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TESTING THE SENSITIVITY OF THE PALAEOCLIMATIC SIGNAL FROM OMBROTROPHIC PEAT STRATIGRAPHY.

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ABSTRACT

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TESTING THE SENSITIVITY OF THE PALAEOCLIMATIC SIGNAL FROM OMBROTROPHIC PEAT STRATIGRAPHY.

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The aim of this thesis is to test the sensitivity of the palaeoclimatic proxy-record from the peat stratigraphy of six paired ombrotrophic raised mires (Bolton Fell Moss and Walton Moss, Raeburn Flow and Bell's Flow, and Coom Rigg Moss and Felecia Moss), and one ombrotrophic blanket mire (Shaft Hill, Moor House), located along an rainfall gradient in Northern England and the Scottish Borders.

Three techniques to reconstruct proxy-climate via mire surface wetness have been used - colorimetric humification, quantitative plant macrofossil, and testate amoebae analyses. Weighted averages ordination (Dupont index) and Detrended Correspondence Analysis (DCA), were used to transform the raw floral and faunal data into indices of mire surface wetness. The chronology of each peat profile was determined by radiocarbon assay, supported by spheroidal carbonaceous particle (SCP) analyses and pollen / landuse correlations. Palaeoclimate reconstructions have been made by linking known documentary / historical changes in climate, and other proxy-climate records, to those inferred from the sites investigated in the study region.

The adoption of multiple proxies to reconstruct mire surface wetness has led to improved palaeoclimate reconstructions, whilst the pollen and SCP chronologies have served to highlight deficiencies in the radiocarbon chronology and the existence of a possible hiatus in the stratigraphy of the blanket mire investigated.

The latter stage of the Little Ice Age (LIA), is the only climatic deterioration registered in all of the study sites. The largest inferred changes in mire surface wetness in Bell's Flow and Coom Rigg Moss occur coevally with the LIA, and suggest it was a severe climatic departure. Conflicting dates between the pollen and calibrated radiocarbon chronology for these two sites suggest the LIA may have occurred between 1420-1800 AD. The other main wet shifts detected in the aggregate peat stratigraphy occur at 3110-2950 BC., 2880-2810 BC., 2670-2390 BC., 1690-1340 BC., 1290-920 BC., 790-440 BC., 440-130 BC., 160 BC.-100 AD., 210-380 AD., 550-810 AD., 790-1060 AD., 1010-1210 AD., and 1290-1530 AD. Dry episodes occur at 2390-2180 BC., 2110-1880 BC., 1550-1240 BC., 830-580 BC., 580-400 BC., 130-40 BC., 20-170 AD., 230-370 AD., 360-530 AD., 640-890 AD., 930-1090 AD., 1110-1290 AD. (The High Middle Ages), 1370-1480 AD., and 1500-1690 AD.

The water balance, size, shape and hydrology of each site has been investigated in an attempt to explain the differences between their palaeoclimatic records. Evidence for differential site sensitivity is presented, which shows that Coom Rigg and Felecia Moss are the most sensitive in recording climatic deteriorations. The absence of potential summer water deficits and a mean annual effective precipitation of 677 mm., may explain the greater sensitivity of these mires, as the *Sphagnum* mosses experience optimal growth conditions here. Extreme effective precipitation within the Moor House Reserve (1373 mm.), may be routed away by throughflow and overland flow, which may possibly account for the lack of wet shifts registered by the flora and fauna. Alternatively, the presence of a fire induced hiatus may explain the climatically insensitive blanket peat stratigraphy. Site specific differences in mire hydrology may be responsible for the divergent plant macrofossil and testate amoebae stratigraphies of Raeburn Flow and Bell's Flow.

The extinction of *Sphagnum imbricatum* in the six raised peat bogs investigated, occurred between 1010-1520 AD., and is associated with climatic deteriorations.

Time-series analysis of the humification and DCA data from Bolton Fell Moss and Walton Moss has demonstrated the existence of a periodicity of c. 260-280 years. This periodicity matches results obtained from Denmark and the Netherlands, possibly suggesting the existence of a common climatic forcing mechanism affecting these North-West European sites.

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Chapter 1 Introduction.

1.1 Background to the study.

The aim of this research project is to test the sensitivity of the palaeoclimatic record from ombrotrophic mires located along an effective rainfall gradient. Sensitivity is defined here as the number and magnitude of hydro-climatic changes registered by each mire during the last 3-4500 years. These changes can be validated by reference to the instrumental/documentary record and to published palaeoclimatic reconstructions. The peatlands of Cumbria and the Scottish Borders form an ideal testing ground to undertake this, since numerous intact mires remain in the region, and there is a strong rainfall and temperature gradient imposed by the topography, which extends from the lowlands of the Solway Firth to the high Fells (up to 848 m.) of the Northern Pennines. This climate gradient is a reflection of temperature lapse rates (Manley, 1970), and increased orographic rainfall on the higher sites in the Northern Pennines and Wark Forest (Chandler and Gregory, 1976).

Wide-ranging palaeoclimatic reconstructions from peat stratigraphy have been undertaken by Haslam (1987), across Northern Europe, where the timing and strength of the main humification change was determined for raised bogs extending from Eire to Poland. Stoneman (1993), adopted a similar methodology to Haslam (1987), and examined the stratigraphy of raised mires extending from Cumbria to the Southern Uplands of Scotland. This analysis differs from these, in that sites from a smaller region have been selected, whilst the level of detailed analysis of biological proxy climatic data has been increased. The term proxy is used here to denote material that provides an indirect measure of climate.

Ombrotrophic mires, which include both raised and water-shedding blanket peat bogs, are directly coupled to the atmosphere, as they receive all their water through precipitation alone. A clear relationship between peat stratigraphy and climate was demonstrated by Barber (1981), where multiple synchronous changes in the plant macrofossil stratigraphy of Bolton Fell Moss were found to coincide with the climate change indices of Lamb (1977). Further research into the relationship between plant macrofossils and palaeoclimates has been undertaken by Smith (1985) and Wimble (1986), using the five point abundance estimate technique established by Barber (1981), whilst a fully quantified Quadrat and Leaf Count Macrofossil Analysis (QLCMA) technique to determine the percentage abundance of vegetative macrofossils has been developed by Haslam (1987) and Clarke (1988). QLCMA has been utilised by Stoneman (1993), and Barber *et al* (1994a, b, c) and Barber (1995; 1996), since it allows plant macrofossil data to be subjected to multivariate analyses. QLCMA has therefore been adopted for this research project, in order to make palaeoclimate reconstructions using Detrended Correspondence Analysis (DCA). The quality of the plant macrofossil data for each site has been improved, where possible, by identification of the sedges present in the stratigraphy to species level, as *Eriophorum angustifolium and Rhynchospora alba* in particular, can highlight periods of higher local water tables, and possibly point to climatic deteriorations. Peat humification (Aaby, 1976; Blackford, 1990; Blackford and Chambers, 1995) and Testate Amoebae analysis (Tolonen, 1979; Charman and Warner, 1992; Warner and Charman, 1994; Woodland 1996) has also been undertaken, as these techniques allow further independent palaeoclimatic reconstructions to be made. Humification and Testate Amoebae analysis are useful techniques where the peat stratigraphy is dominated by single species, such as *Sphagnum imbricatum* or *Sphagnum* section *Acutifolia,* (Stoneman, 1993; Woodland, 1996) as they offer an alternative means to determine the depth of local water tables.

The degree of mire surface wetness on ombrotrophic bogs is dependent on the interaction between precipitation and evapotranspiration (Barber, 1982). An attempt to detect possible temperature changes which may be recorded in peat stratigraphy has been made by Van Geel and Middeldorp (1988), using ratios of $^2H/^1H$ isotopes. Dupont (1985; 1986) proposes fluctuations in $^2H/^1H$ ratios are influenced by temperature, but Van Geel and Middeldorp were unable to show this, as there was no correlation between the measured deuterium ratios and climatic changes during the last 850 years. Van Geel and Middeldorp suggest this is due to differential species enrichment of these isotopes, since vascular plants are enriched in deuterium relative to *Sphagnum* species by 25% (Brenninkmeijer *et al.*, 1982).

Discriminating between precipitation and temperature changes using the available biological proxy climate data is clearly difficult. This data does allow, however, the identification of *relative* changes in mire surface wetness and its *direction.* Known climatic deteriorations which occurred during the latter stages of the Little Ice Age (LIA) around 1800 AD. (Bradley and Jones, 1993; Barber *et al.*, in press) can be identified using biological proxy climate data (Barber *et al.*, 1994a, b; Barber, 1995, 1996). The registration of this allogenic forcing within ombrotrophic peat stratigraphy allows more ancient inferred climatic deteriorations to be validated and calibrated, since there is instrumental and documentary evidence available which attests to the severity of the LIA (Lamb, 1977).

Specific questions that this research project seeks to answer are:

1. Is it possible to identify palaeoclimatic changes in the ombrogenous peat stratigraphy of the study sites which match those already identified in the literature? Palaeoclimatic changes are deemed to have occurred when there is a common period of change in mire surface wetness, both between paired mires and other peatlands in the study region.

2. How similar/dissimilar are the palaeoclimatic reconstructions generated from the plant macrofossil, humification and testate amoebae analyses, and how far do they serve to improve water-level reconstructions derived from biological proxy data?

3. Do ombrotrophic peat bogs display differential sensitivity to record climatic changes ? In this context, sensitivity is defined as the amount of palaeoclimatic changes registered by each of the study sites. If evidence can be presented which highlights any differential climatic sensitivity, can this be explained in terms of the respective water balances, size, shape and hydrologies of the research project sites?

1.2 Thesis structure.

The thesis is organised into seven chapters. The present chapter has served to present the background and general aims of the research project. In Chapter 2 the climate-peat relationship is explored in detail, and the influence of non-climatic factors is considered. Chapter 3 details the methods of investigation used to identify plant macrofossils, testate amoebae and the degree of humification. The techniques adopted to retrieve peat samples and to date them are also discussed (these are radiocarbon assay, pollen and Spheroidal Carbonaceous Particle (SCP) analysis. Site descriptions follow in Chapter 4, including a climatic appraisal, based on 30 year averages of precipitation and potential-evaporation data. The results of the plant macrofossil, testate amoebae and humification analyses are presented in Chapter 5, along with the results of the radiocarbon assays, pollen and SCP analyses. The techniques employed to reconstruct mire surface wetness (Dupont wetness index, and Detrended Correspondence Analysis (DCA), are also discussed in this chapter, along with the results of these techniques. By using the radiocarbon and pollen/SCP chronologies, a search for common periods of wetness/dryness has been made, and the similarities/differences between the biological proxy evidence has been considered. The final section of Chapter 5 concerns the application and results of spectral analysis techniques to the DCA and humification stratigraphy of Bolton Fell Moss - Core L and Walton Moss - Core 11. The significance of the hydro-climatic changes identified in the results chapter are discussed in Chapter 6 by comparing them to the instrumental/documentary record, and with other published palaeoclimatological reconstructions. The possible reasons for differential sensitivities of ombrogenous bogs to record climate changes are also considered. In Chapter 7, the conclusion, the main findings are summarised and suggestions are made for future research.

Nomenclature follows Stace (1991) for vascular plants, Daniels and Eddy (1990) for Sphagna, Smith (1978) for non-*Sphagnum* mosses, and Corbet (1973) for Testate Amoebae species.

Chapter 2: Previous Research.

2.1 Factors affecting ombrogenous peat formation.

The climatic influence upon ombrotrophic ("rain fed") peatlands is particularly acute, since they rely solely on precipitation inputs to maintain and sustain them, and are sensitive to changes in temperature and evapotranspiration (Aaby, 1976). This strong coupling between ombrotrophic mires and the prevailing climatic conditions was impressed upon by Godwin (1954, p. 24), who wrote:

> "how powerful must be the effects upon the central bog surface of those fluctuations of rainfall and evaporation which we know to occur year by year, decade by decade, and which we may by inference suppose also to have operated over longer cycles."

The low pH and anaerobiosis of ombrotrophic peatlands reduces the number and activities of mire bacteria and fungi (Untiedt and Müller, 1985), resulting in an accumulation of dead organic material (Moore, 1987). This material is frequently well preserved, especially where it originates from raised peat ecosystems, and the floral and faunal sub-fossils it contains can be used to infer former mire surface wetness, given their sensitivity to different mire water levels. Since mire surface wetness is dependent solely on precipitation inputs, this parameter can then be used to reconstruct effective precipitation, which is the balance of precipitation remaining after evaporation.

The potential to reconstruct mire vegetation using sub-fossil material was realised early in the nineteenth century, for example, Rennie (1807), remarked,

> "It is perhaps possible to ascertain the state in which any moss was when the several strata of it were formed, by discriminating the plants which prevail in it".

Later climatic reconstructions were made by Blytt (1876) and Weber (1900), using the degree of peat humification as a surrogate for former climates; the simple premise of their work was that highly humified peats were indicative of warmer/drier conditions and the converse for poorly humified peats.

Walker and Walker (1961), examined exposed peat sections from eight Irish bogs and found evidence for the bog surfaces reacting all over in the same direction to changes in mire surface wetness. They found, 'few if any, certain signs', for Cyclic Succession Regeneration (Section 2.2.2), a theory still pertinent at the time, which downplayed the importance of climatic control upon hummock/hollow complexes (Osvald, 1923), and believed firmly in the crucial importance of rainfall They write, (Walker and Walker, 1961, p.182);

> "Of all the external factors, variations in rain-water supply are probably the most likely to initiate changes in bog ecology and the tolerances of these changes by different species are the internal factors of supreme importance."

The micro- and macrofossil analytical work of Barber (1978), supported by independent evidence for climatic change (Lamb, 1977), demonstrated the importance of climatic control, even upon small-scale features of bog stratigraphy, i.e. hummock/hollow systems. It falsified the theory of cyclical peat regeneration and established a clear link between climate and ombrogenous mire stratigraphy. Since this pioneering work, the potential for reconstructing palaeoclimates from peat stratigraphy has been rigorously investigated, often using novel techniques, for example the analysis of isotopes of peat material (Dupont and Brenninkmeijer, 1984).

A thorough review of the literature on the link between climate and peat stratigraphy up to 1978 is available in Barber (1978), whilst the theses of Smith (1985), Wimble (1986), Haslam (1987), Blackford (1990) and Stoneman (1993), further expand the climate/peat link demonstrated by Barber (1978) and offer comprehensive accounts of the merits and problems in establishing palaeoclimatic records from raised and blanket peat bogs. Palaeoclimate reconstructions from ombrotrophic peatlands seem to have progressed to the point where there exists within them, 'a clear proxy-climate record preserved in the peat stratigraphy', (Tallis, 1995). Conversely, Heathwaite *et al.* (1993), claim that 'clear links between climate and peat development are unlikely', and in a further negative vein write that it, 'may be almost impossible to isolate climatic influences on mire formation from the autogenic changes in mire hydrology, chemistry and biota as the mire develops'.

The evidence for these claims will be investigated by first considering the influence of non-climatic factors and autogenic change processes, and the extent to which they may "mask" evidence for climate change, and then by considering evidence for climate change derived from the diverse micro- and macrofossils contained within ombrotrophic peat.

2.2 The influence of factors other than climate, on ombrotrophic peatlands.

2.2.1 The effect of fires.

Fires, whether natural or human initiated are powerful agents of ecosystem change, (Patterson *et al.*,1987), and have affected vegetation communities throughout geological time. Those initiated anthropogenically have been used as a tool for natural resource management since early prehistory.

There are problems in consistently assessing the frequency and severity of fires however, since charcoal may be 'produced in discrete events, often of only a few hours duration and at intervals of many years, so averaging charcoal quantities over several years may be misleading', (Odgaard, 1992).

Burning events, particularly larger fires affecting mires, do, however, have a reasonable chance of detection using macroscopic analysis of charcoal fragments (MacDonald *et al.*, 1991; Aaby and Tauber, 1975; Tallis, 1975), therefore the next question to consider is to what degree the fire affects the ability of the mire to continue to record changes in climate. The flora and fauna and mire hydrology may be drastically altered following fires.

The vegetation may be differentially affected, since *Calluna vulgaris* and *Erica tetralix* can survive fires because the bark of the stem bases is relatively thick, whilst accumulated litter and humus also provide protection (Mallik *et al*., 1984). Wein (1973), found that *Eriophorum vaginatum* can tolerate more fire injury than *Calluna*, since its tussock growth form is effective protection against fires. The selective preservation of these 'dry indicator' plants may lead one, erroneously, to conclude that effective precipitation was low, and complicates any palaeoclimate reconstruction. Runoff from burnt peat is higher (Conway and Millar, 1960), possibly because of ash particles blocking pore spaces (Mallik *et al*. 1984), reduced vegetation litter interception, and decreased surface roughness. Fires therefore, again, may produce possible changes in mire hydrology independently of the prevailing effective precipitation regime, although it is also fair to say that severe fires, which produce significant quantities of charcoal because of their intensity, duration and temperature (Whittaker, 1961; Kenworthy, 1963) are more likely to have occurred when mire water levels were low as a result of prolonged low effective precipitation. Conversely, chance late summer fires on an otherwise 'wet' mire surface, may only char the surface vegetation, and the lack of fuel from standing ericaceous biomass may prevent the high temperatures required for charcoal production (280-500°C, Chandler *et al.* 1983).

In the long term these perturbations to ombrogenous bogs, particularly changes in the bryophyte assemblages, are confined to a few decades after the fire event (Kuhry, 1994). Kuhry analysed Canadian sub-fossil material, and could reconstruct local peat surface fires with confidence, since charred remains of *Sphagna* and *Vaccinium* were encountered. Prefire conditions appeared to return within decades, but the fires did affect peat accumulation, since fire frequencies are negatively correlated with this parameter. Long term vegetation development, however, is not affected, and Kuhry hypothesises that, 'any nutrients released are quickly leached out in these acidic and relatively moist ecosystems', thereby maintaining the oligotrophic flora. Barkman (1992), considers fires as 'one of the least drastic disturbances in living bogs', whilst the robustness of *Sphagnum* spp. and their potential for regeneration has been demonstrated by Clymo and Duckett (1986), since new shoots were observed from what at first appeared to be dead mature gametophyte tissues at least 30 cm. below the surface.

The possible short term nature of fire events affecting raised bogs is also demonstrated by the serious fire that affected Glasson Moss (NY 238603) in 1976. The fire burnt through 15 cm. of peat in the worst affected areas, and crossed and recrossed the mire several times (Lindsay, 1977). One year after the fire, when the report was commissioned, the best remaining area of the bog had only a 28% cover of *Sphagnum* spp. Now this mire has a profuse, intact *Sphagnum* cover with characteristic raised mire microtopography (pers. observation).

2.2.2 The Theory of Cyclic Succession.

This theory, promulgated by Von Post and Sernander (1910), and later by Osvald (1923), proposed that changes in the bryophyte and vascular flora within mires is a response to internally driven, autogenic processes, whereby there is a cyclic and deterministic process of replacement of one plant community with another, and accompanying changes in the microtopography from a pool to a hummock and back again. Small scale changes in stratigraphy are attributed to this process, and the influence of climate was only thought of as significant in the formation of recurrence surfaces, where there are major changes in the degree of peat humification.

Detailed investigations of peat stratigraphy do not however, support the theory. One aspect of the theory was ably falsified by Walker and Walker (1961) and Casparie (1972), since the positions of hummocks and hollows were found to have remained constant. Boatman and Tomlinson (1977), analysed multiple cores from the Silver Flowe complex, Scotland, and found no evidence for full regeneration, only changes from hummock to *Sphagnum papillosum* carpets where hummocks occur, and changes from hollows to carpets in the hollow/pool microtopes.

Van Der Molen and Hoekstra (1988), were also able to demonstrate that systems of hummocks and hollows grew upwards together and did not develop as a result of cyclic processes.

A central tenet of this theory, that small scale changes in stratigraphy represent closed system successional sequences, was conclusively falsified by Barber (1981). Multiple shifts to wetter vegetation assemblages in this instance were *synchronous* and related to independently derived climate variations derived by Lamb (1977b).

A display of the longevity of hummock/hollow complexes was made by Dupont (1986), for the Meerstalblok (a Dutch raised bog remnant), and by Tallis and Livett (1994), for southern Pennine blanket peats. By using 19 radiocarbon dates, and pollen and charcoal records to establish synchronous levels between cores, Tallis and Livett were able to demonstrate that the position of these microtopographic features had remained *unchanged* for more than 2000 years. Backéus (1990, p. 34), in a review of the theory, concluded that:

> "the theory of cyclic regeneration on bogs is a splendid example of how a theory can survive a long time, simply because nobody cares to investigate its fundamentals."

The comprehensive work by Barber (1981) and Dupont (1986), refutes the theory; that this is so is perhaps not surprising since it came to rely so heavily on Clementsian theoretical succession processes. More recent models of succession, (Farrell, 1991), have stressed the complexity and contingency involved in community development and indicate that successional sequences may not be repeatable.

2.2.3 Autogenic Hydrologic Processes.

Intact raised bogs possess internal homeostatic mechanisms which allow only small changes in mire water levels (Ingram, 1992). The "damping" of possible water-level fluctuations may obscure evidence for climate change. For example, mires have only a limited ability to store or release water on short time scales, since the volume occupied by the acrotelm[1], where most of the changes in water table oscillation take place, is small,

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[1] Acrotelm - The uppermost level of the peat column which is not premanently saturated with water (Ivanov, 1975).

perhaps 3-10% by volume (Eggelsmann, 1990). Any excess water infiltrating into the mire surface, once this storage capacity is exceeded, flows laterally in the surficial layers of the acrotelm, particularly the top 10 cm. Bragg (1982), found that at this depth, the hydraulic conductivity of the peat was an order of magnitude greater than the rest of the acrotelm.

Clymo (1992), has investigated this feature of mire hydrology, and attributes it to the high degree of porosity, particularly in the euphotic layer of the acrotelm, which extends to 5 cm. Here bryophytes are still living and photosynthetic, and their vertical stem structure is preserved. In this area 90% of the volume is void, with only 10% water filled, and offers an efficient pathway through which water can flow. In addition to this rapid flow path, rapid subsurface runoff can occur by flow from an anastomosing network of morphological hollows, which initially store excess water by ponding. As this storage is exceeded, movement of water from one depression to the next occurs to the mire margin, from which it is rapidly discharged from the lagg stream.

Another mechanism which may occur to remove excess water, is movement through subsurface pipes. Foster and Fritz (1987), propose that these may develop from 'hydrostatic pressure on the peat floor that follow lines of weakness in the subsurface peat'. If these subsurface pipes collapse they become open channels or rills, but these are largely restricted to the steeper upland slopes of blanket mires (Heathwaite *et al.*, 1993).

These two quickflow processes appear to be the main pathway for water exceeding the storage capacity of raised mires. The occurrence of flooding or sheet flow in the wettest conditions has been observed on *Sphagnum* dominated bog surfaces (Barber, pers. com.). This rapid pathway is potentially very damaging to *Sphagna*, since they have no root systems to provide anchorage against water flowing overland (Ingram, 1992).

Where catastrophic flooding of mires does occur as a result of bog bursts (German, *Moorausbruch*), desiccation of mires need not result. Casparie (1972), mapped the position and extent of a bog lake, based on the abundances of *Sphagnum cuspidatum* and *Scheuchzeria palustris*, and also discovered extensive erosion gullies in this area, possibly resulting from the rapid drainage of this water body. The peat stratigraphy, however, does not indicate changes to drier vegetation assemblages, only a change to more strongly oligotrophic conditions with an expansion of *Sphagnum papillosum* and *Sphagnum imbricatum.* Casparie attributes this to removal of surplus water which contained a high dissolved mineral component.

The water table position is also kept within strict limits during periods of dry weather, since as the water table falls, the permeability of the acrotelm diminishes and less seepage of water to the lagg occurs. The processes that lead to this reduced lateral permeability have again been investigated by Clymo (1992), and are attributed to the collapsed plant structures caused by higher overburden pressures at deeper levels. The water spaces between the collapsed plant structures are severely reduced, and the hydraulic conductivity may be diminished 625 fold. *Sphagnum* spp. living in hollow environments have developed mechanisms which allow them to survive periods of water deficit. For example, *Sphagnum cuspidatum* carpets become white as water loss from the hyaline cells proceeds (van der Molen and Wijmstra, 1994). These white plants have a higher albedo and reflect more light, effectively reducing temperatures below the surface of the carpet. Evaporation from hollow environments is further reduced when *Sphagnum cuspidatum* plants, which normally float, settle to the bottom of the microtope and form a skin which, 'effectively seals the hollow bottom from exchange with the air above it', (van der Molen and Wijmstra, 1994). The operation of these negative feedback processes, where drought conditions are short-lived, may prevent replacement of hollow bryophytes with those from lawn and hummock microtopes, making detection of hydroclimatic changes, certainly in this instance, difficult.

A final process which can stabilise water table fluctuations is that of *Mooratmung,* from the German, meaning mire-breathing, and involves expansion and contraction of the catotelm as a response to changes in water storage (Ingram, 1992). These movements, which are in the order of a few cm, allow the mire surface to follow changes in the position of the water table, with the effect that a rise in the water table in wet periods may be compensated by a rise in the mire surface.

Because of the operation of these processes, there may not be a marked change in mire water levels in response to relatively small increases/decreases in effective precipitation; this potentially reduces the sensitivity of these ecosystems to record climatic change, especially in response to subtle, low magnitude changes in precipitation and/or the evapotranspiration ratio.

2.2.3.1 Impeded drainage and the possible role of methane.

There is a possibility that the position of the water table within raised mires is dependent upon the reservoir of occluded methane that exists in the peat matrix (Brown *et al.*, 1989; Mathur *et al.*, 1989; Brown and Overend, 1993).

Methane is a by-product of anaerobic acetate and carbon dioxide fermentation by methanogenic bacteria (Bryant, 1979). Bubbles form where the capacity of methane to diffuse upward is exceeded, and the gaseous pressure exceeds the hydrostatic pressure of the peat pore water (Young, 1989). These have the potential to block micropores within the peat matrix, where the driving force on the gas bubbles is not sufficient to push them through these constrictions. This is termed the Jamin effect (Wyckoff and Botset, 1936).

The relative insolubility of methane in water (Dean, 1985), combined with the Jamin effect, may prevent peat porewater movement, and allow the development of elevated mire water levels. There is certainly experimental and field evidence to support this; Dinel *et al.* (1988) demonstrated the existence of pressurised pockets of methane at a depth of up to 145 cm. in two Canadian *Sphagnum* peatlands, whilst Brown and Overend (1993), recorded reductions in the volumetric water content of active 60 cm. peat columns, where gas build up of methane occurred.

The degree to which trapped methane affects the position of the water table within raised peat bogs, particularly with regard to the effective precipitation regime, is difficult to assess. Emission rates of methane from seemingly homogeneous areas display spatial variability (Svensson and Rosswall, 1984), whilst there are methodological problems, in that measurements of hydraulic conductivity and gas concentrations in the field involve disturbance to the peat matrix. In this instance, the data may not be a true reflection of the 'natural' state of the peatland. Romanowicz *et al.* (1995) have shown that diffusive fluxes of methane are temporally variable, and suggest the "bubble confining layer" may form and collapse seasonally or possibly after major climatic events, for example after a drought. The northern Minnesota peatlands investigated were only analysed over a eleven month period, therefore again, it is difficult to speculate on the potential hydrological importance of occluded methane.

Supersaturation of porewaters with methane does have the potential to influence the position of the catotelm/acrotelm boundary, and therefore may modulate the degree of mire surface wetness independently of effective precipitation. The relative lack and difficulties of obtaining data to investigate this phenomenon at this juncture, however, precludes any assessment of its importance.

2.2.4 Anthropogenic disturbances to raised mires.

Modern studies of human induced changes to vegetation and corresponding alterations in catchment hydrological processes, suggest that ancient clearance episodes in the catchment areas surrounding raised and blanket mire ecosystems may have increased the supply of telluric water, producing a larger and faster 'pulse' of water to the mire margin area.

Experimental clearcutting of instrumented catchments in North America by Hibbert (1967), Douglas (1967), and Likens *et al.*, (1970) clearly show how clearcutting increases quickflow processes and streamflow, through decreases in water loss by evapotranspiration and interception, and reduced soil water deficits, (Rogerson, 1976). Bosch and Hewlett (1982) and Kovacs *et al.* (1989), also demonstrate the close link between vegetation communities and catchment hydrology, with a forest cover producing a more stable, albeit reduced water yield. The applicability of these results to mires within cleared catchments is unclear, however, as the above work has been performed on mineral soils and not on peat substrates.

The possibility of dramatic increases in runoff produced by clearances, led Wimble (1986), to speculate that a possible flooding horizon at White Moss dated to c. 2000 BP., was the possible result of human disturbances in the Duddon Estuary, Cumbria, as it is synchronous with a period of maximum open conditions indicated by high non-arboreal pollen (NAP) values. Similarly, palynologic evidence of human disturbances to woodland and consequent changes to wetter mire floral assemblages, have been identified by Tipping (1995). Radiocarbon measurements indicate that these disturbances occurred around 7500-7350 cal BP, and possible destabilisation of the surrounding catchment soils led to the demise of *Betula* growing on the mire surface.

However, the apparent relationship between pollen based correlations with wet conditions on the mire surface is far from clear. Stoneman (1993), found that there was little correlation between NAP and reconstructed bog wetness profiles for three of his sites, and for one of his sites, Glasson Moss, decreases in the % of arboreal pollen were associated with drier conditions on the bog surface. The possible implication is that raised mire ecosystems are differentially susceptible to human induced perturbations or perhaps, there is no link at all between NAP and mire surface wetness.

Recent hydrological modelling of relict Dutch raised mires (Poelman and Joosten, 1992), offers an interesting insight into the sensitivity of raised mires to hydrological changes imposed elsewhere in the surrounding catchment. Simulations indicated that drainage of agricultural land up to a distance of c. 2 km. had an effect on the hydrology of the bog reserve under investigation.

The inherent infertility and low agricultural worth of peatlands in their natural intact state may have spared raised mires, up until the seventeenth century, from large scale human impacts. This follows the thoughts of Taylor (1983, p. 21), who proposes:

> "right up to early medieval times, peatlands were scarcely used except for game-hunting and mostly avoided, being for the most part unusable and unhealthy in their undrained state and liable to be flooded in winter."

When major changes are imposed, for example by the imposition of artificial gravitational drainage schemes and/or the removal of large volumes of the peat deposits, there is certainly a marked and potentially irreversible change in mire hydrology and vegetation. These large perturbations, which commenced from the seventeenth century, induce a marked change to dryness in the surviving bog relicts, since the storage capacities of the surviving superficial, strongly humified layers are reduced (Joosten, 1992). In addition to these hydrophysical changes, where vascular plants invade as a result of drier conditions, e.g. *Molinia caerulea*, they further desiccate peat profiles. This particular species maintains high evapotranspiration rates even in dry periods and reduces the chances of *Sphagnum* communities re-establishing (Schouwenaars, 1990).

Similar increases in vascular plants and attendant declines in bryophytes have also been observed at Coom Rigg Moss, by Chapman and Rose (1991). The surrounding moorland has been afforested, but the authors attribute the increases in *Calluna vulgaris, Eriophorum angustifolium, Molinia caerulea* and *Deschampsia flexuosa* to a cessation of grazing and autumnal burning practices, which has consequently allowed an accumulation of standing dead material and litter to build up. Cessation of grazing and subsequent increases in standing dead biomass has also been found to be deleterious to *Sphagnum* blanket mire communities by Rawes (1983).

Emissions of sulphur pollutants since the Industrial Revolution have been harmful to *Sphagnum* species, particularly those growing in areas proximal to conurbations, e.g. the blanket mires in the Southern Pennines. Ferguson and Lee (1980), found that the appearance of soot particles in the peat stratigraphy of these mires was followed by a disappearance of sub-fossil *Sphagnum*. *Sphagnum recurvum* has become recently dominant in the mire communities of North Cheshire, but climatic forcing has not been responsible in this instance, but is instead related to the greater tolerance of this species to sulphur pollutants. This has been experimentally demonstrated by Ferguson and Lee (1978). Wet and dry deposition of nitrogen compounds since the Industrial Revolution and continuing into the present time may also have changed species compositions in polluted mires

(Press *et al.*, 1986), since high concentrations of nitrate and ammonium are deleterious to *Sphagnum* growth (Press and Lee, 1982). Experimental results demonstrate equivocal results however; nitrogen addition experiments have inhibited growth of *Sphagnum palustre* and *Sphagnum fimbriatum* (Hogg *et al.*, 1995), yet Aerts *et al.* (1992) found increases in *Sphagnum* growth, where natural deposition was low. Hogg *et al.*, conclude that the response of individual species depends on the degree of N limitation within the parent ecosystem.

As a result of these disturbances, pollution loading and changes in land use, the palaeoclimate record post-dating these events is either lost or compromised, but the remaining material of disturbed raised bogs may still offer an excellent proxy record of climate, e.g. peat from Bolton Fell Moss seems to offer a high resolution record of climatic change (Barber *et al.*, 1994b) and Stoneman (1993).

2.3 Palaeoclimate Reconstruction from Peat Stratigraphy.

2.3.1 Introduction.

The detection of wet and dry periods from peat stratigraphic components, which enables reconstructions of effective precipitation, has been undertaken using micro- and macrofossils, testate amoebae and humification analysis.

Prior to Barber's (1981) refutation of the theory of cyclic succession, subtle changes in peat stratigraphy were thought not to be due to variations in climate. Once this theory had been falsified, however, the confusion and uncertainty over the mechanisms governing ombrogenous peat formation had been reduced, enabling a search for trends in climate to be made.

2.3.2 Palaeoclimate reconstruction from plant micro- and macrofossils.

Early work by Casparie (1972) on the Bourtanger Moor, near the Dutch/German border provides interesting evidence for climate change. Casparie was able to detect the synchronous establishment of *Sphagnum papillosum* and *Sphagnum imbricatum* at c. 2000 BC. on a highly humified brown/black peat surface. Casparie suggested that the immigration of these *Cymbifolia* species could have been due to increases in precipitation.

Van Geel (1978), examined the macrofossil and pollen stratigraphy of the Engbertsdijksveen and compared his findings with those from Wietmarscher Moor (Van Geel, 1972), which is located 32 km. away. Once again there was a synchronous establishment of *Sphagnum imbricatum* in both of the sections examined from the two sites, and synchronous declines of *Corylus avellana* (from 1400-600 BC.), were also apparent. Van Geel proposes that declines in the pollen representation of *Corylus* may have been due to very wet rainy winters and springs; under these conditions *Corylus* catkins may degenerate before any pollen is produced. The macrofossil components corroborate the pollen record, since over the similar time period of 1400-800 BC., there were instances of hygrophilous *Sphagnum cuspidatum* establishment, indicating increases in precipitation or decreases in evaporation, mediated by reduced summer temperatures.

A more convincing display of the close coupling between climate and mire stratigraphy was demonstrated by Barber (1978, 1981), who had the crucial advantage of being able to relate stratigraphic changes to the independently determined climatic changes of Lamb (1977). The existence of long sections of exposed peat cuttings allowed the author to trace stratigraphic changes over large distances. Careful analysis of the subfossil vegetation components from 21 profiles was undertaken and using details of the ecology of these species, wet and dry episodes or 'phase shifts' were identified. Using the climatic reconstruction's of Lamb (1965a, 1965b, 1966, 1977a, 1977b), Barber was able to show a striking similarity between the wettest periods identified from the peat stratigraphy and those determined from Lamb's climatic curves, for the time periods 900-1100 AD., 1320-1485 AD. and 1745-1800 AD. Even more impressive, was the fact that these changes were recorded in seven monoliths, which demonstrated that the bryophyte components of this raised mire (Bolton Fell Moss), had reacted in a similar manner to climate induced stress.

Thorne Waste and Hatfield Moors, two raised mires from the Humberhead levels investigated by Smith (1985), also possibly provide evidence for climatic change, since accumulation of *Sphagnum imbricatum,* under relatively wet mire surface conditions, coincided at both sites based on the radiocarbon chronology. At Thorne Waste unhumified *Sphagnum imbricatum* peat formed c. 2380 BP, whilst at Hatfield Moors the inception date for this type of peat was c. 2265 BP.

Wimble (1986), examined multiple short peat sections (up to 110 cm. deep) from the bogs of south Cumbria (Foulshaw, Helsington and White Moss), using a similar methodology developed by Barber (1981), and found evidence for wetter and drier phases. The geochronology for these sites was extensive, as Wimble (1986) had between 6 and 10 radiocarbon dates available for each metre monolith. Using this chronology he was able to show strikingly synchronous, mire hydroclimatic changes both within the mires investigated and between sites in the same region. Wet shifts dated to c. 3100-3150 BP were time parallel between sites in this doctoral thesis. Similar wet shifts have been identified by Haslam (1987) from Bolton Fell Moss, particularly episodes of *Sphagnum cuspidatum* replacing *Sphagnum imbricatum* as the main mire bryophyte component. One of the wet shifts dated to 3270 ± 50 BP, was found to be contemporaneous with a similar wet shift identified by Wimble and offers encouraging evidence for regional climate change at this time.

The production of 'hydroclimatic curves' from mire species assemblages has been developed using the computationally simple technique of weighted averages ordination (Dupont, 1985; Haslam, 1987). Using this technique, Dupont produced humidity indices from a raised bog remnant (The Meerstalblok, The Netherlands) based on the vegetation components of peat monoliths taken from both hummock (K1) and hollow (K2) microtopes. These were subsequently compared to two sequences of wet/dry curves produced from the Engbertsdijksveen (ENG1 and ENG7). All four sequences displayed marked parallelism between 3700 and 3500 BP. (wet conditions), whilst changes to drier conditions were revealed in the K2 and ENG1 stratigraphies between 4500 and 4000 BP. These synchronous responses identified in different sites may indicate allogenic forcing, possibly changes in effective precipitation.

Stoneman (1993), examined ten mires from northern Britain which had similar temperature regimes, but markedly different precipitation totals, for example, Ellergower Moss, located in the Silver Flowe Complex, Galloway, has mean annual precipitation of 1900 mm. By comparison, Drone Moss in Berwickshire receives only 555 mm. The sensitivities of the mires to record hydroclimatic changes was investigated and although evidence was found for synchronous wet and dry shifts, in many instances, not all of the mires demonstrated clear wet or dry changes. The hydrologic negative feedback processes discussed in Section 2.2.4 may mask climate changes. A further factor which possibly masked potential periods of climate change was the existence of the stable bryophyte association of *Sphagnum* section *Acutifolia* and *Sphagnum imbricatum*. These bryophytes grow under a wide range of mire water levels and where they dominate in the mire stratigraphy, the quality of the hydroclimatic curves produced from them is reduced, since they may 'mask' climate signals. For example, *Sphagnum imbricatum* ssp. *austinii* can grow in both aquatic and hummock microtopes, by simply changing its growth form, i.e. it has different ecads or ecophenes (Green, 1968). It was specifically the occurrence of this potential problem, identified by Stoneman, that testate amoebae analysis was undertaken (Section 2.3.4). Stoneman recognised a further caveat in his research, in that monocotyledonous remains were not identified down to species level and valuable information on the degree of mire surface wetness was foregone. For example, macrofossil *Rhynchospora alba* and *Eriophorum angustifolium* remains can be used to infer the occurrence of wetter mire surface conditions, since these sedges grow in pool margins and shallow pools respectively (Rodwell *et al.*, 1991 and Phillips, 1954). Because of the potential to refine palaeoclimate reconstructions using monocotyledon species, their identification and quantification was attempted (Chapter 3).

Notwithstanding these problems, Stoneman (1993) was able to demonstrate the possible synchronous response within a single raised peat bog (Walton Moss) to higher mire water levels, a feature also displayed by the stratigraphy from Bolton Fell Moss (Barber, 1981). Two cores (Walton Moss core 1 and 2) displayed the same bryophyte species changes to increased mire surface wetness, with abundant *Sphagnum* section *Cuspidata* leaves between 40 and 20 cm depth. A pool from Walton Moss, core 2 was dated to 200 ± 45 BP., and may be contemporaneous with the coolest and wettest part of the Little Ice Age (1650-1770 AD., Lamb, 1977).

Further palaeoclimate reconstructions from mires have been made by Barber *et al.* (1994b), in this instance from sites in the British Isles, Germany and Denmark. Two of the Irish raised mire sites investigated (Abbeyknockmoy and Mongan bog), display time parallel changes to increased surface wetness between 3500 Cal. BP. and 3500-3000 Cal. BP. respectively. The macrofossil bryophyte components of Abbeyknockmoy and Dosenmoor (located near Keele in northern Germany) also record a very wet period at c. 1740 AD., possibly resulting from the 'Little Ice Age'. A key finding of the NERC supported work of Barber *et al.* (1994b), was the clustering of dates where evidence was found for marked changes to increased surface wetness (from multiple sites), at 4000 BP., 3500-3000, 2800-2500, 2000-1800 and 1000 BP. Barber *et al.* (1994b) suggests that the hydroclimatic changes that occurred around 4000 BP. may be the major Holocene event.

