting effect on the birch tree cover. Instead, the final decline in birch can be attributed to an initial increase in surface wetness, followed by the resumption of on-site burning. Thus, early ombrotrophic peat growth cannot be primarily attributed to the effects of fire on the extant woodland. Decreased soil porosity following later burning of *Calluna* heath may however have been instrumental in subsequent peat growth in these more marginal situations.

Fire of presumed anthropogenic origin has therefore been a part of the evolution of peatland in the Flow Country, but it was probably not the major cause of early ombrotrophic peat growth, either directly over mineral ground or in the transition from minerotrophic basin peats. The role of fire as an influence upon mire ecology throughout the postglacial has yet to be evaluated and charcoal analyses should become part of peatland research programmes.

The effects of combined data analyses are also shown in Chapter 7, where the effects of environmental change are evident at different times in different analyses. This allows a much more accurate interpretation of the timing and type of change occurring than any one single analysis.

All the laboratory analysis has emphasised the utility of various techniques, with a distinct objective in mind. It is suggested that this pragmatic approach is more fruitful than more traditional approaches where the emphasis seems to have been on sometimes over-structured investigation and

the minutia of change.

9.5 Palaeoecological research in northern Scotland

Chapter 5 relates the results of pollen analysis of peats and lacustrine sediments spanning the whole of the Holocene and the greater part of the Devensian Lateglacial. It was necessary to perform this analysis as a background of environmental change against which the other events were taking place. The general paucity of such data for this area is, however, surprising in view of the many opportunities available in a landscape which consists almost entirely of peatland and lochs of varying sizes. Although western Sutherland was a focus of attention for a period during the 1970's (Pennington *et al*, 1972; Pennington, 1975), there is only one other complete Holocene pollen record with reasonable detail and radiocarbon dates from the whole of the area (Peglar, 1979). There is opportunity for a major research programme in this field, which would help answer many of the questions related to the extent and time course of peatland development in Sutherland and Caithness. Also particularly worthy of attention is the Devensian Lateglacial, particularly in eastern Sutherland and Caithness in relation to the proposed ice free area of north east Scotland and the North Sea (Sutherland, 1984; Nesje and Sejrup, 1988), recently challenged by Hall and Bent (1990).

9.6 A last comment

Popular interest in the conservation problems of the Flow Country peatlands has decreased over the last year to eighteen months, although the threats still remain. Reasonable resources and a strategic conservation approach have now been adopted and it is hoped that controversies over land use can be solved in future with proper regard to the importance of the mire ecosystems and the landscape as a whole. Although this thesis has been primarily concerned with scientific aspects of the ecology and palaeoecology of

the peatlands, the relevance of this problem should not be missed. If we are concerned to continue such research we must argue for the preservation of our 'outdoor laboratories' not only for the myriad of other justifiable objectives but also for their importance to a little appreciated field of research.

