High-resolution Palaeoenvironmental Reconstructions of the Late Holocene using Ombrotrophic Mires from western Britain

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Abstract

The aim of this thesis has been to reconstruct proxy-climatic conditions from three ombrotrophic mires across the western side of Britain (Bolton Fell Moss, Langlands Moss, Mynydd Llangatwg). Detailed investigations of core material has incorporated the application of a range of palaeoecological techniques including colorimetric humification, plant macrofossil and testate amoebae analyses at high-resolution intervals. Results from the humfication analyses indicate significant fluctuations in mire surface conditions which, in the case of Bolton Fell Moss, appear to be replicatable. Plant macrofossil datasets also record variations in surface conditions, indicated by changes in species composition, although, in contrast to the humification datasets, records obtained from Bolton Fell Moss have been found to differ markedly. Statistical modelling of these raw macrofossil datasets using multivariate techniques has enabled the transformation of the data into indices of relative mire surface conditions, thereby generating proxy-climatic curves which are directly comparable with the humifcation records. Having identified a number of correlating shifts in relative surface conditions, interpolated timescales were developed for each of the sites investigated using a combination of wiggle-matched AMS dating, lead-210 and spheroidal carbonaceous particle (SCP) analyses. Comparison of the proxy-climate records has led to the identification of correlating shifts in mire surface conditions. A number of these shifts have been found to be associated with established shifts in regional climatic conditions, such as the coldest stages of the Little Ice Age, the Medieval Warm Period, the AD 540 tree-ring event and the Sub-boreal/Sub-atlantic transition.

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Author's Declaration

I declare that the work in this thesis was carried out in accordance with the regulations of Cheltenham & Gloucester College of Higher Education and is original except where indicated by specific reference in the text. No part of the thesis has been submitted as part of any other academic award. The thesis has not been presented to any other education institution in the United Kingdom or overseas.

Any views expressed in the thesis are those of the author and in no way represent those of the College.

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Chapter 1 Introduction

1.1 Background to the Study

Ever since the pioneering work of Blytt (1876), peat bogs have been used as sources of information on past climates, but according to Chambers *et al.* (1997), their use to provide detailed continuous reconstructions of past climates has until recently been neglected owing to misconceptions as to how peat bogs grow. However, since the 1970s continuous proxy-climate records have been generated from ombrotrophic mires. Ombrotrophic mires, which include both raised and water-shedding blanket peat bogs, are rain-generated peat-forming ecosystems, receiving all their water nutrient supplies from atmospheric precipitation alone (Lindsay, 1988). The surfaces of these mires are isolated from the influences of the regional groundwater table, resulting in the development of an independent ombrotrophic plant community, being largely dependent on precipitation, temperature and evaporation, making them highly sensitive to variations in climate (Aaby, 1976). The combination of highly acidic conditions, low nutrient status and waterlogging in this type of bog greatly reduces the number and activities of bacteria and fungi, resulting in the build up of well-preserved organic material. Owing to their sensitivity to variations in mire water levels, the identification of these floral and faunal sub-fossils can be used to infer former levels of mire surface wetness. Since mire surface wetness in these ecosystems is solely dependent on precipitation inputs, this parameter can then be used to reconstruct effective precipitation. However, in addition to the influence of climate on peat growth, there are several other factors that have the effect of altering the surface conditions of mires, including inter-species competition and anthropogenic activities such as drainage, afforestation and grazing.

1.2 Review of the Literature

1.2.1 Climatic Influences on Ombrogenous Peat Formation

Owing to processes involved in the formation of raised peat bogs, the surface of the mire is isolated from the influences of the regional groundwater table, resulting in the development of an independent ombrotrophic plant community, being solely dependent on water nutrients derived from the atmosphere. Since mire surface wetness in these ecosystems is solely dependent on precipitation inputs, this parameter can then be used to reconstruct effective precipitation.

Early climatic reconstructions drew upon the relationship between degree of humification and climate, where highly humified peats were assumed to be indicative of warmer/drier conditions. The effectiveness of these reconstructions, when combined with those of Sernander (1908), was considered so great that they formed the basis for the division of the Holocene into major climatic periods (Blackford, 1993). The identification of alternating bands of light and dark peat, known as 'recurrence surfaces', occurring across large areas of a bog were later identified by Granlund (1932) in southern Sweden. Granlund was convinced that variations in the level of precipitation were largely responsible for the development of these horizons, as they were thought to have formed during periods of climatic deterioration (Rowell and Turner, 1985). However, problems with the Blytt-Sernander scheme concerning its level of simplicity finally led to the rejection of this concept altogether.

The incorporation of radiometric dating into palaeoecological studies, together with the advancement of palaeoecological methodologies then enabled the progression of more detailed reconstructions of climate change from mires (Barber, 1981). By recording a detailed stratigraphy of selected sections of eight Irish bogs, Walker and Walker (1961) found evidence for synchronous changes in surface wetness. Casparie (1972) then produced well-dated peat sequences and macrofossil analyses from a raised bog near Emmen, but owing to the close proximity of the bog to a lake, was unable to establish a clear climatic signal in the datasets produced. With the advantage of having a very well dated stratigraphy of a raised bog in Denmark, Aaby and Tauber (1975) and Aaby (1976) were then able to identify shifts to phases of wetter peat formation that had occurred with a statistically tested periodicity of 260 years. Focusing their attention on the relationship between degree of humification and rate of accumulation of the peat, Aaby and Tauber were able to establish that the relation between these variables differed in different parts of the profile. The implication that the relationship between degree of humification of peat and its rate of accumulation was more complex than was previously supposed then led the way in producing more data from a variety of sites using a range of varying techniques.

Later work carried out by Barber (1981) on Bolton Fell Moss, a site also chosen for this study, adopted a multi-proxy approach by applying both micro- and macrofossil analysis techniques when demonstrating the importance of climatic control on peat bog ecosystems. Supported by the evidence of Lamb (1977), Barber was able to falsify von Post and Sernander's (1910) original theory of cyclic peat regeneration and confirm Walker and Walker's (1961) findings of a bog surface reacting all over in the same way. One of the first truly high-resolution studies (i.e., continuous 1 cm intervals) of peat bogs, carried out by van Geel (1978), also uncovered cyclic fluctuations, where detailed curves of local moisture conditions and variations in oceanic climate were produced. Based on correlations between *Corylus* pollen curves, zygospores of *Mougeotia* and a range of macrofossils including *Sphagnum* leaves from a peat section of the Engbertsdijksveen, The Netherlands, van Geel was able to correlate changes in vegetation with the Atlantic-Subboreal transition.

Through studies carried out by the above authors and others (e.g. Barber, 1981, 1993; Blackford, 1993; Barber *et al.*, 1994a, b) it became clear that proxy-climate signals are preserved in peat stratigraphy, recorded as fluctuations in degree of peat humification and by variations in the abundances and species type of selected micro- and macrofossil components. While assessing the significance of *Racomitrium lanuginosum* remains from blanket mires in the Southern Pennines and North Wales, Tallis (1995) was able to support the presence of these proxy-climate signals, as this species signifies prolonged periods of drier climate succeeded by a return to a wetter more humid climate. He was also able to detect the onset of the 'Early Medieval Warm Period' (AD 1150-1300) and suggests that gulley erosion and the development of a 'stagnation complex' in pool-hummock systems commenced as a result of this period.

1.2.2 The Influence of Non-climatic Factors

1.2.2.1 Autogenic hydrological processes in mires

Peat is predominantly composed of water either locked up in the vegetation, occupying space between plant material and soil particles or filling pools on the bog surface. Ombrotrophic mires are therefore particularly sensitive to fluctuations in local hydrology. All water that reaches the mire water table is climatically derived, and not as once thought (Moore and Bellamy, 1974) derived through capillary forces at the base of the mire. A major mechanism by which water is lost from the system and returned to the atmosphere is evapotranspiration; however, a large proportion of water is also transported through the body of peat in the form of seepage. The movement of this water, through pores between plant material, within *Sphagnum* hyaline cells and between soil particles is dependent on its hydraulic potential (Brookes and Stoneman, 1997). The rate of movement partly depends on the size of pore spaces and the number of channels, with a greater density of restrictions resulting in lower levels of hydraulic conductivity.

Water movement is also dependent on climate. During wet weather, the storage of water increases, raising the water level into the more permeable layers of the acrotelm, thereby increasing the rate of lateral seepage through the system. Whereas, in dry weather, when stored water diminishes and water levels drop into the zone of low hydraulic conductivity, seepage is extremely slow (Ingram, 1992). Ingram (1982) discovered that lateral movement of this water in the form of seepage creates a groundwater mound in the catotelm, which increases the slope of the water-table, moulding the characteristic domed shape of these landforms. The supply of this water is unstable, relying on a constant level of equilibrium between recharge and seepage (Ingram, 1982). Therefore, it can be assumed that the peat body constitutes a single hydrological system, where any variation in either the supply or loss of water will affect the rest of the system, and that lateral seepage controls the stability of the system (Brookes and Stoneman, 1997).

1.2.2.2 Anthropogenic influences

The drainage of peatlands, whether for peat production, agricultural cultivation, forestry or fuel, has often been identified as the greatest threat to the ecohydrology of mires (Egglesmann, 1993). Ingram (1992) examined the affects of drainage on the internal hydrology of mires. He found that drainage effects the stability of the acrotelm/catotelm boundary by lowering the peat water table. Once de-watered, the rate of decomposition is accelerated, resulting in the irreversible physical alteration of the colloidal constituents of the catotelm (Ingram, 1992). The ability of peat bogs to act as sinks, removing excess carbon from the atmosphere and locking it up in the peat system, can also be significantly affected by drainage. Francez and Vasander (1995) found that forest drainage lowered the water table of two *Sphagnum-Carex* peatlands in France and Finland, resulting in an increase in microbial activity which had the effect of doubling emissions of CO_2 from the sites.

Forest clearance is also thought to have a significant impact on peat ecosystems, primarily by increasing runoff and exposing the peat surface to erosional processes. Studies of human-induced vegetation changes suggest that ancient clearance episodes may have increased the supply of telluric water into the catchment, producing a larger and faster 'pulse' to the mire margin. Using a range of proxy indicators, Tipping (1995) carried out investigations into the evolution of a raised bog in eastern Dumfriesshire. His analyses reveal that the transformation from fen-peat to raised moss at Burnfoothill Moss was clearly identifiable at *c.* 7700 cal. BP, marked by a rapid shift to wetter conditions. Tipping suggests that partial deforestation around the basin at this time may have caused an imbalance in the precipitation/evaporation ratio, accelerating runoff and sustained waterlogging, leading to the establishment of ombrotrophic plant communities (Tipping, 1995). However, Stoneman (1993) found little correlation between non-arboreal pollen and reconstructions of bog surface wetness profiles, suggesting that mires are either differentially susceptible to human disturbance or that no link exists between non-arboreal pollen and mire surface wetness.

1.2.2.3 The impact of fires

Fire has long been recognised as a powerful agent of environmental change on mires, although the precise roles of human intervention and of climate remain equivocal (Shaw *et al.*, 1996). Macroscopic analysis of charcoal fragments has been widely employed in the detection of past burning events (Aaby and Tauber, 1975), although differential survival capabilities of plant species often restricts the usefulness of this technique in palaeoclimatic reconstructions. This was demonstrated by Wein (1973) who found that *Eriophorum vaginatum* could tolerate more fire injury than *Calluna vulgaris*, since its tussock growth form is effective protection against fires. Selective preservation of these 'dry indicator' species may lead one to assume falsely that effective precipitation was low at this time.

1.2.3 Palaeoclimatic Analysis of Peat Stratigraphy

Until recently, most of the palaeoclimatic studies carried out on ombrotrophic mires have incorporated coarse-sampling (i.e., > 4 cm intervals) strategies (e.g. Barber, 1981; Haslam, 1987; Stoneman, 1993; Barber *et al.*, 1994a, b), and at many sites only one principal palaeoecological technique has been employed. At sites where more than one method has been used, correlations have been identified in the datatsets, but discrepancies in the data have also been found. The use of blanket mires as archives of proxy-climate data has also been deterred in the past, owing to the perception that the stratigraphy of many blanket mires was relatively uniform and contained few identifiable macrofossils that could be used in climatic reconstructions.

1.2.3.1 Plant macrofossil analysis

One of the earliest techniques used in the reconstruction of Quaternary environments in the British Isles was the analysis of plant macrofossil remains. Plant macrofossils range in size from minute fragments of plant tissue to metre-length (or longer) pieces of wood and come in a variety of forms including fruits, leaves, seeds, stamens, megaspores, buds, cuticle fragments and flowers. The acidic, slowly decomposing conditions found in ombrotrophic mires are ideal for preservation of these fossils, thereby enabling identification to genus and often to species. Early attempts at reconstructing changes in climate using plant macrofossils focused on detecting changes in species composition of one fossil type. Casparie (1972) assessed the relationship between bog microforms (hummock, high ridge, low ridge, hollow, and pool) and the growth of different bryophytes, grasses and shrubs. From studies carried out on Bourtanger Moor, he was able to reconstruct the synchronous establishment of *Sphagnum papillosum* and *Sphagnum imbricatum* around 2000 BC, which he attributes to increases in precipitation around this time. The full potential of the technique was not realised, however, until the late 1970s, when researchers began to combine the identification of plant macrofossils with other palaeoecological techniques.

When comparing macrofossil and pollen stratigraphy of the Engbertsdijksveen, The Netherlands, with existing data from Wietmarsher Moor, van Geel (1978) was also able to detect the synchronous establishment of *Sphagnum imbricatum*, this time associated with a decline in *Corylus avellana* pollen, a dry indicator species. He suggests that the reason for this species change may be as a result of excessively wet winters and springs during the period 1400-600 BC. A clear link between peat stratigraphy and climate change was then established by Barber (1981), through the quantitative analysis of macrofossil species from profiles taken across Cumbria. Stratigraphic changes in these profiles were related to Lamb's (1977) extensive record of climate change, enabling the identification of a series of wet and dry episodes. The potential for using macrofossils in palaeoclimatic reconstructions was extended when Haslam (1987) developed the weighted average ordination technique, based on studies pioneered by Dupont (1985). By assigning weights to individual *Sphagnum* species and other sensitive peat components, Haslam was also able to identify established wet shifts at Bolton Fell Moss and produce hydroclimatic curves for the site. The effectiveness of this technique was further highlighted when Stoneman (1993) carried out hydroclimatic investigations of ten mires from various locations across northern Britain. Again, he detected synchronous wet and dry shifts at most of the sites, but encountered problems uncovering a signal where stable bryophyte associations appeared to mask potential periods of climate change.

It was not until the 1990s, however, that blanket peatlands were recognised as effective sources of proxy-climate information. The characteristically uniform stratigraphy associated with most British blanket peats suggested that the vegetation found on this type of mire was ineffective at responding to relatively minor fluctuations in climate. In order to test these claims, Tallis (1994) undertook detailed macrofossil analysis of hummock and hollow sequences on blanket mires in the southern Pennines. He discovered that high abundances of *Sphagnum* leaves were laterally continuous and that dated *Sphagnum*-rich and *Sphagnum*-poor levels could be correlated with established climatic phases recorded by Lamb (1977) for the last 1000 years (Tallis, 1994). By identifying remains of *Racomitrium lanuginosum* in the peat profile, Tallis (1995) was able later to support his theories further on the sensitivity of blanket mires when he provided clear evidence for climate changes dating from the 'Little Climatic Optimum' period.

A significant breakthrough in the interpretation of data recorded through macrofossil analysis was reached with the application of Detrended Correspondence Analysis, or DCA (Stoneman, 1993; Barber *et al.*, 1994a,b). This technique is used to detect any structure in the data, formed as a result of changes in a few unknown environmental variables, indicating the relevance of each one (Barber *et al.*, 1994c). Using this technique Barber *et al.* (1994b) uncovered a water level gradient for taxa from Bolton Fell Moss, with Axis 1 accounting for most variation of the dataset. DCA Axis 1 scores for each level were then plotted against an interpolated ^{14}C axis, providing a proxy-representation of climate change over the last 6300 years. Assuming a constant rate of accumulation, the DCA Axis 1 scores were then analysed using time series analysis techniques, thereby enabling the identification of possible cyclic variations in regional climate (Barber *et al.*, 1994c).

Recent studies have concentrated on testing the replicability of macrofossil results within individual sites. Barber *et al.* (1998) carried out analyses of ten short cores from two adjacent raised bogs in Cumbria. By employing the Quadrat and Leaf Count Macrofossil Analysis technique (QLCMA), developed by Haslam (1987), at 1-4 cm intervals throughout all cores, Barber *et al.* (1998) were able to support earlier work on the synchroneity of species changes across both sites studied (Stoneman, 1993; Barber *et al.*, 1994c). Their results provide confirmation that the dominant taxa of both bogs during the last two centuries were *Sphagnum magellanicum* and *Sphagnum* section Cuspidata, and that the local extinction of *Sphagnum imbricatum* took place between AD 1300-1800 (Barber *et al.*, 1998).

1.2.3.2 Humification analysis

An alternative technique used in the reconstruction of proxy climatic information, which has developed in parallel to the progression of the macrofossil analysis technique, is the assessment of the extent to which peat has decomposed, as shown by the degree of peat humification (Blackford and Chambers, 1993). Early studies showed that the degree of peat humification is closely linked to surface wetness at time of deposition. Aaby and Tauber (1975) uncovered a clear negative correlation between these two variables, where mire surface wetness was independently reconstructed from analysis of rhizopods (i.e., testate amoebae), pollen frequencies and *Sphagnum* species assemblages. Advancements in the measurement of the degree of humification, using chemical extraction procedures, then enabled the combination of local reconstructions of peat-surface wetness to reconstruct regional changes in bog hydrology (Blackford and Chambers, 1991; Blackford, 1993). The basic principle of the colorimetric humification technique involves the extraction (using sodium hydroxide) and measurement (using light spectroscopy) of humic and fulvic acids, which are produced by the decomposition of organic material. Studies have assumed that the colour of the NaOH extracts are indicative of the degree of humification, and therefore the extent of decomposition (Blackford and Chambers, 1993). As decomposition is primarily a function of the degree of surface wetness of the bog, and surface wetness on ombrotrophic mires is determined by climate, the humification record represents a palaeoclimatic record, although there may also be some influence of botanical composition of the peat (Caseldine *et al.*, 2000).

During the course of his thesis, Blackford (1990) found that out of the seven blanket peat profiles he analysed, five demonstrated periods of abrupt climatic deterioration corresponding to the 'Little Ice Age'. Nilssen and Vorren (1991) undertook colorimetric analyses of fourteen ombrotrophic peat sequences from northern and central Norway and compared the group average ^{14}C-dated humification shifts with Aaby's (1976) humification data. When clustering Aaby's original dates for each dark to light humification shift into one average ^{14}C date, Nilssen and Vorren identified a similar series of shifts, highlighting their use as possible indicators of climate change.

Several humification-based studies have uncovered possible climatic oscillations in peat profiles. Aaby (1976) found evidence for 260- and 520-year periods of cyclicity in peat humification shifts from four different Danish bogs. Attempts to identify possible climatic forcing mechanisms in peat have also been made using this technique. When Blackford and Chambers (1995) generated humification curves from two cores extracted from blanket mires near Letterfrack, County Galway, they uncovered a possible link with solar variability. Curves produced display periods of low peat decomposition, indicating wetter and/or cooler climatic conditions, coinciding with periods of reduced sunspot activity and atmospheric ^{14}C anomalies. However, it is also acknowledged that a major constraint of the study was the imprecision of radiocarbon dates, which impaired comparison between cores, and constrained correlation between the cores and the record of solar variability (Blackford and Chambers, 1995).

1.2.3.3 Analysis of testate amoebae

Testate amoebae analysis involves the identification and quantification of subfossil shells (tests) of freshwater amoebae (Protozoa: Rhizopoda), so that an estimation of the palaeohydrological changes in peatlands can be obtained (Tolonen, 1986). The moist conditions found in ombrotrophic mires are particularly favourable to testate amoebae, with high densities found in peat bogs worldwide. Their most important characteristic, however, in terms of their use as palaeohydrological indicators, is their ecological sensitivity to varying levels of moisture, which has been the focus of a number of recent studies (Buttler *et al.*, 1996; Charman and Warner, 1992, 1994; Warner, 1987; Woodland, 1996; Woodland *et al.*, 1998). Early studies by de Graaf (1956) identified a clear relationship between peatland soil moisture and species assemblages. He found that the most important parameter governing testate distributions and community composition is their sensitivity to changes in mire water level. However, de Graaf's research only explained the relationship in qualitative terms. It was not until the late 1980s, when a clearer understanding of the ecology of testate amoebae had been established, that studies began to uncover the relationship with depth to water table (Woodland, 1996). A number of studies (e.g., Ogden, 1981; Ogden and Hedley, 1985) demonstrated that testates are sensitive palaeoecological species, able to respond rapidly to local autogenic and allogenic changes. Their sensitivity was tested when van Geel (1978) carried out a combination of testate, pollen, fungal micro- and macrofossil analyses at the Engbertsdijksveen. The results enabled him to subdivide the time period covering the Subboreal-Subatlantic deterioration into wetter and drier phases.

Beyens (1985) then attempted to reconstruct climate changes in the Belgian Campine from testates and uncovered two distinct phases. A strong continental phase, with dry summers from *c.* 4680 BP - 4350 BP was detected, being dominated by the dry indicators *Hyalosphenia subflava* and *Cyclopyxis curystoma*, and an oceanic phase at *c.* 4350 BP - 4075 BP was also identified, based on the presence of the aquatic species *Difflugia rubescens*. By constructing humidity curves from testates and *Sphagnum* macrofossil components, van der Molen and Hoekstra (1988) supported the use of testates in multi-proxy approaches when they found correlations in two independently dated palaeo-wetness curves. Once an understanding of the optimum hydrological conditions and some measure of the tolerance for individual species of testates had been achieved (Tolonen *et al.*, 1994; Woodland, 1996), Warner and Charman (1994) successfully applied transfer functions to testates, based on weighted averages derived from a modern surface moss dataset. Using this technique, Warner and Charman (1994) were able to reconstruct palaeo-mire water depths from a *Sphagnum*-dominated peatland in northwestern Ontario. It was not until very recently, however, that the suggested relationship between hydrology and testate amoebae assemblages had been identified at British sites. Woodland *et al.* (1998) employed canonical correspondence analysis (CCA) to relate testate assemblages to their environmental parameters and so derived transfer functions, based on four underlying models: weighted averaging, tolerance downweighted averaging, weighted averaging partial least squares and partial least squares. Results uncovered from the analysis of nine mires across Britain suggest that palaeohydrological reconstructions should be based on the relationship between testates and mean annual water table (Woodland *et al.*, 1998).

1.2.4 Effective Dating of Ombrotrophic Mires

Effective dating of peat profiles is now considered an essential requirement of any palaeoecological study where proxy-indicators are used in the climatic reconstruction of a location. In the past, many palaeoenvironmental studies of the Holocene have adopted conventional ^{14}C dating and calibration methods, where the radioactivity of the remaining ^{14}C in a bulk sample of peat is measured by gas or scintillation counting (Pilcher, 1991). However, over the past few decades, research has demonstrated that significant variation of dates can occur when applying the bulk dating technique. The reason for this variation has been identified as being due to a number of different anomalies including variations in the type of fraction dated, variations in the methods of sample pre-treatment (Shore *et al.*, 1995), and the influence of the so-called 'reservoir effect' (Kilian *et al.*, 1995).

Numerous studies have attempted to identify the 'ideal' fraction of peat deposits that would give the most accurate radiocarbon measurement. Dresser (1971) analysed the components of a range of different types of bog including blanket mire, raised mire and reedswamp peats, by breaking down and dating a range of different fractions from each type of macroform. By analysing such fractions as the whole sample, water soluble organics, humic acids, insoluble organic detritus larger than 250μm and insoluble fraction smaller than 250μm, he was able to conclude that *Sphagnum* peats from raised bogs would provide the most reliable chronology (Dresser, 1971). The influence of water movement in transporting sediment at a site where peat had accumulated on a gentle slope was investigated by Bartley and Chambers (1992). They suggest that the relatively insoluble humin fraction of peat would be more likely to give a true age than the more soluble and therefore potentially more mobile humic material. Alternatively, Johnson *et al.* (1990) suggest that the humic fraction for some material would produce more reliable dates from their studies on a site near Featherbed Moss in north Derbyshire.

Discrepancies between dates obtained from peat and other mediums are commonly documented. Olsson (1986a) compared dates obtained from charcoal at an archaeological site with peat from contemporaneous layers in a nearby *Cladium* peat bog in Sweden and found the peat to be interpreted as being 500 years too old.

Although he suggests that the relative ^{14}C deficiencies in bogs must be small and that the influence of roots may counteract or even overcompensate for the proposed ageing effect (Olsson and Florin, 1980), he recommends that, where possible, well-defined plant remains be dated instead of the bulk sediment. Other authors such as Mehringer and Warren (1976) have rejected the use of peat as a dating medium altogether as a result of its apparent unreliability.

1.2.4.1 AMS dating and wiggle-matching

To overcome the inherent problems associated with bulk dating of peat deposits, it has been suggested by various authors (e.g. Olsson, 1986a; van Geel and Mook, 1989; Kilian *et al.*, 1995) that high-resolution dating combined with wiggle matching provides a better ^{14}C age determination of organic deposits. The selection of individual plant remains, such as mosses, fruits and seeds, extracted within very narrow vertical bands, reduces the potential of contamination by deeper (younger) roots (van Geel and Mook, 1989), while the matching of natural ^{14}C variations in the peat with the dendrochronological calibration curve greatly improves dating accuracy.

However, the effectiveness of the combined AMS/wiggle-matching technique is highly dependent on sediment accumulation rates. As calculated by Aaby and Tauber (1975), the mean peat accumulation rate in north-western European bogs varies between 0.2 and 0.9 mm/yr, with younger peat layers having faster rates owing to lower levels of compaction. For this reason, successful application of wiggle matching requires ^{14}C dating of 5-10 mm slices of peat. An additional requirement for effective wiggle matching is that the ^{14}C age range obtained coincides with a relatively sloped part of the calibration curve (van Geel and Mook, 1989). Problems occur when matching these 'floating' peat chronologies to portions of the calibration curve that are relatively horizontal or only partly steep. In these cases, more ^{14}C age determinations covering a longer time period are required (van Geel and Mook, 1989).

1.2.4.2 Other dating methods

The limitations of radiocarbon dating methods, as mentioned above, often restrict palaeoecological studies to time scales of hundreds, if not thousands of years. Owing to the need for precise chronologies when studying the dynamics of peatland ecosystems, authors are constantly looking for alternative methods of dating recent peat. One possible candidate is the lead-210 (^{210}Pb) dating technique, first introduced by Goldberg (1963), but has only been used in palaeoecological studies since the early eighties (Olsson, 1986b). The use of this relatively short-lived radioisotope ($t_{½}$ = 22.26 yr) initially showed great promise for accurate and precise dating of peat, but recently concerns about its stability in the peat profile have resulted in a sharp reduction in its application (Belyea and Warner, 1994). Anomalies in concentration profiles (Damman, 1978), differential burdens in adjacent hummocks and hollows (Urban *et al.*, 1990), and lack of correspondence with independently derived dates (Oldfield *et al.*,1979) have all been cited as evidence that lead is leached from sub-water table peat (Urban *et al.*, 1990). Urban *et al.* (1990) suggest that age resolutions are limited to ±10 years with the ^{210}Pb technique, and that results should be routinely checked against those of other methods. Joosten (1995) also questions the reliability of this technique, suggesting that the high hydraulic conductivity of the newly formed peat deposits may lead to post-depositional reallocation and other methodological problems.

Another method used to date recent peat profiles is moss-increment dating where the annually produced innate markers, found on the stems of *Sphagnum* and *Polytrichum* mosses, are identified and counted (Tolonen *et al.*, 1988). Unfortunately, owing to difficulties in identification this technique is somewhat subjective and is restricted to profiles in which moss stems are intact and vertically orientated (Belyea and Warner, 1994). Middeldorp (1982) developed a pollen-density based method of dating peat in the Netherlands, based upon the assumption of a constant rate of pollen influx and accumulation. The average rate of pollen accumulation over a contiguously sampled interval is estimated using a known age at the base. Any variations in pollen concentration through the sampled interval are then used to signify changes in rate of the accumulation of organic matter (Belyea and Warner, 1994). Problems include poor pollen preservation and changes in the pollen productivity and composition of the regional vegetation.

1.3 Aims and Objectives of the Project

The main aim of this research project is to test the ability of specific palaeoecological techniques in detecting established and/or previously documented changes in mire surface conditions, and by inference climate, that have been found to occur in regionally associated ombrotrophic mires over the last *c.* 3000 years. Of most interest is the detection of synchronously occurring fluctuations in the proxy-climate datasets, reflecting shifts to wetter or relatively drier conditions. Using fine resolution sampling procedures and high-precision AMS wiggle-match dating techniques, inferred shifts in climatic conditions have been chronologically ordered, thereby enabling direct comparison with regionally associated palaeoclimatic records. A major advantage in carrying out high-resolution analyses of each core is that it would permit the identification of climatic changes that may otherwise have remained undetected if a coarser sampling approach had been adopted.

Specific objectives intended to be achieved through this research project are as follows:

- The multi-proxy application of specific palaeoecological techniques to be used in the analysis of peat samples from four profiles from selected sites across north-western and western Britain, providing proxy-climatic records covering the last *c.* 3000 years.

- It is intended that the use of high-resolution sampling procedures will facilitate the identification of previously undetected shifts in regional climate.

- Statistical analysis of raw macrofossil datasets, using a range of multivariate techniques, will enable the generation of proxy-climatic curves, being directly comparable with humification records.

- Comparison of the proxy-climate records generated in this project with regionally associated palaeoclimatic records will lead to the identification of correlating shifts in past climates.

- Application of high-precision AMS dates and wiggle-match procedures will constrain the chronological control of each core and provide a standard for future comparison with other palaeoclimatic studies.

1.4 Structure of the Thesis

The thesis is organised into six chapters. Chapter 2 provides a comprehensive account of the methods applied in this project, including descriptions of the various palaeoecological techniques and dating procedures employed in the study. The results of the project is then divided into two sections. Chapter 3 opens with a detailed listing of the components of each of the diagrams, followed by a description of the initial interpretations of each dataset in a site-by-site format. The final section of this chapter provides an account of calibration of the radiocarbon determinations for each core, and reports on the increased precision obtained through the application of wiggle-match dating procedures. Results obtained from relative dating techniques are also listed (Lead-210 and SCP chronologies). Chapter 4 then provides an account of the statistical analysis of each of the macrofossil datasets using multivariate techniques, whereby proxy-climatic curves have been generated as a direct comparison against the humification records. Proxy-climate curves are then compared with humification curves against an interpolated ^{14}C time-scale, in order that any correlating shifts in relative climate may be inferred. Chapter 5 is in the form of a discussion, where synchronously occurring shifts to wetter and relatively drier conditions inferred from this study are compared with other, regionally associated studies, and established changes in climate are identified. The conclusions and further research forms the final part of the thesis, Chapter 6, where the main findings of the study are listed and possible extensions to the project are suggested.

Chapter 2 Methods

2.1 Background to Methodology

Although closely associated, a number of distinctions can be made between studies of ecology and studies of palaeoecology based upon differences in scale. Whereas ecologists generally work within well-defined boundaries of space and time, the scales that palaeoecologists study are forced on them by the state of preservation and morphological characteristics of the site studied (Birks and Birks, 1980). Ecologists are also able to determine selectively which area is to be investigated, whereas palaeoecologists are restricted to specific locations, upon which they are expected to base holistic reconstructions. One method of improving the links between palaeoecology and ecology would be to improve the resolution of the sampling interval of any analyses (Birks *et al.*, 1988), thereby identifying vegetational changes that occur over shorter timescales. Another solution, which would provide a more general reconstruction of past vegetational conditions, would be to carry out multi-core analyses of each site.

Owing to the descriptive nature of palaeoecological studies, it is often difficult to present valid and accurate interpretations as realistic falsifiable hypotheses. To overcome this problem, Heck and McCoy (1979, pp. Birks *et al.*, 1988) suggest accumulating all available data without any *a priori* assumptions about underlying causes, and then select from multiple causal explanations the one that is most consistent with the available evidence. However, some observations may be so localised in time or space that they reflect isolated events and, in this case, causal explanations may not be testable with datasets derived from other sites. For this reason, care must be taken when interpreting proven causal explanations, as they may simply reflect local descriptions, inductively derived narratives, or plausible but untested and untestable scenarios (Birks *et al.*, 1988).

2.2 Introduction

This study adopts the method of multiple working hypotheses, as mentioned previously, where speculations as to causal mechanisms of change were not attempted until all datasets were accumulated. Following analysis and interpretation, a range of possible scenarios will be suggested, and the most likely reason for change will be selected. Using a range of established palaeoecological techniques, peat cores have been analysed from a number of selected sites across the western side of the British Isles. As well as carrying out primary high-resolution analyses on core material, using both macrofossil and humification analyses, other secondary techniques have also been employed as a means of supporting these datasets. Testate amoebae analysis has been applied, providing an independent record of changes in local hydrological conditions, while spheroidal carbonaceous particle (SCP) analysis has been used to extend the chronological control of each site to the near-surface layers of peat. The development of an effective chronology has formed an integral part of this research project, and for this reason high-resolution AMS ^{14}C dates have also been obtained for three of the four cores analysed. In addition to radiocarbon and SCP chronologies, sediment accretion rates have also been determined for the uppermost sections of cores extracted from Bolton Fell Moss and Mynydd Llangatwg using Lead-210 dating procedures.

2.3 Site Selection

The potential for using mires in the reconstruction of environmental change is heavily reliant upon the minimal existence of any background noise in the palaeo-record, which may have the effect of concealing possible climatic signals. Human disturbance to a bog, in the form of drains, gulleys or peat excavation, has been found to alter the vegetational record significantly and so, in these cases, alternative coring locations need to be located. Studies have revealed that drainage of these balanced ecosystems often results in primary consolidation, with Hobbs (1986) reporting that subsidence to a depth of 1.5 m occurred within 12 months of drainage. Any shrinkage of the peat has the effect of compressing the fossil record, thereby reducing the resolution of any proxy-climatic reconstruction, while exposure of the material to aerobic decomposition processes renders interpretation of the humification signal problematical.

The vegetational characteristics of potential sites were also required to meet certain criteria, as ombrotrophic mires displaying low concentrations of climatically responsive *Sphagnum* species would be limited in their ability to reconstruct changes in surface wetness. Until recently, blanket mires were considered ineffective as archives of proxy-climatic records, owing to their alleged uniform stratigraphy and lack of identifiable macrofossils (Chambers *et al.*, 1997). Interpretation of blanket peat macrofossil datasets was also thought to be problematic owing to the effects of long-term differential decomposition (Clymo, 1984), and the varying response rates to changes in moisture regime, with some displaying relative insensitivity to past climatic change (Haslam, 1987). However, more recent work carried out by Blackford and Chambers (1991) and Chambers *et al.* (1997), with respect to humification analysis, and Tallis (1995), with respect to macrofossils, has refuted these misconceptions. For this reason the three sites selected for this study include one ombrotrophic blanket mire, namely Mynydd Llangatwg in South Wales, as well as two raised ombrotrophic mires, namely Bolton Fell Moss in Cumbria and Langlands Moss, situated just north of East Kilbride in southern Scotland.

2.4 Coring Strategy

Profiles were extracted using both open-ended aluminium monolith tins and Russian-type peat corers. At Bolton Fell Moss and Mynydd Llangatwg, 50 x 10 x 10 cm aluminium monolith tins were used to remove the upper section of sediment, while the remaining sections from these locations, and all from Langlands Moss, were extracted using a combination of wide-bore (30 x 9 cm diameter) and narrow-bore (50 x 6 cm diameter) Russian-type corers. As a prerequisite of this study is to investigate changes in climate that have occurred over the last c. 3000 years, evidence was obtained, both from the field and from previous studies carried out at the relevant site, as a means of estimating the required core depth. The rationale for extracting 2.55 m of material from Bolton Fell Moss was determined by reference to investigations carried out by Barber *et al.* (1994a) where, based upon the radiocarbon dating of twelve peat horizons, the accumulation rate was calculated as being a relatively constant 12.4 yr cm^{-1}. Preliminary investigations at Langlands Moss carried out by the Palaeoecology Laboratory at University of Southampton had revealed that 2 m of core material would be sufficient to cover the last 3000 years (Langdon, pers. com.), while for Mynydd Llangatwg, a pine stump, estimated to be dated to *c.* 2000 BC, was found to be underlying the base of the core, taken to 2.46 m depth.

Careful consideration was also made with regard to the position of the coring point as, for example, it is possible that cores taken from the edge of mires may hold an incomplete palaeo-record as the peat is thin and more likely to have suffered from disturbance, either from natural processes (e.g., bog-bursts) or human activity (i.e., peat cutting) (Barber *et al.*, 1994a). Therefore, all cores were taken from intact areas of the bog, away from boundaries and noticeable areas of past drainage activity. Surface hummocks were also avoided as it has been shown that these microforms are more likely to be insensitive to changes in climate (Aaby, 1976). Wherever possible, profiles were extracted from the same lawn microform, usually displaying a dominance of *Sphagnum magellanicum.*

Primary factors influencing the number of cores extracted were (a) the need to establish a good chronology for each site, and (b) the time required to carry out in-depth analyses of core material. Owing to the high cost of radiocarbon measurement, and the considerable length of time needed to apply proxy-climate techniques at high-resolution intervals (0.5 - 1 cm), single cores were extracted from Langlands Moss (LAG/4) and Mynydd Llangatwg (MLA/2). Justification for this approach can be found in studies carried out by Barber (1981), Stoneman (1993), Barber (1995) and Barber (1996), where stratigraphic levels within single raised peat bogs were found to respond synchronously to variations in proxy-climate, suggesting that a single borehole would hold a representative record for the whole site. Although two cores were taken from Bolton Fell Moss (BFM/MC and BFM/3), radiocarbon dating was only carried out on Core MC, as a parallel investigation performed by researchers from University of Bristol, provided a number of supplementary dates for Core 3.

2.5 Colorimetric Humification Analysis

As well as reconstructing the variations in vegetational assemblage that occur on the surface of a peat bog over time, an understanding of the chemical properties of the peat matrix can also assist in the generation of a proxy-climate record. Early studies carried out by Aaby and Tauber (1975) revealed that a measure of the degree of peat humification is a valuable indicator when attempting to reconstruct bog surface wetness at time of deposition. Using this technique, local reconstructions of bog surface wetness can be combined, thereby providing a record of changes in regional peat hydrology, and by inference, changes in regional climate (Blackford and Chambers, 1991). Although the presence of organic material in the peat matrix is thought to disrupt the humification signal when using this method (Chambers, 1984), only ombrotrophic mires have been investigated in this study and since these ecosystems only receive minerals from the atmosphere, any inorganic material present should be small and therefore not influence the colorimetric determinations.

2.5.1 Preparation and Analysis

Sub-samples of *c.* 4cm^3 were taken from all cores at between 0.5 - 1 cm intervals (sampling interval applied was dependent upon the consistency of the peat) continuously throughout, and colorimetrically analysed using a variation of the methodology originally developed by Bahnson (1968), modified by Aaby and Tauber (1975), and later applied by Blackford (1990) (see Appendix 1). Following alkali-extraction using 8% NaOH and filtration procedures, samples were analysed colorimetrically using a Cecil Instruments, CE-303 Grating Spectrophotometer at 540 nm, and recorded as absorbance residuals.

2.6 Plant Macrofossil Analysis

One of the primary analysis techniques used in this project is the semi-quantitative analysis of vegetational macrofossils. Unlike many other palaeoecological indicators, such as pollen or testate amoebae, the relatively large size and *in situ* growth characteristics of plant macrofossils restrict the extent to which methods of dispersal and deposition affect their position relative to the water table. In ombrogenous mires, *Sphagnum* species form the majority of the peat matrix and so reconstruction of changes in their assemblages form the basis for this technique. At levels where little or no sub-fossil *Sphagnum* is present, palaeoclimatic reconstructions are solely reliant upon the identification of monocotyledonous remains to species level, through examination of the structure of the epidermal tissue. Varying rates of decomposition is also problematic when using this technique, as the rate of decay in *Sphagnum* is species controlled (Johnson and Damman, 1991).

2.6.1 Preparation and Analysis

The methodology selected for this study is a variation of the Quadrat and Leaf Count Macrofossil Analysis (QLCMA) technique, as developed by Haslam (1987). Although this is a time-consuming technique, it enables accurate reconstruction of the vegetation components and allows the data to be subject to multivariate analyses. It is a compromise between the simplistic 5-point scale scheme, developed by Walker and Walker (1961), and more comprehensive techniques such as that used by Janssens (1983) where loose leaves, branches and whole *Sphagnum* plants are counted, and a preservation index is assigned to create a 10-point 'reliability' index. The technique has also been utilised by a number of different authors at regionally related sites (e.g. Stoneman *et al.*, 1993; Barber *et al.*, 1994a, 1998; Mauquoy, 1999) in similar studies, therefore enabling direct comparison with these datasets.

After extracting 1 cm slices (measuring *c.* 4 cm^3) of peat contiguously throughout each core, samples were then washed using a strong jet of water over a 125 µm sieve, thereby removing the fine, highly humified material and disaggregating the sample, then placed in a glass Petri dish for inspection. Proportions of each of the major peat components (i.e., Unidentified organic matter (UOM), Ericales roots, monocotyledons, identifiable *Sphagnum* and other bryophytes) were then estimated from 10 averaged quadrat counts under low power magnification (× 10), using a 10 x 10 square grid graticule in the eyepiece of a Nikon stereozoom microscope. The presence of other macrofossil components, such as seeds, flower heads and charcoal was represented using the 5-point scale methodology. Where a component covered more than one half of a square, a score of 1% was assigned. Individual *Sphagnum* leaves were then randomly extracted (> 100 per sample) and identified to the lowest taxonomic level possible using a compound microscope (Nikon Optiphot-2) at × 100-400 magnification. Although every effort was made to extract the minimum number of *Sphagnum* leaves (i.e., 100), there were levels where Sphagna were rare and in some instances absent altogether. At these levels, identification of *Sphagnum* species was only attempted if the number of leaves exceeded 50. A reference collection of type slide material and the drawings in Daniels and Eddy (1990) aided in the identification of *Sphagnum* species.

What follows is a morphological description of each of the major macrofossil components identified. Detailed descriptions of ecological preferences of each component are provided in the next Chapter.

2.6.2 *Sphagnum* Species

General distinctions between the various species identified in this study can be made on the basis of the leaf structure. The shape of the leaf itself is often evidence enough on which to base a preliminary classification at × 100 magnification. The hyaline cells, which store and enable transport of water, are also often distinguishable between species with hummock-forming species of drier habitats often having larger cells than those species occupying wetter habitats (Daniels and Eddy, 1990). At higher magnification (× 400), the internal walls of these hyaline cells can also aid species identification as they often have distinctive structures.

2.6.2.1 Sphagnum imbricatum

Two subspecies of *Sphagnum imbricatum* can be identified in European peatlands today: ssp. *affine*, which is restricted to minerotrophic habitats and ssp. *austinii*, which can only be found at ombrotrophic locations. *S. imbricatum* is clearly recognisable in sub-fossil state by an abundance of densely arranged comb-like fibrils, positioned along the internal (commissural) walls of the hyaline cells (Daniels and Eddy, 1990) (Plate 2.1).

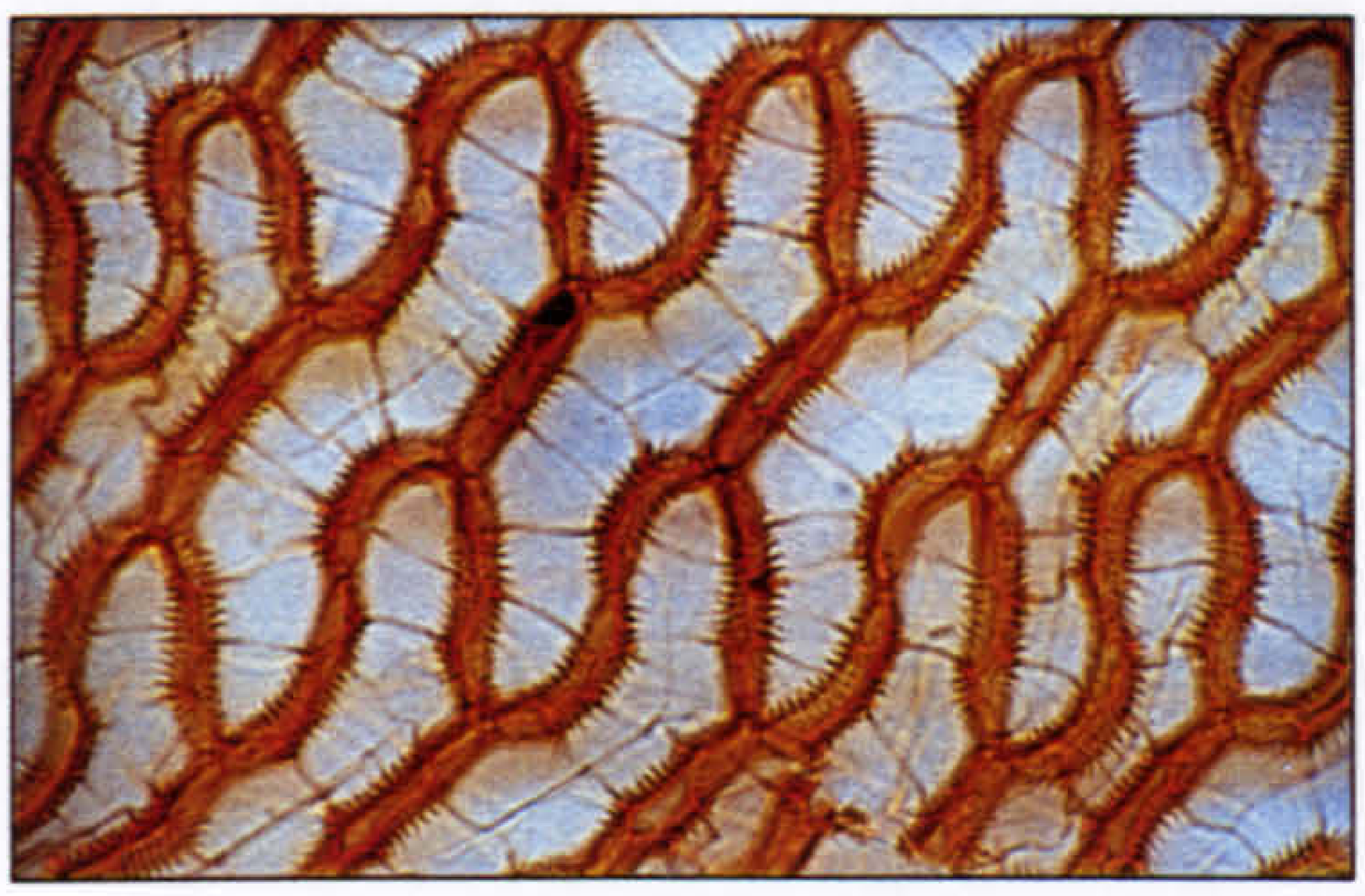


Plate 2.1. *Sphagnum imbricatum* (×400)

2.6.2.2 *Sphagnum* section Acutifolia

All species of this section possess small to medium sized leaves, typically 1.2 - 1.9 mm long, and have triangular shaped photosynthetic cells (Daniels and Eddy, 1990). These common factors make it difficult to identify leaves beyond section level, which consequently makes it difficult to reconstruct changes in surface wetness based on the presence of leaves from this section.

2.6.2.3 Sphagnum papillosum

This species is very distinctive by the presence of numerous little bumps (papillae) along the edge of the commissural walls (Plate 2.2). The leaves are also relatively wider than most other *Sphagnum* species.

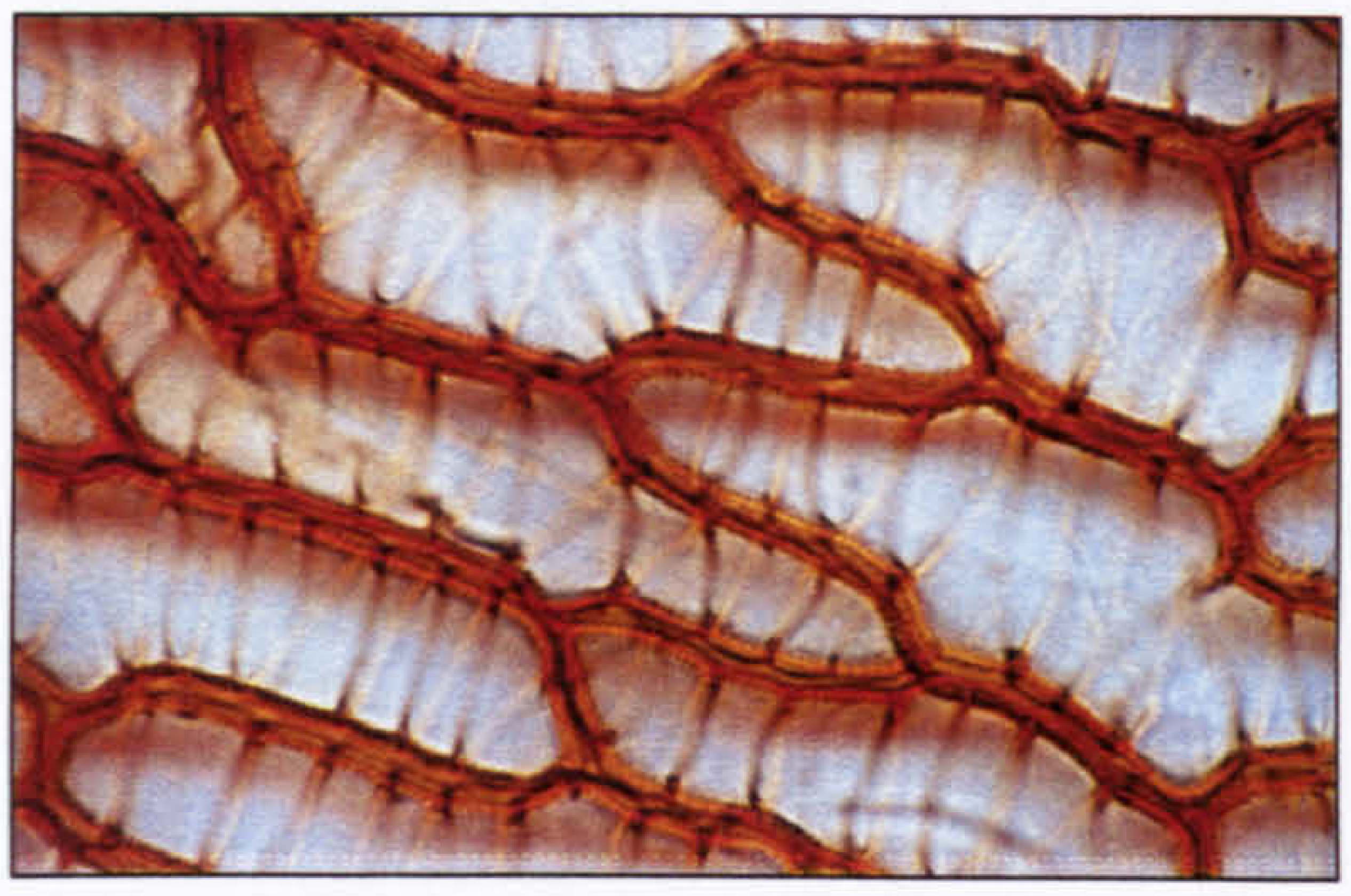


Plate 2.2. *Sphagnum papillosum* (×400)

2.6.2.4 Sphagnum magellanicum

Identification of this species is achieved by variable magnification of the photosynthetic cells, which are mostly enclosed by the hyaline cells (Plate 2.3).