Tallis (1994) and Tallis and Livett (1994), have undertaken a detailed analysis of an area of hummock and hollow blanket mire in the southern Pennines. The macrofossil and charcoal signals in eighteen cores were examined to see how the mire ecosystem had developed over the millennia. The pollen content of the eighteen cores was also examined to establish contemporary levels and provide dating control, since twelve radiocarbon dates were available. Tallis and Livett found that periods characterised by high abundances of *Sphagnum* leaves and possibly indicative of high effective precipitation, were laterally continuous for c.10 m., and again indicate that ombrotrophic mires seem to respond uniformly to environmental change. By plotting the *Sphagnum* rich and poor levels with the radiocarbon dates and the climate phases of Lamb (1977), Tallis and Livett cautiously found a close agreement between the bryophyte record of wetness and the historical record of Lamb. This caution stems from the difficulty of accurately dating thin layers of peat which have accumulated slowly. Their phase P1 possibly corresponds to 1560 AD., a period of cold winters and wet summers, P2 to the drier period of 1500-1560 AD., whilst P3 may coincide with the time period before 1060 AD. and that of 1350 and 1390 AD. (wetter summers). Within this latter phase there were *Sphagnum* poor bands which may match the Little Climatic Optimum period (Lamb, 1977), of 1060-1350 AD.

Further evidence for climate changes dating from the Little Climatic Optimum period has also been presented by Tallis (1995), in this instance by using macrofossil *Racomitrium lanuginosum* remains from blanket mires. This bryophyte has an unusual ecology, in that it requires high atmospheric humidity, but is restricted to drier and/or fire damaged/grazed areas of blanket mires, because of competition from faster growing *Sphagna* and nanophanerophytes. Tallis proposes that in the absence of peat erosion and fires, sub-fossil *Racomitrium lanuginosum* leaves from uneroded sites may indicate the occurrence of an unusual palaeoenvironmental setting, with antecedent dry mire surface conditions to reduce the cover of competitive *Sphagna* and a wet climate in order for the *Racomitrium* to attain dominance. Tallis hypothesises that such a scenario could have occurred during the early stages of a wetter period of climate, before *Sphagnum* species attained dominance, following a drier climatic phase. Abundant *Racomitrium* leaves were found in two uneroded southern Pennine sites, Holme Moss and Over Wood moss, and dated by linking their *Plantago* pollen values to those from both radiocarbon dated levels from other profiles (Tallis and Livett, 1994), and by using historical evidence (Tallis and Switsur, 1973). Tallis (1995) suggests the lower *Racomitrium* bands in these cores represent the period immediately following the 'Early Medieval Warm Period'. In western Europe at this time (1220-1310 AD.), there was a preponderance of warm springs and dry summers (Alexandre, 1987). Abundant *Empetrum* and *Vaccinium* pollen from Over Wood Moss corroborates the macrofossil signal, and again indicates dryness coincident with the 'Early Medieval Warm Period'. The incidence of fires does not seem in this case to be responsible for the stratigraphic signal of mire surface dryness (Tallis, 1995, p. 1025), since in the Over Wood Moss site, charcoal is found before and after the inferred dry event, and also occurs in *Sphagnum* rich, and possibly wetter levels. The fusain signal in the form of massive burning horizons and soot from the Holme Moss site also post-dates the lower *Racomitrium* zone. The incidence of fires, again, does not seem to be responsible for desiccation of the mire surface and strengthens the existence of a climate signal in the peat stratigraphy.

Stoneman (1993) and Barber *et al.* (1994a, b, c), have attempted to quantify bog surface wetness conditions further by employing Detrended Correspondence Analysis. This ordination technique detects latent environmental variables and is capable of indicating the importance of each one. Barber *et al.* (1994c), found strong evidence for the presence of a water level gradient for the taxa from Bolton Fell Moss, with this variable (Axis 1), accounting for most of the variation in the fossil data set. Given the close link between mire water levels and effective precipitation, the DCA Axis 1 scores for each sub-fossil level were plotted against a time axis, generated from twelve radiocarbon determinations, to give an indication of the possible nature of climatic change for the last 6300 years. The changes identified appeared to be cyclic, which was confirmed by undertaking time series analysis. Given that the technique is based on the assumption that the mean and variance of the series has remained constant over time (Kendall and Ord, 1990), it demonstrated, after detrending, a strong spectral peak with a wavelength of c. 800 years. An attempt was also made to compare the macrofossil assemblages with the wetness/dryness and mildness/severity indices of Lamb (1977), using a multinomial logit model. The best model obtained using this methodology gave a 'goodness of fit' ($r^2_{adj.}$) value of 0.5, where $r^2_{adj.}$ is the ratio of deviance to the deviance of a null model. Using this type of statistical model $r^2_{adj.}$ values greater than 0.4 are indicative of a good fit (Domenreich and McFadden, 1975), therefore in this instance, the response of the macrofossil components to independent evidence for climate change does seem to have been successfully modelled, and again indicates the existence of a strong climate link. A degree of caution in interpreting these results is warranted however, since the model relies on the assumption that the correct age-depth models were selected and that the independent evidence of Lamb (1977) for climate change to 1100 AD. is correct.

The uniformity of bryophyte species response to increased mire surface wetness *within* single raised peat bogs, which has been successfully demonstrated by Barber (1981) and Stoneman (1993), has again been found in the stratigraphy of four short cores (60 cm. depth) from Bolton Fell Moss (Barber, 1995). Each short core was spaced at c.10 m. intervals, and macrofossil analysis on 1 cm. slices again revealed a replicate species signal in each core at comparable depths (38-32 cm.). Semi-aquatic *Sphagnum* section *Cuspidata* leaves were abundant in the peat matrices, and indicate mire surface wetness, which may be possibly coeval with the 'Little Ice Age'. This research has important implications; not only does it show a possible close coupling of the peat stratigraphy to climate, it also indicates a uniform *intra*-mire response to allogenic forcing.

2.3.3 Humification analysis and palaeoclimate reconstruction.

The accuracy of reconstuctions of mire surface wetness derived from colorimetric determinations of peat humification has been demonstrated by Aaby and Tauber (1975). They found a negative correlation between degree of humification and mire surface wetness, which was independently derived from the analysis of rhizopods, pollen frequencies and *Sphagnum* species.

Blackford (1990), has also shown the potential to determine palaeoclimates using humification signals, since his climatic reconstructions derived from major humification changes were coeval with alternative palaeoclimate reconstructions. For example, five of the seven blanket peat profiles analysed by Blackford revealed periods of abrupt climatic deterioration corresponding to the 'Little Ice Age', which Lamb (1982), believes to have been marked by a similar abrupt change in the middle of the sixteenth century. Humification curves generated from two cores taken from water shedding blanket peat sites near Letterfrack, County Galway, western Ireland, displayed striking similarities and are contemporary with reduced sunspot activity and atmospheric ^{14}C anomalies (Blackford and Chambers, 1995, Figure 2.1). Only limited radiocarbon dates were available in this instance, (two dates per core), but peaks and troughs in the humification signals, with one exception, mirror each other, and inferred drier and wetter mire surface conditions do coincide with the 'Medieval Optimum' and 'Little Ice Age' periods respectively. Blackford (1990), suggests that the humification signal in blanket peats represents a semi-quantitative measure of average summer effective rainfall.

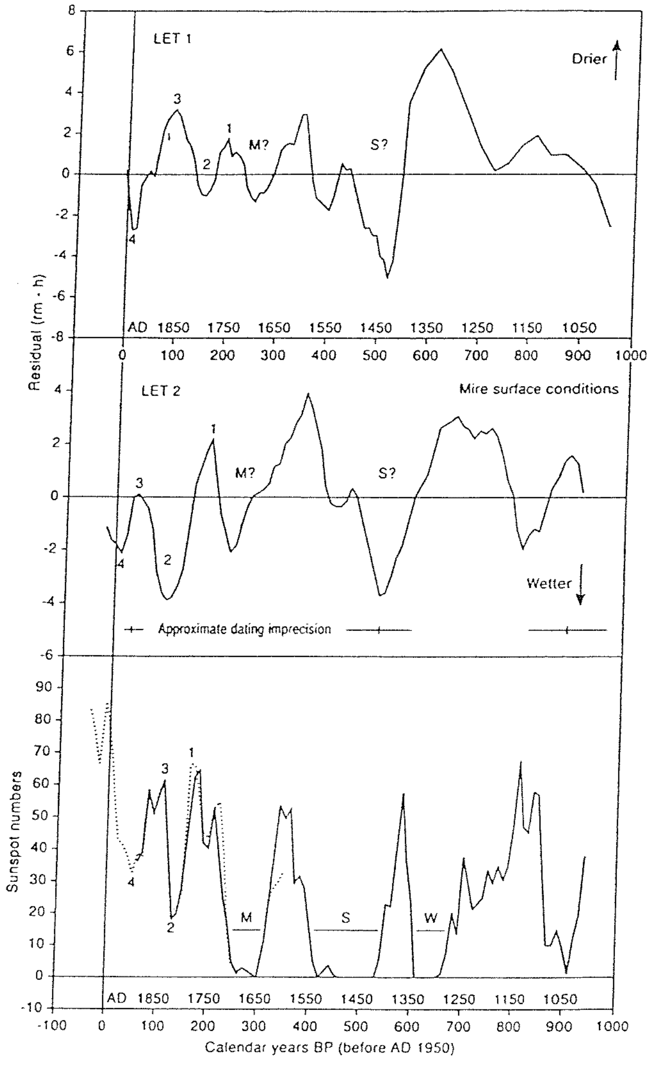

Figure 2.1 Detrended humification values from Let 1 and Let 2 (Letterfrack, County Galway, Ireland). For the sunspot numbers, M = Maunder minimum; S = Spörer minimum; W = Wolf minimum (from Blackford and Chambers, 1995).

Nilssen and Vorren (1991), colorimetrically analysed fourteen ombrotrophic peat sequences (the authors do not state whether the sites were raised or blanket mires), from northern and central Norway and compared the group average ^{14}C dated humification shifts with those of Aaby and Tauber. By grouping Aaby and Tauber's dates into clusters, another ^{14}C average date was derived for each shift from high to low humification. The two series of dates from Danish and Norwegian mires showed striking similarity, and possibly indicate evidence for regional climatic change, although there is also the possibility, certainly for the Norwegian data, that the humification shifts were human induced. Clearance of vegetation for agriculture can cause a rise in groundwater levels independently of changes in effective precipitation (Section 2.2.4), and may explain the correlation between humification shifts and five agricultural expansion periods identified by Vorren *et al.* (1990).

Evidence for the possible cyclical nature of climate change has been presented using changes in the degree of peat humification. For example, periodic regression analysis of alkaline soluble humic acids, *Alnus, Quercus,* and *Corylus* percentage curves derived from a peat section from the Engbertsdijksveen by Wijmstra *et al.* (1984), have revealed signals similar to the 800 year wavelength identified by Barber *et al.* (1994c, Section 2.3.2). In addition to the 800 year oscillation, wavelengths of 1450, 1000, 600, 500, 350, 200, 145, 40 and 22 year periodicities were also identified. Aaby (1976) did not employ time series analysis *per se*, but also found evidence for 260 and 520 year cyclicity in peat humification shifts from four different Danish bogs. One site, Draved Mose, was subjected to 55 radiocarbon determinations, so the evidence for this cyclicity is strong. Contrary to Wijmstra *et al.* (1984), Aaby could not find evidence for shorter wavelength climate mediated changes, possibly (again) because of mire negative feedback processes.

Plaut *et al.*, (1995), analysed the 335 year Central England Temperature record (Manley, 1974), which comprises the longest continuous record of temperature, and also found evidence for oscillatory behaviour. Using single spectrum analysis, oscillations of 7-8 year periodicity were tentatively linked to the North Atlantic's wind driven circulation, whilst longer cycles of 15-25 year periodicity were linked to the North Atlantic's thermohaline circulation.

The 22 year periodicity identified by Wijmstra *et al.* (1984) may be linked to the 15-25 year periods independently identified by Plaut *et al.*, alternatively the similarity of the periodicities in this instance may be purely coincidental. However, the existence of a possible land/ocean climate link may explain the greater palaeoclimatic sensitivity of maritime ombrotrophic mires, if these cycles are indeed ocean driven as suggested by Barber *et al.* (1994c). The work of Haslam (1987) and Barber *et al.* (1994a, b), supports this hypothesis, since sites from inland Germany and Poland displayed remarkably 'complacent' stratigraphies, whilst those from maritime British and Irish sites displayed multiple shifts in their species compositions and degree of humification.

A potential problem when interpreting the degree of humification in peat stratigraphy, is that the signal may be dependent on the microtopographic position of peat sections, rather than solely resulting from changes in effective precipitation. The tussock habit of *Eriophorum vaginatum* for example, enables the plant to modify its micro-environment, since it is an effective receiver of insolation, and allows a deep organic horizon to develop above the mire surface. Chapin *et al.* (1979), found tussock soils to be warmer, and in combination with good aeration and favourable moisture regimes, proposed that rates of decomposition and recycling of organically bound nutrients within the tussock were faster than beneath it.

Eriophorum species also pose another problem, as their roots can grow to considerable depths (up to c. 1 m., Heal *et al.,* 1978). This may distort palaeoecological reconstructions, since this rhizome material is younger and potentially less humified than the neighbouring *Sphagnum* remains.

The potential for secondary decomposition poses further problems in palaeoclimate reconstruction using colorimetric determination of alkaline extracts (Tipping, 1995). Where ground water tables are lowered to an extreme extent, during a severe drought period for example, material which has already passed into the catotelm after its passage through the biologically more active acrotelm, will be decomposed aerobically once again. In this situation, the colorimetric signal will not be a true reflection of the conditions under which the peat section was originally formed. In the light of this, any palaeoclimate reconstruction using the degree of humification alone would be dangerous.

2.3.4 Palaeoclimate Reconstruction from Testate Amoebae.

Testate amoebae, (or rhizopods), are microscopic protists which are sensitive to changes in mire water level. This parameter is the most important governing testate amoebae distributions and community composition (De Graaf, 1956). The importance of moisture content and depth to the water table in peats has been demonstrated by Tolonen *et al.* (1994). Using DCA, these two variables accounted for 40% of the variation along ordination axis 1. Multivariate analysis has also been employed by Charman and Warner (1992) and Warner and Charman (1994), which again demonstrated that water table is the main environmental variable affecting testate amoebae, with pH exerting a lesser influence.

The differential sensitivities of testate amoebae to mire water levels and their relatively robust shells which are preserved in sub-fossil peats, makes them a useful tool for reconstructing mire water tables and through this, palaeoclimates.

There are complications, however, in that testates have the ability to encyst, in order to survive desiccation, anaerobiosis and depletion of food supplies (Ogden and Hedley, 1985). Fantham and Porter (1945), investigated the time periods that testate amoebae species could survive after initial collection and storage in receptacles. When cultures of the specimens from dry bryophytes were made, some of the rhizopods displayed impressive longevity, for example, *Centropyxis aculeata* survived for 7 years and 362 days, similarly *Assulina seminulum* was able to survive for 7 years and 329 days in a desiccated state. This ability may render palaeoecological reconstructions of mire surface wetness inaccurate, since the presence of a particular species need not necessarily indicate the former occurrence of conditions optimal to it.

There are also inherent problems interpreting the fossil record, for example, Jung (1936), suggests the fossil shells of *Assulina muscorum* and *Phyrganella hemisphaerica* may be preferentially downwashed to enrich sub-fossil peat levels, possibly reducing the usefulness of environmental reconstructions made using these species. Tolonen (1979), downplays this potential source of error, albeit with limited evidence to support his claim. Without quantitative estimates of this potential problem it is difficult to assess its importance, but the enumeration of multiple rhizopod species, combined with other proxies for mire water level reconstruction, should minimise its importance.

Another problem encountered with testate amoebae is the difficulty of identifying some species from their tests alone, as many identification manuals use structures of living thecamoebae species (pseudopodia, the cytoplasm and the nucleus), which do not survive the fossilisation process (see Corbet, 1973). For example, rhizopods in the family *Phryganellidae* are primarily differentiated from Cyclopyxids on the basis of their pseudopodia [2] (Ellison and Ogden, 1987); clearly this is impossible to accomplish with sub-fossil tests.

Notwithstanding these potential problems, Tolonen (1979, p. 272), has been a key proponent for their inclusion in palaeoecological studies, and claims,

> "Rhizopod analysis can help to reconstruct a reliable and much more detailed picture about the successional changes of mire surfaces than can a peat analysis alone, for example in a case where a single *Sphagnum* species (often *S. fuscum*) has been responsible for the peat growth throughout several millennia."

Production studies of testaceans by Ogden (1981) and Lousier (1984a, b), have shown that doubling times (the time required for a doubling of the population), can be very rapid. *Euglypha* spp. cultures doubled within 2.3-4.4 days, whilst *Assulina muscorum* populations doubled between 2.3 and 2.9 days (Ogden, 1981). Of the thirteen soil litter species examined by Lousier (1984a, b) , the longest doubling time was 15.9 days for *Euglypha laevis*, which again highlights the rapid turnover of these protists. Testaceans are also potentially capable of rapidly colonising new favourable sites, as they have been found attached to the mesothorax of beetle species (Chardez, 1986). These features of their ecology may make them sensitive palaeoecological indicator species, as they have the ability to respond rapidly to autogenic and allogenic changes. This is clearly apparent from the work of Warner and Chmielewski (1992), where thecamoebae species were used to monitor the effects of drainage between forested, *Picea mariana* mires and virgin forested mires. The disturbed site had been drained two and a half years before examination of its testate fauna, yet this time was sufficient for differences to be recorded in the species encountered, principally with an increase in the representation of *Assulina muscorum*. This particular species has xerophile tendencies (De Graff, 1956; Grospietsch, 1958; Heal, 1961; Tolonen, 1994). Rhizopods are therefore capable of responding quickly to environmental changes, albeit human induced, in this instance.

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[2] Pseudopodia - flowing extensions of the amoebae body (Barnes, 1980).

Van Geel (1978), undertook an exhaustive study of a peat section of the Engbertsdijksveen (The Netherlands), employing testate amoebae, pollen, fungal microfossil, and macrofossil analysis. Van Geel was able to subdivide the time period covering the Subboreal-Subatlantic climate deterioration into wetter and drier phases, using abundances of *Amphitrema flavum* thecae and *Sphagnum* macrofossils. Periods of human disturbance detected by the presence of *Fagopyrum* pollen could also be correlated with the testate record, since at this level, *Hyalosphenia subflava* tests were recorded. This species is indicative of very dry conditions on the bog surface, and led Van Geel to speculate that local cultivation of *Fagopyrum* had been practised on the mire surface.

Climate reconstructions using testate amoebae have been made by Beyens (1985). A continental phase with dry summers from ± 4680 BP. to ± 4350 BP. in the Belgian Campine, was detected from peat levels dominated by xerophile *Hyalosphenia subflava* and *Cyclopyxis eurystoma*. An ensuing oceanic phase at ± 4350 to ± 4075 BP. was also tentatively identified, based on the presence of the aquatic species, *Difflugia rubescens*. Changes in the diatom flora of a peat core taken from a river valley c.10 km. away were coeval with the testate derived mire moisture reconstructions, and provide possible evidence for climate change. Unfortunately, only two radiocarbon dates were available for each of the two sites investigated; the possibility therefore exists that the dates for the synchronous hydrological changes linking the two sites may be incorrect.

Witte and Van Geel (1985), identified a wet phase in a peat section from the Assendelver Polder, the Netherlands, using testate amoebae and macrofossil analysis and a range of microfossils. An abundance of *Sphagnum cuspidatum* leaves and Copepod spermatophores in zone J of their reconstruction (dated to 1450 BP. based on ^{14}C and peat accumulation rates derived from pollen concentrations), was synchronous with high numbers of *Amphitrema flavum*. This hygrophilous species is commonly found in pools and the wetter parts of hummocks (Heal, 1961; Corbet, 1973).

Van Der Molen and Hoekstra (1988), constructed humidity index curves from both the rhizopod and *Sphagnum* macrofossil components, from the Engbertsdijksveen, for the time period, 1000 BC. to 960 AD., and found that the two independently generated palaeo-wetness curves correlated well. A similar finding was made by Tolonen (1966), since there was a positive correlation between the less well humified peat sections and wet periods derived from testate amoebae thanatocenoeses.

Warner and Charman (1994) detected a change to drier mire communities using a range of testate amoebae species, during the historic period (based on the dominance of *Ambrosia* pollen) from a bog in Ontario, Canada. Palaeo-mire water table depths were reconstructed using weighted averages derived from a modern surface moss data set.

Reliance on testate amoebae analysis alone to reconstruct palaeowater levels, however, would be premature, since there has been little work done on quantifying the positions and composition of different testate communities in relation to water level, between different habitat types and over several seasons (De Graaf, 1956). The work of Charman and Warner (1992), Warner and Charman (1994), Tolonen *et al.* (1992, 1994), and Woodland (1996), on Canadian, Finnish, and British mires respectively, has attempted to answer this question using multivariate analysis and measurements of water table position. However, the precise variation of testates in different microsite types *within* mires remains unclear. The exact position of some species along moisture gradients is also unclear and sometimes contradictory, for example, Warner and Charman (1994), found that *Euglypha* species occur at relatively low moisture levels in NW. Ontario, but in NE. Ontario and Finland occur at middle to high moisture levels. There are nevertheless, encouraging examples of species displaying the same preferences for mire water level; *Amphitrema flavum* is indicative of very high moisture levels in both Canadian and Finnish data sets, similarly, *Hyalosphenia papilio* and *H. elegans* also indicate high moisture levels, whilst *H. subflava* is restricted to drier conditions.

2.4 Conclusion.

Palaeoclimate reconstructions have been attempted using peat micro- and macrofossils, testate amoebae, and humification analysis. Many of these reconstructions display synchroneity, and where more recent palaeoclimate reconstructions have been attempted, in particular those spanning the 'Medieval Optimum' and 'Little Ice Age', there is further parallelism between the peat proxy record and historical records (Barber *et al.* 1994a, Blackford and Chambers, 1995 and Tallis, 1995). This is very encouraging.

Attempting to reconstruct mire surface wetness and thereby infer former climates, particularly using any single proxy alone, however, is unsatisfactory, as each one is subject to different sources of error, whether one is using plant macrofossils, testate amoebae or peat humification. Because of this, an eclectic approach is necessary, (Tipping, 1995), and is the preferred approach of this research, in order to reconstruct with the best possible accuracy, mire surface wetness.

The degree of mire surface wetness in ombrotrophic peatlands is, in addition to effective precipitation, affected by non-climatic factors, for example episodes of anthropogenic disturbance, particularly clearing of the vegetation growing within the mire catchment, and burning events. Autogenic hydrological processes may, in addition, "damp" a mire's response to increases in effective precipitation. To counter these problems, the detection of charcoal rich layers allows one to recognise and allow for possible human disturbance to sites, whilst the analysis of multiple regional sites allows a search for synchronous hydroclimatic events to be made, for it is these that are likely to be climatically driven. Despite the undoubted potential occurrence of non-climatic parameters, autogenic processes are by definition, site specific, and can be detected by selecting paired sites for analysis.

Chapter 3: Methods.

3.1 Introduction.

The potential to reconstruct palaeoclimates using peat micro and macrofossils, testate amoebae and humification analysis has been reviewed in section 2.3. Since each technique is subject to different sources of error, the use of all three was attempted rather than relying on any single technique alone to reconstruct mire surface wetness. In order to potentially improve the radiocarbon geochronology for each site, pollen analysis was additionally undertaken. Spheroidal Carbonaceous Particle (SCP) analysis was used to extend the radiocarbon chronology derived from the Shaft Hill monoliths[3] .

3.2 Site Selection.

In order to reconstruct palaeoclimates and test the sensitivities of the remaining mires in the region to record climate change, sites had to be selected which had suffered minimal human disturbance, since this may "mask" evidence for climate change. Where deep drains were evident, and/or where the surface vegetation was highly modified, sites were discounted. Drained sites suffer from primary consolidation, for example Hobbs (1986), reports subsidence of the peat surface by 1.5 m. in a peat depth of 10 m. *within* 12 months of drainage, if the water table is maintained at 1 m. depth. The compression of the fossil record reduces the resolution of palaeoecological reconstructions, whilst the exposure of sub-fossil material to aerobic decomposition processes, renders interpretation of the humification signal difficult. In a similar manner, raised mire sites which did not possess a flora comprising water-level sensitive *Sphagnum* species (M18 *Erica tetralix-Sphagnum papillosum* community of Rodwell, 1991), were also rejected, since the ability to reconstruct effective precipitation from them is reduced. Where blanket mire sites (*Calluna-Eriophorum* blanket bog, NVC, M19), were investigated, water-shedding plateaux were sought out which possessed good *Sphagnum* cover with lawn and pool microtopes. Areas of bare peat and those with gullying, which is the commonest form of damage afflicting blanket bog ecosystems (Tallis, 1995), were obviously avoided.

To test the importance of autogenic processes in shaping mire development, paired sites were actively looked for, to investigate just how closely juxtaposed sites had developed. Conversely, to detect allogenic forcing, i.e. climate change, mires had to be selected from the study region which stretches from the Solway Firth to the North Pennines (Figure 3.1).

This task was not straightforward, because in the first instance, there are simply not many sites which satisfy all these criteria. The biggest problem is human disturbance to bog ecosystems, indeed 96% of raised peat bogs in the UK. have been destroyed (Lindsay and Ross, 1994). The need to investigate paired sites also imposed limitations, as the number of relatively intact sites within c. 10 km. of each other is also rather limited. Despite these difficulties, analysis of the literature and discussions with the staff of English Nature, Scottish Natural Heritage and Forest Enterprise, enabled a short-list of possible sites to be drawn up, before a

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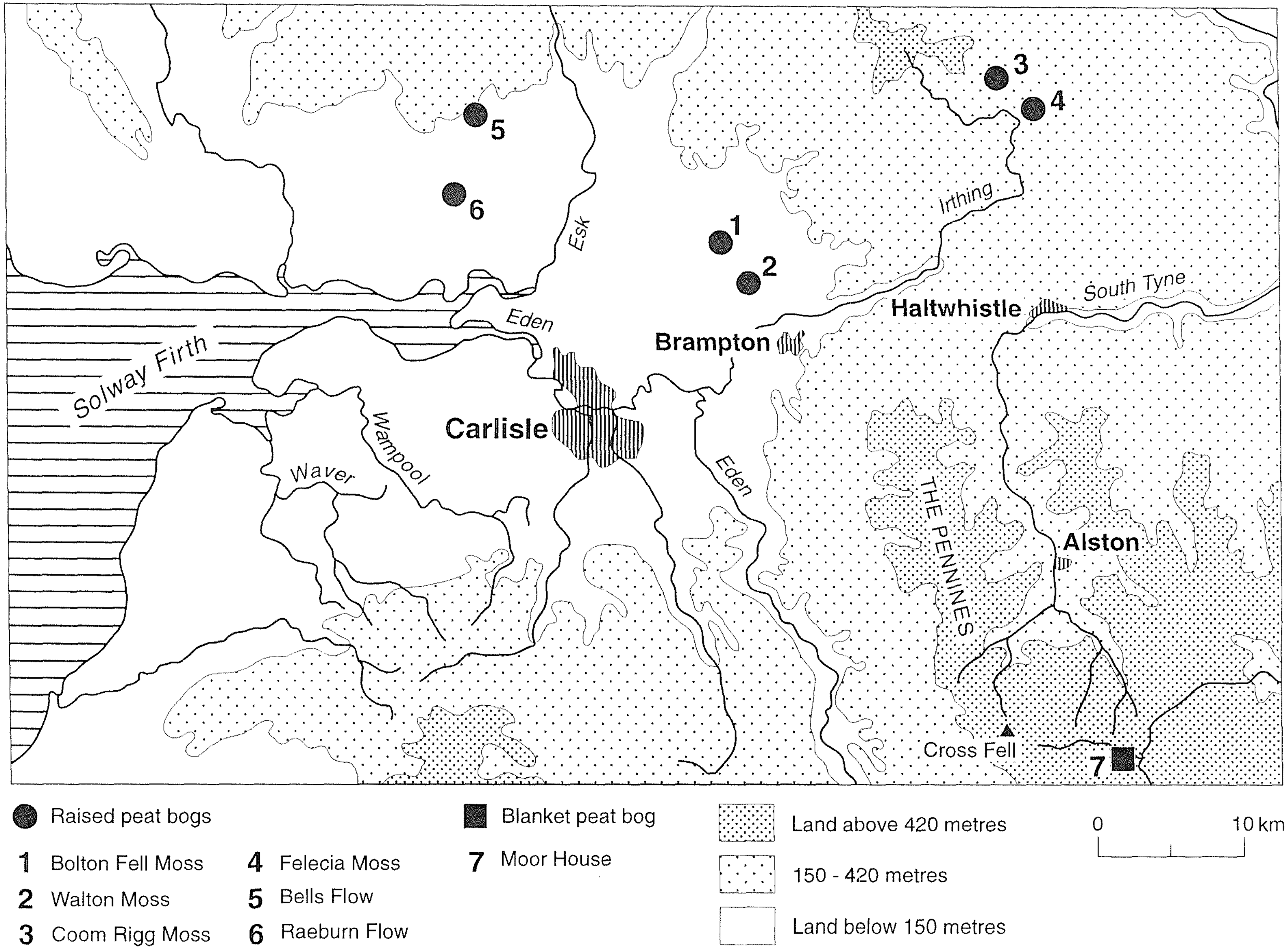
[3] SCP analysis was undertaken by Mark Garnett, at the Institute of Terrestrial Ecology, Merlewood.

Figure 3.1


3
4
5
6
1
2
Esk
Irthing
South Tyne
Haltwhistle
Brampton
Eden
Solway Firth
Carlisle
Wampool
Waver
Eden
THE PENNINES
Alston
Cross Fell
7
Raised peat bogs
1 Bolton Fell Moss
2 Walton Moss
3 Coom Rigg Moss
4 Felecia Moss
5 Bells Flow
6 Raeburn Flow
Blanket peat bog
7 Moor House
Land above 420 metres
150 - 420 metres
Land below 150 metres
0
10 km

reconnaissance field trip was undertaken. The acceptance/rejection of sites, and the reasons for these decisions are listed in Table 3.1.

Six paired raised peat bogs were selected; Bolton Fell Moss and Walton Moss, Bells Flow and Raeburn Flow, and Coom Rigg Moss and Felecia Moss. Since there are no suitable raised peat bogs in the Northern Pennines area, blanket bog sites had to be investigated within the 3500 ha. Moor House NNR. The topography of the reserve is very heterogeneous and ranges in height from 290-848 m. Due to time constraints, a single site, Shaft Hill was identified, and three peat monoliths taken from it.

3.3 Coring Strategy.

A prime factor influencing the number of cores taken was the availability and cost of radiocarbon dates. The establishment of a good chronology is essential if rates of change and (a)synchroneity of changes between sites is to be accurately determined. In addition to this, the time required to examine multi-proxy evidence severely reduces the number of cores that can be analysed fully for each site. Given these constraints, a single core was taken from each study site, (with the exception of the Shaft Hill blanket mire site) using 50x10x10 cm. aluminium monolith tins for the first 50 cm. of peat and subsequently a 30x9 cm. "Russian" pattern corer (Barber, 1984) to recover material down to 3 or 5 m; a borehole from Walton Moss was sunk to a depth of five metres to allow a direct comparison of sub-fossil peat from this site with that from Bolton Fell Moss Core L (two radiocarbon dates, provided by NERC, as part of the Palaeoclimate Special Topic Programme, were already available for this latter core). The remainder of the sites were sampled down to three or four metres depth.

The Shaft Hill site was investigated in collaboration with Mark Garnett, a Ph.D student, based at the Institute of Terrestrial Ecology, Merlewood, Grange Over Sands. Since we both wanted to analyse material from the same borehole to make the best use of radiocarbon dates granted to myself and Mark, a large hinged stainless steel monolith tin, (15 x 15 cm.) was used to extract material to 92 cm. depth. Sufficient material was available to perform humification, plant macrofossil and testate amoebae analysis for two of the monoliths (SHL2 and 3), but unfortunately, there was not enough peat from SHL1 to examine all three proxies, precluding thecamoebae analysis.

Samples were wrapped in airtight carbon-stable plastic bags and stored horizontally in a refrigerator at 4 °C. The large sample size provided by the monolith tins and the wide-bore “Russian” corer ensured adequate material was available for radiocarbon dating.

Cores were taken away from the mire edge, as the peat is thin here and therefore may not contain a long palaeo-record, is more likely to have suffered from human disturbance, and may receive nutrients flowing off the bog. Cores were not necessarily all taken from the centre of the bogs investigated, but from locations where the peat was deepest and more likely to contain 'raised' ombrotrophic peat deposits spanning the last 3000-5000 years. The complex subsurface drift topography of Coom Rigg Moss, which was determined by Chapman (1964), illustrates the potential hazard of coring sites uncritically. The 'centre' of the mire is underlain by a mineral ridge, which supports only a shallow layer of peat, composed mainly of *Eriophorum vaginatum* and *Trichophorum cespitosum,* with a relatively small percentage of *Sphagnum* sub-fossils (c.20%) below 50 cm. The deepest peat sediments (from which the core was taken) are found in a basin c. 150 m. from the northern edge of the site, from which the mire subsequently paludified outwards.

Table 3.1 Sites investigated for the research project.

Site	Grid reference	Accept/Reject	Remarks
Bolton Fell Moss	NY 490690	A	Cut-over, commercially exploited site. Peat remnant does, however, provide suitable material for analysis.
Walton Moss	NY 504667	A	Intact raised mire.
Bells Flow	NY 320760	A	Intact raised/transitional mire.
Raeburn Flow	NY 295717	A	Intact raised mire.
Coom Rigg Moss	NY 692796	A	Intact raised mire.
Felecia Moss	NY 721777	A	Intact raised/transitional mire.
Shaft Hill	NY 747333	A	Water shedding, ombrotrophic blanket mire.
Deer Dike Moss	SD 336822	R	Drained, with Birch and Rhododendron invasion.
Fish House Moss	SD 336827	R	Deep 1 m. drains, c.11 m. apart cross the entire bog. Birch and Rhododendron scrub has been cleared from the site, but the mire surface is very dry.
Gowany Knowe Moss	NY 730788	R	Largely afforested. There is no perceptible 'raised' part on the mire. There is also evidence of flushing, as there is *Juncus conglomeratus* growing at the mire margin.
Grain Head Moss	NY 745736	R	Site inaccessible; surrounded by impenetrable 'thicket' stage of commercial conifers.
Pundershaw Moss	NY 775792	R	The moss is very hummocky, and is dominated by 'dry' species, e.g. *Empetrum nigrum* and *Calluna vulgaris.*
Rusland Moss	SD 335885	R	Very dry peat surface dominated by *Molinia caeruleae* and *Myrica gale.* Very sparse *Sphagnum* cover.

Where there was no stratigraphic data or peat depths available for the sites investigated (Felecia Moss, Raeburn Flow and Bells Flow), peat depths and stratigraphy were determined by "probing" with a 50 cm. "Russian " pattern corer to confirm the presence of "raised" peat stratigraphy. The Troels-Smith (1955) system and the 10-point humification scale of von Post (1924), proved useful in this confirmation.

Barber (1981), Stoneman (1993), Barber (1995), and Barber (1996), have demonstrated that stratigraphic levels within single raised peat bogs (Bolton Fell Moss and Walton Moss) have reacted synchronously to possible climatic forcing (Section 2.3.2), therefore a single borehole taken from other raised mires ought to be representative for the whole site. In the light of this very encouraging evidence, one core was taken from each of the raised peat bog sites, with the implicit assumption that it was representative for the whole site. Three peat monoliths were taken from Shaft Hill, to determine whether blanket stratigraphy also responds synchronously to allogenic forcing and replicate the findings of Blackford and Chambers (1995).

Coring was undertaken by taking samples from the same microtopographic position, in this instance lawns, and from carpets (where possible) containing *Sphagnum magellanicum* as the dominant bryophyte. Boreholes were not taken from surface hummocks, since these microtopes are climatically insensitive; Casparie (1972), used evidence from rhizopods to show how "drier" macrofossil assemblages (from a hummock) could continue to grow without change, whilst adjacent lower lawns supported markedly wetter peat macrofossils.

In addition to this resistance to climate change, relative decay rates of hummocks (determined from weight loss of standard cotton strips) and depths of the oxic zone, are generally higher than those of other microtopes (Doyle and Dowding, 1990). This has the potential to reduce preservation of sub-fossil material from hummock microtopes, with the attendant risk that subsequent reconstructions of the former mire vegetation are more likely to be in error.

3.4 Plant Macrofossil Analysis.

3.4.1 Introduction.

The identification and quantification of plant macrofossils (tissues from stems, roots and leaves) forms a key part of this research. They have been either classified as sub-fossil materials visible to the naked eye (Birks and Birks, 1980), or as is more often the case, as material larger than pollen grains (Clarke, 1988).

There are few problems of deposition and dispersal because of their relatively large size, and the majority of the floral remains recovered from ombrogenous peats, particularly the vegetative material, originally grew *in situ*, which reduces the potential error of any local vegetation reconstruction.

Variable preservation does occur, however, so that the sample population in the peat sediments *sensu* Krumbein and Greybill (1965), may not correspond to the original target population of the bog flora which grew at the bog surface. For example, *Sphagnum* spp. growing in hummocks with a 30-40 cm. acrotelm may be subjected to aerobic decomposition processes for more than 100 years and loose up to 80% of their original carbon (Hogg, 1993). This figure agrees with the estimate made by Clymo (1984), of a 90% loss of the original organic matter during its course through the acrotelm. Fluctuations in the depth of the acrotelm in particular will lead to variable preservation, since it is in this layer, which comprises the euphotic layer and layer of collapse (Clymo, 1992), where rates of (aerobic) decay are greatest (Clymo, 1965). Periods of reduced average water table position will therefore tend to have more humified, amorphous plant structures, rendering identification and reconstruction of the former vegetation more difficult.

Sphagnum leaves and to a lesser degree stems, form a large part of the subfossil peat components recovered from ombrogenous mires. *Sphagnum* plants break down selectively, with the loss first of the stems and branches, though the leaves tend to remain largely intact (Johnson and Damman, 1990). That this is so attests to the decay resistance of these structures, which may be attributable to the high proportion of resistant organic compounds, such as hemicelluloses and lignin like compounds in the leaves. *Sphagnum* acid, extracted by Tutschek (1975), a phenolic compound unique to the Genus, and waxes and lipids, which are the components of suberin and cutin in higher plants, may convey further decay resistance (Karunen *et al.*, 1983). The accumulation of long chain (greater than or equal to C_{22}) polymerized-hydroxyl acids during the ageing of *Sphagnum* shoots has also been implicated in the decay resistance of these bryophytes. The presence of these polymerized polyhydroxy acids may also be responsible for the slower decay rates displayed by *Sphagnum* species in comparison to vascular plant species (Lehtonen and Ketola, 1993).

Breakdown by micro-organisms rather than detritivores (beetle larvae, rhizopods, mites and chironomid larvae) seems to be the main cause of the mass loss from *Sphagnum* spp. (Clymo, 1965). Attempting to reconstruct *Sphagnum* populations, however, can be problematic since these bryophyte species have different decomposition rates. Johnson and Damman (1991), propose that the decay in *Sphagnum* is species controlled, as they found that *Sphagnum cuspidatum* (a pool species) decayed 1.5 times as fast as *Sphagnum fuscum*, despite the latters habitat position in a hummock, where, potentially, the most favourable conditions for decay are found. Johnson and Damman (1993), recorded further differential species decay rates, with *Sphagnum fuscum* displaying the smallest losses in mass, intermediate losses for *Sphagnum magellanicum* and the highest losses in mass for *Sphagnum cuspidatum* once again. Rochefort *et al.* (1990), speculate that the low decomposition rates of *Sphagnum fuscum* on hummocks may be due to a combination of higher uronic acid content and low pH.

A further potential problem that can lead to errors in reconstructing former bryophyte communities is the differential contribution of leaves from different *Sphagnum* species (Green, 1965; Barber, 1981). For example, species from *Sphagnum* section *Acutifolia* lose leaves from their branches more easily than those from *Sphagnum* section *Sphagnum*, leading to a possible over-representation of section *Acutifolia* leaves in the sub-fossil record.

Liverworts may be the dominant bryophytes in shallow pools, decaying hummocks and under dense canopies of *Calluna vulgaris* (Duckett and Clymo, 1988), yet during the course of this research, although *Odontoschisma sphagni* was recorded in the surface levels of peat from Bolton Fell Moss and Felecia Moss, it was not recovered in any of the sub-fossil material. A similar finding was made by Jaansens *et al.* (1992), since none of the six liverworts species growing in the Minnesota sites investigated was recovered in any of the fossil material.

The subterranean axes of the Genera Lepidozioideae, Cephalozioideae and Odontoschismatiodeae, which forms the bulk of the biomass of these liverworts, is composed simply of elongated parenchyma cells with surrounding isodiametric cells, (Duckett and Renzaglia, 1988). The inherent fragility and susceptibility of these tissues to decomposition processes may be the reason why these hepatics are only found in the surficial layers of *Sphagnum*.

Vascular plants are subject, also, to differential preservation, which can be due to differences in decomposition resistance, e.g. *Eriophorum vaginatum* sheaths are broken down only slowly (Grosse-Braukman, 1986). The aerial parts of *Calluna vulgaris* and *Rubus chamaemorus*, on the other hand, are broken down readily by mire aerobic detritivores (Coulson and Butterfield, 1978), since following the death of the parent plants, leaves and flowers are deposited into the biologically active, oxic acrotelm (Doyle and Dowding, 1990). Where the aerial parts of vascular plants are recorded they possibly indicate the operation of special preservation conditions, perhaps due to a very high peat accumulation rate (Eggelsmann *et al.,* 1993).