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Variable print quality

Appendix I: Ordered vegetation table of patterned fen rele

Relative number	23	47	60	127	135	137	21	30	56	140	50	59	114	120	24	52	54	63	69	71	77	112	119	138	13	15	17
Carex dioica	3	3	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Carex lepidocarpa	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Campylium stellatum	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sphagnum contortum	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Selaginella selaginoides	-	-	-	-	-	-	-	-	-	-	2	3	2	2	3	3	2	3	3	3	3	2	2	-	-	-	-
Succisa pratensis	-	-	-	-	-	3	-	-	-	-	-	3	2	2	-	2	3	3	-	-	-	-	-	2	-	-	-
Carex panicea	-	-	-	-	-	-	-	-	-	-	3	+	-	2	-	-	+	+	-	-	2	-	2	-	-	-	-
Pinguicula vulgaris	-	-	-	-	-	+	1	-	-	1	-	2	-	2	-	2	2	2	1	2	2	1	-	-	2	-	-
Potentilla erecta	2	2	2	3	2	3	2	2	3	2	2	3	3	3	3	2	3	3	3	-	4	3	+	3	3	2	1
Carex echinata	3	2	-	-	3	-	4	-	4	-	-	-	-	-	3	-	2	2	3	4	-	2	-	+	2	-	-
Erica tetralix	4	6	4	5	5	6	5	6	5	5	6	4	5	5	4	4	4	4	5	5	6	6	4	6	6	5	6
Narthecium ossifragum	4	7	6	5	-	5	7	6	6	5	-	6	-	7	8	4	7	6	6	6	6	5	-	6	8	6	4
Tricophorum cepitosum	5	6	5	-	4	7	6	5	4	8	5	7	7	6	4	6	4	8	6	5	8	4	6	5	6	7	6
Sphagnum subnitens	-	+	-	-	2	2	-	4	-	5	4	4	3	4	-	6	-	-	-	3	6	5	3	-	5	-	-
Drosera rotundifolia	2	3	2	-	2	2	3	2	3	3	2	3	2	2	3	3	-	-	3	3	3	3	2	2	3	2	3
Racomitrium lanuginosum	3	8	5	3	4	5	5	4	5	4	4	5	6	5	3	5	5	5	5	6	-	5	5	5	5	4	3
Calluna vulgaris	5	5	6	5	4	6	4	4	1	5	5	4	3	3	3	5	5	4	5	6	4	3	5	5	5	4	5
Drosera rotundifolia	2	3	2	-	2	2	3	2	3	3	2	3	2	2	3	3	-	-	3	3	3	3	2	2	3	2	3
Pleurozia purpurea	5	8	4	5	4	6	3	2	4	4	3	-	5	2	3	4	4	5	4	4	3	4	6	8	-	-	-
Sphagnum capillifolium	3	3	3	4	3	4	3	3	+	-	4	+	4	4	3	3	-	6	4	5	-	4	3	4	-	2	2
Sphagnum papillosum	5	6	5	4	2	4	6	5	6	7	3	4	3	6	5	4	5	4	5	7	6	6	5	5	6	5	6
Sphagnum subsecundum	3	3	4	3	2	-	-	3	2	3	-	-	-	-	2	-	-	2	-	5	3	-	4	-	-	-	-
Cladonia impexa	3	-	5	4	3	3	4	2	-	5	4	3	-	-	+	-	4	4	-	+	-	2	-	+	-	3	+
Cladonia uncialis	-	2	3	2	2	3	2	-	2	-	3	3	-	+	2	3	2	-	2	3	+	-	-	2	2	-	3
Drosera anglica	2	2	3	-	2	+	2	3	3	3	3	3	3	2	3	3	3	2	3	3	2	+	-	2	2	2	3
Molinia caerulea	6	6	5	6	6	6	8	6	5	5	6	5	-	5	5	7	7	-	6	7	7	8	7	6	6	7	8
Schoenus nigricans	-	-	-	-	-	-	-	-	-	-	4	5	-	-	-	-	-	-	2	-	-	-	-	-	-	-	-
Myrica gale	4	4	-	4	-	-	5	3	-	-	5	-	4	5	4	-	-	-	-	-	-	5	4	-	4	5	5
Carex lasiocarpa	-	7	6	8	8	4	3	8	6	4	9	7	4	6	8	8	-	4	8	9	5	5	6	8	3	4	-
Carex rostrata	6	5	4	-	5	4	4	-	5	5	3	4	6	5	-	-	-	-	-	-	4	-	2	+	3	4	-
Scorpidium scorpioides	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Eriophorum angustifolium	3	5	6	3	-	3	4	3	-	3	3	3	2	2	2	3	2	3	-	2	5	3	3	4	4	5	4
Menyanthes trifoliata	-	-	2	-	-	-	3	2	2	4	3	3	2	3	-	-	-	2	+	2	-	-	-	-	3	3	3
Potamogeton polygonifolius	-	-	-	-	1	-	-	-	-	-	-	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Utricularia intermedia	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sphagnum auriculatum var. auri	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Carex limosa	-	-	-	-	-	-	2	-	-	-	-	2	-	-	-	-	8	-	-	-	-	-	-	-	-	-	-
Juncus bulbosus	3	-	2	-	7	-	-	-	3	3	-	3	7	-	2	3	3	-	3	-	-	-	3	2	2	-	-
Drosera rotundifolia	2	3	2	-	2	2	3	2	3	3	2	3	2	2	3	3	-	-	3	3	3	3	2	2	3	2	3
Euphrasia agg.	-	-	-	-	-	+	3	3	3	2	-	+	-	2	3	-	3	-	2	-	3	-	2	3	3	3	4
Hypnum cupressiforme	-	-	3	2	-	2	-	-	3	-	-	2	-	-	-	2	-	3	-	5	-	3	-	-	-	2	2
Polygala serpyllifolia	-	-	-	-	-	-	-	-	-	2	-	-	3	2	-	2	-	2	-	-	+	2	-	2	-	2	2
Sphagnum auriculatum var. inun	-	-	-	-	-	-	-	-	-	-	-	+	4	-	4	4	3	3	3	3	4	3	2	2	-	-	-
Sphagnum tenellum	3	5	3	3	2	5	4	-	-	3	2	-	-	-	-	-	-	4	-	-	-	-	-	-	2	-	-
Cladonia arbuscula	4	-	3	-	3	4	4	4	3	-	-	3	-	-	+	+	2	-	+	2	-	-	-	+	-	-	-
Pedicularis sylvatica	-	-	-	-	1	-	-	-	-	-	-	-	2	-	-	-	2	-	-	-	-	-	2	2	-	1	-
Sphagnum compactum	-	-	4	-	-	-	3	-	2	4	-	-	-	-	-	-	-	-	-	-	-	-	-	3	2	2	-
Equisetum fluviatile	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-
Breutelia chrysocoma	-	-	-	-	-	-	-	-	-	-	3	-	2	-	-	-	-	3	-	-	-	-	-	-	-	-	-