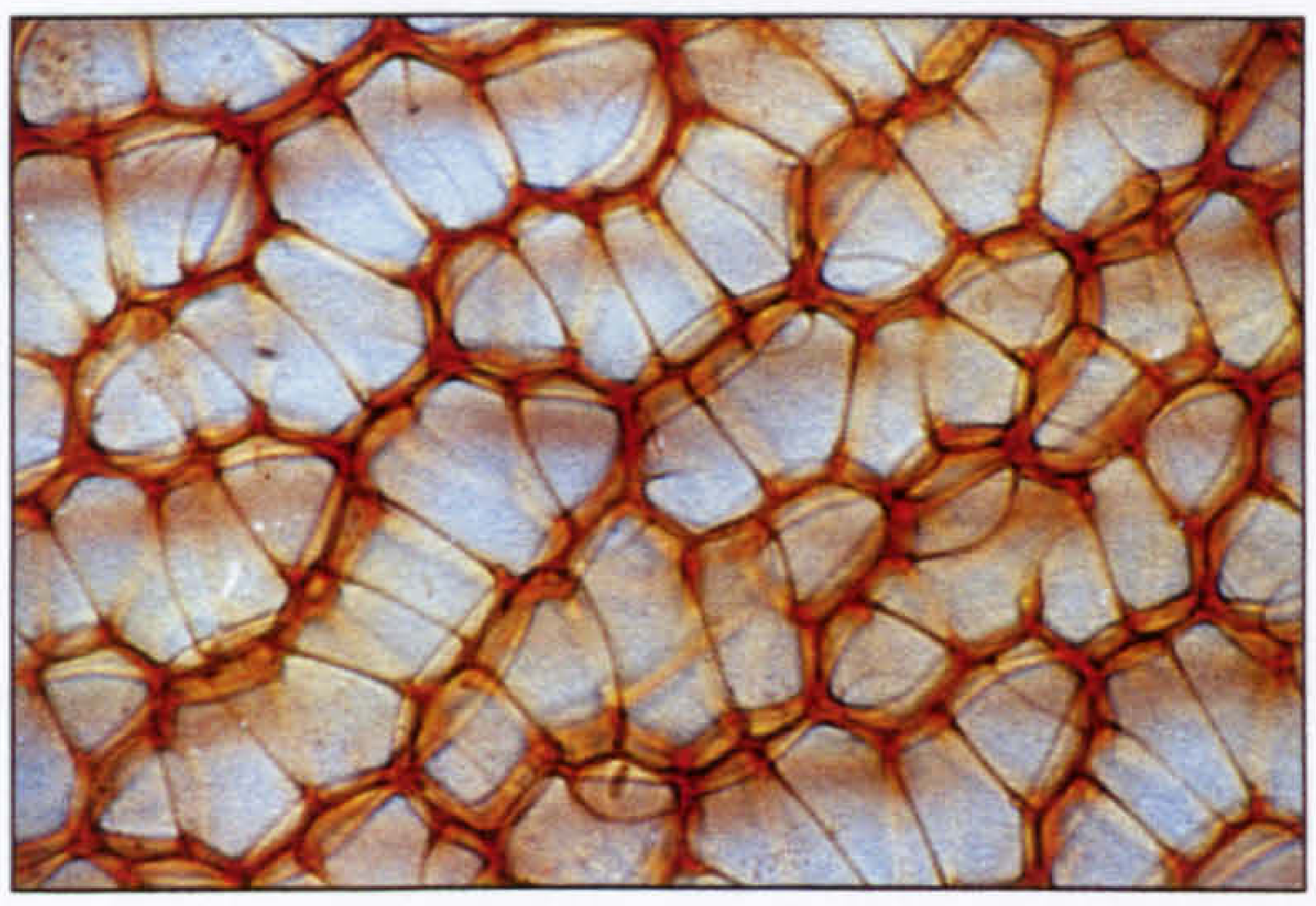


Plate 2.3. *Sphagnum magellanicum* (×400)

2.6.2.5 *Sphagnum* section Cuspidata

Species within section Cuspidata are easily identified by their ovate to lanceolate shape, narrow hyaline cells, and their triangular to trapezoidal shaped photosynthetic cells (Daniels and Eddy, 1990). The leaves of *Sphagnum cuspidatum* are particularly distinctive, as they are 3 to 6 times as long as they are wide.

2.6.3 Monocotyledonous Remains

An additional indication of changes in mire surface conditions over time can also be potentially determined through the identification of specific monocotyledonous remains. However, this can prove problematical as the state of preservation and morphological structure of the monocotyledonous epidermal tissues is critical to obtaining accurate species identification. Using a combination of reference type material, annotated drawings in Grosse-Brauckmann (1972) and Smith (1980), and assistance from working colleagues, it was possible to identify the following species through the comparison of epidermal cell morphology:

2.6.3.1 Eriophorum vaginatum

The epidermal structure of this species is very distinctive (Plate 2.4), with each cell being many times longer than it is wide and having a 'crinkled' texture. The cells are arranged in an orderly fashion, and are characteristically transparent in appearance.

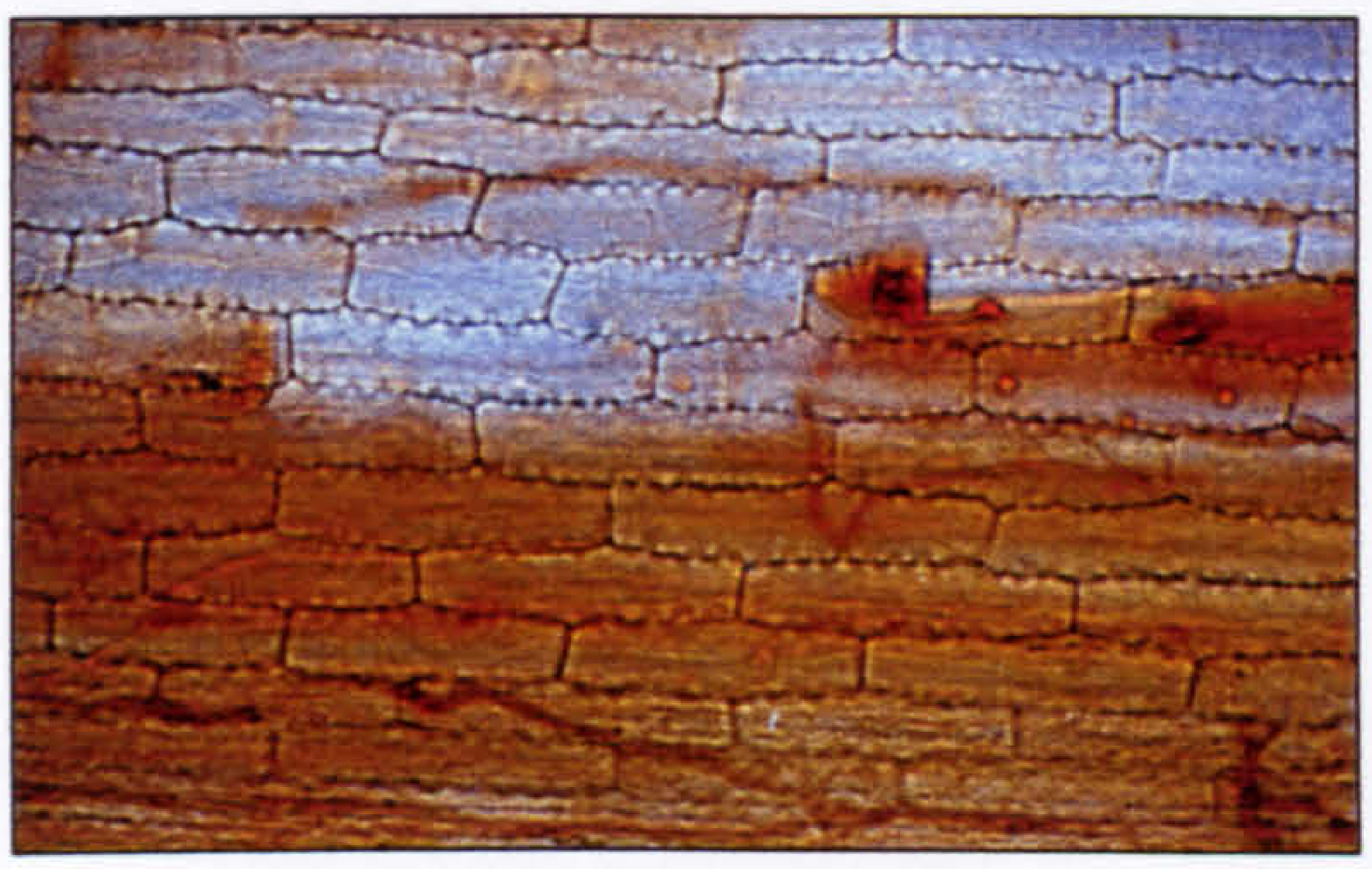


Plate 2.4. *Eriophorum vaginatum* epidermis (×400)

2.6.3.2 Eriophorum angustifolium

Although having a similar 'crinkled' texture, the cells of this species are much shorter and wider than those of *Eriophorum vaginatum*. Another striking characteristic of this species is the red-stained colour of the rhizomes (Plate 2.5).

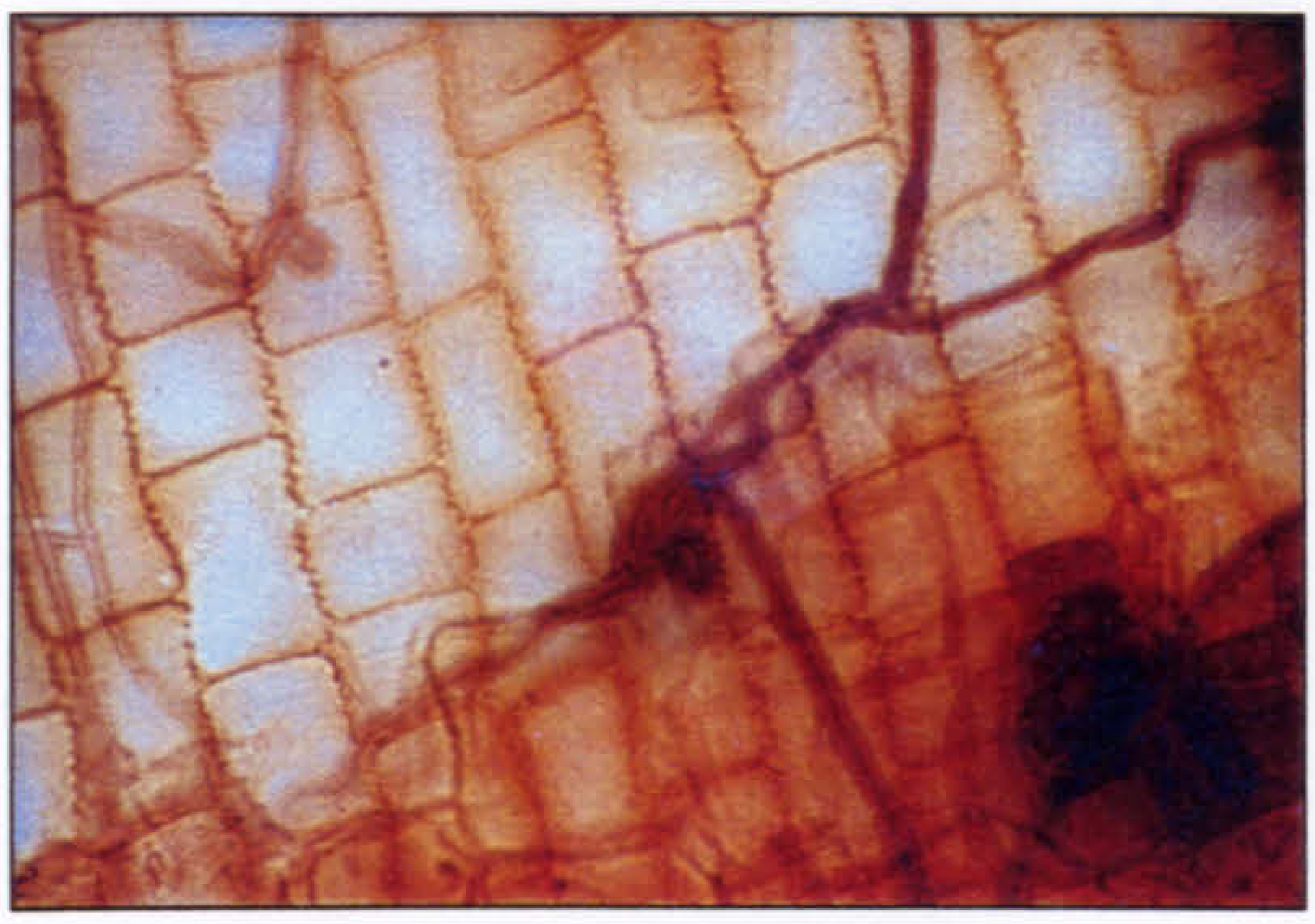


Plate 2.5. *Eriophorum angustifolium* epidermis (×400)

2.6.3.3 Rhynchospora alba

The stem sheaths of this species of sedge have a very distinctive arrangement, in that the cells are longer than they are broad at the edge, whilst at the centre of the stem sheath the opposite pattern is displayed (Plate 2.6).

Plate 2.6. *Rhynchospora alba* epidermis (×400)

2.6.3.4 Trichophorum cespitosum

This species is characterised by the arrangement of short epidermal cells that lie adjacent to chains of longer parallel cells (Plate 2.7).

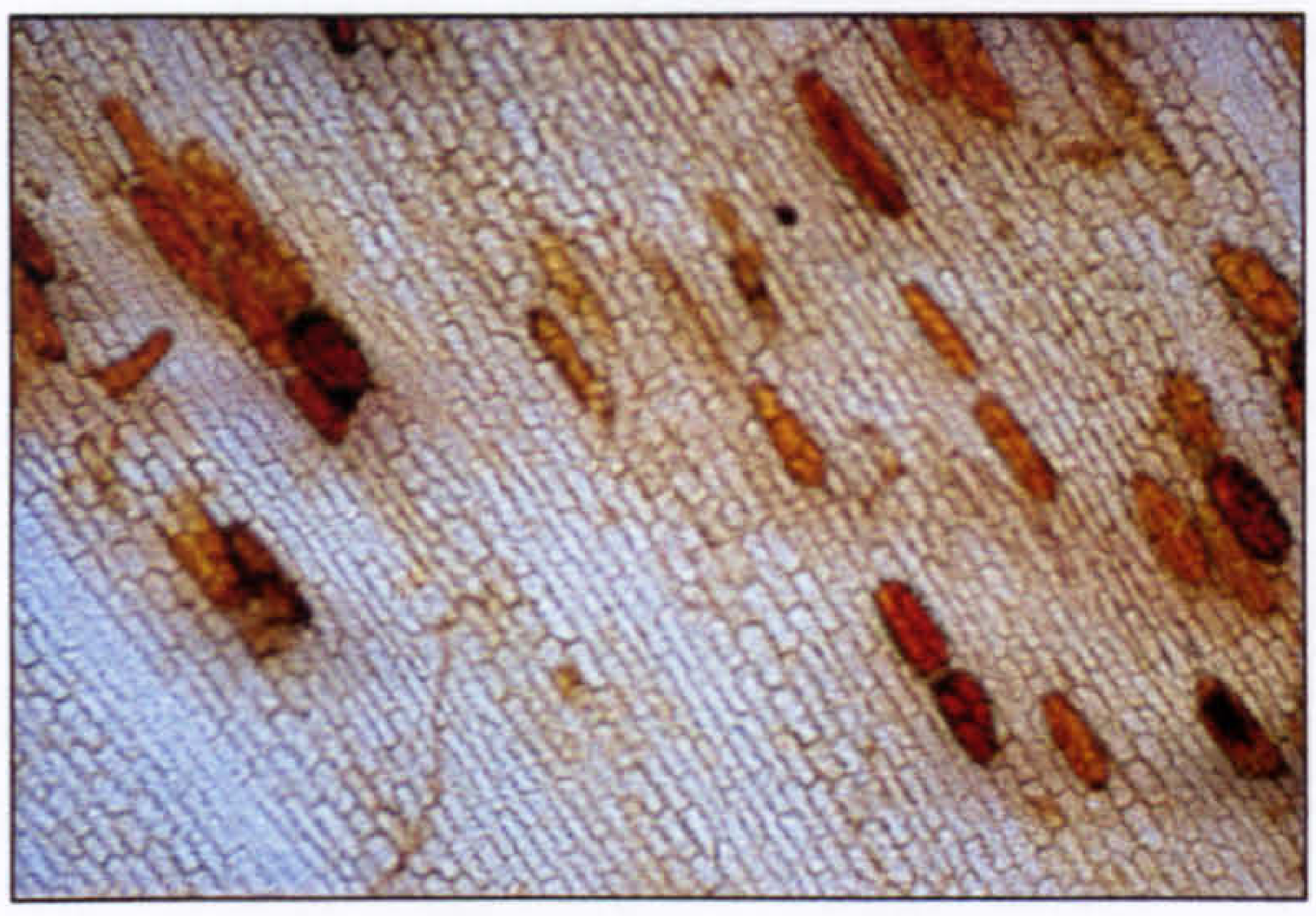


Plate 2.7. *Trichophorum cespitosum* epidermis (×400)

Where possible, readily identifiable fragments of epidermal tissue, clearly displaying the cell structure, were removed and examined at × 100 - 400 magnification, enabling identification to species level. The proportion of each species of epidermal tissue identified was then calculated and presented as a percentage of the peat matrix at each level. In cases where it was not possible to identify the remains to species level, and where there was no epidermal tissue present, monocotyledonous remains were simply classified as monocotyledons undifferentiated (monocots. undiff.), and expressed as a percentage value (Mauquoy, 1997). As well as epidermal remains, the spindles from *Eriophorum vaginatum* were commonly found and these were recorded using the 5-point scale methodology (where 1= rare, 2= occasional, 3= frequent, 4= common and 5= abundant).

2.6.4 Ericaceous Remains

The majority of ericaceous remains largely consisted of rootlet material, and as these cannot be identified beyond group level (Charman, 1990), they were simply classified as Ericales roots. However, certain species, such as the leaves of *Vaccinium oxycoccus*, the leaves and seeds of *Calluna vulgaris* and the woody remains of *Erica tetralix* could be identified using a type reference collection and the photographs in Grosse-Brauckmann (1972, 1974) and Grosse-Brauckmann and

Streitz (1992). Subfossil remains of *Calluna vulgaris* and *Erica tetralix* were recorded using the 5-point scale methodology, while the presence of *Vaccinium oxycoccus* was expressed as a mean percentage value of the peat matrix.

2.6.5 Non-*Sphagnum* Bryophytes

Five species of non-*Sphagnum* bryophyte were encountered during the analysis of the four cores. These were *Aulacomnium palustre, Polytrichum juniperum/alpestre* type, *Racomitrium lanuginosum, Hypnum cupressiforme* and *Odontoschisma sphagni* Assistance with identification of these bryophytes was provided by Smith (1980, 1990) and the photographs in Grosse-Brauckmann (1974). As with the major peat components, their proportions were expressed as a mean percentage value of the peat matrix at each level.

2.7 Testate Amoebae Analysis

Until very recently, the majority of mire surface water-level reconstructions carried out on peat bogs were reliant upon, at the most, two proxy-climate techniques (e.g., Walker and Walker, 1961; van der Molen, 1988; Barber *et al.*, 1994a; Blackford and Chambers, 1995; Barber *et al.*, 1998). However, owing to the lack of modern training sets through which palaeo-indicator values are derived, techniques such as macrofossil analysis and humification analysis provide only semi-quantitative records of surface wetness (Woodland *et al.*, 1998). A relatively new and potentially quantitative technique, used in the reconstruction of hydrological change in peatlands, is testate amoebae (Protozoa: Rhizopoda) analysis. Testate amoebae are unicellular organisms, typically between 20 - 250 µm in size, which can be found in a variety of ecological environments including the surface layers of peat (Woodland *et al.*, 1998). Being responsive to variations in both local water table depth and moisture conditions, these organisms have the potential to complement reconstructions of mire water-level based on other proxy-climate techniques. The shells of these organisms, known as tests, are well preserved in *Sphagnum* peatlands and form a major component of the peat matrix with up to 1.6 x 10^7 individuals per m^{-2} (Heal, 1962).

2.7.1 Preparation and Analysis

In this study, analysis of testate amoebae was included as a means of supporting datasets generated through humification and macrofossil analyses. For this reason, and as a means of conserving time, analyses were restricted to the identification and recording of specific indicator-species using a slightly coarser sampling strategy, relative to that applied to the primary analysis techniques. Five species were chosen, based on their characteristic preferences to variable positions on the moisture gradient, and their generally wide-scale distribution throughout north-western Europe. These species were *Amphitrema flavum*, *Amphitrema wrightianum*, *Assulina muscorum*, *Hyalosphenia subflava* and *Trigonopyxis arcula*. Sub-samples of *c.* 2 cm^3 were extracted at 2 cm intervals throughout all cores (except BFM-3), and processed using a variation of the methodology developed by Tolonen (1986).

Each sample was initially disaggregated by boiling for ten minutes in 50 ml of distilled water, then washed through a coarse sieve (250 µm mesh) to remove the larger detritus, while retaining the washed-through material. Following back-sieving of this material through 15 µm mesh, to remove the fine fraction detritus, samples were then centrifuged at 3000 rpm for three minutes, decanted, and stained with safranine. Unlike other procedures involving chemical treatment, this simple technique avoids damage to the delicate thecae of the testate amoebae (Hendon and Charman, 1997). Once mounted, slides were scanned at × 400 magnification, using a Nikon Optiphot-2 microscope, until a minimum of 100 testate amoebae were counted. The presence of any of the five chosen indicator-species was recorded, while all other species of testate amoebae were simply accrued. Proportions of each species were then calculated for each level investigated.

Taxonomic identification of the five indicator-species was based upon the following morphological test characteristics:

2.7.1.1 Amphitrema flavum

Species of the genus *Amphitrema* are the only testate amoebae with two apertures (pseudostomes), symmetrically positioned at either end of a round elongate test (Plate 2.8). This particular species is abundant throughout ombrotrophic peatlands in north-west Europe, and is easily identifiable by its smooth, amber-brown test (Charman *et al.*, in press).

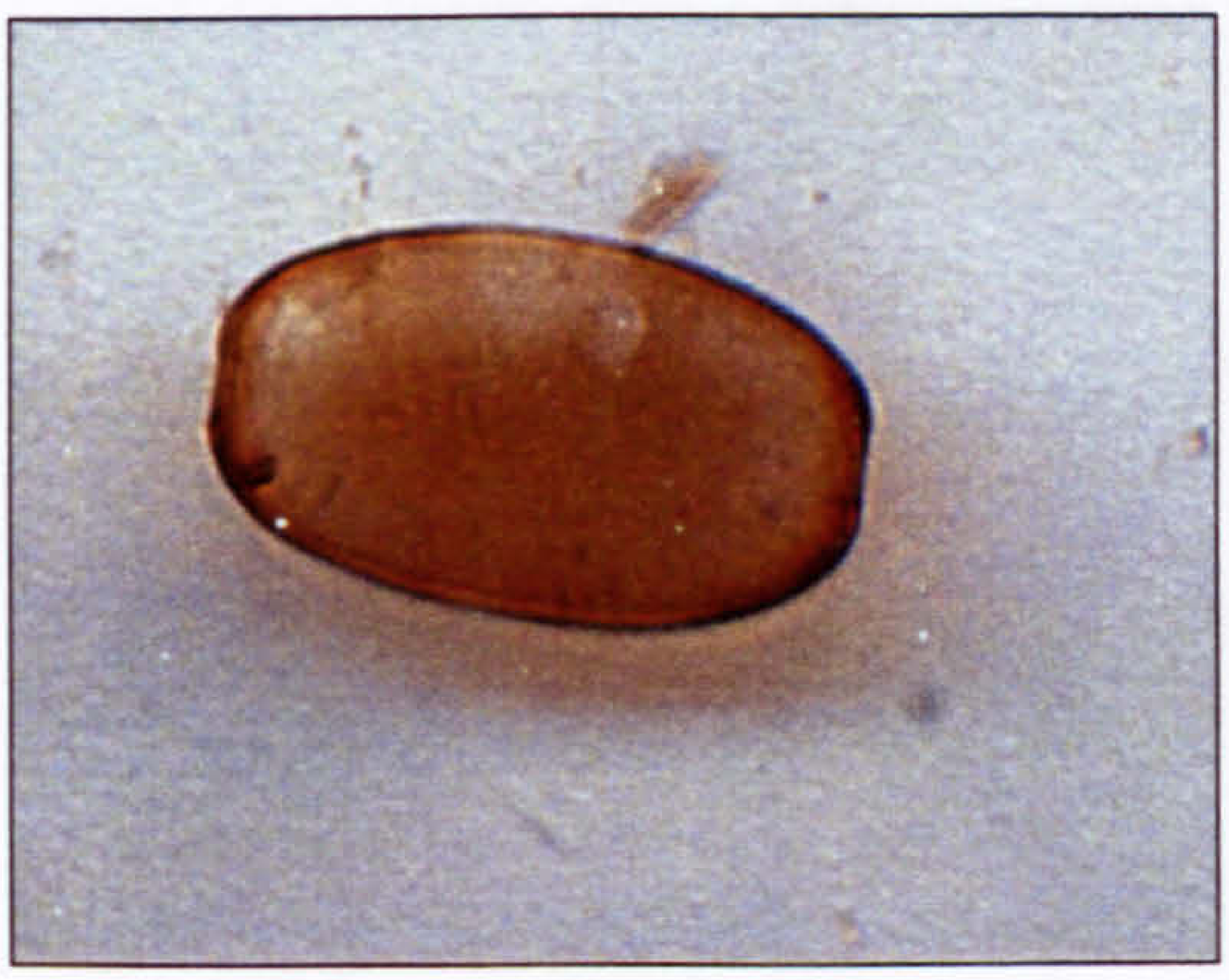


Plate 2.8. *Amphitrema flavum* (×400)

2.7.1.2 Amphitrema wrightianum

Although it is possible to confuse this species with *A. stenostoma*, particularly when the mineral/organic particles (xenosomes) obscure the pseudostomes, *A. wrightianum* is generally more ovoid and has distinctive collars extending each of the pseudostomes (Plate 2.9). In fossil form, it has a yellow to amber-brown colour with a proteinaceous test, commonly concealed by siliceous particles, including diatoms, flagellate cysts, and fragments of quartz (Charman *et al.*, in press).

Plate 2.9. *Amphitrema wrightianum* (×400)

2.7.1.3 Assulina muscorum

The genera *Assulina* are of the family Euglyphidae, which are differentiated from other taxa by their regular pattern of siliceous plates (Plate 2.10). This particular species is relatively small, usually russet-brown to pale pink in colour and has oval plates, normally arranged in neat rows, but irregularities may be present (Charman *et al.*, in press). Although marginally similar in appearance to *A. seminulum*, *A. muscorum* generally have relatively broader tests and a less-defined pattern of plates.

Plate 2.10 *Assulina muscorum* (x 400)

2.7.1.4 Hyalosphenia subflava

Species of the genus *Hyalosphenia* are characterised by their clear, smooth-walled tests, being entirely composed of secretion (Plate 2.11). The test outline of *H. subflava* is ovoid in broad lateral view (as seen from the broadest side of the test, with the pseudostome uppermost) and elliptical in narrow lateral view (as seen from the narrowest side of the test, with the pseudostome uppermost), and is often folded or distorted with a number of different possible morphological variations (Charman *et al.*, in press).

Plate 2.11. *Hyalosphenia subflava* (×400)

2.7.1.5 Trigonopyxis arcula

This species is characterised by its large, normally non-circular mouth, which commonly appears as a rough triangle but may also be four-sided or more irregular, occasionally forming a ragged triangle (Brobrov *et al.*, 1995) (Plate 2.12). The test has a circular form in broad lateral view and is hemispherical in narrow lateral view (Charman *et al.*, in press). Although generally rustic red to dark brown in colour, the test is largely composed of xenosomes, bound by organic cement, and so displays a mosaic-effect texture.

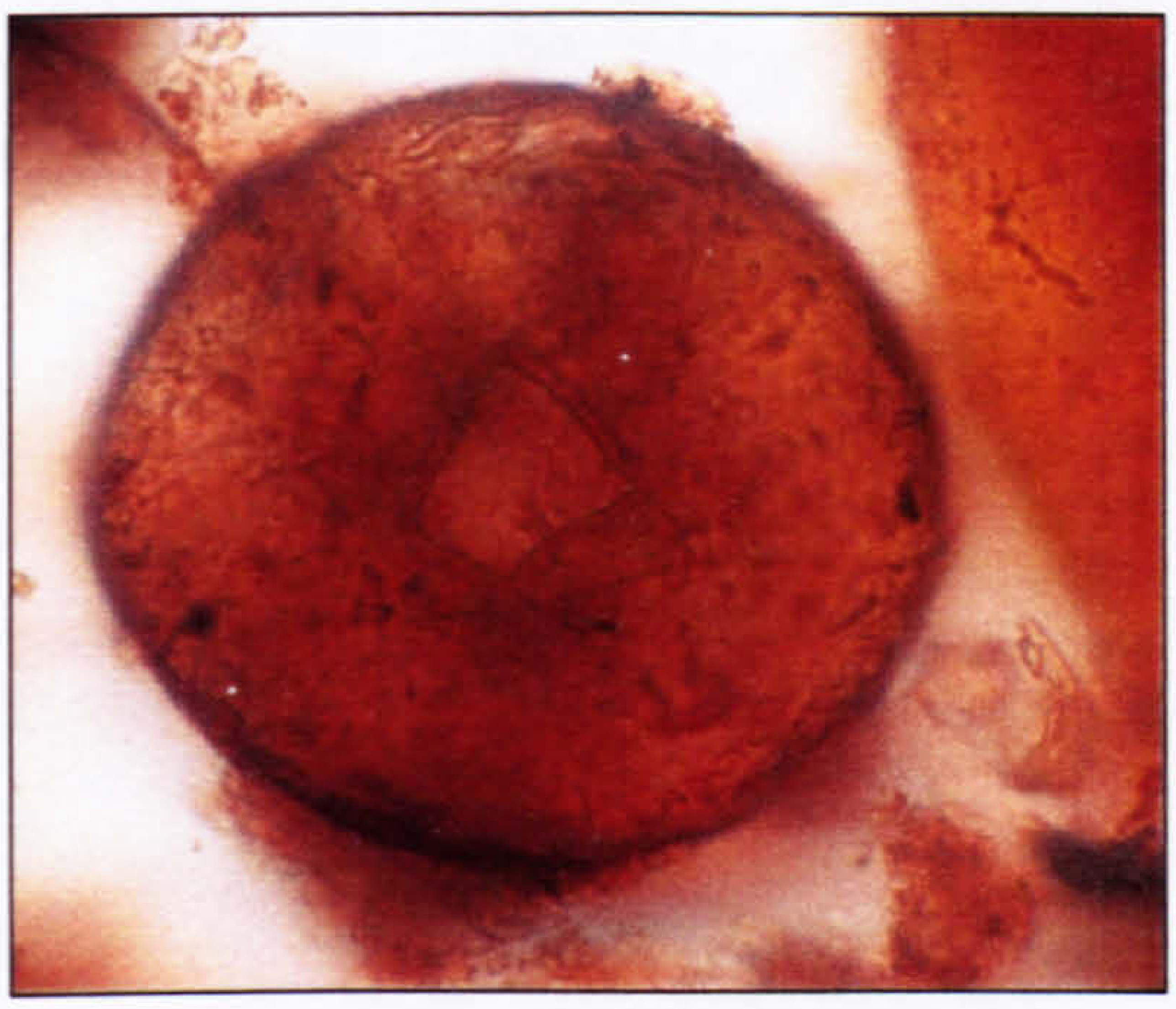


Plate 2.12. *Trigonopyxis arcula* (×400)

Detailed descriptions of the ecological preferences of these indicator-species are provided in the next chapter. Although a type collection was not available for identification purposes, texts containing plates of testate amoebae were extensively used (Corbet, 1973; Lee *et al.*, 1985; Ellison and Ogden, 1987), as was the identification key provided by Charman *et al.* (in press), which includes a comprehensive range of microphotographic images.

2.8 Chronology

2.8.1 Introduction

The establishment of an effective chronology is essential if reconstructed variations in mire surface wetness are to be matched either with established changes in regional climate or with synchronous variations recorded in other peat-based palaeoclimatic investigations. For this reason, the majority of proxy-climate studies utilise radiocarbon technology to date specific horizons in the peat profiles. However, problems can arise when attempting to use radiocarbon measurement to date more recent peat (i.e., above *c.* 50 cm depth) owing to possible contamination caused by, among others, burning of fossils fuels and the presence of 'bomb-carbon' derived from the detonation of thermonuclear devices. For these uppermost peats, it is possible to extend the radiocarbon chronology by applying a number of alternative dating techniques including spheroidal carbonaceous particle (SCP) analysis and Lead-210 (^{210}Pb) dating procedures.

2.8.2 Radiocarbon and AMS wiggle-match dating

Conventional radiocarbon dating involves extracting a bulk peat sample which is then measured using either gas proportional or liquid scintillation counting by a radiocarbon dating facility. An alternative approach, requiring only a fraction of the material and taking considerably less time to process is Accelerator Mass Spectrometer (AMS) dating. As well as having the advantage of being able to date selected components of the peat matrix, such as *Sphagnum* leaves or seeds, the ability to date narrow bands of core material enables the application of the wiggle-match dating (WMD) strategy (van Geel and Mook, 1989). Using this procedure, it is possible to match groups of AMS dates to natural ^{14}C variations, known as Suess wiggles, in the dendrochronological calibration curve, thereby improving the precision of each date.

2.8.2.1 Laboratory procedures

Effective wiggle-matching of AMS ^{14}C dated horizons to variations in the dendrochronological calibration curve requires groups of dates, spaced at regular intervals. It has been suggested that between 4 - 7 dates are required (van Geel and Mook, 1989; Pilcher, 1993) for an effective 'match'. In order to match separate Suess wiggles with the individual characteristics of each group, the time resolution of samples should be kept to a minimum, with each sample representing ≤ *c.* 25 yr (van Geel and Mook, 1989). Aaby and Tauber (1975) calculated average accumulation rates for north-west European bogs as being between *c.* 0.2 and 0.9 mm/yr (with younger, faster accumulated peat layers being up to 1.8 mm/yr), therefore ^{14}C dating should be carried out on 5 - 10 mm slices of peat. Following this rationale, 5 x 1 cm thick slices of peat (with a volume of *c.* 4 cm^3 each) were extracted at regular 5 cm intervals for each group. The position of each group of dates was determined by the presence of synchronous shifts in both the humification and macrofossil-derived curves, reflecting changes to either drier or wetter conditions. Wherever possible, rootlet material, fungal hyphae and other forms of detritus were removed, leaving only *Sphagnum* leaves. In areas of the profile containing high concentrations of *Eriophorum* with low, and in some cases, no trace of *Sphagnum* species, only monocotyledonous remains were singled out for dating. Following component selection, samples containing enough carbon (> 1 mg) were then submitted to NERC Radiocarbon Laboratory, East Kilbride, where they were pre-treated, chemically and/or physically to remove any unwanted material from each sample before being converted to carbon dioxide (by combustion) and then to graphite. After pre-treatment, samples were then forwarded to NFS Arizona AMS Facility, University of Arizona, for final ^{14}C analysis.

2.8.3 Spheroidal Carbonaceous Particle (SCP) Analysis

The analysis of spheroidal carbonaceous particles (SCPs) offers an extra degree of dating control, as it allows the relative dating of recent peat deposits. Formed from the high temperature combustion of fossil fuels, analysis of SCPs was originally applied to lake sediment studies by Griffin and Goldberg (1981), Renberg and Wik

(1985) and Rose *et al.* (1995), where it served to detect the onset of coal and oil burning in the various countries studied. This technique has since been applied to peatland investigations (Mauquoy, 1997; Barber *et al.*, 1999; Chambers *et al.*, 1999), where it has been found to be an equally effective dating tool. Used in studies of this nature, the varying concentration of fly-ash particles held in the uppermost section of peat (up to a depth of *c.* 32 cm) is assessed, as a means of detecting the onset of the Industrial Revolution. Rose *et al.* (1995) suggest that in the case of the UK, an initial rise in concentration of these soot particles signifies this historical event, dated at around the mid-nineteenth Century. Using ^{210}Pb dating and coal and oil consumption rates, they also suggest that peaks in SCP concentration are recorded at British sites, reflecting the period between 1950-1960 AD period, when there was a significant increase in fossil fuel combustion in this Country.

2.8.3.1 Preparation and analysis

The top section of each profile was initially sub-sampled at 1 cm continuous intervals, removing *c.* 4 cm^3 slices of material at each level. Starting from the surface, groups of eight samples were consecutively prepared for concentration assessment, using a variation of the experimental procedure developed by Rhodes (1996) (see Appendix 2), as used by Mauquoy (1997). Unlike the methodology developed by Rhodes, the 'simplified' technique applied here relies solely upon the use of concentrated nitric acid to remove organic material as, owing to the absence of siliceous material in the sediment, the use of hydrofluoric and hydrochloric acids was deemed unnecessary. This procedure was repeated until no further SCPs could be identified. Counting was carried out at × 400 magnification using a Nikon Optiphot-2 microscope, where diameters of the SCPs ranged from 5 - 30 μm. SCP concentrations are expressed as per gram dry mass of sediment (g DM^{-1}).

2.8.4 Lead-210 dating

Unlike lake sediments, ombrotrophic peatlands record both particulate and soluble fluxes, and are not complicated by processes in the catchment or by mineral particle influx from the catchment (Clymo *et al.*, 1990). This enables them to record changes in rates of deposition of atmospheric fluxes, such as ^{210}Pb. ^{210}Pb is one of a series of unstable daughter nuclides, derived from radon gas (^{222}Rn) as a result of radioactive decay. Dating is based on determination of the vertical distribution of ^{210}Pb derived from atmospheric fallout (termed unsupported ^{210}Pb, or ^{210}Pb$_{excess}$), and the known decay rate of ^{210}Pb (Appleby and Oldfield, 1992). By measuring the concentration levels of ^{210}Pb in the uppermost sections of cores from Bolton Fell Moss and Mynydd Llangatwg, and comparing these fluctuations with an established model, known as the 'constant flux constant sedimentation rate' model, or the 'simple' model (Robbins, 1978), a relative accumulation rate can be determined. These ^{210}Pb-based chronologies were also used to support results obtained through SCP analysis, as both techniques were carried out at directly comparable depths.

2.8.4.1 Laboratory procedures

Samples of 1 cm thickness, with a volume of *c.* 10 cm^3, were extracted at regular 3 cm intervals to a depth of 28.5 cm for Core's Bolton Fell Moss, BFM/3 and Mynydd Llangatwg, MLA/2. Owing to an appreciable level of ^{210}Pb still being present at 28.5 cm, an extra two samples were dated from Core Bolton Fell Moss, BFM/MC at 34.5 and 40.5 cm. Following drying in an oven at 50°C, samples were sent to Dr Andy Cundy at Southampton Oceanography Centre to be processed. Sediment accretion rates were determined using the 'simple' model of ^{210}Pb dating (Robbins, 1978), where the sedimentation rate is given by the slope of the least squares fit for the natural log of the ^{210}Pb$_{excess}$ activity versus depth.

Chapter 3 Results

3.1 Introduction

The results chapter is structured in the following way. The opening section serves as an aid to interpretation of the diagrams, with descriptions of the preferred ecological niches of each of the components and, in terms of the testate species, previously documented depths to water table.

The next section presents the results of each of the analysis techniques, in a site-by-site format, providing site descriptions and interpretations of each of the datasets against depth. As a means of segregating the data into manageable sections, macrofossil/testate amoebae diagrams have been zoned on the basis of significant changes in vegetational assemblage.

The final section details the development of an effective chronology for each of the sites investigated, involving calibration of radiocarbon determinations, the application of wiggle-match dating, and interpretations of ^{210}Pb and SCP chronologies.

3.2 Components of the diagrams

3.2.1 Peat Humification

The degree of peat humification is directly related to the extent of decomposition of plant material which, in turn, is linked to surface wetness at time of deposition (Aaby and Tauber, 1975). As peat decomposition progresses, the proportion of humic material increases, leading to a darkening in colour of the solution. Measurement of this change in colour is achieved through colorimetric analysis, where higher values of absorbance reflect more humified peat and, by inference, drier conditions.

The extent of decomposition is dependent on the position of the water-table over the transition period, when sub-fossil peat passes from the biologically active acrotelm into the catotelm. At times of increased water levels, under regimes of high effective precipitation, rates of decomposition are comparatively slow (Ingram, 1982).

3.2.2 Macrofossil components

3.2.2.1 Unidentified organic matter (UOM)

This component consists of vegetative fragments from a wide range of sources and lacks any visible structure. In their examination of biomarkers in ombrotrophic peat, Ficken *et al.* (1998) suggest that lichens may make a greater contribution to UOM than is indicated by macrofossil analysis due to their rapid breakdown in peat. The presence of UOM is generally taken to represent well-humified conditions, reflecting higher rates of decomposition, and by inference a drier climate.

3.2.2.2 Ericaceous remains

These include Ericales, *Calluna vulgaris*, *Erica tetralix* and *Vaccinium oxycoccus*. Ericales are the fine rootlets and woody remains of a range of dwarf shrubs, most likely including one or more of the following species: *Calluna vulgaris*, *Erica tetralix*, *Vaccinium oxycoccus*, *Vaccinium myrtillus*, *Empetrum nigrum*.

Calluna vulgaris has been found to have a distinct hydrological distribution on mires, primarily favouring hummock tops (Wallen, 1987). Casparie (1972), however, stresses that although *C. vulgaris* favours a dry bog surface, its presence alone cannot be taken as an indicator of a change to drier conditions.

Having a greater tolerance to wetter conditions than *Calluna vulgaris*, *Erica tetralix* generally occupies lower hummocks and upper lawn microforms. Van der Molen and Hoekstra (1988) found it coexisting with *Sphagnum papillosum* and *Rhynchospora alba*, confirming its ability to withstand slightly wetter growing conditions.

The presence of *Vaccinium oxycoccus* has been linked to wet, *Sphagnum*-rich margins around deep watershed pools (Lindsay *et al.*, 1988), whereas *Vaccinium myrtillus* reflects relatively drier conditions.

3.2.2.3 Monocotyledons undifferentiated (Monocots. undiff.)

In the absence of identifiable epidermal tissue, monocotyledonous material, consisting of stems, rhizomes and roots were simply represented as monocotyledonous undifferentiated (Monocots. undiff.).

3.2.2.4 Eriophorum vaginatum

Although mainly found on hummocks, *Eriophorum vaginatum* can be found over a wide range of hydrological conditions (Wein, 1973), however, dominance is often attained in peat communities that have a surface water-table level in the spring, but become drier in the summer (Tansley, 1939). The fibrous nature of *E. vaginatum* tussocks enable this species to withstand a range of potentially hazardous conditions including very cold temperatures, strongly fluctuating water levels and fire. The deep roots and high moisture-holding ability of this species provide protection from drought; indeed, *E. vaginatum* often becomes more luxuriant and tussocky as the bog dries out (Wein, 1973). Studies carried out by Casparie (1972) reflect the tolerance of this species, where it was found to occupy both highly and less humified layers of peat. However, when found to be growing in conjunction with *C. vulgaris*, it is confirmed as an indicator of drier conditions (Barber, 1981; Casparie, 1972; Walker and Walker, 1961). It is clear from the above studies that although the presence of *E. vaginatum* may reflect a drier climate, further supporting evidence is required from associated species in the assemblage.

3.2.2.5 Eriophorum angustifolium

The parameters of this sedge are considerably more well-defined. Studies carried out by Haslam (1987) revealed that the presence of *E. angustifolium* consistently indicated high mire surface wetness, confirmed by low colorimetric humification absorbance values and the presence of hygrophilous rhizopods. Having a tolerance to a range of soil moisture conditions, this species can be found to dominate in permanent shallow pools or in dried-up hollow bottoms (Phillips, 1954). Despite omitting the presence of *E. angustifolium* from his diagrams, Barber (1981) records its presence in conjunction with *Sphagnum cuspidatum*, a species commonly found growing in pools. The sub-fossil presence of this sedge can therefore be taken to represent relatively high mire water levels.

3.2.2.6 Rhynchospora alba

Rhynchospora alba is a good indicator of an elevated mire water tables as it grows in low lawns and at pool margins (Godwin and Conway, 1939). From their assessment of peatlands around Caithness and Sutherland, Lindsay *et al.* (1988) record the presence of this sedge on low ridges, where it is often associated with *Sphagnum papillosum*, or in hollows just below the water table. Rodwell *et al.* (1991) describes the position of *Rhynchospora alba* as being confined between low lawns and the shallower water around pool margins, from where it may be found to extend across smaller mire pools.

3.2.2.7 Trichophorum cespitosum (syn. *Scirpus cespitosus*)

Rodwell *et al.* (1991) describe this densely tufted sedge, also known as *Scirpus cespitosus*, as a lawn species, tolerant of surface-waterlogging. However, fragments of *Trichophorum cespitosum* were identified by Haslam (1987) in both wet lawn and dry hummock environments. Owing to its varied habitats, the indicator value of this species is difficult to ascertain and so other evidence would be required in any surface wetness reconstruction.

3.2.2.8 Aulacomnium palustre

This non-*Sphagnum* bryophyte appears to be able to tolerate a range of different bog conditions, although when associated with *Polytrichum* and *Sphagnum* species, it is most likely an indicator of wetter conditions (Smith, 1990).

3.2.2.9 Odontoschisma sphagni

Usually, but not invariably associated with *Sphagnum* species, this liverwort is a good indicator of elevated mire water tables as it occurs in low lawns and at pool margins (Watson, 1981).

3.2.2.10 Hypnum cupressiforme

As part of their studies of Tregaron Bog, Wales, Godwin and Conway (1939) found this species to be associated with *Calluna* hummocks, suggesting a growth preference for drier conditions. However, van der Molen *et al.* (1994) record *Hypnum cupressiforme* as a slope species, grouping it with *Sphagnum papillosum*, *S. magellanicum* and *S. capillifolium*. Once again, further evidence would be needed to derive an indication of surface wetness based on the presence of this species.

3.2.2.11 Polytrichum juniperum/alpestre

Although it is difficult to distinguish between these two species in the sub-fossil form, both varieties are characteristically found in drier areas of the bog surface, with *Polytrichum juniperum* growing on well drained acidic soils on heaths and moors (Smith, 1980) and *Polytrichum alpestre* favouring drier microsites, since it forms dense tussocks on ombrogenous bogs (Dickson, 1973).

3.2.2.12 *Sphagnum imbricatum*

Although typically a hummock-forming component of modern-day peat bogs, various palaeoecological studies have indicated that this species may have occupied a much broader range in the past. In Europe two sub-species are found and, according to Stoneman *et al.* (1993), any *Sphagnum imbricatum* found on ombrotrophic mires is likely to be the sub-species *austinii*. Investigations carried out by Barber (1981) at Bolton Fell Moss revealed that *S. imbricatum* also formed lawn microforms, while van der Molen and Hoekstra (1988) found it to be present in both hummock and hollows, although more particularly associated with hummocks. In his investigation of bogs on a transect from Ireland to Poland, Haslam (1987) suggests a preference of this species as a low hummock-former. Casparie (1972) describes a transition from highly humified to fresher *Sphagnum* peat, which is marked by large increases in hygrophilous rhizopods (*Amphitrema flavum* and *A. wrightianum*), and the coeval appearance of *Sphagnum papillosum* and *S. imbricatum* in south-eastern Drenthe, The Netherlands. There is, therefore, a problem when attempting to make hydroclimatic reconstructions from the presence of this species, since it appears to have had the ability to grow over a range of mire water levels in the past. In addition to this, it is now absent from many north-west European mires, and so there are fewer analogues in the modern flora on which to base comparative studies.

3.2.2.13 *Sphagnum* section Acutifolia

Although difficult to identify leaves to species level, all species of this section are generally found in drier parts of peat bogs, forming small hummocks or lawn-type microforms (Daniels and Eddy, 1990). The driest species are *Sphagnum fuscum* and *Sphagnum capillifolium* var. *rubellum*, which are characteristically found to form hummocks. Other varieties include *Sphagnum molle* and *Sphagnum subnitens*, which are commonly found on lawns (Daniels and Eddy, 1990). Dupont (1986) interpreted the presence of section Acutifolia leaves and *Calluna vulgaris* as signalling drier mire surfaces. It is clear that any reconstruction of mire surface wetness based upon the presence of leaves from this section must be supported by other alternative proxy evidence.

3.2.2.14 Sphagnum papillosum

Common and widely distributed, this species grows in distinct hummocks or carpets, where it is often the principal peat former (Daniels and Eddy, 1990). Godwin and Conway (1939) found this bryophyte growing in lawn microtopes on Tregaron West bog, while in his study of a raised bog in the former Bourtanger Moor, the Netherlands, Casparie (1993) reconstructed its presence in wet hollows. Under laboratory conditions, Li *et al.* (1992) found *S. papillosum* to occupy lower positions and to be a better drought tolerator than *S. magellanicum.* Although this species is tolerant of a range of different ecological niches, it seems to favour lawns.

3.2.2.15 Sphagnum magellanicum

Daniels and Eddy (1990) record *Sphagnum magellanicum* in common association with *S. papillosum* and *S. capillifolium,* where it forms carpets or low hummocks. Li *et al.* (1992) found this species to be a superior competitor for water to *S. papillosum* under dry conditions, where growing as hummocks, it is an effective 'drought-avoider'. This species is a useful indicator of low hummock microforms.

3.2.2.16 *Sphagnum* section Cuspidata

The majority of species in this section are found in the consistently wet areas of bogs, favouring low lawn to pool ecotopes (Daniels and Eddy, 1990), and are therefore effective indicators of elevated mire water levels.

3.2.2.17 Charcoal

The presence of macro-scale fragments of charocal in the peat matrix has been taken as evidence of fire, either on the surface of the mire or within the local area. However, without corroborating evidence from other characteristically dry indicators, recording of charcoal should not necessarily be taken as evidence of drier conditions.

3.2.3 Testate Amoebae Components

Classifications of testate amoebae are based on the small-scale moisture requirements of certain species. De Gaff (1956, pp. Tolonen, 1986) was able to define three distinct groups by correlating the distribution of these species to specific wetness habitats (Corbet, 1973):

Hydrophiles: testate amoebae that inhabit plants constantly submerged in water. These species are not limited to the water film on *Sphagnum* leaves.

Hygrophiles: species are found in moist plants and are less likely to suffer from desiccation. They normally inhabit water film.

Xerophiles: testate amoebae that typically occupy relatively dry habitats and are able to withstand desiccation, usually by encysting.