The penetration of the root systems of *Eriophorum vaginatum* and *Eriophorum angustifolium* up to c. 75 cm. below the surface, where they can absorb nutrients even under completely anaerobic conditions (Boggie *et al.*, 1958; Gore and Urquhart, 1966), can lead to there over-representation in subfossil material (Clymo, 1965), since this material avoids aerobic decomposition and as a consequence suffers less from mass loss and structural alteration.

Considering the potential for differential preservation and representation of ombrogenous mire flora, the subsequent vegetation reconstructions produced from sub-fossil assemblages need to be interpreted cautiously.

3.4.2 Methodology.

A methodology had to be selected which would allow an accurate reconstruction of the vegetation components and at the same time be relatively quick, as this research involves analysis of multiple proxies from multiple profiles. In the light of this, the Quadrat and Leaf Count macrofossil analysis technique (QLC) developed by Haslam (1987) and Clarke (1988), was employed without any modification. This experimental methodology has been adopted by Stoneman *et al.* (1993), Barber *et al.* (1994a, b, c), Barber and Scaife (1995), Barber (1996) and Barber *et al.* (in press), therefore its adoption here will allow direct comparison with the palaeoclimatic reconstructions undertaken in the above literature.

This technique is a compromise between the simple and qualitative technique, whereby macrofossil components are classified on a three or five point scale (where 1= rare, 2= occasional, 3= frequent, 4= common and 5= abundant), e.g. Walker and Walker (1961), Barber (1981), Smith (1985) and Wimble (1986), and the intricate technique of Jaansens (1983), where loose leaves, branches and whole *Sphagnum* plants are counted, and a preservation index assigned to create a 10 point 'reliability' index. Whole plants which retain their branches are given the highest weighting, conversely, damaged single leaves have the lowest weighting. Fossil bryophytes are ultimately expressed as fragments 100 ml^{-1}, after first dividing the number of fossil leaves and branches recorded by 100 and 10 respectively.

This technique has much to offer, whole plants ought to give a more reliable reconstruction of former bryophyte species composition than one made from the presence of leaves alone, whilst the division of the number of leaves recovered by 100 reduces the importance of *Sphagnum* section *Acutifolia* species, since they lose leaves more readily than those from *Sphagnum* section *Sphagnum* (Barber, 1981). Unfortunately the methodology also has drawbacks; the division of fossil leaves by 100, and branches by 10 is an arbitrary figure, and it is also assumed that all *Sphagnum* species have the same representation in fossil assemblages in terms of whole plants, branches and leaves. The need to express bryophyte fragments as a concentration value also poses a problem because of the extra time required to derive this value using displacement techniques.

The methodology adopted here allows an assessment of the volume percentages of the floral macrofossils to be made. The schema of events for the analysis of each sub-sample follows the sequence;

Each core, with the exception of the Shaft Hill blanket mire monoliths, was sampled at 4 cm. intervals to 3m. depth. The longer 5m. cores from Bolton Fell Moss Core L, and Walton Moss Core 11 were sampled at 4 cm. increments for the first 3m. and then at 8 cm. intervals from 3 to 5m., simply because of the time restraints imposed by the macrofossil analysis methodology. The three monoliths from Shaft Hill were sampled at 2 cm. intervals, since they only extended to 92 cm. (maximum). This may improve the resolution of subsequent palaeoclimate reconstructions from this site.

A slice of peat measuring 1 cm. x 1 cm. x 4 cm. was cut from each level with a surgical scalpel.
The samples were placed on a 125 μm sieve and sprayed with a high pressure jet of water from a narrow plastic pipe connected to a tap, which served to force fine, highly humified material through the sieve and disaggregate the sample. This procedure is preferred to using NaOH or KOH to disperse the peat, since this treatment renders macrofossils mucilaginous, involves longer processing times, and makes the sub-samples unsuitable for use with several mounting media (Barber, 1981).

Macrofossils retained on the 125 μm sieve were placed in a glass trough and 70 ml. of water added to create a monolayer of remains. These were scanned using a Nikon stereozoom microscope (SMZ-10) at x10 magnification, and the abundance of unidentified organic matter, identifiable *Sphagnum*, monocotyledons, ericaceous remains, and the proportion of empty space in each quadrat, was estimated using a 10x10 square grid graticule inserted into the eyepiece of the microscope. Where a component covered more than half each individual square, a score of 1% was given to it.

Haslam (1987) and Stoneman (1993), carried out 15 quadrat counts for the trough estimation stage (representing a 8% subsample of the total macrofossil sample; Clarke, 1988), and found that this number of analyses represented an accurate estimate of the sample population. This is based on the assumption that the sample population approximates to a Gaussian distribution. A computer programme, using Bessel's correction, was subsequently used to calculate the running standing error of the mean (Haslam, 1987). This confirmed that 15 random quadrats represents the optimum sample size (Clarke, 1988). Charman (1990), recognised that these errors do not relate to estimation errors but to sampling and counting errors, but it was still felt that the methodology offered the best balance of accuracy and speed of implementation.

The next step of the analysis is the identification and estimation of the *Sphagnum* sections/species in each level. In order to do this, the sub-fossil material was stained with toluidine blue and the trough shaken. A random selection of *Sphagnum* leaves are then identified at x400 to the lowest taxonomic level and expressed as percentages. The drawings and keys in Smith (1980) and Daniels and Eddy (1990), as well as an extensive bryophyte reference collection, were extensively consulted to aid and confirm identifications. This procedure routinely entailed the removal of c.80 to 130 leaves depending on the presence of each *Sphagnum* section/species in each sample; the number of leaves removed from levels rich in *Sphagnum* section *Acutifolia*

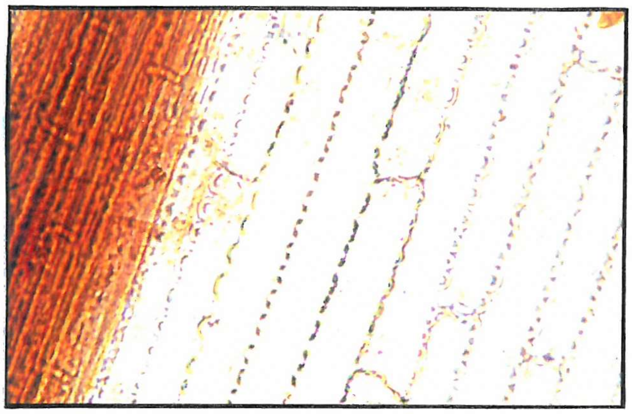
$$Ps = \frac{Nli}{n} . Plds$$

where Ps: percentage of leaves in the fossil sample, Nli: number of leaves of species i counted, n: total number of leaves in the fossil sample and Plds: percent identifiable *Sphagnum* in the sample.

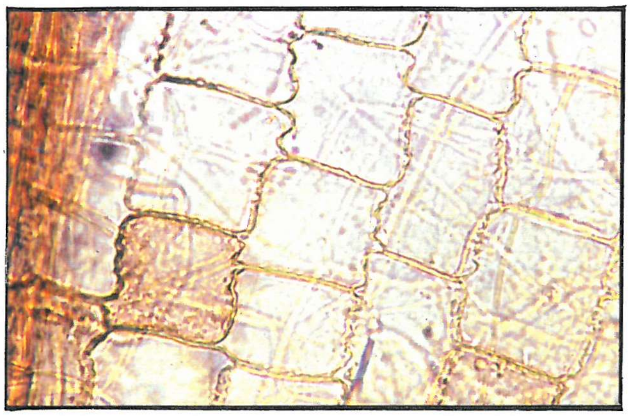
3.4.2.1 Monocotyledon macrofossils.

More accurate reconstructions of mire surface wetness or dryness can potentially be determined from the specific monocotyledons present in the peat stratigraphy, and can extend and refine the palaeoclimate signal derived from bryophyte and rhizopod analyses. Identification of monocotyledonous macrofossils to species level is difficult however. There is a dearth of published keys and identification manuals, but the excellent drawings in Katz *et al.* (1977), and Clarke (1988) proved useful. By using these and a reference collection of type material, the following species could be identified using for the most part, details of epidermal cell morphology;

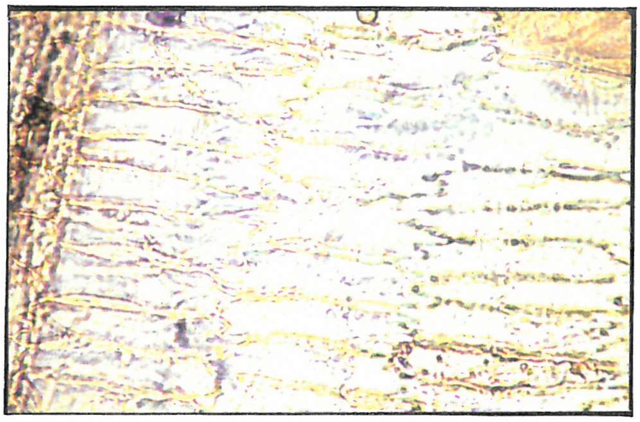
- *Eriophorum vaginatum* (Plate 3.1, x400), the epidermal cells of this species are very distinctive, since they have a orderly arrangement, and are many times longer than they are wide. The presence of sclerenchymatous spindles was also diagnostic for this species, and has been used by Charman (1990).



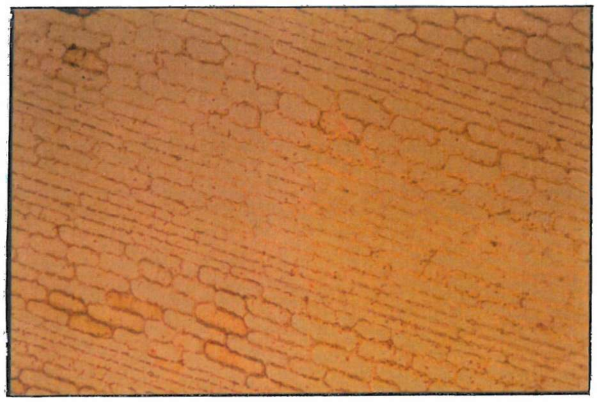
- *Eriophorum angustifolium* (Plate 3.2, x400), the cells of this species are much shorter and squatter than those of Hare's Tail Cotton Grass, whilst the marked red colour of the rhizomes is also diagnostic for this species.



- *Rhynchospora alba* (Plate 3.3, x400), the stem sheaths of this sedge have a very distinctive arrangement, in that the cells are longer than broad at the edge, whilst the opposite holds true in the centre of the stem sheath.



- *Trichophorum cespitosum* (Plate 3.4, x100), is readily identified by the arrangement of short epidermal cells which lie alongside chains of parallel longer cells.



Wherever epidermal cells were visible in the glass trough, there were removed using watchmaker's forceps, mounted in Aquamount, and examined at x100 - x400 to confirm the species present. Each monocotyledon species is expressed as a mean percentage value of the peat matrix scanned while performing the 15 quadrat counts.

In many instances, the Cyperaceous remains could not be identified to species level, particularly where macrofossils were largely derived from rhizome material; in this case, and where there was no epidermal material present in sub-fossil samples, monocotyledonous remains were simply classified as monocotyledons undifferentiated (monocots. undiff.), which is again expressed as a percentage value.

Although the presence of some of the ericaceous species could be confirmed, for example leaves and seed boxes of *Calluna vulgaris* were sometimes present, whilst the stems of *Erica tetralix* could also be identified from their leaf scar macromorphology, the majority of dwarf shrub macrofossils encountered were rootlets. Since this material cannot be identified beyond group level (Charman, 1990), all the dwarf shrub macrofossils were classified as Ericaceae, with the exception of the sub-fossil peat samples collected from Shaft Hill, Moor House. Since only three short monoliths were recovered from this site, more time was available for more detailed palaeoecological analysis, and leaves of *Calluna vulgaris*, and *Erica tetralix,* seed boxes of *Calluna vulgaris*, and *Erica tetralix* wood were identified using the Southampton type reference collection and recorded on a 1-5 scale (where 1= rare, 2= occasional, 3= frequent, 4= common and 5= abundant).

3.4.2.2 Fruits and Seeds.

Seeds are more readily identified to species level, in comparison to plant macrofossils, but production (Grubb, 1987), dispersal (Carey and Wilkinson, 1993) and deposition processes for each species are different, which renders interpretation of their presence difficult. Predation losses from the seed bank also occur, as rodents, birds, and smaller soil fauna utilise them as a food source (Russi *et al.*, 1992). Notwithstanding these undoubted problems, the seed bank does however, offer the potential to indicate the former presence of Cyperaceae and Ericaceae and corroborates the plant macrofossil record.

Identification of seeds was undertaken from the Shaft Hill blanket monoliths only, again because more time was available to study the stratigraphy from this site. Seeds and bracts were identified using the type collections at Southampton University. The texts of Beijerinck (1947), Martin and Barkley (1961), Berggren (1969), Korber-Grohne (1964) and Berggren (1982) proved useful in this instance. In order to simplify the graphical presentations, the word seed is used to describe both fruits and seeds. Seeds were simply counted on a 1-5 basis, after Hall *et al.* (1995), where 1 = one seed, 2 = 2-5 seeds, 3 = 5-20 seeds, 4 = 20-40 seeds and 5 = more than 40 seeds counted.

3.4.2.3 Non-*Sphagnum* bryophytes.

Four non-*Sphagnum* bryophytes were encountered during the analysis of the various peat matrices. These were *Aulacomnium palustre, Drepanocladus fluitans, Polytrichum juniperum/alpestre* type and *Racomitrium lanuginosum*. Their abundances are expressed as a mean percentage value of the peat matrix examined.

3.5 Rhizopod Analysis

3.5.1 Introduction.

Testate amoebae represent the largest faunal element in the *Sphagnum* communities of raised mires, (Heathwaite *et al.*, 1993), reaching abundances of 16,000,000 m^{-2} in peat (Heal, 1962), where they live mainly in the concavities of peat moss leaves. The fauna vary in size from 10-250 μm. and the morphologically distinct shells they produce, which are relatively abundant in sub-fossil peats, are diagnostic to species level. There is great diversity in the material used for shell construction. Shells can be either proteinaceous (incorporating 'pseudochitin' and mucoproteins), agglutinate (where quartz grains, and diatoms are incorporated into the shell matrix), siliceous or calcareous. In addition to these features, testates can also be differentiated on the basis of their size, shape, ornamentation, surface pattern and features of the pseudostome (Bobrov *et al.,* 1995), which is the aperture through which cytoplasm is 'extruded' for feeding and locomotion.

3.5.2 Laboratory Procedures.

Because *Sphagnum imbricatum* may 'mask' climate signals, levels where this bryophyte dominated the peat stratigraphy were sampled at 8 cm. intervals. An initial attempt was made at sampling at 4 cm. intervals (Raeburn Flow), but this proved to be too time consuming and was abandoned. The stratigraphy of each site which did not contain abundant *Sphagnum imbricatum* leaves was sampled at 16 cm. intervals, again because of time constraints. Sufficient peat was available from Shaft Hill - Monoliths 2 and 3 to undertake thecamoebae analysis, and in this instance, samples were taken at 2 cm. intervals, which will allow a direct comparison with the plant macrofossil and humification data. From each level, a subsample of 5 $cm.^3$ of peat for fossil testate amoebae analysis was taken using a volumetric sampler and processed in the laboratory using the techniques of Tolonen (1986). For each sample, this simply involves boiling in 50 ml. of distilled water for ten minutes.

The peat residue was then sieved through a 250 μm mesh to remove larger macroscopic material, as this may obscure rhizopod shells (pers comm. Wendy Woodland). Each sample was then centrifuged at 3000 rpm. for three minutes, decanted, 0.5 ml. of glycerol added, and stained with safranine. The simple preparation procedure adopted preserves the delicate thecae of these protists, since more vigorous chemical treatments used to isolate pollen grains and spores have been found to be deleterious to rhizopods. This has been confirmed by Van Der Molen and Hoekstra (1988). Using both the preparation techniques developed by Tolonen (1986) and standard pollen preparation procedures (Moore and Webb, 1978) to extract fossil testate amoebae, they found reduced numbers of *Arcella* spp. and *Amphitrema flavum* from samples which had undergone pollen preparation treatment.

Counting was undertaken until either 150 or a minimum of 100 amoebae shells were recorded (Warner, 1990).

3.5.3 Testate Amoebae identification.

In the absence of a SEM, identification of testaceans down to genus and species level is difficult (Woodland, 1996). In addition to this, thecamoebae species display polymorphism, for example, *Nebela tincta* individuals may be smaller in drier sites than those in wetter *Sphagnum* microtopes (Heal, 1963). Because of this, they may be misidentified as *N. parvula,* as these two species share similar size ranges (Woodland, 1996). Bobrov *et al.* (1995), have similarly noted shell morphology differences in *Trigonopyxis arcula* populations from Western Siberia and Ontario, Canada, which can further complicate testate identifications. Staining rhizopods with safranine-O makes identification of *Heleopera rosea* difficult, since it naturally has a wine-red colouring; the addition of the stain to sub-fossil samples will equally stain all *Heleopera* species present in the sample, reducing the accuracy of species identification (Woodland, 1996). Because of this, *Heleopera rosea* and *H. sphagni* were grouped together as *Heliopera rosea/sphagni* type. The taxonomy of other disputed species has been reviewed by Woodland in her doctoral thesis, and Table 3.2 displays how these species have been grouped together by various authors.

There is a distinct lack of testacean identification keys, therefore it was necessary to consult a range of texts to help identifications. The electron micrographs of Ogden and Hedley (1985) were of some use, but the keys and drawings of Grospietsch (1958), Corbet (1973), Lee *et al.* (1985) and Ellison and Ogden (1987), were more useful, as they relate to optical microscopy images. The photographs and identification key produced by Woodland (1996), was extremely helpful, since it extended the species list produced by Corbet (1973). The reference collection of testate amoebae in the Department of Zoology, The Natural History Museum, London, was kindly made available by Dr. Alan Warren, and also proved to be very useful in the identification of thecamoebae.

Table 3.2 *Peatland testate amoebae with disputed taxonomy (from Woodland, 1996).*

Taxa	**Indistinct from**	**Other comments**
Assulina muscorum.	*A. seminulum.*	Polymorphism in *A. muscorum* affects size and colour of tests (range from russet to colourless - Schönborn and Peschke, 1990). Usually brown, but colourless (Ogden, 1981).
Arcella artocrea.	*A. gibbosa* (Tolonen *et al.*, 1992).	
Arcella discoides.	*A. megastoma and A. polypora* (Warner, 1987).	Systematics of *Arcella* poorly understood. Intermediate forms difficult to identify (Tolonen, 1986).
Centropyxis aculeata.	*C. hirsuta* (Tolonen, 1986).	Regarded by Heal (1962) as a species complex.
Corythion dubium.	*Trinema lineare* (Tolonen, 1986).	Plates diagnostic, but very small test size (18-35 μm, Ogden and Hedley, 1980), makes identification very difficult. Often grouped together as the same species.
Centropyxis aerophila type.	*C. cassis; C. constricta; C. ecornis* and *C. platystoma* (Warner, 1987).	Conglomerate group which may contain a number of separate species with specific niches (Tolonen, 1986; Warner and Chmielewski, 1992).
Cyclopyxis arcelloides type.	*Cyclopyxis arcelloides.*	As for *Centropyxis aerophila* type.
Euglypha strigosa type.	*E. compressa, E. ciliata* (Warner, 1987).	
Heleopera petricola.	*H. rosea* (Warner, 1987).	Samples stained with safranine-O invalidates wine-red colour of *H. rosea* as diagnostic feature (Warner, 1987).
Phyrganella hemispherica.	*Centropyxis eurystoma* (Tolonen, 1986); *Difflugia globulosa* (Tolonen, 1986); *Cyclopyxis arcelloides* (Meisterfeld, 1979).	Also referred to as *Phryganella acropodia* (Warner, 1987).

3.6 *Other zoological remains.*

Whilst scanning slides for testate amoebae, sub-fossil parts of Cladocera and Copepoda and virtually complete Oribatid mites were frequently encountered.

The suborder Cladocera or *water fleas* are exclusively freshwater (Barnes, 1980), and may yield clues on the degree of mire surface wetness. Head shields and postabdomen of these Crustacea (Plate 3.5 and 3.6), are readily distinguishable (Frey, 1964), particularly the postabdoma, as these bear special claws and spines for cleaning the carapace of the animal. The only remains of Copepods (Class Copepoda) identified were spermatophores (Plate 3.7). Given the confinement of these crustaceans to freshwater and moss water films, their abundance's may also reflect the degree of mire surface wetness.

Oribatid mites (Acari: Cryptostigmata) are minute (<500 µm.) arthropods of the Class Arachnida. Oribatids are flightless, are usually habitat specific and are preserved where they lived (Erickson, 1988). Identification is based on details of the notogaster (the fused dorsal shield), and the shape and setation of the genital and anal plates. Mire water level reconstruction's can potentially be made using fossil oribatids, as Markkula (1986), was able to show changes in 21 oribatid mite species, when Finnish virgin and forest-ameliorated pine bogs were compared.

Plate 3.5 - Cladocera head shield (x200).

Plate 3.6 - Cladocera postabdomen (x200).

Plate 3.7 - Copepod spermatophore (x200).

Given the potential of these zoological remains, a simple 1-5 scale abundance estimate of cladocera and copepod microfossils was attempted for the Shaft Hill, blanket mire site only, since it was anticipated that the degree of preservation of plant macrofossils from this blanket bog site would be low compared to the raised mire sites. Their inclusion would possibly allow better palaeoecological reconstruction's to be made, due to their mire water level indicator value.

Identification of oribatids was not attempted, however, since compared to the Finnish, Swedish, German and Dutch literature, there is a dearth of information relating to the ecology of the British Isles fauna.

3.7 Humification Analysis.

3.7.1 Introduction.

The degree of peat humification seems to be a valuable indicator for reconstructing bog surface wetness, and is based on a simple premise, in that where the average mire groundwater position is low, or where groundwater levels fluctuate widely, high rates of decomposition ensue. Where water levels are high and relatively stable, under regimes of greater effective precipitation, peat is weakly decomposed and passes through the biologically active acrotelm relatively rapidly (Eggelsmann *et al.*, 1993).

The humic matter produced from the decomposition of the mire biota is a complex collection of macromolecular compounds. The original plant structures may disappear during the course of humification, and chemically new material may be produced; some of the material may be from the original plant polymers and only undergo slight modifications, whilst other chemically new components may be produced by the mire bacterial flora (Clymo, 1992). The other end products of peat humification are the decay resistant compounds, especially lipids and longer chain polymerised-hydroxyl acids (Lehtonen and Ketola, 1993).

Specific techniques used to assess or quantify the degree of humification can be classified into those which are based on visual examination, measurement of physical properties, measurement of chemical properties, and the chemical extraction of soluble material (Blackford and Chambers, 1993).

The humification scale of Von Post (1924) and the more detailed schema of Troels-Smith (1955), whilst useful in the field, cannot pick out subtle changes in humification, as their reliance on colour changes are dependent on the condition of natural light, whilst rapid changes in colour through oxidation may also reduce the accuracy of this visual technique. Examination of the physical properties of peat, particularly the fibre content, can be used to indirectly measure the humification of peat, since as humification proceeds large fibres are increasingly broken down and converted into fine material (Levesque and Mathur, 1979). Blackford (1990) found this technique useful, and found multiple changes of humification which were not visible in the stratigraphy of the sites investigated. Reconstructions of mire surface wetness based on fibre content may be hazardous, however, since under a given uniform decay regime, remains of different plant species decay at different rates, i.e. there is a species signal. The leaf bases and rhizome material of *Eriophorum vaginatum* are especially resistant to decay, and may mask periods where the potential for humification is high (dry mire conditions with a deep acrotelm).

Determination of the chemical properties of the peat matrix, for example, the calorific value and cation exchange capacity of the humus, may have potential in the future, but again there are problems, in that these variables are species dependent, whilst the chemical processes responsible for decomposition itself are extremely complex and not completely understood (Mathur and Farnham, 1985).

Humic and fulvic acids produced as decomposition proceeds can be extracted using, among others, sodium hydroxide. Contaminant, non-humic material is also extracted from peat using this chemical (Hayes, 1985), but whilst other extractants may not alter the peat humification macromolecules, they are inefficient and yield less humic and fulvic acids from a given sample (Hayes *et al.,* 1975), making sodium hydroxide 'the more reliable single-process reagent', (Blackford and Chambers, 1993).

The promising climatic reconstructions made by Blackford (1990), using colorimetric analysis of chemical extracts, in addition to the use of the technique by Aaby and Tauber (1975), Chambers (1984), Rowell and Turner (1985), Wijmstra *et al.* (1984), Blackford and Chambers (1991), Nilssen and Vorren (1991), and Tipping (1995), warranted its inclusion in this study, as it appears to be the best compromise proxy for peat humification.

3.7.2 Colorimetric determination of peat humification.

Absorption of light from an alkaline extract of peat is proportional to the amount of humic matter dissolved, with greater transmission of light through less humified material (Aaby and Tauber, 1975).
Subsamples of 4 cm^3 were taken from the peat cores, and analysed using the methods of Blackford (1990). After treatment with NaOH and filtration, a WPA HC 6000 Hydrocheck photometer was used for colorimetric analyses (a full description of the method can be found in Appendix 1).

Rather than using a sample of 200 mg., a smaller sample of 100 mg. was taken to conserve peat material for other palaeoecological determinations; this was the only divergence from the experimental procedure described in Blackford (1990) and Blackford and Chambers (1993).

Inorganic material residing in the peat matrix may alter the colorimetric determination of humification and lead one to make subsequent erroneous reconstructions of bog surface wetness (Chambers, 1984). Where inorganic material is in the form of clay particles, errors may arise, in that these may surround humic molecules and prevent their solubility in alkali (Schnitzer, 1967).

Blackford (1990), experimentally demonstrated a linear relationship between increasing mineral matter content and absorbance, and corrected absorbance values by determining loss on ignition values for each level. The above analyses, however, were conducted on blanket peats, which may receive colluvial inwash of material from steeper slope segments. In this study, however, only raised mires and water-shedding plateau blanket peat bogs have been investigated. Since these ecosystems only receive minerals from the atmosphere, any inorganic material present should be small and therefore not influence the colorimetric determinations. This was confirmed by conducting loss on ignition determinations, which revealed that the raised peat deposits investigated were almost entirely organic, indeed the presence of inorganic material was so small after combustion, that it was perhaps beyond the means of detection of the weighing apparatus employed (Mettler A30 balance).

3.8 Pollen analysis.

The aim of the pollen analysis was only to establish the take-off of *Pinus* pollen, as this occurred c. 1800 AD., when these trees were utilised in plantations in the study region. Barber (1978), undertook an extensive literature review to more accurately determine the age of the Pine rise for Bolton Fell Moss. The notes made by Houseman in Hutchinson (1794), confirm the presence of small plantations of fir (i.e. Scots Pine), in the parishes near to the mire around this time. Similarly, the Pine rise at Ellergower Moss, Dumfriesshire, has been ^{14}C wiggle matched to 1835 AD., by Clymo *et al.* (1990). This radiometric date was consistent with a ^{210} Pb date from the same mire. Dumayne (1992), also discussed the timing of agricultural improvement in Northern Cumbria and Northumberland, as part of her investigation into the Hadrianic and Antonine walls, and found documentary evidence for the existence of extensive coniferous plantations within the region by (again) 1794 AD. (Bailey and Culley, 1794). A ^{14}C measurement of 175 ± 25 cal. BP for an increase in *Pine, Fagus* and *Picea/Abies* pollen spectra from Burnfoothill Moss, near to Kirkpatrick Fleming on the Solway Firth, was obtained by Tipping (1995), and demonstrates, once again, the relative regional synchroneity of the planting of these trees.

Since a detailed vegetation reconstruction was not required, counting was rapid and straightforward, because of the saccate structure peculiar to the pollen of these taxa.

Microscope slides were prepared from 5 cm^{-3} sub-samples using standard methodologies (Moore *et al.*, 1991). Sub-samples were taken using a volumetric sampler, at 8 cm. intervals down to 64 cm. depth, from the six raised peat bog sites, whilst the three blanket peat monoliths were sampled at 4 cm. intervals down to 79, 81, and 64 cm. depth for Shaft Hill - Monoliths 1, 2, and 3 respectively. *Pinus* pollen concentrations were calculated using marker grains of Lycopodia (Stockmar, 1971). Counting of Pine pollen continued until either 50 Pine pollen grains or 800 Lycopodia spores had been counted.

3.9 Radiocarbon dating.

The establishment of a good geochronology is essential to confirm the possible (a)synchroneity of ombrotrophic mire hydroclimatic changes identified in this project. Without this vital element, they are meaningless. Good chronological control will allow cross-correlation and validation of the palaeoclimatic reconstructions made here with those that have been published from humification, pollen, tree-ring, ice core and historical records. In order to facilitate this, ^{14}C assay of plant remains has been undertaken by the N.E.R.C. Radiocarbon Laboratory in East Kilbride. The technique is widely used to estimate ages of Holocene organic material (Kilian *et al.*, 1995), and measures the residual ^{14}C remaining in each plant sample; since the half life of this isotope is 5568 ± 30 years (Stuiver and Pollach, 1977), the time elapsed since the plant material ceased to exchange carbon with the biosphere can be calculated (Olsson, 1968), and a radiocarbon measurement of the sample assigned. In this instance, 0 BP is equated with 1950 AD. and the conventional radiocarbon age is expressed relative to this. Known age controls in the form of tree rings and dendrochronologically dated wood have demonstrated that the production rate of ^{14}C has not remained constant over time (de Vries, 1958, 1959). There is a major trend visible in Holocene ^{14}C secular variation which has a 'sine wave' characteristic, and superimposed upon these are higher frequency components which are known as 'wiggles', 'kinks', 'windings' or 'warps' (Taylor *et al.*, 1996). The intercept point of a ^{14}C age estimate with the calibration scale allows one to calculate a calibrated age range for each sample. Software packages which contain both the algorithms and the primary calibration data to perform this transformation are readily available, for example the CALIB program developed by Stuiver and Reimer, (1986), and OxCal (Ramsey, 1995), allow one to rapidly calibrate ^{14}C sample measurements. Problem areas where radiocarbon sample measurements intersect the calibration curve a number of times (Pearson *et al.*, 1986), or where the slope of the calibration curve is almost flat, can be readily identified. In these areas, even a high precision radiocarbon measurement may represent a considerable period of time on the calendrical scale (Buck *et al.*, 1994), due to the 'elastic' nature of ^{14}C time (Taylor *et al.*, 1996). Clearly in this instance, the precision of the age assignment, in terms of the time span within which the ^{14}C measurement falls, is reduced, but unless one selects new samples which fall outside the calibration plateaux or 'time warps', *sensu* Taylor *et al.*, (1996), there is little one can do to remedy this.

In addition to these potential problems, additional sources of error may prevent the establishment of an accurate geochronology. Contamination of each sample with older or younger material in the field and/or whilst taking and handling the samples in the laboratory, may lead to accuracy errors. Every effort, however, was made to reduce this contamination; any fresh vegetative material which fell into the chamber of the Russian corer was removed, and whilst in the laboratory, clean stainless steel instruments were used to cut samples out of the peat matrix and to remove any roots, which may introduce 'young' carbon. Wherever possible, samples were taken from levels containing predominantly *Sphagnum*, as these species exhibit similar fractionation of carbon isotopes (Pilcher, 1991).

There are further potential problems with ^{14}C assay, which are, unfortunately, more difficult for the researcher to circumvent, for example, different chemical fractions of the same bulk sample can contain markedly different levels of ^{14}C, even where *Sphagnum* is dominant (Shore *et al.*, 1995). High resolution AMS dates from a Dutch raised bog (Engbertsdijksvenen), have been 'wiggle matched' to the tree-ring calibration curve of Stuiver *et al.* (1993), and reveal a 100-250 ^{14}C year discrepancy between conventionally dated peat cores from the same site. This occurred in samples containing 2-4% very fine Ericaceae rootlets (Kilian *et al.*, 1995). Kilian *et al.* suggest the cause of this reservoir effect may be due to the presence of mycorrhizal fungi associated with *Calluna vulgaris* roots. These fungi may fix CO_2 produced by methane consuming bacteria. This methane, in its turn, may have diffused from anaerobic peat layers, and may therefore account for the anomalously older dates associated with the levels possessing fine Ericaceae roots. AMS ^{14}C measurements of fungal remains will strengthen this hypothesis, but this aside, there does, in this instance, seem to be a problem associated with conventionally dated peat cores, which future work will help to resolve.

In the light of the above work, it may be difficult to detect rapid century-scale climatic changes, especially when one includes the 2 σ (95.4%) calibrated age from the radiocarbon measurement (Dumayne *et al.*, 1995). In this instance, one runs the danger of potentially 'sucking in' or 'smearing' palaeoclimatic events, after Baillie (1991). For example, one may 'suck in' age estimates with large confidence ranges and assign them to known phenomena (for example, events in the Little Ice Age), or conversely, the radiocarbon errors may be so great as to 'smear' real synchronous events 'into a *period* of time' Baillie (1991).

There is the possibility to date younger samples using other radioisotopes, for example ^{210}Pb and ^{137}Cs (Oldfield *et al.*, 1979). Oldfield *et al.* (1995) present encouraging evidence for the accuracy of a ^{210}Pb chronology established from Ellergower Moss, Galloway, SW Scotland using ^{241}Am and Pollen derived dates to independently verify the ^{210}Pb chronology. There is a risk, however, that dates obtained using these markers may also be imprecise and inaccurate. Movement of ^{137}Cs may be extensive (Olson, 1983), whilst ^{210}Pb can be remobilised and transported laterally by through flowing water (Urban *et al.*, 1990). Oldfield *et al.* (1995) also suggest ^{210}Pb may be rapidly downwashed in hummocks which have high hydraulic conductivities, whilst hollow microenvironments may scavenge through flowing organically complexed ^{210}Pb. Because of the potential operation of these processes, dating of recent peat samples using ^{210}Pb and ^{241}Am radioisotopes was not undertaken.

Clearly there are problems with radiocarbon dating, but it remains the only way of dating with reasonable accuracy, organic deposits which are greater than 200 years old. AMS dating of *Sphagnum* leaves would reduce the problem of intrusive, contaminant material, for example the root tissues of Ericaceae and Cyperaceae, but its great cost and limited availability at this juncture, precluded its use.

3.10 Spheroidal Carbonaceous Particle (SCP) Analysis.

The analysis of SCP's offers an extra degree of dating control, since it allows peat from the very recent past to be dated. SCP's are formed from the high temperature combustion of fossil fuels, and analyses of their concentrations in lake sediments by Griffin and Goldberg (1981), Renberg and Wik (1984, 1985), and Rose *et al.* (1995), and in peat stratigraphy (Barber *et al.*, in press), has served to indicate the historical development of coal and oil burning in each of the countries studied. Rose *et al.* (1995), suggest the SCP record started in the mid-nineteenth century for sites in the United Kingdom, and reflects the combustion of coal during the Industrial Revolution. Variability in the starting date for SCP deposition has been attributed to the inception of local industries. Palaeoecological analyses of South Cumbrian mires by Gedye (pers. com.) supports this, since she found possible evidence for the SCP signal commencing in the mid. sixteenth century, due to the prevalence of charcoal fuelled smelters. This is supported by the pollen stratigraphy, as declines in *Alnus* occur at the same levels which contain the pollution signals. This regional pollen decline in the mid-sixteenth century relates to monastery dissolution and the activities of yeoman farmers (Oldfield, 1963, 1969).

Rose *et al.* identify a rapid increase in the SCP concentration in the British Sites investigated, which dates to the 1950s or the 1960s, although it can commence as early as the 1940s (Llyn Glas, Wales; Lough Muck, Ireland). There is also a characteristic peak and decline in all of the lake SCP profiles examined, which relates respectively, to the coal consumption maxima in the 1970s, and the introduction of emission control measures from the mid 1970s onwards.

SCP analysis is clearly a useful technique to date very recent peat and lake stratigraphy. Time constraints with this research project precluded its wholesale adoption, but the SCP stratigraphy of the three monoliths from Shaft Hill, The Moor House Reserve, was determined by Mark Garnett, (Institute of Terrestrial Ecology, Merlewood), in order to complement the collaborative plant macrofossil, testate amoebae, and peat humification analyses already undertaken. The experimental methodology has been adopted from Rhodes (1996), and is detailed in full in Appendix 2.

3.11 Charcoal analysis

3.11.1 Introduction.

In order to assess the frequency and possible severity of fire events affecting the mires under investigation, macroscopic charcoal (fusain) fragments (>125 μm) were identified at the same time as the peat components in the glass trough. Charcoal is formed of carbon derived from the incomplete combustion of plant tissues, and can be identified by its silky lustre and its tendency to break into angular fragments (Wein *et al.*, 1987).

Because of their relatively large size, macroscopic charcoal fragments can only be transported short distances by aeolian saltation and traction processes (400 m. for large fragments up to 0.277 mm. during an experimental fire, with a wind speed of 5 km. h.$^{-1}$; Wein *et al.*, 1987). Even if macroscopic particles are suspended under conditions of high turbulence, their high terminal velocities are equal to or greater than the vertical eddy velocities in the air (Pasquill, 1974), with the result that they fall out closer to the source. Clark (1988b), proposes that macroscopic fusain is also transported relatively short distances by hydrologic processes, since surface flow is inefficient because of its low velocity and laminar flow. These attributes reduce the potential for overland flow processes to entrain and transport charcoal fragments, because of the high cohesive forces built up among them. Because of this apparent difficulty of macroscopic fusain transport, any macroscopic charcoal quantified should represent and indicate the severity of former fires on the mire surface, or within its immediate vicinity.

Macroscopic charcoal fragments have been used by Aaby and Tauber (1975), Tallis (1975) and MacDonald *et al.*, (1991), to reconstruct fire histories. These relatively large charcoal fragments correlate well with known local fires (MacDonald *et al.* 1991). Clark (1988a), reached a similar conclusion for fragments in the relatively large size range of 50-10,000 μm, in petrographic thin sections.

Pollen slide sized material, on the other hand, was not recorded, since it is capable of long distance transport and does not correspond consistently with known areas of local fires (MacDonald *et al.* 1991). With a potential source area of subcontinental to global scale, it behaves as dust in the atmosphere, since 90% of pollen slide charcoal is 5-20 μm in length.

3.11.2 Charcoal quantification.

Charcoal contents of sediments can be estimated by chemical-combustion procedures. Winkler (1985), has developed a technique which involves digestion of non-charred organic material, carbonate and pyrite using HNO_3. Samples are subsequently dried, desiccated and weighed, combusted at 500°C. to determine the mineral content, desiccated and weighed again, and the charcoal content is expressed as a percentage of the dry weight of sediment. This technique does have limitations, however; where sediments are less than 100 years old, carbon from the combustion of fossil fuels may distort the signal from natural fires (MacDonald *et al.*, 1991). The technique may also under-record charcoal, since the elemental carbon of naturally produced charcoal is variable and may be as low as 30% (Winkler, 1985). Because of these problems and the time needed to process samples, this technique was not adopted.

MacDonald *et al.* (1991), examined macroscopic charcoal by washing 1 cm.^{2} of lake sediment through a 53 μm. sieve. This residue was subsequently placed into a gridded petri-dish, and all fragments of charcoal were identified and counted using a x40 Nikon stereozoom microscope. Lengths and widths of individual charcoal fragments were measured and multiplied to produce an estimate of their area. These fragments were subsequently grouped into five size classes; 2500-5300 μm.^{2}, >5300-10,300 μm.^{2}, >10,300-20,300 μm.^{2}, >20,300-40,300 μm.^{2} and >40,300 μm.^{2}. Robinson (1984), has also examined sieve residues using low power microscopy, but rather than employing size classes, estimated charcoal abundance by using a 7 point scale, where 0 corresponds to an absence of fusain and 5 to very abundant charcoal. Where charcoal was also present in very small amounts, a + symbol was employed. Robinson, however, is critical of the method, in that the 7 subjective point scale is not large enough to express the large range of abundances often displayed by charcoal fragments in sub-fossil material, and questions its consistency, especially when all the samples are not sampled at the same time.

Because of these caveats, an essentially modified version of the technique adopted by MacDonald *et al.* (1991) was employed; charcoal fragments were identified and counted at the same time as the plant macrofossil components of the peat matrix were determined (Section 3.3.2). Rather than using a gridded petri-dish, the graticule in the Nikon stereozoom microscope was employed to assign charcoal fragments to six size classes; <15,625 $\mu m.^2$, 15,625-62,500 $\mu m.^2$, 62,500 $\mu m.^2$-0.25 $mm.^2$, 0.25-1 $mm.^2$, 1-4 $mm.^2$ and >4 $mm.^2$.

3.12 Conclusion.

The palaeoecological techniques adopted here are by no means exhaustive. Dutch researchers, for example Casparie (1972), Van Geel (1978), and Van der Molen (1988), have undertaken more detailed, exemplary, microfossil and plant macrofossil analyses. The labour intensive nature of these palaeoecological analyses to obtain this level of detail is prohibitive, however, in terms of the time one has to devote to it. The level of detail adopted in this research project does fulfil the recommendations of Stoneman (1993), and offers the potential of improving the accuracy of mire water level, and through this palaeoclimate reconstructions.

Chapter 4. Site Descriptions.