Drosera intermedia	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Equisetum palustris	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Melampyrum pratense	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	-	-	-	-	-	-	-	-	-
Eleocharis multicaulis	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Phragmites australis	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Aneura pinguis	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Carpylopus atrovirens	-	-	3	3	+	-	-	-	-	-	6	4	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sphagnum cuspidatum	-	-	-	-	-	-	-	-	-	3	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-
Carex demissa	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Carex nigra	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Carex pulicaris	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Eriophorum latifolium	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Eriophorum vaginatum	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	-	-	-	-
Huperzia selago	-	-	-	-	-	-	-	-	-	1	2	-	-	-	-	-	3	-	-	-	-	-	-	-	-	-	-
Juncus articulatus	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Triglochin palustris	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Hylocomnius splendens	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Eleocharis quinqueflora	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Galium saxatile	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pinguicula lusitanica	-	-	-	-	-	-	-	-	-	-	-	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ctenidium molluscum	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Odontoschisma sphagni	-	-	-	-	-	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Rhytidiadelphus squarrosus	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sphagnum molle	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-
Sphagnum recurvum	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sphagnum strictum	-	-	-	-	-	-	-	-	-	-	-	-	2	-	-	-	3	-	-	-	-	-	-	-	-	-	-
Anthoxanthum odoratum	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Carex hostiana	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Carex pauciflora	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Chara spp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Juncus conglomeratus	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Luzula multiflora	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Nardus stricta	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Rhyncospora alba	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Utricularia minor	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Viola palustre	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Calliergon sarmentosum	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Drepanocladus revolvens	-	-	-	-	-	-	-	-	-	-	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fissidens adianthoides	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pleurozium schreberi	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pseudoscleropodium purum	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sphagnum magellanicum	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sphagnum palustre	-	-	-	-	-	-	-	-	-	-	-	-	-	3	-	-	-	-	-	-	-	-	-	-	-	-	-
Pedicularis palustris	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	2	-	-	-	-	-	-	-	-
Epilobium palustris	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Empetrum nigrum	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Festuca vivipara	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ranunculus acris	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ranunculus flammula	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Leucobryum glaucum	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Plagiothecium undulatum	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Rhytidiadelphus loreus	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Number of species per sample	22	21	25	18	23	22	26	21	22	26	26	28	24	27	23	25	25	26	21	23	20	22	23	22	24	22	19