3.2.3.1 Amphitrema wrightianum

Amphitrema wrightianum is a particularly effective hydrophilous indicator, as it is most commonly found in bog pools (Heal, 1961; van der Molen and Hoekstra, 1988). Woodland *et al.* (1998) assign an optimal mean water table depth of 3.5 cm for this species.

3.2.3.2 Amphitrema flavum

This is another typical hydrophilous species, commonly found in *Sphagnum* bogs, particularly in the wetter parts of hummocks (Corbet, 1973). Through analysis of surface moss samples and measurements of depth to the local water table, Charman and Warner (1992), Tolonen *et al.* (1992, 1994) and Warner and Charman (1994) all record consistent preferences to high moisture conditions for this species. Woodland *et al.* (1998) assign an optimal mean water table depth of 4.6 cm for this species.

3.2.3.3 Assulina muscorum

This species appears to occupy a mid-range position relative to the water table and is therefore often referred to as a hydro-xerophilous species. In their assessment of testate relationships to microenvironmental parameters, Charman and Warner (1992) assign a mid-range score to this species, as it has no preference to a particular range of moisture conditions. In contrast, van der Molen and Hoekstra (1988) assigned a relatively high weight to this species, suggesting a preference for drier conditions. Woodland *et al.* (1998) assign an optimal mean water table depth of 6.8 cm for this species.

3.2.3.4 Trigonopyxis arcula

Trigonopyxis arcula is a typical xerophilous species which Tolonen *et al.* (1994) record as being a good indicator of dry habitats. Woodland *et al.* (1998) assign an optimal mean water table depth of 7.9 cm for this species.

3.2.3.5 Hyalosphenia subflava

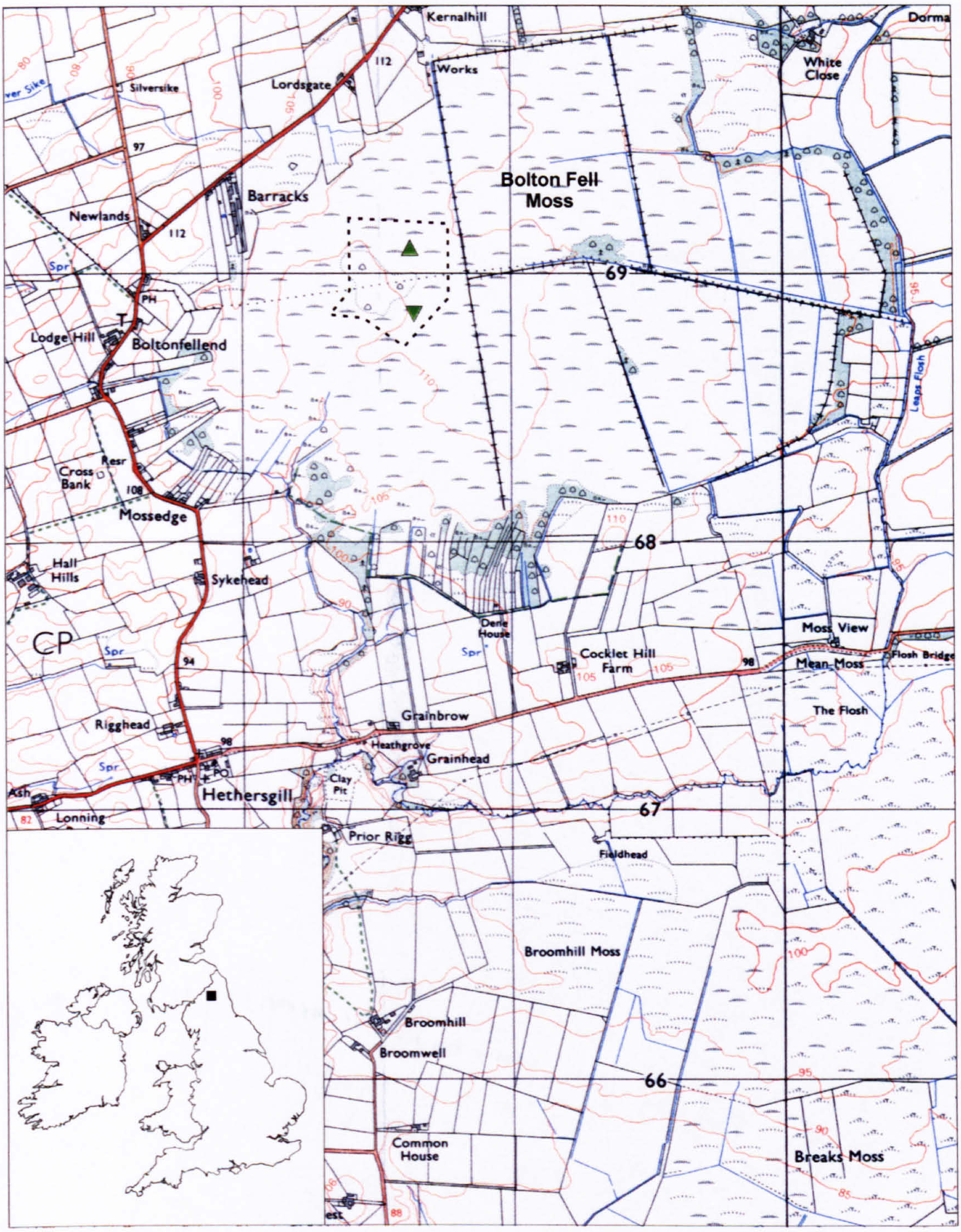
Hyalosphenia subflava is another xerophilous species and thereby an effective indicator of dry conditions (Beyans, 1985; Mitchell *et al.*, 2000; Tolonen, 1986; Warner, 1987). Through studies of mires in southern Finland, Tolonen *et al.* (1992) found this species to be present in a low *Sphagnum fuscum* hummock and later, using multivariate analysis, considered *H. subflava* to be critical in the identification of dry conditions, being restricted to the very lowest moisture levels and drained peatlands (Tolonen *et al.*, 1994). Woodland *et al.* (1998) assign an optimal mean water table depth of 8.8 cm for this species.

3.3 Bolton Fell Moss (BFM) - NY 495 695

3.3.1 Site Description

This is a large ombrotrophic raised mire (originally covering an area of 365 ha), situated just north-west of Hethersgill, in northern Cumbria (Figure 3.1; Plate 3.1). Ever since the late 1960s, this site has been heavily exploited by the horticultural industry through the use of large-scale peat-cutting machines. There does however remain a considerable reserve area towards the north-west of the site, where several proxy-climate studies have been carried out (e.g., Barber, 1981; Haslam, 1987; Stoneman, 1993; Mauqouy, 1997). The surface vegetation is primarily composed of *Sphagnum magellanicum* with *Sphagnum capillifolium* var. *rubellum*, *Eriophorum angustifolium*, *Eriophorum vaginatum* and *Calluna vulgaris* (Barber, 1981). Two cores, Core MC and Core 3, were extracted from the reserve area, approximately 150 m apart, with Core MC being taken near the perimeter of the bog while Core 3 was more centrally located.

Climate monitoring facilities at Carlisle, *c.* 16 km south-west of the site, record strongly oceanic conditions for this region, with a mean annual temperature of 9.5°C and average precipitation of 825 mm (Barber *et al.*, 1994c). Relative humidity has been found to average *c.* 85% over the year, generating a moist environment with a long effective growing season (Haslam, 1987).



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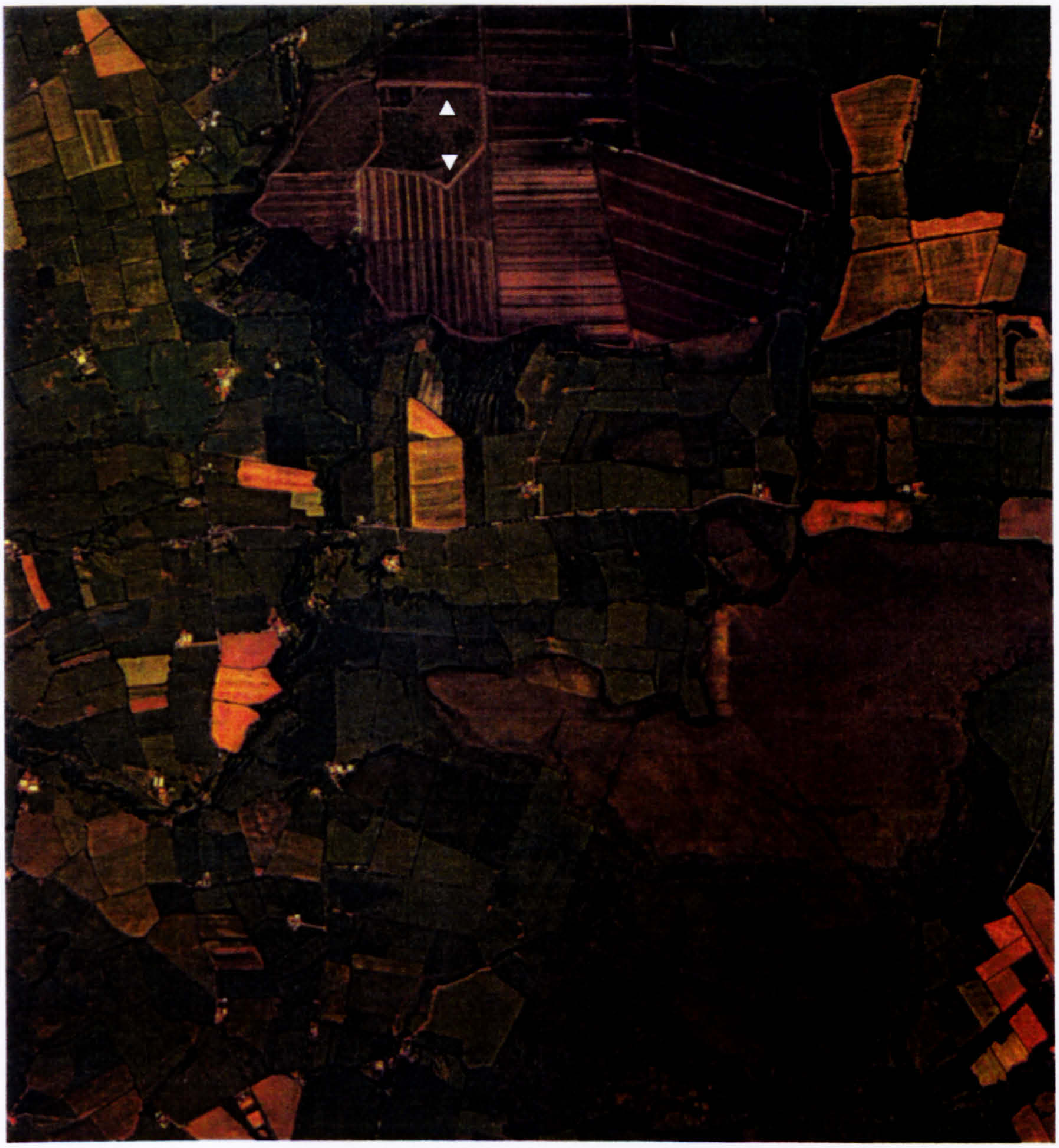
Borehole locations: ▲ - Core MC - - - - - - Reserve area

▼ - Core 3

Figure 3.1 Map showing location of Bolton Fell Moss with borehole positions

Plate 3.1. Aerial photograph of Bolton Fell Moss (to the north) and nearby Walton Moss (Scale 1:10000)



Borehole locations: △ - Core MC
▽ - Core 3

3.3.2 Humification Results - Bolton Fell Moss - Core MC

Overall, there appears to be considerable variation in the humification absorbance record for this core (Figure 3.2). There is a sustained period of generally low absorbance residuals, reflecting wetter conditions, between *c.* 120-65 cm depth, although within this phase, significant fluctuations have occurred. Low residual values are also recorded at *c.* 140, 85 cm and *c.* 65 cm depth. The low readings in the upper layers (up to a depth of *c.* 20 cm) most likely reflects the presence of recent root material, while the higher values from *c.* 25 cm depth may delimit the acrotelm-catotelm boundary (Blackford and Chambers, 1993). The driest conditions, reflected by pronounced peaks in absorbance residuals, occur at the base of the core between *c.* 245-235 cm, while other dry phases can be suggested as occurring between *c.* 205-150, 55-25 cm and at *c.* 75 cm depth.

3.3.3 Macrofossil/testate Amoebae Results - Bolton Fell Moss - Core MC

Macrofossil and testate amoebae results for Bolton Fell Moss - Core MC are shown in Figure 3.3. The diagram is divided into six zones (a-f), based on major changes in vegetational assemblage of the mire flora.

Zone BFM/MC-a (255 - 225 cm): High proportions of *Sphagnum* section Cuspidata and *Amphitrema wrightianum* are sustained throughout this zone, reflecting increased wetness, where pools are most likely forming on the surface of the mire. This is briefly interrupted by a peak in *Sphagnum papillosum*, suggesting low-ridge conditions at *c.* 250 cm depth. Following this period, *S.* s. Cuspidata returns to dominance and, combined with *Eriophorum angustifolium* and *Rhynchospora alba* epidermal remains, signifies a sustained period of elevated mire water levels within this zone.

Zone BFM/MC-b (225 - 168 cm): S. s. Cuspidata *and S. papillosum* continue to dominate the flora in this zone, alternating in dominance, and once again reflecting periods of increased surface wetness interspersed with drier, possibly low- to high-ridge conditions, respectively. Sub-fossil *Sphagnum imbricatum* is also marginally represented, with peaks coinciding with increases in *S. papillosum* leaves. *Sphagnum* section Acutifolia also joins the assemblage from the base of this zone, with a pronounced rise between *c.* 220-212 cm coinciding with a rise in *Aulacomnium palustre*, most likely reflecting a drier phase. Proportions of *Assulina muscorum*, a mid-range water level species, are also seen to rise throughout this zone, suggesting drier conditions than those recorded in zone BFM/MC-a.

Zone BFM/MC - c (168 - 126 cm): The base of this zone displays a rapid decline in proportions of *S.* section Cuspidata, *S. papillosum* and *A. wrightianum*, which coincides with a rise to dominance of *S.* s. Acutifolia. This 85% peak in *S.* s. Acutifolia coincides with an increase in *Calluna vulgaris* leaves and a brief rise in *S. imbricatum* at 163 cm depth, reflecting a shift to drier conditions, most likely forming a high-ridge or hummock microform. This is then followed by a temporary shift to wetter conditions at 150 cm, once again signified by rises in *S.* s. Cuspidata, *S. papillosum* and *E. angustifolium*. This wet period is interrupted by a rapid reversion to dominant *S.* s. Acutifolia, accompanied by the presence of *Eriophorum vaginatum* epidermis and *E. tetralix* leaves, suggesting yet another rapid shift to rather drier conditions. However, these conditions are not sustained, as *S.* s. Cuspidata and *S. papillosum* regain their dominance for the remainder of this zone.

Zone BFM/MC - d (126 - 70 cm): S. s. Acutifolia and *S. imbricatum* regain dominance at the base of this zone, although small proportions of *S. papillosum* are still recorded, as are fragments of *E. angustifolium* epidermis, suggesting a low-ridge to hollow community. From 120 cm depth *S. imbricatum* and *S. papillosum* are no longer represented, while the *S.* s. Cuspidata/*A. wrightianum* assemblage and *S.* s. Acutifolia are found to alternate in dominance for the remainder of the zone. *Sphagnum magellanicum* also joins the assemblage in this zone, with fluctuating proportions below 20%, broadly corresponding to levels of *S.* s. Acutifolia. A marked decrease in Sphagna representation at 98 cm is associated with peaks in *E. angustifolium* epidermis, Monocots. undiff. and, surprisingly, *A. muscorum*, most likely reflecting a rapid influx of water at this level.

Zone BFM/MC - e (70 - 30 cm): There is a significant increase in proportions of *S. magellanicum* at the bottom of this zone. *S.* s. Cuspidata remains marginally represented until 60 cm depth, where its decline is associated with the presence of *Trichophorum cespitosum* epidermis. This most likely signifies a shift to rather drier conditions, and is supported by the increasing representation of Ericales. The dominance of *S. magellanicum* is sustained until 45 cm depth, where there are corresponding peaks in *S.* s. Acutifolia and *S. papillosum* and a significant rise in charcoal. Dominance of *S. magellanicum* is regained for the remainder of this zone, which is accompanied by high levels of Ericales, UOM and xerophilous testate amoebae species and the reappearance of *S.* s. Acutifolia, indicating a move to much drier conditions.

Zone BFM/MC - f (30 - 0 cm): S. s. Acutifolia takes over as the dominant peat-former at the base of this zone, coinciding with a rapid drop in *S. magellanicum* representation and peaks in concentration of Ericales and UOM. This major change in vegetation assemblage may reflect the catotelm-acrotelm boundary. Proportions of *A. wrightianum* and *A. flavum* are seen to diminish in this zone, while traces of *Hyalosphenia subflava*, a typically dry indicator, are found to coincide with rises in charcoal. *Vaccinium myrtillus* joins the assemblage from *c.* 7 cm depth, with a steady increase in representation right up to the upper layers, where, associated with high proportions of *S.* s. Acutifolia, it reflects the relatively dry conditions of this part of the bog.

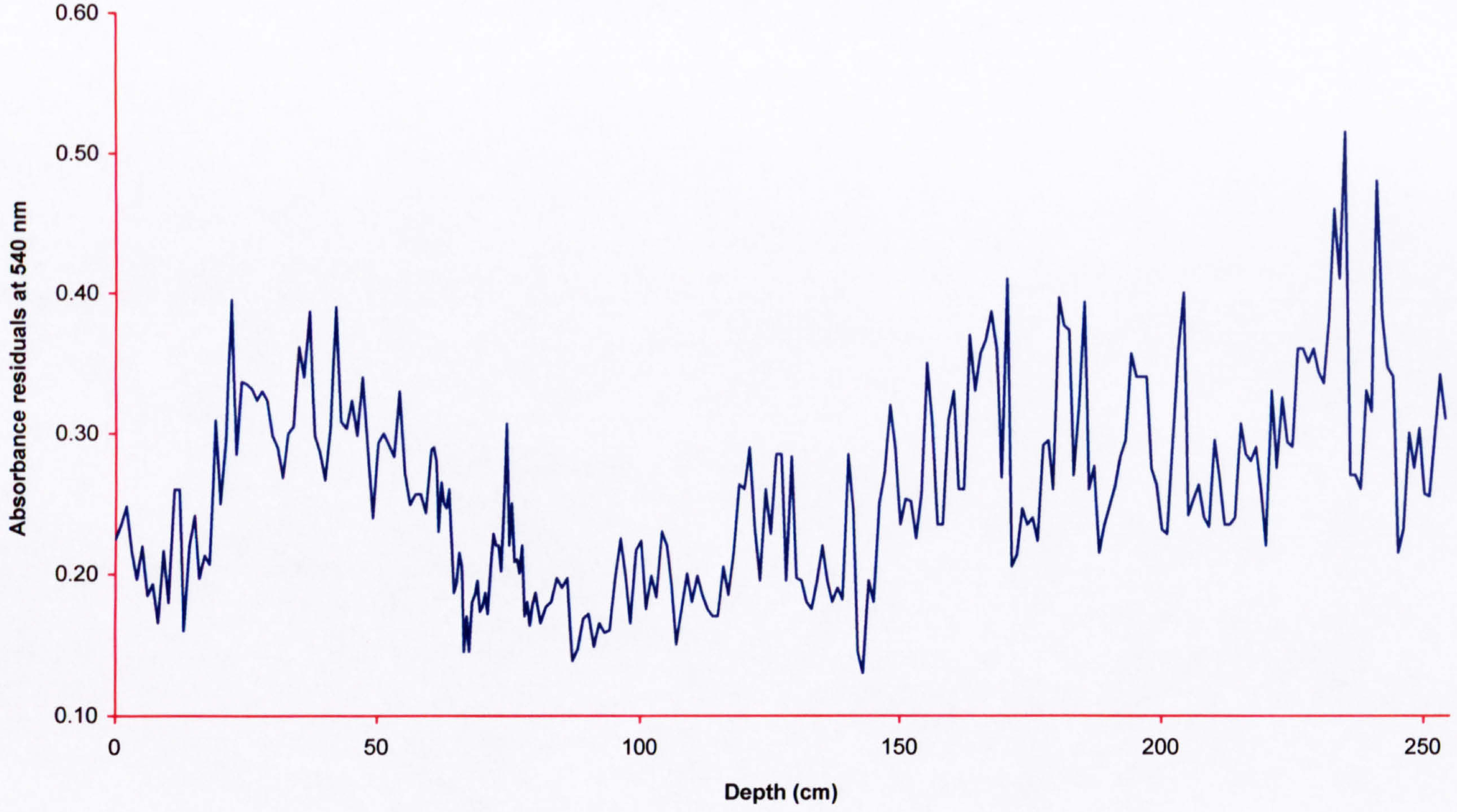


Figure 3.2 Humification absorbance values for Bolton Fell Moss - Core MC

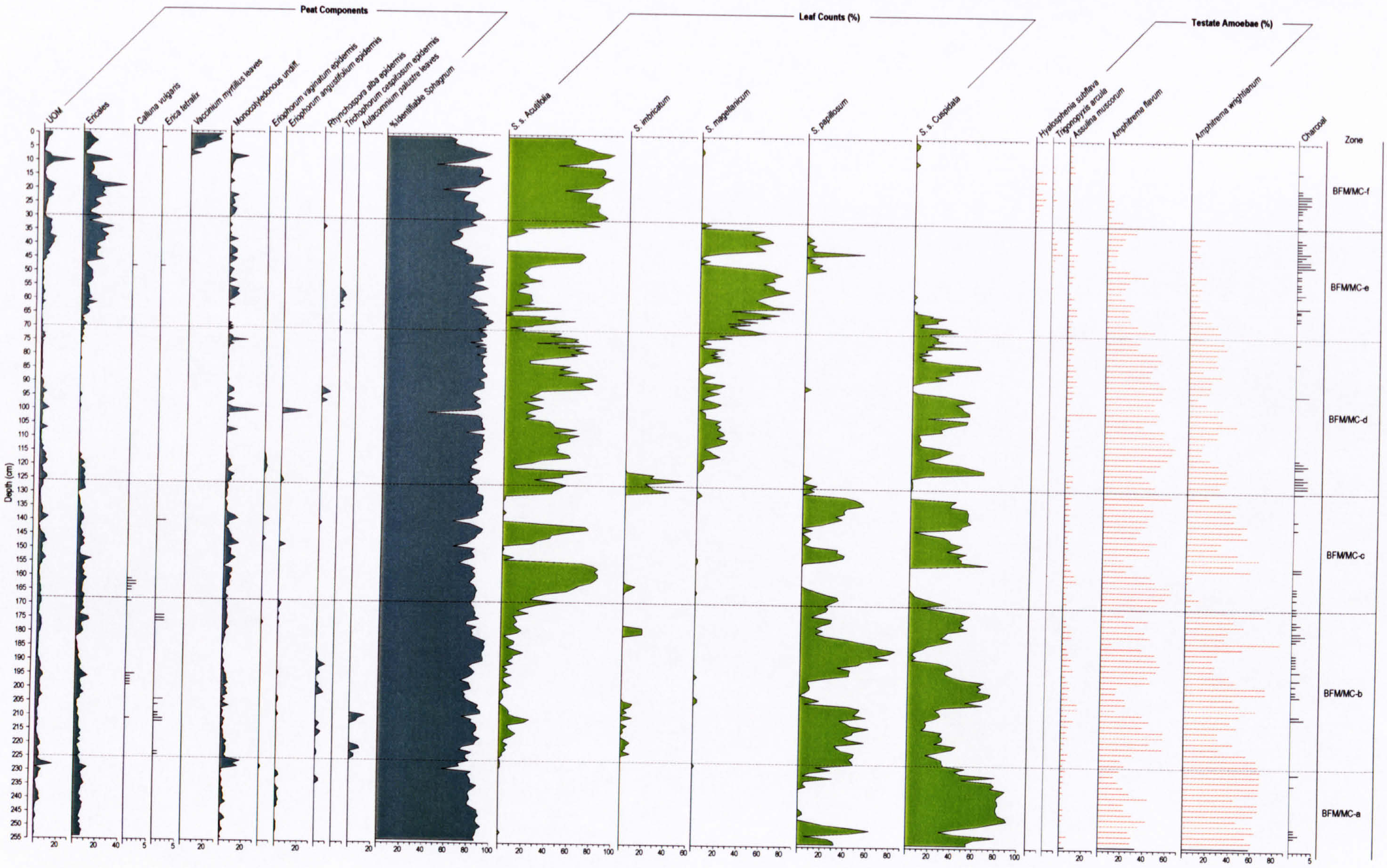


Figure 3.3 Macrofossil diagram for Bolton Fell Moss - Core MC

3.3.4 Humification Results - Bolton Fell Moss - Core 3

As with Core MC, there is considerable variation in the humification record for this core (Figure 3.4). Pronounced lows, reflecting wetter conditions, are found between *c.* 245-225, 140-105 cm and *c.* 60-45 cm depth, while high levels of absorbance can be identified between *c.* 225-205, 170-140 cm and *c.* 45-10 cm depth, reflecting drier periods. As with Core MC, the abrupt drop in absorbance residuals recorded at the top of the core most likely reflects the presence of fresh, unhumified rootlet material.

3.3.5 Macrofossil Results - Bolton Fell Moss - Core 3

Plant macrofossil data is presented diagrammatically in Figure 3.5. As with Core MC, this diagram has also been divided into six zones (a-f).

Zone BFM/3 - a (255 - 215 cm): The dominance of *S. imbricatum* at the base of this zone is briefly interrupted at *c.* 250 cm depth by increases in UOM, Ericales, *C. vulgaris*, *E. tetralix*, Monocots. undiff. and charcoal, suggesting a rapid shift to drier conditions, possibly as a result of a fire event. Dominance of *S. imbricatum* is regained by *c.* 245 cm, which also signals the inclusion of *S.* s. Acutifolia into the assemblage. Traces of *S.* s. Cuspidata leaves can also be found from this level, although not in significant quantities until *c.* 240 cm. Peaks in *S.* s. Cuspidata are found to coincide with rises in proportions of *Rhynchospora alba* and *Trichophorum cespitosum* epidermis, indicating wetter conditions. Unfortunately, there is a break in the record from *c.* 225 cm to the top of this zone, owing to damage caused to this section of the core during storage.

Zone BFM/3 - b (215 - 165 cm): Once again there is a drop in *Sphagnum* representation at the base of this zone, coinciding with increased proportions of UOM, Ericales, Monocots. undiff. and charcoal, although on this occasion high levels of *E. vaginatum* epidermis also recorded. Without the presence of wetter indicators, this can confidently be interpreted as a rapid shift to drier conditions. *S. imbricatum* regains dominance shortly after this period. Proportions of *S.* s.

Cuspidata are also found to increase in this zone, with dominant phases coinciding with high levels of *E. angustifolium* and/or *R. alba* epidermis, implying rapid shifts to wetter conditions.

Zone BFM/3 - c (165 - 120 cm): The most striking feature of this zone is the rapid extinction of *S. imbricatum*, associated with a distinct wet phase demonstrated by peaks in *S.* s. Cuspidata, *E. angustifolium* and *R. alba* epidermis at *c.* 140 cm depth. This is a common signature of previous vegetational reconstructions from this site (e.g., Barber, 1981; Stoneman *et al.*, 1993; Mauquoy, 1997), although often occurring at a shallower depth. Further evidence for a sudden shift to wetter conditions is provided by a rapid decrease in proportions of UOM, Ericales and *C. vulgaris* at this level. Following the peak in *S.* s. Cuspidata leaves at *c.* 135 cm, peaks in *S. papillosum* are recorded until *S. magellanicum* takes over as the dominant peat-former at *c.* 127 cm depth.

Zone BFM/3 - d (120 - 75 cm): S. magellanicum sustains its dominance for the majority of this zone, with a stepwise increase of inter-dispersed 20-50% peaks of *S.* s. Cuspidata occurring throughout, possibly forming a low-ridge microform near to a pool margin. A significant drop in proportions of *S. magellanicum* at *c.* 85 cm, preceded by high levels of *C. vulgaris* and charcoal, occurs synchronously with a 65% peak in *S.* s. Cuspidata. This sequence most likely reflects a local fire event, followed by wetter conditions, which is supported by the presence of *S. papillosum* leaves. Rises in Ericales and *S.* s. Acutifolia at the top of this zone suggest a shift to drier, possibly low hummock conditions.

Zone BFM/3 - e (75 - 40 cm): Levels of *S. papillosum* fall at the base of this zone, while an increase in *S.* s. Acutifolia leaves corresponds to an increase in representation of Ericales and Monocots. undiff., reflecting sustained drier conditions. A shift to low hummock formation is then suggested by a drop in levels of *S.* s. Acutifolia, Ericales and Monocots. undiff. at *c.* 65 cm, and the re-establishment of *S. magellanicum* as the dominant peat-former. This is then followed by a steady rise in proportions of *S.* s. Cuspidata to the top of the zone, and a moderate peak in *S.* s. Acutifolia at *c.* 48 cm associated with a few *Polytrichum juniperum/alpestre* leaves.

Zone BFM/3 - f (40 - 0 cm): While levels of *S.* s. Cuspidata and *S. magellanicum* begin to decline at the base of this zone, there is a rise in *E. vaginatum* epidermis and spindles, peaking at *c.* 17 cm and corresponding with increases in UOM and Ericales, suggesting a short-lived dry phase. Just preceding this dry shift is a brief peak in *S. papillosum* leaves, most likely unable to compete with the drier conditions. A rise in charcoal counts beginning at *c.* 25 cm, culminates in a drop in *Sphagnum* levels and a rise in *P. juniperum/alpestre*, reflecting a possible fire. Wetter conditions prevail in the surface layers of peat, signalled by the presence of *Odontoshisma sphagni*, *Erica tetralix* and a rise in *S. magellanicum.*

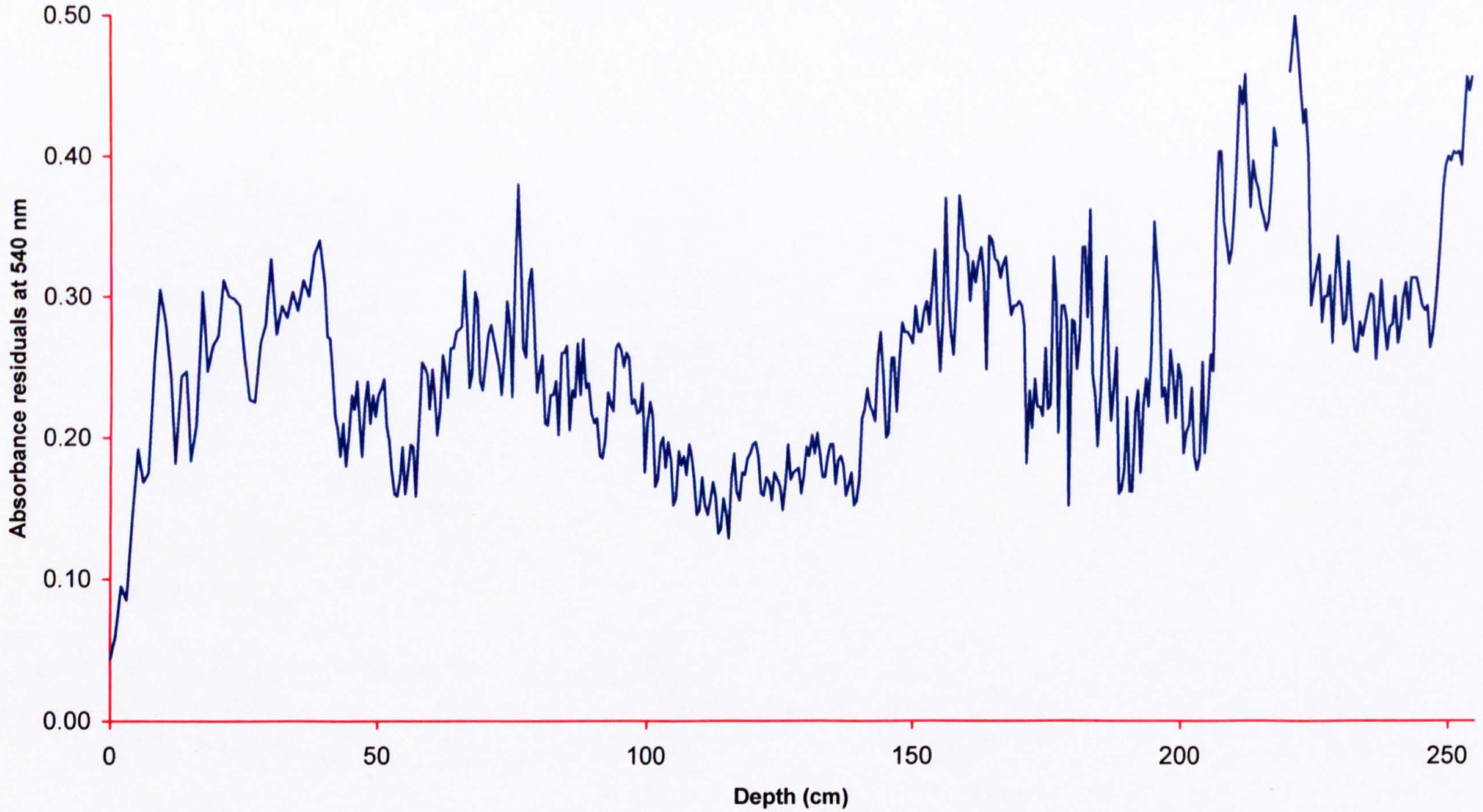


Figure 3.4 Humification absorbance values for Bolton Fell Moss - Core 3

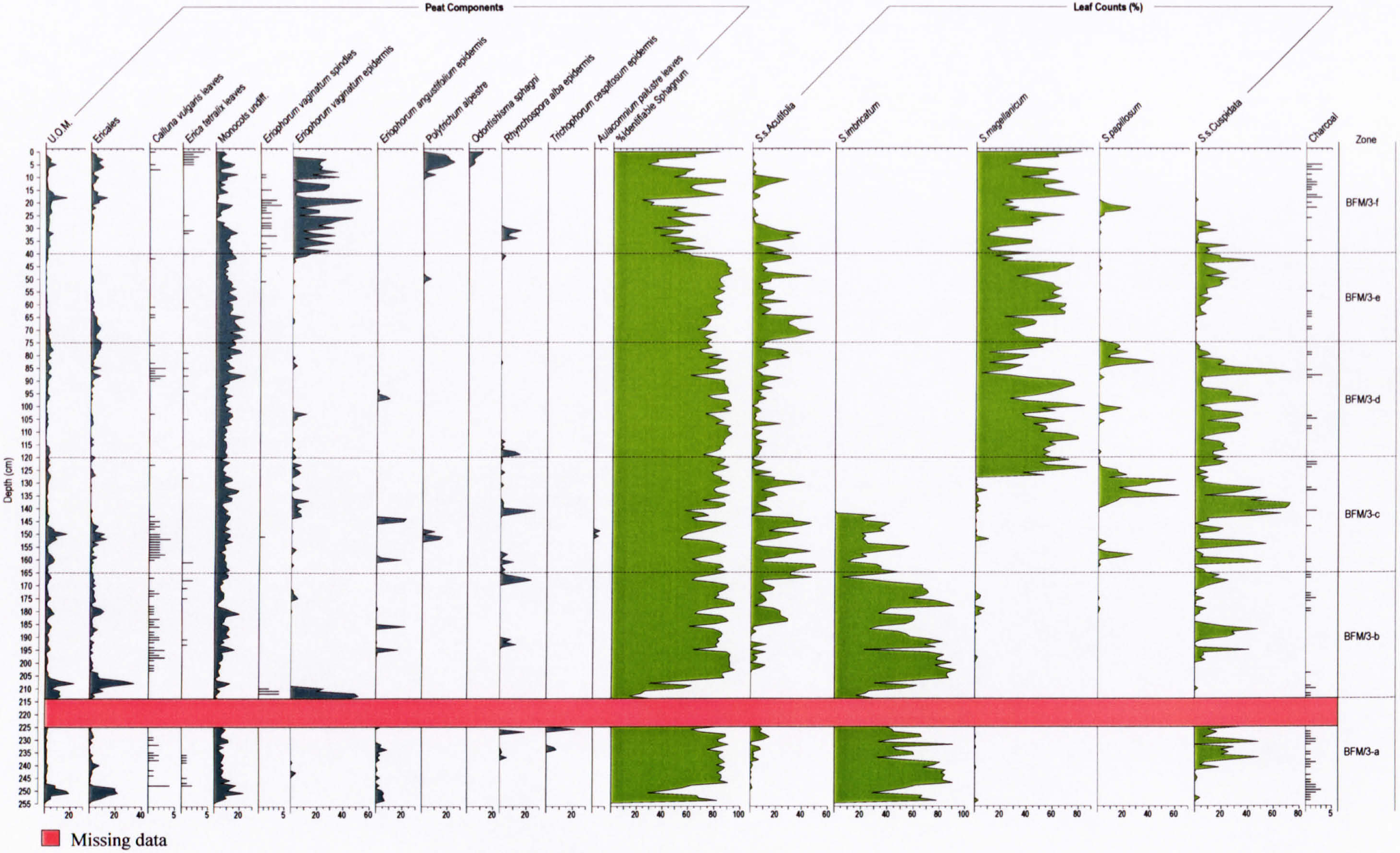


Figure 3.5 Macrofossil diagram for Bolton Fell Moss - Core 3

3.3.6 Intra-site Comparisons - Humification and Macrofossil Results

Owing to the relatively close proximity of the two cores extracted from Bolton Fell Moss (*c.* 250 m), macrofossil and humification datasets will initially be compared against depth.

3.3.6.1 Humification results

Humification absorbance curves for both cores are shown in Figure 3.6. Comparisons between the two curves clearly demonstrate similarities in the overall trend, although this appears to be reduced when nearing the surface layers. Most striking is the almost stepwise drop in absorbance values from *c.* 230 cm, recorded in both profiles, at similar depths. The peak in values at *c.* 70 cm depth in Core MC may also have been synchronously recorded in Core 3 as the more steady rise in values recorded between *c.* 100-60 cm depth.

3.3.6.2 Macrofossil results

The differences between these two vegetational reconstructions are quite considerable. Although significant proportions of *Sphagnum* section Acutifolia and *Sphagnum* section Cuspidata are recorded in both cores, other *Sphagnum* taxa display little, if any, correlation. As with previous studies carried out at this site (e.g., Barber, 1981, Barber *et al.*, 1994a; Stoneman *et al.*, 1993; Mauquoy, 1997), Core 3 records a sustained dominance of *Sphagnum imbricatum* until its rapid extinction, associated with increases in proportions of *S.* s. Cuspidata, and a rise to dominance of *Sphagnum magellanicum*. Whereas, Core MC displays no such pattern, with only minimal representation of *S. imbricatum*, and only a temporary dominance of *S. magellanicum*, which is then out-competed by *S.* s. Acutifolia. Generally, Core MC records much wetter conditions in the lower levels than Core 3, with greater proportions of *S.* s. Cuspidata and *S. papillosum*. It is likely that the strong hold of *S.* s. Acutifolia was significant enough for it to remain the dominant peat-former for the remainder of Core MC, overcoming the competition from *S. magellanicum* in the upper levels. The absence of *Polytrichum* species and *Odontishisma sphagni* from the surface layers of Core MC also demonstrates the contrast between these two locations, with the much drier conditions of Core MC enabling the inclusion of *Vaccinium myrtillus* into the local flora.

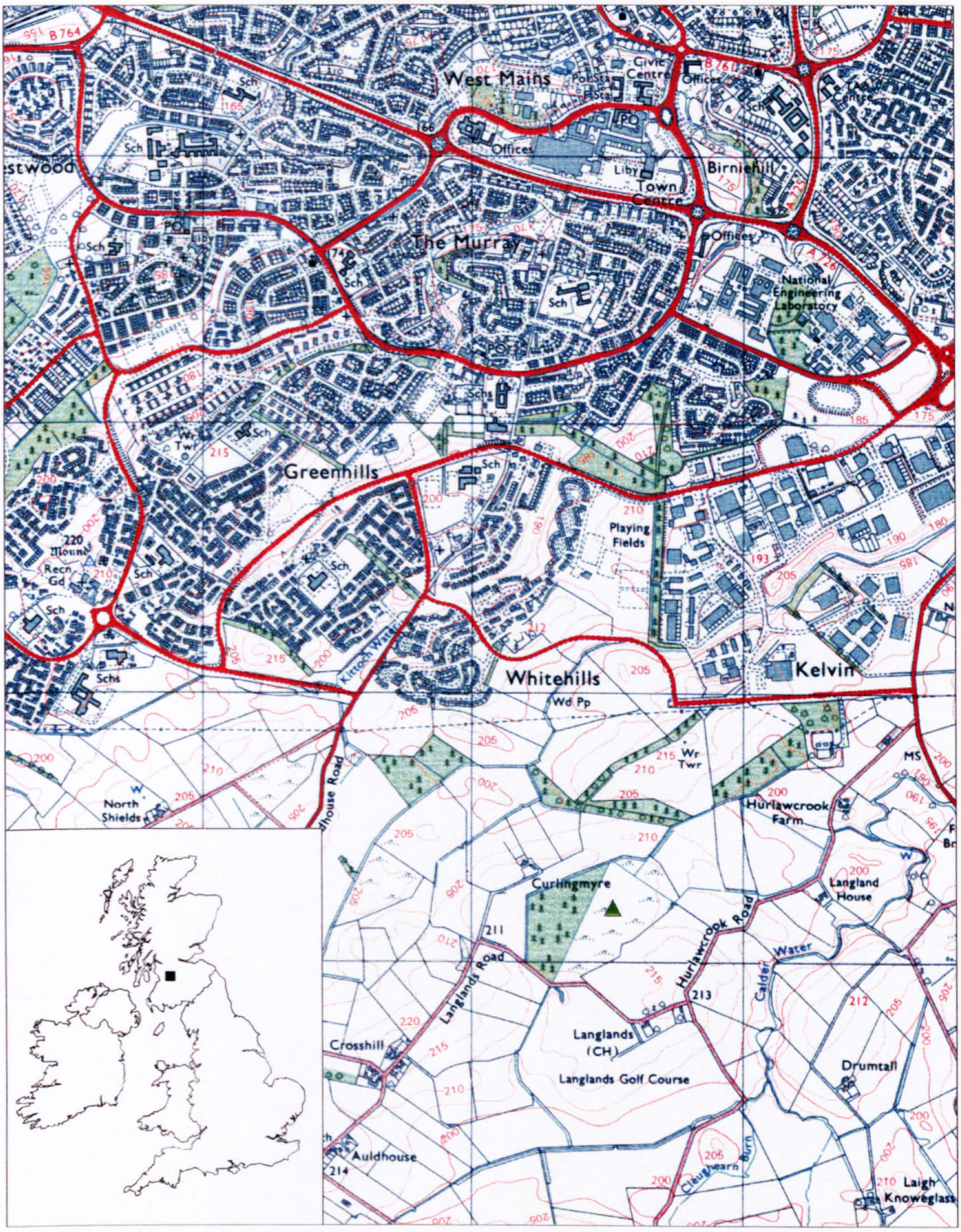
Figure 3.6 Comparison of humification values for Bolton Fell Moss; (a) Core 3 and (b) Core MC

3.4 Langlands Moss (LAG) - NS 635511

3.4.1 Site Description

Approximately 20 ha in size, Langlands Moss is a small, though still largely intact, raised mire with a clearly domed shape (Figure 3.7; Plate 3.2) (Brooks and Stoneman, 1997). Although a considerable portion of the bog was afforested up to 1995, the area used for this study remains clear, with the surface vegetation still containing typical raised bog species. However, some marginal peat cutting, drainage, and afforestation has led to a general lowering of bog water-levels, resulting in a loss of pool and lawn bog-vegetation communities. Erosion runnels have developed on the marginal slopes of the bog, which may have been initiated by previous fire damage. The current dominant peat-forming species include *Calluna vulgaris*, *Erica tetralix* and *Eriophorum vaginatum*, as well as non-*Sphagnum* bryophytes, including *Hypnum cupressiforme* and *Polytrichum juniperum/alpestre* type.

Situated at an altitude of 214 m O.D., Langlands Moss has a mean annual temperature of 7.3°C and relatively high levels of precipitation, with a mean annual rainfall of 1461 mm (Brooks and Stoneman, 1997).



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Borehole location: ▲ - Core 4

Figure 3.7 Map showing location of Langlands Moss with borehole position

Plate 3.2. Aerial photograph of Langlands Moss (Scale 1:5000)

Borehole location: △ - Core 4

3.4.2 Humification Results - Langlands Moss - Core 4

Overall, considerably higher humification absorbance residuals are recorded for Langlands Moss than those recorded for Bolton Fell Moss (Figure 3.8). Peaks in absorbance residuals, reflecting drier phases are recorded between *c.* 148-142, 75-60, 48-33 cm and at *c.* 187 and 88 cm depth. Relatively low residual values, reflecting wetter phases, occur between *c.* 165-155 and at *c.* 80, 55 and 25 cm depth, with the lowest residual values recorded from 28 cm to the surface, most likely owing to the high density of modern root material at these levels.

3.4.3 Macrofossil Results - Langlands Moss - Core 4

The plant macrofossil diagram for Langlands Moss is shown in Figure 3.9, with five zones (a-e) established through the identification of significant changes in the vegetational assemblage.

Zone LAG/4 - a (200-170 cm): The base of this core is dominated by high proportions of *Sphagnum imbricatum* leaves, suggesting the presence of a high-ridge microform. However, this is only sustained until *c.* 195 cm depth when there is a rapid decline in proportions of *S. imbricatum*, followed by a rise in drier mire taxa (UOM, Ericales, *Calluna vulgaris*, *Erica tetralix* and *Eriophorum vaginatum*). The switch in dominance from *S. imbricatum* to *Sphagnum* section Acutifolia at this stage, together with the species replacement of *Amphitrema wrightianum* (commonly found in bog pools) by *Assulina muscorum* (a hydro-xerophilous species) and later by *Hyalosphenia subflava* and *Trigonopyxis arcula* (typically drier species), suggests a shift to considerably drier conditions, possibly leading to the formation of a high-hummock microform. Charcoal levels are also significant in this area of the zone, raising the possibility that fire may have influenced this change in assemblage. *S.* s. Acutifolia remains the dominant peat-former until *c.* 174 cm when, accompanied by a rise in proportions of *Amphitrema flavum* (reflecting a shift to relatively wetter conditions), *S. imbricatum* regains dominance at the top of this zone.

Zone LAG/4 - b (170-135 cm): The high proportions of *S. imbricatum* leaves at the bottom of this zone, corresponds to falls in the representation of drier mire taxa and increases in hydrophilous testate species (*A. wrightianum* and *A. flavum*) suggesting a return to wetter conditions in this part of the zone. However, this wet phase is only sustained for a short period as proportions of *S.* s. Acutifolia increase from *c.* 165 cm, while the wetter testate species begin to decline from *c.* 155 cm. The peak in *S.* s. Acutifolia leaves at *c.* 148 cm, once again associated with increases in UOM, Ericales, *E. vaginatum* epidermis and *H. subflava* species signifies a return to drier conditions at this depth. This drier period is only maintained for a short period, as proportions of *S. imbricatum* rise at the top of this zone, as do proportions of the more hydrophilous species of testate amoebae.

Zone LAG/4 - c (135-85 cm): The continued dominance of *S. imbricatum*, combined with a steady increase in proportions of *A. wrightianum* and *A. flavum* signify relatively wet conditions from the base of this zone until *c.* 115 cm depth. Levels of *Sphagnum* and testate species decline sharply at *c.* 113 cm depth, having been replaced by high levels of UOM and Monocots. undiff., suggesting a rapid shift to drier conditions. The remainder of this zone records rapid alternations in dominance between a drier (UOM, Monocots. undiff.) assemblage and peaks in *S. imbricatum*/*S.* s. Acutifolia species. Dry shifts occur at *c.* 111 and 105 cm and between *c.* 100-90 cm depth, while wetter peaks are recorded at *c.* 110 and 103 cm depth. A return to a more stable period of *S. imbricatum* dominance at the top of this zone is accompanied by increasing levels of *A. flavum*, supporting the evidence for a return to wetter conditions.

Zone LAG/4 - d (85-45 cm): Proportions of *H. subflava* rise from the base of this zone, peaking from *c.* 70 cm, when there is a further replacement of *S. imbricatum* by *S.* s. Acutifolia. The presence of *Erica tetralix* and *Calluna vulgaris* at this level confirms the shift to drier conditions. This dry phase continues until *c.* 58 cm, when proportions of *S. imbricatum* rise to dominance once more, as do levels of *A. flavum*, reflecting a return to wetter conditions until *c.* 49 cm depth. At this point, there is a sudden decline in *Sphagnum* and testate representation, and a rise in proportions of UOM, Ericales and Monocots. undiff., with high levels maintained to the top of this zone.

Zone LAG/4 - e (45-0 cm): Aside from a brief peak in *S.* s. Acutifolia at *c.* 43 cm depth, a considerably drier assemblage, consisting of UOM, Ericales and Monocots. undiff., dominates the peat matrix at the base of this zone. The lack of *Sphagnum* leaves and high levels of UOM recorded for a large section of this zone suggests possible disturbance to the surface of the mire during this period. Evidence of disturbance is also provided by the high proportions of *H. subflava*, as this species is often associated with drained peatlands (Tolonen *et al.*, 1994). Peaks in *A. wrightianum* are also recorded in this section of the zone which further complicates the vegetational reconstruction during this period. There is a significant change in vegetation from *c.* 20 cm, with the reappearance of *Calluna vulgaris* and *Erica tetralix* and a few *Sphagnum* leaves (*Sphagnum magellanicum* and *Sphagnum* section Cuspidata). High levels of charcoal are also associated with this change in assemblage, suggesting that fire may have been an influence. The presence of erosion runnels at the margins of the bog (see Section 3.4.1) may have been a consequence of this fire activity and may also be connected with the surface disturbance during this period. A range of other grasses and bryophytes are found in the upper layers, with *S.* s. Acutifolia regaining its role as the dominant peat-former from *c.* 8 cm to the surface.