All of the sites studied lie within northern England and the Scottish Borders (Figure 3.1). They are all, with the exception of Shaft Hill, Moor House, ombrotrophic raised mires. The Shaft Hill site is an example of *Calluna-Eriophorum* blanket bog (NVC, M19).

4.1. Bolton Fell Moss *(NY 490690).*

This mire has been extensively mined for the horticultural industry, and only a small part of the bog (it formerly covered 365 ha.), to the north-west, remains today (Figure 4.1 and Plate 4.1). Early drainage attempts were made as early as 1800 AD., but systematic hand-cutting of the moss commenced in 1956, and continued up to 1968, when hand-cutting of the peat was replaced, at first, by the use of small machine-cutters and thence by large-scale mechanised peat-cutting. This equipment was introduced in the early 1970's (Barber, 1978).

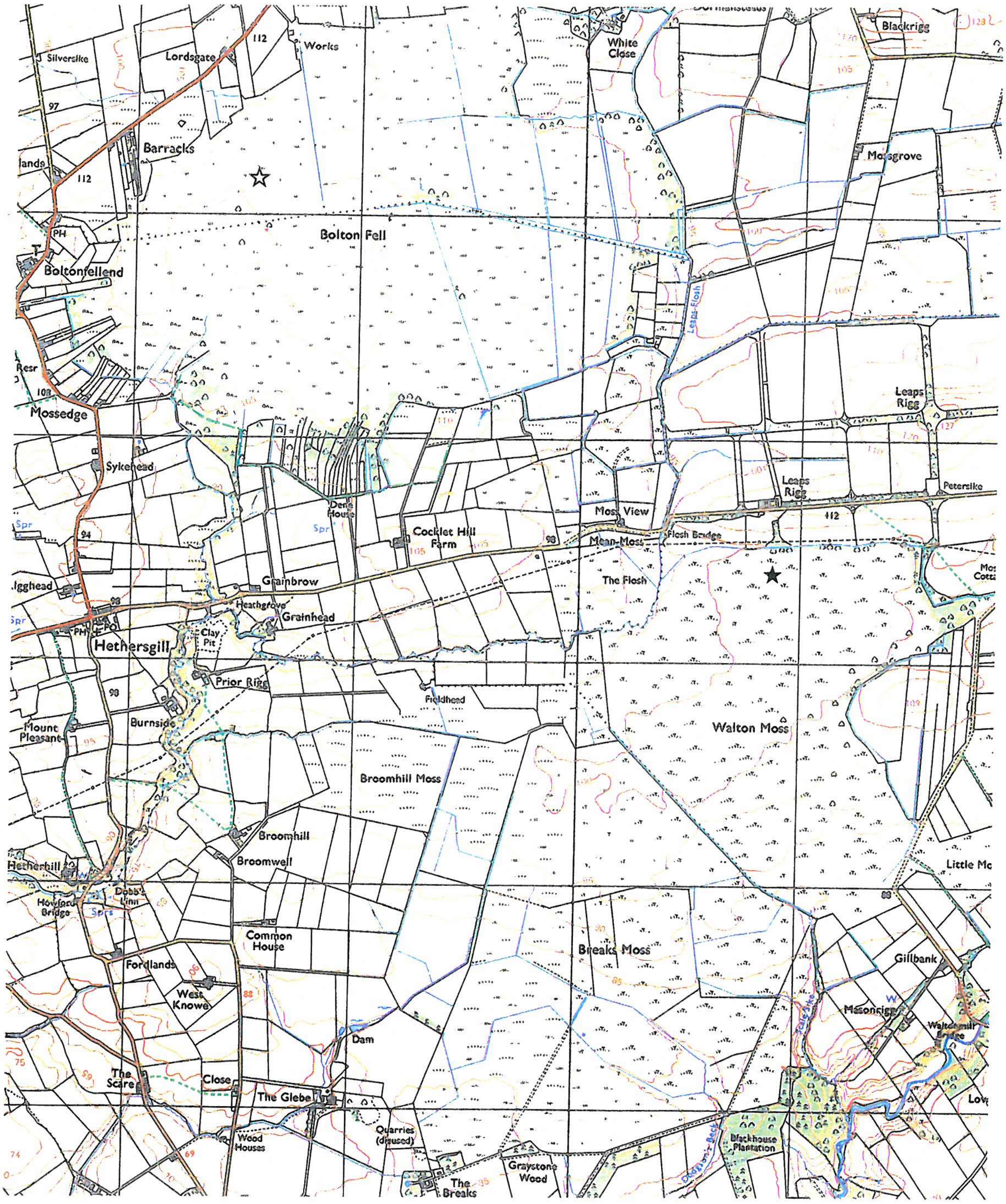
The vegetation, described by Barber (1981) was formerly (in the late 1960's), dominated by *Sphagnum magellanicum* with *Sphagnum capillifolium* var. *rubellum*, *Eriophorum angustifolium*, *Eriophorum vaginatum* and *Calluna vulgaris*. The latter two species were common in hummocks, whilst *Erica tetralix, Narthecium ossifragum* and *Rhynchospora alba* were frequently encountered in low lawn microtopes. Examples of *Drosera rotundifolia* and *Vaccinium oxycoccus* were also found scattered in the *Sphagnetum* community.

Barber (1981) studied the site as part of his doctoral thesis, and found peat depths reach 10.6 metres in places. The moss is underlain by glacial drift, which consists of till and glacial lake alluvium, deposited during the latter stages of the Devensian (Day, 1970).

4.1.1 Climatic data.

The nearest meteorological station which holds both precipitation and potential evaporation data for Bolton Fell Moss, and its paired site, Walton Moss, is at Carlisle, which is c. 12 km. away. The 1951-1980 average annual rainfall for this station was 825 mm., and the daily mean temperature 9.4°C. In order to get a better idea of the amount of water available to the flora and fauna inhabiting these mires and the other ombrotrophic mires studied in this research project, effective precipitation data covering a 30 year monthly period was sought after. This represents the balance of precipitation remaining after evaporation. This data is expensive, as it is not published in the Monthly Weather Report Series of the Meteorological Office, and requires computing time to calculate potential-evaporation using the Penman-Monteith model (Penman, 1963; Monteith, 1981) and associated equations. To overcome this, a 1961-90 Baseline Climatology dataset for the UK. (Barrow *et al.,* 1993), was very kindly made available by Dr. David Viner at the Climate Impacts LINK Project, The Climatic Research Unit, University of East Anglia. This data set consists of 10x10 km. gridded mean monthly 1961-90 climate variables for precipitation, rain days, maximum and minimum temperature, sunshine hours, wind

Figure 4.1 Map of Bolton Fell Moss and Walton Moss.



☆Borehole location Bolton Fell Moss. ★Borehole location Walton Moss.

Source: Ordnance Survey (1:25, 000).

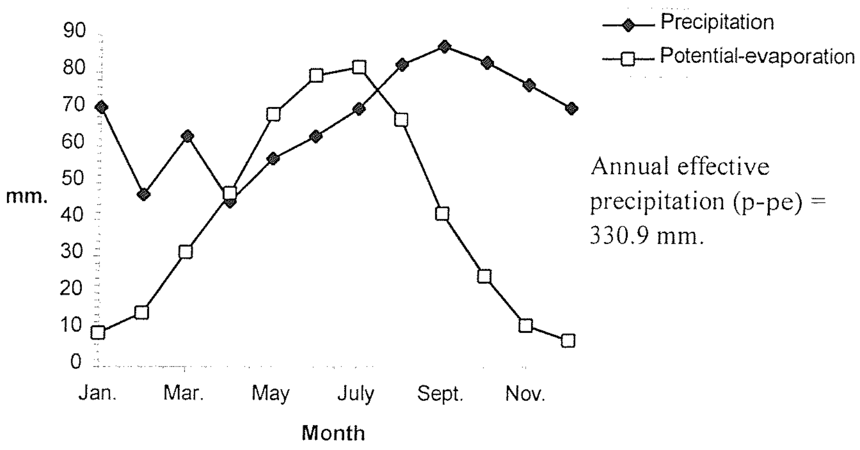
Plate 4.1 Aerial photograph of Bolton Fell Moss and Walton Moss.

⇑ N. 0.________________________________2 km.

☆ *Bolton Fell Moss - Core L* - borehole location. ★*Walton Moss - Core 11* - borehole location.

speed, vapour pressure and frost days. Using this data, potential-evaporation was computed (reference crop = grass), using software written by Dr. Nigel Arnell, Department of Geography, Southampton University. The effective annual precipitation (330.9 mm.) was simply derived by subtracting the potential evaporation values from the precipitation data, and is displayed in Figure 4.2. From April to July, both Bolton Fell and Walton Moss experience water deficits based on the potential-evaporation data. This may be an artefact of the potential evaporation (PE) data, but calculating actual evaporation is even more problematic, since it is data intensive and requires accurate measurements of radiation, soil heat flux, and vertical profiles of temperature and humidity (Ward and Robinson, 1990). This was clearly not feasible, but the calculation of PE was undertaken using the same equations for each of the paired sites, and will therefore allow, at least, a comparison of this important climatic variable between the research sites.

Figure 4.2 Water balance for Bolton Fell /Walton Moss.



Annual effective precipitation (p-pe) = 330.9 mm.

4.2. Walton Moss *(NY 504667).*

This largely intact raised mire is one of the finest examples of its kind in England, and possibly resembles in its form and vegetation, the former virgin state of Bolton Fell Moss, before peat-cutting operations. Because of its pristine nature, it was declared a National Nature Reserve in late 1996. The mire covers 283.9 ha. and lies c. 2 km. to the south-east of Bolton Fell Moss (Figure 4.1, Plate 4.1). Some peripheral, piecemeal peat-cutting has been undertaken at the southern and south-eastern fringes, and this is reflected in the vegetation, as communities of *Molinia caerulea, Juncus effusus* and *Juncus acutiflorus* exist here (unpublished N.C.C. report).

It has abundant *Sphagnum magellanicum*, and *Sphagnum cuspidatum* bryophyte cover, with additionally, frequent *Sphagnum recurvum, Sphagnum papillosum*, and *Sphagnum capillifolium* var. *rubellum*. The vascular flora consists of *Rhynchospora alba*, *Drosera rotundifolia*, *Andromeda polifolia*, *Eriophorum vaginatum* and *Erica tetralix*. The representation of *Calluna vulgaris* is low in comparison to other raised mires.

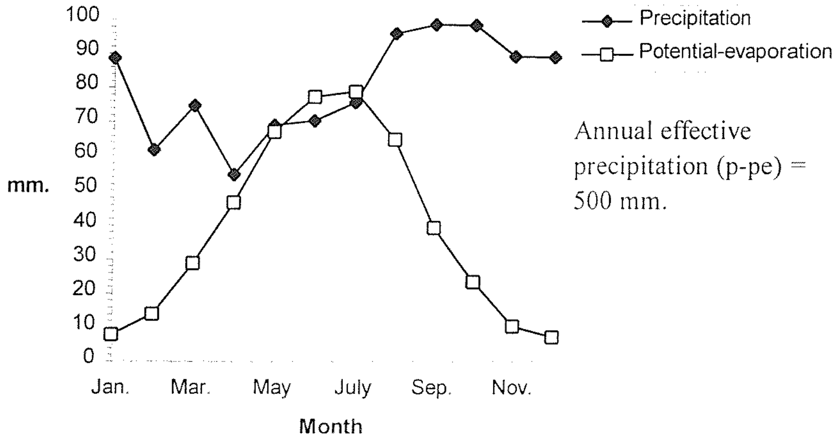
4.3. Raeburn Flow *(NY 295717)*.

Raeburn Flow is a 65 ha. remnant of a more extensive raised/blanket bog which has been reclaimed for agriculture. It lies on the Scottish side of the Solway Firth, c. 6 km. from Gretna (Figure 4.3). The main part of the domed bog surface is dominated by *Calluna vulgaris*, *Erica tetralix* and *Eriophorum angustifolium*, whilst *Eriophorum vaginatum*, *Empetrum nigrum*, *Hypnum cupressiforme*, *Andromeda polifolia*, *Vaccinium oxycoccus* and *Narthecium ossifragum* are locally common. Scrub (*Betula pubescens* and *Salix* spp.) and open areas with *Molinia caerulea* form a peripheral zone, whilst many examples of Birch and Pine are scattered over the mire surface. At the eastern and southern corner of the mire, peat has been cut by hand. The cut area at the southern edge has two banks 10 to 15 m. long and 1 to 1.5 m. high. Along the southern edge there is a 40 m. wide band of *Molinia caerulea* and *Deschampsia flexuosa*. The western edge by the road has a fringe of *Molinia caerulea* with *Deschampsia caespitosa, Urtica dioica, Rumex acetosa, Potentilla erecta, Galium saxatile, Viola palustris, Juncus effusus* and some Birch scrub. The mire seems to be drying out at the surface, as there is a large area of Pine regeneration (*Pinus sylvestris*) with a little Birch, over *Calluna vulgaris* in the centre of the bog (unpublished N.C.C. report, 1985).

4.3.1 Climatic data.

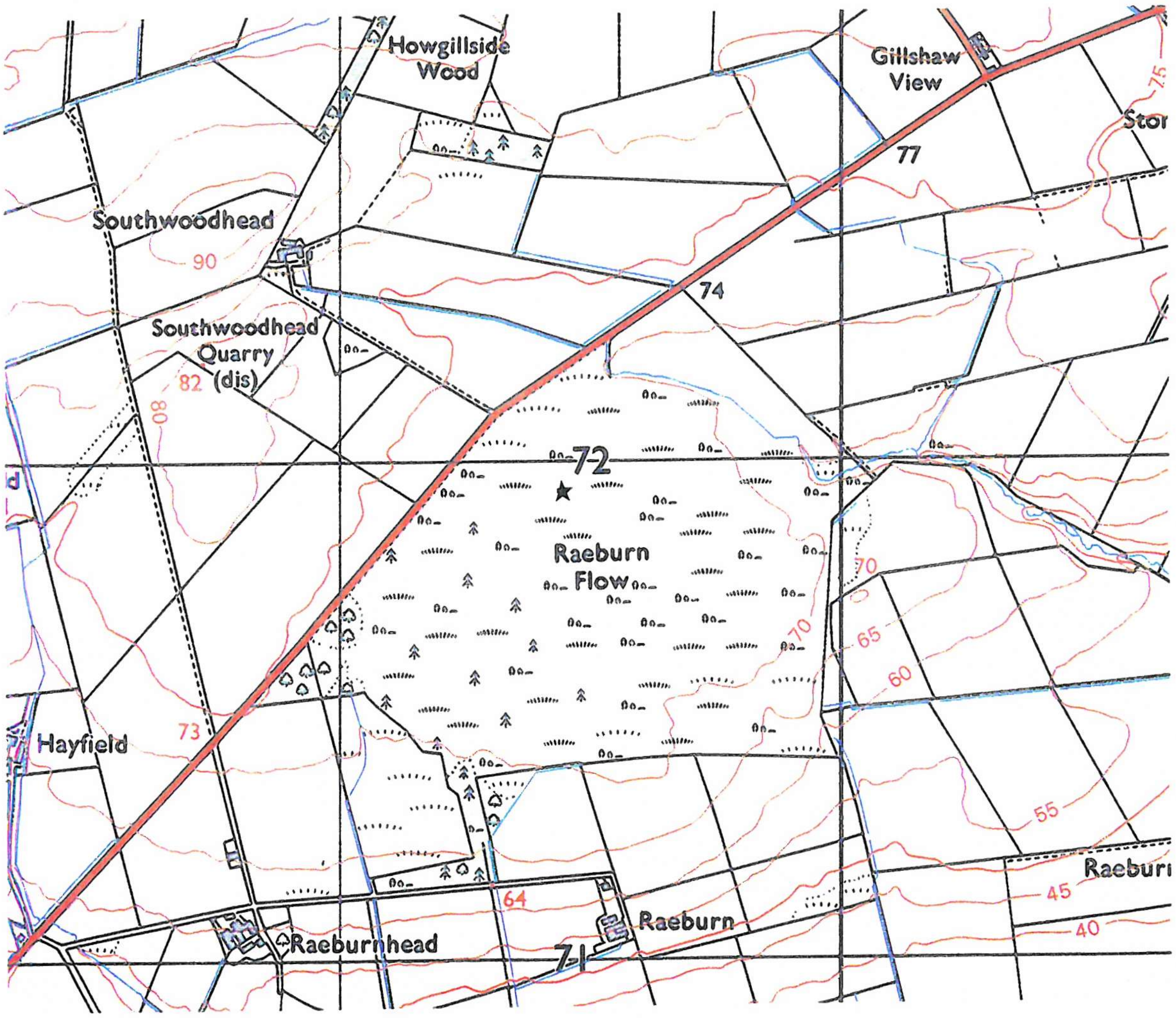
The 1961-90 mean precipitation for this site and Bell's Flow is 965 mm. (Barrow *et al.*, 1993), and represents a 18.6% increase on the mean precipitation values of Bolton Fell Moss and Walton Moss. The 30 year daily mean temperature for this site, is additionally, slightly cooler at 8.9 °C., which is reflected in the lower potential evaporation values. There is a reduced water deficit in the summer months (June and July only, Figure 4.4), and effective precipitation for Bell's Flow and Raeburn Flow is 500 mm., a 51% increase compared to Bolton Fell and Walton Moss.

Figure 4.4 Water balance for Raeburn/Bell's Flow.



Annual effective precipitation (p-pe) = 500 mm.

Figure 4.3 Map of Raeburn Flow.



★Borehole location. **Source: Ordnance Survey (1:25, 000).**

4.4. Bell's Flow *(NY 320760).*

Bell's Flow is a 71.8 ha. raised bog and lies on sloping ground at an altitude of 105-110 m. asl., and is bordered to the east and west by small streams (Figure 4.5 and Plate 4.2). It lies 5 km. to the north-east of Raeburn Flow, and is a high quality site with a well developed *Sphagnum* cover, few drains and little encroachment by trees. The mire has clearly diminished in extent through human agency, as one can discern areas on the aerial photograph where drains have been put into place, particularly to the north-west and north-east of the Flow.

Dominant species over the mire are *Eriophorum vaginatum*, *Erica tetralix* and *Sphagnum capillifolium*. In wetter areas of the Flow *Sphagnum magellanicum*, *Sphagnum papillosum,* and *Sphagnum tenellum,* occur, whilst *Vaccinium oxycoccus*, *Andromeda polifolia* , *Drosera rotundifolia* and *Narthecium ossifragum* are locally common. Occasional hollows occur with *Sphagnum cuspidatum* and an increased cover of *Eriophorum angustifolium*. There is generally little tree colonisation of the site, but occasional young birch are scattered around the site. There are three old open drains on the Flow; one runs across the southern end, another runs along the eastern side, whilst a third crosses the western part of the site close to derelict grouse butts.

On the south and eastern sides of the Flow, *Calluna vulgaris* is locally dominant. The margins of the mire below the peat rand are dominated by *Molinia caerulea* and dense to scattered birch, *Betula pubescens.*

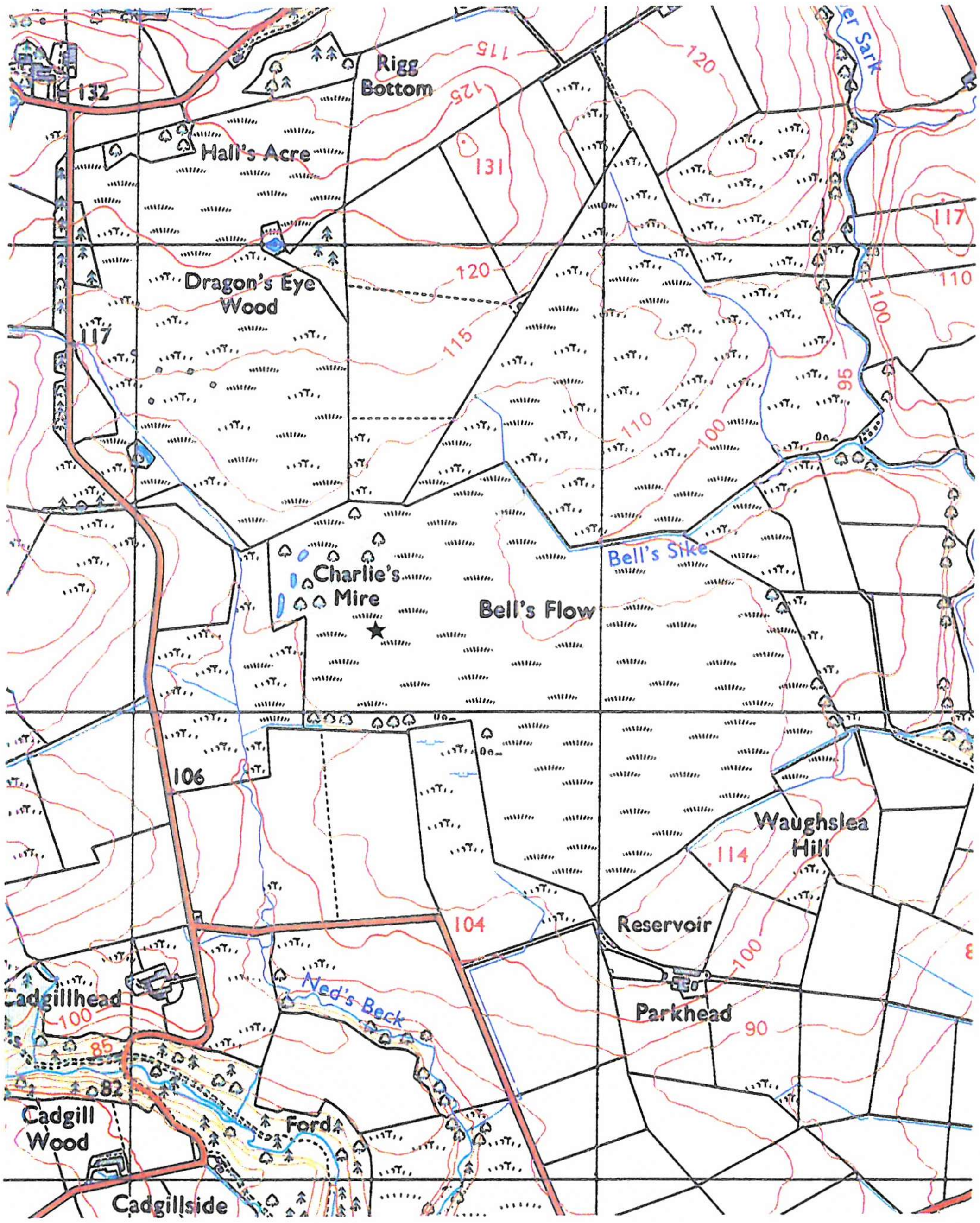
4.5. Coom Rigg Moss *(NY 692796).*

Coom Rigg Moss is located within Kielder Forest, Northumberland, and forms part of the 'Border Mires', a collection of 48 mire sites, which collectively have a total of 955 ha. of open bog vegetation. The area has been extensively afforested, and 623 ha. of mire around the remaining extant mire sites has been afforested with Sitka Spruce, *Picea sitchensis* and Lodgepole Pine, *Pinus contorta* (Smith *et al.*, 1995).

This 40 ha. site lies at c. 300 m. above sea level on the watershed between the River Irthing to the south and the Chirdon Burn to the north. It forms a saddle between higher ground to the north and south, and lies 3 km. to the north-west of its paired site, Felecia Moss (Section 4.6). Numerous drainage outflow points are situated around the edges of the site (Rumsby and Newson, 1991); the principal ones are located at the north-west (visible on Plate 4.3), east, south-east and south-western corners. The south-western edge, which lies in a valley, is lower than the remaining part of the bog. There are no input slopes onto the mire, other than the area around the afforested northern edge.

Chapman (1964), has determined its (complex) stratigraphy, and has demonstrated the existence of four areas of deep peat (up to 6.6 m.), linked by shallower peat units. The shallower peat is composed of *Sphagnum-Eriophorum* remains typical of blanket mire ecosystems, whilst the deeper parts of the mire display a 'typical raised bog sequence' (Chapman, 1964), of fen peat, brushwood peat and *Sphagnum-Eriophorum* peat. Three metres of peat were recovered from a 6.6 m. deep basin c. 150 m. from the northern edge of the site.

Figure 4.5 Map of Bell's Flow.



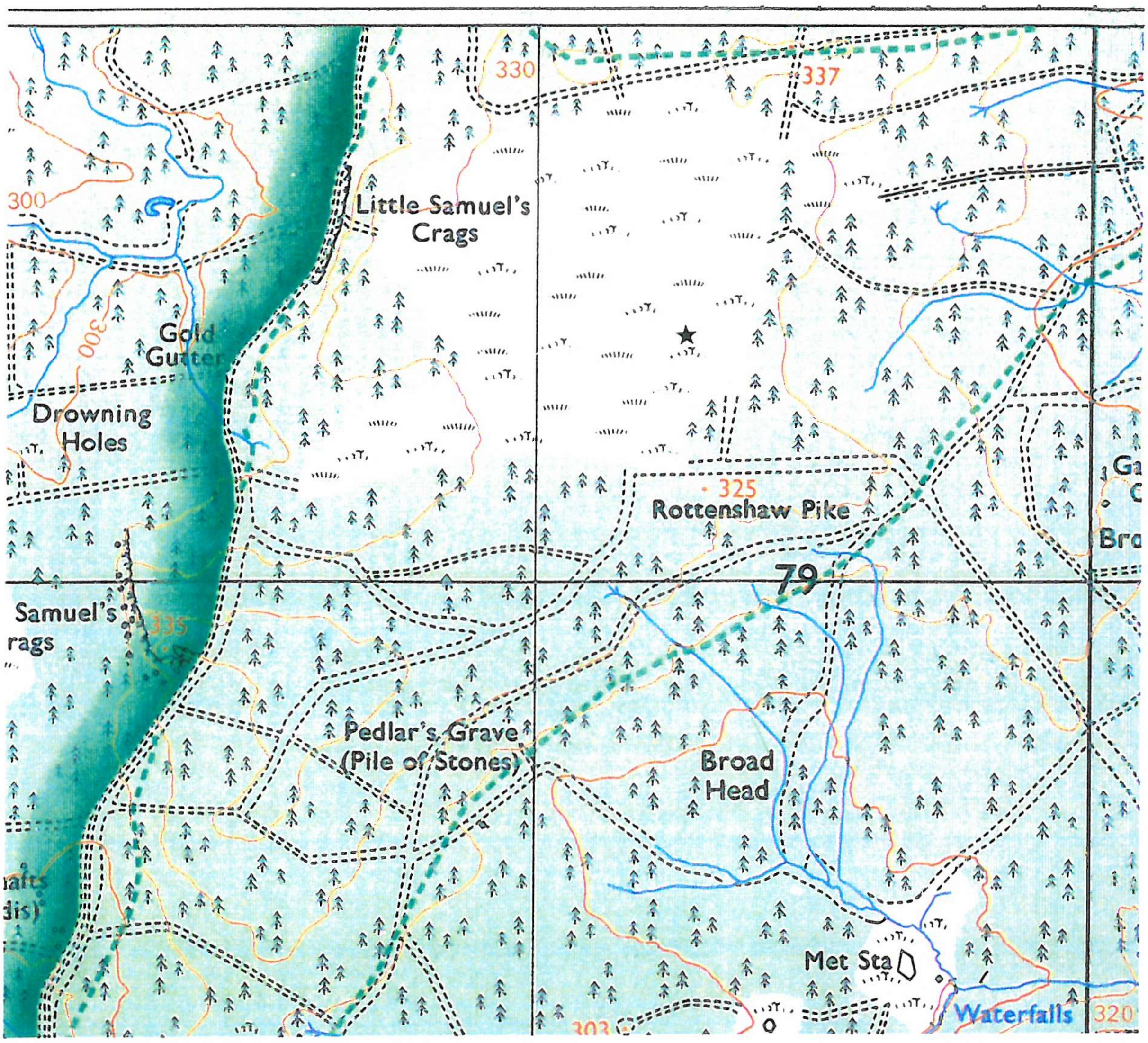
★ Borehole location. **Source: Ordnance Survey (1:25, 000).**

Plate 4.2 Aerial photograph of Bell's Flow.

⇑ N. 0.______________________500m.

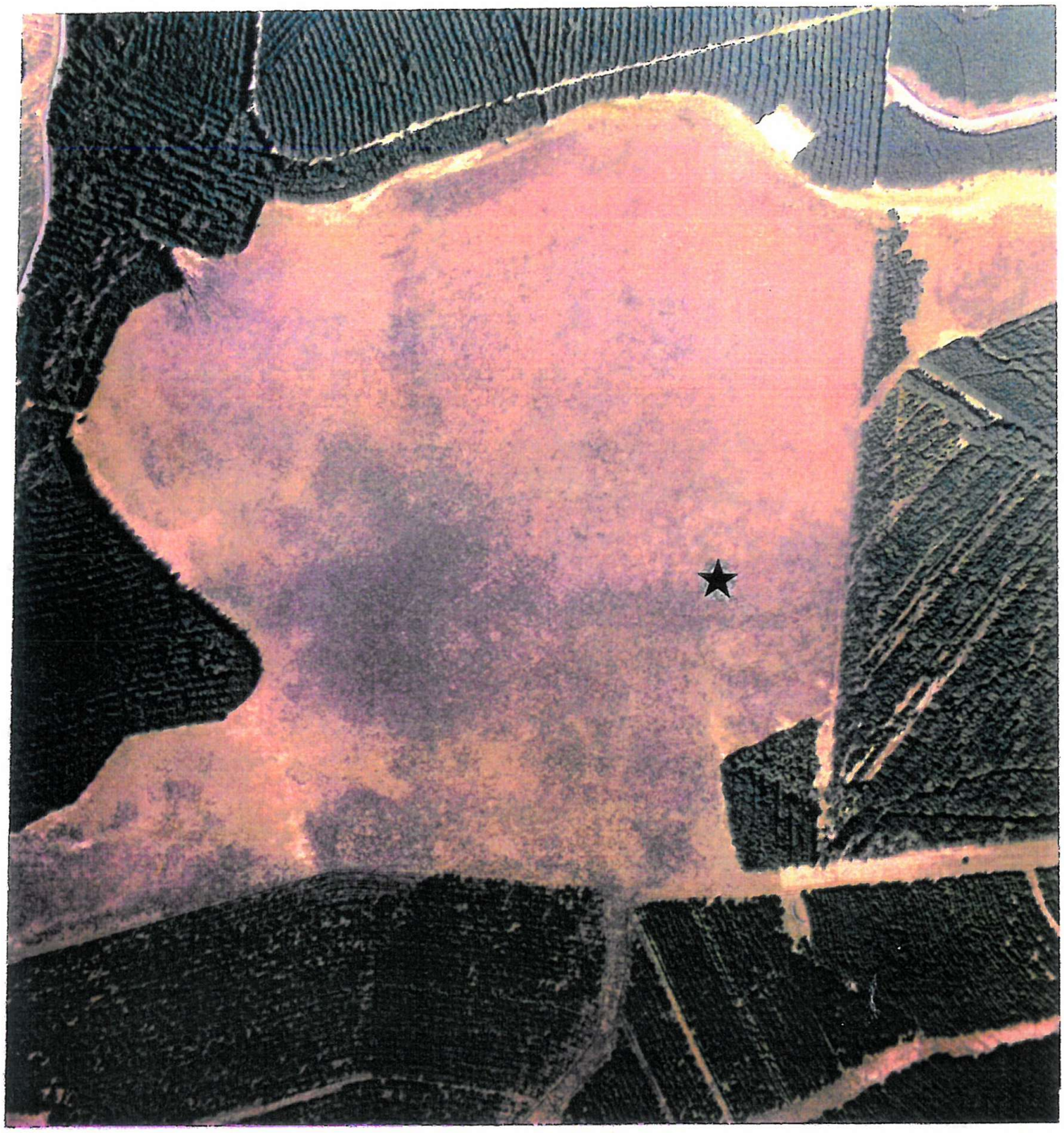
★ Borehole location.

Figure 4.6 Map of Coom Rigg Moss.



★Borehole location. **Source: Ordnance Survey (1:25, 000).**

Plate 4.3 Aerial photograph of Coom Rigg Moss.



⇑ N. 0.______________________________________500 m.

★ Borehole location.

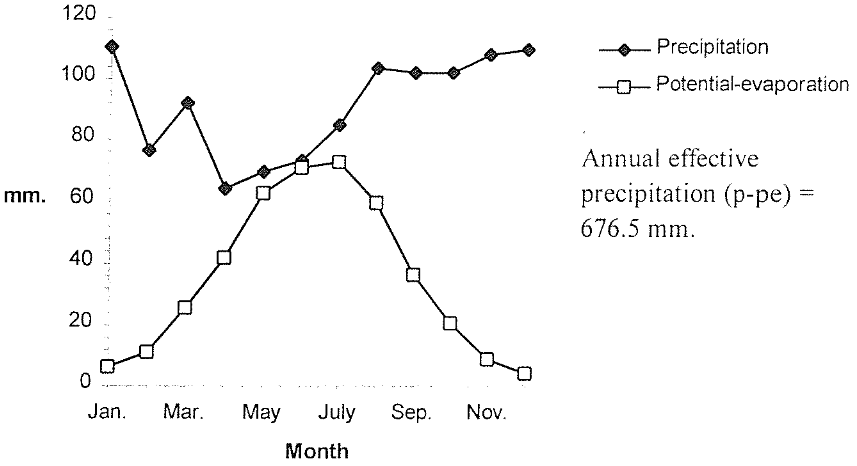
Calluna vulgaris, Eriophorum angustifolium, Molinia caerulea and *Deschampsia flexuosa* are very abundant on the mire surface. *Sphagnum magellanicum, Sphagnum papillosum*, and *Sphagnum capillifolium* form carpets, but their abundances, in addition to those of *Drosera rotundifolia* and *Narthecium ossifragum*, have reduced drastically (up to 40% or more) since 1958, to be replaced by sedges and grasses (Chapman and Rose, 1991).

4.5.1 Climatic data.

The effective precipitation of this site (676.5 mm., Figure 4.7) exceeds the figure for Bell's Flow and Raeburn Flow by 35%, and for the first time, precipitation exceeds potential evaporation, even during the summer months.

This is a reflection of the greater altitude of Coom Rigg Moss (320 m.), compared to Bell's Flow (70 m.)/Raeburn Flow (100 m.) and Bolton Fell/Walton Moss (110 m. and 90 m. O.D., respectively), since forced uplift of moist air bodies allows cooling and condensation of water droplets. The mean annual precipitation for this site is 1163 mm., and represents a 20.5% increase over the rainfall for Bell's Flow/Raeburn Flow, whilst the mean annual temperature is a degree Celsius lower (11.2 °C.) than the Scottish sites, again because of the altitude and its influence on temperature lapse rates. Hills at higher elevations also act as 'high level heat sources on sunny days' (Chandler and Gregory, 1976), allowing convective clouds to form over them preferentially, which again enhances precipitation inputs.

Figure 4.7 Water balance for Coom Rigg /Felecia Moss.



4.6. Felecia Moss *(NY 721777).*

Felecia Moss is a SSSI of the highest conservation value within the Border Mires (after Holmes, unpublished data, 1992), and has been described by Rumsby and Newson (1991) as a 'perfect watershed mire.' Mineral soils largely derived from boulder clay form part of the high ground surrounding the site, but this provides a minimal area of input.

It is a small site (33 ha.), and lies in a saddle formed by Hawthorne Rigg (a drumlin in the southern corner), Felecia Crags and Hobbs Hill. Water courses flow from three edges, particularly from the western margin, as Thross Burn originates here. Hagg complexes, visible on the aerial photograph (Plate 4.4), occur in the north-west, south-west and eastern corners of the mire; four main hagg channels in the eastern part of the Moss drain water from west to east and are up to six feet deep in certain places (unpublished N.C.C. report).

There is a well developed hummock-hollow microtopography within the Moss, with *Sphagnum cuspidatum* and *Sphagnum papillosum* common in the pool and low lawn microtopes, whilst on the drier hummocks *Calluna vulgaris* and *Empetrum nigrum, Andromeda polifolia, Narthecium ossifragum* and *Drosera rotundifolia* occur. Two pools near the centre of the Moss support examples of *Sphagnum subsecundum*, whilst within temporary pools, *Drosera anglica* may be found. Drier vegetation communities exist towards the edges of the mire, with frequent *Deschampsia flexuosa, Molinia caerulea* and *Eriophorum vaginatum.*

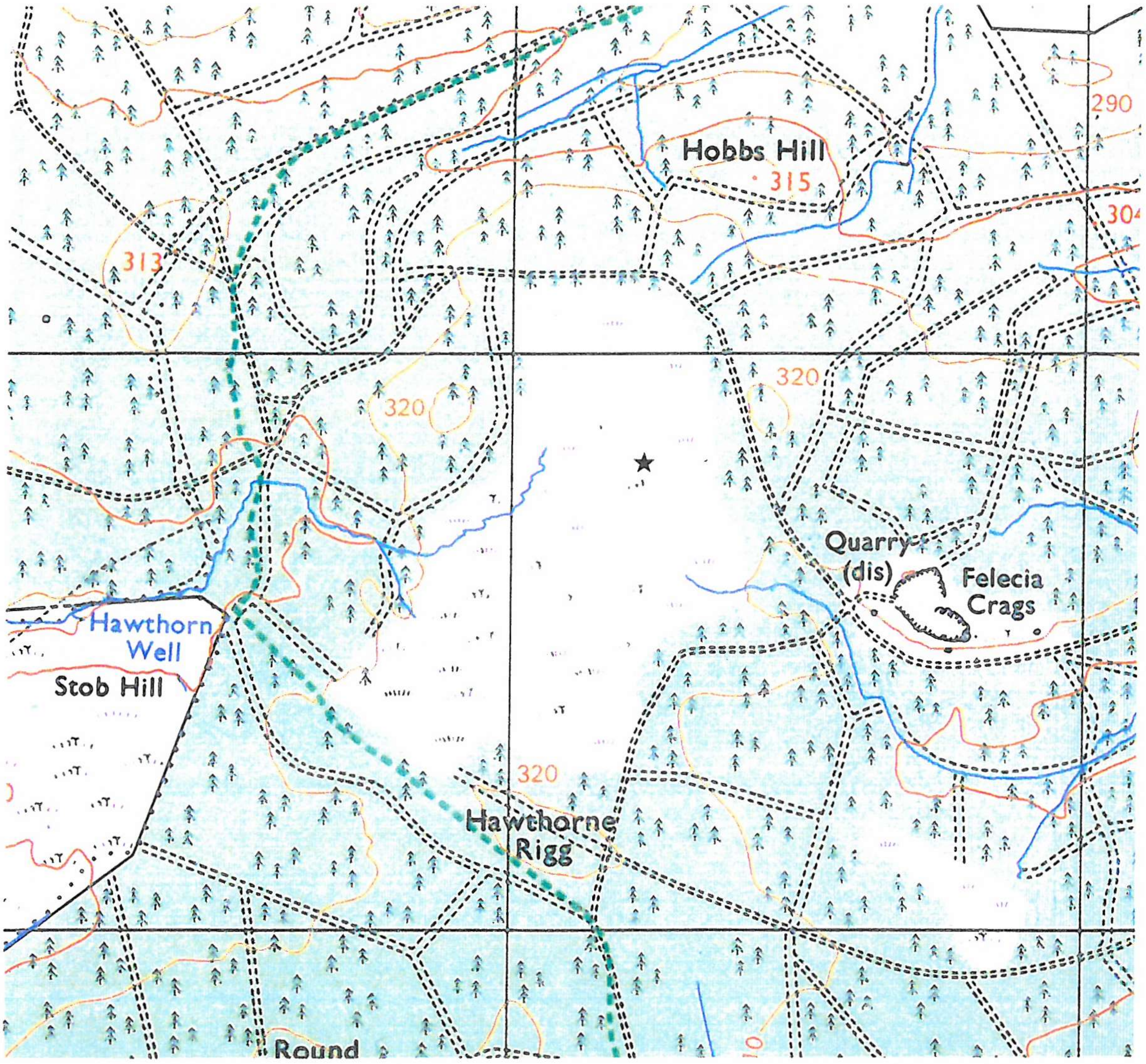
A road constructed by Forest Enterprise has cut off a small portion of the mire below Hawthorne Rigg.

4.7. Shaft Hill, Moor House National Nature Reserve *(NY 747333).*

Moor House NNR. lies in the Northern Pennines, covers c. 3500 ha. and ranges in height from 290-848 m. The reserve extends from the upper edge of enclosed land within the Eden Valley, over the Dun Fells, to the upper end of Cow Green Reservoir on the River Tees. Ombrogenous bog of 0.5-5 m. depth covers over one half of the reserve (Rawes and Welch, 1969), and much of the uneroded peat below 630 m. supports Calluneto-Eriophoretum on sloping ground, whilst flatter areas with deeper peat deposits support Tricophoro-Eriophoretum (Eddy *et al.*, 1968).