leves

15	17	26	37	42	74	93	107	110	132	28	33	64	66	79	80	81	82	91	94	109	115	122	123	126	129	133	19	35	38	68	117	40	44	48	83	90	92	95	96	106	76	32	73	101	1
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2	5	4	◆	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	◆	2	4	-	-	-	-	-	◆	4	2	4	5	-	-
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Appendix II: Identification source and full species names (where known) of non-pollen microfossils.

Type no.	Species name	Source
1	Gelasinospora spp.	Van Geel 1978
2a	Gelasinospora cf.reticulispora	"
3B	Pleospora spp.	"
5a		"
8		"
8B	? Microthyrium spp.	"
8C	? Actinopeltis spp.	"
8E		"
10		"
13	Entophlyctis lobata	"
16		"
18		"
20		"
23		"
25a	cf. Clasterosporium caricinum	"
27	Tilletia sphagni	"
28		"
30	Helicoon pluriseptatum	"
31A	Amphitrema flavum	"
32A	Assulina muscorum	"
32B	Assulina seminulum	"
33		"
37	Callidina angusticollis	"
55	Sordaria spp.	"
58	Zygnemataceae	"
60		"
62	Zygnemataceae	"
69		"
72A	Alona rustica	"
77	Geoglossum sphagnophilum	"
77B	Trichoglossum cf. hirsutum	"
88	Invertebrate mandibles	"
100	cf. Cylindrocystis brebisonii	"
110		Van Geel *et al* (1981)
115		"
303		"
313	Mougeotia spp.	"
315	Spirogyra spp.	"
340		"
341A		"
342	Spirogyra cf.scrobiculata	"
351		"
353	Rhabdocoela spp	"
354		"
708		Bakker and Van Smeerdijk (1982)

Unidentified microfossils

A number of microfossils are indicated on the diagrams, which could not be identified by consulting published descriptions. These are numbered upwards from 1001 and are briefly described below. Original slides where the microfossils were found are held at the Palaeoecology Laboratory, University of Southampton. None of these types were particularly abundant (except 1005) and many occurred only in the surface sediments, perhaps indicating that they are susceptible to decay. Only those marked with an asterisk occurred in the diagrams presented here.

*Type 1001:

These are clear, circular objects with no obvioous surface or internal features. They appear to fall into three size groups of ca.25µm (1001A), ca.50µm (1001B) and ca.100µm (1001C).

*Type 1002:

Similar to 1001, but more variable in size (50-120µm) and irregularly shaped with a central, circular aperture.

Type 1003:

A flask shaped microfossil, with its surface sculptured into patterned similar to fish scales.

Type 1004:

A narrow bag-like structure, similar to Type 353, and eventually included within that group.

*Type 1005:

Irregularly shaped, clustered pale brown globules, usually occurring in groups of four. Associated solely with the detrital pool material in core CLP2. Algal?

Type 1006:

Long (>100µm), narrowly triangular, opaque brown microfossil. Invertebrate limb?

*Type 1007:

Rounded, rectangular, opaque brown microfossil with distinct warty surface. Fragment of invertebrate exoskeleton?

*Type 1008:

Thin, ovoid·structure with faint hairs or spines (ca.5µm long).

Appendix III: Sources used for basal peat dates in Figure 8.10.

Source	Region
Bartley (1975)	North central England
Birks (1975)	Western Scotland
Bohncke (1988)	Outer Hebrides
Brown (1977)	South west England
Case *et al* (1969)	Northern Ireland
Chambers (1981)	South Wales
Chambers (1982a)	South Wales
Conway (1947)	North central England
Cundill (1977)	North east England
Hafsten and Solem (1976)	Western Norway
Hicks (1971)	North central England
Jones (1987)	South west Scotland
Merryfield and Moore (1974)	South west England
Moore (1968)	West Wales
Moore (1972)	Mid Wales
Moore (1973)	West Wales
Pennington (1965)	North west England
Robinson (1987)	North East Scotland
Simmmons (1964)	South west England
Simmons (1969)	North east England
Smith and Cloutman (1988)	South Wales
Solem (1989)	Western Norway
Tallis (1964)	North central England
Tallis and Maguire (1972)	North west England
Tallis and Switsur (1973)	North central England

Dates were either radiocarbon dates on the authors' interpretations of 'basal peat' or estimated from well marked changes in pollen diagrams.