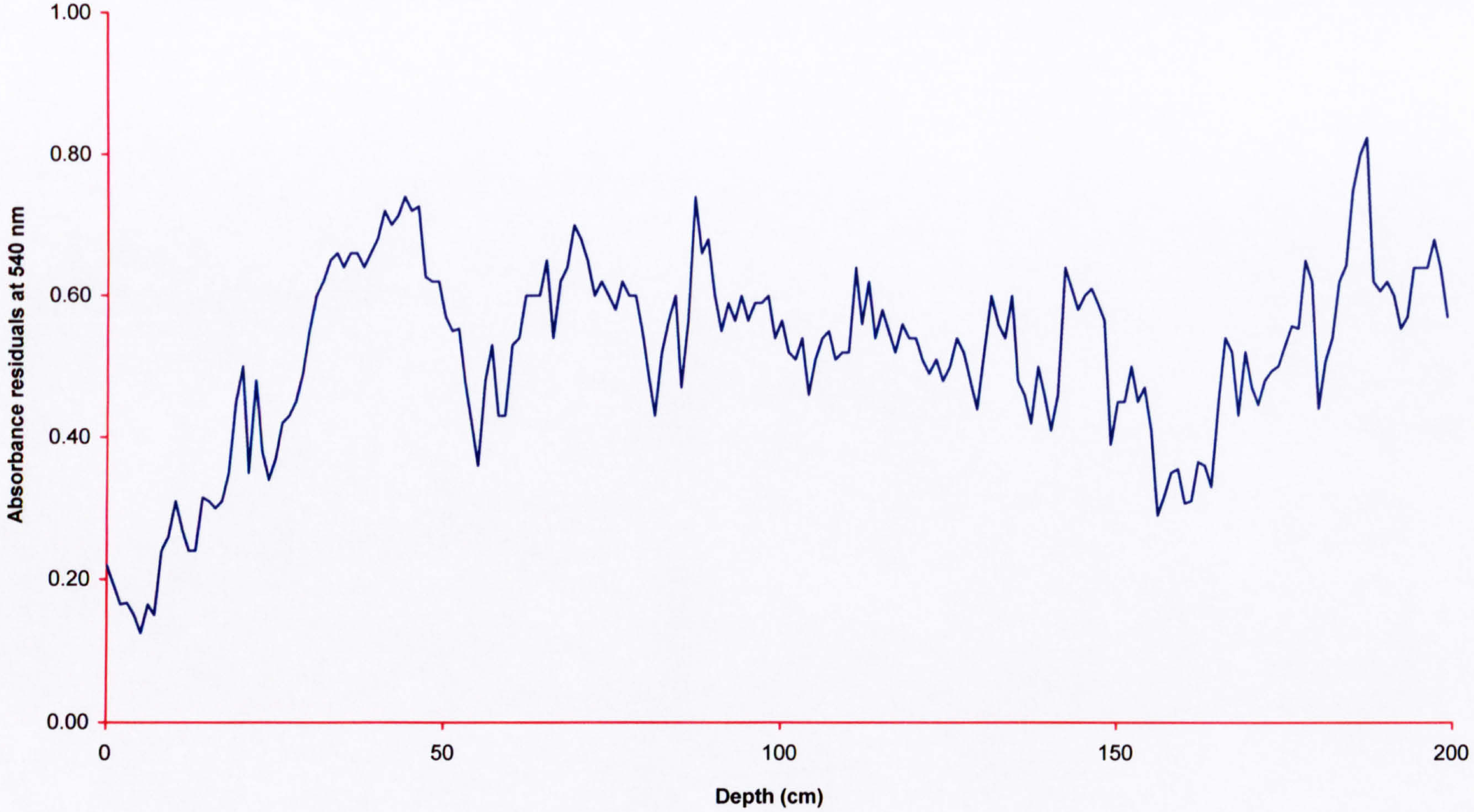


Figure 3.8 Humification absorbance values for Langlands Moss

Figure 3.9 Macrofossil diagram for Langlands Moss

3.5 Mynydd Llangatwg (MLA) - SO 177153

3.5.1 Site Description

Mynydd Llangatwg is a gently sloping peat-covered plateau, which falls from an elevation >520 m O.D. in the north to <400 m O.D. some 3.5 km to the south (Smart and Gardener, 1989). The actual sampling location is situated approximately 3.5 km north of Brynmawr, South Wales, 1 km east of the B4560 (Figure 3.10). The underlying limestone is covered by a layer of relatively deep ombrotrophic blanket peat, with an eroding peat front, on the northern perimeter of a sink hole (Plate 3.3). Although the present vegetation was dominated by *Calluna*, preliminary field investigations revealed the presence of sub-fossil *Sphagnum* to at least 2 m depth. As a pilot project, Chambers and Mauquoy (1998) extracted two profiles at this locality and recorded the current vegetation as consisting of *Calluna-Eriophorum vaginatum* mire, *Erica tetralix* sub-community (M19a). As well as frequent *Calluna*, traces of *Molinia*, *Eriophorum vaginatum*, *E. angustifolium* and *Erica tetralix* were also found to be present in the top 50 cm of the core.

The characteristically oceanic climate of this region of South Wales generates a mean summer temperature of 16.5°C and consistently high levels of precipitation, with over 2400 mm at high altitude (Chambers, 1996).

Borehole location: ▲ - Core 2

Figure 3.10 Map showing location of Mynydd Llangatwg with borehole position

Plate 3.3. Aerial photograph of Mynydd Llangatwg (Scale 1:10000)

Borehole location: △ - Core 4

Source: Countryside Council for Wales

3.5.2 Humification Results - Mynydd Llangatwg

The range of absorbance readings recorded at this site was found to vary considerably more than for any of the other sites investigated (Figure 3.11). There is also a clear trend in the curve, with the lowest residual values recorded at the surface and the highest residual values recorded at the base, supporting the theory that decomposition continues into the catotelm (Clymo, 1984). In order to aid the identification of directional changes in mire surface conditions, this trend was removed by applying a linear regression equation to the data points and plotting these against depth (Figure 3.12). It is possible to detect clear phases of lower and higher residual values from the detrended dataset, reflecting changes to wetter and drier conditions respectively. The wettest phases are seen to occur between *c.* 215-190, 100-95 cm and from *c.* 85-70 cm depth. The highest residual values at the base of the core suggest drier conditions, with other dry phases occurring between *c.* 230-220, 190-150, 60-38 cm and at *c.* 95 cm depth. As with the other humification records in this study, the relatively low residual values recorded in the upper levels (from 35 cm depth to the surface) most likely reflect the presence of young rootlet material in the acrotelm.

3.5.3 Macrofossil Results - Mynydd Llangatwg

The plant macrofossil diagram for Mynydd Llangatwg is shown in Figure 3.13. The diagram has been segregated into six zones (a-f).

Zone MLA/2 - a (246-205 cm): Sphagnum leaves are absent from the base of the core, as the peat matrix is dominated by an assemblage composed of UOM, Ericales and Monocots. undiff. These components each sustain a *c.* 20% proportion of the peat matrix for the majority of this zone, with the occasional peak in *Eriophorum vaginatum* epidermis occurring throughout. It is most likely that drier conditions dominated this period. The peak in UOM at *c.* 225 cm depth correlates well with a peak in *Trigonopyxis arcula*, a xerophilous indicator, and high levels of *E. vaginatum* reflecting the driest period in this zone. The charcoal counts are also high at the top of this zone, indicating the occurrence of local fire events. High proportions of

Sphagnum magellanicum are recorded at *c.* 210 cm, although its dominance is short-lived.

Zone MLA/2 - b (205-170 cm): High proportions of *Hyalosphenia subflava* dominate the testate amoebae assemblage throughout this zone, indicating a sustained period of drier conditions, although significant peaks in *S. magellanicum* and *Sphagnum* section Acutifolia are also recorded at *c.* 200 and 190 cm depth, suggesting shifts to wetter conditions at these levels. The driest peat components (UOM, Ericales and Monocots. undiff.) remain moderately represented throughout this zone, and as with Zone A, there are occasional peaks in *E. vaginatum* epidermis, supporting the testate evidence for generally dry conditions. Charcoal fragments are also abundant from *c.* 205-185 cm depth, reflecting local burning. There is a distinct decline in *H. subflava* representation at the top of this zone, where it is replaced by *Amphitrema flavum*, a species characteristically found in wetter areas.

Zone MLA/2 - c (170-125 cm): Drier conditions return in this zone, with a steady increase in UOM, comprising up to 60% of the peat matrix at its maximum. Proportions of Ericales and Monocots. undiff. also remain high throughout, with a peak at *c.* 145 cm depth correlating well with high levels of *Calluna vulgaris* and *E. vaginatum* epidermis. Although *H. subflava* is the dominant testate species from *c.* 185 cm, numbers are seen to steadily decline toward the top of the zone, as it is replaced by *A. flavum* and *Assulina muscorum* species, suggesting a change to a more moist environment. Some *Sphagnum imbricatum* leaves are recorded, but the most significant presence is a 60% peak in *S.* s. Acutifolia leaves at the top of this zone. This coincides with a sharp rise in *Amphitrema wrightianum* species and falls in UOM representation, suggesting a rapid wet shift at this level.

Zone MLA/2 - d (125-90 cm): A 40% peak in *Eriophorum angustifolium* epidermis immediately follows the decline in *S.* s. Acutifolia at the base of this zone and precedes a peak in UOM. Proportions of the drier mire taxa are seen to decline following this peak, while *Sphagnum* takes over as the dominant peat-former, firstly in the form as *S.* s. Acutifolia which is in turn out-competed by *S. imbricatum*. This *Sphagnum* phase is interrupted at *c.* 100 cm depth by a peak in UOM and, quite uncharacteristically, a peak in *E. angustifolium* epidermis. *S. imbricatum* then recovers, and remains dominant for the rest of the zone. There is a steady decline in the more hydrophilous testate species toward the top of this zone, while proportions of *H. subflava* are seen to rise, with an 80% peak at *c.* 94 cm depth. This may signify a transformation from pool to drier, possibly low-ridge conditions, thereby justifying the presence of *E. angustifolium.*

Zone MLA/2 - e (90-50 cm): S. imbricatum remains the dominant peat-former throughout this zone, aside from a rapid decline at *c.* 66 cm depth. There is a brief peak in UOM, Ericales and Monocots. undiff. at this depth, suggesting a rapid shift to drier conditions, which is supported by high levels of *H. subflava.* The rise in proportions of *A. flavum* and *A. wrightianum* following this event indicates a change to wetter conditions which is sustained for the rest of the zone.

Zone MLA/2 - f (50-0 cm): A peak in proportions of *Sphagnum papillosum* and hydrophilous testate species at *c.* 45 cm depth signifies a rapid drop in *S. imbricatum* leaves at the base of this zone, possibly representing part of the widespread demise of this species, as recorded at many sites in the British Isles (Barber, 1981; Barber *et al.*, 1994a, Stoneman *et al.*, 1993, Mauquoy, 1997). As with these other studies, following this event there is a rise in *S. magellanicum*, although this species seems unable to attain dominance as drier mire taxa appear to take over. Proportions of UOM and Monocots. undiff. rise dramatically toward the surface layers, most likely as a consequence of either dry climatic conditions or local anthropogenic disturbance.

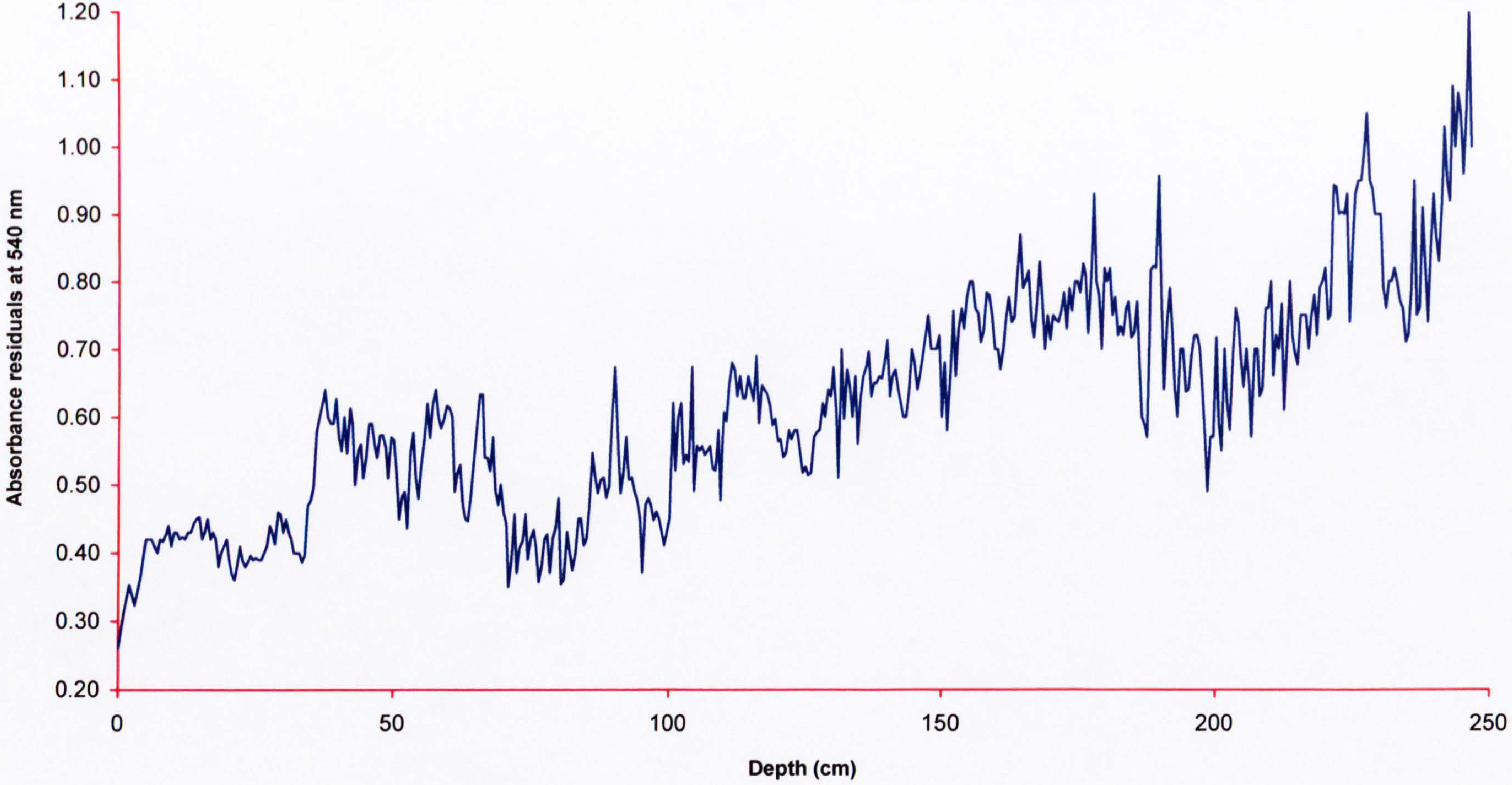


Figure 3.11 Humification absorbance values for Mynydd Llangatwg

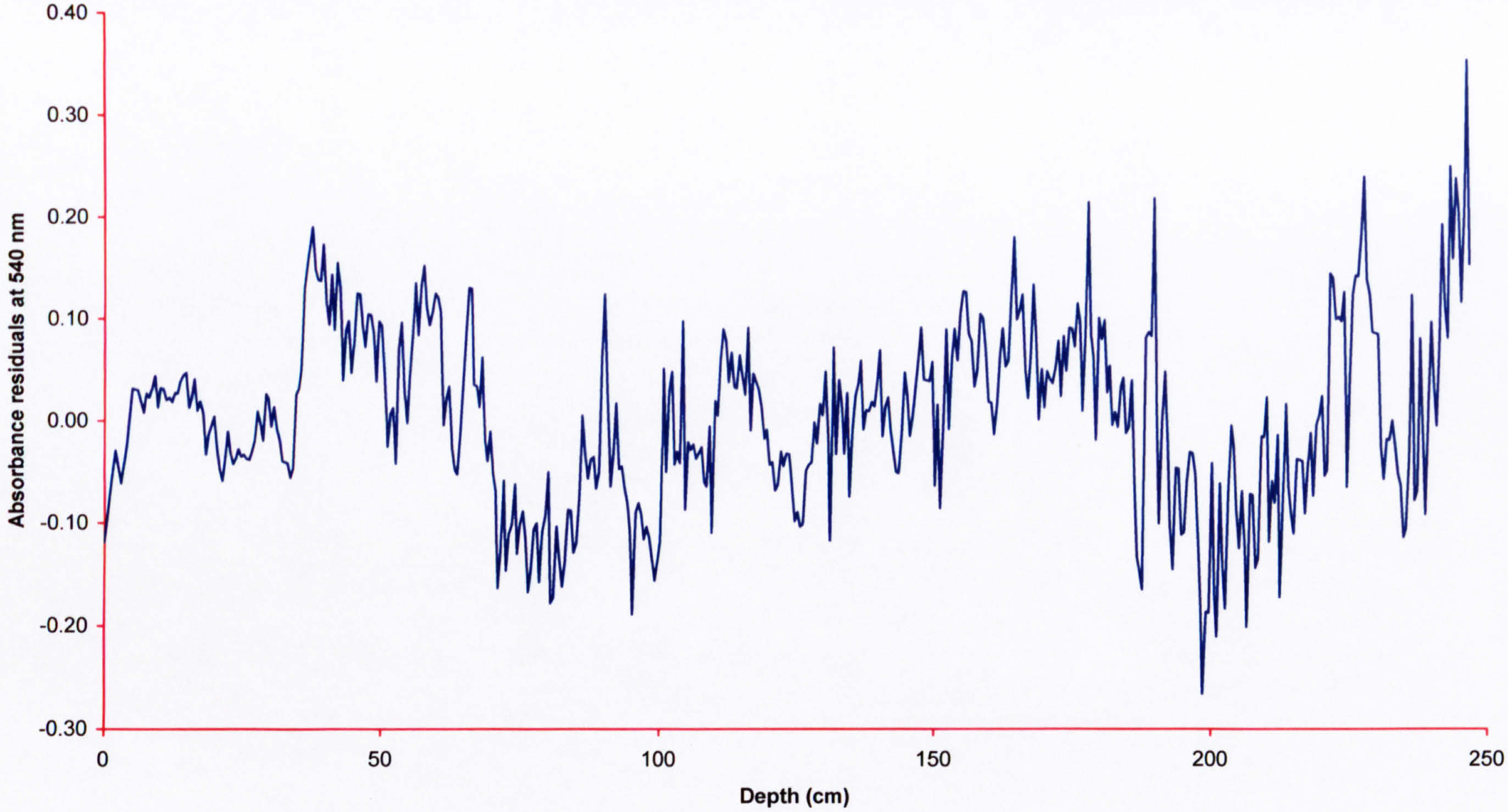


Figure 3.12 Detrended humification absorbance values for Mynydd Llangatwg

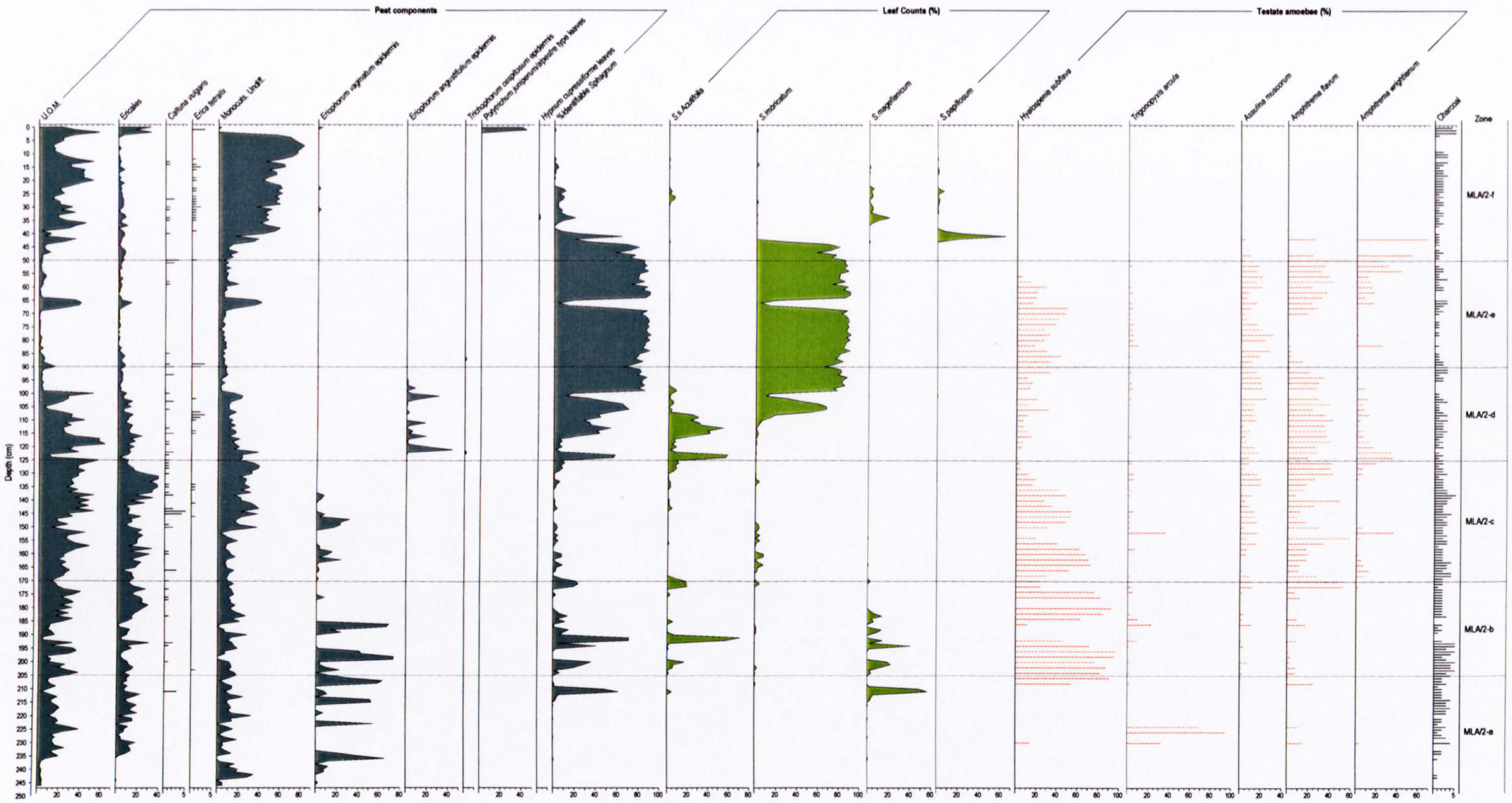


Figure 3.13 Macrofossil diagram for Mynydd Llangatwg

3.6 Chronology

3.6.1 Radiocarbon Chronology

Some 51 AMS ^{14}C dates were obtained for use in this project. Within each site, groups of samples have been dated at specific locations along each core. The positioning of these groups of dates was determined through the identification of areas of significant fluctuation in the colorimetric humification curve. Three groups, each containing 5 equally spaced dated horizons, have been applied to both Langlands Moss - Core 4 and Bolton Fell Moss - Core MC, while four groups, also containing 5 dates each, were obtained for Mynydd Llangatwg - Core 2. Only 1 dated horizon was made available for Bolton Fell Moss - Core 3 and this was provided by researchers from University of Bristol, who were concentrating their investigations on the lower sections of the core.

Each raw ^{14}C date was initially calibrated using OxCal version 3.4 (Ramsey, 2000), which incorporates the INTCAL98 calibration curve (Stuiver *et al.*, 1998). However, transfer of individual ^{14}C dates into calendar years often yields problematic interpretations in palaeoecology (Dumayne *et al.*, 1995). Owing to the irregular shape of the calibration curve, the Gaussian distribution of a dated organic sample often corresponds to an irregular calendar age probability distribution, commonly encompassing a relatively long period (van der Plicht and Mook, 1987). It has been general practice, in studies of this nature, to use the mid-point of the two dates that enclose the 95.4% confidence limits (2-sigma error range) in order to produce a singular calendar date for each sample. Using this technique, preliminary age-depth models have been generated for each site by plotting the mid-points of each ^{14}C date against time (cal. AD/BC). SCP inception markers have also been included in the age-depth models, as a means of improving control for the last 200 years of past accumulation. By fitting a trend line (second order polynomial) through each of the age-depth curves, the variability of each date can be smoothed and average accumulation rates for each core can be estimated. However, as one of the criteria of this study is to make high-resolution reconstructions of mire surface conditions for each site, the mid-point age estimates generated through calibration are too imprecise a marker on which to base an effective reconstruction.

An alternative method of chronological ordering, whereby a potentially more precise age assignment can be determined, is wiggle-match dating (WMD). Using a series of ^{14}C age determinations of stratigraphically consecutive samples, instead of individual dates, matches can be made between the natural variations (wiggles) in the dendrochronological calibration curve and the recorded signal of ^{14}C held in the peat. In other words, this procedure uses the stratigraphical order of the ^{14}C dates to narrow the probability range in calendar ages. Using the most recent edition of the Groningen Radiocarbon Calibration Program, CAL25 (van der Plicht, 1998), each group of 'floating' dates was matched to the relevant section of the INTCAL98 calibration curve.

Within the program, each group of dates can be shifted horizontally (as a unit), in either direction, until a sufficient 'match' is obtained. To compensate for the varying rates of accumulation throughout the core, there is also an option to compress or expand the distance between each date. However, using this option, the dates are compressed/expanded as a group, therefore assuming that no overall linear change in the depth scale has occurred (Speranza *et al.*, 2000). Using age-depth models, derived through calibration of the radiocarbon dates, it was possible to derive estimated accumulation rates for each section of the cores, and these were taken into account when applying this function. There is also an option to shift the group vertically to compensate for any systematic error such as a general reservoir effect (Kilian *et al.*, 1995), in which case the wiggle may be reproduced, but the radiocarbon ages are consistently older. However, this option was not applied, thereby keeping the overall data manipulation to a minimum.

The visual approach of WMD is also supplemented by the automatic calculation of a goodness-of-fit, which is the distance in ^{14}C years between average sediment and calibration curve data, expressed as a standard deviation (Kilian *et al.*, 2000). The lower the value, the better the fit of the 'floating' dates to the curve. However, perfect fits are still prone to significant error, causing a scattering of some of the ages of the geological samples around the curve. The two major sources of this error are ^{14}C measurement error and sample error (Kilian *et al.*, 2000). The ^{14}C measurement error is the usual 1-sigma standard deviation of the Gaussian probability distribution, while the sample error encompasses the number of years in which a sample formed, together with species error, arising from dating botanically mixed samples (Törnqvist and Bierkens, 1994).

Ages of samples between the wiggle-matched groups have also been estimated through simple linear interpolation. Again, it is assumed that peat accumulation has remained relatively constant between the dated areas of each core, and so the risk of inaccuracy would be expected to rise the further each sample lies from a wiggle-matched level. For this reason, a clear distinction has been made between wiggle-matched ^{14}C horizons and interpolated dates, where the prefix *c.* has been applied.

3.6.1.1 Bolton Fell Moss - Core MC - Calibration

AMS ^{14}C dates received for Bolton Fell Moss - Core MC are listed in Table 3.1, with calibrated age ranges (2-sigma) and mid-point values for each sample. Plotting these mid-point values against depth enables the generation of a preliminary age-depth model for this core, with an r^2 value of 0.974 (Figure 3.14). Average accumulation rates range from 1.29 mm yr^{-1} in the lower section to 3.25 mm yr^{-1} in the upper section of the core.

Table 3.1 List of AMS ^{14}C determinations for Bolton Fell Moss - Core MC

Date number	Depth (cm)	Radiocarbon age BP (incl. 1σ error)	2σ calibrated range 95.4% conf. level	Mid-point of 2σ range
1	60	160 ± 45	cal. AD 1660-1960	cal. AD 1810
2	65	330 ± 45	cal. AD 1450-1650	cal. AD 1550
3	70	375 ± 40	cal. AD 1590-1630	cal. AD 1610
4	75	535 ± 45	cal. AD 1300-1450	cal. AD 1375
5	80	440 ± 45	cal. AD 1400-1630	cal. AD 1515
6	132	600 ± 45	cal. AD 1290-1420	cal. AD 1355
7	137	775 ± 45	cal. AD 1160-1300	cal. AD 1230
8	142	635 ± 45	cal. AD 1280-1410	cal. AD 1345
9	147	805 ± 45	cal. AD 1120-1300	cal. AD 1210
10	152	970 ± 45	cal. AD 980-1190	cal. AD 1085
11	225	1535 ± 45	cal. AD 420-620	cal. AD 520
12	230	1530 ± 45	cal. AD 420-630	cal. AD 525
13	235	1550 ± 45	cal. AD 410-620	cal. AD 515
14	240	1595 ± 45	cal. AD 380-600	cal. AD 490
15	245	1770 ± 45	cal. AD 130-390	cal. AD 260

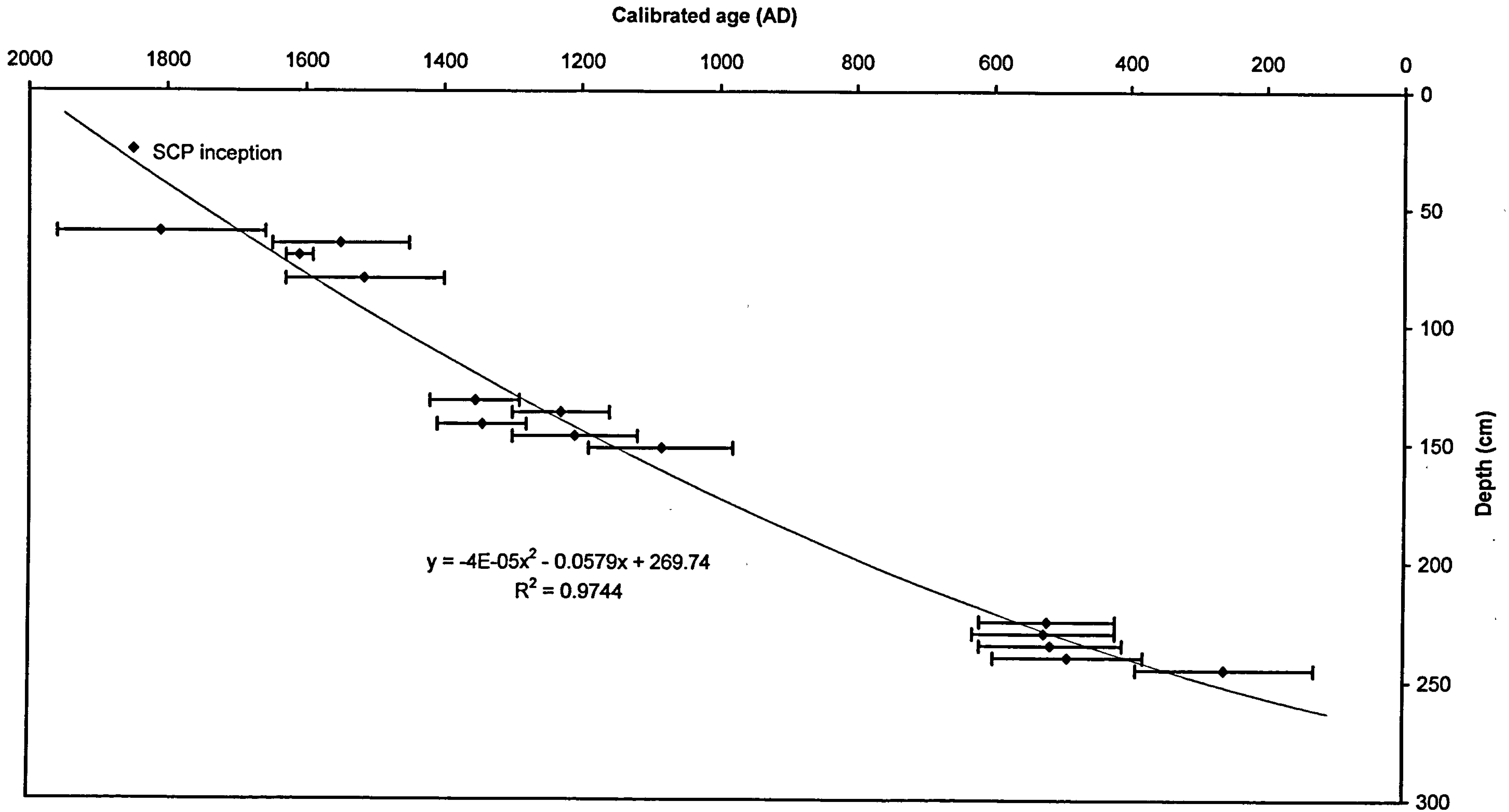


Figure 3.14 Age-depth model: Bolton Fell Moss - Core MC

3.6.1.2 Bolton Fell Moss - Core MC - Wiggle-match dating

Singular calendar dates for each group, derived through WMD of the ^{14}C age determinations, are listed in Table 3.2. The AMS dates were matched to the dendrochronological calibration curve, obtaining the best fit possible both visually and statistically. Three of the dates in Group 1 (1-5) are seen to float above the calibration curve, possibly owing to the influence of the 'reservoir effect' (see Section 1.2.4), although the trend of the calibration curve is still clearly replicated (Figure 3.15). Group 2 (6-10) is closely matched to a part of the curve displaying a relatively sharp increase in $\Delta^{14}C$, ranging from *c.* cal. AD 1150-1340, with only one date (8) being out of phase with the group (Figure 3.16). Figure 3.17 shows the best match for Group 3 (11-15), with dates 11-14 being positioned tightly across a plateau in the calibration curve. Date 15 is raised slightly above the curve, but it's position is justified by the rest of the group.

Table 3.2 Wiggle-matched calendar dates (AD) for Bolton Fell Moss - Core MC

Group	Date number	Depth (cm)	Radiocarbon age BP (incl. 1σ error)	Wiggle-matched calendar dates
	1	60	160 ± 45	cal. AD 1680
	2	65	330 ± 45	cal. AD 1654
1	3	70	375 ± 40	cal. AD 1629
	4	75	535 ± 45	cal. AD 1604
	5	80	440 ± 45	cal. AD 1579
	6	132	600 ± 45	cal. AD 1307
	7	137	775 ± 45	cal. AD 1267
2	8	142	635 ± 45	cal. AD 1226
	9	147	805 ± 45	cal. AD 1186
	10	152	970 ± 45	cal. AD 1146
	11	225	1535 ± 45	cal. AD 557
	12	230	1530 ± 45	cal. AD 517
3	13	235	1550 ± 45	cal. AD 477
	14	240	1595 ± 45	cal. AD 436
	15	245	1770 ± 45	cal. AD 396

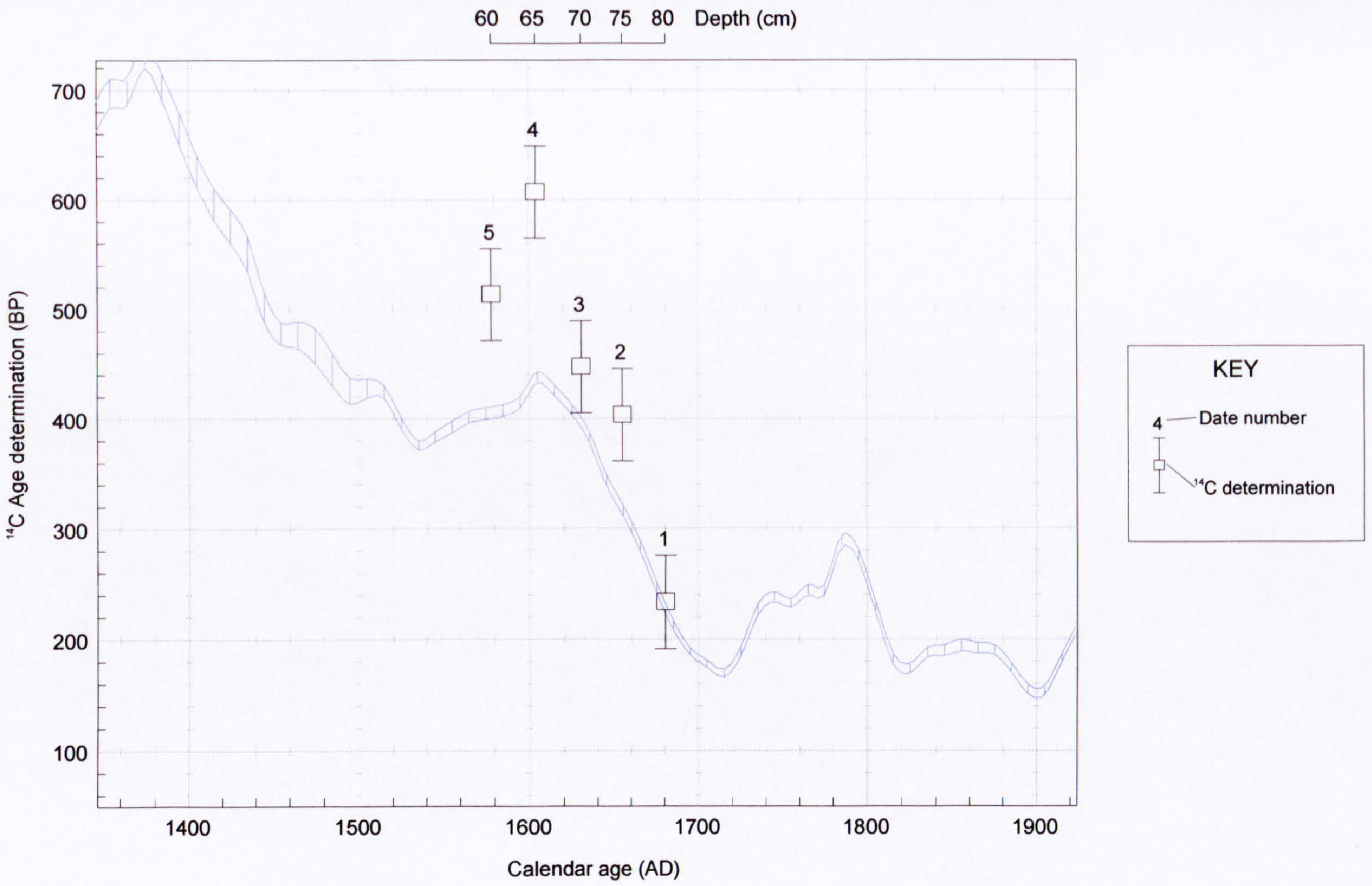


Figure 3.15 Best Match for Group 1: Bolton Fell Moss - Core MC

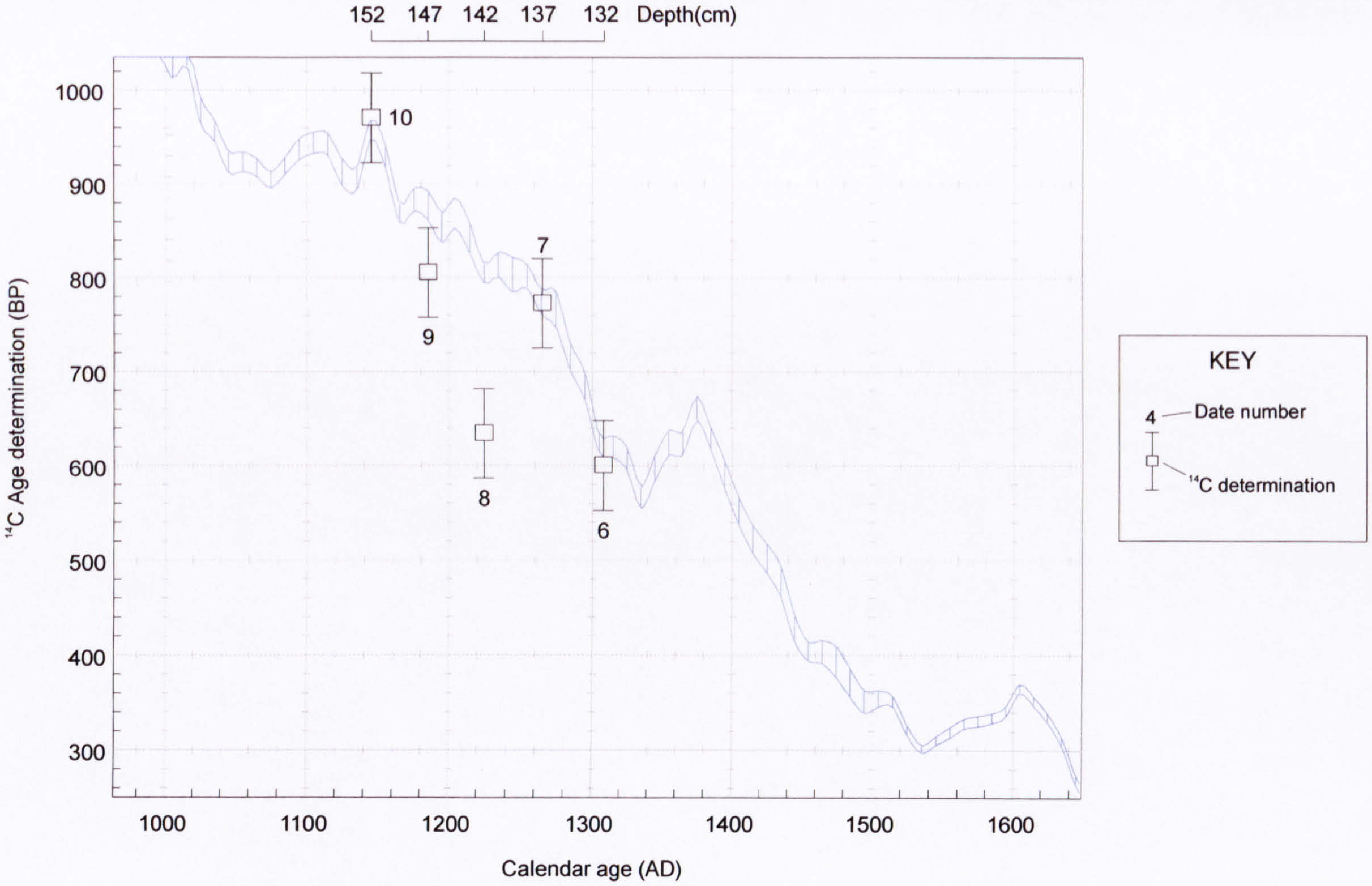


Figure 3.16 Best Match for Group 2: Bolton Fell Moss - Core MC

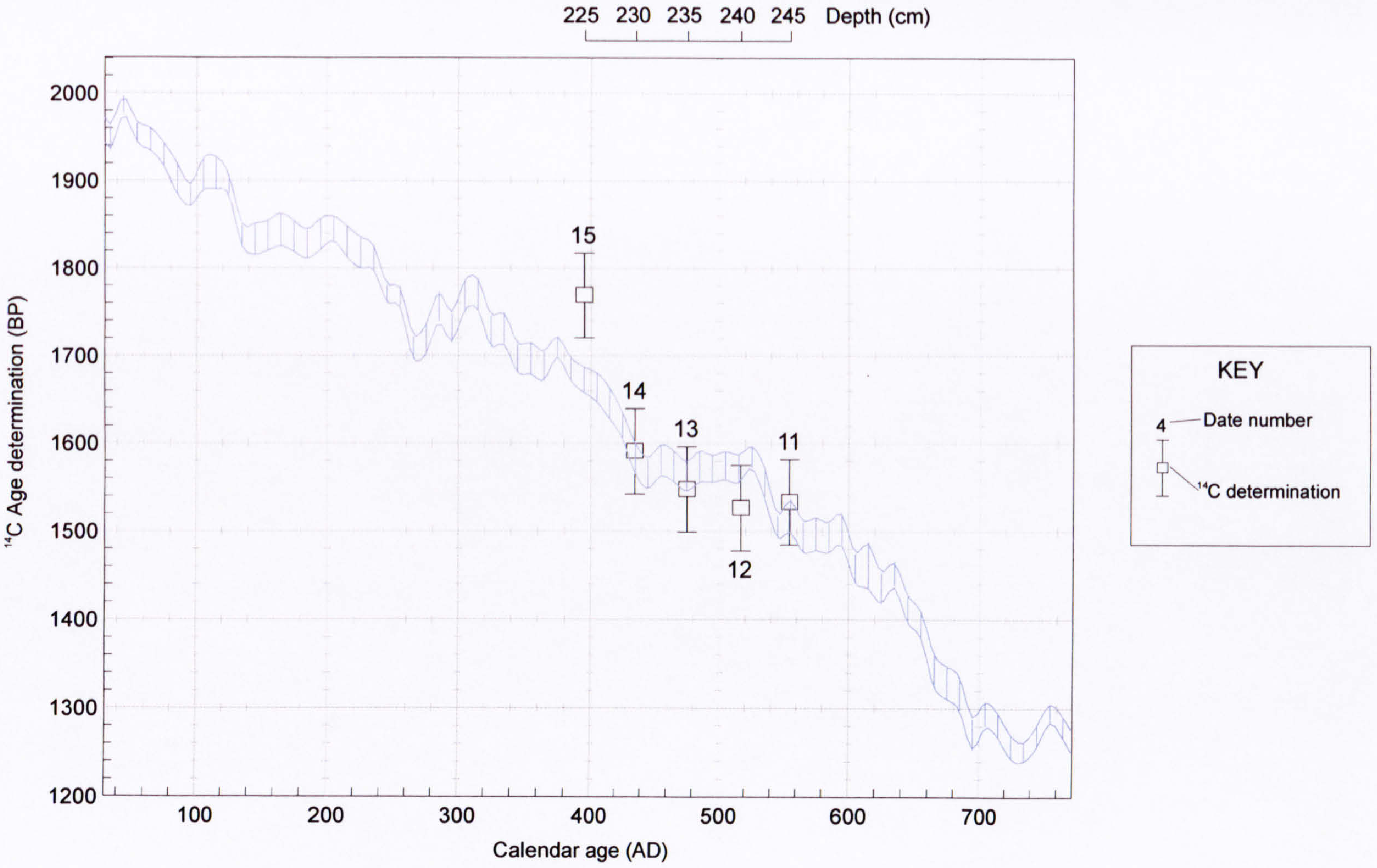


Figure 3.17 Best Match for Group 3: Bolton Fell Moss - Core MC

3.6.1.3 Bolton Fell Moss - Core 3 - Calibration

Owing to the lack of AMS ^{14}C determinations carried out on this core, both lead-210 (see section 3.6.3) and one of the radiocarbon dates obtained for deeper sections of this core, have been incorporated into the age-depth model (Figure 3.18). The AMS dates used in this model are listed in Table 3.3, and were obtained by University of Bristol researchers from the Oxford Radiocarbon Facility, who used the same core material in a parallel study.

Table 3.3 List of ^{14}C AMS determinations for Bolton Fell Moss - Core 3

Date number	Depth (cm)	Radiocarbon age BP (incl. 1σ error)	2σ calibrated range 95.4% conf. level	Mid-point of 2σ range
1	39	260 ± 40	cal. AD 1480-1950	cal. AD 1735
2	423	3995 ± 40	2630-2400 cal. BC	2515 cal. BC

Using this model, average accumulation rates range from 0.90 mm yr^{-1} in the mid-section of the core to 1.0 mm yr^{-1} in the upper section, and 1.8 mm yr^{-1} in the surface layers. Although the considerable distance between the two AMS dates may make any interpolation of dates between these points subjective, the accumulation rates obtained from this model are in line with the findings of other age-determination studies carried out at this site (e.g., Barber *et al.*, 1994a; Mauqouy, 1997; Stoneman, 1993).

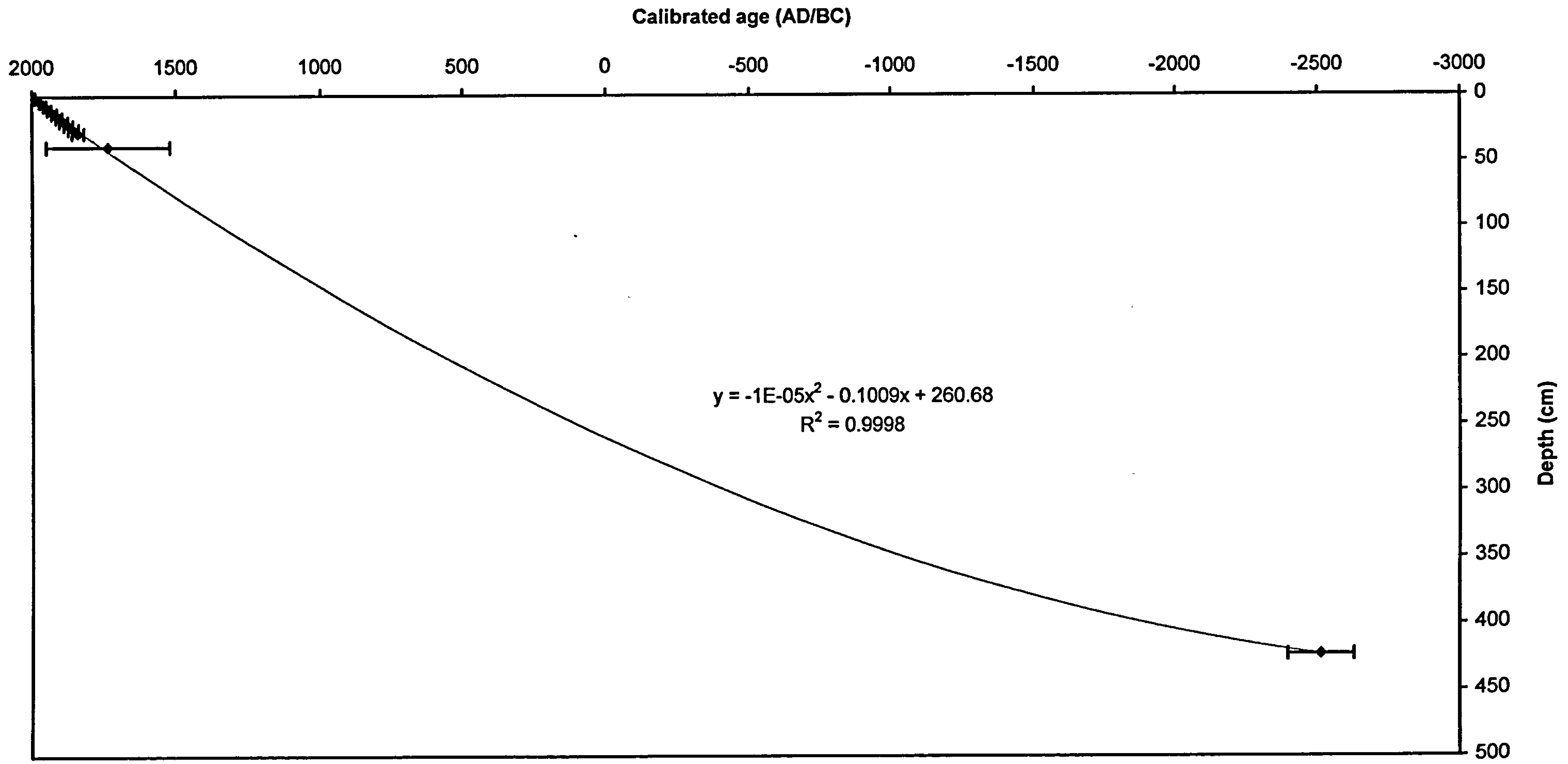


Figure 3.18 Age-depth model for Bolton Fell Moss - Core 3

3.6.1.4 Langlands Moss - Calibration

AMS ^{14}C determinations obtained for Langlands Moss are listed in Table 3.4, while the age-depth model is shown in Figure 3.19. A second-order polynomial trendline has again been used to represent the age-depth relationship for this site, producing an r^2 value of 0.984.