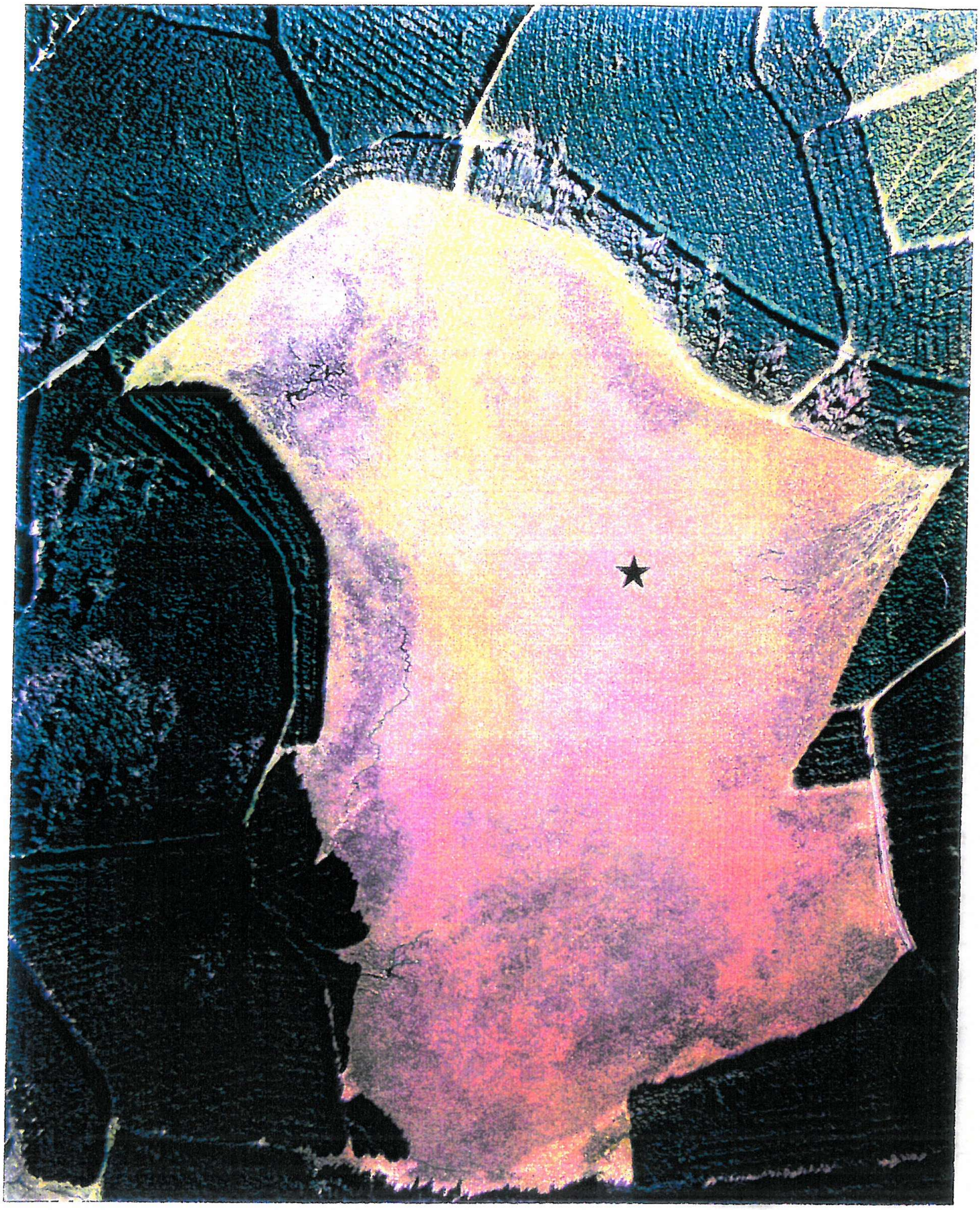
The reserve as a whole is grazed by sheep in the summer only (free range grazing regime), at a stocking rate of one sheep per 0.44 ha. (Rawes and Hobbs, 1979). High intensities of sheep grazing can reduce *Calluna vulgaris* to extinction, whilst favouring *Eriophorum vaginatum*, which may complicate any palaeoclimate reconstruction based on plant macrofossils, since mountain sheep may have been introduced to the area by the Norse as long ago as 900 AD. (Welch and Rawes, 1964). Welch and Rawes (1966), however, found that in the long term, grazing can improve the species diversity of blanket bog, which potentially increases the chance of detecting a climate signal using sub-fossil plant material. Notwithstanding this, the low stocking densities practised on the Northern Pennine Fell's, should reduce the importance of this perturbation to the ecosystems, and allow changes of the flora to be considered as a response largely to climate forcing. Equally,

Figure 4.8 Map of Felecia Moss.



★ Borehole location. **Source: Ordnance Survey (1:25, 000).**

Plate 4.4 Aerial photograph of Felecia Moss.



⇖ N. 0.____500m.

★ Borehole location.

since the sheep are removed from the reserve in the winter, which is the time when they would eat heather, the grazing intensity from where the monoliths were taken will be almost zero (pers com., John Adamson, Institute of Terrestrial Ecology, Merlewood).

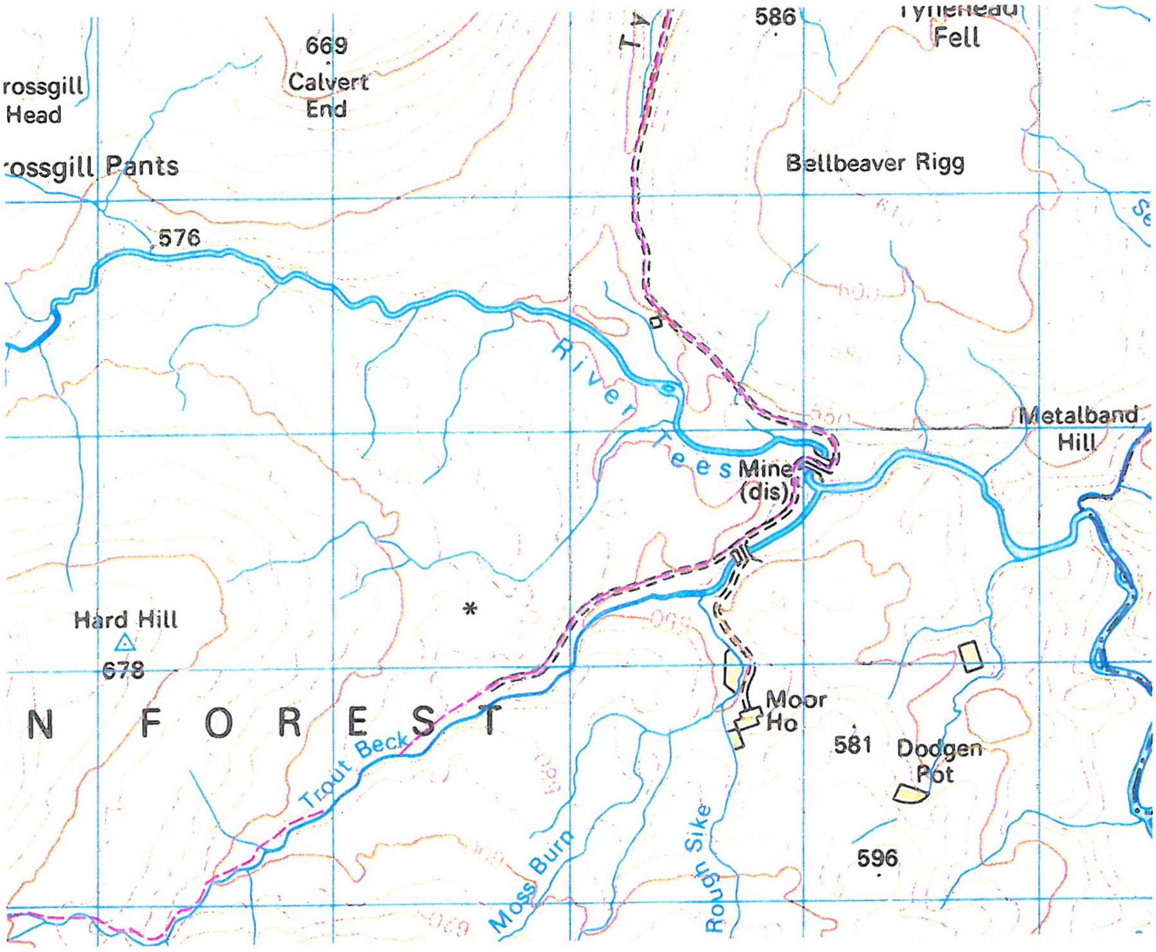
Shaft Hill is located on the eastern side of the reserve at an altitude of c. 580 m. (Figure 4.9, Plate 4.5), in an area of gentle slopes which are underlain by glacial tills, and has a blanket bog vegetation cover. The site is purely ombrotrophic, since it forms a plateau which is raised above the surrounding input slopes. There is abundant *Calluna vulgaris* and *Eriophorum vaginatum*, with constant *Empetrum nigrum* and *Rubus chamaemorus*, whilst in the wetter areas *Trichophorum cespitosum* and *Eriophorum angustifolium* predominate. There are pool microtopes within the site which contain abundant *Sphagnum cuspidatum*, whilst fringing lawns are largely comprised of *Sphagnum papillosum*, with some *Erica tetralix* and *Drosera rotundifolia*. Where lawns grade into hummocks, *Sphagnum capillifolium* var. *rubellum* is encountered, along with scattered *Racomitrium lanuginosum* (pers. observation).

There is little evidence of disturbance to the site, although there are some erosion gullies towards the periphery. This section of the reserve has not been burnt since 1952, when the site became a NNR. (John Adamson, pers. com.) Prior to this, parts of the reserve, from the nineteenth century onwards, were burnt in order to encourage an abundant growth of young heather for grouse. Large scale shooting of these birds commenced in 1842, when a shooting lodge called Moor House was established (Welch, 1974).

4.7.1 Climatic data.

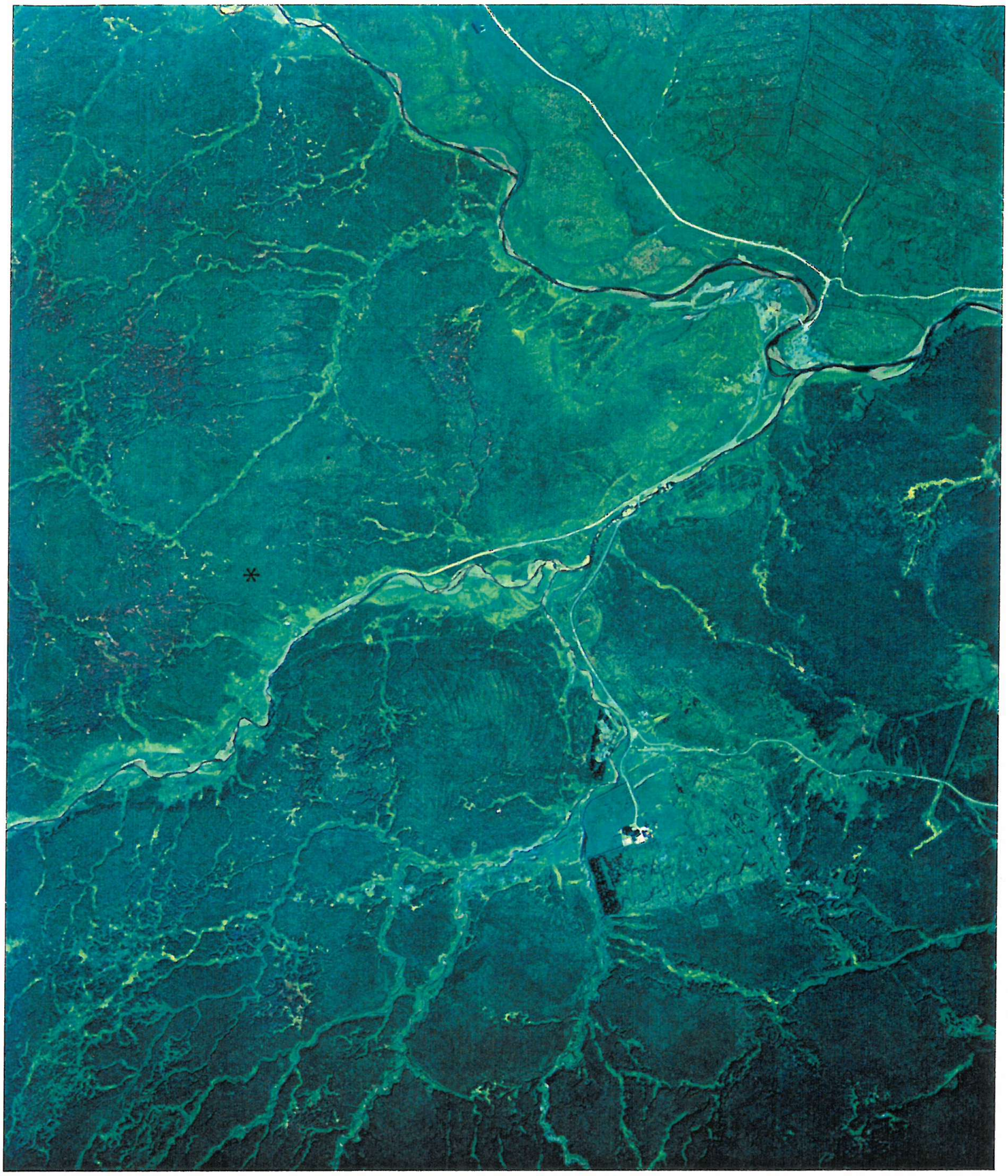
Manley (1942), described the climatic conditions as resembling those of southern Iceland, whilst Eddy *et al.*, (1968), categorise it as sub-alpine and Atlantic with July mean temperature 10.9 °C, January mean temperature -0.6°C, with 24 km/h. average wind speed. Heal (1971), describes the climate as sub-arctic with warm winters and cool summers, and reports a similar July mean temperature of 11.0 °C. Precipitation and temperature data for this key Environmental Change Network site was very kindly supplied by John Adamson, at the Institute of Terrestrial Ecology, Merlewood, and is displayed in Figures 4.10 and 4.11. The extreme nature of this upland site is evident from these graphs, since annual precipitation may exceed 2400 mm., whilst the mean temperature (1932-1995) is only 4.89 °C. The 16 year mean precipitation for the site is 1945 mm. (Forrest, 1971), ground frost normally occurs in every month, with evaporation rarely exceeding precipitation (Heal, 1971). This is corroborated by the estimated potential evaporation data using the 1961-90 Baseline Climatology dataset (Barrow *et al.*, 1993), since precipitation exceeds potential evaporation in every month (Figure 4.12). The high effective precipitation the site receives (1372.5 mm.), is a reflection of the sub-alpine climate of the Moor House Reserve.

Figure 4.9 Map of Shaft Hill, Moor House.



* Monoliths taken from this area. **Source: Ordnance Survey (1:50, 000).**

Plate 4.5 Aerial photograph of Shaft Hill, Moor House.



⇑ N. 0______________________________________1000m.

* Monoliths taken from this area.

Figure 4.10 Moor House Reserve - Precipitation 1953-1978.

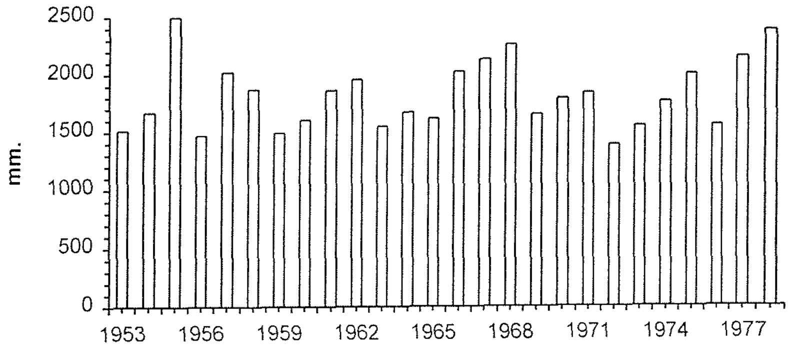


Figure 4.11 Moor House - Mean annual temperature.

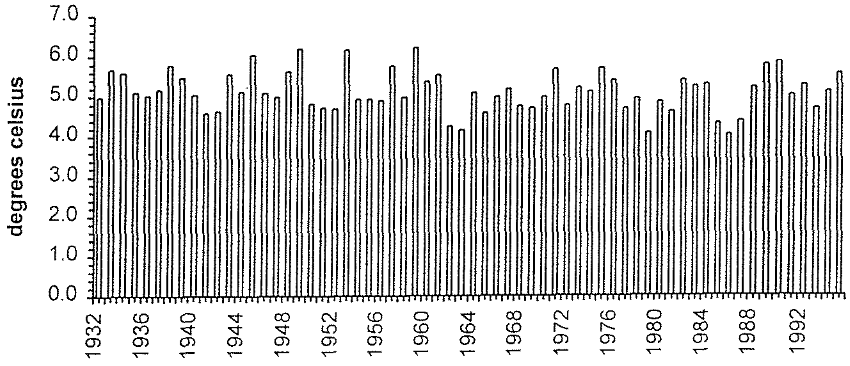
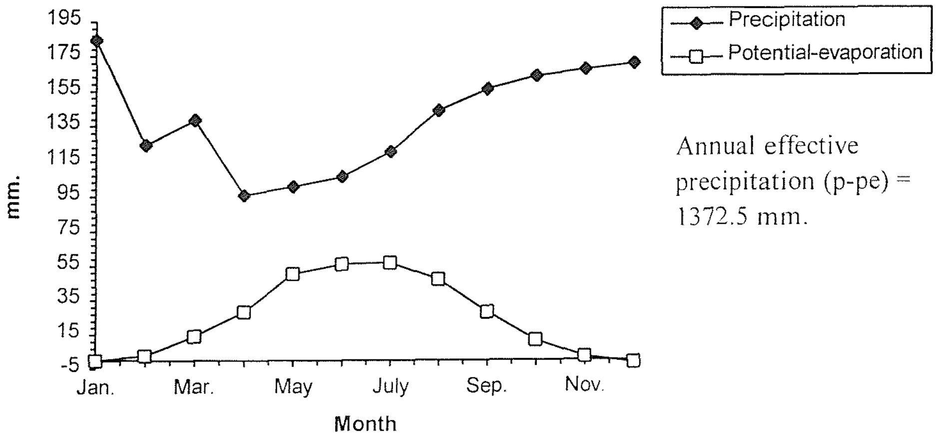


Figure 4.12 Water balance for Shaft Hill, Moor House Reserve.



Annual effective precipitation (p-pe) = 1372.5 mm.

Chapter 5: Results and Analysis.

5.1 Introduction.

The results of the radiocarbon dating, pollen, and SCP analyses are presented in Section 5.3, whilst the colorimetric humification, plant macrofossil, and testate amoebae analysis data are presented in Section 5.4. The information each component can contribute to reconstructing mire surface wetness and through this, effective precipitation, is considered first, however, in section 5.2.

Techniques to reconstruct mire surface wetness from the relatively complex plant macrofossil and testate amoebae data sets are discussed in Section 5.4, along with the results of this analysis. The specific techniques employed to generate mire surface wetness curves from both the vegetative macrofossil and thecamoebae assemblages are the Dupont Wetness Index and Detrended Correspondence Analysis (DCA).

Mire surface wetness curves generated from the humification, plant macrofossil and testate amoebae assemblages are cross-correlated in Section 5.5, using radiocarbon and pollen/SCP chronologies. Time Series Analysis (Section 5.6) of selected sites has additionally been undertaken, to ascertain the possible existence of common periodicities within the data.

5.2 The components of the diagrams.

5.2.1 Peat humification.

The degree of peat humification is a measure of the decomposition state of the sub-fossil peat matrix. Higher absorbance values indicate the presence of more humified levels, since these contain more dissolved decomposition macromolecules (see Section 3.5). The decomposition state is dependent on the time sub-fossil peat has taken to pass from the biologically active acrotelm into the more inert catotelm. This is controlled by water-table depth; where it is shallow, under regimes of high effective precipitation, there is less scope for decomposition before peat passes into the catotelm (decomposition here, by comparison, is extremely slow, (Clymo, 1983).

The humification signal may be out of phase with those from other mire surface wetness proxies, since it represents the position of the average mire water-table position, during the time peat takes to pass from the acrotelm to the catotelm (Stoneman, 1993). This may be for extended periods, as *Sphagnum* peat may undergo aerobic decomposition for more than 100 years (based on ^{210}Pb and ^{14}C chronology), and lose 80% of its original carbon in hummocks with a 30-40 cm. acrotelm, (Malmer and Holm, 1984).

A degree of caution is warranted when interpreting the humification curves as part of the signal may be macrofossil driven, since Overbeck (1975), found that recent vascular plants tend to yield higher values of alkaline extracts than the various *Sphagnum* species.

5.2.2 Unidentified organic matter (U.O.M.).

Vegetative material lacking any visible structure was assigned to this component. The poor preservation of this material is assumed to result from extended decomposition of plant organic matter, due to lowered mire water-table levels. Conversely, it may indicate the presence of former bog pools, since oxygenation by pool algae speeds decomposition of pool vegetation, and converts dead algae into algal muds (Johnson *et al.*, 1990).

5.2.3 Ericaceae.

With the exception of the Shaft Hill blanket bog site, macrofossil remains (largely rootlets and twigs, with some leaves), of *Empetrum nigrum*, *Vaccinium myrtillus, Vaccinium oxycoccus, Erica tetralix* and *Calluna vulgaris* have been grouped into ericaceous remains (Ericaceae).

Although *Erica tetralix* can withstand some waterlogging under experimental conditions, (Bannister, 1964), the other dwarf shrub species cannot tolerate extended periods of waterlogging. The roots of *Calluna vulgaris*, for example, are shallow and extend to c. 15 cm. below the surface (Rutter, 1955).

Hammond *et al.* (1990), investigated the position of *Calluna vulgaris* in relation to local mire water tables, and found that it occurred under minimum and maximum water table depths of 10 cm. and 52 cm. respectively, with 90% of occurrences restricted to 30 cm. depth. Individuals of *Erica tetralix* displayed a greater range (water-tables from 5 to 52 cm. below the surface), with 90% of its occurrences recorded at sites with a 35 cm. water-table.

Dwarf shrubs such as *Calluna vulgaris* and *Empetrum nigrum* are restricted to drier microhabitats with a relatively deep water-table, because the roots and their endomycorrhizae need an aerated layer about 10-20 cm. deep, (Lindholm and Markkula, 1984). This and the above literature confirms that Ericaceae are a good indicator of dry and/or hummock top microtopes.

5.2.4 Monocotyledons undifferentiated (undiff.).

Where suitable epidermal tissue for specific monocotyledon identification was absent, macroremains of these plants were simply classified as Monocotyledons undifferentiated. *Eriophorum angustifolium* and (particularly) *Eriophorum vaginatum*, are the most abundant sedges encountered on raised peat bogs (personal observation), so there is the possibility that these remains represent these species. There is, however, the equal possibility they represent *Rhynchospora alba* and *Trichophorum caespitosum* individuals. Given this, and the wide range of niches that these species can grow under, it is difficult to pinpoint the degree of mire surface wetness using this component.

5.2.5 *Eriophorum vaginatum.*

Eriophorum vaginatum can grow over a large range of moisture conditions, and forms a dominant component of those peat communities which experience surface water levels in the spring and subsequent reduced water levels in the summer (Tansley, 1939; Gimingham, 1964; Wein, 1973). Drought conditions are not unduly deleterious, as the species can survive them by virtue of its deep rooting habit, for example its rhizomes may extend to 60 cm. below the surface (Boggie *et al.*, 1958; Gore and Urquhart, 1966). *Eriophorum vaginatum* is capable of invading pools (Osvald, 1923), and palaeoecological evidence supporting this observation, has been made by Walker and Walker (1961) and Barber (1978). The latter author identified the characteristic field macrofossils scattered in the peat matrix of a pool infill, and found no evidence for a tussock, i.e. a tangled mass of *Eriophorum* fibres. The ability of *E. vaginatum* to conserve nutrients and intercept solar radiation early in the growing season (Robertson and Woolhouse, 1984), makes it a difficult species for *Sphagnum* species to replace, given that it grows under wet and dry mire conditions, resists smothering by upwards growing *Sphagnum* carpets, and has the same productivity as *Sphagnum* species.

Hammond *et al.* (1990) most frequently encountered this species in peat with a water table at 24 cm. depth, although it had a range spanning 0 to 28 cm., which demonstrates the wide tolerance of this species to this environmental variable. Økland (1990), undertook a phytoecological study of 1419 sample plots in the Kisselbergmosen mire complex in SE Norway, and concluded that it was 'ubiquitous and omnipresent', although it was less common in carpets and low lawn microtopes.

Meade (1992), found this sedge growing over a waterlogged surface with *Sphagnum*, whilst van der Molen *et al.* (1994), who similarly undertook a detailed study of mire flora and their position relative to water table (Clara Bog, Co. Offaly, Ireland), found that *Eriophorum vaginatum* was abundant in positions 25-35 cm. above the hollow bottom.

Clearly the presence of this species needs to be interpreted cautiously, as it can grow under a variety of hydrological conditions, making reconstructions of mire surface wetness using it difficult. In this instance the palaeoecological recommendations of Casparie (1972, pp 152-153) are pertinent, since 'its occurrence may not be linked with desiccated peat without further qualification'.

5.2.6 ***Eriophorum angustifolium.***

This sedge, by comparison, has a better defined niche. Godwin and Conway (1939) and Phillips (1954) describe it as a species which characteristically colonises drying pools. Competition with *Sphagnum* species prevent it from entering hummocks and hollows as it experiences nutrient deficiency, whilst its rhizomes are unable to penetrate tussocks of *Eriophorum vaginatum.* In a similar manner to *E. vaginatum*, the well protected stem apex of *E. angustifolium* offers it a degree of fire resistance (Phillips, 1954). Boatman (1977) and Rodwell *et al.* (1991), confirm its position at the edges of pools (where it can dominate), in permanent shallow pools and in dried up hollow bottoms, as it can tolerate a range of soil moisture conditions. Madden and Doyle

(1990) examined nine 50 x 50 cm. quadrats from Mongan Bog, Co. Offaly, Eire, (six from hummocks and three from hollows), and found the species had a preference for the wetter hollows, although it was also recorded from the hummocks. Van der Molen (1986), noted its occurrence in hollow microtopes, with a mean height above the water table of 8 to 10 cm.

Haslam (1987) analysed 15 mires from the British Isles and northern Europe, and routinely identified sub-fossil epidermal tissues of *E. angustifolium,* along with *Rhynchospora alba* (see below), and selected testate amoebae species. In many instances, the occurrence of this sedge consistently indicated high mire surface wetness, which was confirmed by low colorimetric humification absorbance values and hygrophilous rhizopods. Macrofossil *E. angustifolium* has been recovered from Chat Moss, along with abundant *Sphagnum* section *Cuspidata* leaves by Hall *et al.*, (1995). These components and a decline in the abundance of subfossil *Calluna vulgaris* and *Eriophorum vaginatum* in zone Bm-4 of Hall *et al.*, have been interpreted as an increase in mire surface wetness, and dated to CAL 5840-5583 BC.

5.2.7 *Rhynchospora alba.*

Rhynchospora alba is a good indicator of elevated mire water tables as it occurs in low lawns and at pool margins (Godwin and Conway, 1939; Tansley, 1939). Van der Molen (1986), calculated its mean height above the water-table, and found it to be 12-14 cm. Hammond *et al.* (1990) and Økland (1990) report slightly lower values of 8 cm. and 5-7 cm. respectively to the water table, with the range extending from 0 to 10 cm.

Rodwell (1991) describes the position of *Rhynchospora alba* as being confined between low lawns and the shallower water around pool margins, from where it may, sometimes, extend across smaller mire pools. The indicator value of subfossil *Rhynchospora alba* has been demonstrated by Joosten (1985), where remains of this sedge and leaves of *Sphagnum cuspidatum*, *Drepanocladus fluitans*, and high numbers of *Amphitrema flavum* tests, have been used to infer the existence of elevated mire surface wetness in old peat pits in the Peel bog reserve, the Netherlands.

5.2.8 *Trichophorum cespitosum.*

Deer grass is found in wetter areas of blanket mires, as Eddy *et al.* (1969) found it growing on flat areas of blanket bog with a high water table within the Moor House Reserve, whilst Rodwell *et al.* (1991), describe it as a lawn species tolerant of surface-waterlogging. Within the M19 *Calluna vulgaris-Eriophorum vaginatum* blanket mire, it occurs patchily on drier peats, and may become abundant along tracks, where trampling can reduce aeration of the peat matrix. Equally, however, *Trichophorum cespitosum* can be locally abundant in tussocks within the NVC M19 Community (Rodwell *et al.*, 1991), therefore in this respect, its ability to survive a range of mire water levels may mirror that of *Eriophorum vaginatum.*

Fibres and roots of this species and *Eriophorum vaginatum*, along with Ericaceae rootlets, dominate the peat matrices of humified British peats (Godwin and Mitchell, 1938; Godwin, 1946), therefore its identification in peat stratigraphy may indicate episodes of reduced mire surface wetness, especially where other drier mire indicator species are present. Equally, however, fragments of *Trichophorum cespitosum* were identified by Haslam (1987), in both inferred wet lawn (Juhrdener Moor, Germany) and dry hummock environments (The Engbertsdijksveen, the Netherlands). Clearly the ecological indicator value of this species is uncertain, and other qualifying evidence must be used in conjunction with it.

5.2.9 *Polytrichum juniperum/alpestre* type.

Mosses in this genus are classified as endohydric, since they are cuticularized and possess a well developed central strand (Tansley and Chick, 1901). Experimental work by Mägdefrau (1935), affirmed that internal conduction was predominant in *Polytrichum*, whilst Bayfield (1973), demonstrated that water loss in *Polytrichum commune*, was actively controlled by a (complex) series of changes in leaf arrangement, which increases the species desiccation tolerance.

Both species appear to avoid hydric microtopes, since *Polytrichum juniperum* grows on well drained acidic soils on heaths and moors (Smith, 1980; Dickson, 1973). Additionally, it has been recognised as an important invader of exposed moraines in Iceland (Persson, 1964).

Polytrichum alpestre similarly displays a preference for drier microsites, since it forms dense tussocks on ombrogenous bogs (Dickson, 1973). Both *P. alpestre* and *P. juniperum* are confined to peat baulks and cuttings within Thorne Waste, eastern England (Smart *et al.,* 1986), which further confirms the drier microsites in which these species are found.

5.2.10 *Aulacomnium palustre.*

This non-*Sphagnum* bryophyte grows at relatively high positions above the water table, for example Andrus *et al.*, (1983) recorded it at positions 30.0 to 31.4 cm. above the spring water table, in small patches on hummock sides, in two mires in the Adirondack mountains, New York state. Økland (1990), similarly confirms this species presence within upper hummocks and, additionally, as 'single shoots among *Sphagnum* species'. Nicholson and Gignac (1995), found it growing at a greater range of heights above the water table (10-40 cm.), in 82 peatland stands in the Mackenzie River Basin, Canada, but its absence at lower positions above the water table does confirm its preference for drier hummock microtopes. The rhizoids of this species may wind around *Sphagnum* stems, which in this instance, possibly helps it to intercept and conduct water.

Aulacomnium palustre was the only bryophyte of 28 species noted by Barry and Synnott (1987), to be found consistently in both Irish fen and bog peats, suggesting a broad tolerance to nutrients. Li and Vitt (1994), propose that its occurrence (in western Canada), is governed not by nutrient availability, since it occurs on disturbed peat banks in both rich and poor fens and bogs, but by its ability to regenerate quickly in disturbed microhabitats. The relative unimportance of nutrients has been demonstrated experimentally by Li and Vitt, as nitrogen inputs had negative effects, whilst phosphorous additions had no effect on the establishment of *A. palustre*. The fast production of large numbers of this species has been experimentally confirmed by Li and Vitt (1995), since it displayed early vegetative reproduction and rapidly colonised experimental communities of four *Sphagnum* species and *Polytrichum strictum,* only to be displaced from the mature community by competition from the *Sphagna.* In addition to indicating possible disturbance to mire ecosystems, Li and Vitt (1995), monitored the water content of the peat in which *Aulacomnium palustre* grew, and found it performs best in peat which was not excessively wet or dry, with a water content (as % dry weight) between 580 and 750%.

5.2.11 *Racomitrium lanuginosum.*

Leaves of this species were only encountered in the monoliths taken from the Shaft Hill blanket mire site. This is a reflection of the high number of rain days in this area (296.6 rain days year^{-1}, Barrow *et al.,* 1993), since *Racomitrium lanuginosum* is an extremely oceanic species (Lindsay *et al,* 1988). Within blanket mires it is largely found in areas with lowered water tables; for example in high hummocks, peat mounds and gully sides (Boatman, 1957, Ratcliffe, 1964, Rodwell, 1991, Tallis, 1995). Fires may help to increase its abundance within blanket mire communities (Lindsay *et al.*, 1988), since it recovers quickly after burning (Pearsall, 1956). Given the dry mire surface indicator value of *R. lanuginosum*, one may speculate that sub-fossil levels of peat containing leaves of this species may indicate the existence of a low effective precipitation regime. This has been demonstrated by Tallis (1995), as levels containing abundant *Racomitrium* leaves from southern Pennine blanket mires were found to be coincident with the 'Early Medieval Warm Period' (1220-1310 AD, Alexandre, 1987), where warm springs and dry summers were predominant. In one site, Claish Moss, north-west Scotland, abundant *R. lanuginosum* leaves have been identified in the peat matrix which spans 5000 years, and Moore (1977), has interpreted this as reflecting the stability of the ridge system in which it is found today. Within the ridge system, *R. lanuginosum* forms hummocks, which in some instances are up to a metre high.

5.2.12 *Drepanocladus fluitans.*

Drepanocladus fluitans is found in pools in blanket bog, sometimes with *Sphagnum cuspidatum* (Osvald, 1949). Watson (1968), describes it as a species which can tolerate both aquatic and wholly terrestrial habitats, since it is found in both deep pools and sites which are only periodically wet. Dickson (1973), however, places *Drepanocladus fluitans* as a species primarily found in base-poor pools. Ohlson and Malmer (1990), corroborate this, as they recorded *Dreplanocladus fluitans.* with *Rhynchospora alba* growing in mud bottom communities.

Drepanocladus spp. leaves have been recovered by Casparie (1972) from peat face I, Emmen section 25, and their occurrence, along with *Sphagnum cuspidatum* leaves in the peat matrix, has been used to infer very moist peat growth. Sub-fossil leaves of this bryophyte, however, were only recovered from Shaft Hill, Monolith 1, and then only in a very limited quantity (<5%) from a single level. In this instance, given its very low representation in all cores, little ecological information can be gained from it.

5.2.13 Identifiable *Sphagnum.*

There are c.150 species of *Sphagnum* within the single Sphagnaceae family (Smith, 1980). Within the genus there are distinct sub-generic groups, which are referred to as sections, after Isoviita (1966). There are five sections which are commonly encountered on British raised mires (Figure 5.1), and where possible, species have been identified within each section.

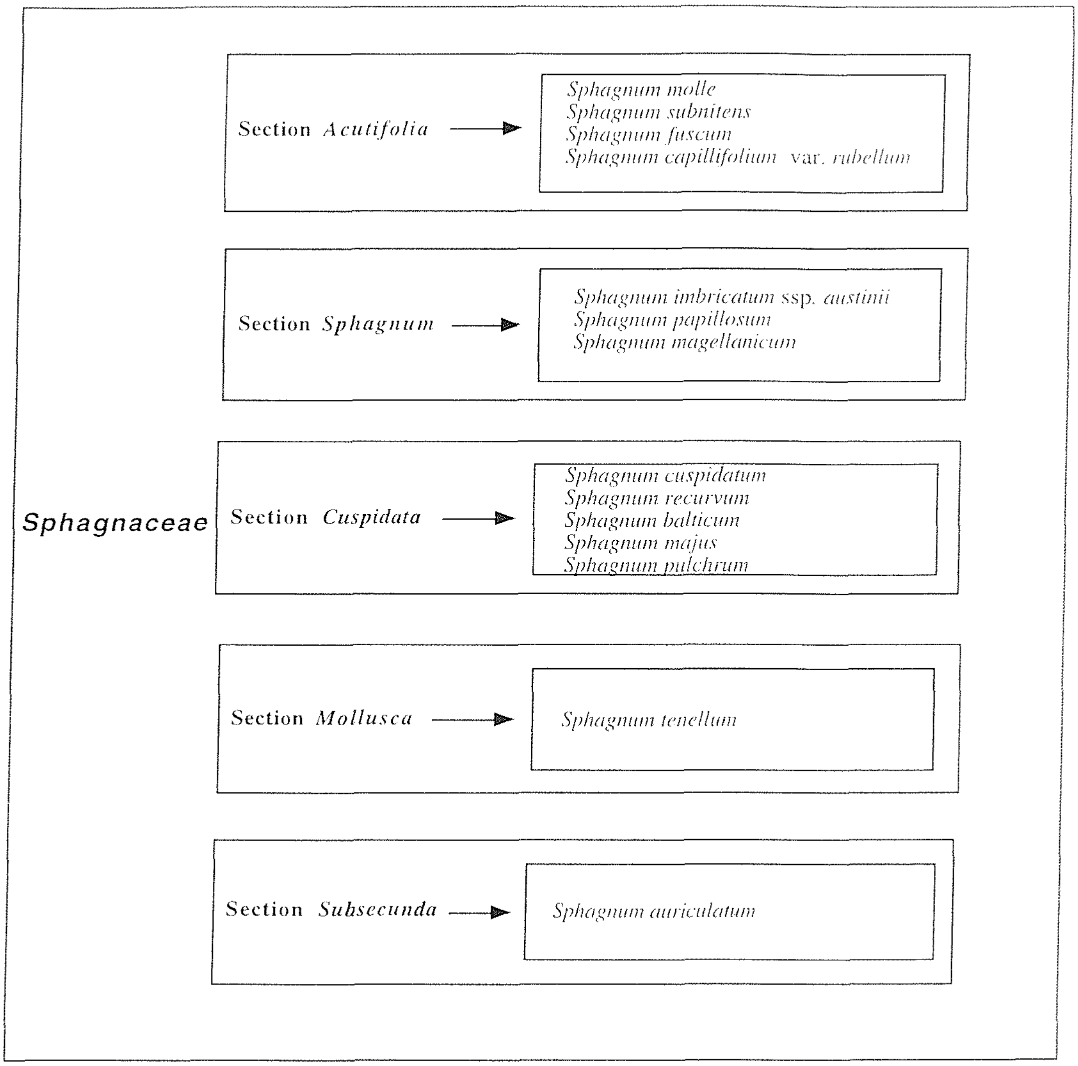
5.2.14 *Sphagnum* section *Acutifolia.*

Leaves from this section are readily recognised by their ovate to narrow ovate branch leaves (Smith, 1980; Daniels and Eddy, 1990), which are small in *Sphagnum fuscum* (1.1 - 1.3 mm. in length) and *Sphagnum capillifolium* (0.8-1.4 mm.) and rather bigger in *Sphagnum subnitens* (1.2 - 2.7 mm.) and *Sphagnum molle* (1.4 - 2.3 mm.). All of the species within the section possess triangular photosynthetic cells, have similarly sized dorsal pores (up to 30 μm), which combined with the overlapping size ranges of the leaves, renders positive identification to species level difficult. Tolonen (1966), encountered this problem with sub-fossil leaves of this section, finding it difficult to distinguish between *Sphagnum fuscum* and *Sphagnum capillifolium* var. *rubellum*. Because of these constraints and the need to identify c. 50,000 *Sphagnum* leaves, individual sub-fossil leaves were assigned to section Acutifolia only.

The difficulty of consistently and accurately identifying leaves to species level also poses problems in determining the degree of mire surface wetness. This is not such a problem for both *Sphagnum fuscum* and *Sphagnum capillifolium* var. *rubellum* leaves, since they occupy hummocks; Andrus *et al.* (1983) found the two species growing at mean heights of 30.9 ± 10.6 cm. and 24.8 ± 9.4 cm. above the spring water table respectively. Rydin and McDonald (1985), similarly found the two species at respective heights of 35 and 25 cm. above the water table, whilst Janssens (1992), derived an optimum height of 27.5 cm. above the mean water table for *Sphagnum fuscum*. Nicholson and Gignac (1995, p449), propose that *Sphagnum fuscum*, 'is an excellent indicator of drier conditions on peatlands', given its confinement to the tops of hummocks.

Sphagnum molle and *Sphagnum subnitens* are, however, lawn species, (Daniels and Eddy, 1990), which potentially reduces the accuracy of any palaeoecological reconstruction made using section *Acutifolia* leaves alone. Leaves of *Sphagnum tenellum* (from Section *Mollusca*), may also be misidentified and recorded as section *Acutifolia* leaves, as they too are small in size (0.8-1.5 mm.).

Figure 5.1 *Sphagnum* species encountered on British ombrotrophic mires (after Daniels and Eddy, 1990).



This species can grow over a wide range of water levels, for example, Godwin and Conway (1939), found it associated with raised *Calluna* associations and deer sedge, whilst Økland (1990) recorded it at positions 2 cm. above the water table. On a more encouraging note, *Sphagnum capillifolium* var. *rubellum* is the dominant section *Acutifolia* species on lowland raised mires in Scotland and NW England (Ratcliffe and Walker, 1958; Barber, 1981), which may reduce the possibility of inaccurate water level reconstructions using this vegetation component.

The identification of *Sphagnum* section *Acutifolia* leaves can be taken to indicate drier mire surface conditions, provided it is qualified with other plant macrofossil/microfossil evidence. Kuhry (1985) and Dupont (1986), interpreted the presence of section *Acutifolia* leaves and *Calluna vulgaris* stems, flowers and seeds, to support the existence of drier mire surfaces, in addition to fungal spore and rhizopod assemblages. In both these two examples, either *Sphagnum fuscum* or *Sphagnum capillifolium* var. *rubellum* may have once grown on the bog surfaces investigated, given their preponderance in drier microsites. The difficulty of assigning a reliable indicator value to this plant macrofossil, however, demonstrates the importance and value of a multi-proxy approach, since any environmental reconstruction of mire water levels made using this *Sphagnum* section alone would be possibly ambiguous. This strategy was adopted by Haslam (1987), as he encountered this precise difficulty with section Acutifolia leaves, and circumvented it by undertaking both colorimetric humification and testate amoebae analysis of selected species.