Table 3.4 List of AMS ^{14}C determinations for Langlands Moss

Date number	Depth (cm)	Radiocarbon age BP (incl. 1σ error)	2σ calibrated range 95.4% conf. level	Mid-point of 2σ range
1	50	1310 ± 50	cal. AD 640-870	cal. AD 525
2	55	1380 ± 50	cal. AD 560-780	cal. AD 670
3	60	1390 ± 50	cal. AD 540-770	cal. AD 655
4	65	1310 ± 50	cal. AD 640-870	cal. AD 755
5	70	1530 ± 50	cal. AD 420-640	cal. AD 530
6	150	2670 ± 50	930-780 cal. BC	855 cal. BC
7	155	2620 ± 40	900-590 cal. BC	745 cal. BC
8	160	2760 ± 50	1010-800 cal. BC	905 cal. BC
9	165	2730 ± 50	1000-800 cal. BC	900 cal. BC
10	170	2790 ± 50	1080-820 cal. BC	950 cal. BC
11	180	2800 ± 50	1130-820 cal. BC	975 cal. BC
12	185	2800 ± 50	1130-820 cal. BC	975 cal. BC
13	190	2840 ± 40	1130-890 cal. BC	1010 cal. BC
14	195	2940 ± 40	1290-1000 cal. BC	1145 cal. BC
15	200	3060 ± 50	1430-1130 cal. BC	1280 cal. BC

From this model, average accumulation rates are estimated as ranging from 0.37 mm yr^{-1} in the lower section of the core, increasing to 0.58 mm yr^{-1} in the mid-section, and slowing down again to 0.34 mm yr^{-1} in the upper section. These accumulation rates are clearly problematic, with particular emphasis on the upper section, as the mid-point age assigned to date number 1 (*c.* cal. AD 525) assumes 1472 years of peat growth in just 50 cm. This suggests that within the upper 50 cm either a hiatus exists within the stratigraphy, or some form of surface disturbance has previously occurred. This same problem has also identified been identified by Langdon (1999) who, as part of a similar study carried out *c.* 50 m to the south of this coring location, suggested that some form of disturbance had occurred within the upper layers of the bog. Owing to the presence of fingerprinted AD 860 tephra shards and a number of bulk radiocarbon assignments at this depth, he was able to constrain the disturbance to the top 30 cm of peat. He further constrained the event by suggesting that the characteristic extinction of *Sphagnum imbricatum* and subsequent replacement by *Sphagnum magellanicum*, which can be clearly identified in his macrofossil record as occurring at *c.* 16-20 cm depth, was correctly dated as occurring between cal. AD 890-1030.

Unfortunately, the shallowest radiocarbon determination for this study is at 50 cm depth and owing to time constraints, no tephra analysis has been attempted in this study. Added to these restrictions, no characteristic extinction of *S. imbricatum* and replacement by *S. magellanicum* has been identified for this part of the bog, with *Sphagnum* species deminishing rapidly from *c.* 45 cm depth where they are replaced by drier components (i.e., UOM, Ericales and Monocots. undiff). An alternative source of chronological control for the upper levels of the core is the SCP record. A clear rise in particle concentration can be identified from these results, with an inception depth of *c.* 22 cm, which is assumed to represent the mid-nineteenth century period. This suggests that no disturbance has occurred in the uppermost layers and is confined to between *c.* 22-50 cm depth. However, without further chronological evidence for this section of the core, the extent and location of the disturbance is unclear. Owing to the chronological uncertainty for the upper section of this core, any attempts at correlation with other cores will not employ the top 40 cm of proxy-evidence from this study.

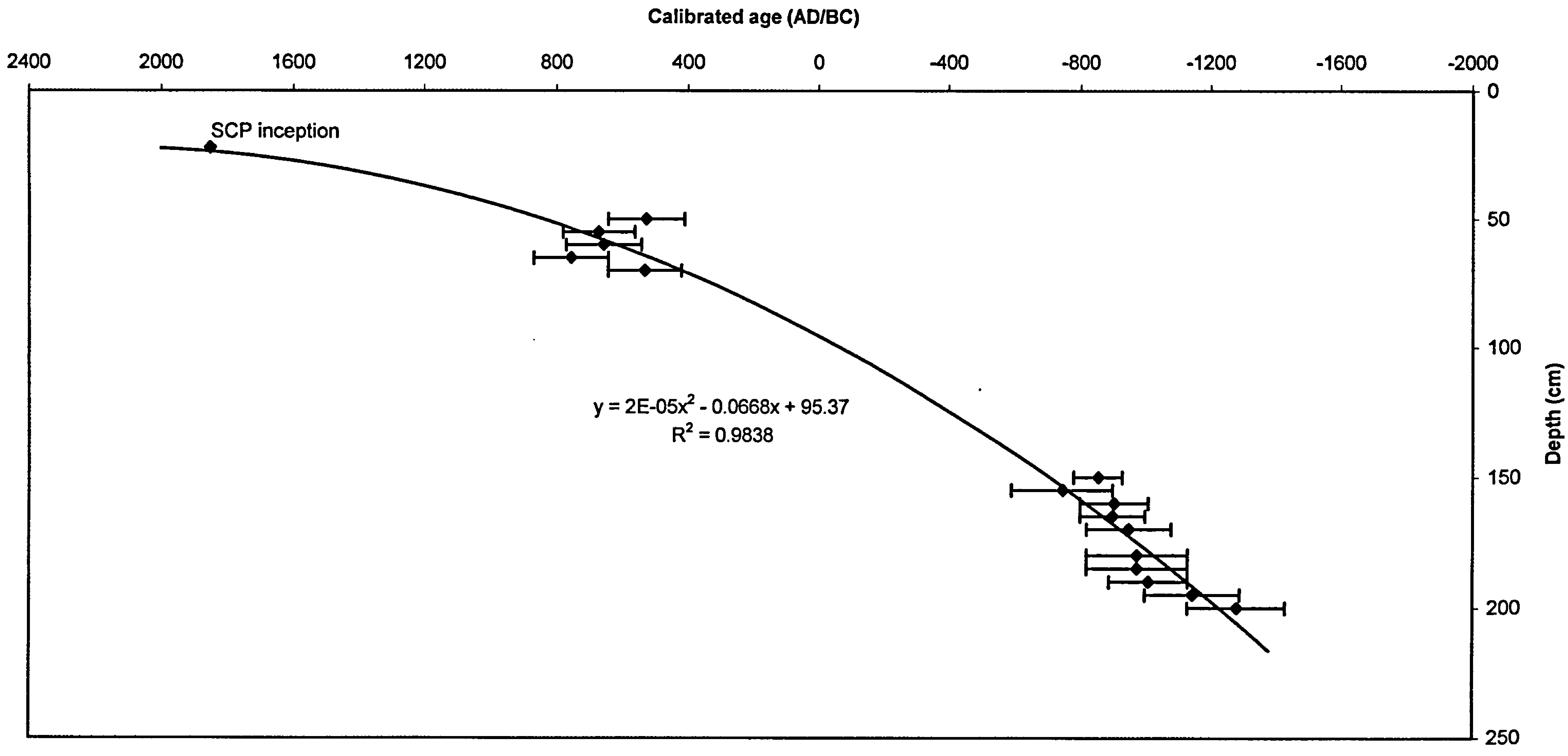


Figure 3.19 Age-depth model for Langlands Moss

3.6.1.5 Langlands Moss - Wiggle-match dating

Wiggle-match derived calendar ages are listed in Table 3.5. Owing to the close proximity of dates 6-15, these two clusters of dates have been amalgamated (Group 2). Figure 3.20 represents the best match for the ^{14}C age determinations in Group 1 (dates 1-5). The majority of the dates appear to match the curve; however, date number 4 is clearly erroneous, as it is positioned *c.* 200 ^{14}C years below the calibration curve. Apart from the last 3 dates in Group 2 (dates 6-15), the wiggle-match positions most of the dates close to the calibration curve (Figure 3.21). Although dates 6-8 appear to float above the calibration curve, they still reproduce the variations of the curve, suggesting they may also have been influenced by a possible reservoir effect. The raised positioning of the last three dates directly above what is known as the *Hallstatt*-plateau (ranging from between *c.* cal 750-400 BC), may be significant, as this phenomenon was found to occur at five out of the six cores investigated at Engbertsdijksvenen bog (The Netherlands) (Kilian *et al.*, 1995).

Table 3.5 Wiggle-matched calendar dates (AD/BC) for Langlands Moss

Group	Date number	Depth (cm)	Radiocarbon age BP (incl. 1σ error)	Wiggle-matched calendar ages
1	1	50	1310 ± 50	cal. AD 714
	2	55	1380 ± 50	cal. AD 670
	3	60	1390 ± 50	cal. AD 626
	4	65	1310 ± 50	cal. AD 582
	5	70	1530 ± 50	cal. AD 539
2	6	150	2670 ± 50	785 cal. BC
	7	155	2620 ± 40	827 cal. BC
	8	160	2760 ± 50	870 cal. BC
	9	165	2730 ± 50	912 cal. BC
	10	170	2790 ± 50	955 cal. BC
	11	180	2800 ± 50	1040 cal. BC
	12	185	2800 ± 50	1082 cal. BC
	13	190	2840 ± 40	1125 cal. BC
	14	195	2940 ± 40	1167 cal. BC
	15	200	3060 ± 50	1210 cal. BC

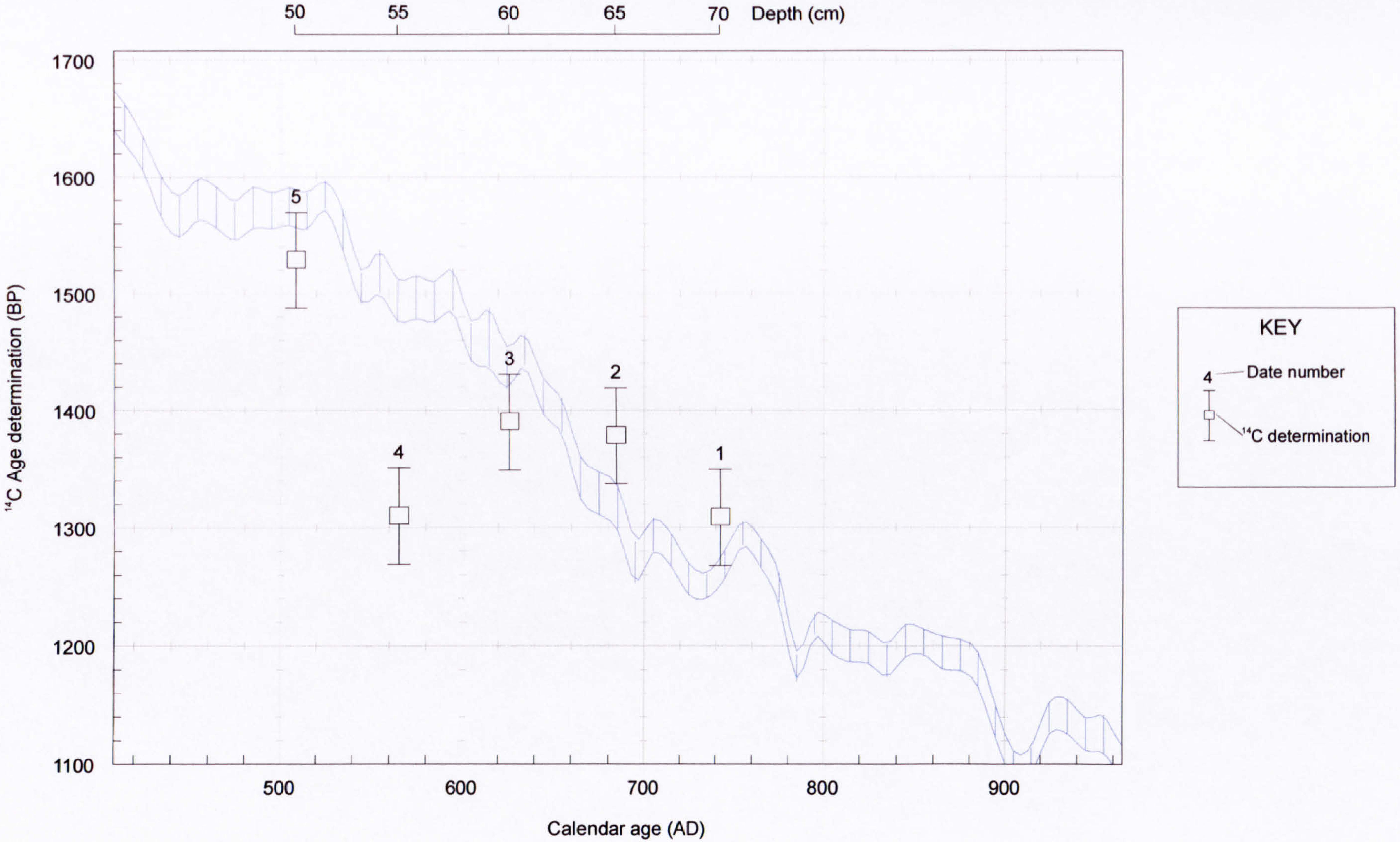


Figure 3.20 Best Match for Group 1: Langlands Moss

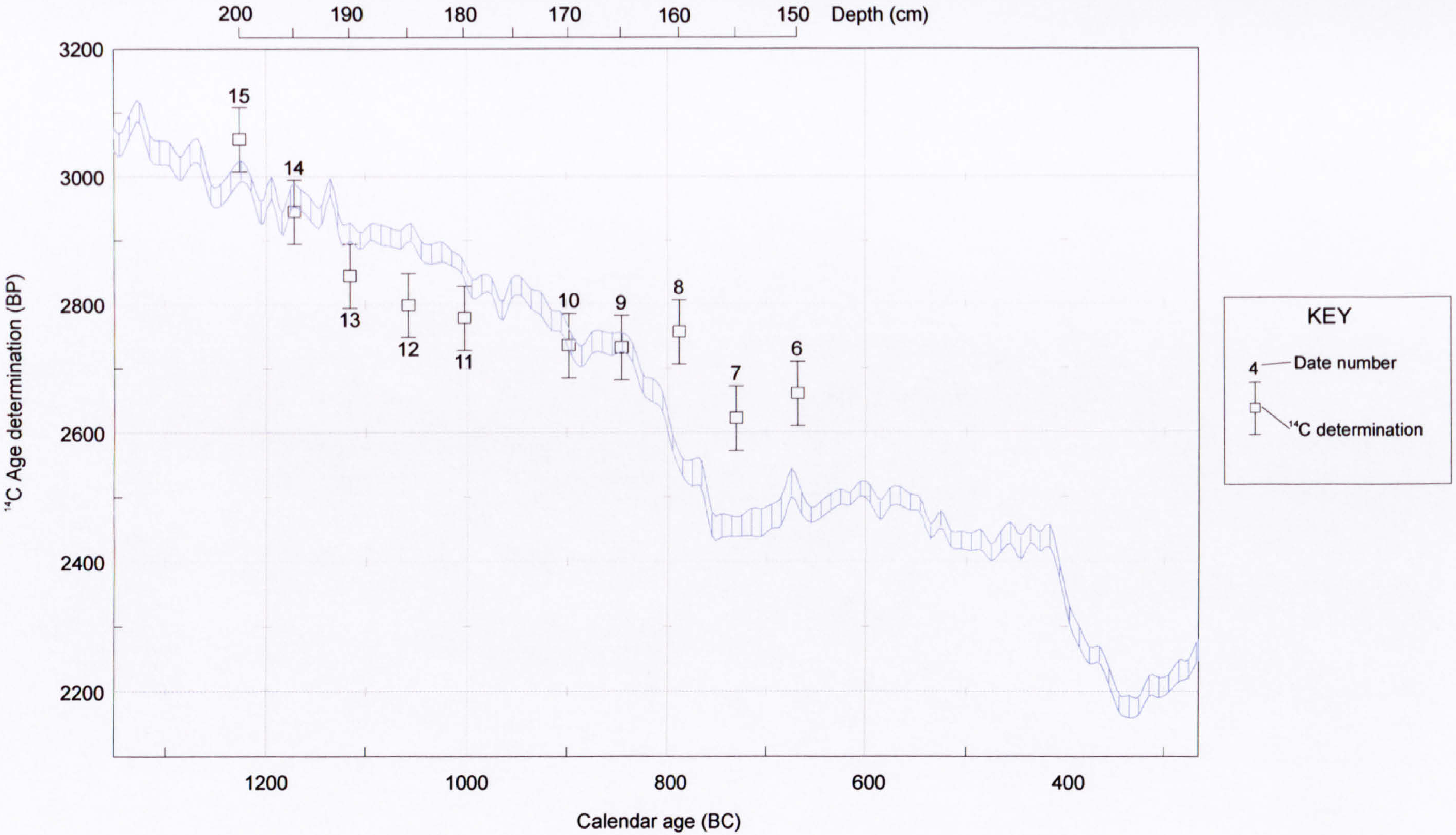


Figure 3.21 Best Match for Groups 2 and 3: Langlands Moss

3.6.1.6 Mynydd Llangatwg - Calibration

AMS ^{14}C dates obtained for Mynydd Llangatwg are listed in Table 3.6. Plotting the mid-point values against depth produces the age-depth model shown in Figure 3.22. The age-depth relationship for this site has an r^2 value of 0.989. A clear change in accumulation rates can be determined from the trendline, with a considerable reduction in peat growth from *c.* 400 cal. BC to the surface layers. The modelled accumulation rate remains relatively constant in the lower section of the core with an average rate of between 0.76-0.77 mm yr^{-1}, which steadily decreases to 0.43 mm yr^{-1} in the last *c.* 30 cm of peat growth.

Table 3.6 List of AMS ^{14}C determinations for Mynydd Llangatwg

Date number	Depth (cm)	Radiocarbon age BP (incl. 1σ error)	2σ calibrated range 95.4% conf. level	Mid-point of 2σ range
1	29	675 ± 45	cal. AD 1260-1400	cal. AD 1330
2	33	875 ± 50	cal. AD 1030-1260	cal. AD 1145
3	37	1450 ± 45	cal. AD 530-670	cal. AD 600
4	41	1855 ± 45	cal. AD 60-320	cal. AD 190
5	45	2065 ± 45	200 cal. BC-cal. AD 50	75 cal. BC
6	94	2760 ± 55	1020-800 cal. BC	910 cal. BC
7	98	2990 ± 45	1380-1040 cal. BC	1210 cal. BC
8	102	2705 ± 45	970-790 cal. BC	880 cal. BC
9	106	2710 ± 45	970-790 cal. BC	880 cal. BC
10	110	2785 ± 55	1080-810 cal. BC	945 cal. BC
11	183	3565 ± 50	2040-1740 cal. BC	1890 cal. BC
12	187	3485 ± 55	1950-1680 cal. BC	1815 cal. BC
13	191	3630 ± 45	2140-1880 cal. BC	2010 cal. BC
14	195	3680 ± 40	2200-1910 cal. BC	2055 cal. BC
15	199	3670 ± 50	2200-1890 cal. BC	2045 cal. BC
16	229	3965 ± 50	2580-2300 cal. BC	2440 cal. BC
17	233	3950 ± 50	2580-2290 cal. BC	2435 cal. BC
18	237	3995 ± 50	2670-2340 cal. BC	2505 cal. BC
19	241	3965 ± 50	2580-2300 cal. BC	2440 cal. BC
20	245	3995 ± 50	2670-2340 cal. BC	2505 cal. BC

As with Langlands Moss, there appears to have been some form of disturbance in the upper section of the core which has resulted in a considerably reduced rate of accumulation. Although dates 1-5 are consecutively ordered, they reflect *c.* 200-400 years of growth in just 4 cm of peat. This strongly suggests a change in hydrological conditions at this period in time, most likely caused by local drainage or subsidence. For this reason, any attempt at correlation with other datasets in this study will not employ the top 45 cm of proxy-evidence from this core.

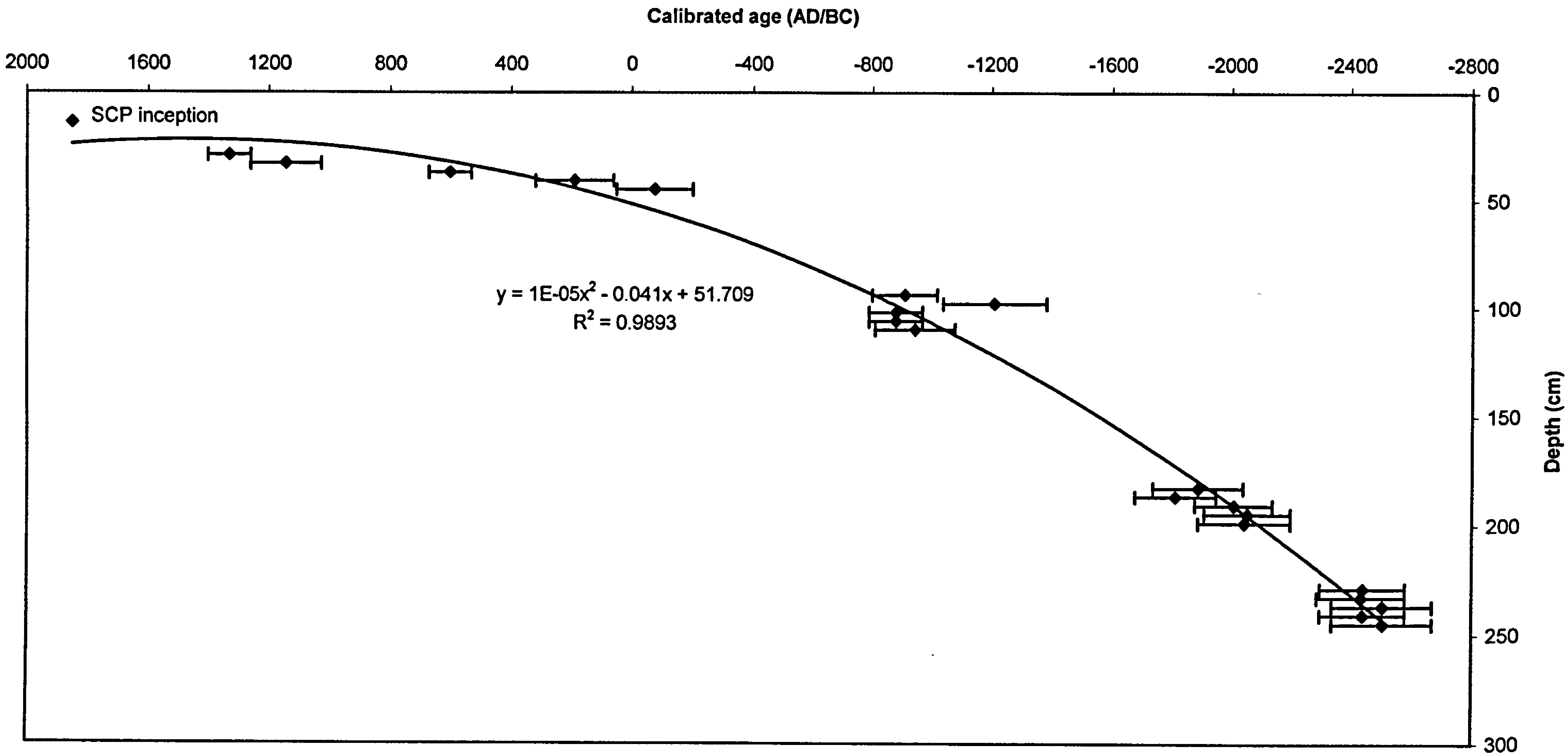


Figure 3.22 Age-depth model for Mynydd Llangatwg

3.6.1.7 Wiggle-match dating - Mynydd Llangatwg

AMS determinations were matched to the dendrochronological calibration curve in three groups, producing the singular calendar dates listed in Table 3.7. As the ^{14}C dates in Group 1 (dates 1-5) are in line with a steep part of the calibration curve, matching is straightforward and, as found by van Geel and Mook (1989), only minor compression of the dates has been required (Figure 3.23). However, on the basis of these dates, peat growth would have occurred at an extremely slow rate (*c.* 0.11 mm yr^{-1}) during this period. Group 2 (dates 6-10) cover the rapid increase in $\Delta^{14}C$ concentration beginning at *c.* 850 cal. BC (Figure 3.24). Dates 8-10 appear in line with the calibration curve, while dates 6 and 7 mirror the variation of the curve, but appear to float *c.* 100-200 ^{14}C years above the curve. As with Langlands Moss - Figure 3.21, dates 6 and 7 are positioned directly above the *Hallstatt*-plateau, which may have affected the accuracy of the ^{14}C determinations at these levels. The close proximity of the last two clusters of dates permits their matching to the calibration curve as one unit. The dates in Group 3 (dates 11-20) are generally well-matched to the curve, although, as with Group 2, dates 16-18 are floating slightly above the curve (Figure 3.25). Again, the raised positioning of these dates may have been influenced by the plateau in the calibration curve from *c.* 2450-2320 cal. BC.

Table 3.7 Wiggle-matched calendar dates (AD/BC) for Mynydd Llangatwg

Group	Date number	Depth (cm)	Radiocarbon age BP (incl. 1σ error)	Wiggle-matched calendar ages
1	1	29	675 ± 45	cal. AD 1380
	2	33	875 ± 50	cal. AD 1025
	3	37	1450 ± 45	cal. AD 670
	4	41	1855 ± 45	cal. AD 315
	5	45	2065 ± 45	39 cal. BC
2	6	94	2760 ± 55	712 cal. BC
	7	98	2990 ± 45	778 cal. BC
	8	102	2705 ± 45	844 cal. BC
	9	106	2710 ± 45	910 cal. BC
	10	110	2785 ± 55	977 cal. BC
3	11	183	3565 ± 50	1836 cal. BC
	12	187	3485 ± 55	1881 cal. BC
	13	191	3630 ± 45	1925 cal. BC
	14	195	3680 ± 40	1970 cal. BC
	15	199	3670 ± 50	2014 cal. BC
	16	229	3965 ± 50	2348 cal. BC
	17	233	3950 ± 50	2392 cal. BC
	18	237	3995 ± 50	2437 cal. BC
	19	241	3965 ± 50	2481 cal. BC
	20	245	3995 ± 50	2526 cal. BC

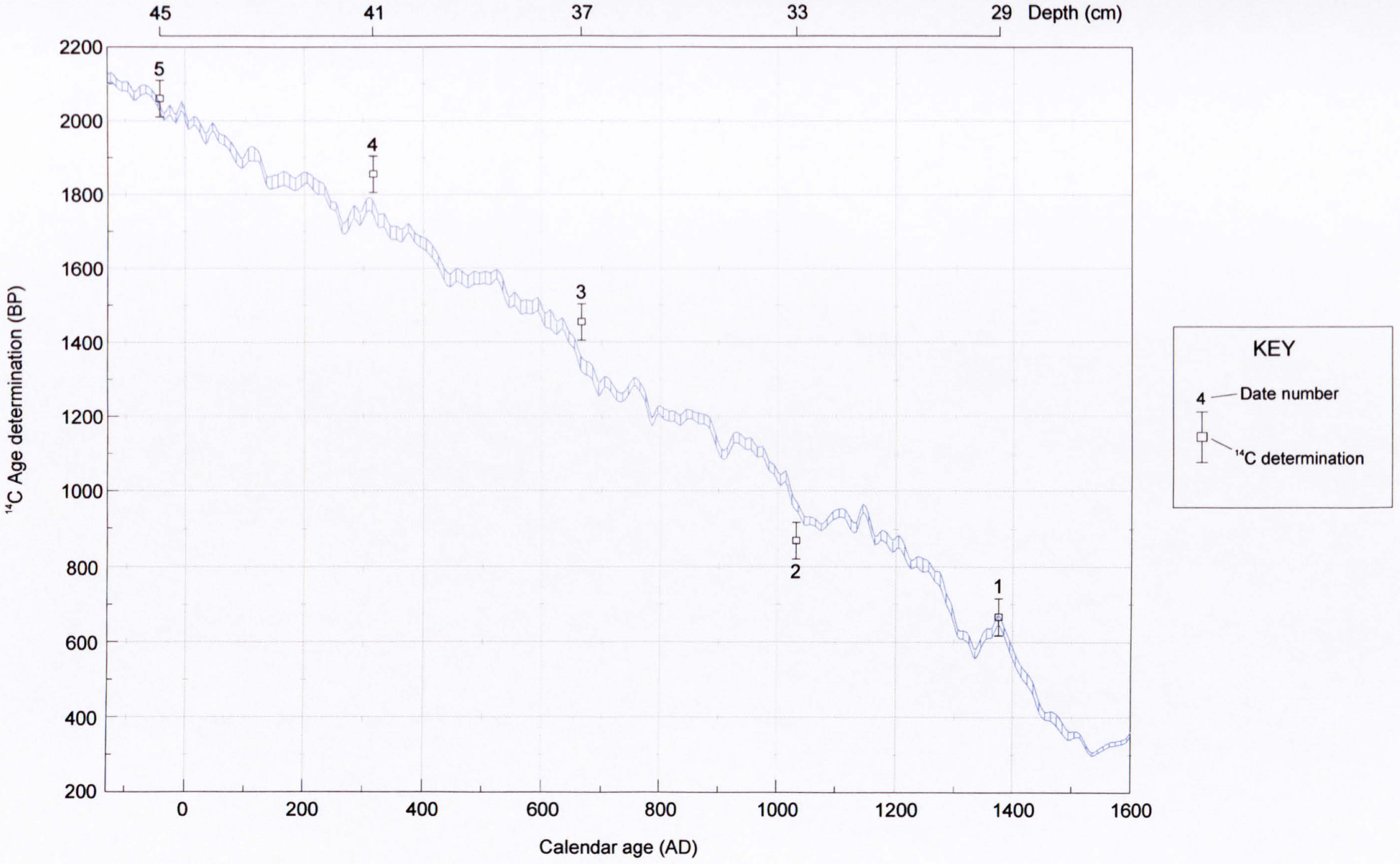


Figure 3.23 Best Match for Group 1: Mynydd Llangatwg

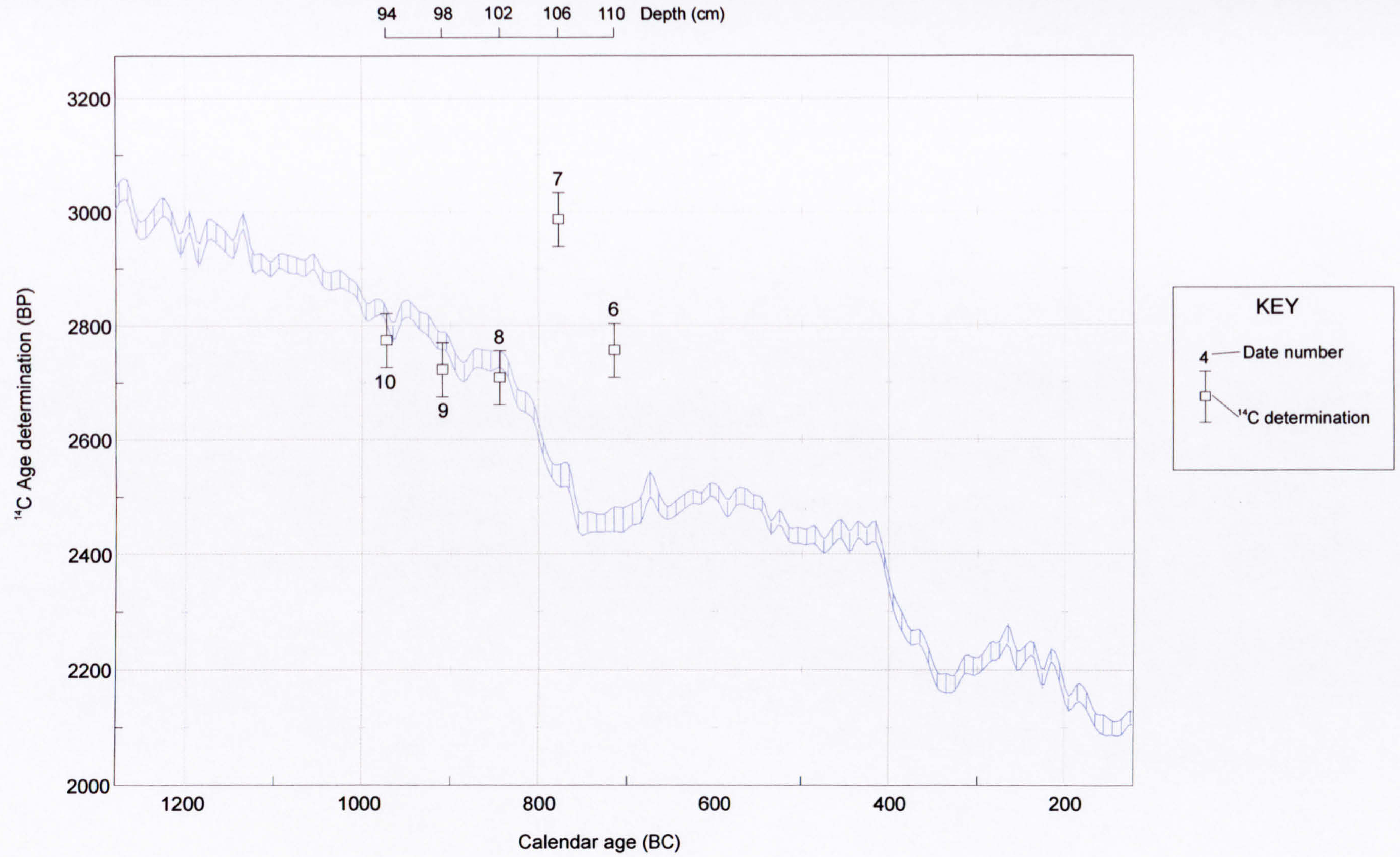


Figure 3.24 Best Match for Group 2: Mynydd Llangatwg

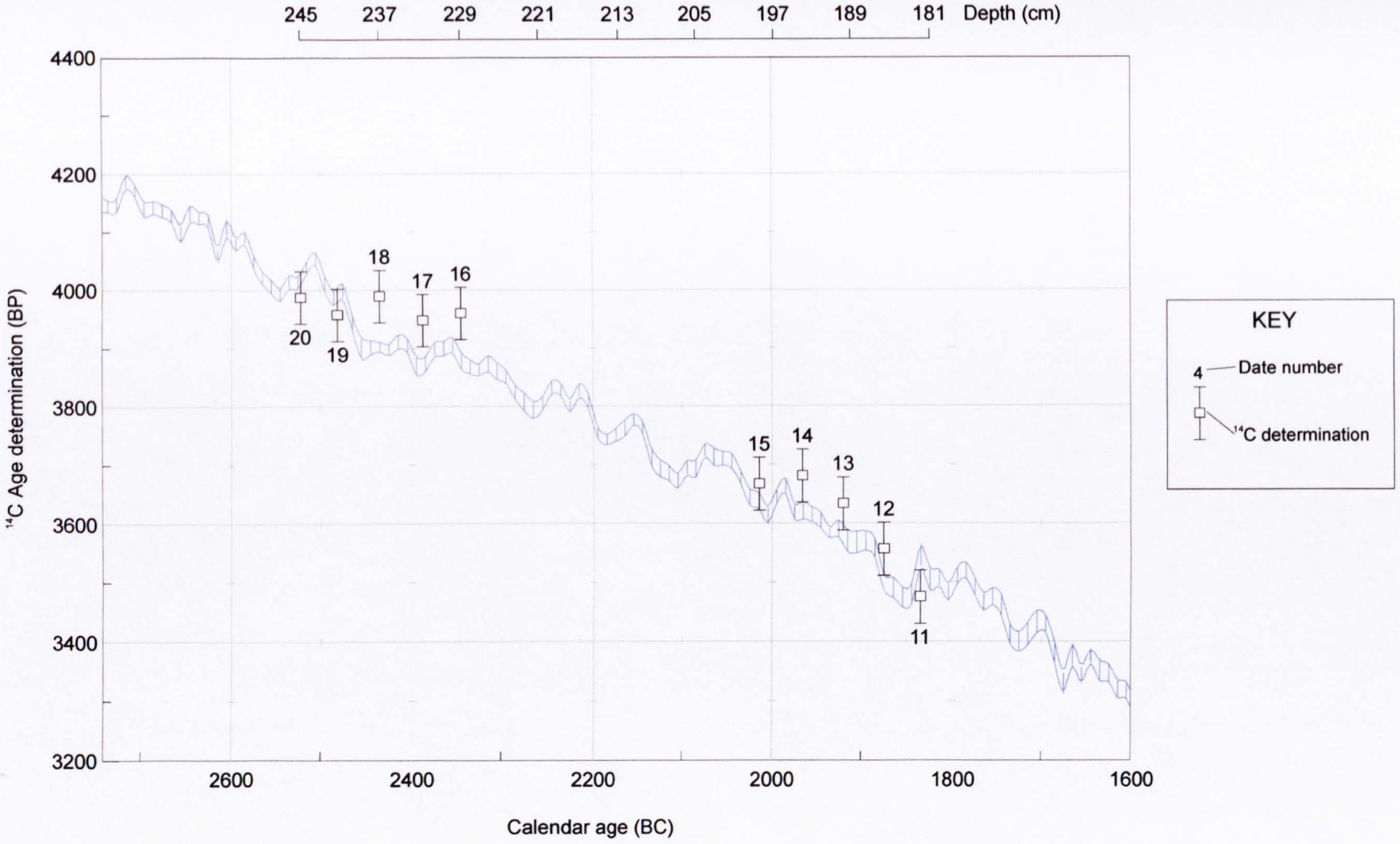


Figure 3.25 Best Match for Group 3: Mynydd Llangatwg

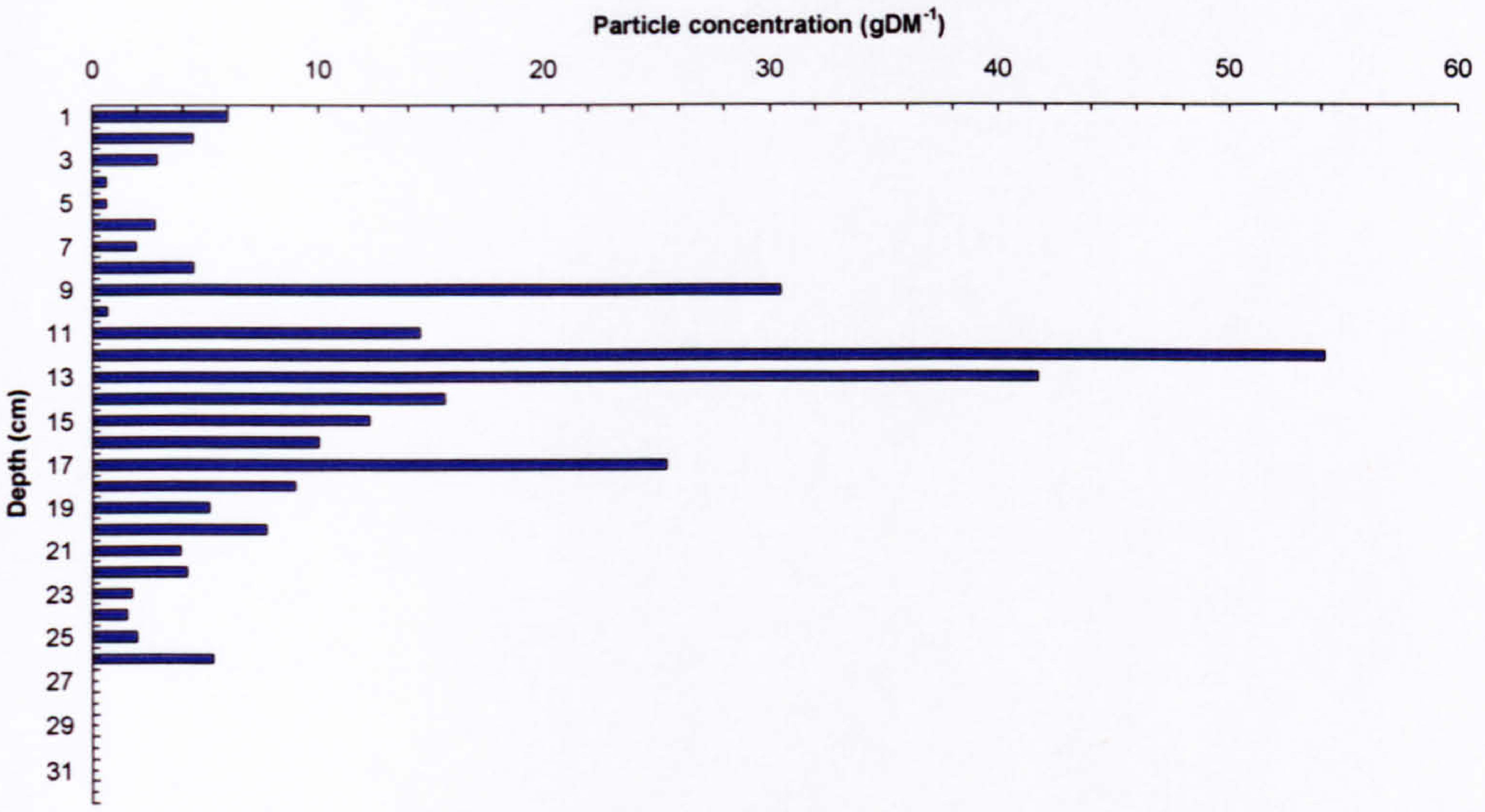
3.6.2 Spheroidal Carbonaceous Particle (SCP) Chronology

Assessment of spheroidal carbonaceous particle (SCP) concentrations has been carried out on all cores, as a means of extending the chronological control to the surface layers of peat. The beginning of particle deposition can clearly be identified at all of the locations investigated, and is taken to represent the onset of the Industrial Revolution, dated to around the mid-nineteenth century (Rose *et al.*, 1995). Rapid increases in SCP concentration are also evident in all records, which are thought to represent peaks in fossil fuel consumption, usually dating to around the 1950s or 1960s in British lakes (Rose *et al.*, 1995). In terms of cores extracted from Bolton Fell Moss (cores MC and 3), results obtained through SCP analysis can be cross-correlated with the accumulation models generated through ^{210}Pb dating, as the material used in both techniques is the same. Analysis of Core 3 was carried out by Dr. Dmitri Mauquoy, as part of collaborative research with the University of Bristol. The SCP inception depths have also been included on the ^{14}C age-depth models for each site, as a means of improving chronological control for the upper layers of peat.

3.6.2.1 SCP results - Bolton Fell Moss - Cores MC and 3

The SCP profiles for Bolton Fell Moss - Cores MC and 3 are shown in Figure 3.26. Both profiles follow similar trends, with the inception of the SCP record from *c.* 26 - 27 cm depth, rapid increases in SCP concentration and pronounced peaks in concentration at 12 cm depth and 10 cm depth, for cores MC and 3 respectively. Although both profiles appear to record synchronously both the onset of the Industrial Revolution and peaks in fossil fuel consumption, they differ in a number of other ways. Firstly, the overall rates of concentration are markedly different for the two cores, with Core MC recording almost double the particle concentration of Core 3. This may be a reflection of the difference in microform between the two coring points, with macrofossil results depicting an overall higher position on the hummock-hollow gradient for Core MC, possibly increasing the exposure of the microform to particle attraction. Secondly, the decline in concentration observed in the surface layers of Core 3 is not reflected in Core MC, where, conversely, a rise in concentration is recorded.

A



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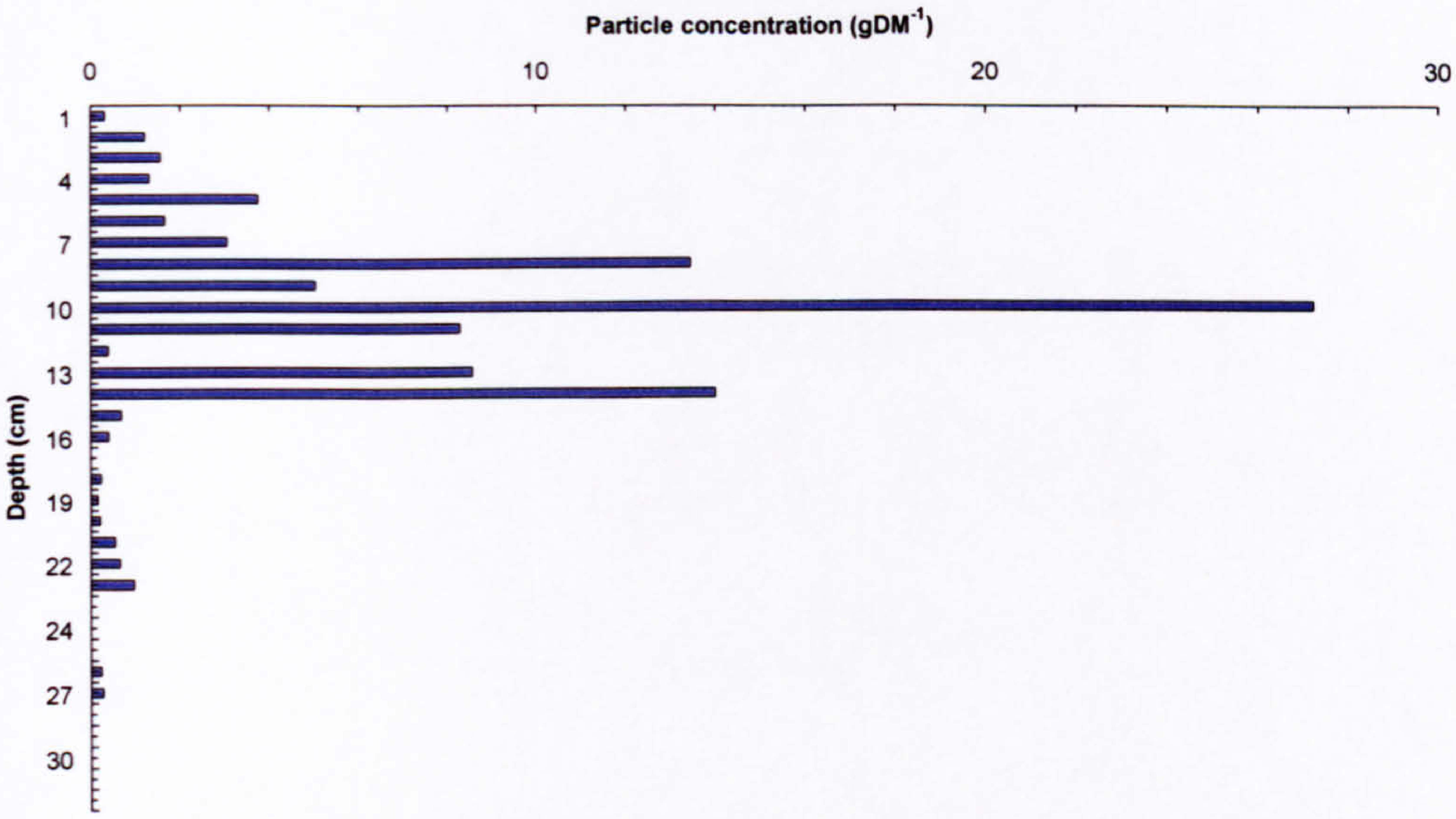

Figure 3.26 SCP profiles for Bolton Fell Moss (a) - Core MC and (b) - Core 3

(analysis of Core 3 was carried out by Dr. Dmitri Mauqouy)

3.6.2.2 SCP results - Langlands Moss

The SCP profile for Langlands Moss is shown in Figure 3.27. Particle accumulation appears to commence at *c*. 22 cm depth and there is a clear rise in concentration with a peak at *c*. 13 cm depth. It can therefore be assumed from this record that *c*. cal. AD 1850 corresponds to *c*. 22cm depth, although local fossil fuel production may have commenced at an earlier date.

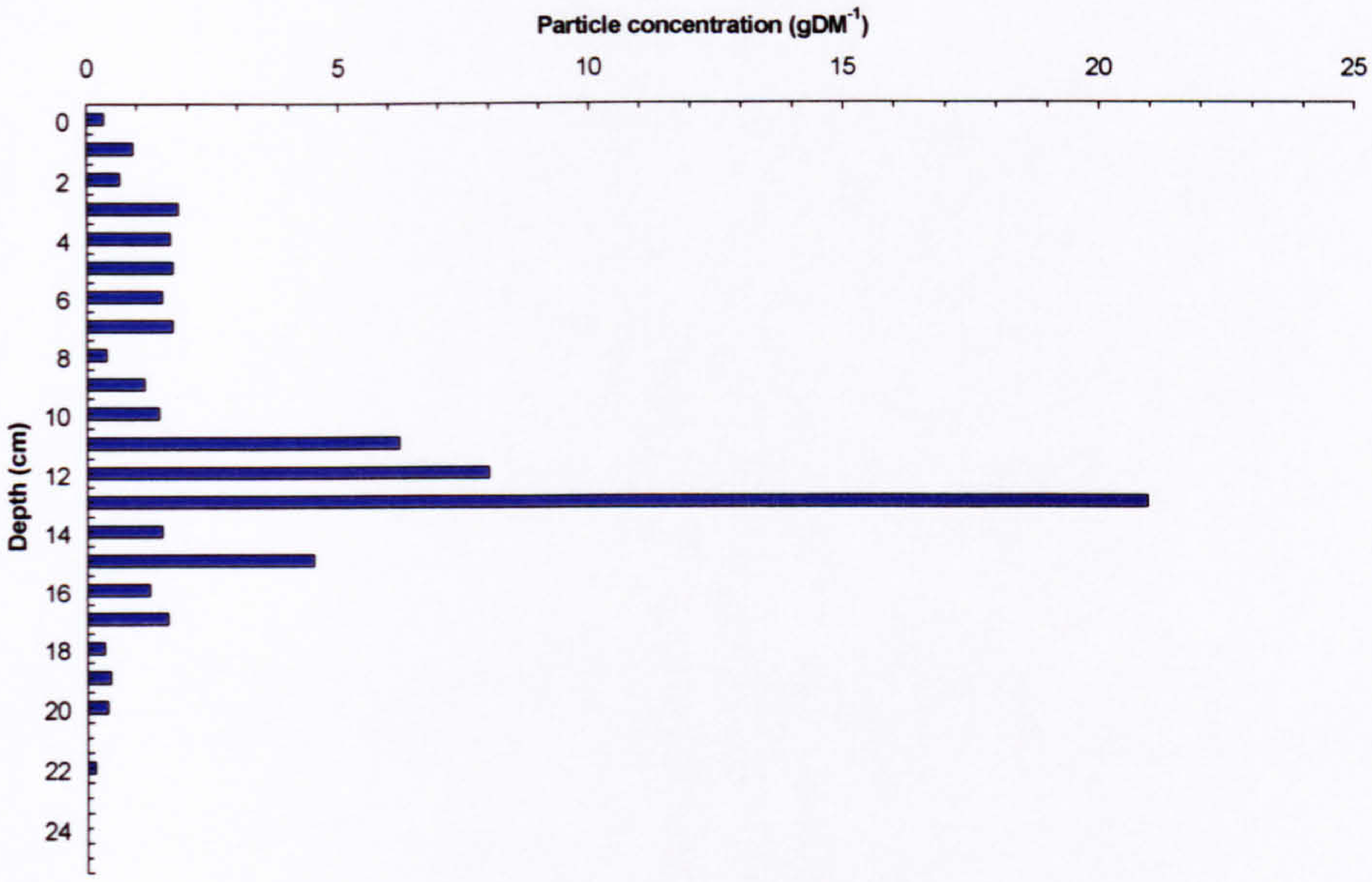

Figure 3.27 SCP profile for Langlands Moss

3.6.2.3 SCP results - Mynydd Llangatwg

The SCP profile for Mynydd Llangatwg is shown in Figure 3.28. As with the profiles from the other sites investigated, there is a clear beginning of the SCP record at *c.* 14 cm depth. Although the record begins at a much shallower depth than encountered at the other sites, this is justified by the extremely slow accumulation rates determined by the ^{14}C record in this section of the core. The overall concentration of SCPs is considerably greater for this site, with 10× the number of particles counted at the peak of the record than was recorded for Bolton Fell Moss profiles. This is most likely a reflection of the close proximity of this site to the Rhondda and Merthyr valleys, where fossil fuel burning was far more intense during this period.