5.2.15 *Sphagnum imbricatum* ssp. *austinii.*

This species is particularly striking since its hyaline cells possess numerous transverse lamellae, which appear to be comb-like (Daniels and Eddy, 1990).

The ecology of modern examples of this species indicate that it is a bryophyte capable of growing under relatively xeric conditions. Like other members of Section *Sphagnum*, it has both inrolled cucullate (hooded at the apex) leaves, and grows in a compact form with a very close and imbricate arrangement of the branch leaves. This serves to reduce the surface area for evaporation (Flatberg, 1986). Green (1968), experimentally demonstrated its ability to retain water, whilst Andrus (1984) and Flatberg (1986), confirmed its presence in (high) hummocks. Detailed palaeoecological macrofossil analysis undertaken by Van der Molen and Hoekstra (1988), highlight the ability of this bryophyte to grow under drier mire conditions. In this instance, sub-fossil leaves of *Sphagnum imbricatum* occur in zone D of their reconstruction along with *Calluna vulgaris*, 'type 18' fungal spores (which indicate the presence of *Eriophorum vaginatum*) and xeric testate amoebae tests.

Sphagnum imbricatum spp. *austinii* does however, have morphologically distinct ecads or ecophenes, which allow it to grow in both hummocks and (low) lawns. The lawn ecad has a lax growth form (Tallis, 1961), which has been experimentally induced by Green (1968). The growth of *Sphagnum imbricatum* under these experimental conditions (the water level was maintained at 1 cm. above the shoot apices) was different to examples growing under drier regimes, for instance the branches were larger and the shoot internodes more elongated. The possible reason for this phenotypic plasticity under these conditions, is the buoyancy afforded by aquatic environments (Rice, 1995). The presence of surface water allows plants to invest more assimilate to photosynthetic tissues, rather than to supporting tissues, allowing faster rates of growth. This has been experimentally confirmed by Rice, since aquatic *Sphagnum* species from Section *Cuspidata* had higher growth rates than non-aquatic taxa from section *Sphagnum*. The growth rate of the 'lax' form of *Sphagnum imbricatum* is faster than ecads grown under dry conditions, but still slow compared to other members of Section *Sphagnum,* for example *Sphagnum papillosum* can grow the same amount in 20 days less time (Green, 1968). Because of this, it is ousted from low lawns by this latter species, unless competition from other *Sphagnum* species is low (Flatberg, 1986).

The ability of this cymbifolian species to grow under wetter mire surface conditions has been demonstrated in the fossil record by Casparie (1972), Van Geel (1978) and Barber (1981). The former describes a transition from highly humified *Sphagnum* peat to a fresher one, 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 Emmen 22/23, south-eastern Drenthe, the Netherlands. Barber (1981), found that in one monolith (H19), leaves of *Sphagnum imbricatum* occur with frequent remains *of Sphagnum cuspidatum* in a minor pool layer. Similar findings have been made by Smith (1985), Wimble (1986), Haslam (1987), and Stoneman (1993), which offer firm evidence for the former existence of lawn ecads. The results from this research project further support the ability of *Sphagnum imbricatum* to grow on a relatively wet mire surface, particularly Bolton Fell Moss - Core L (Figure 5.15), Raeburn Flow (Figure 5.24) and Felecia Moss (Figure 5.38).

There is, therefore, a problem when attempting to make hydroclimatic reconstructions with this species, since it (potentially) can grow over a range of mire water levels. There is in addition, a further problem with this particular species, since it is now largely extinct from many NW European mires. This event violates two Uniformitarian assumptions (Lowe and Walker, 1984), since in the first instance, there are no longer analogues in the modern flora, and secondly, the niche widths of the surviving mire flora may have changed following the removal of this strong competitor (Stoneman *et al.*, 1993).

The decline is very marked in all of the sites studied for this research project, and has been noted by many palaeoecologists (Godwin and Conway, 1939; Barber, 1981; Smith, 1985; Wimble, 1986; Van Geel and Middeldorp, 1988; Stoneman, 1993). The specific pattern of its replacement by *Sphagnum papillosum* and/or *S. magellanicum* is a feature which all of the above authors have identified. The timing of the decline of this species, is however, diachronous. It persisted up to 1800 AD. on Bolton Fell Moss (Barber, 1981), although major declines occurred at 1450 AD. A similar date of 1400 CAL. AD. was determined for the decline of *S. imbricatum* at Carbury Bog, Eire (Van Geel and Middledorp, 1988), although Smith (1985) had the decline dated to 1250 CAL. AD. for the Goole Moors, in the Humberhead levels. Charman (1990) found it declined earlier, at 500 CAL. AD., at Cross Lochs in the Flow Country.

The specific reasons for this decline are uncertain: theories presented to account for the extinction of this species have been reviewed by Stoneman (1993), and include climate change (Godwin, 1956; Barber, 1981), direct anthropogenic disturbance through burning, grazing and trampling (Pearsall, 1956; Piggot and Piggot, 1963), and indirect human impacts through airborne contamination (Van Geel and Middeldorp, 1988). Further discussion will follow in Chapter 6, based on the results presented in Chapter 5.

5.2.16 *Sphagnum magellanicum.*

Sub-fossil leaves of *Sphagnum magellanicum* are readily recognised by their photosynthetic cells, which are oval and largely enclosed by hyaline cells (Daniels and Eddy, 1990).

Andrus (1983) recorded it in lawns and low hummocks (25.8 ± 9.5 cm. above the spring water table). Van der Molen (1986), found it to be a lawn species, with a mean height above the water table of 15 cm. Hammond (1990), found that 90% of occurrences of the species occurred at 24 cm., which again, confirms it as a lawn species. Økland (1990), however, suggests it has a broad habitat niche, since although it was recorded most frequently in lower and upper lawn microtopes, it was also dominant in lower hummocks in the Norwegian mire investigated. The findings of Janssens (1992), offer further support for the possible wide range of mire water levels under which this species occurs, since the optimum height recorded in this instance, was 8.3 cm. above the water level, which represents a low lawn position. Økland has adopted the terminology of Grime (1979), and suggests that *Sphagnum magellanicum* is a competitive species, since it avoids microtopes where water supply is unstable (hummocks), and disturbed areas of the habitat space (hollows, which may become seasonally desiccated). Van der Molen and Wijmstra (1994), in a similar vein to Økland (1990), suggest that *Sphagnum magellanicum* is a generalist and uses 'the contours of the microtransect where and when possible'.

Van Geel and Middledorp (1988), suggest the replacement of *Sphagnum imbricatum* by *S. magellanicum* may have arisen because of enhanced wet and dry deposition of nitrate contained in dust, as a result of human agricultural activities. The decline of tree pollen from Carbury Bog, and the presence of sand particles in the peat matrix, does coincide with the demise of *S. imbricatum*, and the reduced sensitivity of *S. magellanicum* to nitrate concentrations may explain its competitive advantage in this situation, as it would be able to increase productivity and carbon fixation (Aerts *et al.*, 1992). Nitrogen deposition experiments by Aerts *et al.* have indicated that productivity increases until plant growth becomes phosphorous limited, at which point there is no further increase in carbon fixation. Because *S. magellanicum* can tolerate nitrogen concentrations up to 322 µm. compared to 100 µm. for other *Sphagnum* species (Rudolph and Voigt, 1986), it may be able to have a competitive advantage and potentially oust *S. imbricatum*, if atmospheric contamination is responsible for this phenomenon.

Although *Sphagnum magellanicum*, would appear to be a 'generalist', it does however avoid the driest and wettest parts of hummock/hollow microtransects, and is therefore useful as a palaeoecological indicator species.

5.2.17 *Sphagnum papillosum.*

The internal commissural walls of this species are rough, since they possess projecting papillae (Daniels and Eddy, 1990). This distinctive feature of the hyaline cells makes identification of *Sphagnum papillosum* straightforward.

Godwin and Conway (1939), found this bryophyte growing in lawn microtopes on Tregaron West bog. Ratcliffe and Walker (1958) and Boatman (1983), similarly found it predominantly in low lawns and pools in the Silver Flowe complex of bogs in SW Scotland, where 'large flaccid forms extended well below the surface', Boatman (1983). Rydin and McDonald (1985), found the maximum productivity of this species occurred in intermediate lawn habitats, but Van der Molen (1986), found its mean height above the water table to be just 4 cm., suggesting a low lawn position. Conversely, Hammond *et al.* (1990), found that 90% of the occurrences of the species were at relatively high positions on lawns (23 cm.), just below the optimum value for *Sphagnum magellanicum* (24 cm.). Økland (1990), made similar findings, since it was recorded largely in lawn microtopes, and only rarely in hummocks as single shoots. Janssens (1992), however, recorded it at a mean height of 12 cm. above the water table. Li *et al.* (1992), investigated the water relations of the two species and concluded that (under laboratory conditions), *Sphagnum magellanicum* appeared to be a superior competitor for water under dry conditions than *Sphagnum papillosum.* They further suggest that *Sphagnum papillosum* is a better 'drought tolerator', than *Sphagnum magellanicum*, since the lower positions that the former species occupies on microtransects are more likely to undergo severe and frequent desiccation (Wagner and Titus, 1984; Rydin, 1985). This is supported by the experimental results, as *Sphagnum papillosum* did in this instance demonstrate higher survival rates following desiccation than *Sphagnum magellanicum.*

Clearly this species has a wide ecotope breadth, like *Sphagnum magellanicum*, although its optimum position would appear to be centred on low lawn positions.

5.2.18 *Sphagnum* section *Cuspidata.*

Species within Section *Cuspidata* can be identified by their ovate to lanceolate shape, narrow hyaline cells, and their triangular to trapezoidal shaped photosynthetic cells. The leaves of *Sphagnum cuspidatum* are particularly distinctive, as they may extend to 3.5 mm. in length.

Section *Cuspidata* leaves are predominantly found in pool and low lawn ecotopes, and are therefore a good indicator of raised mire water levels (Table 5.1). Even the most aquatic of these species cannot, however, survive under extremely wet conditions, since Goode (1970), found that *Sphagnum cuspidatum* died within seven weeks when totally immersed in stagnant water under laboratory conditions. Boatman (1977), has also observed shoots of *Sphagnum cuspidatum* to be piled on top of each other by water and wind movements, causing the death of the smothered species.

Table 5.1 Ecology of *Sphagnum* Section *Cuspidata.*

Species	**Author**	**Ecology**
Sphagnum cuspidatum.	Andrus *et al.* (1983). Van der Molen (1986). Hammond *et al.*(1990). Johnson *et al.* (1990).	Mean height above the spring water table of 12.1±5.4 cm. 1 cm. above the water table. 90% occurrences at 5 cm. above the water table. 0-1 cm. above the water table.
Sphagnum recurvum.	Daniels and Eddy (1990).	Intermediate habitat between *Sphagnum cuspidatum* and *Sphagnum papillosum/magellanicum.*
Sphagnum balticum.	Økland (1990). Rydin (1993).	Optimally found at the lower lawn to upper lawn transition. The modal height above the water table is 9-12 cm. May occasionally be found above 30 cm:, where it benefits from the water transport capacity of surrounding *Sphagnum fuscum.*
Sphagnum majus.	Økland (1990).	Optimum position in lawns, but also found in pools.
Sphagnum pulchrum.	Daniels and Eddy (1990).	May form extensive carpets. It can be submerged in shallow pools.

Records of sub-fossil leaves of *Sphagnum pulchrum* are rare (Daniels, 1982), and Dickson (1973) does not mention any British finds. In addition to this, it has a highly disjunct distribution in Britain, and within the areas where it is present, populations are often small and localised (Daniels, 1982). *Sphagnum majus* and *S. balticum* are both rare in Britain, and are both confined to north-east Britain (Daniels and Eddy, 1990). In the light of this, sub-fossil leaves of Section *Cuspidata* recovered during the course of this research project are most likely to be either those of *Sphagnum cuspidatum* or *Sphagnum recurvum*. The latter species is found in more eutrophic conditions, and can form extensive carpets in poor fens (Proctor, 1955). Barber (1981) found it in only a few localities on Bolton Fell Moss, where it was confined to the south-west part of the bog, under birches and with stunted *Phragmites*. Given this, macrofossil section *Cuspidata* leaves identified in this project are most likely to represent *Sphagnum cuspidatum*, although there is the possibility that slight changes in nutrient supply may have allowed *Sphagnum recurvum* individuals to have become established in some instances.

5.2.19 Charcoal fragments.

Macroscopic charcoal fragments (>125 μm) are good indicators of fire on the mire surface, or in close proximity to it (see Section 3.10.1). These fragments have simply been counted and grouped into six size classes; <15,625 μm^2, 15,625-62,500 μm^2, 62,500 μm^2-0.25 mm^2, 0.25-1 mm^2, 1-4 mm^2 and >4 mm^2. The interpretation of fusain rich levels, is not straightforward (Section 2.2.1), however, as 'the presence of charcoal (in pollen preparations) merely tells us that combustible materials have been ignited', (Edwards, 1987), but not how they were ignited (Rhodes, 1996), or under which mire hydrological conditions. A similar analogy can clearly be made for macroscopic charcoal fragments. A further potential problem with this material relates to the variable production of fusain, as more charcoal need not necessarily mean more fires (Clark, 1983). There is, clearly, a danger of over-interpreting charcoal records, particularly when one is attempting to reconstruct mire surface wetness, highlighting once again, the need for qualified evidence from other mire surface wetness proxies.

5.2.20 Testate Amoebae.

5.2.20.1 Introduction.

The importance of the degree and constancy of mire surface wetness and its influence on the micro-distribution of Testate Amoebae species has been recognised since 1910 by Heinis, and later by Harnisch (1927), Bartos (1940) and Schönborn (1962b). Woodland (1996), has reviewed the progress of testate amoebae research from this early qualitative and semi-quantitative research, to the latest quantitative analysis of peatland testaceans by Tolonen *et al.* (1985), Warner (1987), Warner (1991), Charman and Warner (1992), Tolonen *et al.* (1992, 1994), and Warner and Charman (1994). Her resumés of the hydrological optima of thecamoebae are very informative and are included here to highlight the preferences of individual species (Tables 5.2 to 5.4).

Although moisture appears to be the primary ecological variable affecting thecamoebae communities, other parameters may affect their composition. For example, the influence of pH has been investigated by Heal (1961), Corbet (1973), Costan and Planas (1986), Beyens *et al.* (1986b) and Charman and Warner (1992). Heal (1961), found the division between fen and bog groups of species to be clearly delimited, occurring at pH 4.5-5.0. Beyens *et al.* (1986b), noted a positive relationship between alkalinity and species diversity, whilst Charman and Warner (1992), consider pH exerts a secondary control on species distribution and abundance.

Tolonen *et al.* (1992) examined oligotrophic and minerotrophic mires in Finland, and demonstrated a wide species distribution in relation to peat carbon : nitrogen ratios and dissolved organic carbon in the peat water, suggesting carbon and nitrogen are less important than moisture content of the peat substrate. Woodland (1996), however, examined oligotrophic mires only, and found it impossible to differentiate between species assemblages on the basis of pH and water chemistry (Ca^{2+}, SO_4^{2-} and Cl^-). Since all of the mires examined in this research project are oligotrophic ombrotrophic mires, the range of pH and water chemistry values are also very likely to be restricted, reducing the importance of these environmental variables.

The optima of testate amoebae species are reviewed in the next sections, based on a generic arrangement, given the lack of ecological data for some of the species. It is based to a large degree on the ecology of modern species, as there is a dearth of published palaeoecological analysis of testate amoebae, with some exceptions (Tolonen, 1966; Tolonen, 1971; Barber, 1981; Beyens, 1985; Joosten, 1985; Van der Molen, 1988; Van der Molen and Hoekstra, 1988; Warner and Charman, 1992).

5.2.20.2 *Amphitrema.*

Heal (1961), examined nine fen and bog sites in northern England, and found tests of *Amphitrema flavum* were commonly present in bog pools and 'wet' *Sphagnum* lawns, where 'wet' is defined as little hand pressure to release water from a moss sample. Tolonen (1966), examined the modern rhizopod fauna of Varrassuo bog, Finland and noted the (dominant) presence of *Amphitrema flavum* in moss hollows and depressions. Peaks in sub-fossil thecae of *Amphitrema flavum* in Monolith HI9 from Bolton Fell Moss occur with increased numbers of hygrophilous *Sphagnum cuspidatum* leaves (Barber, 1981). Drawing from this, Van der Molen (1988), interprets the presence of increased *Amphitrema flavum* tests as indicative of elevated mire water tables, since there were also concurrent increases in seeds and pollen of *Rhynchospora alba* in the Irish bog investigated.

Analysis of surface moss samples and measurements of depth to the local water table have been undertaken by Charman and Warner (1992), Tolonen *et al* (1992; 1994), and Woodland (1996), for both Canadian, Finnish and British mires respectively. In each case, this species demonstrated consistent preferences in relation to peat moisture conditions, by occupying microsites with high moisture levels (Table 5.2), although Woodland (1996), found the species can exist where moisture is less than 70%.

Grospietsch (1958), recorded *Amphitrema wrightianum* in very wet *Sphagnum*, whilst Heal (1961), encountered this thecamoebae in bog pools. Tolonen (1966) also recorded this species in moss depressions, although in comparison to *Amphitrema flavum*, it was recorded in smaller numbers. Using this information, Tolonen (1971) interpreted their presence palaeoecologically to infer the former existence of very wet microsites on a Finnish raised bog (Klaukkala Isosuo). Tolonen *et al.* (1994), employed canonical correspondence analysis (CCA), to examine the species-environment relationships between rhizopods and their (untouched) *Sphagnum* bog habitats. Six sites were examined, and the effect of 12 environmental variables investigated. Soil moisture content was found to be the most important environmental factor, and this species, in a similar manner to *Amphitrema flavum*, was found to be an indicator of wet, nutrient poor, and low pH sites. Interpreting British fossil *A. wrightianum* may be problematic, however, as there is no modern analogue to model the species response to mire water levels, since this thecamoebae was absent in the modern peat assemblages examined by Woodland (1996). She proposes that the modern demise of this species may be due to either atmospheric pollution, as it disappeared in the top 15 cm. of the peat profile from Bolton Fell Moss, Cumbria (Bolton Fell Moss - Monolith J2), or to competition, since both *A. wrightianum* and *A. flavum* thrive in microsites with high water tables.

5.2.20.2 *Arcella.*

Tolonen *et al.* (1992), found *Arcella discoides* had a moisture optima of 96.7% and a water table depth optima of 4.8 cm. Woodland (1996), also found it occurred abundantly in wetter locations (moisture optima of 94.4% and water table depth optima of 3.11 cm), but found *A. discoides* to be distributed across a wide hydrological gradient. In a palaeoecological context, Joosten (1985), interpreted the presence of tests of this genus, as indicative of wet mire microenvironments.

5.2.20.3 *Bullinularia.*

From Table 5.4, it is readily apparent that *Bullinularia indica* is a xerophilous species, which corroborates the conclusions of de Graff (1956), since its optimum distribution was recorded in dry *Sphagnum* and amongst non-*Sphagnum* bryophytes in woods.

5.2.20.4 *Corythion-Trinema* type.

In a similar manner to *B. indica*, *Corythion-Trinema* type is also a xerophilous taxon (Table 5.4). Woodland (1996), suggests the small size of *Corythion-Trinema* tests (30-60 µm, Corbet, 1973; Ogden and Hedley, 1980), may allow these thecamoebae to survive in small water films. Tolonen (1966), encountered sub-fossil tests of these species in samples taken from a Finnish bog, but because only a few individuals were identified, no firm palaeoecological reconstructions could be made using these rhizopods.

5.2.20.5 *Assulina.*

Both *Assulina muscorum* and *A. seminulum* appear to be relatively xerophilous species, based on quantitative analysis of their micro-distributions (Table 5.4). This corroborates the qualitative work undertaken by Brown (1912), Schönborn (1962a and b), Laminger (1972), Corbet (1973) and Barber (1981). Sub-fossil thecae of both species have been utilised by Van der Molen and Hoekstra (1988) to produce a humidity index, and were each given a high weighting to reflect their xeric affinities.

Table 5.2 *Testate Amoebae species indicative of wet mire surfaces (after Woodland, 1996).*

	Europe		***Canada/USA.***	
Species.	**Inferred hydrological optima.**	**Author.**	**Inferred hydrological optima.**	**Author.**
Amphitrema flavum.	Wet conditions.	Corbet (1973).	Moisture content = 93.2%.	Tolonen *et al.* (1985).
	Wetter parts of hummocks.	Tolonen (1966).	Moisture content = 90.1%.	
	Water table depth = -2.8 cm.	Tolonen *et al.* (1992).		
	Moisture content = 96%.	Tolonen *et al.* (1992).		
	Water table depth = 5 cm.	Woodland (1996).		
Amphitrema wrightianum.	Mire pools.	Corbet (1973).	Moisture content = >90%.	Warner (1989).
	Water table depth = 0.8 cm.	Tolonen *et al.* (1992).		
	Moisture content = 95%.	Tolonen *et al.* (1992).		
Arcella discoides.	Floating, submerged or very wet *Sphagnum*.	Tolonen (1986).	Very wet conditions.	Warner (1987).
	Water table depth = -4.8 cm.	Tolonen *et al.* (1992).	Water table depth = -9 cm.	Warner and Charman (1994).
	Moisture content = 96.7%.	Tolonen *et al.* (1992).		
	Water table depth = 3.11 cm.	Woodland (1996).		
Centropyxis aculeata.	Aquatic habitats.	de Graff (1956).	Very wet conditions.	Warner (1987).
	Water table depth = -7.8 cm.	Tolonen *et al.* (1992).	Moisture content = 78.5%.	Charman and Warner (1992).
	Moisture content = 95.6%.	Tolonen *et al.* (1992).	Water table depth = -24 cm.	Warner and Charman (1994).
	Water table depth = -4.44 cm.	Woodland (1996).		
Difflugia bacillifera.	Mire pools.	Corbet (1973).	Very wet.	Warner (1987).
	Water table depth = -3.1 cm.	Tolonen *et al.* (1992).		
	Moisture content = 96.4%.	Tolonen *et al.* (1992).		
	Moisture content = 95.8%.	Woodland (1996).		

Table 5.3 *Testate Amoebae species indicative of moderately wet mire surfaces (after Woodland, 1996).*

	Europe		*Canada/USA.*	
Species.	**Inferred hydrological optima.**	**Author.**	**Inferred hydrological optima.**	**Author.**
Hyalosphenia elegans.	Mire hummocks. Moisture content = 95.3%. Water table depth = -8 cm. Moisture content = 91.8%. Water table depth = -3.61 cm.	Corbet (1973). Tolonen *et al.* (1992). Tolonen *et al.* (1992). Woodland (1996). Woodland (1996).	Moisture content = 90.2%. Moisture content = 90.1%. Moisture content = 86.9%. Moisture content = 83.9%. Water table depth = -27 cm.	Tolonen *et al.* (1985). Warner (1987). Warner (1989). Charman and Warner (1992). Warner and Charman (1994).
Hyalosphenia papilio.	Wet *Sphagnum* in mire hummocks. Moisture content = 95%. Water table depth = 7.1 cm. Moisture content = 93.3%. Water table depth = -4.1 cm.	Heal (1961). Tolonen *et al.* (1992). Tolonen *et al.* (1992). Woodland (1996). Woodland (1996).	Moisture content = 93.2%. Moisture content = 90.1%. Moisture content = 93%. Moisture content = 90-95%. Moisture content = 88.8%. Water table depth = - 10 cm.	Tolonen *et al.* (1985). Warner (1987). Warner (1989). Warner (1990). Charman and Warner (1992). Warner and Charman (1994).
Nebela collaris.	Moderately dry.	de Graff (1956).	Moisture content = 90-95%.	Warner (1987).
N. militaris.	Wet *Sphagnum* on mire hummocks. Moisture content = 89.3%. Water table depth = -15.1 cm. Moisture content = 89.07%. Water table depth = -7.68 cm.	Corbet (1973). Tolonen *et al.* (1992). Tolonen *et al.* (1992). Woodland (1996). Woodland (1996).	Moisture content = 90.5%. Moisture content = 85.7%. Moisture content = 52.8%. Water table depth = -42 cm.	Tolonen *et al.* (1985). Warner (1987). Warner (1989). Warner and Charman (1994).
Phryganella acropodia.	Water table depth = -12.8 cm. Moisture content = 91.6%.	Tolonen *et al.* (1992). Tolonen *et al.* (1992).	Moisture content = 90-95%. Water table depth = -53 cm.	Warner (1987). Warner and Charman (1994).

Table 5.4 *Testate Amoebae species indicative of drier mire surfaces (after Woodland, 1996).*

	Europe		*Canada/USA.*	
Species.	**Inferred hydrological optima.**	**Author.**	**Inferred hydrological optima.**	**Author.**
Assulina muscorum.	Xerophilous conditions. Water table depth = -16.6 cm. Moisture content = 86.6%. Water table depth = -7.77 cm.	de Graff (1956). Tolonen *et al.* (1992). Tolonen *et al.* (1992). Woodland (1996).	Moisture content = 90.5%. Moisture content = 85.4%. Moisture content = 88.8%. Moisture content = 68.6%. Water table depth = -44 cm.	Tolonen *et al.* (1985). Warner (1987). Warner (1989). Charman and Warner (1992). Warner and Charman (1994).
A. seminulum.	Hygrophilous. Mire hummocks. Water table depth = -12.7 cm. Moisture content = 92%. Water table depth = -6.41 cm.	de Graff (1956). Corbet (1973). Tolonen *et al.* (1992). Tolonen *et al.* (1992). Woodland (1996).	Moisture content = 90.5%. Moisture content = 62%. Moisture content = 85.3%. Moisture content = 70.4%. Water table depth = -40 cm.	Tolonen *et al.* (1985). Warner (1987). Warner (1989). Charman and Warner (1992). Warner and Charman (1994).
Bullinularia indica	Mire hummocks. Relatively dry conditions. Dry hummock Sphagna. Water table depth = -12.7 cm. Moisture content = 80.9%. Water table depth = -12.9 cm.	Heal (1964) Tolonen (1966) Tolonen (1988). Tolonen *et al.* (1992). Tolonen *et al.* (1992). Woodland (1996).	Moisture content = 70.8%. Moisture content = 86.5%. Moisture content = 67.5%. Water table depth = -50 cm.	Tolonen *et al.* (1985). Warner (1989). Charman and Warner (1992). Warner and Charman (1994).
Corythion dubium	Dry conditions. Dry conditions. Moderately dry conditions. Water table depth = -14.1 cm. Moisture content = 87%. Water table depth = -7.48 cm.	de Graff (1956). Schönborn (1962). Meisterfeld (1977). Tolonen *et al.* (1992). Tolonen *et al.* (1992). Woodland (1996).	Moisture content = 70%. Water table depth = -46 cm.	Charman and Warner (1992). Warner and Charman (1994).
Cyclopyxis arcelloides.	Moisture content = 84.1% Water table depth = -20.6 cm.	Tolonen *et al.* (1992). Tolonen *et al.* (1992).	Moisture content = 78-89%. Moisture content = 63.6%.	Warner (1987). Charman and Warner (1992).
Hyalosphenia subflava.			Moisture content = 88.3%. Moisture content = 88%. Moisture content = 39.9%.	Tolonen *et al.* (1985). Warner (1987). Warner (1989).
Nebela parvula.	Moisture content = 86.7% Water table depth = -15 cm.	Tolonen *et al.* (1992). Tolonen *et al.* (1992).	Very dry conditions. Moisture content = 64.5%.	Warner (1987). Charman and Warner (1992).
N. tincta.	Xerophilous. Water table depth = -22.4 cm. Moisture content = 83.2%.	de Graff (1956). Tolonen *et al.* (1992). Tolonen *et al.* (1992).	Moisture content = 64%. Water table depth = -32 cm.	Charman and Warner (1992). Warner and Charman (1994).

5.2.20.6 *Centropyxis.*

Centropyxis aculeata was the only member of this genus identified in sub-fossil material. This species is clearly hygroscopic, although Woodland (1996), found it could live in water films where the moisture content of the peat was 92%, making it less strongly hygroscopic in relation to this measure of mire hydrology. Warner and Charman (1994), propose that members of *Centropyxis* can tolerate periods of desiccation, therefore their presence needs to be interpreted with caution.

5.2.20.7 *Cyclopyxis.*

Although thecae of *Cyclopyxis arcelloides* type were identified, these may represent a range of species. The disputed taxonomy of *Cyclopyxis eurystoma, Phryganella acropodia* and *Cyclopyxis arcelloides* (Table 3.2), renders positive species identification difficult, even with the excellent keys and diagrams produced by Woodland (1996). This poses problems in terms of hydrological reconstructions, because *Cyclopyxis eurystoma* lives in peat microtopes with relatively low moisture contents (87.7%), whilst *Phyrganella acropodia* or *Cyclopyxis arcelloides* inhabit wetter microsites with 93% moisture (Woodland, 1996). Clearly, once again, the presence of species within this genus needs to be interpreted cautiously, to avoid spurious water level/climatic reconstructions.

5.2.20.8 *Difflugia.*

Difflugia bacillifera consistently appears to be a mire pool species, based on the hydrological measurements in Table 5.2. Schönborn (1966; 1992b), proposes species in this genus are incapable of encysting, which may explain why *D. bacillifera* is confined to the wettest mire microtopes. The incorporation of freshwater diatoms into the test of *D. bacillifera* may also account for its restriction to pools, as it only here that it will encounter suitable frustules of these algae (*Tabellaria, Frustulia, Pinnularia* and *Eunotia*, Ogden and Hedley, 1980) for construction of its test (Woodland, 1996). Quantitative analysis of *D. bacillariarum* has not to date been attempted, but Grospietsch (1958), Heal (1961) and Corbet (1973), all regard it as a species confined to aquatic pool habitats. There is a similar dearth of ecological material covering *D. globulosa*, but Grospietsch (1958), regards it as an aquatic species, which also utilises diatoms for construction of its test.

5.2.20.9 *Euglypha.*

Euglypha species are capable of surviving periods of desiccation by using mineral particles to seal off the pseudostome, thus protecting the naked cytoplasm (Foissner, 1987; Schönborn, 1992a). Despite the xerophilous affinities of *Euglypha strigosa*, (Heal, 1961, recorded them abundantly in *Sphagnum* hummocks), Woodland (1996), did not encounter them where water levels exceeded 25 cm. below the mire surface, and suggests *Euglypha* species are not extreme xerophiles.

5.2.20.10 *Heleopera.*

Woodland (1996), suggests *Heleopera* species (*Heleopera petricola, H. rosea* and *H. sphagni)* are moderately xerophilous, since she found they had similar moisture optima (between 91 and 93%), and occupied water levels (optimum value), between 7 and 8 cm. depth. This compares favourably with the optimum depth of 9.1 cm., calculated by Tolonen *et al.* (1992) for *H. sphagni* from Finnish mires. *Heleopera* species were found at water table depths ranging from 0 to 20 cm. depth, and Woodland suggests their occurrence in drier peats may be explicable in terms of their compressed tests, which allows them to survive in thin water films.

5.2.20.11 *Hyalosphenia.*

Hyalosphenia elegans is a hydrophilous species, found in both 'wet *Sphagnum*' (Grospietsch, 1958), and in low *Sphagnum fuscum* hummocks (Tolonen, 1966). Modern quantitative analysis of this species (Table 5.3) have indicated it is indicative of moderately wet mire surfaces, which has been corroborated by Woodland (1996), as *H. elegans* occupied sites with intermediate water content (91%), but with high water tables (water table depth -3.11 cm.). Because of this, she suggests it may be able to colonise microsites that desiccate quickly, for example the area around pool margins.

H. papilio also appears to be a hydrophilous species, commonly occurring in 'very wet and wet *Sphagnum'* (de Graff, 1956). Confirmation of the indicator value of this species is apparent from the range of values displayed in Table 5.3, where its hydrological optima is commonly inferred to exceed 90% moisture content.

H. subflava, conversely, is a xerophilous indicator species (Grospietsch, 1954; Tolonen, 1986; Warner, 1987; 1990), indeed in the British data set compiled by Woodland (1996), it tolerated the deepest water table depths (20 cm. + to the water table). Analysis of surface samples from a continental Canadian peatland (Warner and Charman, 1994), similarly demonstrated the ability of this species to survive under xeric conditions, as it was noted in samples with a water table depth exceeding 50 cm. below the surface. The flat test of this species (Heal, 1962; Foissner, 1987), in a similar manner to *Heleopera* spp., may enable it to survive in thin water films associated with dry microsites.

Based on the modern hydrological tolerances of this thecamoebae, sub-fossil tests of this species have been interpreted by Beyens (1985) and Joosten (1985), to indicate dryness and disturbance respectively, in the peatland ecosystems under investigation.

5.2.20.12 *Nebela.*

Grospietsch (1958), commonly encountered *Nebela carinata* in wet *Sphagnum,* whilst Heal (1961) recorded it in pools. Schönborn (1963) and Meisterfeld (1977), similarly identify *N. carinata* as a hydrophilous species. Tolonen *et al.* (1992), has developed these observations further, and proposed a weighted average water table depth of -1.4 cm. Woodland (1996), similarly recorded *N. carinata* in microtopes with 96.5% moisture and an optimum water table depth of -3.9 cm. She also noted this species is strongly stenotopic, as it displayed a narrow tolerance range for both moisture and water table depth. In the light of this, she suggests *N. carinata* may be intolerant of unstable mire hydrological conditions.

Nebela militaris is described as a xerophilous species by Meisterfeld (1977), Warner (1987; 1989), Tolonen *et al.* (1994) and Woodland (1996). Conversely, Corbet (1973, p 820), recorded *N. militaris* in 'the wet *Sphagnum* of bog hummocks', whilst Charman and Warner (1992), found it displayed no specific hydrological preference. Continental Canadian peatlands are not strictly comparable to British mires, and the 'one shot sampling' approach of Corbet (1973), may not adequately represent species seasonal hydrological relationships. In the light of this, the longer term monitoring of water levels and species abundance in experimental plots by Tolonen *et al.* (1994), and Woodland (1996), are probably more accurate, suggesting this species is indeed provisionally xerophilous.

Nebela parvula and *N. tincta* appear to be relatively eurytopic species, since they can tolerate a wide range of hydrological conditions. The wide ecotope breadth of *N. tincta* can be explained in terms of phenotypic plasticity in the size of the shell. Both Heal (1962) and Woodland (1996) report a reduction in size of the test, allowing greater chances of survival in thinner water films, when individuals were collected from hummock tops, compared to those recorded from hummock bases.

Although both *N. parvula* and *N. tincta* have relatively deep water table depth optima (-9.17 and -6.18 cm., respectively), their occurrence over a large range of water levels limits their use as mire hydrology indicators.

Hydrological data on the remaining species is very limited, but *Nebela flabellulum* is described as a *Sphagnum* hummock species by Corbet (1973), whilst *Nebela griseola* and *Nebela marginata* indicate intermediate mire surface wetness (weighted average water table depth of -9.3 cm. and -7.8 cm. respectively, Tolonen *et al.*, 1992).

5.2.20.13 *Placocista.*

Corbet (1973) and Tolonen *et al.* (1992), propose *Placocista spinosa* is hydrophilous, since it was recovered in both cases from bog pools. Woodland (1996), calculated a moisture optima of 94.4% and a water table optima of -5.36 cm., which supports this earlier work. The occurrence of *P. spinosa* in samples which had a deep water table depth (-15 cm., Woodland, 1996), argues against simple hydrological reconstructions, however, as its compressed test allows it to survive in thin water films, in a similar manner to *Hyalosphenia subflava.*

5.2.20.14 *Trigonopyxis.*

Trigonopyxis arcula consistently indicates drier mire surfaces. Both Tolonen *et al.* (1992) and Charman and Warner (1992), recorded it from surface samples with relatively deep water tables (-19.5 and -50 cm. +, respectively). Woodland (1996), also reports an optimum water table depth of -9 cm. and a moisture content of 90%. This supports the earlier qualitative observations of Heal (1961), where *T. arcula* was characteristically found in dry hummocks, and Barber (1981), where both abundances of this species and U.O.M. increased in Monolith HI9 from Bolton Fell Moss.

5.2.21 Other zoological remains.

The abundance of Cladocera head shields and postabdoma, and Copepod spermatophores, has been expressed on a 1-5 scale of abundance for Shaft Hill monolith 2 and 3. The abundance of these zoological remains was assessed in the same 5 cm^{-3} subsample used to count the testate amoebae. There was, unfortunately, insufficient material to perform this and testate amoebae analysis for Shaft Hill, monolith 1. Since these crustaceans are largely aquatic and confined to freshwater and moss water films (Section 3.6), there inclusion in the analysis of the peat matrices from the two plateaux blanket peat monoliths, may help identifying and corroborating levels with increased mire surface wetness.

Large quantities of Copepod spermatophores and abundant tests of *Amphitrema flavum* have been interpreted by Witte and Van Geel (1985), as indicating the presence of mire pools on the Assendelver Polder, the Netherlands. Van Geel and Middeldorp (1988) conducted an extremely detailed pollen and micro/macrofossil analysis of peat from Carbury Bog, Eire, and found increased representation of Cladocera and Copepods in samples which also contained *Narthecium ossifragum* roots and *Sphagnum papillosum* leaves. The presence of these plants indicate a shallower mire acrotelm, and possibly slight eutrophication, based on the presence of *Narthecium ossifragum* (Malmer, 1962). Van der Molen (1992), has also similarly used Cladocera and Copepods to investigate the local vegetation history of Clara Bog, Eire, and found changes in mire surface wetness from these microfossils were consistent with those indicated by testate amoebae species.

5.3 Chronology.

5.3.1 Radiocarbon Chronology.

The results of 34 radiocarbon assays are presented in Table 5.5. Each radiocarbon date has been calibrated using OXCAL (Bronk Ramsey, 1994), which employs the calibration curves (Stuiver and Pearson, 1986; Pearson and Stuiver, 1986) published in Stuiver and Kra (1986). Following the recommendations of Van der Plicht and McCormac (1995), the 1986 calibration curve was used in preference to the 1993 calibration issue published by Stuiver *et al.* (1993), as the latter curve may produce dates which are out by c. 15 calendar years. Following Barber *et al.* (1994d) and Dumayne *et al.* (1995), the mid-points of the 2 σ error ranges form the basis of the age-depth models constructed for each site (Figures 5.2 to 5.9). A trend line (second order polynomial) has been fitted to each of the age-depth curves with the exception of the Shaft Hill Monoliths, since the number of dates for each of these was limited (two for Monolith 2, and 3 for Monolith 3 [a fourth date, SRR-5863 was contaminated with modern carbon]). For each diagram the rate of peat accumulation between each set of dated points has been interpolated, and expressed as years of peat accumulation per cm. For some of the sites, these has been remarkably constant, for example inferred rates of peat accumulation for Bolton Fell Moss - Core L have only varied between 11.1 yr. cm.$^{-1}$ and 11.95 yr. cm.$^{-1}$, (CAL 90-350 AD. to CAL 3500-3100 BC.). These values have been used to interpolate the age of each sample between the dated horizons. The interpolations between the dated samples assume that peat growth has remained constant, however, the further each sample lies from a dated horizon, the greater the risk of inaccuracies. Where dates are quoted in the text, a clear distinction is made between calibrated dated horizons (for example on the plant macrofossil and testate amoebae diagrams), and interpolated dates.

5.3.2 *Pinus* Chronology.

Pinus grains are a useful biostratigraphic marker, allowing a fast, cheap, and reliable technique to date modern peat samples (<250 years old). Their presence in Cumbria and the Scottish Borders, in addition to changes in the pollen spectra of other taxa, has been used by Barber (1981), Tipping (1995a, b), and Barber (1996), to extend the geochronology for each of the sites investigated. The timing of the Pine rise, at c. 1800 AD. (see Section 3.8), offers a check on the reliability of surficial samples dated radiometrically, since these may suffer from contamination by modern carbon. The position of the Pine rise date has been marked on the age/depth curves for each site with a white square. There is a clear conflict between the radiocarbon and pollen stratigraphies in Bell's Flow (Figure 5.5), Coom Rigg Moss (Figure 5.6), and Shaft Hill - Monoliths 2 and 3 (Figure 5.8 and 5.9). Possible reasons for the differences between the Pine 'dates' and the radiocarbon dates will be discussed in Chapter 6. The *Pinus* concentration stratigraphy for each site is also presented in this Chapter, in Figures 6.1 to 6.9.

5.3.3 Spheroidal Carbonaceous Particle (SCP) Chronology.

The results of the SCP analyses are presented in Figures 5.10 - 5.12. These were undertaken by Mr. Mark Garnett at the Institute of Terrestrial Ecology, Merlewood. On the basis of these diagrams, peat appears to have accumulated very rapidly in this blanket peat stratigraphy, since rapid increases in SCP concentration occur at 21 cm. in Monolith 1, 30 cm. in Monolith 2, and 35 cm. in Monolith 3. Similar rapid increases in the SCP particle concentration from three lakes in southern Scotland have been dated by Rose *et al.* (1995), to the decades 1940-1950 AD. using ^{210}Pb chronology and coal and oil consumption statistics.