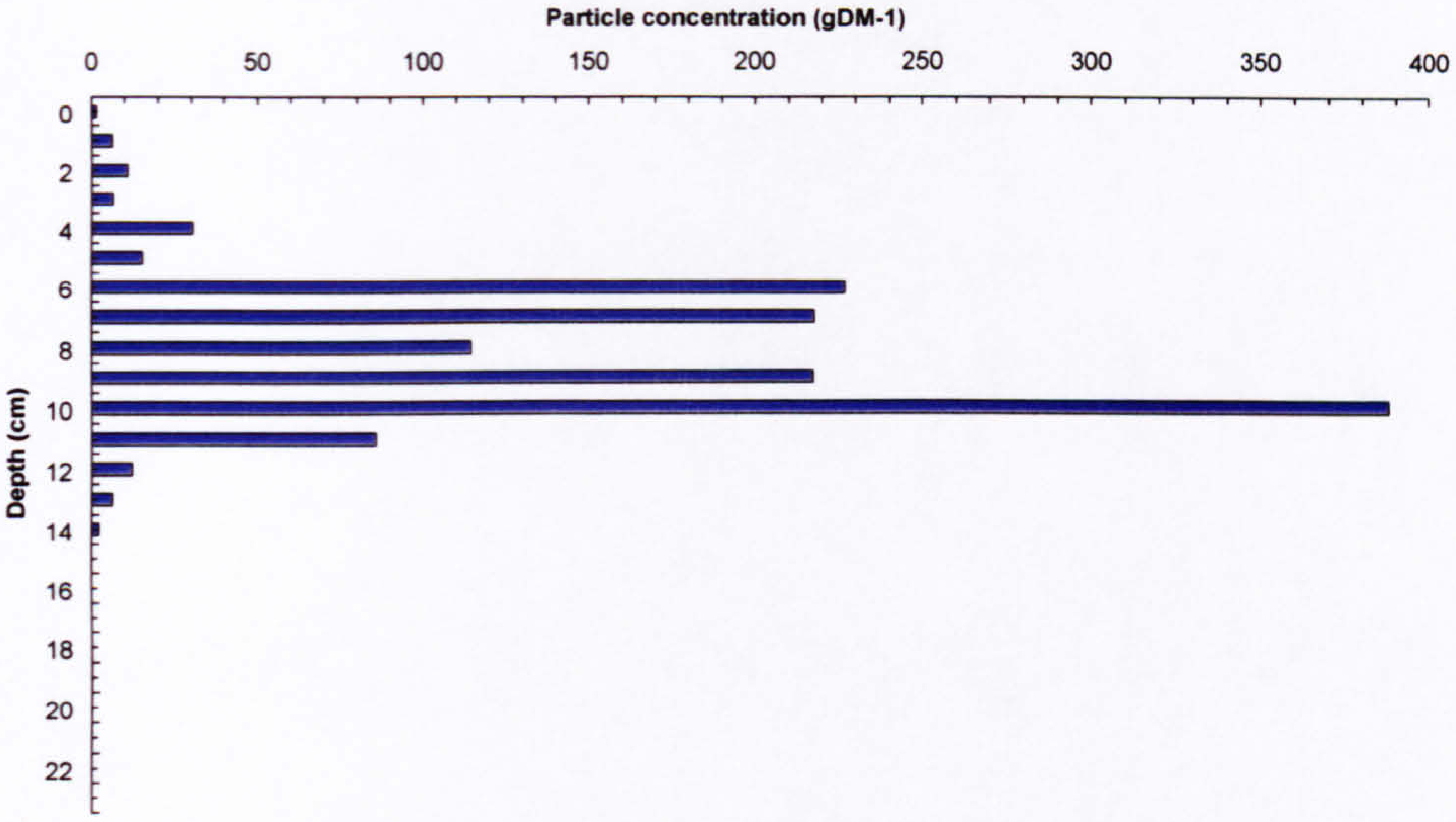

Figure 3.28 SCP profile for Mynydd Llangatwg

3.6.3 Lead-210 Chronology

Further chronological control for the top sections of cores extracted from Bolton Fell Moss has been determined using ^{210}Pb dating. Average accumulation rates have been modelled for the upper peat layers, thereby providing supporting evidence for the SCP results and radiocarbon chronologies for this site.

Lead-210 concentration profiles for Cores MC and 3 are shown in Figure 3.29.

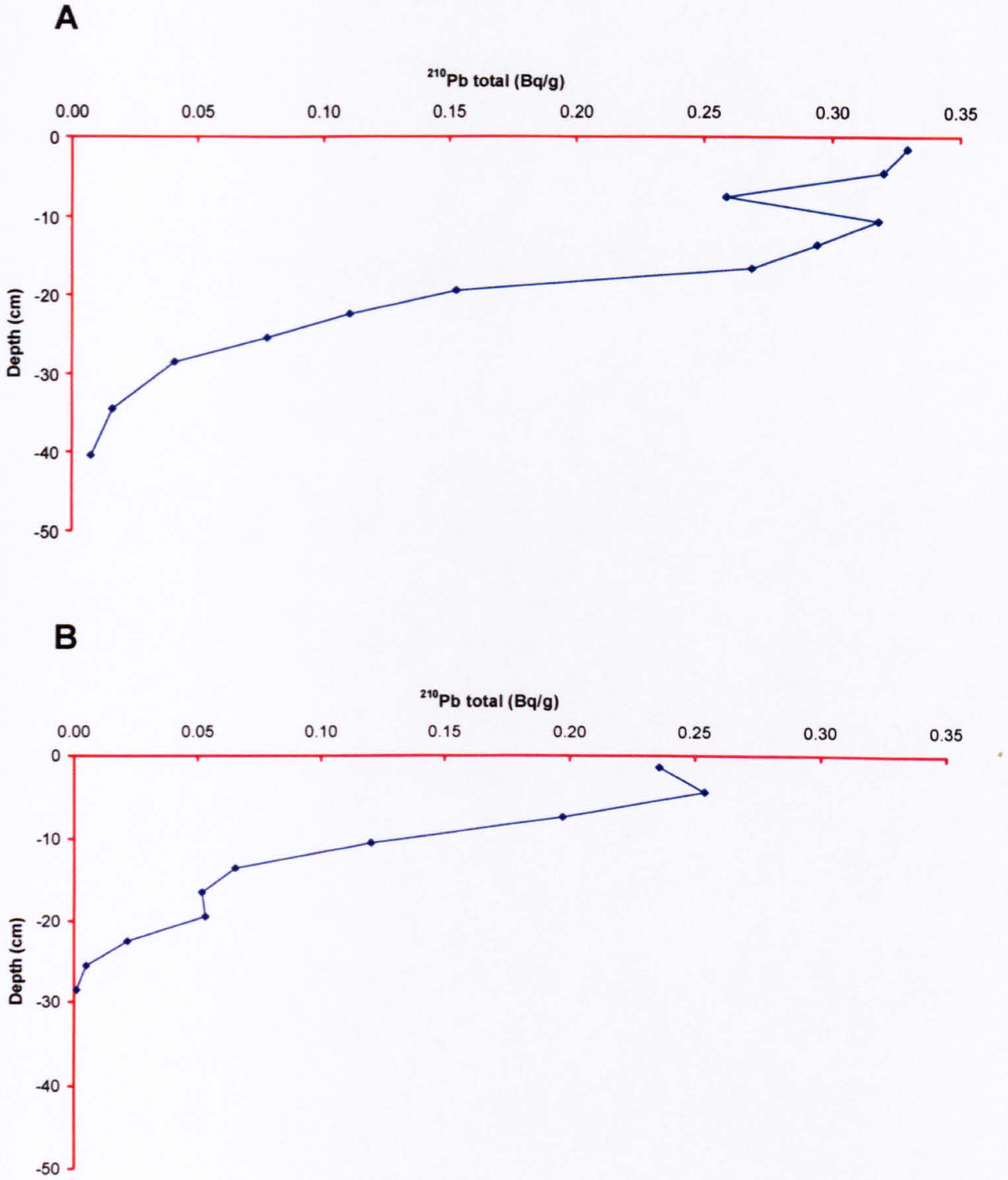

Figure 3.29 Lead-210 concentration profiles for Bolton Fell Moss (a) - Core MC and (b) - Core 3 (analysis carried out by Dr Andy Cundy, University of Southampton)

The considerable differences between the two curves, with higher concentrations of ^{210}Pb being recorded to a greater depth for Core MC, may also be a result of the difference in microform between these two coring points. Macrofossil results suggest that conditions around coring point MC, especially in the upper layers, were considerably drier than at coring point 3, possibly forming a low-hummock microform. This may have led to higher concentrations of ^{210}Pb being deposited at coring point MC, as is often the case with elevated microforms (Appleby and Oldfield, 1992). This difference in concentration is also reflected in the age-depth model (Figure 3.30). By applying the 'constant flux constant sedimentation rate' (CF:CS) model (also known as the 'simple' model) of ^{210}Pb dating (Robbins, 1978), an average accumulation rate can be determined by the slope of the least squares fit for the natural log of the $^{210}Pb_{excess}$ activity versus depth.

The steepness of the trend line for Core MC clearly demonstrates the high accumulation rate modelled for this part of the bog, with a sediment accretion rate of 3.0 mm/yr^{-1} (standard error range = 2.7 - 3.4 mm/yr, 2 standard deviation range = 2.4 - 4.1 mm/yr). This compares with a sediment accretion rate of 1.8mm per year (standard error range = 1.6 - 2.1 mm/yr, 2 standard deviation range = 1.3 - 2.8 mm/yr) for Core 3, extracted from a lawn microform only *c.* 150 m away. Comparisons between the ^{210}Pb profile and the SCP record can be made, as the two dating techniques have been carried out at directly comparable depths. Plotting the inception depth of the SCP rise against its estimated calendar date (i.e., *c.* AD 1850) (see Figure 3.30) clearly demonstrates the correlation between these two dating methods for Core 3.

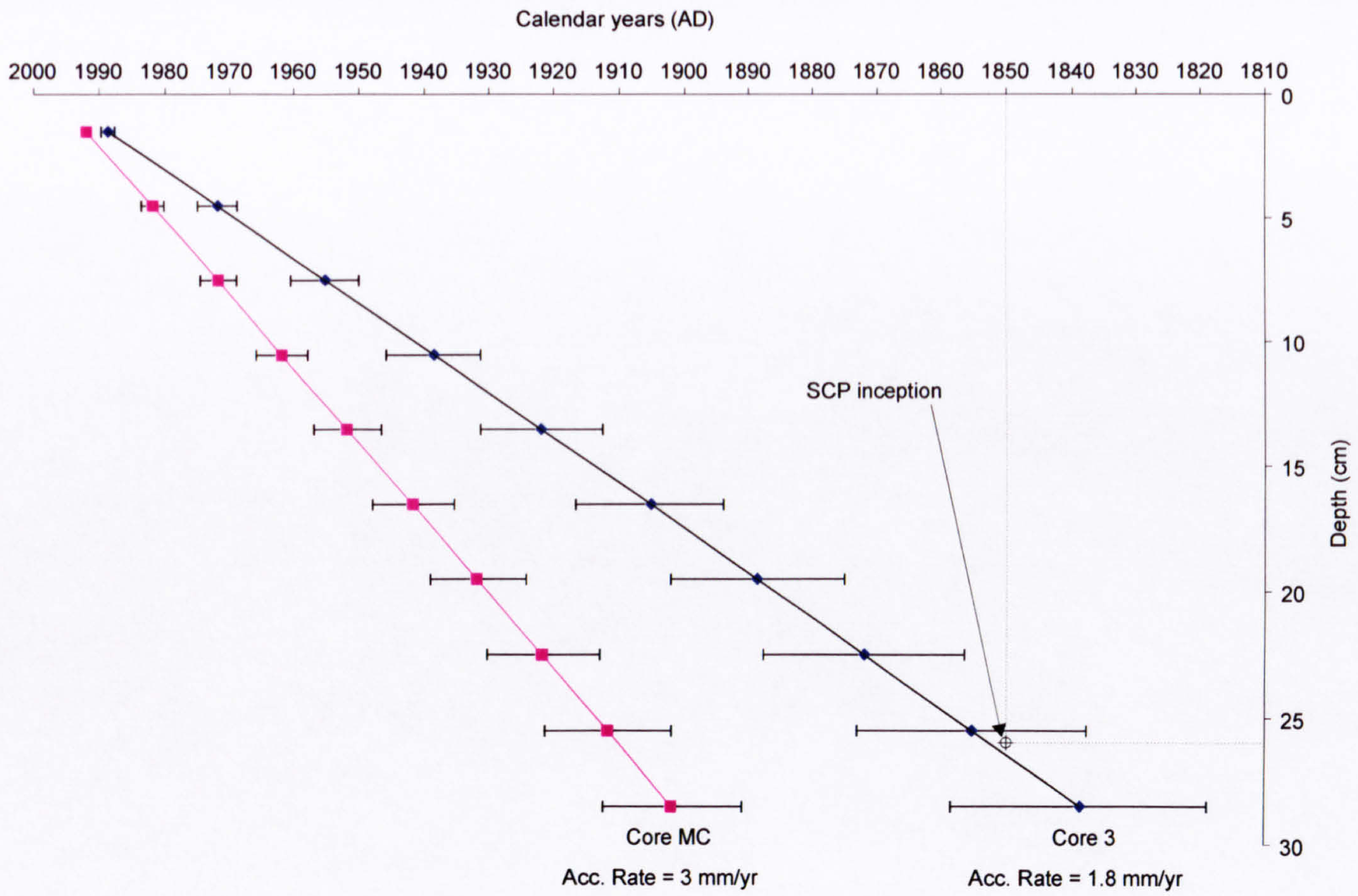

Figure 3.30 Age-depth graph showing modelled ^{210}Pb accumulation rates for Bolton Fell Moss - Core MC and 3

3.7 Summary

Curves generated through the colorimetric humification analysis of core material appear to record a series of rapid fluctuations in mire surface conditions at each of the sites investigated. Results of the high-resolution macrofossil analyses also record numerous changes in species composition at each site, demonstrating the considerable variation in the vegetational composition of peat bogs in the British Isles. Contrary to the findings of previous studies carried out in this region of north-west Europe, the characteristic extinction of *Sphagnum imbricatum* and its subsequent replacement by *Sphagnum magellanicum* was only recorded in one out of the four cores analysed in this study. Despite both cores being extracted from low-ridge microforms, evidence for intra-site variability is also apparent from the macrofossil records, which demonstrate a remarkably different pattern of vegetational change. Conversely, the humification records from this site both appear to record a similar pattern of fluctuations in mire surface conditions, suggesting that this technique is a more sensitive measure of proxy-climatic change.

The application of wiggle-match dating has provided more precise chronological control than would otherwise be achieved through simple calibration. The combination of these wiggle-matched dates and the relative dates obtained for the more recent peat, derived through SCP analysis and lead-210 dating, has enabled the generation of interpolated time-scales for each of the sites investigated. In the following chapter, comparisons of these dated proxy-climatic curves are made against time, and further statistical analyses of the raw macrofossil datasets provide additional sources of mire surface reconstructions.

Chapter 4 Proxy-Climate Reconstructions

4.1 Introduction

In this chapter, attempts are made to reconstruct changes in mire surface conditions by statistically analysing the macrofossil datasets for each site investigated. Using Weighted Averages Ordination (WAO) and Detrended Correspondence Analysis (DCA), proxy-climate curves are generated and compared with the humification absorbance curves as a means of identifying synchronous shifts to either wetter or relatively drier conditions.

Proxy-climate curves are plotted against a reconstructed time-scale, developed through linear interpolation of the wiggle-matched ^{14}C AMS chronologies, thereby enabling the dating of these individual variations in mire surface conditions. Inferences are made as to possible mechanisms for these changes, based upon comparisons with other studies and documented records for each of the relevant regions studied.

4.2 Weighted-averages Ordination (WAO)

This simple technique, originally developed by Dupont (1986), is employed here to reconstruct mire surface conditions at time of deposition from plant macrofossil components. It involves the development of a wetness index, where each macrofossil taxon is assigned a weight, reflecting its relative position on the hummock-hollow gradient (Figure 4.1). The abundance of each taxon is multiplied by this value and repeated for each taxon at that level. By adding together these values and dividing by the total abundance of macrofossil taxa in the sample, an average mire wetness index value can be determined. Since the development of this 'Dupont' index, a number of other authors, including Haslam (1987), have employed the technique unaltered, while others (Stoneman, 1993; Mauquoy, 1997) have added new components and adjusted the weights assigned to each taxon.

In an attempt to improve the accuracy of the mire surface reconstructions, Stoneman (1993) assigned equal weights to *Sphagnum imbricatum* and *Sphagnum magellanicum*, reflecting the take over of the former by the latter at all sites he investigated. He also assumed leaves of *Sphagnum* section Acutifolia to be largely composed of *Sphagnum capillifolium* var. *rubellum*, a low hummock-former, and so assigned a mid-range weight to this component. Mauquoy (1997) also made some minor alterations to the index, although the majority of the weights applied by Stoneman (1993) remained unaltered. An exception is *Sphagnum papillosum*, to which he applied a slightly lower weight, as in Cumbria it occupies a lower position on the hummock-hollow gradient (Mauquoy, 1997). He also included sedge species and non-*Sphagnum* mosses in the index, as a means of improving mire water level reconstructions.

The index employed by Mauquoy (1997) has also been adopted for this study, although distances between weight changes have been increased, as a means of highlighting the reconstructed fluctuations in surface conditions (Table 4.1).

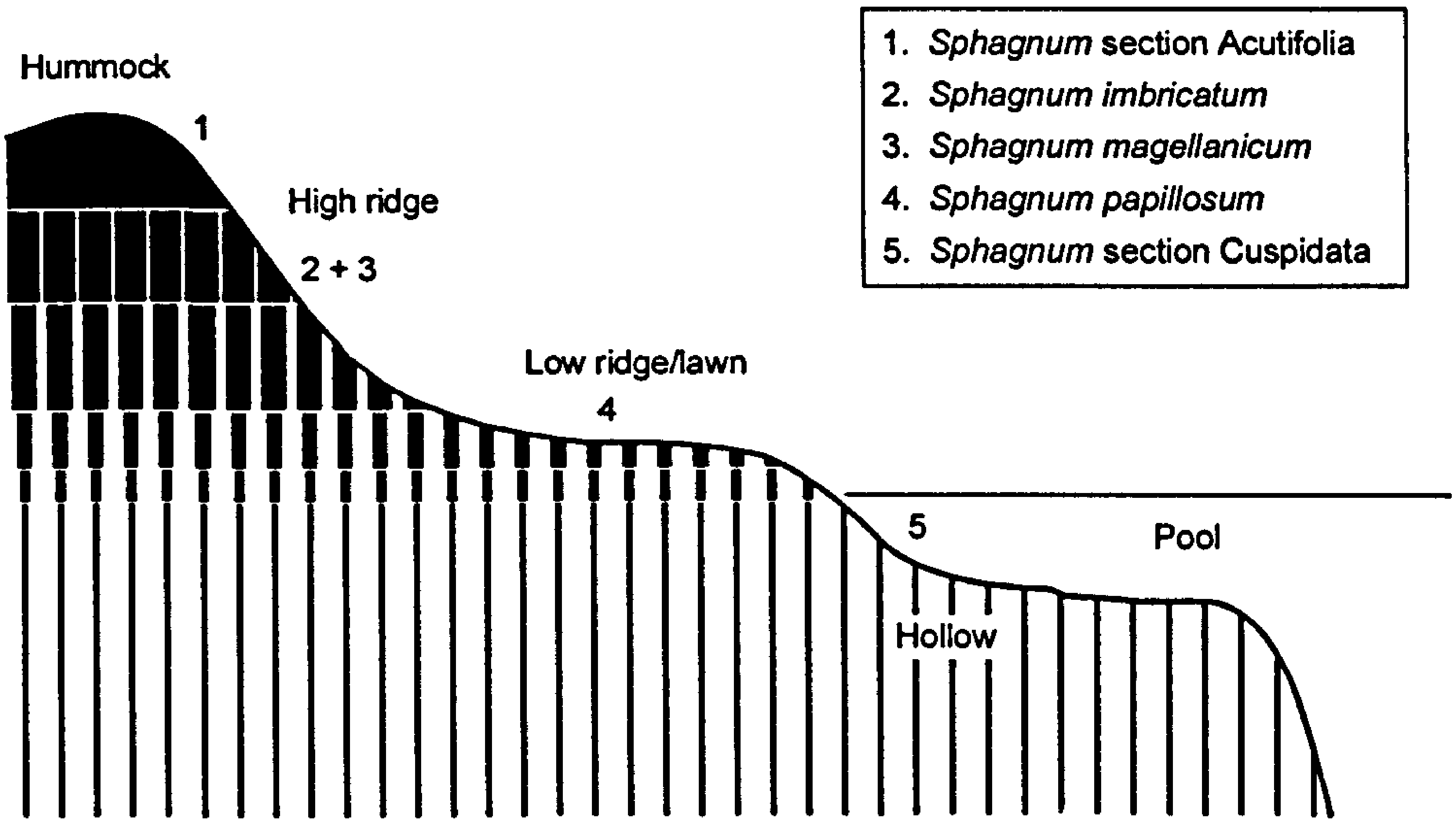

Figure 4.1 Generalised distribution of *Sphagnum* species across hummock-hollow gradient (adapted from Lindsay *et al.*, 1988)

Table 4.1 Macrofossil weights and Dupont index values

Component	Weight
Unidentified organic matter (UOM)	13
Ericales	13
Monocotyledons undifferentiated	11
Eriophorum vaginatum	11
Trichophorum cespitosum	9
Polytrichum juniperum/alpestre type	9
Aulacomnium palustre	7
Sphagnum section Acutifolia	7
Sphagnum imbricatum	5
Sphagnum magellanicum	5
Rhynchospora alba	3
Sphagnum papillosum	3
Eriophorum angustifolium	2
Sphagnum section Cuspidata	1

No attempt was made to develop a wetness index for testate amoebae species, as the selective identification of indicator species would most likely produce rather subjective results.

4.2.1 Bolton Fell Moss - Core MC - Dupont Index Values

As with the humification record for this core, reconstructed Dupont index values record highly variable conditions for this part of the bog (Figure 4.2). The lowest values, implying wetter conditions, are sustained from the base of the core (*c.* cal. AD 324) until *c.* cal. AD 1010, reflecting the high proportions of *Sphagnum* section Cuspidata and hydrophilous testate amoebae species in this section.

Other inferred wet phases occur between cal. AD 1130-1160, cal. AD 1250-1315, *c.* cal. AD 1485-1505 and at *c.* cal. AD 1380, *c.* cal. AD 1475, *c.* cal. AD 1570 and cal. AD 1625. Inferred drier phases, reflected by higher index values, occur between *c.* cal. AD 1050-1130, cal. AD 1190-1240, *c.* cal. AD 1320-1360, *c.* cal. AD 1420-1440, *c.* cal. AD 1515-1530, cal. AD 1580-1605 and from cal. 1670 to the surface. The majority of these values correlate well with the humification record (see Figure 3.2), which displays a clear rise in absorbance residuals from *c.* 65 cm to the top of the core.

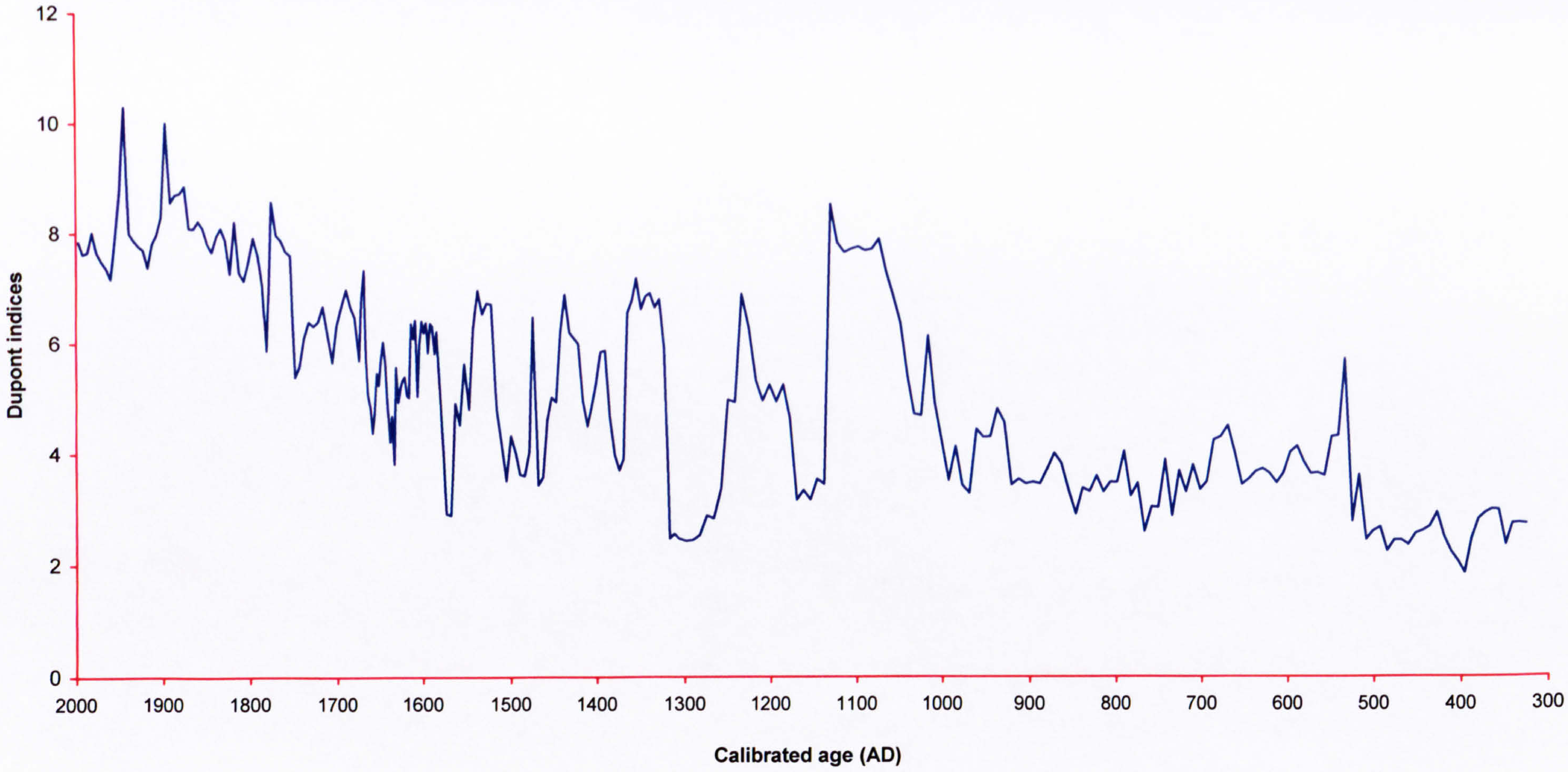

Figure 4.2 Dupont index values: Bolton Fell Moss - Core MC

4.2.2 Bolton Fell Moss - Core 3 - Dupont Index Values

The reconstructed Dupont curve for the second core taken from Bolton Fell Moss (Core 3) is shown in Figure 4.3. The estimated time-scale has been generated through linear interpolation between AMS dates (at 39 and 423 cm depth) and the lead-210 chronology.

The lowest index values, reflecting inferred wet phases, are recorded between *c.* 490-350 cal. BC, *c.* cal. AD 50-110, *c.* cal. AD 580-750, *c.* cal. AD 1450-1680 and at *c.* cal. AD 15, *c.* cal. AD 100, *c.* cal. AD 390, *c.* cal. AD 460, *c.* cal. AD 950, *c.* cal. AD 1070, *c.* cal. AD 1200 and *c.* cal. AD 1240. The rapid decline in values at *c.* cal. AD 580 is reflected in the macrofossil record by the extinction of *Sphagnum imbricatum* which, coinciding with a peak in *Sphagnum* section Cuspidata, can also be identified in the humification record as a distinct trough at this level. The highest index values, recorded at *c.* cal. 600 BC, *c.* cal. 200 BC and at *c.* cal. 140 BC, reflect a significant decrease in *Sphagnum* species representation, and rises in proportions of drier mire taxa (UOM and Ericales), implying abrupt shifts to drier mire surface conditions. Unfortunately, core material between 224-216 cm was damaged during storage and so no macrofossil data were available for this section of the core. Other inferred dry phases occur at *c.* cal. AD 155, *c.* cal. AD 490, *c.* cal. AD 1180 and between *c.* cal. AD 1250-1440 and *c.* cal. AD 1710 and the surface.

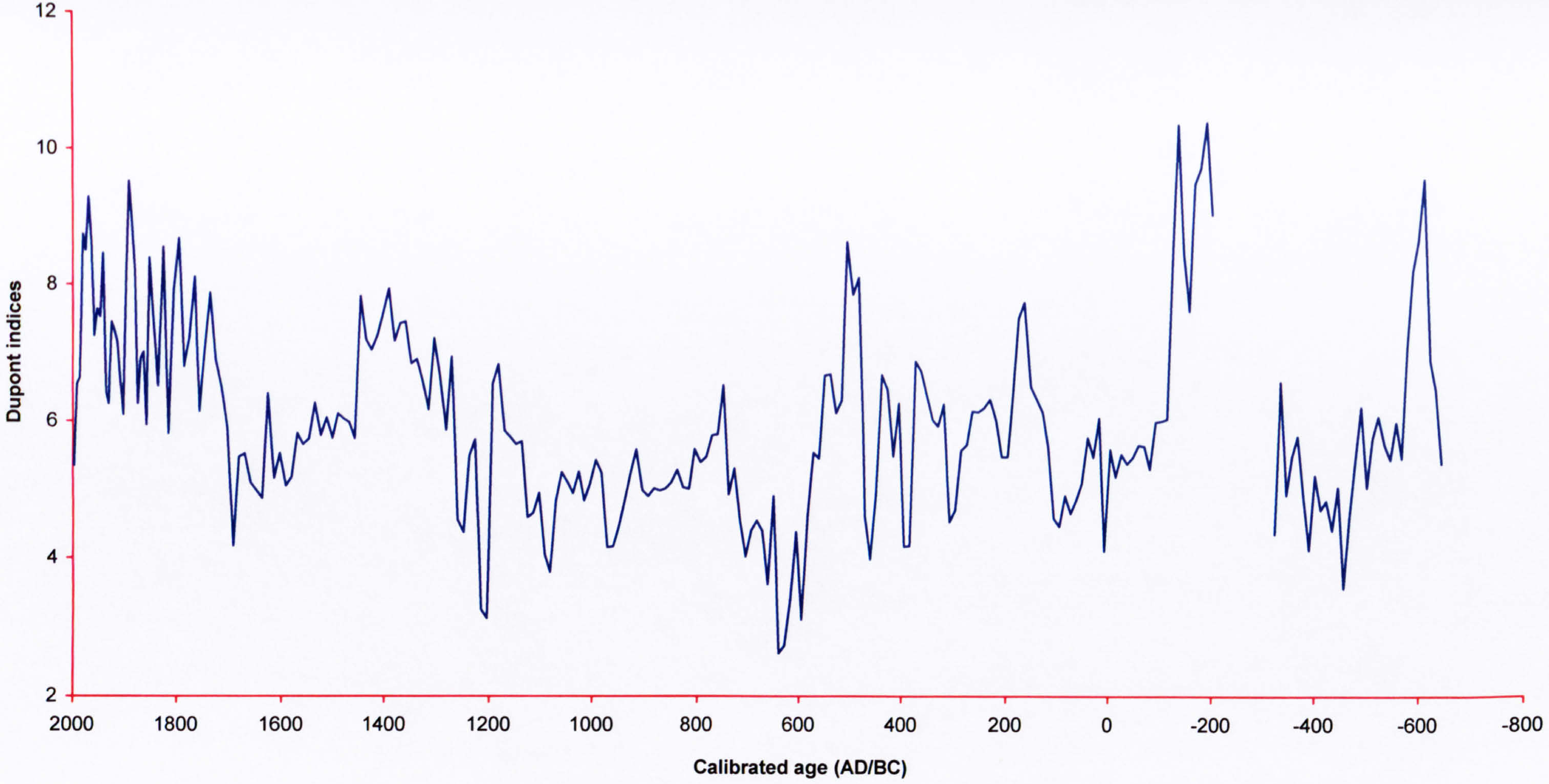

Figure 4.3 Dupont index values: Bolton Fell Moss - Core 3

4.2.3 Langlands Moss - Dupont Index Values

The Dupont curve for Langlands Moss is shown in Figure 4.4. In contrast to curves generated for Bolton Fell Moss, the index values are generally higher for this site. The highest peaks, reflecting drier phases are recorded between *c.* 180 cal. BC-cal. AD 230 and *c.* cal. AD 720-1750. These dry phases are clearly represented in the raw macrofossil dataset by high proportions of UOM, Ericales and Monocots. undiff.

Inferred wet phases, reflected by a decline in index values, are recorded between *c.* 960-760 cal. BC, *c.* 560-210 cal. BC, *c.* cal. AD 210-450, cal. AD 680-710 and at *c.* 90 cal. BC and *c.* cal. AD 5.

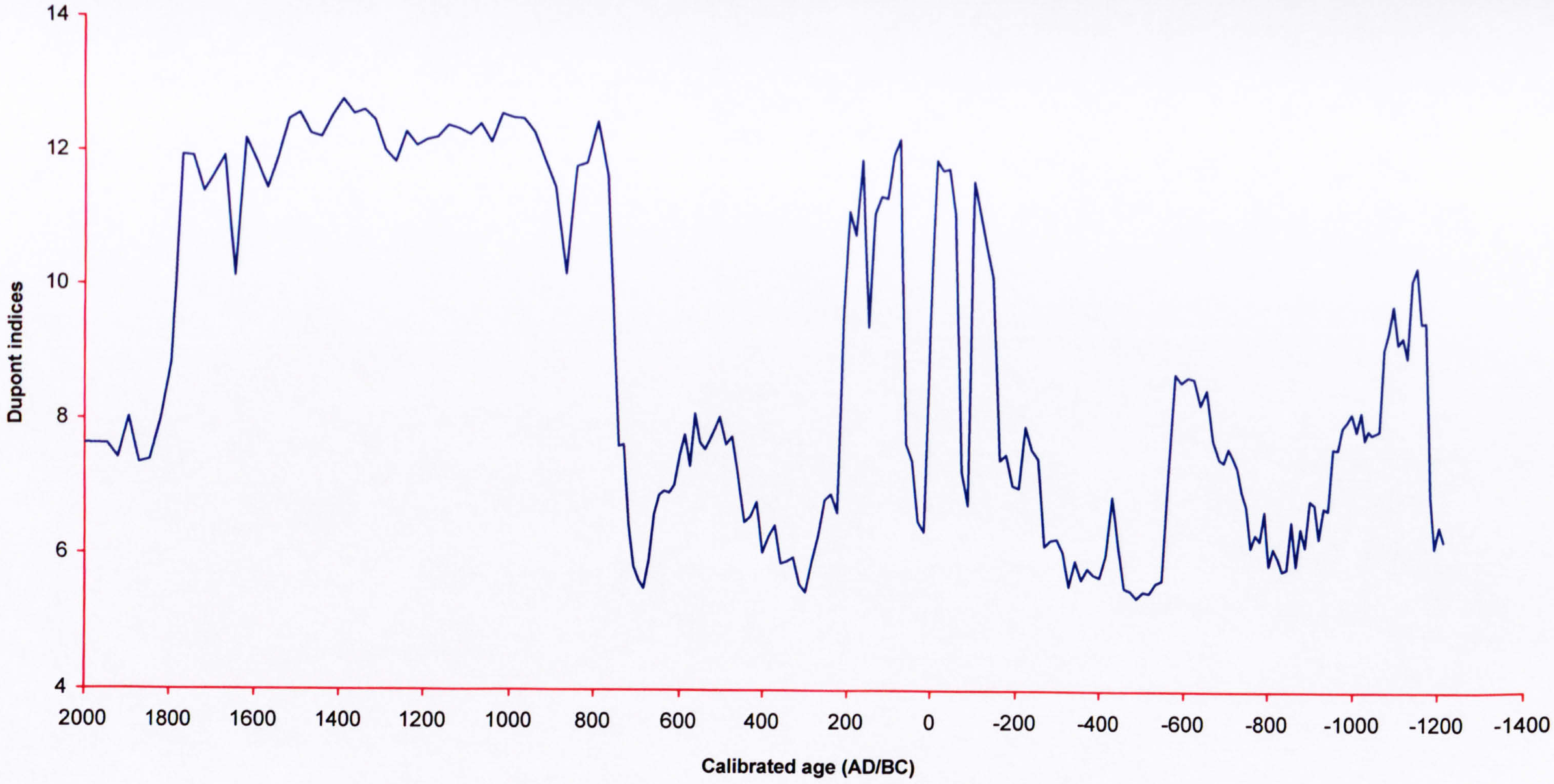

Figure 4.4 Dupont index values: Langlands Moss

4.2.4 Mynydd Llangatwg - Dupont Index Values

The Dupont curve generated for Mynydd Llangatwg is shown in Figure 4.5. As with Langlands Moss, generally high values are recorded for the majority of the core, reflecting the high levels of dry components in the macrofossil record for this core. As previously described in Section 3.6.1.6, the extremely slow accumulation rates modelled for the upper section of this core has the effect of stretching the last *c.* 2000 years of the record, thereupon reducing the resolution of the curve and possibly masking inferred wet/dry shifts in climatic conditions.

Dupont values are generally high for the majority of the core, implying dry conditions, which is reflected by the lack of Sphagna in the macrofossil record. The two distinctively wet phases, shown by low index values from between *c.* 800-380 cal. BC and *c.* 280-50 cal. BC, reflect the dominance of *Sphagnum imbricatum* leaves in this section of the core. Other distinct wet shifts, responding to increases in proportions of other *Sphagnum* species occur at *c.* 2150 cal. BC, *c.* 2110 cal. BC, 1950 cal. BC, *c.* 1130 cal. BC, 920 cal. BC and at cal. AD 300. Owing to the generally high values sustained throughout the core, determining inferred shifts to drier conditions is problematic from this curve.

Figure 4.5 Dupont index values: Mynydd Llangatwg

4.2.5 Summary of Dupont Index Results

From the Dupont curves generated for each of the cores under investigation, it is clear that weighted averages ordination is capable of uncovering moisture variations in macrofossil datasets, thereby enabling the identification of synchronous fluctuations in mire surface conditions. Although the curves generated vary considerably between sites, a number of shifts to relatively wet/dry conditions can be seen to occur synchronously, which may have been as a response to changes in regional climatic conditions.

However, there are also a number of limitations associated with this technique. Assigning single weights to each of the macrofossil components can produce misleading results, as the habitats of some mire taxa are quite broad, covering a range of different moisture conditions. Problems are also encountered when assigning a weight to species that no longer inhabit the region under investigation. An example of this is *Sphagnum imbricatum*, which is largely extinct from most of the British Isles today, and habitats where it is still found differ from its past preference. As a result of these potential problems, another alternative ordination technique is required, thereby providing an independent proxy-climate dataset for comparison.

4.3 Detrended Correspondence Analysis (DCA)

A more objective alternative to weighted averages ordination, where datasets are statistically decoded and environmental gradients detected, is Detrended Correspondence Analysis (DCA). DCA is another form of ordination technique, originally developed by Hill and Gauch (1980), and is a modification of Correspondence Analysis (CA), which is extensively used by ecologists. Thorough reviews of this technique can be found in ter Braak, (1995) and Kovach (1995), and for this reason only an overview of the technique will be provided here.

As with all ordination techniques, the objective of DCA is to represent data relationships in an ordered fashion, along an axis, on the basis of species composition (ter Braak, 1995). Results are usually presented as two-dimensional scattergrams, where closely associated samples, comprising related species, would be clustered together and, conversely, disassociated samples comprising unrelated species components would be spread wide apart.

DCA transforms multidimensional datasets by performing *eigenanalysis*. This is a process of performing linear transformations on the multidimensional data to extract new axes that summarise as much of the data as possible. Each new axis is described by an *eigenvalue*, which indicates the relative amount of the total variation in the data that is summarised on that one axis, and an *eigenvector*, which is a set of new scores for each object in the original data matrix (Kovach, 1995). The eigenvalue is equal to the maximum dispersion of the species scores on the ordination axis, and is thus a relative measure of the importance of the axis, with the first axis having the largest eigenvalue, the second axis the second largest eigenvalue, and so on (ter Braak, 1995). The eigenanalysis technique, originally employed for introducing CA into ecology, is known as reciprocal averaging, which is essentially a double weighted averaging or two-way weighted averaging procedure.

Using two-way weighted averaging, initial arbitrary site scores are selected, and species scores are derived by calculating the weighted average of the site scores for each species (ter Braak, 1995). These species scores are then used to derive new site scores by calculating the weighted average of the species scores for each site. Then, new species scores are recalculated from the preceding site scores until the values of the species and the site scores stabilise. This produces the first ordination axis, which has the maximum eigenvalue and maximum dispersion for each site. Further axes can be extracted which follow the iteration steps listed above, with an added step, which makes the trial scores of the second axis uncorrelated with the first. However, CA is susceptible to two main faults, of which the most prominent is the arch effect. This effect arranges the points into an arched pattern along the first two axis and is particularly common when sampling from a long environmental gradient. The second fault, which is a product of the first, is the compression of data points at the end of the axes, thereby misrepresenting the degree of similarity between them (Kovach, 1995).

DCA reduces the arch effect by applying a 'detrending procedure', whereby any polynomial relation between the first and higher ordination axes is removed (Karadzic, 1999). Hill and Gauch (1980) also describe the use of non-linear rescaling to overcome the data point compression problem, by ensuring the Gaussian response curve widths for all species are approximately equal. Details of this, and the modified two-way weighted averaging algorithm CANOCO used to detrend the arch effect is given in ter Braak (1995).

The scaling of each axis is expressed as standard deviation (s.d.) units × 100, and reflects the amount of biological turnover within that axis. By standardising the site scores so that within-site variance equals 1, the tolerances of the curves of the species will also approach 1. A Gaussian response curve with tolerance 1 rises and falls over an interval of *c.* 4 s.d. units (ter Braak, 1995). Owing to the rescaling, most species would therefore be expected to have a tolerance of 4 s.d. units. It can therefore be assumed that samples which differ by more than 4 s.d. would have few taxa in common, whilst a change of 1 s.d. unit would reflect a 50% change in sample composition.

In order to carry out DCA analyses of the datasets and present the outcome as scattergrams, raw data first had to be transformed. Macrofossil datasets were converted from the original Tilia (ASCII code) spreadsheet format via TRAN (Version 1.41) (Juggins, 1992) into Condensed Cornell format, so that it could be read by CANOCO (ter Braak, 1987). Following analysis in CANOCO, data were reimported into Microsoft Excel for presentation as scattergrams of the species and sample scores.

Although DCA is probably the most effective ordination technique at interpreting species distribution in palaeoecological datasets, there are certain limitations. One such limitation concerns outliers (rare species). Within CANOCO, there is the option to downweight outliers, as DCA places them at the far edges of the scattergram. However, the only real effective way to deal with extreme outliers is to remove them from the dataset, as they may dominate the first axis, making interpretation of underlying environmental gradients difficult. For this reason, species that have been counted at only one level were removed from the dataset for the purposes of DCA. Another limitation of DCA is its inability to cope with datasets composed of dominating species. As several of the macrofossil datasets generated in this study are dominated by one taxon of Sphagna, approaches aimed at transforming the data into unbiased formats may be considered. However, Hill and Gauch (1980) advise against transforming datasets without good reason, and even then, to attempt first an ordination on the untransformed data.

Further problems with DCA may occur when applying the 'detrending by segments' option. In selecting this option, it is possible that data loss may occur, owing to the second (and a higher) axis being arbitrarily defined, which makes interpretation problematic (Karadzic, 1999). An alternative approach would be to select the 'detrending by polynomials' option, where only specific defects of CA are removed (i.e., the polynomial dependence between the first and higher ordination axes). However, preliminary DCA analyses using the detrending by polynomials option were found to produce unsatisfactory results. Species often appeared bunched together and moisture gradients were not clearly defined. For this reason, all datasets were detrended using the detrending by segments option, which, in most cases, provided a much improved spread of variables and enabled the clear identification of moisture gradients.

DCA results for each macrofossil dataset are presented as scattergrams, with sample scores being derived from the weighted-averaging analysis of species scores. Therefore, the closer the sample score is to any particular species score, the greater the proportion that sample has of that species. DCA axis 1 eigenvalues have also been plotted against time (except for Bolton fell Moss - Core 3), derived through interpolated wiggle-matched AMS dates, in order that any shifts in reconstructed wet/dry conditions may be correlated with the other proxy records.

4.3.1 DCA Results - Bolton Fell Moss - Core MC

The DCA ordination for this dataset is presented in Figure 4.6. Species scores are well spread along DCA axis 1, accounting for 57% dispersion of the data points. There is a clear separation of the more hygrophilous mire taxa (*Sphagnum* section Cuspidata, *Sphagnum papillosum*, and *Eriophorum angustifolium*) with consistently higher eigenvalues, while the more tolerant *Sphagnum* species (*Sphagnum* section Acutifolia and *Sphagnum magellanicum*) have considerably lower values. What is surprising is the relative positioning of the driest mire taxa (UOM and Ericales), being centrally located along DCA axis 1. This is most likely a reflection of their consistently low proportions throughout the core, resulting in their being assigned relatively mid-range values. When comparing the scattergram with the raw macrofossil data (see Figure 3.3), it is clear that the dominance of *Sphagnum* section Acutifolia/*S. magellanicum* in the upper section of the core and the dominance of *S.* s. Cuspidata/*Sphagnum papillosum* in the lower section has significantly influenced the positioning of the species scores.

By plotting the DCA axis 1 scores against the interpolated time-scale, a number of possible variations in wetter/drier conditions can be identified (Figure 4.7). High eigenvalues (over 200) are taken to represent wetter conditions, while eigenvalues below this threshold signify drier conditions. As with the Dupont indices, the DCA curve for Core MC also records a distinctively wetter period from the base of the core at *c.* cal. AD 324, continuing until *c.* cal. AD 920. An overall drier period is also recorded from *c.* cal. AD 1310 which, aside from a number of short-lived wet shifts, continues to the surface of the mire. Within these periods, there are many rapid fluctuations from inferred wet to dry conditions, with the most extreme inferred wet phases occurring at *c.* cal. AD 350, *c.* cal. AD 890 and between *c.* cal. AD 1130-1180 and cal. AD 1230-1320.

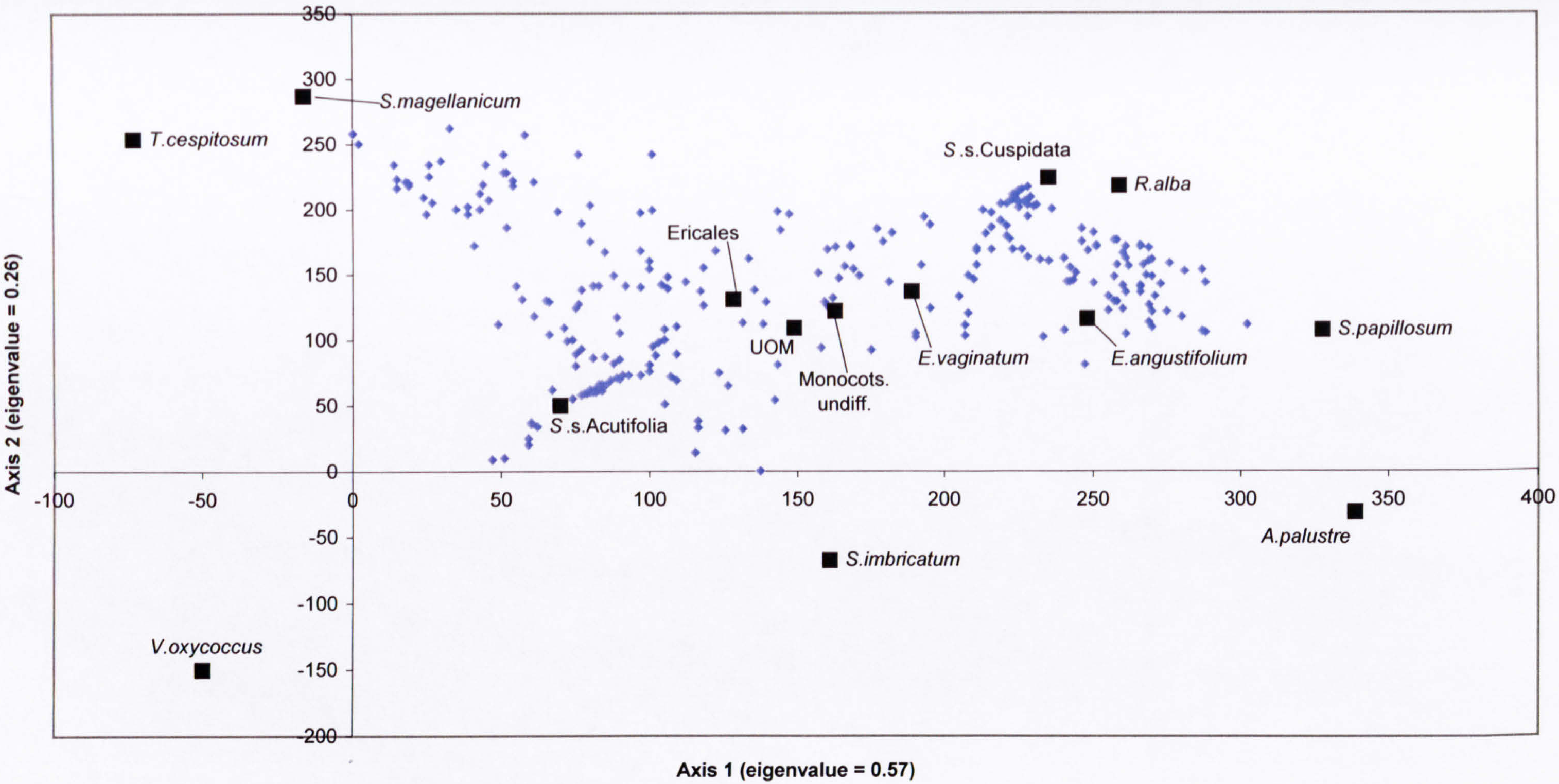

Figure 4.6 DCA scattergram: Bolton Fell Moss - Core MC

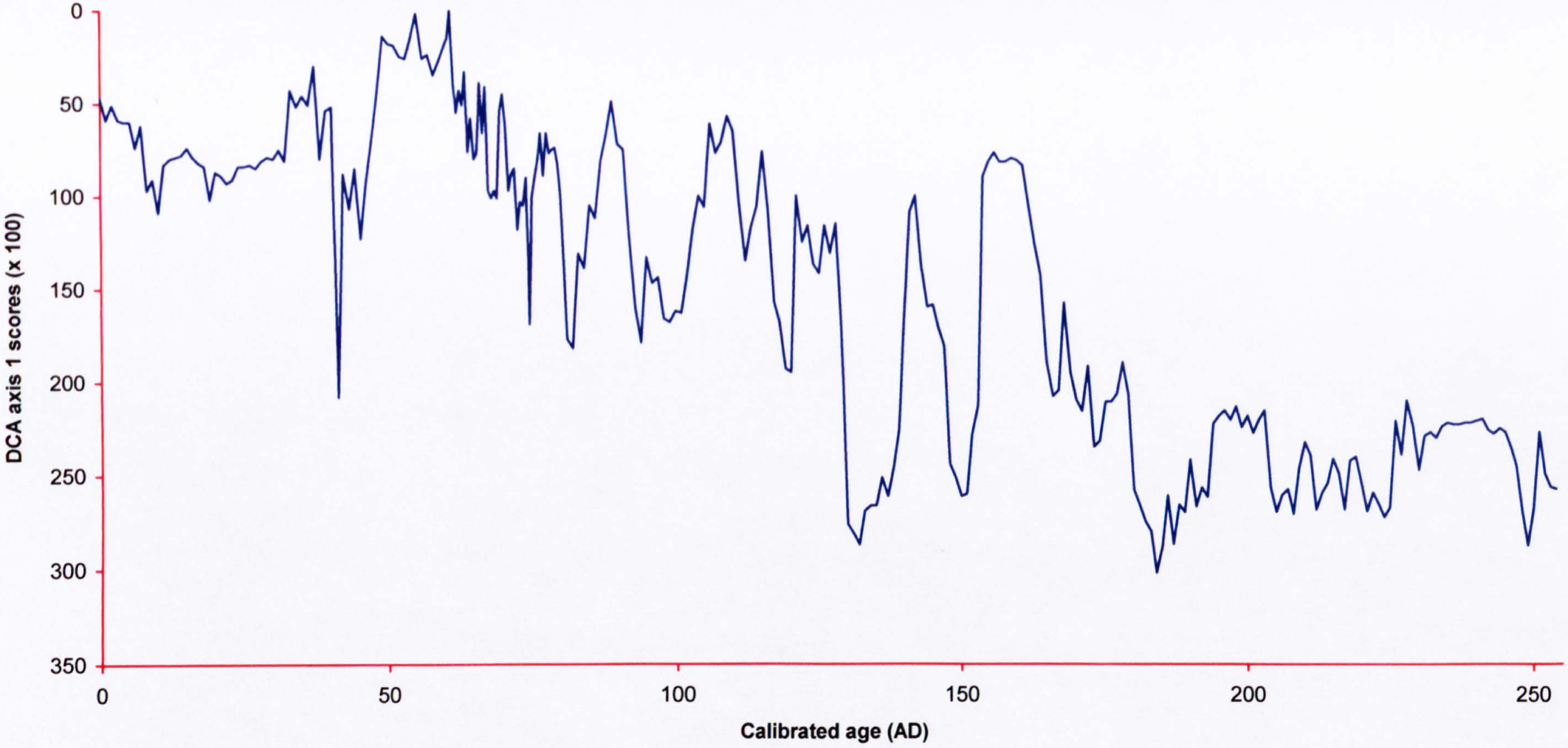

Figure 4.7 DCA axis 1 scores against time: Bolton Fell Moss - Core MC

4.3.2 DCA Results - Bolton Fell Moss - Core 3

Numerous studies have identified the wide-ranging demise of *Sphagnum imbricatum* and its subsequent replacement by *Sphagnum magellanicum* (Stoneman, 1993, Barber *et al.*, 1994a, Mauquoy, 1997). The DCA biplots in Stoneman (1993) clearly demonstrate the effect of this change, which show axis 1 being dominated by the two species at either end, thereby representing a species replacement gradient (Mauquoy and Barber, 1999a). The consistency of this change prompted Stoneman *et al.* (1993) to conclude that the niche of *S. imbricatum* has been replaced by *S. magellanicum*, and therefore the two may be considered as one species unit. Owing to the fact that the same characteristic species replacement has been identified in the macrofossil record for this core, the same strategy has been adopted here.