For the blanket peat stratigraphy (the monoliths were taken in 1996), this suggests accumulation rates between 2.7-2.2 yr. cm.$^{-1}$ (Monolith 1), 1.9-1.5 yr. cm.$^{-1}$ (Monolith 2), and 1.6-1.3 yr. cm.$^{-1}$ (Monolith 3). These accumulation rates are very high, as the highest inferred accumulation rate of 1.3 yr. cm.$^{-1}$ (80 mm. yr.$^{-1}$) in Monolith 3 exceeds the highest value of 30 mm. yr.$^{-1}$ reported by Ohlson and Dahlberg (1991), for unconsolidated peat derived from *Sphagnum* hummock communities (*Sphagnum fuscum* and *Sphagnum magellanicum*).

The *Pinus* rise dates (c. 1800 AD.) support the SCP chronology, as this component of the pollen stratigraphy also suggests the surficial peats are of very recent origin, since it occurs at 44 cm. in Monolith 1, 57.5 cm. in Monolith 2 and at 32 cm. in Monolith 3 (Figures 6.8 and 6.9). If the *Pinus* 'dates' are correct, SCP's are present in all three monoliths at and *before* c. 1800 AD., which may support the research of Gedye (pers com.). She found evidence for early pollution signals, using SCP's and mineral magnetics in southern Cumbrian mires (Ellerside Moss, Foulshaw Moss, and Helsington Moss), which has a pollen derived date as early as c. 1550 AD., based on the regional decline of *Alnus*, determined by Oldfield (1969).

The rapid increase in SCP's between 35 and 36 cm. in Monolith 3, in addition to the large increases in *Pinus* pollen concentrations, suggests there is a marked hiatus post-dating this level, which has been tentatively dated to c. 1940-50 AD. This feature of the SCP chronology, in addition to the radiometric and pollen dates derived from Shaft Hill - Monolith 2, Bell's Flow and Coom Rigg Moss, will be considered further in Chapter 6.

Table 5.5 Radiocarbon dates.

Lab. No.	Site	Depth below peat surface (cm.)	^{14}C date BP	Calibrated range AD/BC* (2 sigma)	Mid-point of the two sigma calibrated range.
SRR-5863	Shaft Hill- Monolith 3	28-32	99.37 ± 0.47% mod. C.	*Out of calibration range*	
SRR-5864	Shaft Hill- Monolith 3	38-42	1155 ± 45	770-990 AD	880 AD
SRR-5865	Shaft Hill- Monolith 3	48-52	1475± 45	450-660 AD	555 AD
SRR-5866	Shaft Hill- Monolith 3	58-62	1625 ± 45	260-550 AD	405 AD
SRR-5867	*Walton Moss - Core 11*	*32-40*	*360 ± 40*	*1440-1640 AD*	*1540 AD*
SRR-5868	Walton Moss - Core 11	52-60	630 ± 40	1280-1400 AD	1340 AD
SRR-5869	Walton Moss - Core 11	156-164	1790 ± 45	110-370 AD	240 AD
SRR-5870	Walton Moss - Core 11	192-200	2145 ± 45	370-90 BC	230 BC
SRR-5871	Walton Moss - Core 11	264-272	2860 ± 45	1220-910 BC	1065 BC
SRR-5872	Walton Moss - Core 11	400-408	3775 ± 50	2460-2040 BC	2250 BC
SRR-5873	Raeburn Flow	52-60	625 ± 55	1270-1410 AD	1340 AD
SRR-5874	Raeburn Flow	72-80	650 ± 45	1270-1400 AD	1335 AD
SRR-5875	Raeburn Flow	132-140	1395 ± 45	550-690 AD	620 AD
SRR-5876	Raeburn Flow	240-248	2295 ± 45	480-200 BC	340 BC
SRR-5877	Raeburn Flow	344-352	4250 ± 40	3020-2660 BC	2840 BC
SRR-5878	Bell's Flow	16-24	465 ± 45	1320-1510 AD	1415 AD
SRR-5879	Bell's Flow	24-32	790 ± 45	1160-1290 AD	1225 AD
SRR-5880	Bell's Flow	92-100	1460 ± 45	450-670 AD	560 AD
SRR-5881	Bell's Flow	140-148	1730 ± 45	140-420 AD	280 AD
SRR-5882	Bell's Flow	216-224	2400 ± 45	770-390 BC	580 BC
SRR-5883	Coom Rigg Moss	24-32	350 ± 50	1450-1640 AD	1545 AD
SRR-5884	Coom Rigg Moss	44-52	470 ± 40	1395-1485 AD	1440 AD
SRR-5885	Coom Rigg Moss	136-144	1445 ± 45	530-670 AD	600 AD
SRR-5886	Coom Rigg Moss	204-212	2140 ± 45	370-80 BC	225 BC
SRR-5887	Bolton Fell Moss - Core L	80-88	885 ± 45	1030-1230 AD	1130 AD
SRR-5888	Bolton Fell Moss - Core L	96-104	1145 ± 45	780-990 AD	885 AD
SRR-5889	Bolton Fell Moss - Core L	196-204	1795 ± 45	90-350 AD	220 AD
SRR-5890	Bolton Fell Moss - Core L	324-332	3030 ± 45	1420-1160 BC	1290 BC
SRR-4936†	Bolton Fell Moss - Core L	400-408	3725 ± 45	2290-1980 BC	2135 BC
SRR-4937†	Bolton Fell Moss - Core L	500-508	4575 ± 45	3500-3100 BC	3300 BC
SRR-5891	Felecia Moss	60-68	895 ± 55	1020-1240 AD	1130 AD
SRR-5892	Felecia Moss	80-88	1250 ± 45	670-880 AD	775 AD
SRR-5893	Felecia Moss	112-120	1460 ± 45	450-670 AD	560 AD
SRR-5894	Felecia Moss	224-232	2220 ± 50	400-170 BC	285 BC
SRR-5900‡	Shaft Hill - Monolith 2	58-59	820 ± 45	1040-1280 AD	1160 AD
SRR-5901‡	Shaft Hill - Monolith 2	76-77	1675 ± 45	230-450 AD	340 AD

* Calibrated using the data from Stuiver and Reimer (1986) in OXCAL (Bronk Ramsey, 1994).

† Dates supplied as part of NERC Palaeoclimate Grant GST/02/539.

‡ Dates granted to Mark Garnett, Institute of Terrestrial Ecology, Merlewood, Grange Over Sands, Cumbria.

Figure 5.2 Bolton Fell Moss - Core L.

Plot of mid-point of 2 sigma confidence of ^{14}C dates.

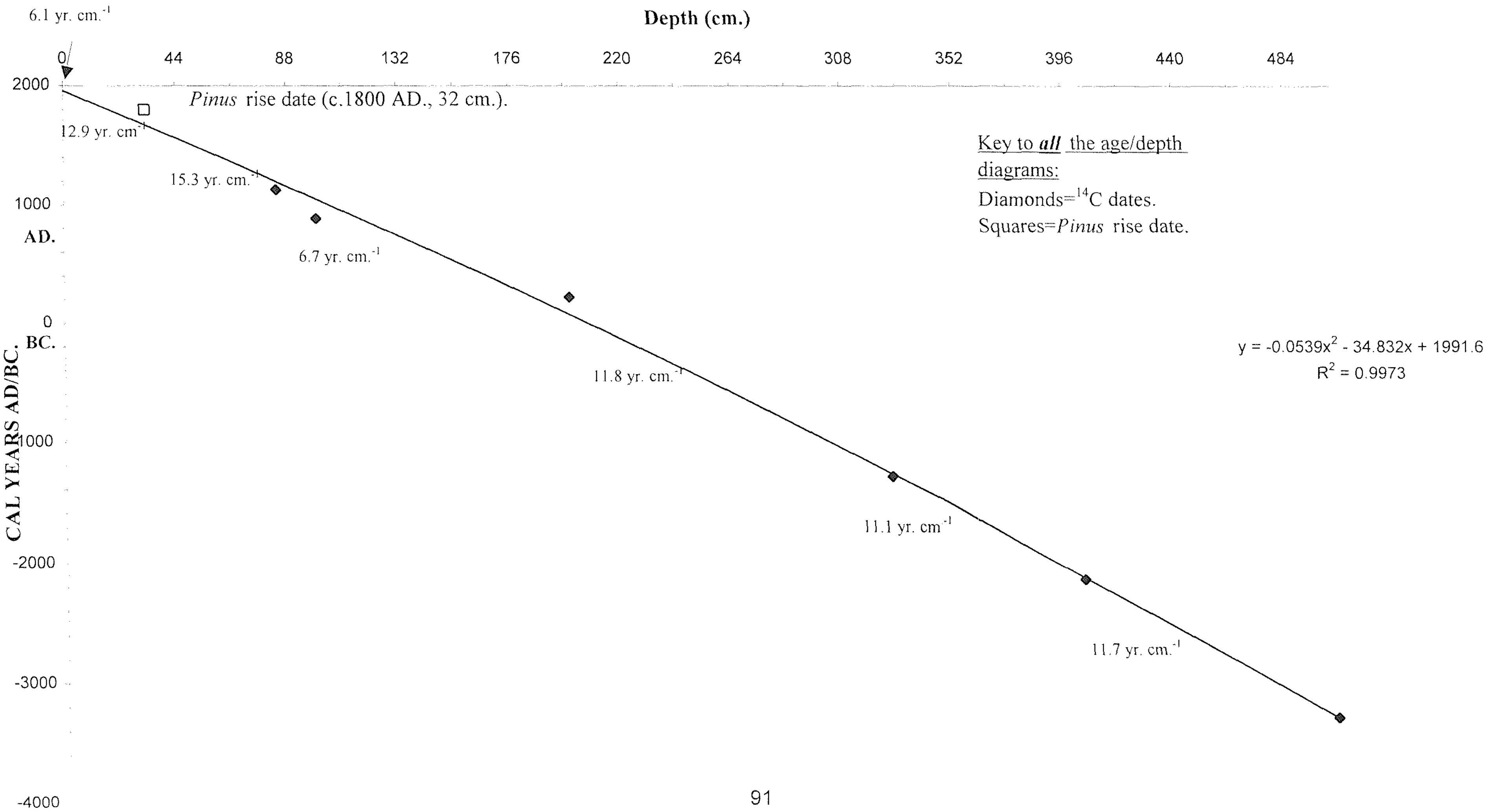


Figure 5.3 Walton Moss - Core 11.

Plot of mid-point of 2 sigma confidence of ^{14}C dates.

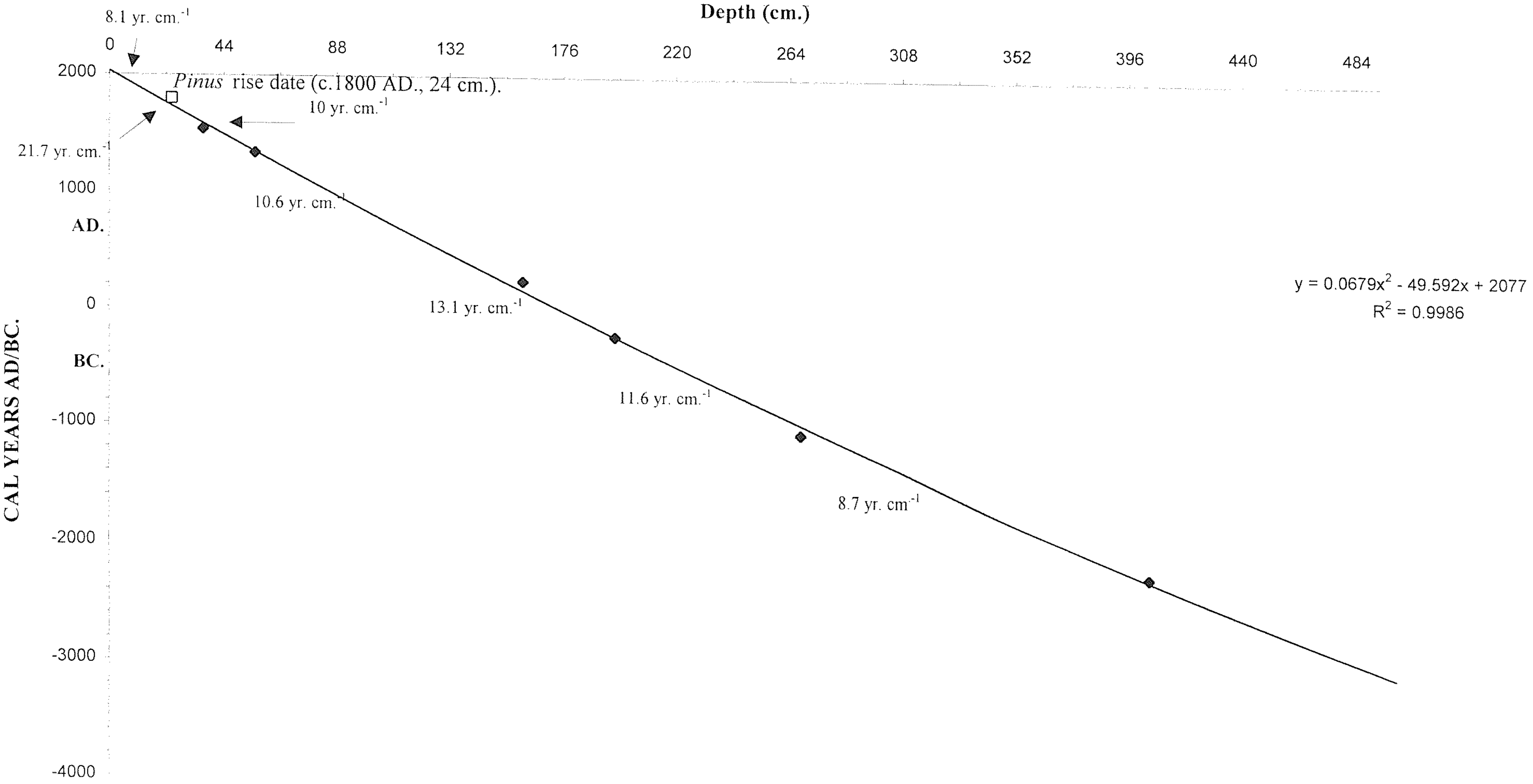


Figure 5.4 Raeburn Flow.

Plot of mid-point of 2 sigma confidence of ^{14}C dates.

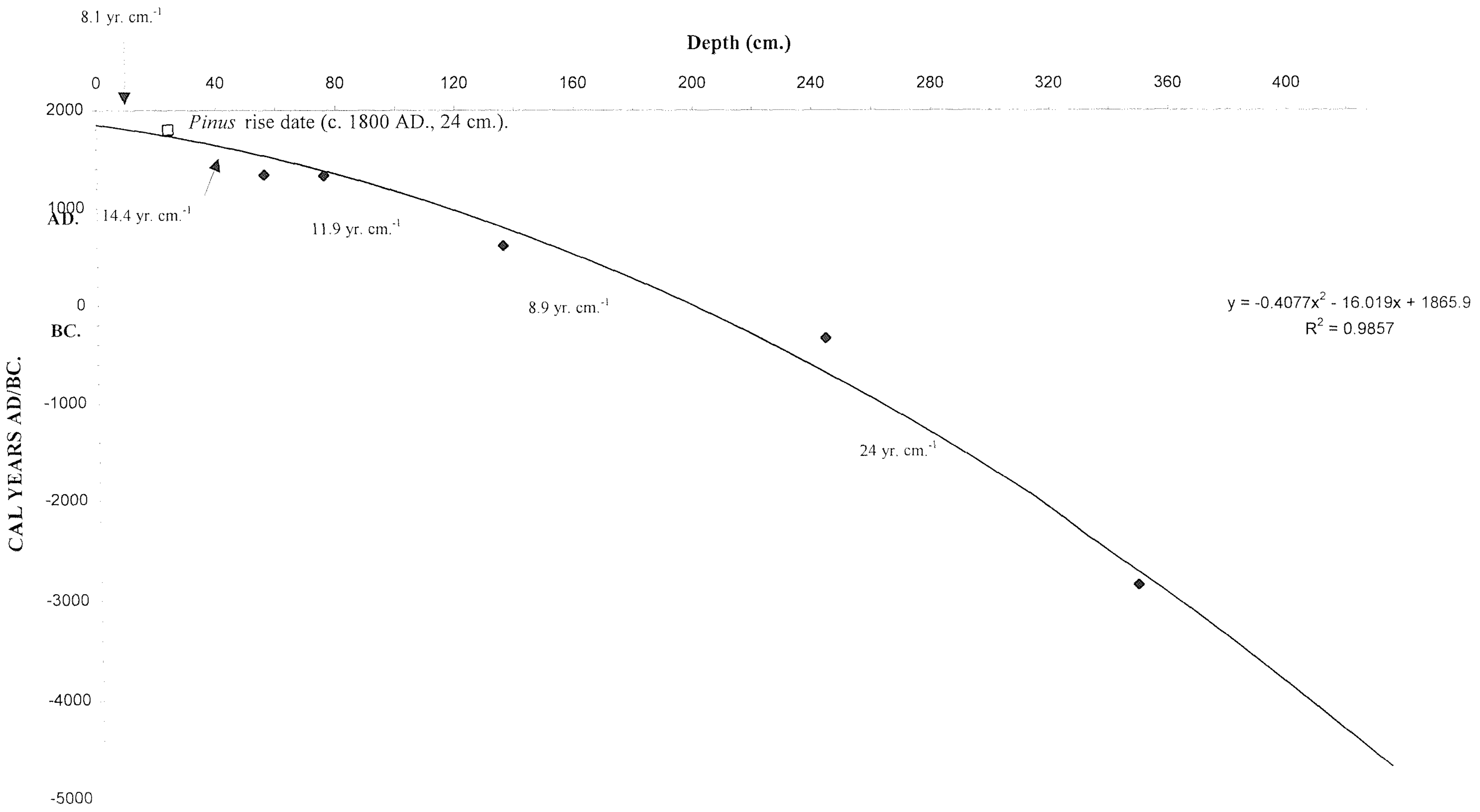


Figure 5.5 Bell's Flow.

Plot of mid-point of 2 sigma confidence of ^{14}C dates.

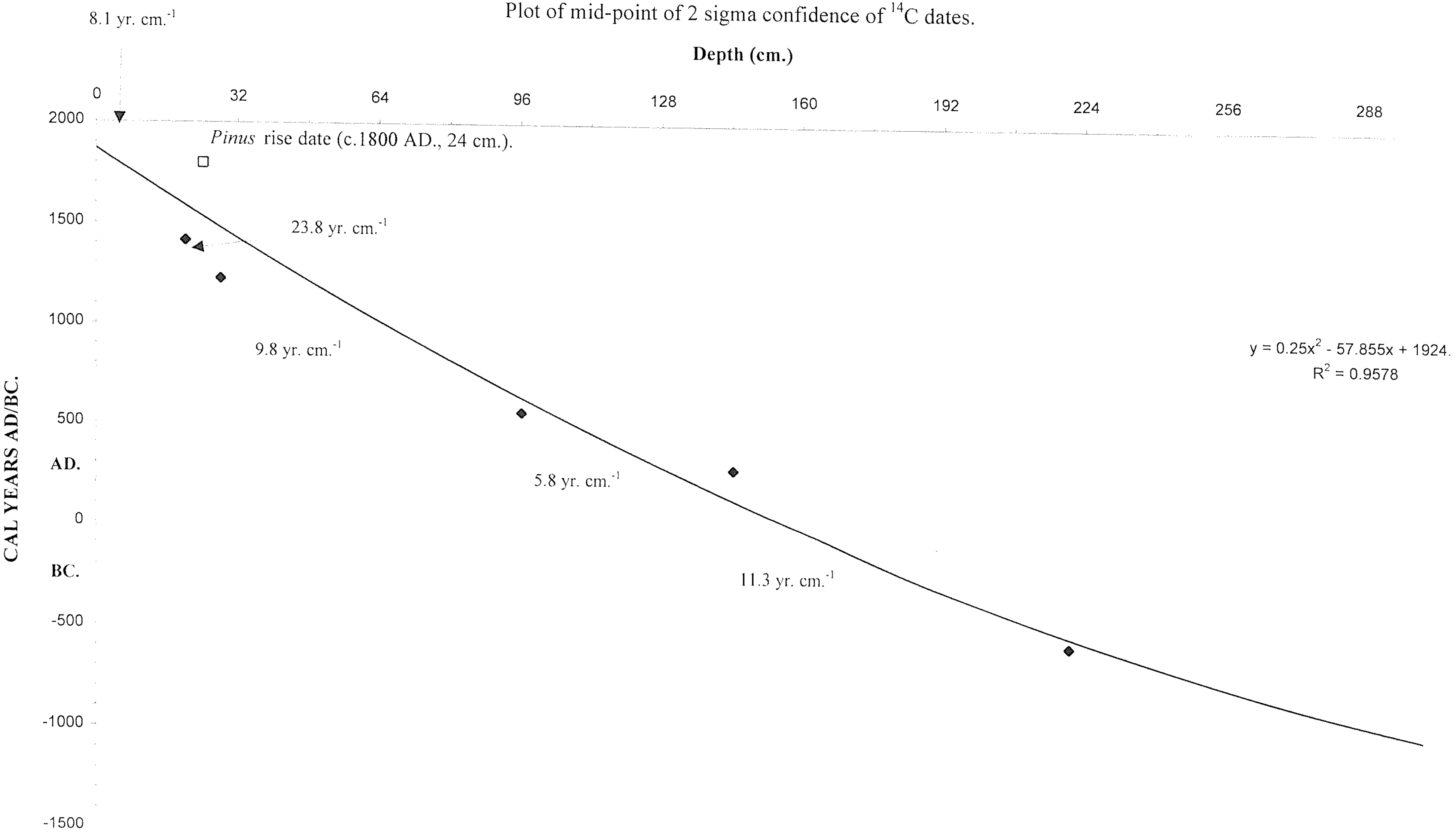


Figure 5.6 Coom Rigg Moss.

Plot of mid-point of 2 sigma confidence of ^{14}C dates.

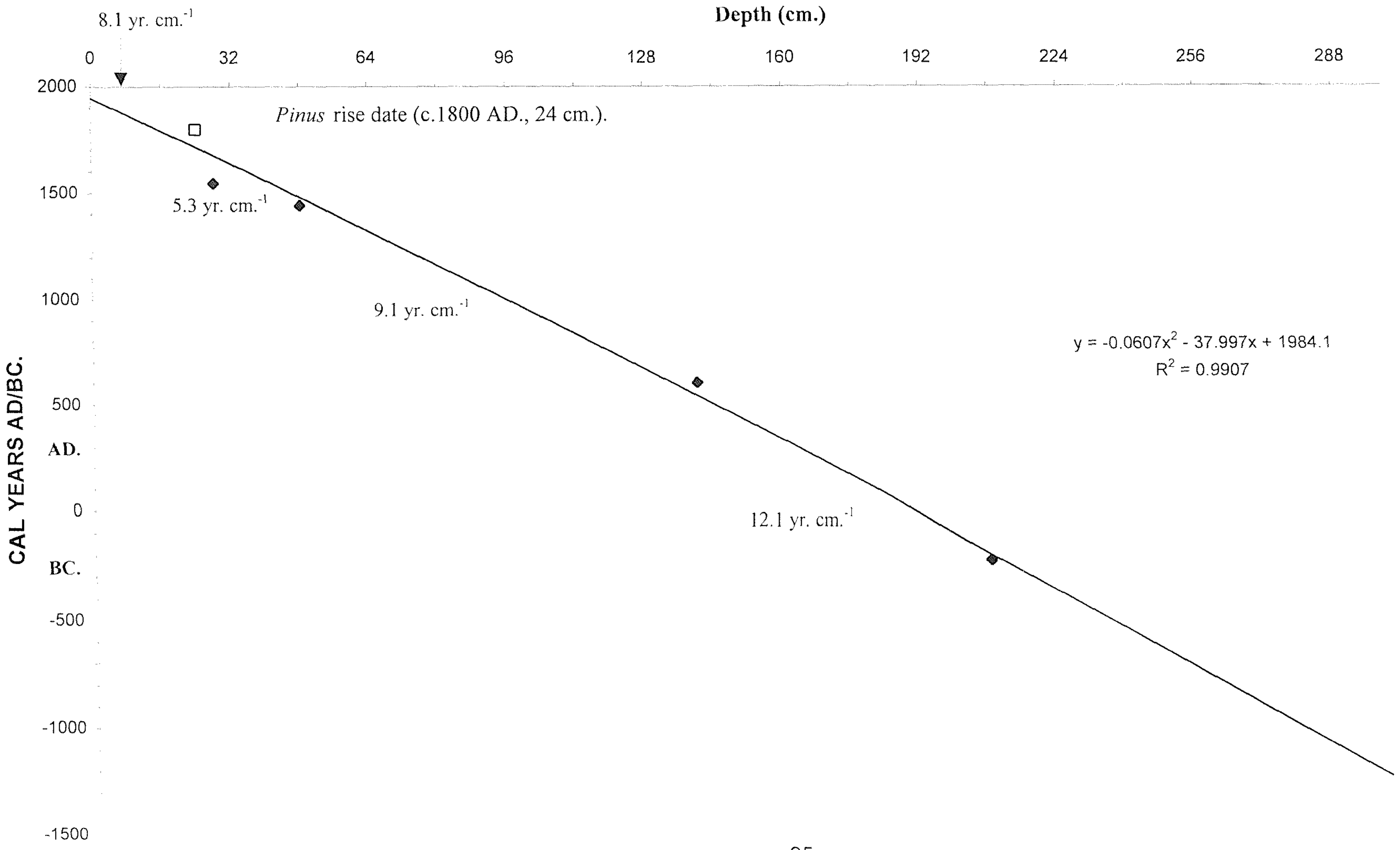


Figure 5.7 Felecia Moss.

Plot of mid-point of 2 sigma confidence of ^{14}C dates.

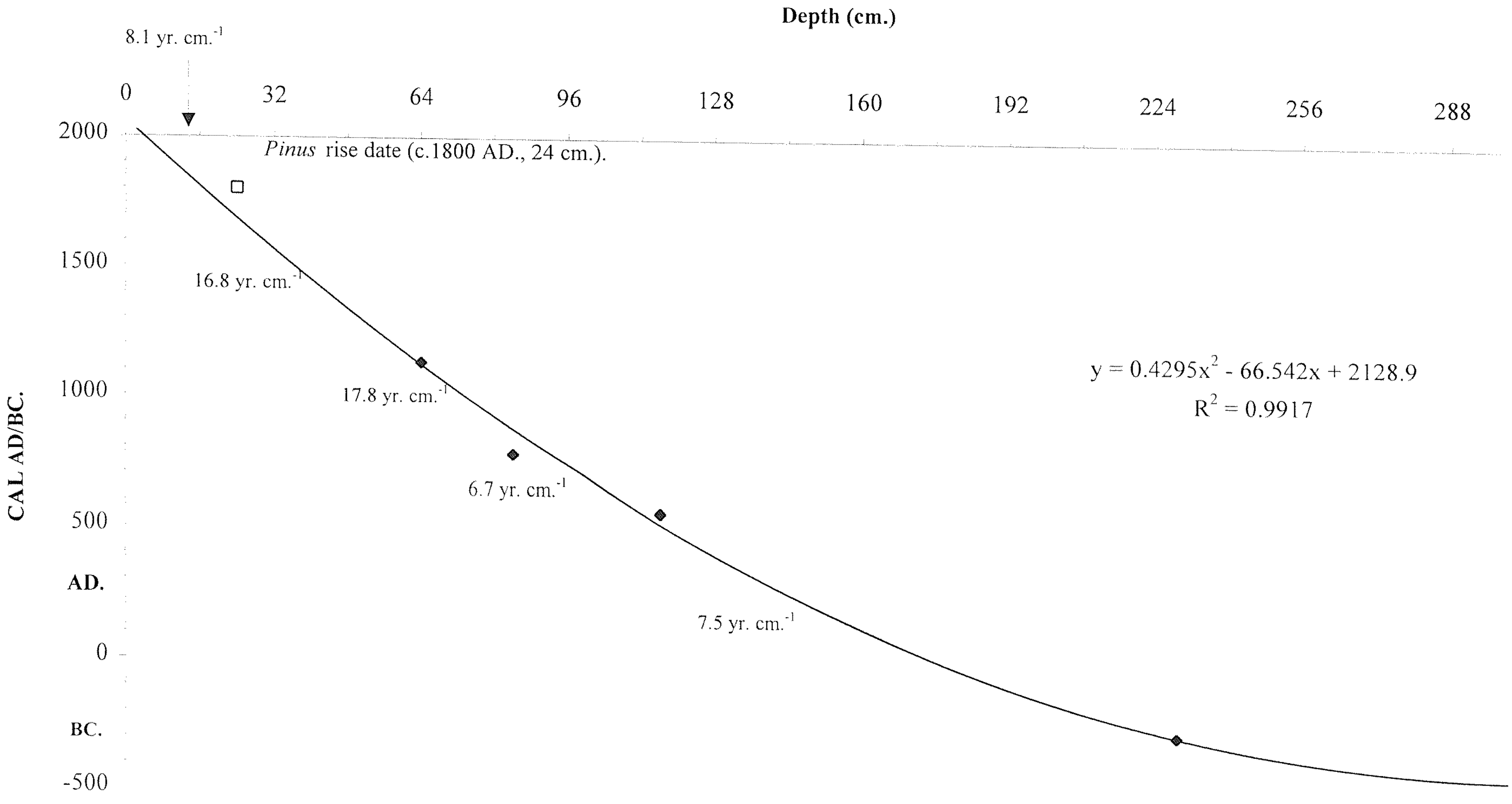


Figure 5.8 Shaft Hill - Monolith 2.

Plot of mid-point of 2 sigma confidence of ^{14}C dates.

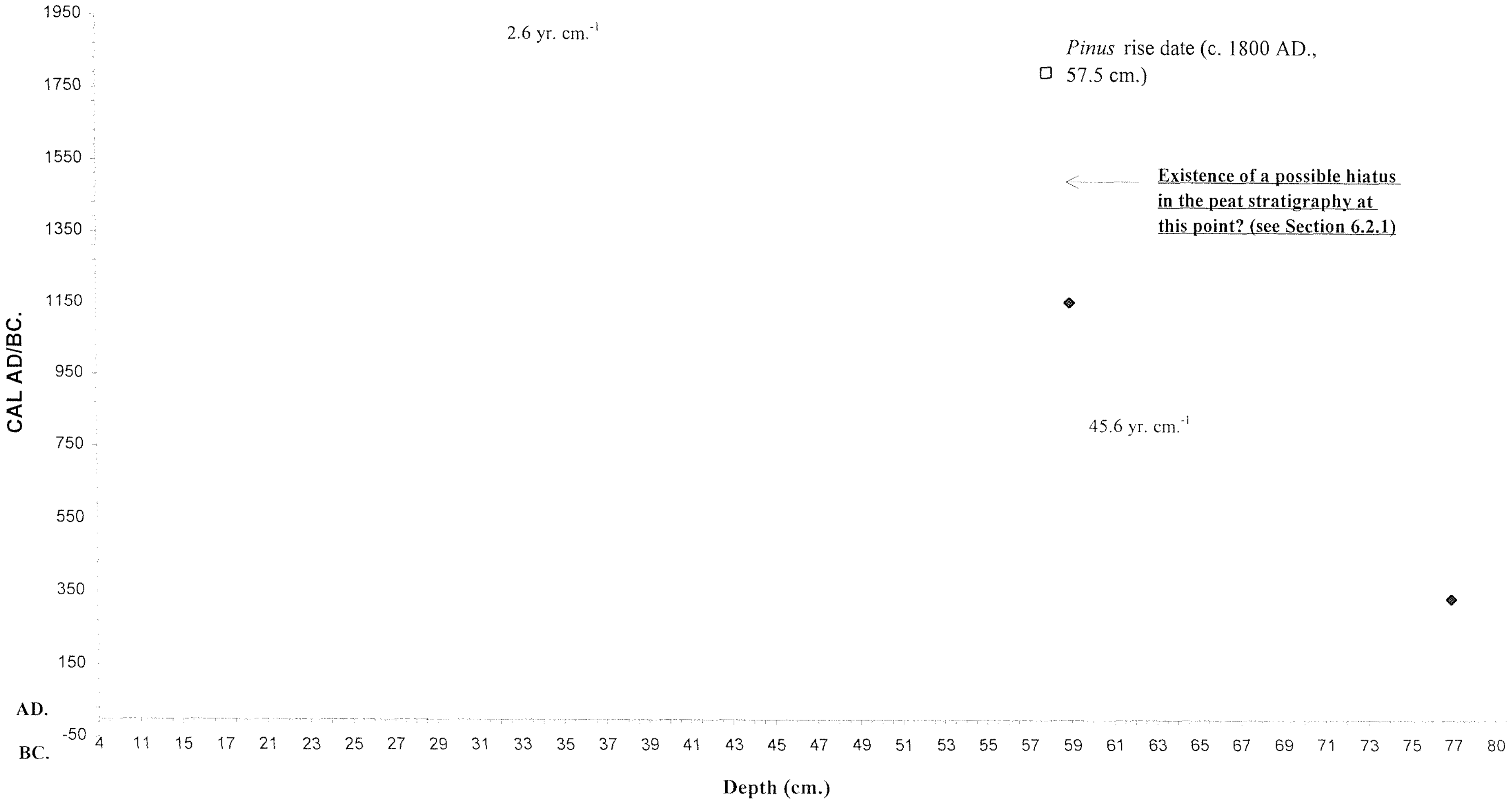


Figure 5.9 Shaft Hill - Monolith 3.

Plot of mid-point of 2 sigma confidence of ^{14}C dates.

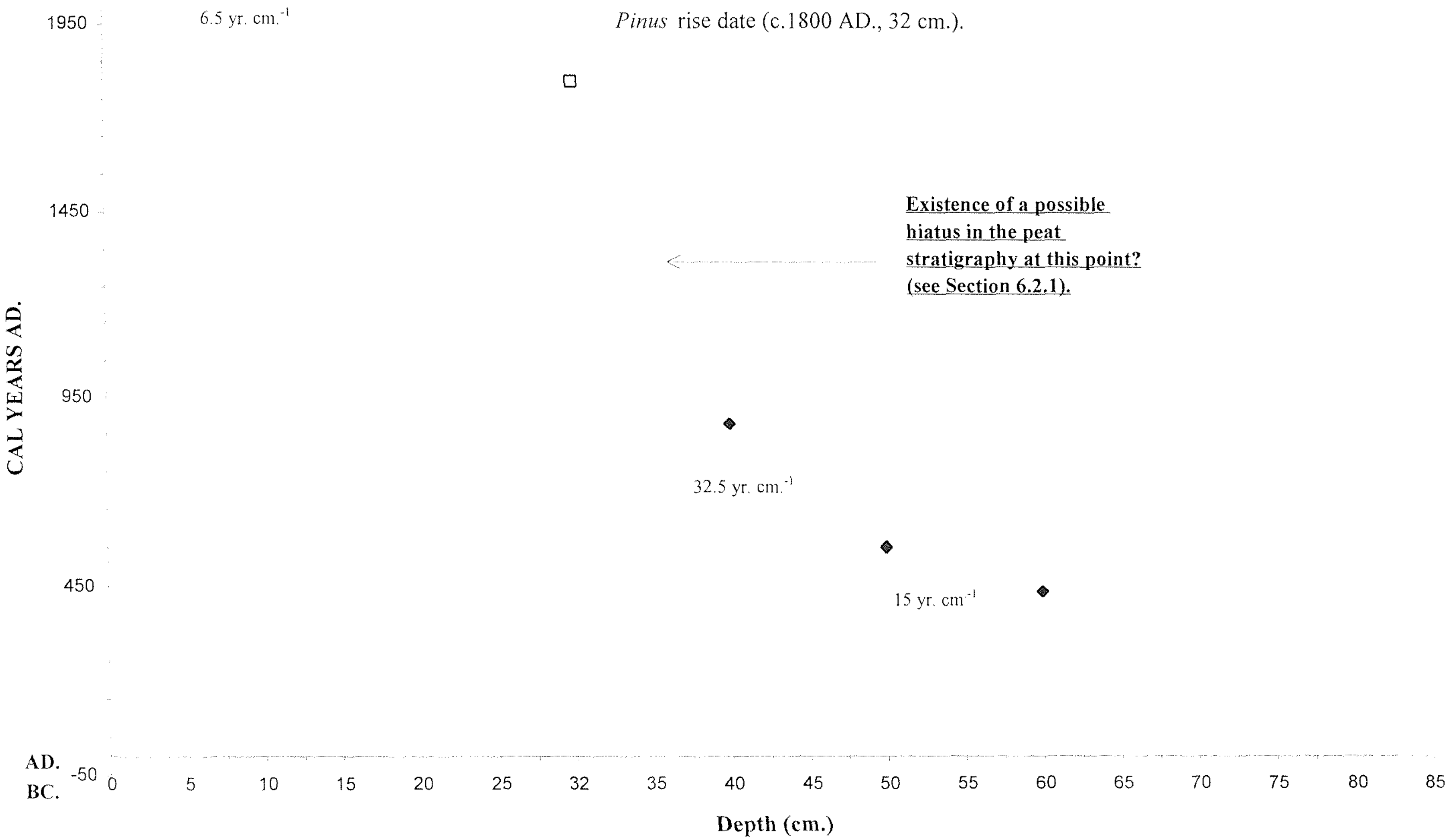
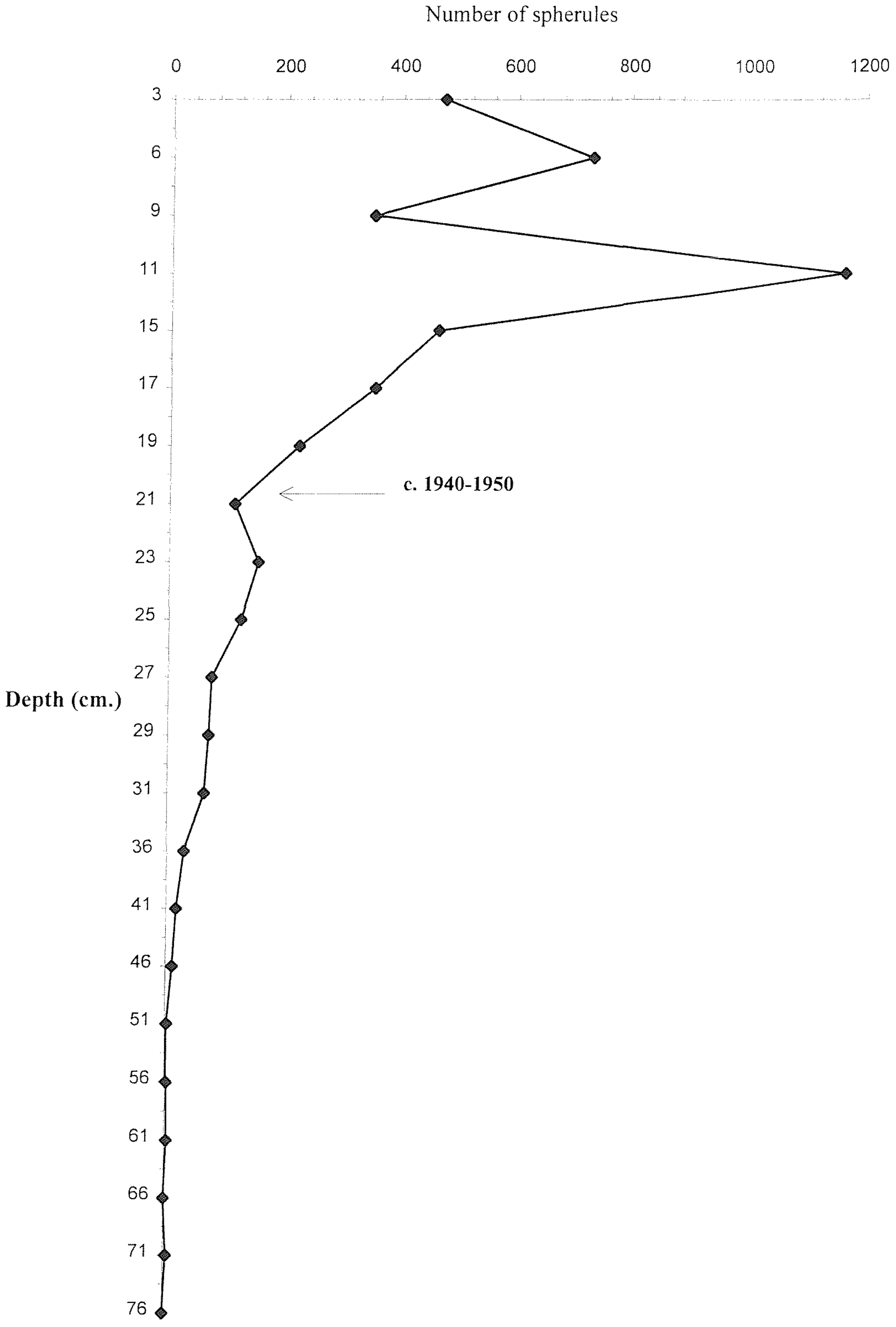


Figure 5.10 Shaft Hill Monolith 1 - SCP stratigraphy.
Analysis: Mark Garnett, Institute of Terrestrial Ecology.