Sample scores derived through the DCA ordination of this dataset are not as widely dispersed along DCA axis 1 as they are for Core MC (Figure 4.8). However, a clear distinction can still be made between the more hygrophilous components (*Sphagnum section* Cuspidata and *Sphagnum papillosum*) with the higher eigenvalues, and the drier indicator species (*Eriophorum vaginatum* and *Polytrichum juniperum/alpestre* type) having the lower values. As with Core MC there are exceptions as, for example, *Rhynchospora alba*, typically a more hygrophilous species, is positioned to the far left of DCA axis 1. The position of *Eriophorum angustifolium* is also problematic, as it is commonly found growing in or near bog pools and would therefore be expected to have a relatively high eigenvalue.

DCA axis 1 scores have been plotted against time, and as with Core MC, high eigenvalues (over 200) represent wetter conditions (Figure 4.9). Although no data are available between 224-215 cm, owing to damage caused to the raw material, a clear shift to drier conditions can be identified at *c.* cal. 195 BC. The only other relatively dry phase is recorded as occurring from *c.* cal. AD 1700 to the surface, although conditions are seen to rapidly fluctuate during this period. Despite marked wet phases occurring between *c.* cal. AD 280-490, *c.* cal. AD 580-770 and *c.* cal. AD 1190-1300, conditions remain relatively constant for the majority of the core, only fluctuating within the 150-200 eigenvalue range.

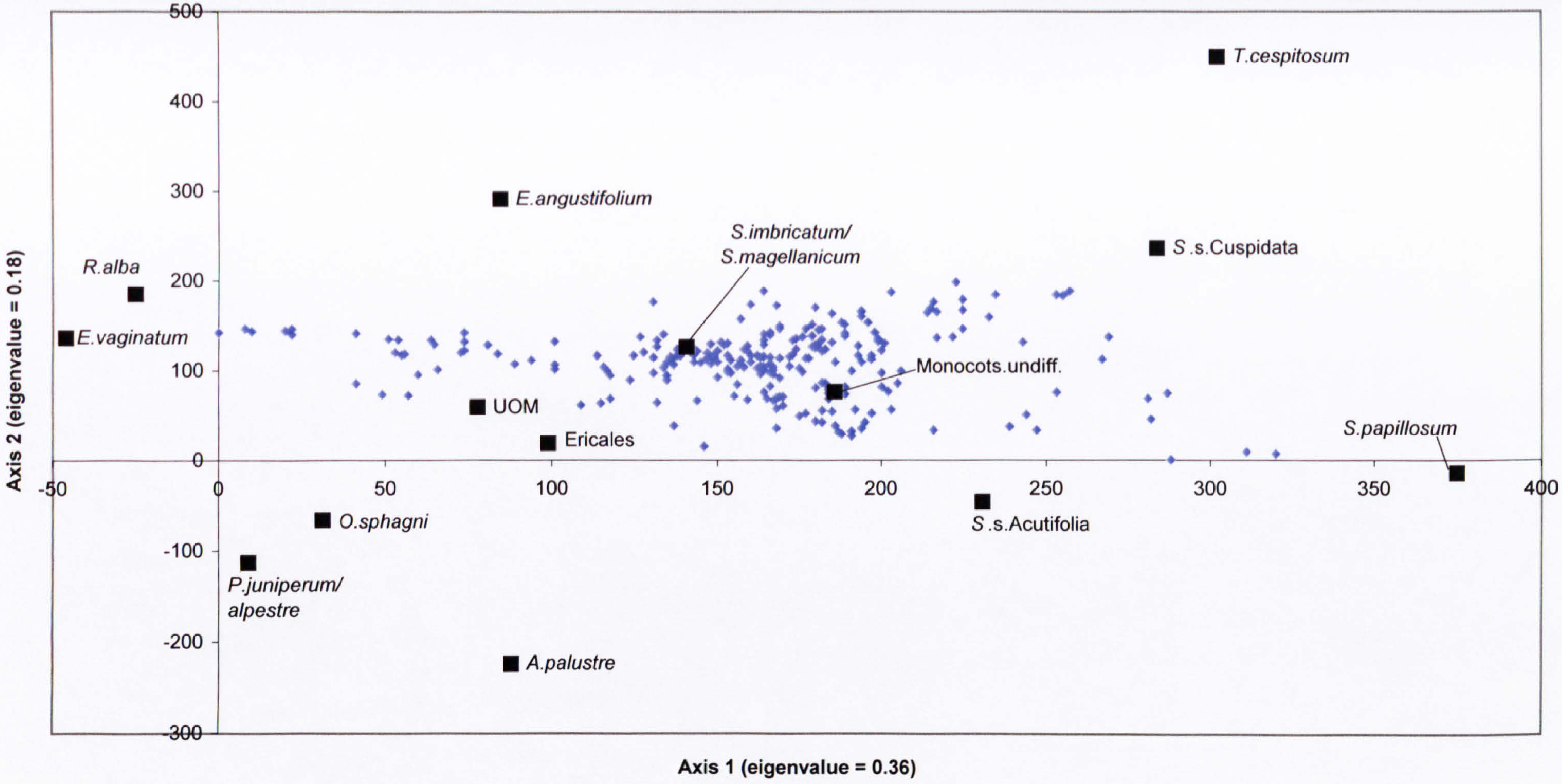

Figure 4.8 DCA scattergram: Bolton Fell Moss - Core 3

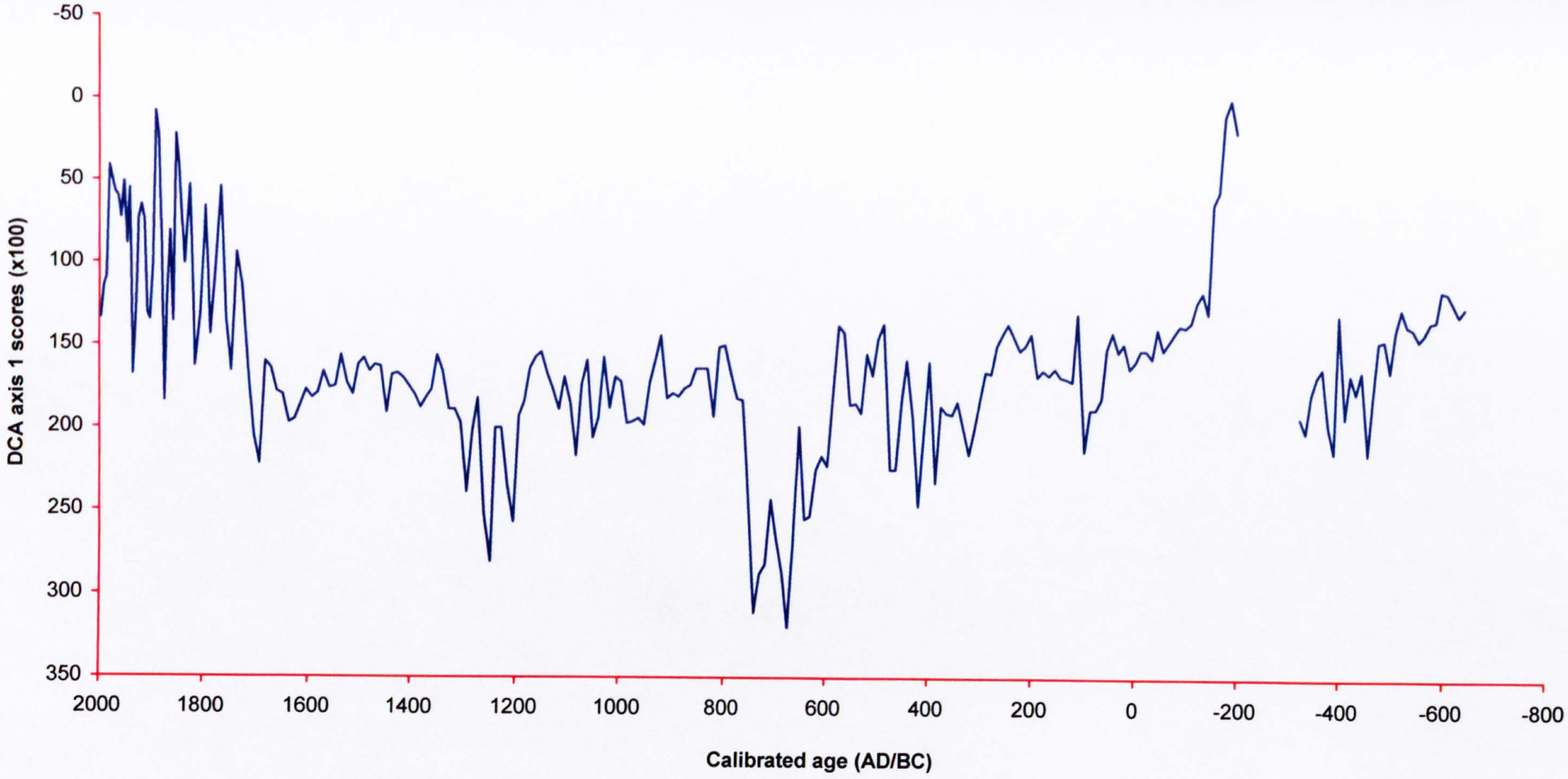

Figure 4.9 DCA axis 1 scores against time: Bolton Fell Moss - Core 3

4.3.3 DCA Results - Langlands Moss

The DCA scattergram for Langlands Moss is shown in Figure 4.10. Sample scores are well spread across axis 1, representing 57% of the total dispersion. There is also a clear separation of species scores, with the majority of the driest peat components (UOM, Ericales) having the lowest eigenvalues and most of the wetter components (*Sphagnum papillosum*, *Odontoschisma sphagni*) having the higher values. Again, there are exceptions, with *Polytrichum juniperum/alpestre* type, typically a drier species, being positioned to the far right of axis 1. As with the outlying positioning of *Hypnum cupressiforme*, this is a result of the minimal representation of these two components. Although *Eriophorum vaginatum* is positioned mid-range along axis 1, this reflects its ability to withstand a variety of different moisture levels.

DCA axis 1 scores have been plotted against the interpolated time-scale generated for this core and this is shown in Figure 4.11. Unlike plots produced for Bolton Fell Moss cores, higher eigenvalues (> 150) reflect wetter conditions, as indicated in the scattergram. The curve generated for this site bears a striking resemblance to the Dupont indices curve, thereby supporting the recorded signals from these two techniques. The same distinct dry phases are recorded between *c.* 200 cal. BC-cal. AD 220 and cal. AD 700-1780, again reflecting the high proportions of UOM, Ericales and Monocots. undiff. at these levels. Wet phases can be identified as occurring between *c.* 950-760 cal. BC, *c.* 550-270 cal. BC, *c.* cal. AD 180-450, cal. AD 630-710 and *c.* cal. AD 1790 and the surface of the mire.

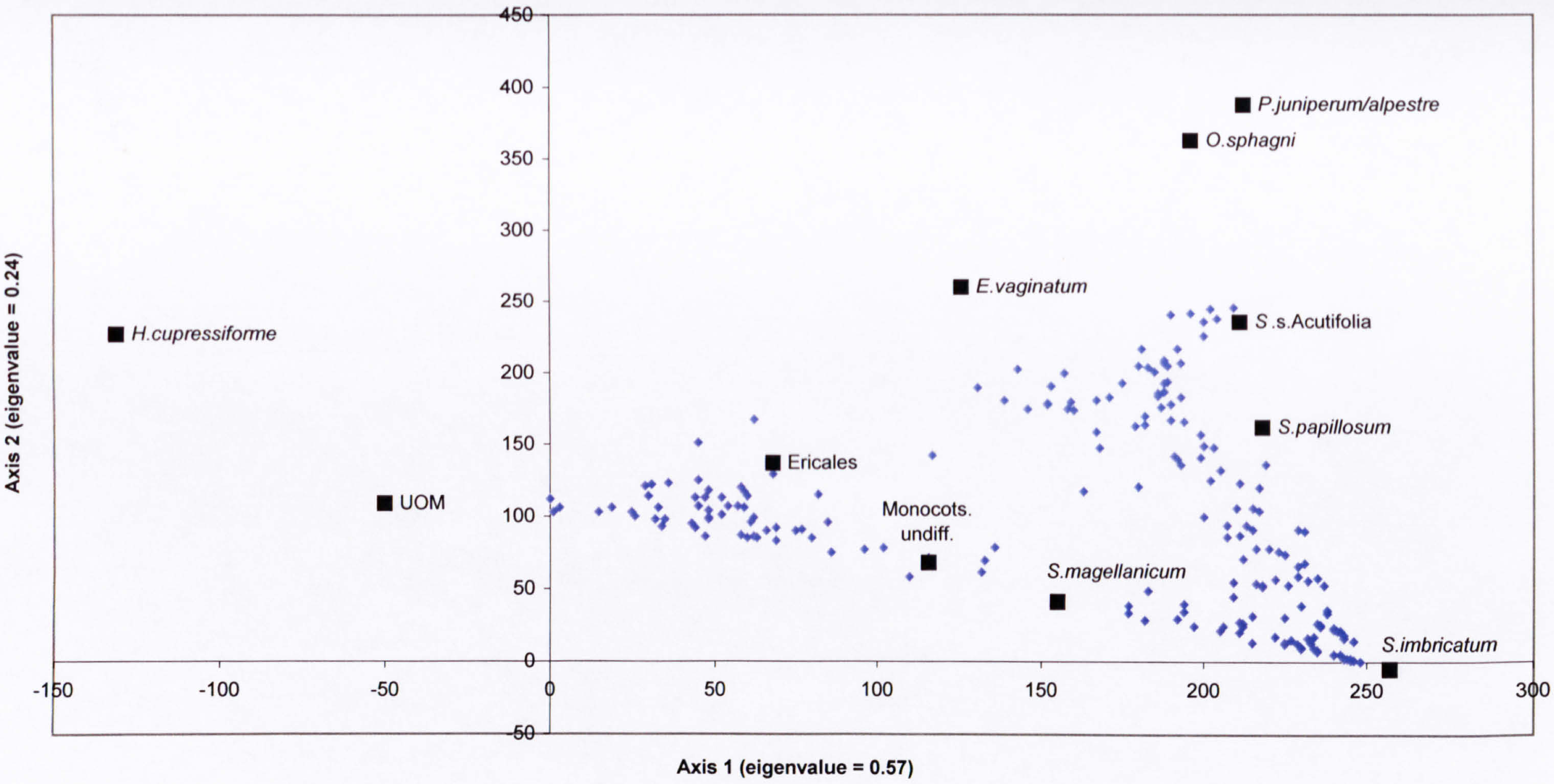

Figure 4.10 DCA scattergram: Langlands Moss

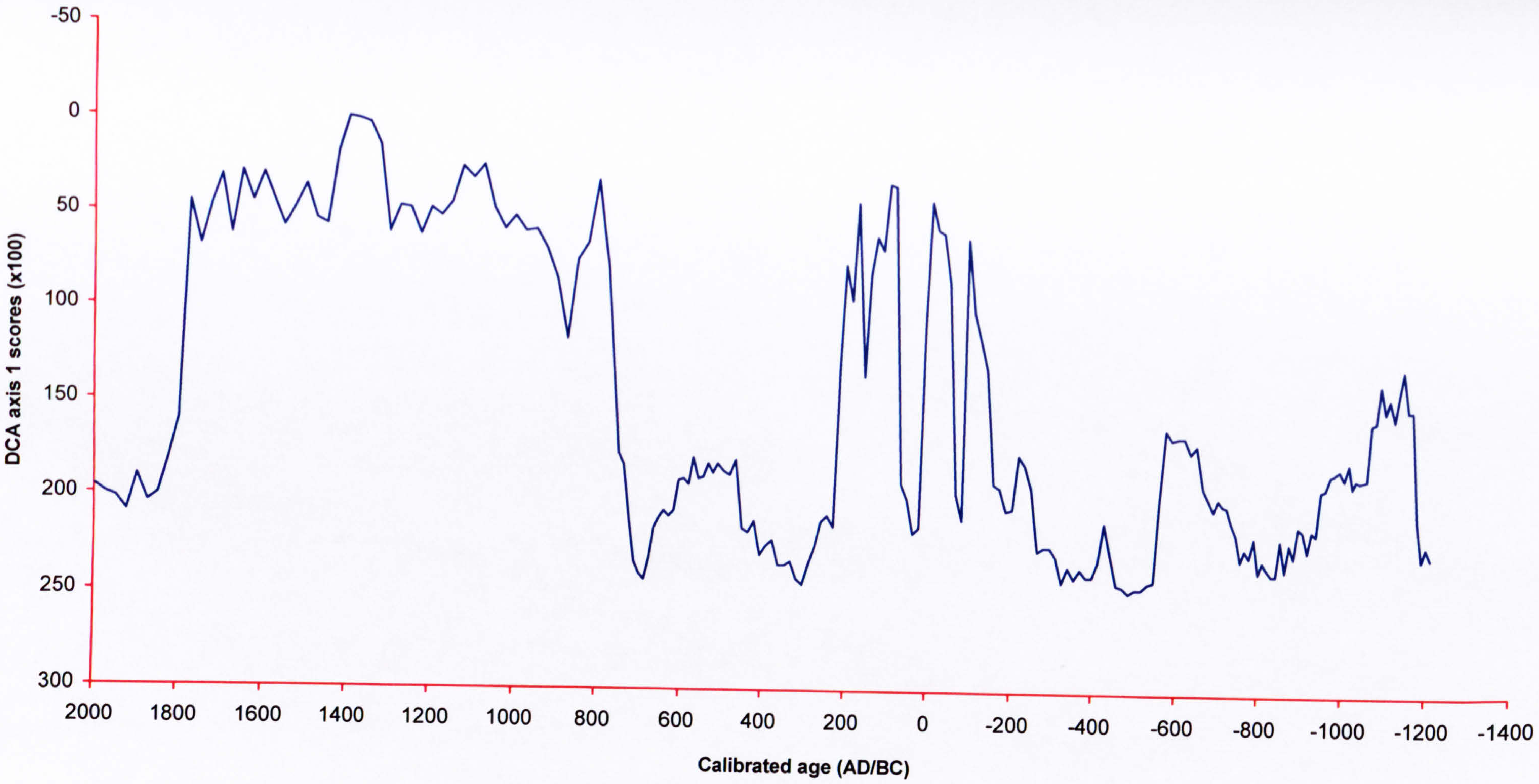

Figure 4.11 DCA axis 1 scores against time: Langlands Moss

4.3.4 DCA Results - Mynydd Llangatwg

The DCA scattergram for Mynydd Llangatwg is shown in Figure 4.12. The samples are well spread across axis 1, displaying a 76% dispersion; however, a number of species scores do seem to be out of position. As with Bolton Fell Moss - Core MC, the driest components (UOM, Ericales, Monocots. undiff.) are centrally located, reflecting the relatively high representation of these components throughout the core. The high proportions of drier components is also reflected by the high density of sample scores clustered around the central region. The other components are generally well positioned, with the more hygrophilous species (*Sphagnum imbricatum*, *Eriophorum angustifolium*) at one end of the axis, and the relatively drier components (*Eriophorum vaginatum*, *Sphagnum* section Acutifolia) at the other end. The misplaced positioning of *Sphagnum magellanicum* and *Sphagnum papillosum* reflects their minimal representation in the macrofossil record. The general lack of *Sphagnum* species in this core make any moisture gradient reconstruction problematic, as without these more sensitive components, changes in moisture levels can remain undetected.

DCA axis 1 scores have been plotted against the interpolated time-scale generated for this core and this is shown in Figure 4.13. As the majority of the drier components appear to be positioned on the right side of axis 1, in this case, higher eigenvalues (> 150) reflect relatively drier conditions. As with the Dupont indices, there is a clear wet phase recorded from *c.* 800 cal. BC-AD 50, which is only briefly interrupted by a return to drier conditions at *c.* 380 cal. BC, reflecting the peak in UOM and Monocots. undiff. at this level. The only other wet phase occurs at 930 cal. BC, most likely as a response to increased proportions of *E. angustifolium* epidermis and *S.* s. Acutifolia at this level. Unlike the Dupont index values, the high proportions of *E. vaginatum* epidermis in the lower section of the core is reconstructed here as a number of rapid dry shifts from *c.* 2450-1880 cal. BC. Other significant dry phases occur at *c.* 1590 cal. BC, *c.* 1430 cal. BC and between cal. AD 170-420.

Figure 4.12 DCA scattergram: Mynydd Llangatwg

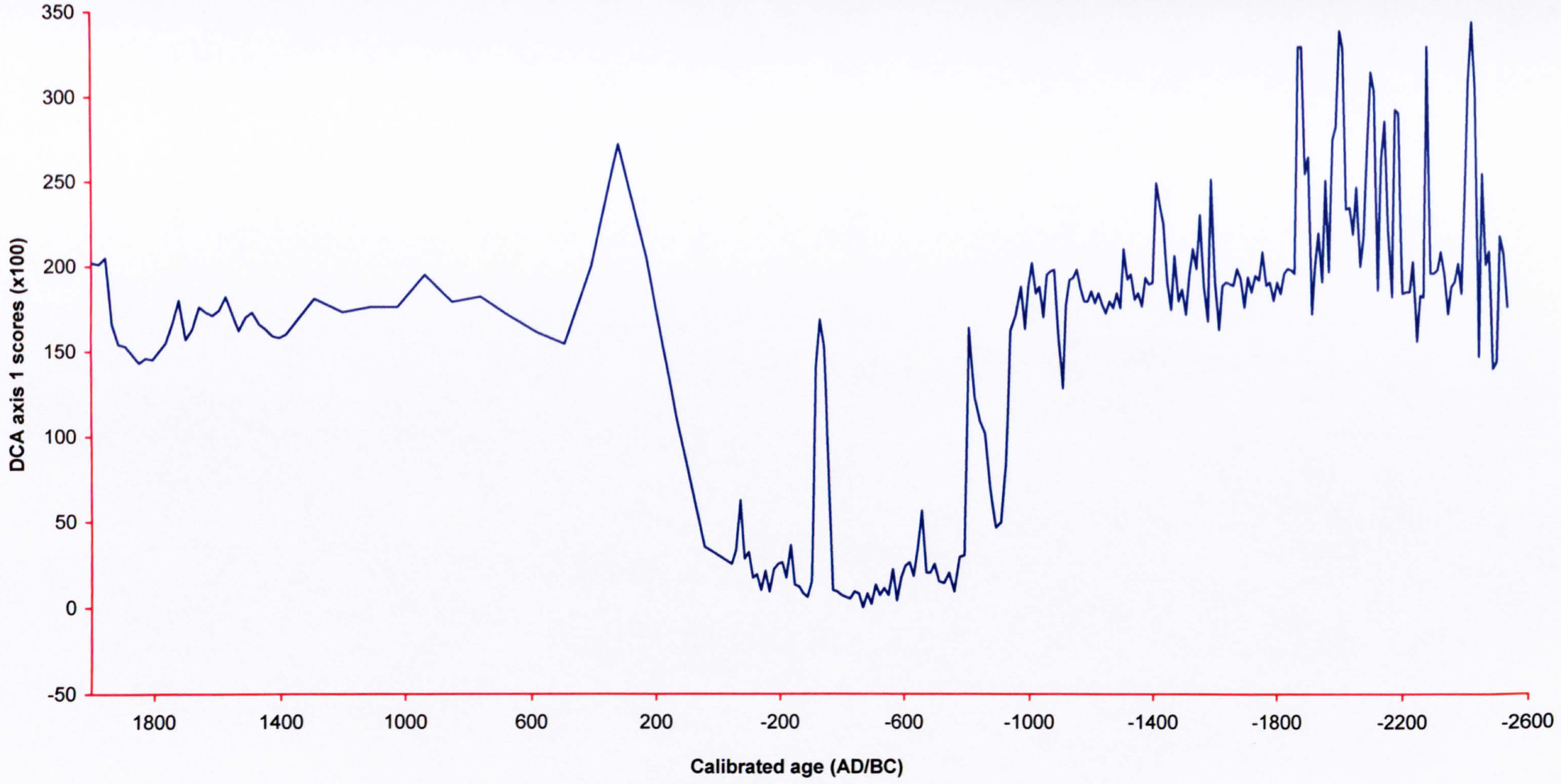

Figure 4.13 DCA axis 1 scores against time: Mynydd Llangatwg

4.4 Intra-site Proxy-Climate Comparisons - Humification, WAO Index and DCA Ordination Curves

In this section, comparisons are made between the raw humification absorbance curves and curves generated through multivariate analysis of the macrofossil datasets (see Sections 4.2 and 4.3). The interpolated time-scales developed in Chapter 3 enable the detection of synchronous shifts in inferred wet/dry conditions, thereby facilitating the comparison of these fluctuations with those recorded at other sites. Inferred climatic deteriorations, where all curves synchronously record a distinct decline have been highlighted (shown as blue bars), and reflect shifts to inferred wetter conditions. Inferred dry shifts, indicated by synchronously occurring rises in the curves, have also been highlighted (shown as red bars), and reflect shifts to relatively drier mire surface conditions.

4.4.1 Bolton Fell Moss - Core MC

Humification absorbance, Dupont and DCA curves have been plotted against calendar time, shown in Figure 4.14. As well as being indicated on the diagram, inferred wet and dry shifts are also listed in Table 4.2. Testate amoebae results have been omitted from this comparative study, as the dominance of hydrophilous species (*Amphitrema flavum, A. wrightianum*) throughout the majority of the core appears to masks drier shifts.

Table 4.2 List of inferred wet and dry shifts for Bolton Fell Moss - Core MC (interpolated date ranges have been marked with the prefix *c.*)

Wet shift	Dry shift
c. cal. AD 1820-1835	*c.* cal. AD 1950-1975
c. cal. AD 1765-1780	*c.* cal. AD 1785-1805
c. cal. AD 1725-1745	*c.* cal. AD 1710-1720
cal. AD 1635-1650	cal. AD 1665-1680
c. cal. AD 1565-1575	cal. AD 1580-1610
c. cal. AD 1475-1510	*c.* cal. AD 1310-1335
c. cal. AD 1360-1380	cal. AD 1160-1185
cal. AD 1240-1260	*c.* cal. AD 1010-1020
c. cal. AD 1125-1145	*c.* cal. AD 765-785
c. cal. AD 950-970	*c.* cal. AD 660-675
c. cal. AD 875-895	cal. AD 515-540
c. cal. AD 840-855	
c. cal. AD 680-695	
cal. AD 540-560	

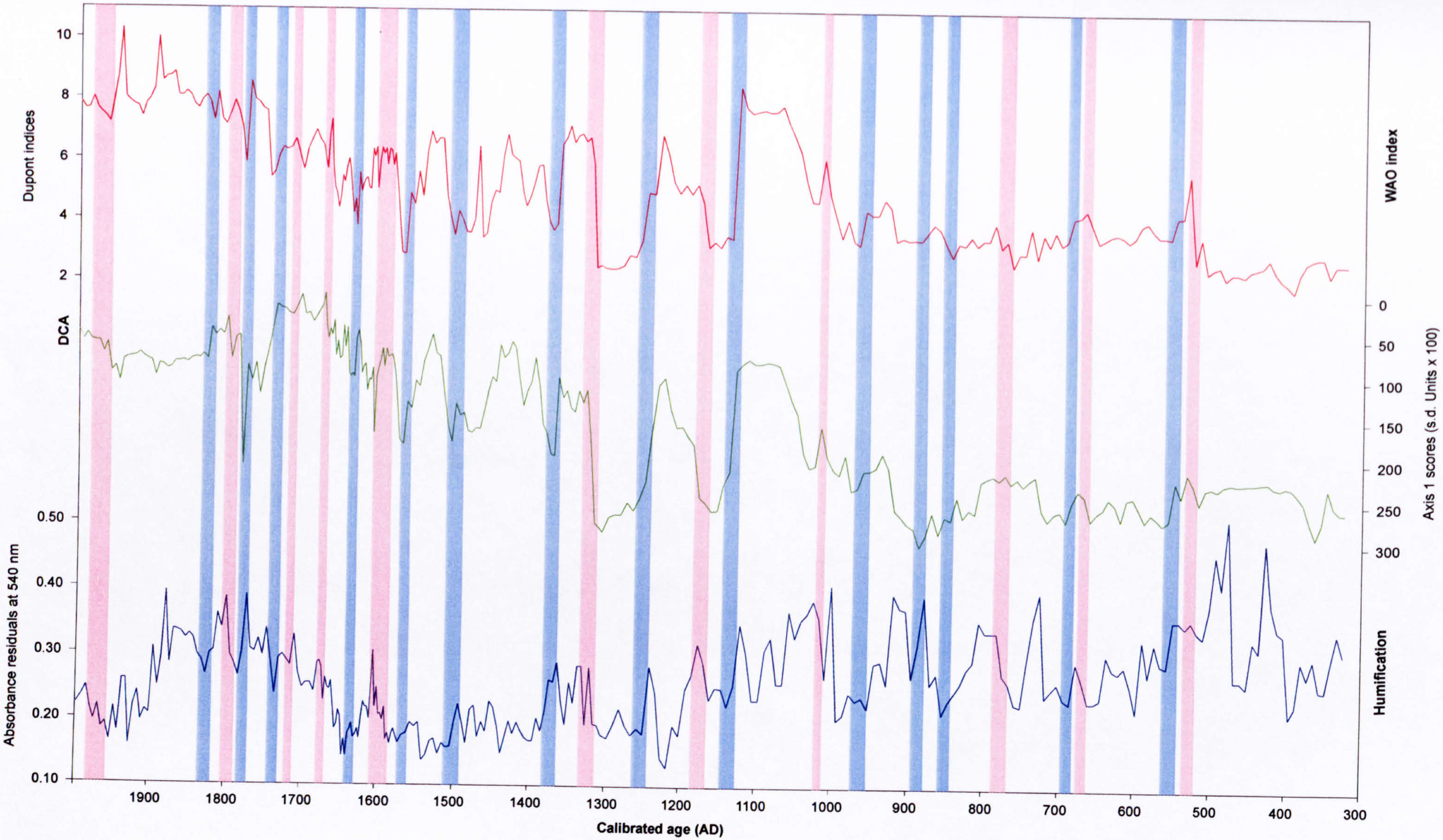

Figure 4.14 Comparison of proxy-climate curves for Bolton Fell Moss - Core MC (blue bars indicate inferred wet shifts; red bars indicate inferred dry shifts)

4.4.2 Bolton Fell Moss - Core 3

As with Core MC, the three proxy-climate curves have been plotted against calendar time (Figure 4.15), while inferred wet and dry shifts are listed in Table 4.3.

Table 4.3 Inferred wet and dry shifts for Bolton Fell Moss - Core 3 (interpolated date ranges have been marked with the prefix *c.*)

Wet shift	Dry shift
c. cal. AD 1800-1825	cal. AD 1935-1960
c. cal. AD 1645-1705	cal. AD 1710-1740
c. cal. AD 1435-1485	*c.* cal. AD 1290-1335
c. cal. AD 920-965	*c.* cal. AD 1100-1140
c. cal. AD 525-615	*c.* cal. AD 320-360
c. cal. AD 40-75	*c.* cal. AD 100-120
c. 155-100 cal. BC	
c. 575-540 cal. BC	

Figure 4.15 Comparison of proxy-climate curves for Bolton Fell Moss - Core 3 (blue bars indicate inferred wet shifts; red bars indicate inferred dry shifts)

4.4.3 Langlands Moss

As with cores from Bolton Fell Moss, humification absorbance, Dupont and DCA curves have been plotted against calendar time and are shown in Figure 4.16. Inferred wet and dry shifts are highlighted on the diagram and listed in Table 4.4.

Table 4.4 List of inferred wet and dry shifts for Langlands Moss (interpolated date ranges have been marked with the prefix *c.*)

Wet shift	Dry shift
cal. AD 665-705	cal. AD 730-780
c. cal. AD 255-290	*c.* cal. AD 460-530
c. cal. AD 5-45	*c.* cal. AD 70-105
c. 105-80 cal. BC	*c.* 60-30 cal. BC
c. 550-510 cal. BC	*c.* 145-115 cal. BC
845-810 cal. BC	*c.* 270-225 cal. BC
c. 965-920 cal. BC	*c.* 455-410 cal. BC
1075-1030 cal. BC	*c.* 655-600 cal. BC
	735-695 cal. BC
	1115-1050 cal. BC
	1200-1155 cal. BC

Testate amoebae results for this core generally support the timing of these shifts, with wetter shifts correlating with a dominance of more hydrophilous species (*Amphitrema flavum* and/or *A. wrightianum*), while drier shifts are seen to correlate well with dominant proportions of *Hyalosphenia subflava*, a xerophilous species, and *Assulina muscorum*, a mid-range species. The only exception appears to be at *c.* 225-270 cal. BC, where a dominance of *Amphitrema wrightianum* is sustained during an inferred dry shift.

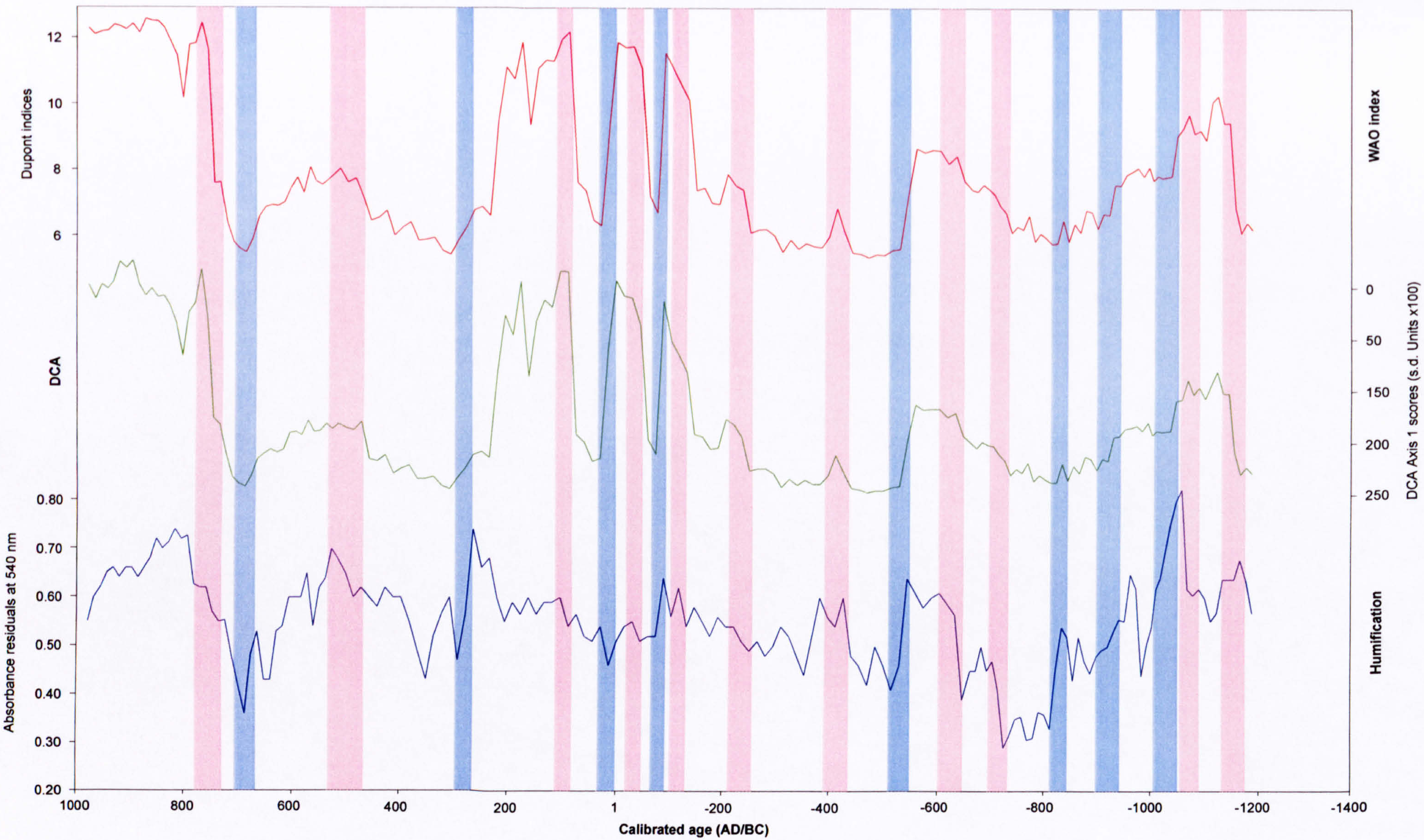

Figure 4.16 Comparison of proxy-climate curves for Langlands Moss (blue bars indicate inferred wet shifts; red bars indicate inferred dry shifts)

4.4.4 Mynydd Llangatwg

Humification, Dupont and DCA curves have been plotted against calendar time and shown in Figure 4.17. Inferred wet and dry shifts have been highlighted on the diagram and listed in Table 4.5.

Table 4.5 Inferred wet and dry shifts for Mynydd Llangatwg (interpolated date ranges have been marked with the prefix *c.*)

Wet shift	Dry shift
c. 315-285 cal. BC	*c.* 90-65 cal. BC
c. 600-570 cal. BC	*c.* 255-230 cal. BC
815-770 cal. BC	*c.* 345-325 cal. BC
950-920 cal. BC	*c.* 680-650 cal. BC
c. 1115-1095 cal. BC	835-815 cal. BC
c. 1590-1570 cal. BC	895-875 cal. BC
c. 1705-1690 cal. BC	*c.* 1055-995 cal. BC
1970-1940 cal. BC	*c.* 1355-1325 cal. BC
	c. 1445-1420 cal. BC
	1915-1895 cal. BC
	2530-2510 cal. BC

As with Langlands Moss, the results from the testate amoebae analysis generally support these shifts in mire surface conditions, with wetter phases mostly coinciding with high proportions of *Amphitrema flavum* and/or *A. wrightianum*. Exceptions occur between 1970-1940 cal. BC and *c.* 1590-1570 cal. BC, when *Hyalosphenia subflava* manages to sustain dominance during these inferred wetter periods. Dry shifts largely correlate with high proportions of *Hyalosphenia subflava*, except between *c.* 1000-975 cal. BC and *c.* 90-65 cal. BC, when *Amphitrema flavum* dominates the assemblage.

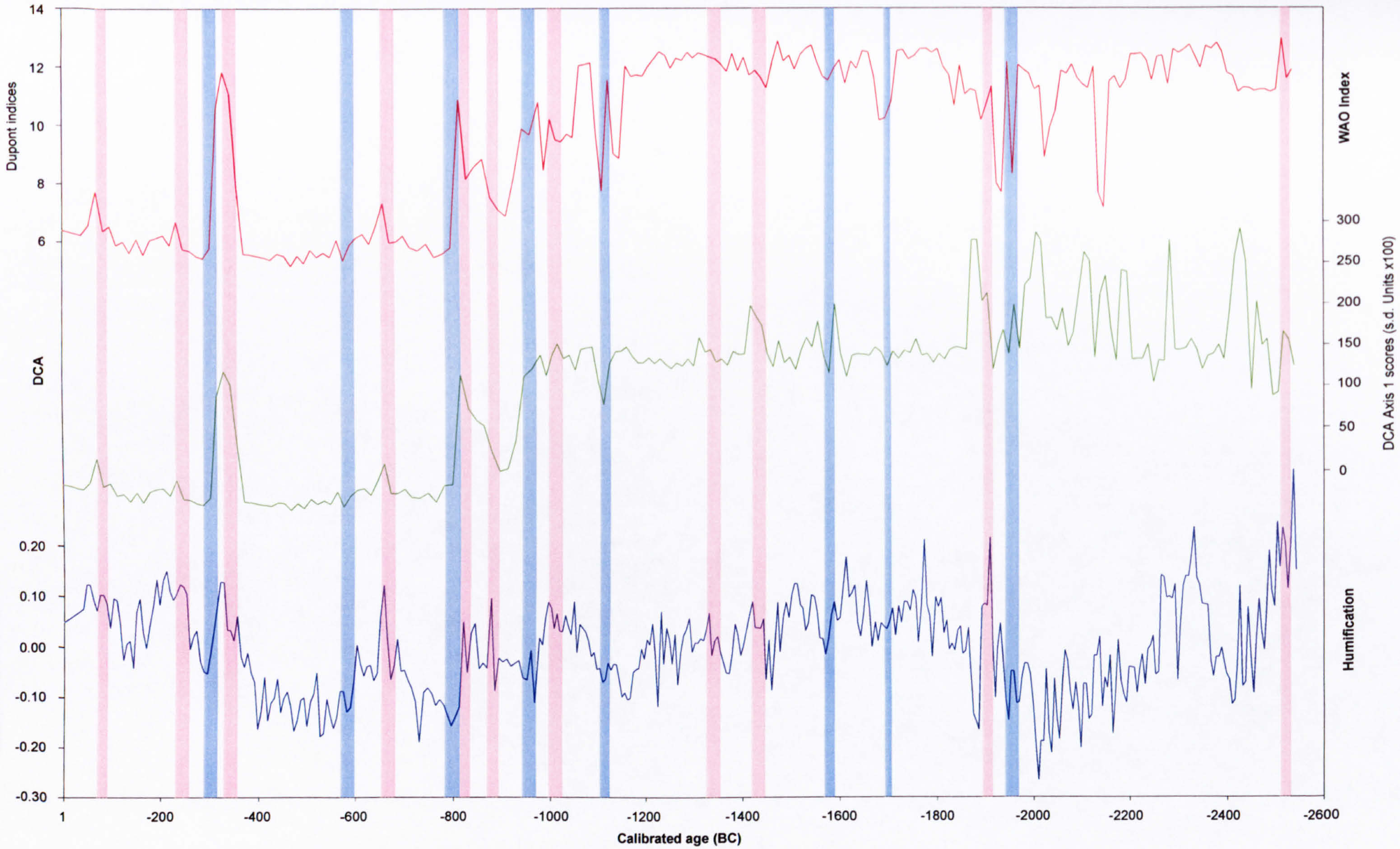

Figure 4.17 Comparison of proxy-climate curves for Mynydd Llangatwg (blue bars indicate inferred wet shifts; red bars indicate inferred dry shifts)

4.5 Summary

Multivariate analysis of the macrofossil datasets has enabled the generation of proxy-climate curves for each of the sites investigated. By comparing these curves with humification absorbance curves against an interpolated time-scale, a number of synchronous shifts to inferred wet/dry mire surface conditions have been identified. Testate amoebae results have been found largely to support these fluctuations, suggesting the possible influence of regional climatic forcing during these periods. There appear to be only slight leads and lags between the various proxy records, and so periods of inferred change have be confined to decades rather than centuries.

Unfortunately, two of the sites, Langlands Moss and Mynydd Llangatwg, appear to have suffered the effect of some form of disturbance in the upper layers. In the case of Langlands Moss, the effects of disturbance was also reported by Langdon (1999) in a similar study of the same site where, occurring at similar depths, it was been attributed to surface drainage and/or afforestation. The dramatic slow down in peat accumulation at Mynydd Llangatwg may have been a result of surface drainage, however, owing to the close proximity of the coring location to a sinkhole, it may have been initiated by collapse. This would have resulted in the subsequent erosion of the peat around the doline, thereby lowering the water table in the surrounding peat, leading to a reduction in rate of peak accumulation.

In Chapter 5, comparisons will be made between each of the proxy-climate reconstructions, thereby enabling the identification of synchronous fluctuations in mire surface conditions that have occurred on a regional scale. These synchronous shifts in inferred climatic conditions will then be compared with previously published palaeoclimatological studies and documented climatological records, as a means of correlating these recorded events with established changes in regional climate.

Chapter 5 Discussion

5.1 Introduction

Comparisons of the proxy-climate curves generated for each of the cores investigated have revealed a number of synchronously occurring shifts to inferred wetter and drier conditions. Dating of these inferred variations in mire surface conditions, using an interpolated radiocarbon chronology, provides a common scale by which all the sites investigated can be compared, and enables direct comparison with other regionally associated palaeoenvironmental records and documentary evidence. Owing to the significant distance between the three sites investigated, synchronous shifts of the same direction, which have been recorded across two or more of the sites investigated, have been attributed to allogenic (climate) forcing.

In the first part of this chapter, proxy-climatic evidence from this study will be compared with other regionally associated palaeoclimatic studies and documentary records and, on the basis of these correlations, suggestions will be made as to likely forcing mechanisms for these changes. The effectiveness of each of the palaeoecological techniques employed in this study will then be considered, with regard to their potential for identifying changes in regional climate, followed by an assessment of the site-specific characteristics that may have affected the extent of the climatic reconstruction at each location.

5.2 Climatic Change

The inferred fluctuations in mire surface conditions discussed in Chapter 4 are summarised in Tables 5.1 and 5.2. A number of inferred shifts to wetter or relatively drier conditions appear to have occurred synchronously, and in the same direction, across two or more of the cores investigated, and these are highlighted. Owing to the dependence of the sites investigated on atmospheric precipitation for both water and nutrient supply, it has been assumed that these synchronous shifts are generally a result of changes in regional climate. However, as suggested by Conway (1948), although broad agreements would be expected for any major climatic change, the crossing of a critical threshold would be expected at slightly different times over north-western Europe, owing to differences in latitude and proximity to the Atlantic. Comparisons of the results obtained from this study with other regionally associated palaeoclimatic studies and documentary records have revealed a number of correlating shifts in inferred climate which will be discussed here.

Table 5.1 List of inferred wet shifts (synchronous changes across two or more cores have been highlighted in blue)

Bolton Fell Moss Core MC	Bolton Fell Moss Core 3	Langlands Moss	Mynydd Llangatwg
c. cal. AD 1820-1835	*c.* cal. AD 1800-1825	-	-
c. cal. AD 1765-1780	-	-	-
c. cal. AD 1725-1745	-	-	-
cal. AD 1635-1650	*c.* cal. AD 1645-1705	-	-
c. cal. AD 1565-1575	-	-	-
c. cal. AD 1475-1510	*c.* cal. AD 1435-1485	-	-
c. cal. AD 1360-1380	-	-	-
cal. AD 1240-1260	-	-	-
c. cal. AD 1125-1145	-	-	-
c. cal. AD 950-970	*c.* cal. AD 920-965	-	-
c. cal. AD 875-895	-	-	-
c. cal. AD 840-855	-	-	-
c. cal. AD 680-695	-	cal. AD 665-705	-
cal. AD 540-560	*c.* cal. AD 525-615	-	-
-	-	*c.* cal. AD 255-290	-
-	*c.* cal. AD 40-75	*c.* cal. AD 5-45	-
-	*c.* 155-100 cal. BC	*c.* 105-80 cal. BC	-
-	-	-	*c.* 315-285 cal. BC
-	*c.* 575-540 cal. BC	*c.* 550-510 cal. BC	*c.* 600-570 cal. BC
-	-	845-810 cal. BC	815-770 cal. BC
-	-	*c.* 965-920 cal. BC	950-920 cal. BC
-	-	1075-1030 cal. BC	-
-	-	-	*c.* 1115-1095 cal. BC
-	-	-	*c.* 1590-1570 cal. BC
-	-	-	*c.* 1705-1690 cal. BC
-	-	-	1970-1940 cal. BC

Table 5.2 List of inferred dry shifts (synchronous changes across two or more cores have been highlighted in red)

Bolton Fell Moss Core MC	Bolton Fell Moss Core 3	Langlands Moss	Mynydd Llangatwg
c. cal. AD 1950-1975	cal. AD 1935-1960	-	-
c. cal. AD 1785-1805	-	-	-
c. cal. AD 1710-1720	cal. AD 1710-1740	-	-
cal. AD 1665-1680	-	-	-
cal. AD 1580-1610	-	-	-
c. cal. AD 1310-1335	*c*. cal. AD 1290-1335	-	-
cal. AD 1160-1185	-	-	-
-	*c*. cal. AD 1100-1140	-	-
c. cal. AD 1010-1020	-	-	-
c. cal. AD 765-785	-	cal. AD 730-780	-
c. cal. AD 660-675	-	-	-
cal. AD 515-540	-	*c*. cal. AD 460-530	-
-	*c*. cal. AD 320-360	-	-
-	*c*. cal. AD 100-120	*c*. cal. AD 70-105	-
-	-	*c*. 60-30 cal. BC	-
-	-	-	*c*. 90-65 cal. BC
-	-	*c*. 145-115 cal. BC	-
-	-	*c*. 270-225 cal. BC	*c*. 255-230 cal. BC
-	-	-	*c*. 345-325 cal. BC
-	-	*c*. 455-410 cal. BC	-
-	-	*c*. 655-600 cal. BC	*c*. 680-650 cal. BC
-	-	735-695 cal. BC	-
-	-	-	835-815 cal. BC
-	-	-	895-870 cal. BC
-	-	1115-1050 cal. BC	*c*. 1055-995 cal. BC
-	-	1200-1155 cal. BC	-
-	-	-	*c*. 1355-1325 cal. BC
-	-	-	*c*. 1445-1420 cal. BC
-	-	-	1915-1895 cal. BC
-	-	-	2530-2510 cal. BC

5.2.1 2600-1200 BC

The only site with a chronology extending back to the beginning of this period is Mynydd Llangatwg. The earliest wet phase to be inferred for this site occurred between *c.* 1970-1940 cal. BC. Using a combination of macro- and microscopic analysis techniques van Geel (1978) also uncovered a wet phase around this time from Engbertsdijksveen in The Netherlands. Another shift to wetter conditions is inferred as occurring between *c.* 1705-1690 cal. BC which also falls within the boundaries of the wet phase identified by Dupont (1986) in Bourtangersven, The Netherlands, suggesting that these two wet shifts may reflect generally deteriorating conditions for this period. A further shift to wetter conditions is inferred as occurring between *c.* 1590-1570 cal. BC. This correlates well with wet phases identified in a number of other palaeoecological studies, both from the British Isles and areas of north-western Europe, including Dupont (1986: 1700-1350 cal. BC), Hughes *et al.* (2000: *c.* 1550 cal. BC) and Stoneman (1993: *c.* 1600 cal. BC).

5.2.2 1200 - 700 BC

The first wet shift to be inferred for this period is recorded at both Langlands Moss and Mynydd Llangatwg, between *c.* 965-920 cal. BC. This correlates well with a change to wetter conditions identified at Bolton Fell Moss by Barber (1981) around 950 cal. BC. Charman (1990) also records a change to wetter conditions in Scotland during this period (*c.* 960-800 cal. BC) as part of his study of the Cross Lochs fens of northern Scotland. Evidence also exists from other parts of Europe, with van Geel (1978) recording a change to wetter conditions at *c.* 900 cal. BC from Engbertsdijksveen bog in The Netherlands, and Nilssen and Vorren (1991) detecting a wet phase in Norway around 950 cal. BC.

The second abrupt climatic deterioration to be recorded in cores from Langlands Moss and Mynydd Llangatwg between *c.* 845-765 cal. BC has been widely detected at numerous sites across north-western Europe. The limits of this change were clearly defined at an early stage, and were used by Blytt and Sernander in their classic division of the Holocene, marking the change from Sub-boreal to Sub-atlantic conditions (Sernander, 1910). At this transition, Godwin (1975) notes the rapid waterlogging of desiccated surfaces of raised and blanket bogs and the deposition of aquatic *Sphagnum* species in pools on mire surfaces. Testate amoebae and humification analyses of an intermediate raised-blanket mire in Northumberland also identified a number of wet shifts between *c.* 950-750 cal. BC (Charman *et al.*, 1999). The macrofossil record from a raised mire in The Netherlands clearly demonstrates a change to wetter conditions between *c.* 850-760 cal. BC which coincides with $\delta^{18}0$ and deuterium/hydrogen ratio fluctuations, and a fall in pollen percentages of *Corylus avellana* (van Geel *et al.*, 1996). This sudden change has been associated with the Sub-boreal/Sub-atlantic transition, which can often be visibly determined in the stratigraphy of bogs across north-western Europe.

A synchronously occurring dry phase has also been detected at Langlands Moss and Mynydd Llangatwg around 1115-995 cal. BC, which is supported by a shift to drier conditions identified by Stoneman (1993) during palaeoclimatic studies at Bolton Fell Moss.

5.2.3 700 - 400 BC

Lamb (1982) notes this period as being dominated by high levels of rainfall on the western side of the British Isles, which is supported by the high accumulation rates modelled for Tregaron Bog in west Wales, where nearly a metre of peat was deposited over these four centuries (Haslam, 1987). The inferred wet shift recorded at Bolton Fell Moss - Core 3, Langlands Moss and, most significantly, at Mynydd Llangatwg between *c.* 600-510 cal. BC can therefore also be attributed to these deteriorating climatic conditions. Further evidence from Bolton Fell Moss is also provided by Stoneman (1993) who reconstructed a change to wetter conditions *c.* 520 cal. BC, based upon a vegetation change from monocotyledons to hygrophilous *Sphagnum* species. The inferred wet phase detected by Nilssen and Vorren (1991) at *c.* 500 cal. BC, in bogs from north and central Norway, may also be associated with this recorded change, suggesting that this inferred climatic shift may have influenced other areas of north-western Europe.

5.2.4 400 BC - AD 1

There is a rapid decline in the proxy-climate signal within this time-frame, recorded at Bolton Fell Moss - Core 3 and Langlands Moss from between *c.* 155-80 cal. BC, which coincides with a synchronously detected wet shift identified by Stoneman (1993; *c.* 130 cal. BC-*c.* cal. AD 150). Tipping (1995) also appears to have registered this change at Burnfoothill Moss, where humification levels indicate a wet shift between *c.* 1950-2050 cal. BP (*c.* 100-0 cal. BC).

A dry phase has also clearly been recorded at Langlands Moss and Mynydd Llangatwg between *c.* 270-225 cal. BC; however, there appears to be no other evidence to support this inferred shift in conditions.

5.2.5 AD 1 - 400

An inferred shift to wetter conditions has been recorded at Bolton Fell Moss - Core 3 and Langlands Moss within this period, between *c.* cal. AD 5-75. This shift appears to have been recorded at Burnfoothill Moss, situated roughly midway between the two sites in eastern Dumfriesshire (Tipping, 1995), and possibly at Wood Moss in the Peak District, where Blackford and Chambers (1991) record generally wetter conditions between *c.* 145 cal. BC-*c.* cal. AD 255.

Once again, there appears to be a lack of proxy evidence supporting the inferred shifts to warmer conditions recorded at Bolton Fell Moss - Core 3 and Langlands Moss between *c.* cal. AD 70-120, although Stoneman (1993) provides correlating evidence from Bolton fell Moss, with a change from *Sphagnum imbricatum* to drier mire taxa around AD 70.

5.2.6 AD 400 - 800

There are two major shifts to wetter conditions inferred for this period, occurring between *c.* cal. AD 525-615 and *c.* cal. AD 665-705. The earliest of these deteriorations (*c.* cal. AD 525-615) can be identified in both sets of proxy-climate curves reconstructed for Bolton Fell Moss. This change in conditions also coincides with the extinction of *Sphagnum imbricatum* in Core 3 which, although generally recorded as taking place earlier in other palaeoecological studies (e.g., *c.* cal. AD 1030-1460: Mauquoy and Barber, 1999a), is a common characteristic of the mire flora in this region of the British Isles. A wide range of palaeoecological evidence supports a climatic deterioration within this period from a variety of sources across northern Europe.

Through his analysis of the relatively few available documentary records for this period - known as the Dark Ages - Lamb (1977) notes the presence of cool summers in north-west Europe. Evidence from the western side of the British Isles can also be used to support adverse weather conditions during this period, as the county of Cantref y Gwaelod, on the west coast of Wales in Cardigan Bay, was lost to the sea around AD 520 (Lamb, 1982). Blackford and Chambers (1991) also identify a distinct drop in humification levels around 1400 BP (*c.* cal. AD 550-740), recorded in three blanket mires in a transect from western Ireland to North Yorkshire. Stoneman (1993) also identified a phase of increased mire surface wetness for this period, although covering a wider time-window, from between *c.* cal. AD 470-660. There also appears to be supporting evidence from the dendrochronological record for a change to wetter conditions during this period, with Baillie and Munro (1988) identifying narrow tree-rings in Irish oaks, reflecting adverse summer growing conditions, which have been dated to between AD 536-541. Temperature-sensitive reconstructions from Fennoscandian pines also reveal deteriorating climatic conditions during this period (Briffa *et al.*, 1990), as do tree-ring records from other parts of Europe and North America, suggesting that this event caused at least a hemispheric downturn around this time (Baillie, 1999) (Figure 5.1). This event, perhaps coincidentally, coincides with a period of maximum ice acidity in the Dye 3 Greenland ice core, dated to AD 540±10, thereby implying the impact of a major volcanic eruption around this time (Hammer *et al.*, 1980). However, the absence of acidity layers in other Greenland ice cores (i.e., GISP2 and GRIP) at this time suggests that the mechanism for this widespread change in climate was not volcanically driven. One hypothesis put forward by Baillie (1999), which is based on a review of documentary sources, attributes this climatic deterioration to some form of cometary shower, where a significant proportion of the earth was subjected to environmental dislocation during this period.

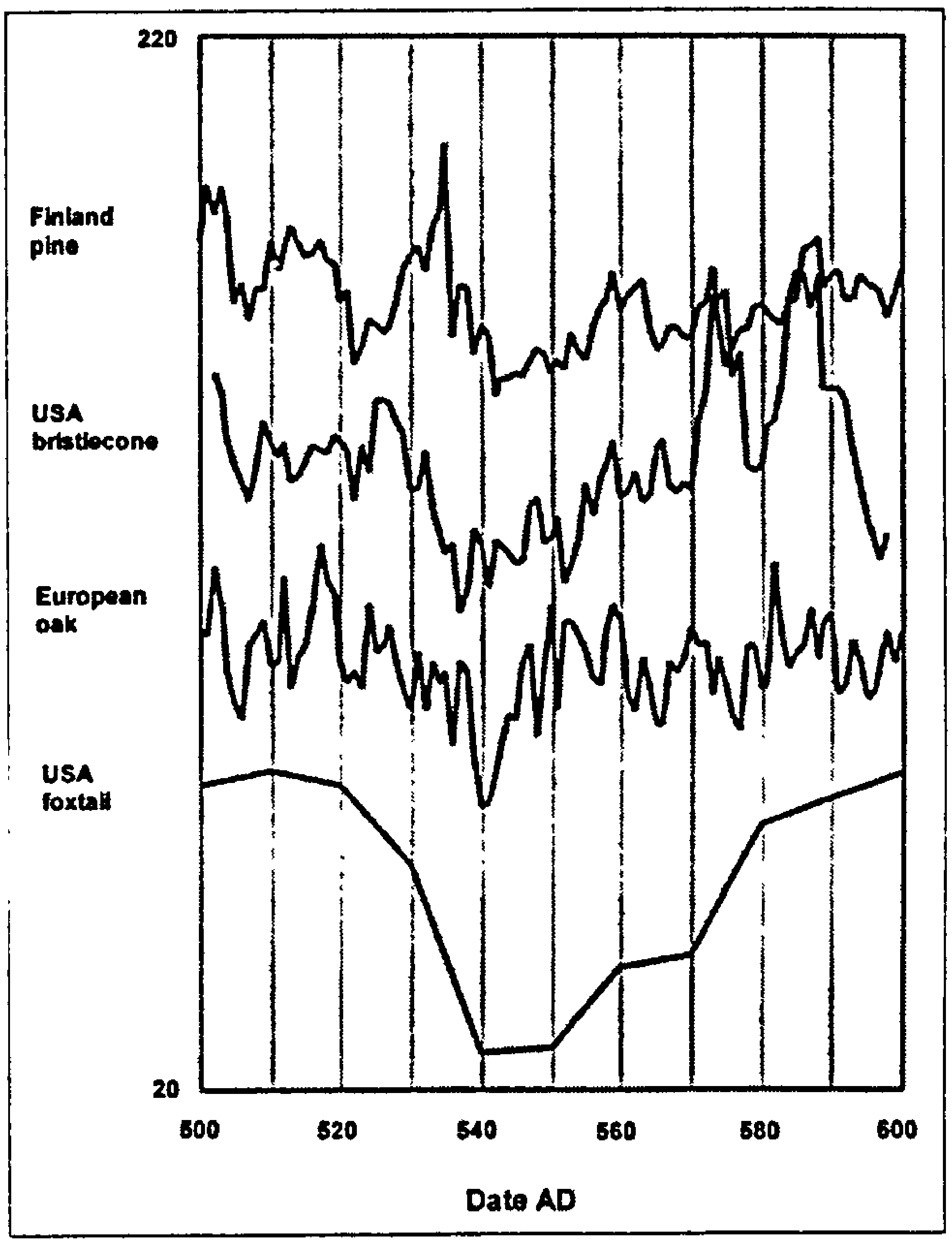

Figure 5.1 Comparison of tree-ring reconstructions from Finland, North America and Europe, showing the synchronous reduction in growth centred around AD 540. Source: Baillie (1999)

The second wet shift to be recorded for this period is inferred as occurring between *c.* cal. AD 665-705 at Bolton Fell Moss - Core MC and Langlands Moss. This shift closely follows a change in humification identified by Chambers (1984) around AD 650, from studies of blanket peat in the Brecon Beacons, South Wales.

The earliest dry shift to be recorded for this period, reconstructed as occurring between *c.* cal. AD 460-540 at Bolton Fell Moss - Core MC and Langlands Moss, precedes the initial dramatic decline in conditions mentioned above. Lamb (1982) highlights sources depicting unusually warm conditions in Britain around this time. A further shift to drier conditions, also recorded at Bolton Fell Moss - Core MC and Langlands Moss, has been reconstructed as occurring between *c.* cal. AD 730-785, although no palaeoecological evidence can be found to support this shift.

5.2.7 AD 800 - 1000

The inferred wet shift identified in both cores from Bolton Fell Moss, reconstructed as occurring between *c.* cal. AD 920-970, coincides with a period of climatic deterioration detected by Stoneman (1993) in a multi-core study of peat stratigraphy from a number of raised bogs in Cumbria and Scotland. Palaeoecological evidence for wetter conditions during this period is also available for other areas of northern England by Barber (1981), Charman *et al.* (1999), Mauquoy (1997) and Mauquoy and Barber (1999b), as well as in Scotland by Anderson (1998) and Chambers *et al.* (1997). It is therefore likely that a change to wetter conditions occurred synchronously across the northern British Isles during this time. The high proportions of UOM and distinct lack of *Sphagnum* species growing at Langlands Moss during this period may have masked any proxy-climatic response at this site.

5.2.8 AD 1000 - 1400

There are no synchronous shifts to wetter conditions recorded for this period, although proxy-climate datasets from both cores taken at Bolton Fell Moss do imply a distinct shift to drier conditions between *c.* cal. AD 1290-1335. This inferred shift coincides with the closing stages of the Medieval Warm Period (AD 1050-1310) which, through interpretation of documentary and meteorological evidence, has been associated with a period of sustained warmth across northern Europe (Lamb, 1982). Using data from the modern limits of wine production, Lamb suggests that average summer temperatures during this period were between 0.7 and 1.0 °C warmer than the twentieth-century average in England. Through detailed stratigraphic analysis of blanket mires in the Southern Pennines and Berwyn Mountains, Tallis (1995) also provides evidence for generally warmer conditions during this period where he used the presence of *Racomitrium lanuginosum* leaves to signify prolonged dry conditions from *c.* cal. AD 1150-1300.

5.2.9 AD 1400 - 1850

Within this period, three phases of climatic deterioration have been synchronously recorded by both cores taken from Bolton Fell Moss, dating from between *c.* cal. AD 1435-1510, *c.* cal. AD 1635-1705 and *c.* cal. AD 1800-1835. These shifts in mire surface conditions may have been in response to the coldest stages of the Little Ice Age (LIA). Although originally thought to have been a period of sustained climatic deterioration across northern Europe, numerous studies have since revealed that the LIA was in fact a period of considerable climatic variation. From their studies of historical, tree-ring and ice core data, Bradley and Jones (1993) uncovered a range of climatic anomalies during this period, demonstrating both warm and cold fluctuations, which also varied in importance geographically. The earliest of these wet phases (*c.* cal. AD 1435-1510) coincides with a series of severe winters recorded across central and western Europe (Lamb, 1982). In an earlier study of Bolton Fell Moss, Barber (1981) reconstructs generally wet conditions during this time, with *Sphagnum* macrofossils identified in seven monoliths clearly reflecting a move to wetter conditions commencing around AD 1425. Aaby (1976) also uncovered a climatic deterioration around this time (*c.* AD 1500), inferred from humification records at Draved Mose in Denmark, as did Mauquoy and Barber (1999b) in their studies of Coom Rigg Moss and Felicia Moss in Northumberland (*c.* cal. AD 1400-1470).

In terms of the European record, Bradley and Jones (1993) propose a decline in summer temperatures between the 1570s-1690s, with a further decline in the 1810s and 1880s, which correlate well with the two most recent wet shifts reconstructed from cores taken from Bolton Fell Moss. The first of these shifts (*c.* cal. AD 1635-1705) correlates strikingly well with a known period of reduced solar activity, known as the Maunder Minimum (AD 1645-1715) (Figure 5.2). Characterised by a time when observers recorded a minimum number of sunspots, the Maunder Minimum coincides with one of the coldest phases of the LIA (Eddy, 1976). Other palaeoecological evidence for climatic deterioration during this time is provided by Blackford and Chambers (1995), where humification measurements from blanket peat sites in western Ireland were distinctly low during this period, indicating wetter conditions. As part of his study of Burnfoothill Moss, a raised mire in eastern Dumfriesshire, Tipping (1995) records poorly humified conditions between *c.* cal. AD 1550-1700, which is also supported there by the presence of hygrophilous pollen taxa at this time. Evidence supporting both these phases of inferred deterioration is also provided through records of 'bog-bursts'. Bog-bursts occur when raised mires become excessively sodden and swollen with moisture, thereby reaching a point of maximum saturation, and as a result they explode in spectacular fashion. This phenomenon happened at Charleville in Co. Cork in 1697, in Solway Moss (near the England-Scotland border) in 1771 and 1772, and at Haworth in the Yorkshire Pennines in 1824 (Lamb, 1982).

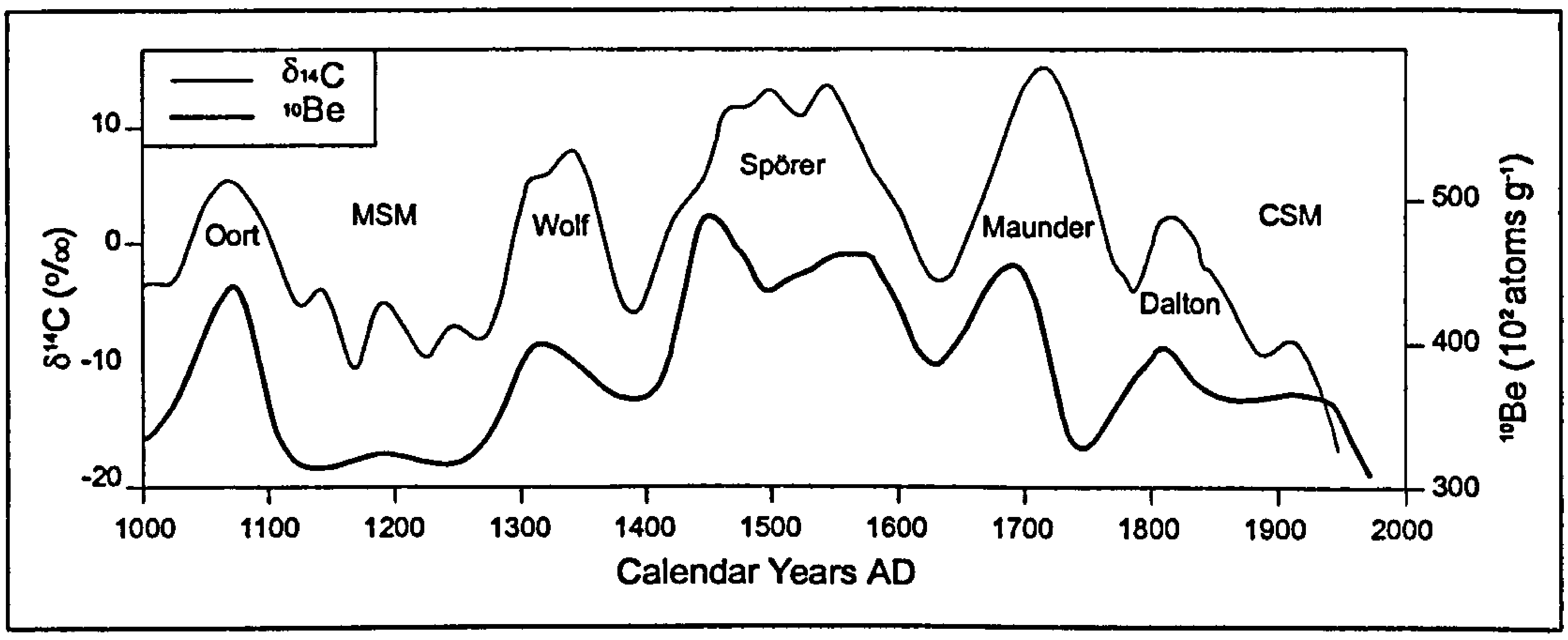

Figure 5.2 Trends in $\delta^{14}C$ and ^{10}Be from AD 1000 to present, showing periods of solar minima (named) and solar maxima (CSM - Contemporary Solar activity Maximum; MSM - Medieval Solar activity Maximum), demonstrating that concentrations of these cosmogenic isotopes in south polar ice apparently relate to historic solar activity. Adapted from Damon *et al.* (1998).

Through his investigations at the same site, Barber (1981) was also able to identify the later stage of the LIA when rises in proportions of *Sphagnum* section Subsecunda, *Sphagnum cuspidatum* and algal muds in multiple monoliths, were dated pollen analytically as occurring between *c.* cal. AD 1780-1800. More recent work, also at Bolton Fell Moss and nearby Walton Moss, has revealed similar replicatable climatic signals which, on the basis of their pollen stratigraphy, indicates synchronous rises in local water table associated with this later stage of the LIA (Barber *et al.*, 1998). Evidence for climatic deterioration during this period can also be derived from studies of blanket peat ecosystems, as Blackford (1990) was able to identify distinct wet shifts between *c.* cal. AD 1750-1810 at three of his sites under investigation.

A phase of relatively drier conditions has also been identified at Bolton Fell Moss, dated as occurring between *c.* cal. AD 1710-1740. Tree-ring evidence from northern Fennoscandia suggests that summer temperatures were near normal from AD 1660-1750, and that only after this time (AD 1750-1770) conditions were extremely warm (Briffa *et al.*, 1990). This may indicate that the same improvement in climatic conditions was also registered at Bolton Fell Moss, but owing to the limitations of the chronology, it has been recorded at an earlier time.

5.2.10 AD 1850 - 1997

Proxy-climatic signals reconstructed from cores taken from Bolton Fell Moss are extremely noisy during this period, with numerous rapid fluctuations between relatively wet and dry conditions. However, it is still possible to determine a synchronous shift to drier conditions between *c.* cal. AD 1935-1975. This rapid change to drier mire surface conditions may be a reflection of the increase in global temperatures, as reported by Horel and Geisler (1997), during the 1940s (see Figure 5.3). Attributing these shifts to changes in climate is, however, hazardous, as large-scale disturbance at Bolton Fell Moss, in the form of peat-cutting and drainage, may have affected the climate signal in the upper layers.

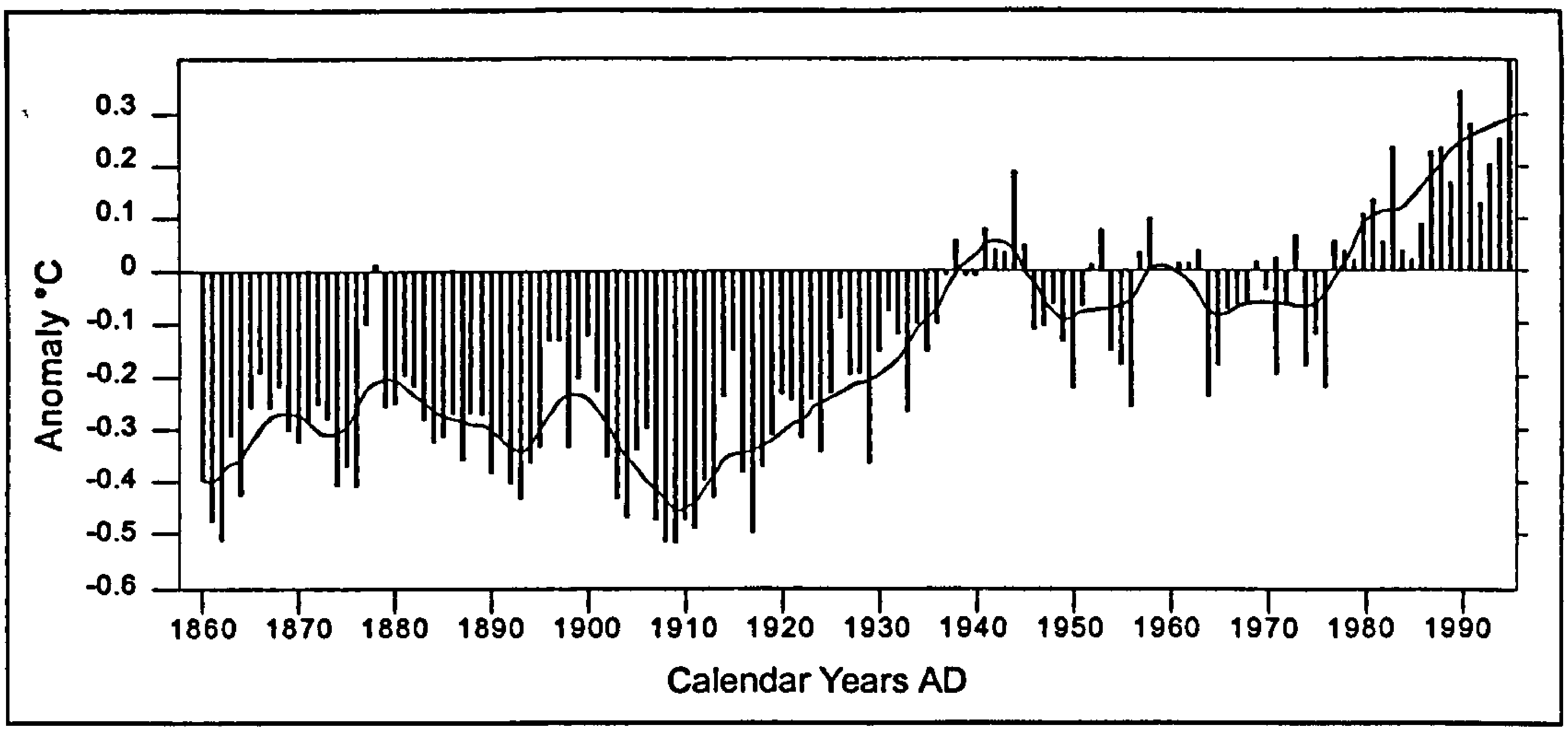

Figure 5.3 Recorded global temperature rise 1860-1995, based on instrumental data from selected meteorological recording stations and marine records. Adapted from Horel and Geisler (1997)

5.2.11 Summary of Proxy-Climatic Reconstructions

The above evidence strongly implies that the use of a multi-proxy approach in the generation of proxy-climatic datasets has enabled the detection of established fluctuations in regional climate. However, owing to the probable effects of drainage and/or afforestation at Langlands Moss, and a change in the internal hydrological dynamics at Mynydd Llangatwg, the potential to uncover shifts in climate that occurred across all cores investigated has been restricted. For this reason, the palaeoclimatic record has been segregated, and there is only a short overlap period when a maximum of three cores have had the potential to show any correlation. Despite this limitation, major periods of climatic change that have occurred across the British Isles over the last 3000 years appear to have been detected. Although there is a possibility that the twentieth century rises in northern hemisphere average temperatures has been identified at Bolton Fell Moss, the latest established palaeoclimatic shift to be recorded appears to be the Little Ice Age (LIA). Both sets of proxy-climate curves from Bolton Fell Moss appear to record the same pattern of changes in mire surface conditions for this period, reconstructing two distinct phases of inferred climatic deterioration. The most recent of these inferred shifts (*c.* cal. AD 1800-1835) is also supported by independent chronological evidence in the form of

SCP and ^{210}Pb dated profiles, which serve to support further the reliability of the proxy-climate records. The second cold phase to be recorded at Bolton Fell Moss has been reconstructed as occurring between *c.* cal. AD 1635-1705, and this shift correlates strikingly well with an observed period of minimal solar activity (AD 1645-1715), known as the Maunder minimum. Both these inferred shifts are comparable with other regionally associated palaeoclimatic studies and instrumental records covering the LIA, thereby fulfilling a major prerequisite of this investigation, that proxy-climatic records produced in this study have effectively reconstructed changes in regional climate.

Notwithstanding the difficulties in reconstructing shifts to drier conditions, the proxy-climate records also appear to reconstruct the increase in summer temperatures experienced during the Medieval Warm Period (MWP). Another reconstructed shift to wetter conditions has been found to coincide with an established period of climatic deterioration, identified through the analysis of tree-rings as occurring around AD 540. Numerous palaeoclimatic reconstructions have identified a general climatic deterioration in northern hemispheric conditions around this time, with some authors attributing the volcanic eruption of Rabaul in Indonesia as the primary forcing mechanism (Rampino, 1985), while tree-ring records, supported by documentary evidence, seem to imply that a widespread cometary shower may have influenced the climate during this time (Baillie, 1999). This wet shift also coincides with the extinction of *Sphagnum imbricatum* in one of the cores extracted from Bolton Fell Moss, which has often been thought of as being climatically induced (Barber, 1981; Stoneman *et al.*, 1993). Proxy-climate curves also replicate an abrupt shift to wetter conditions between *c.* 845-765 cal. BC, which falls within the time period highlighted by other palaeoclimatic records as a phase of increased effective precipitation. Van Geel *et al.* (1996) attribute variations in heat transportation by ocean currents and atmospheric circulation patterns as mechanisms for the transition. However, further studies involving comparisons of cosmogenic isotope records with known periods of climatic change identify a sudden and sharp rise in atmospheric ^{14}C and ^{10}Be during this period, and imply the influence of solar activity as the primary driving mechanism for these changes (van Geel *et al.*, 1999).

Although variations in the proxy-climate records produced in this study do appear to reconstruct fluctuations in regional climate effectively, it has been suggested that the relationship between climate and peat stratigraphy may be more complex than was previously recognised. Evidence suggests that mires may react in phase to a spatially coherent temperature signal and asynchronously to a zonal precipitation signal (Barber *et al.*, 1999), and for this reason estimations regarding the extent of any change in climate must be treated with caution.

5.3 Assessment of the Palaeoecological Techniques

The high-resolution multi-proxy strategy employed in this study has enabled the generation of detailed proxy-climatic curves covering the last 2500 years of change across the western side of Britain. Unlike the majority of previous peat-based palaeoclimatic investigations, where a coarser-sampling interval has been employed (typically 4 cm +), primary analyses in this study have been performed at between 0.5-1 cm intervals. This approach has a number advantages over the coarse-sampling strategy. Firstly, changes in vegetational assemblage and variations in the rate of decomposition, with respect to macrofossil and humification analysis, can be observed on a decadal rather than a century-based time-scale. Secondly, the high-resolution palaeoclimatic records produced using this methodology suggests, theoretically at least, that direct comparison can also be made with other high-resolution palaeoenvironmental datasets, such as ice core and tree-ring records. Each of the palaeoecological techniques employed in this study will now be considered individually, in terms of their effectiveness in reconstructing variations in mire surface conditions, and by inference, changes in regional climate.

5.3.1 Colorimetric Humification Record

Blackford (1993) suggests that the most likely cause of variability in the humification record is that of changes in summer peat-surface wetness, which could result from temperature and/or precipitation changes. The effectiveness of this technique in registering such proxy-climatic signals is clearly demonstrated when comparing the two humification records obtained for Bolton Fell Moss (Figure 5.4). Despite considerable differences in the vegetative content of the two profiles, both cores appear to replicate a number of proxy-climatic signals. The dramatic reduction in absorbance around cal. AD 540 correlates directly across both cores, as do the synchronous increases in absorbance values at *c.* cal. AD 1300, reflecting the favourable conditions of the Medieval Optimum, and the wettest stages of the LIA. There are however also problems with the record. Between *c.* cal. AD 600-1200 there is an apparent negative correlation and lags can clearly be seen to occur between a number of correlating peaks. The limitations of the radiocarbon

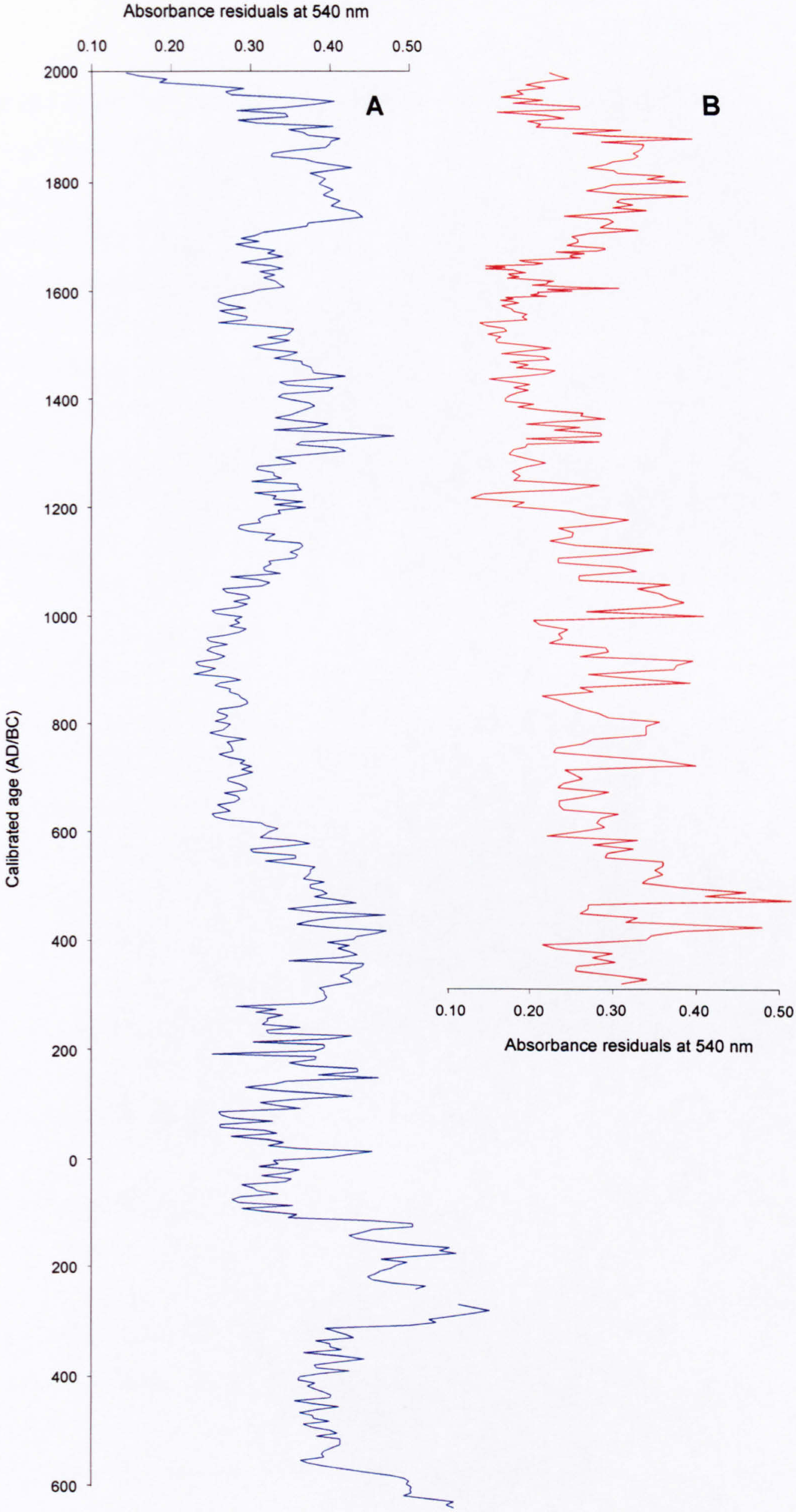

Figure 5.4 Comparison of humification records from Bolton Fell Moss; (a) Core 3; (b) Core MC

chronology generated for Core 3 may account for some these variations, although the affect of within-site variability cannot be ruled out.

There are a number of advantages of using humification analysis in conjunction with macrofossil analysis. Colorimetric analyses have been shown to be replicatable, applicable to all peat types and able to show greater variation than is seen in the visible stratigraphic record (Blackford, 2000). Unlike the macrofossil record, where a time lag is thought to occur between climatic change and response (Haslam, 1987), fluctuations in the degree of humification are not generally thought to be dependent upon species change, thereby reducing the response time. This potentially enables the identification of short-term variations in climate, thereby enhancing the probability that cyclic oscillations may be able to be detected using this proxy-technique. This hypothesis was tested by Blackford and Chambers (1995) who predicted a link between peat humification and solar variability, suggesting that an increase in the frequency of sunspots resulted in summer anticyclonic conditions becoming more common in north-west Europe (Lamb, 1982), resulting in warmer/drier climate across the western British Isles, which in turn leads to increased peat humification. Conversely, during periods of reduced sunspot activity effective insolation is decreased, and cooler/wetter conditions prevail, leading to the accumulation of less-humified peat (Blackford and Chambers, 1995). There is some evidence to suggest that solar variability has been the driving mechanism behind a number of inferred shifts reconstructed from this study, but without further statistical analysis of the datasets incorporating time series analysis techniques, it is difficult to ascertain the extent of any specific influence with any degree of certainty.

Despite the apparent effectiveness of this technique in registering changes in mire surface conditions, there is however still a considerable amount of scepticism, which derives from the possible influence of differential rates of decay between bog species. Field experiments conducted by Coulson and Butterfield (1978) demonstrated that *Sphagnum fuscum* and *Racomitrium lanuginosum* have relatively slow decay rates, while other studies have indicated that *Sphagnum cuspidatum* is susceptible to a more accelerated level of breakdown in peat (Johnson *et al.*, 1990; Johnson and Damman, 1991). Caseldine *et al.* (2000) comment on the suggestion that these species-dependent rates of decay at the bog surface would influence 'natural rates' of humification, and infer that there would be a similar differential susceptibility to the NaOH treatment.

5.3.2 Macrofossil Record

The majority of the cores analysed have been found to contain substantial quantities of *Sphagnum* leaves, with identifiable species covering a range of different moisture conditions along the hydrological gradient. This is particularly true of Bolton Fell Moss, where macrofossil-based DCA and WAO index reconstructions demonstrate considerable variation and a high degree of correlation with the humification records. The distinct lack of sub-fossil Sphagna in material extracted from Mynydd Llangatwg does however restrict the effectiveness of any multivariate reconstruction, as any variation in the proxy-climate signal here is largely based upon fluctuations in the proportion of drier, less responsive macrofossil components. Areas where outlying species dominate the peat matrix also appear to have led to conflicting signals, which is highlighted by the high proportions of *Eriophorum vaginatum* found in the lower section of this core. Although the DCA curve reflects a series of rapid dry shifts for this period, the WAO index appears to ignore the presence of the *Eriophorum*, and instead indicates a change to wetter conditions, reflected by the interspersed increases of *Sphagnum* section Acutifolia and *Sphagnum magellanicum*. The method of assigning a single weight to each taxon, as is applied in weighted averages ordination, may provide an easily interpretable record of relative surface wetness, but may also be guilty of over simplifying the proxy-climatic signal. *E. vaginatum*, with its characteristically bimodal response curve, can tolerate a wide range of climatic conditions, from deep winter freezing of the peat surface (Wein, 1973) to burning events. This has led to a mid-range weight being assigned to this species, which has had the effect of masking any proxy-climatic signal its presence may represent.

As mentioned in the previous section, *Sphagnum* remains may either be absent or unidentifiable as a result of differential rates of decomposition. Although the acidic conditions and high water content of ombrotrophic mires restricts the activity of microorganisms, rates of decomposition are severely affected by drainage activities, which have the effect of lowering the water table and increasing oxidation. Although cores from Bolton Fell Moss both contain high proportions of *Sphagnum* species throughout, sections of cores taken from Langlands Moss and Mynydd Llangatwg appear to have been affected by drainage, which may have instigated an accelerated breakdown of the *Sphagnum* leaves, thereby damaging the macrofossil record. It has also been suggested that inter-species competition, rather than climatic factors, can force changes in assemblage to occur (Blackford, 2000), which may provide an alternative explanation for the extinction and subsequent replacement of *Sphagnum imbricatum* by *Sphagnum magellanicum*, as recorded at Bolton Fell Moss - Core 3, and at numerous other sites across northern Britain (e.g., Barber, 1981; Haslam, 1987; Stoneman, 1993; Mauquoy, 1997). The absence of *Sphagnum magellanicum* from the upper layers of the majority of Welsh mires is also of interest here, as leaves of this species have been identified at Mynydd Llangatwg. Although suppressed by the increasing levels of UOM and monocotyledonous remains in the upper section of this core, *S. magellanicum* appears to replace *S. imbricatum* as the dominant species of Sphagna. The presence of *S. magellanicum* at this site may in itself be significant as the nearest recorded sighting of this species in Wales is at Tregaron Bog, situated some distance away to the west of this location (Hill *et al.*, 1992).

5.3.3 Testate Amoebae Record

The quantification of testate amoebae indicator-species has provided an independent record by which to support correlating signals indicated by the humification and macrofossil records. The fluctuations in moisture conditions, indicated by the varying proportions of testate species, are generally in agreement with the evidence gained from the primary analysis techniques, with the more hydrophilous species coinciding with shifts to wetter conditions, while increases in proportions of xerophilous species have mostly correlated with relatively drier phases.

5.4 Site Disturbance

The only site where it has been possible to reconstruct a continuous record of proxy-climatic change is Bolton Fell Moss. The upper layers of Langlands Moss and Mynydd Llangatwg both appear to have been affected by some form of disturbance, which has restricted their ability to record effectively the changes in mire surface conditions over the last two millennia. Possible mechanisms for this disturbance will now be considered for each of these sites.

5.4.1 Langlands Moss

The potential for recording correlating shifts at Langlands Moss may have been reduced as a result of differences in ecological, hydrological and/or morphological characteristics between the sites investigated. In terms of the macrofossil record, the presence of a substantial quantity of *Sphagnum* leaves is preferable if an accurate palaeoclimatic interpretation is to be achieved. Conway (1948) suggests that variations in the rainfall/evaporation ratio are likely to be the most influential 'moisture factor' determining the growth of *Sphagnum* species, and that these variables are largely governed by variations in altitude, aspects of the local topography and the morphology of the mire itself. The growth of *Sphagnum* can also be negatively influenced by the effects of drainage, grazing and burning, which can enforce considerable change on the development of a stable assemblage.

The interpolated radiocarbon chronology has enabled the identification of a dramatic decrease in the rate of accumulation at Langlands Moss around AD 1000, and this reduction in growth has been attributed to surface disturbance. The unusually high proportions of UOM in the upper section of the core, and perhaps more significantly, the presence of a nearby forest and evidence of previous drainage ditches, suggest that this disturbance was as a direct result of afforestation and/or drainage of this part of the mire. Supporting evidence for this theory has also been provided by Langdon (1999) who, in a similar study of the same site, also encountered chronological problems at a similar depth, from a core taken from a point within 50 metres of where Core 4 was extracted. Prolonged disturbance would have led to compaction of the peat due to water loss, which may have resulted in further loss of material in subsequent phases of drying out and desiccation.

5.4.2 Mynydd Llangatwg

The consistently high levels of charcoal recorded throughout the core taken at Mynydd Llangatwg suggests that fire was frequently used in the management of this site, which most likely influenced the replacement of *Sphagnum* species by *E. vaginatum* in the lower section of the core. Shaw *et al.* (1996) comment on the seriously detrimental effect that fire can have on the growth of peat, often leading to the formation of a hard crust on the surface of the peat which, as well as affecting the infiltration of water, may restrict the recolonisation of certain species of mire taxa. The effects of burning combined with intensive grazing and drainage would have led to severe gullying and erosion causing a drying out of the mire's surface and, consequently, loss of the *Sphagnum* cover. This would explain the relative sparseness of Sphagna at Mynydd Llangatwg, and the evidence of intensive gullying, clearly identifiable from the aerial photograph of the site (see Plate 3.3).

As with Langlands Moss, the age-depth model for Mynydd Llangatwg also reconstructs a considerable reduction in peat accumulation, occurring around cal. AD 50. Although this reduction in peat growth may have been directly attributable to one or all of the mechanisms already mentioned, another possible trigger for this change may have been a rapid change in the water balance of the mire. A sink hole, situated within a few metres of the coring point, may be a relic of this change. Drainage of the now submerged, former peat surface, would have led to primary consolidation, followed by shrinkage, secondary compression and finally subsidence (Hobbs, 1986). This may justify the present water level of the sink hole, situated *c.* 2.5 m below the surface of the hagg, and the cracked formation of the peat edge.

Chapter 6 Conclusions and Further Research

6.1 Conclusions

High-resolution dating techniques have enabled the identification of a number of synchronously occurring wet and dry shifts in mire surface conditions, across two or more of the cores analysed. It is suggested that these inferred fluctuations reflect variations in regional climatic conditions. A number of previously documented shifts in climate appear to have been recorded at sites investigated in this study. These include the rapid decline in conditions around 800 cal. BC, which coincides with the Sub-boreal/Sub-atlantic transition; an event widely recognised in dendrochronological records as being associated with detrimental conditions across most of the northern hemisphere around cal. AD 540; and the coldest stages of the Little Ice Age, reconstructed as occurring between cal. AD 1400-1850.

It is clear from the evidence presented in this study that the adoption of a multi-proxy approach in palaeoclimatic investigations is essential if changes in climate are to be identified effectively. It has been demonstrated that individual proxies may respond to mechanisms other than climatic change, such as species competition and fluctuations in the internal dynamics of the mire system, leading to the production of misleading signals.

The high density of inferred shifts to wetter and drier conditions reconstructed from this study supports the hypothesis that high-resolution sampling procedures, as opposed to using a coarse-sampling strategy, is more effective at uncovering proxy-climate signals that may otherwise go unrecorded.

DCA curves generated through multivariate analysis of the macrofossil datasets have enabled the identification of a common association between climatic deteriorations and changes in vegetational assemblage. Although species of mire taxa have been found to vary between cores, major proxy-climatic shifts are often associated with the rapid replacement of one species of *Sphagnum* with another. Examples of this include the rapid deterioration in conditions inferred for Mynydd Llangatwg around

800 cal. BC, which appears to force the change from a relatively dry macrofossil assemblage to a peat matrix dominated by *Sphagnum imbricatum*. Although based on a weak chronology, the well documented shift to wetter conditions around cal. AD 540 also coincides with a change in the vegetational assemblage, indicated by the extinction and replacement of *S. imbricatum* by *Sphagnum magellanicum* at Bolton Fell Moss - Core 3.

The restrictions imposed by various forms of site disturbance have been highlighted in this study, with the effects of drainage, burning and grazing having a seriously detrimental impact on the proxy-climatic records from both Langlands Moss and Mynydd Llangatwg.

Evidence from this study has been found to reject the long-standing assumption of mire-based palaeoecological studies first put forward by Walker and Walker (1961), and later Barber (1981), whereby mire taxa react synchronously across the surface of a bog. This is demonstrated by the difference in macrofossil content between Bolton Fell Moss - Core MC and Bolton Fell Moss - Core 3. However, despite the differences in assemblage at these two coring locations, a number of correlating shifts in regional climate still appear to have been independently recorded in these cores.

Through the application of wiggle-match dating, a more precise standard of chronological control has been achieved for three of the four cores analysed in this project, than would otherwise have been possible if a conventional ^{14}C dating and calibration strategy had been adopted.

6.2 Further Research

Although not attempted in this study, further statistical analysis of the proxy-climate datasets, using time series analysis techniques, may facilitate the identification of long-term trends and cycles. The potential for using this technique has been demonstrated by such workers as Barber *et al.* (1994a), who identified a possibly ocean-driven, 800-year signal using spectral analysis, and Chambers *et al.* (1997) who were able to reconstruct periods of cyclicity with a frequency of *c.* 210 years in a humification record from Talla Moss, Scotland.

Although the level of chronological control of each core is generally adequate for a study of this nature, (apart from Bolton Fell Moss - Core 3, where a lack of radiocarbon dates has prevented the application of wiggle-match dating) the additional use of tephrochronology would provide precise chronological markers, enabling cross-correlation of fixed points between cores, thereby providing further support for the radiocarbon-based timescales. It has even been suggested that the use of tephrochronology in this context may facilitate correlation with acidity peaks found in ice core records from Greenland (Blackford, 2000).

One of the mires investigated, Mynydd Llangatwg, overlays a network of subsurface cave systems, formed through the continuous erosion of the limestone bedrock. It has been demonstrated by a number of workers that the analysis of stalagmite formations in such caves can provide records of past variations in surface wetness that can be directly compared with colorimetric humification datasets. The effectiveness of this technique has been demonstrated by Baker *et al.* (1999) who, by analysing stalagmite luminescence wavelength variations and comparing these with humification records from the overlying peat, were able to uncover 90-100 year oscillations in bog wetness. So it is recommended that the cave systems under Mynydd Llangatwg be investigated for stalagmite formation and that, if found, these be sampled and analysed at high-resolution for direct comparison with the data produced in this study.

A more comprehensive investigation of the testate amoebae content of each core may also prove beneficial in supporting the proxy-climatic reconstructions, involving the identification of all species and the application of a finer sampling strategy. Using transfer functions based on modern distributions (developed by the University of Plymouth research group), it is possible that species counts can be quantitatively linked to the relative height of the local water table, thereby providing a further proxy-record of relative mire surface conditions.

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Appendix 1 - Method for colorimetric humification analysis, after Blackford (1990); modified from Bahnson (1968):

- Sub-samples of peat were initially air-dried
- Once dry, peat sub-samples were ground with a pestle and mortar (fibrous samples, containing sedges, were cut with scissors)
- 200 mg of the ground peat was then placed into a 150 ml beaker and 100 ml freshly mixed 8% NaOH was added
- The beaker was then heated on a hot plate to boiling point (regularly stirring) and then simmered for 1 hour to reduce evaporation of the solution. This process was carried out in a fume cupboard to avoid intoxication
- Once cooled, each solution was transferred into a 200 ml flask, topped up with distilled water to the mark, shaken, and filtered through 'Whatman Qualitative 1' papers
- 50 ml of the filtrate was then diluted 1:1 with distilled water in a 100 ml flask, and shaken well
- The absorbance of each sample at a wavelength of 540 nm was then recorded using a Cecil Spectrophotometer. The mean absorbance of three samples was recorded, after first zeroing the colorimeter with distilled water.

Appendix 2 - Method for SCP analysis, adapted from Rhodes (1996):

- Each sub-sample of 100-400 mg of peat was initially air dried
- The sample was then heated to 180°C in a Gerdhart acid digestion scrubber unit for *c.* 1 hour
- Following removal of organic content, the residue was centrifuged at 3000 rpm for 3 minutes, decanted, distilled water was added, and this procedure was repeated until only a carbonaceous pellet remains
- The remaining residue was then poured into pre-weighed vials and centrifuged, again at 3000 rpm for 3 minutes
- The supernatant was then carefully removed with a disposable pipette and weighed, together with the vial
- A drop of the residue is then mounted on a slide, placed on a hotplate to evaporate the excess water, and sealed using a single drop of glycerol, then a coverslip is placed on top
- Vial containing remaining residue is then re-weighed, in order that the weight of the sub-sample can be calculated
- Slide is then examined for SCP's at × 400 magnification (size range 5-30 microns).