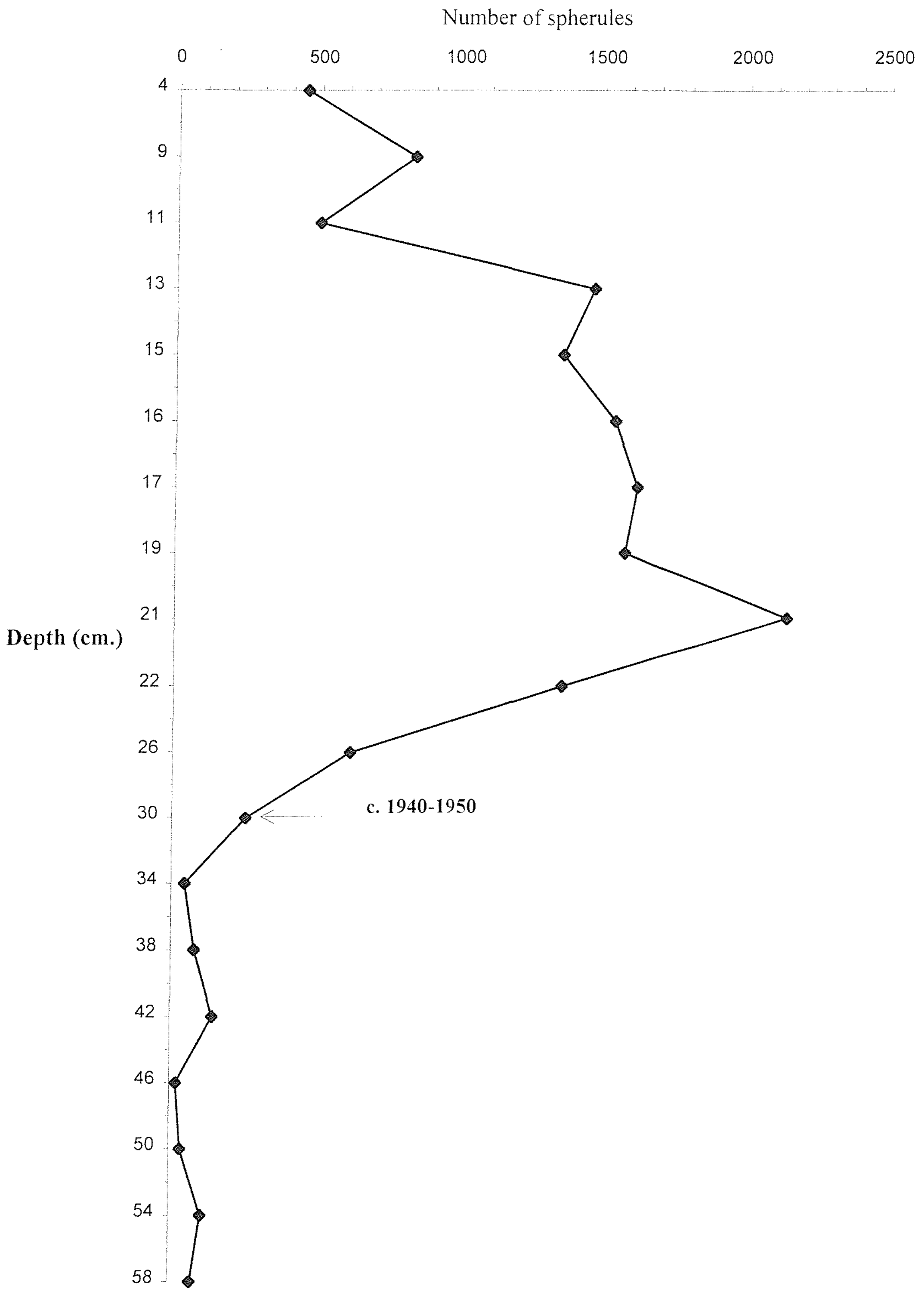
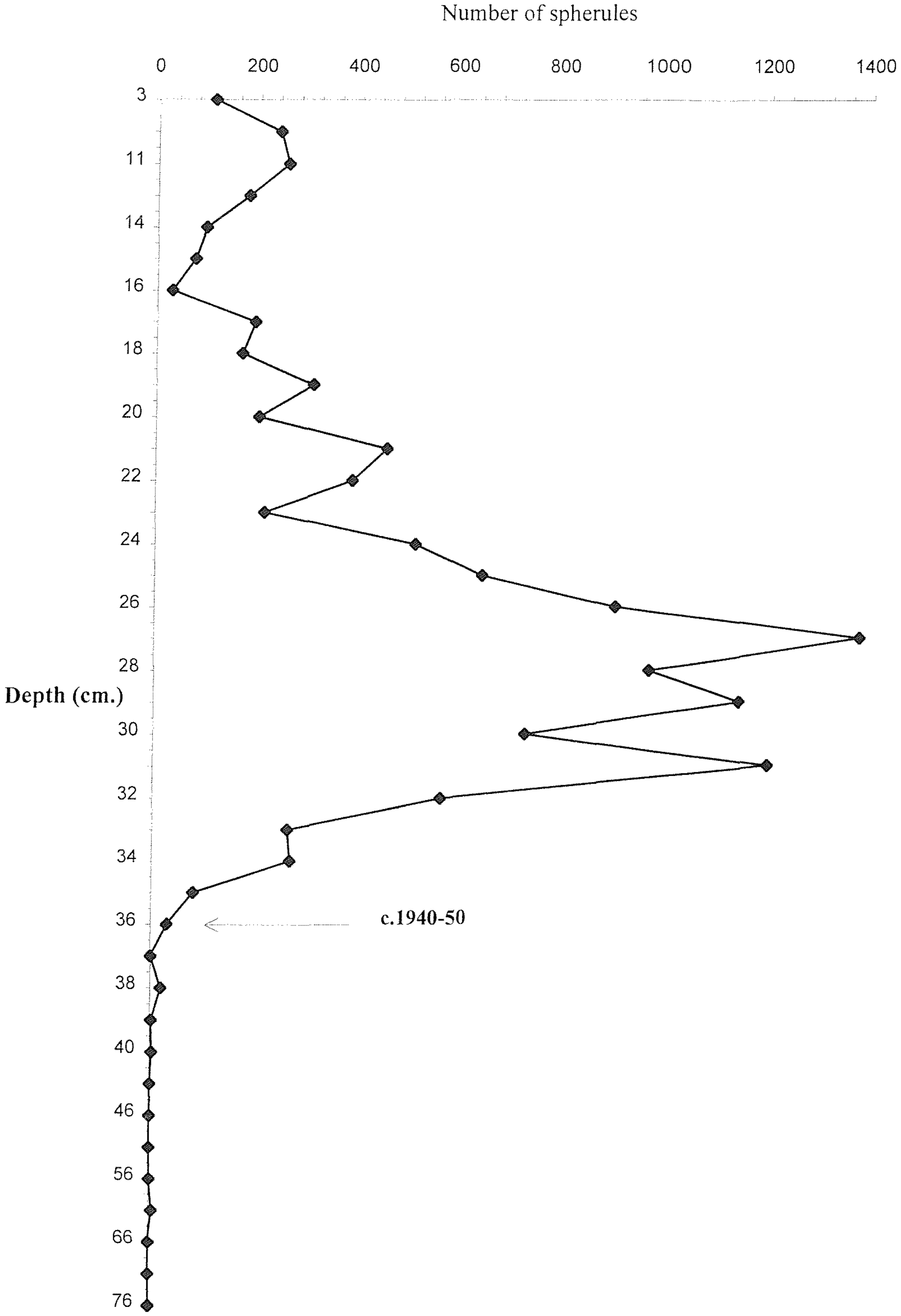


Figure 5.11 Shaft Hill Monolith 2 - SCP stratigraphy.
Analysis: Mark Garnett, Institute of Terrestrial Ecology.

Figure 5.12 Shaft Hill Monolith 3 - SCP stratigraphy.
Analysis: Mark Garnett, Institute of Terrestrial Ecology.



5.4 Humification, plant macrofossil and testate amoebae results: description and interpretation.

5.4.1 Introduction.

Diagrams produced from the colorimetric absorbance data, and the plant macrofossil and testate amoebae stratigraphy, are presented in the following sections. The palaeoecology for each site is discussed based on this data. In order to simplify this discussion, the plant macrofossil and testate amoebae diagrams have been zoned. The zonations for each plant macrofossil and testate amoebae diagram reflect the degree of mire surface wetness based on the ecology of the flora and fauna discussed in Section 5.2. Similar zonation of local vegetation assemblages has been undertaken by Van Geel (1978), Dupont and Brenninkmeijer (1984), Witte and Van Geel (1985) and Stoneman (1993). Cluster analysis techniques, where numerical methods are used to divide objects into groups, (Everitt, 1993; Maddy and Brew, 1995), can be applied to palaeoecological data sets (Gordon and Birks, 1972; Birks and Gordon, 1985). One of the most common techniques uses hierarchical methods, where clusters are arranged into a hierarchy, in the form of a branching tree or dendrogram. Although subtle changes may not be detected by numerical zonation techniques (Birks and Birks, 1980), they can at least be rapidly performed, since Tilia contains a Constrained Incremental Sum of Squares Cluster Analysis (CONISS) option (Tilia version 1.12, Grimm, 1992). This offers a starting point for a more detailed zonation scheme by eye, which has been performed for each of the plant macrofossil and testate amoebae diagrams presented. All of the zonations for the testate amoebae assemblages carry the added 'TA', to differentiate them from those derived from the plant macrofossils. For each site, all of the evidence from the three proxies (humification, plant macrofossil and testate amoebae) is first discussed separately and then together, to identify areas (if any) where they are in agreement.

5.4.2 Bolton Fell Moss - Core L.

5.4.2.1 Bolton Fell Moss - Core L - Humification data.

Contrary to the findings of Blackford (1990), there is no gradual decline of % transmission values with depth (Figure 5.13). Clymo (1984), has demonstrated that decomposition continues in the catotelm, but in this instance, this does not appear to be the case in the five metre peat column investigated. Transmission values, and therefore the degree of alkali-soluble humic decomposition substances at 488 cm., for example, are as low as values from the fresher material from the top 1.5 metres of the borehole. The predominance of *Sphagnum* leaves in the peat matrix from this borehole (Figure 5.10), and their inherent decay resistance (Section 3.4.1), may account for the lack of a depth dependent humification signal.

Pronounced low peaks occur at interpolated dates of 1850, 1070, 680, 270-220 AD., and 60, 440-490, 1010-1290, 1740-1820, and 3110 BC. The dearth of alkali-soluble decomposition products from these levels possibly indicates that the acrotelm at their time of deposition was shallow and mire surface wetness, and therefore effective precipitation, was high (see Section 3.7). High absorbance values occur at 1900, 620, 410, and 170 AD. and 350, 580, 1910 and 2830 BC., based on the age/depth model, and suggest deeper local water tables were prevalent on the bog at these times.

Figure 5.13 Bolton Fell Moss - Core L. Humification data vs. depth.

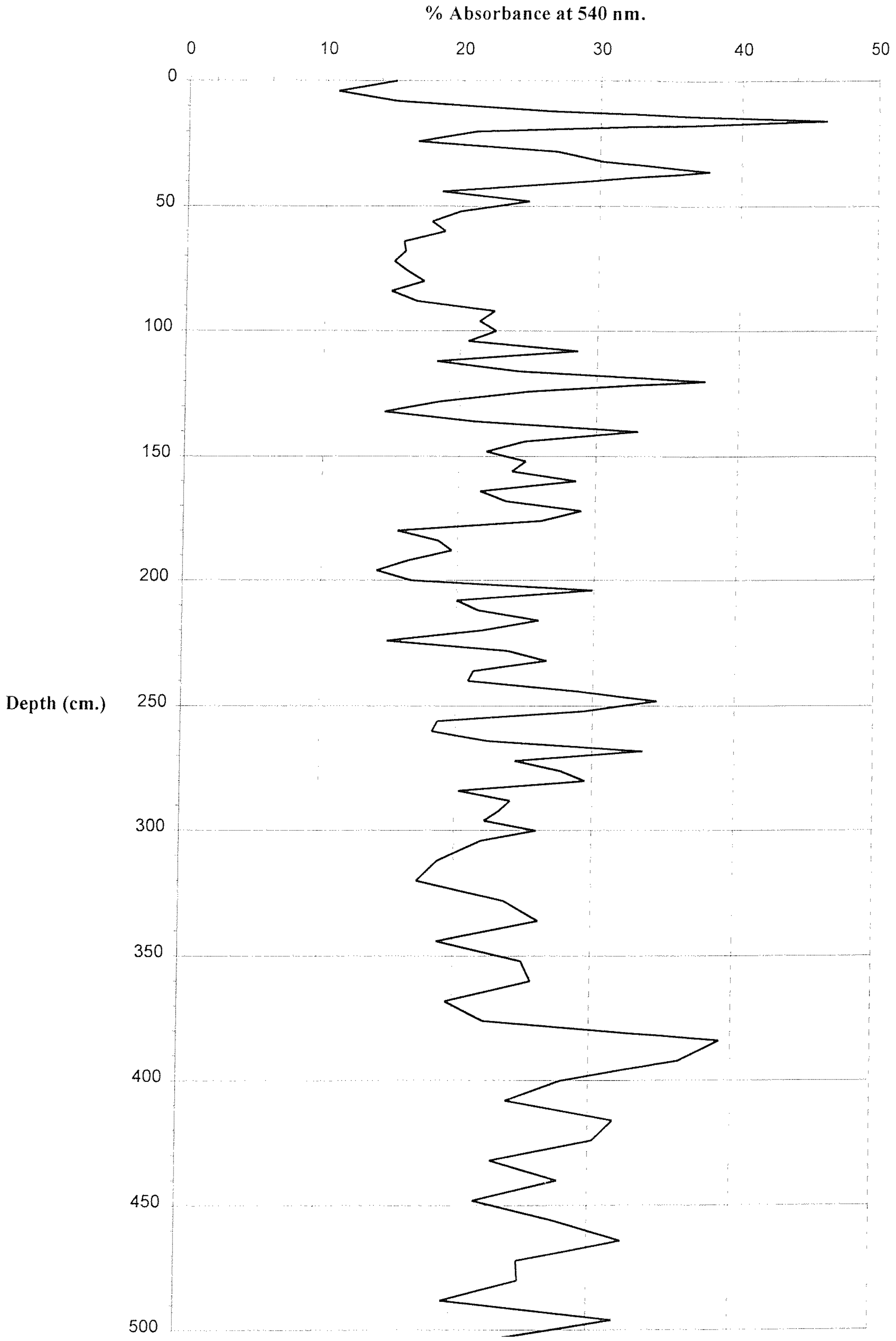
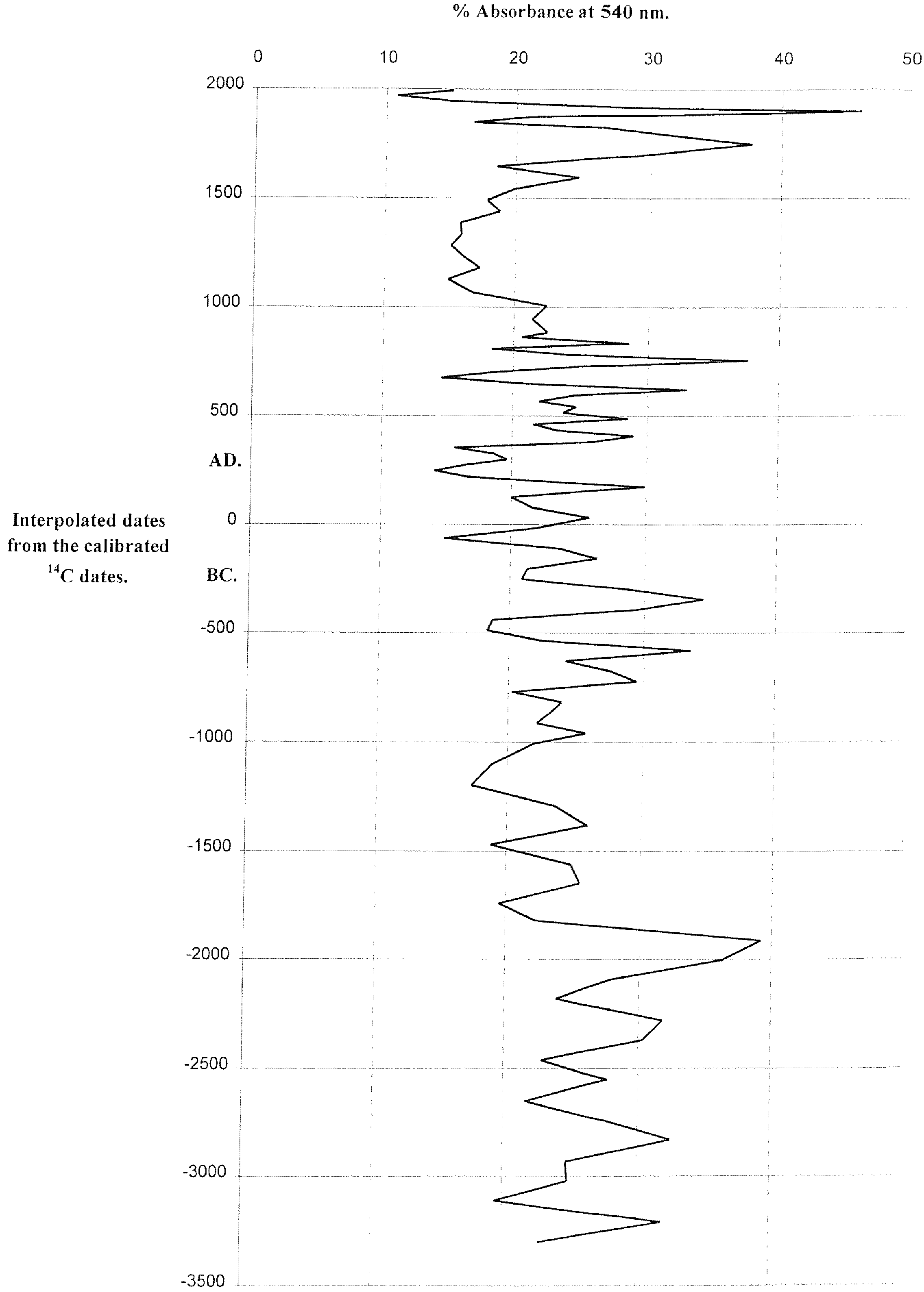


Figure 5.14 Bolton Fell Moss - Core L.
Humification data vs time.



The possibility that there may be a species dependent humification signal in the peat stratigraphy (see Section 2.3.3) is borne out to some extent from this site, as the high humification values recorded at 120 cm. are associated with a level rich in *Eriophorum vaginatum* macro-remains.

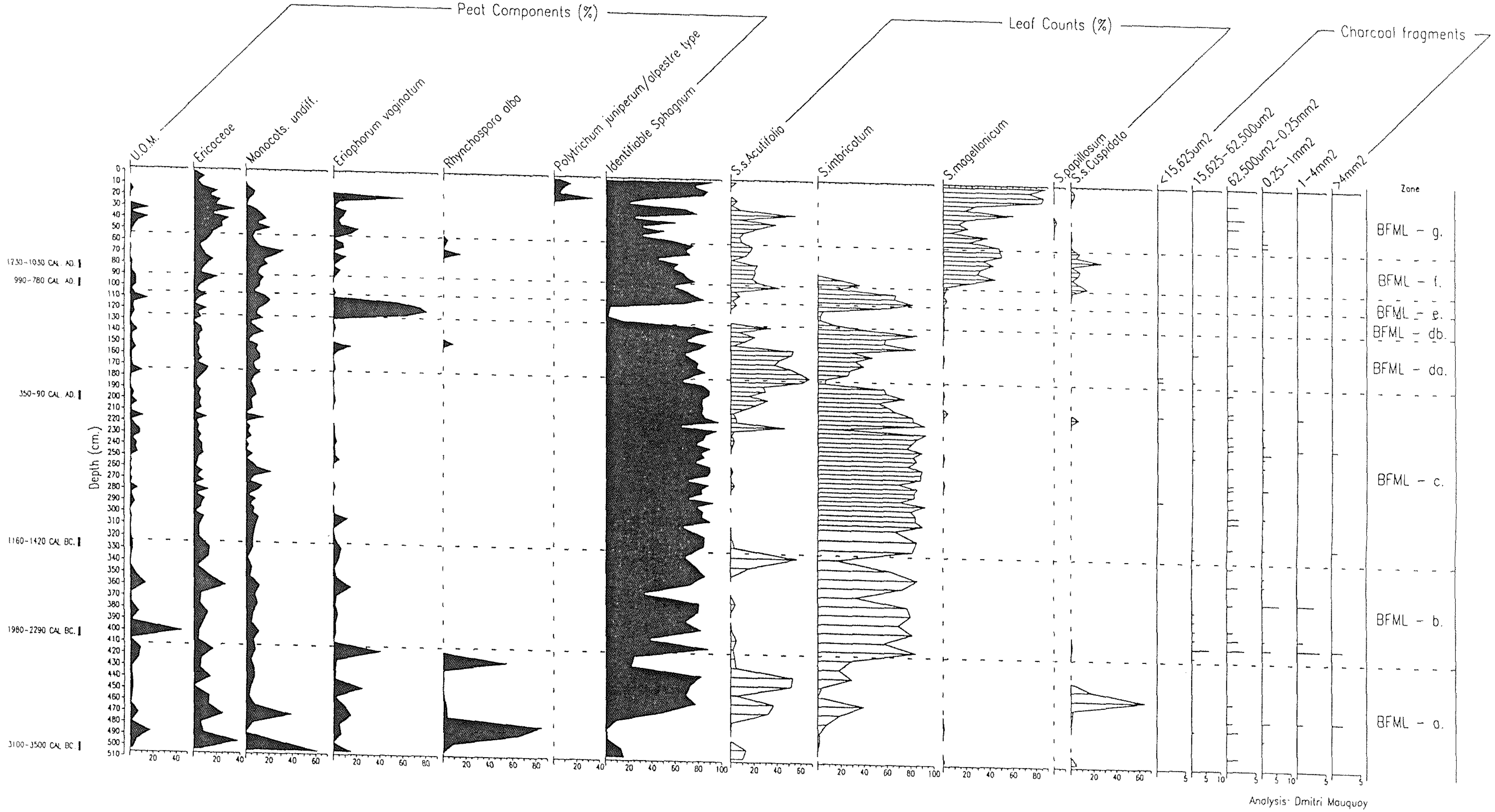
5.4.2.2 Bolton Fell Moss - Core L - Macrofossils.

Zone BFML - a. (samples 91-102, 412-504 cm.). A large peak of *Sphagnum* section *Cuspidata* leaves between 456-440 cm. indicates high mire surface wetness at this depth in the borehole. The presence of relatively abundant epidermal tissues of *Rhynchospora alba*, straddling the pool layer of *Sphagnum* section *Cuspidata* leaves, particularly at 420 and 480 cm., suggests the prolonged existence of an elevated mire water table within this zone, as this sedge usually grows in mud bottom communities (Ohlson and Malmer, 1990). The lack of bryophyte leaves recorded in the levels rich in *Rhynchospora alba* remains, corroborates the findings of Ohlson and Malmer, since it was only found in depression areas of the Swedish bog surface investigated, where it is free from interspecific competition for nutrients from Sphagna and *Eriophorum vaginatum*. The presence of scattered *Eriophorum vaginatum* epidermis, further supports the existence of a shallow acrotelm, since this sedge has the ability to grow over waterlogged mire surfaces (Section 5.2.5). Towards the top of the zone *Sphagnum imbricatum* representation increases markedly to form the predominant component (84%) of the peat matrix. The abundances within this zone of *Sphagnum* section *Cuspidata* leaves and *Rhynchospora alba* tissues are not exceeded in any of the other samples taken from the borehole, and suggest mire surface wetness was consistently high between 2230-3300 BC.

Zone BFML - b. (samples 80-90, 324-412 cm.). Leaves of *Sphagnum imbricatum* are very prevalent (up to 85%) within this zone. Attempting to reconstruct wet and dry phases based on this species alone is hazardous, however, as it has been shown in both experimental and palaeoecological contexts to survive in both aquatic and hummock microtopes (Tallis, 1961; Green, 1968, Van Geel, 1978; Barber, 1981; Haslam, 1987). Ericaceae and *Eriophorum vaginatum* abundances have not changed appreciably from the succeeding zone and therefore yield few clues, although the disappearance of *Rhynchospora alba* and *Sphagnum* section *Cuspidata* macrofossils, does suggest a reduction in mire surface wetness. Combined with this negative evidence, there is a relatively large peak of U.O.M. at 400 cm. (2090 BC.) which may have arisen through greater aerobic decomposition under a deeper mire acrotelm.

Zone BFML -c. (samples 45-79, 174-324 cm.). Sphagnum imbricatum leaves dominate almost uninterrupted the entire zone, which spans from 410 AD. to 1240 BC, with the exception of levels extending from 216 cm. to 172 cm., where there is increased representation of *Sphagnum* section *Acutifolia* and a reciprocal decline of *S. imbricatum*. The prolonged exclusion of other Sphagna in this zone is not atypical; the longevity of *S. imbricatum* domination has been established by Van Geel (1976), for a Dutch mire remnant, where it was shown to have extended for a period of 475 years (825 BC. - 300 AD.). An even longer assemblage of *S. imbricatum* and *Sphagnum* section *Acutifolia* leaves spanning 3300 calibrated radiocarbon years (c. 2500 BC. to 800 AD.), existed on Cranley Moss, near Lanark, Scotland (Stoneman, 1993).

Figure 5.15 Bolton Fell Moss – Core L. Macrofossil diagram.



Zone BFML -da. (samples 33-44, 126-174 cm.). The combined presence of both *Sphagnum* section *Acutifolia* and *Sphagnum imbricatum* leaves in quantity, makes it difficult to reconstruct the degree of mire surface wetness within this zone. Epidermal tissues of *Rhynchospora alba* at 148 cm. (8.5% of the peat matrix), do, however, suggest a relatively high water table. The interpolated date for this level is 570 AD.

Zone BFML -db. (samples 29-32, 110-128 cm.). Sphagnum species are displaced by *Eriophorum vaginatum* fibres, which form a considerable part of the peat matrix. In this instance, a tussock of this sedge may have existed on the mire surface. The Ericaceae and U.O.M. components do not increase markedly in this zone, and do not therefore support the existence of a drier mire surface. Rather than indicating a change in hydrological conditions, *Eriophorum vaginatum* may simply have spread laterally from existing hummocks. Sections of exposed peat faces have been examined by Barber (1981), which demonstrate this lateral expansion.

Zone BFML -e. (samples 24-28, 90 -110 cm.). The *Eriophorum* tussock is overgrown by both *Sphagnum* section *Acutifolia* and *Sphagnum imbricatum* leaves to form a possible lawn, primarily composed of the latter species (up to c. 67% of the peat matrix). The absence of *Sphagnum* section *Cuspidata* leaves, and the moderate presence of U.O.M. and Ericaceae, suggest an intermediate degree of mire surface wetness. A similar instance where an *Eriophorum* tussock has been covered by a fresh *Sphagnum* sward has been noted by Tolonen (1971).

Zone BFML -f. (samples 15-23, 54-90 cm.). A very pronounced feature of the stratigraphy here, is the extinction of *Sphagnum imbricatum* and its replacement by *Sphagnum magellanicum.* This occurs rapidly between 80 and 84 cm., and has been dated to CAL 1030-1230 AD. (SRR-5887). Barber (1981, p155) places the extinction of *Sphagnum imbricatum* in monolith HI9 to 'the early 1200's', whilst the 2 σ age range for its demise in Profile J from Bolton Fell Moss (Barber *et al.*, 1994e) is CAL 1034-1260 AD. (SRR-4560). Both these dates agree very well with the 2 σ date range determined here, and offer further evidence for the synchronous response of lowland raised mires to climatic forcing. There is a clear wet phase associated with the extinction of the former species, as relatively large abundances of *Sphagnum* section *Cuspidata* leaves were recovered here, along with some *Rhynchospora alba* epidermis (c.15% of the peat matrix), at 68 cm.

Zone BFML -g. (samples 1-14, 0-54 cm.). Leaves of *Sphagnum magellanicum* occur abundantly, along with a very small percentage (c. 2%) of *Sphagnum papillosum* leaves. An increase in the representation of Ericaceae, and relatively large amounts of *Polytrichum juniperum/alpestre* leaves (section 5.2.9), invites the possibility that mire surface wetness was drier within this zone.

5.4.2.3 Bolton Fell Moss - Core L - Testate amoebae stratigraphy.

Zone BFML -TA-a (samples 46-52, 396-464 cm.) There are abundant tests of *Amphitrema flavum* throughout this zone (Figure 5.16) and two marked peaks of *Amphitrema wrightianum* tests at 400 and 424 cm. The presence of these species and up to 11% of *Hyalosphenia papilio* tests indicate high mire surface wetness (Section 5.2.19). Similar palaeoecological inferences have been made by Dupont and Brenninkmeijer (1984), Joosten (1985), and Dupont (1986), based on the presence of *A. flavum* thecae. Van der Molen and Hoekstra (1988), recovered high numbers of *A. wrightianum* from a peat section taken from the Engbertsdijksveen, and interpreted this as a high mire water level phase. Associated with these levels were *Sphagnum cuspidatum* leaves and *Eriophorum angustifolium* remains, which support their hydrological reconstruction.

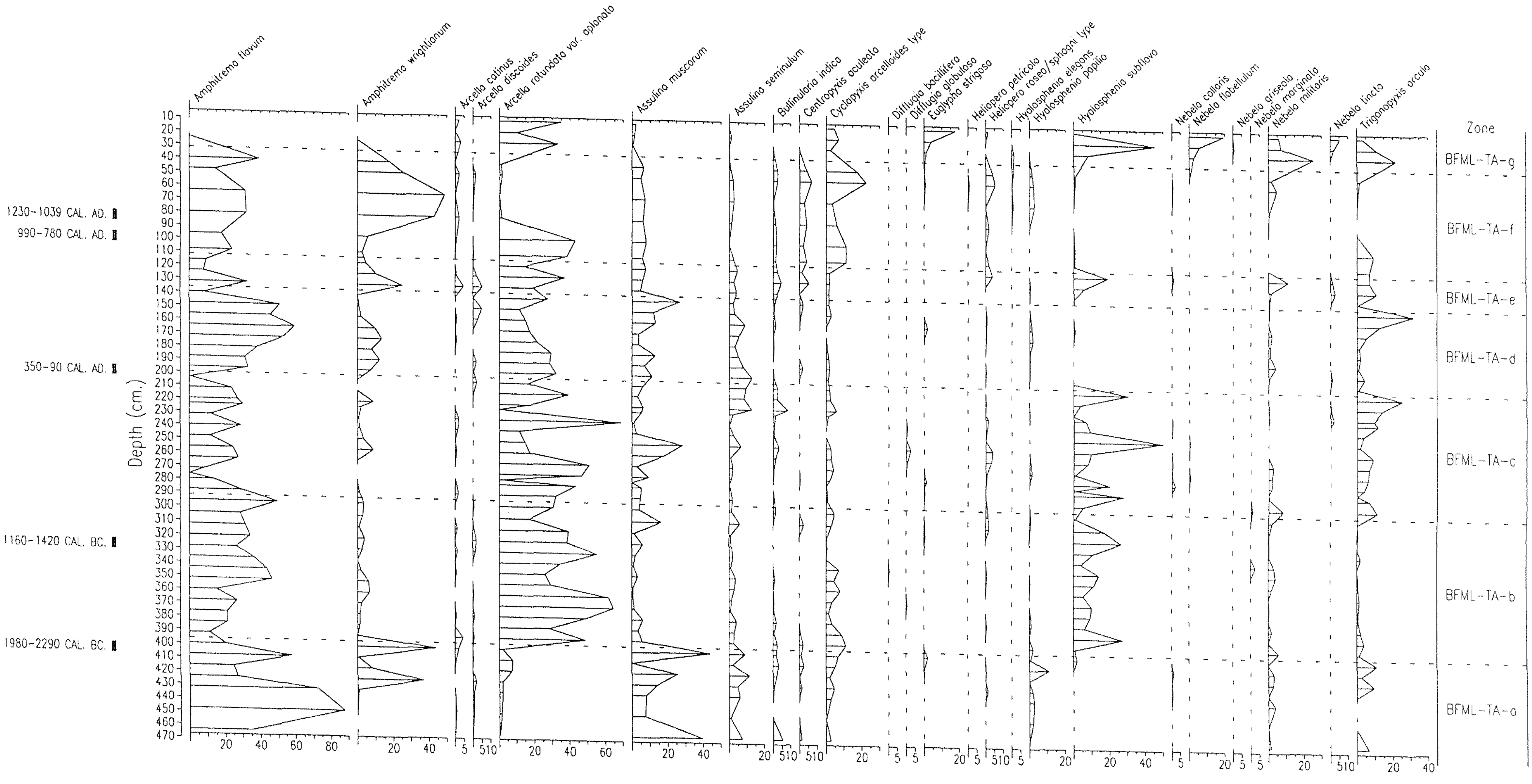
Zone BFML -TA-b (samples 33-45, 292-396 cm.). Tests of *Hyalosphenia subflava* appear for the first time, and reach relatively high abundances (27%). Thecae of these species indicate relatively dry mire surface conditions, as they are found both near to the margins of bogs and in disturbed parts of bogs (Grospietsch, 1972). Beyens (1985) has interpreted their presence in sub-fossil peat from a site in the valley of the Mark river, Belgium, to indicate dryness, and possible dry summers, during the Subboreal ± 4680 BP until ± 4350 BP. A reciprocal decline in *Amphitrema flavum* and *A. wrightianum* tests supports the existence of drier mire surfaces within zone *BFML -TA-b.*

Zone BFML -TA-c (samples 21-32, 200-292 cm.). Further declines in the numbers of *Amphitrema flavum* and *A. wrightianum* tests recovered from the peat matrix suggest even drier mire surface conditions within this zone. Abundances of *Hyalosphenia subflava* remain relatively high, particularly at 240 cm. (250 BC.), where they comprise 50% of the thanatocenoese, whilst abundances of *Trigonopyxis arcula* increase markedly. This latter species is also characteristic of drier microsites (De Graaf, 1956), and was found in the driest moss samples investigated by Warner and Charman (1994), indeed, it was the most 'xeric' of the 30 species examined in this instance.

Zone BFML -TA-d (samples 13-20, 136-200 cm.). Increased representation of *Amphitrema flavum* and *A. wrightianum* thecae and marked reductions in the numbers of *Hyalosphenia subflava* tests (their maximum abundance was 1% of the testate amoebae sum, and in 8 of the samples they were absent), suggests an increase in mire surface wetness.

Zone BFML -TA-e (samples 10-12, 112-136 cm.). Drier mire surface conditions appear to have returned in this zone, as there is an increase in *Hyalosphenia subflava* and *Nebela militaris* tests, and a reciprocal decline in those of *Amphitrema flavum* and *A. wrightianum. Nebela militaris* tests form 11% of the rhizopod assemblage, and given their preponderance in bog hummocks and microsites with a relatively deep acrotelm (Heal, 1961; Tolonen *et al.*, 1992), the possibility that the mire surface was dry is strengthened.

Figure 5.16 Bolton Fell Moss – Core L. Testate amoebae.



Analysis: Dmitri Mauquoy

Zone BFML -TA-f (samples 4-9, 32-112 cm.). An extremely wet phase based on the testate amoebae stratigraphy is apparent, as tests of *Amphitrema wrightianum* exceed those of *A. flavum*. Associated with this increase in hygrophilous species is a decline of xerophile *Hyalosphenia subflava, Nebela militaris* and *Trigonopyxis arcula* tests.

Zone BFML -TA-g (samples 1-3, 8-32 cm.). A possible marked change to a drier mire surface is indicated by the rhizopods from the top sections of the borehole, as in addition to relatively large numbers of *Hyalosphenia subflava,* there are increases in tests of *Nebela flabellulum, N. militaris, N. tincta* and *Trigonopyxis arcula.* Analysis of modern, surface moss samples by Corbet (1973) and Tolonen *et al.* (1994) corroborates this hydrological reconstruction. Corbet recovered tests *of Nebela flabellulum* from bog hummocks, whilst Tolonen *et al.*, identified *Nebela militaris and N. tincta* thecae from hummock top samples.

5.4.2.4 Bolton Fell Moss - Core L - Summary of the humification, plant macrofossil and testate amoebae results.

A clear feature of the stratigraphy of this site is the replacement of *Sphagnum imbricatum* at CAL 1030-1230 AD. (SRR-5887) by *Sphagnum magellanicum*, via a wet phase. This is evident from both the plant macrofossil *(BFML -f)* and testate amoebae stratigraphy *(BFML-TA-f)*, and is also evident from the humification data, as low absorbance values occur at 1280 AD. These results are very encouraging, as all three hydrological proxies indicate the same direction of change. Following this wet shift, and the extinction of *Sphagnum imbricatum*, the bog surface has become drier, based principally on the presence of *Polytrichum alpestre/juniperum* type leaves and *Hyalosphenia subflava* tests, and high absorbance values at 16 and 36 cm., which have interpolated dates of 1920 AD. and 1750 AD. respectively.

A second clear feature in the stratigraphy, is the evidence for wetter conditions at the base of the borehole in zones *BFML - a* and *BFML-TA-a,* which contains hygrophilous *Sphagnum* section *Cuspidata* leaves, *Rhynchospora alba* epidermis and abundant *Amphitrema flavum* tests.

The stratigraphy between these two zones is dominated by *Sphagnum imbricatum* leaves, making mire hydrological reconstructions difficult, but the presence of *Hyalosphenia subflava* thecae in both zones *BFML-TA-b* and *c*, suggests a drier mire surface from 250 AD. to 2090 BC. High humification values at 345 AD., 580 BC. and 2090 BC., offer support to this hydrological reconstruction, although low peat humification values were recorded at 1195 BC., 1470 BC., and 1735 BC. These values suggest that this long period of dryness was punctuated by wetter intervals, or possibly, that mire water levels fluctuated to a degree, allowing both good peat preservation and optimal habitats for *Hyalosphenia subflava.* There is equally the possibility, that one or perhaps both of the proxies do not reflect accurately the degree of mire surface wetness. On a more encouraging note, both the humification data from 132, 180 and 196 cm. (680, 350 and 250 AD. respectively), and the rhizopod stratigraphy from zone *BFML-TA-d*, indicate the same direction of change to increased mire surface wetness, with low absorbance values and increases in *Amphitrema flavum* and *A. wrightianum* tests.

5.4.3 Walton Moss - Core 11.

5.4.3.1 Walton Moss - Core 11 - Humification data.

Pronounced low peaks in the humification absorbance values occur at 1800, 1130, 660, and 280 AD., and 180, 550, 1070, 1690, 2040, and 2600 BC. (Figure 5.16), suggesting the former occurrence of high mire water levels at these depths. The humification curve from this site, in comparison to that from Bolton Fell Moss - Core L, displays larger swings from peat rich in decomposition macromolecules to relatively fresh peat containing a dearth of this material. The possible reason for these higher magnitude changes may be due to the increased presence of *Eriophorum vaginatum* at this site.

There does appear to be some correspondence between levels rich in this sedge and high humification values (80, 96, 176, 208, 308 and 324 cm.). This may be due to higher rates of decomposition and recycling of nutrients within *Eriophorum vaginatum* tussocks (Chapin *et al.*, 1979). There are equally areas, however, where colorimetric absorbance values are high, for example from 236-248 cm. (690-830 BC.), which contain negligible quantities of *E. vaginatum*. In this case, there may not be a species dependent humification signal, or the levels from 236-248 cm. may truly reflect the existence of former drier mire surfaces.

5.4.3.2 Walton Moss - Core 11 - Macrofossils.

Zone WLM - 11a. (samples 91-101, 416-500 cm.). Eriophorum vaginatum and *Sphagna*, principally *Sphagnum imbricatum* with some *Sphagnum* section *Acutifolia,* have alternately replaced each other within this zone, which extends from 2390-3080 BC. The presence of up to 77% U.O.M. at the base of the zone, and scattered occurrences of *Aulacomnium palustre* (Section 5.2.10), suggests the possible existence of a relatively dry hummock. This bryophyte is recorded in sub-fossil levels with diminished identifiable *Sphagnum*, possibly reflecting the weak competitive ability of this species in *Sphagnum* rich swards (Li and Vitt, 1995).

Zone WLM - 11b. (samples 82-90, 344-416 cm.). Sphagnum imbricatum dominates this zone, and the representation of U.O.M., Monocots. undiff, *Eriophorum vaginatum* and *Aulacomnium palustre* declines. In this instance, mire surface wetness could have possibly been higher, and the lawn ecad of *Sphagnum imbricatum* (Tallis, 1961; Green, 1968) may be present in the peat stratigraphy. This section of the bog spanning the assemblage zone seems to have completely escaped from local fires, as there is a total absence of macroscopic charcoal. Walton Moss exceeds 2 km. in diameter, however, and given the short 'skip' distances of macroscopic fusain particles (less than 400 m. for larger particles up to 0.277 mm, Wein *et al.*, 1987), there is every possibility that other parts of the bog of the same age could have been burnt.

Zone WLM - 11c. (samples 77-81, 304-344 cm.). Sphagnum imbricatum leaves are relatively scarce in this zone, and their place has largely been taken by leaves of *Sphagnum* section *Acutifolia.* Relatively large abundances of sub-fossil *Eriophorum vaginatum* may suggest a degree of fluctuation of bog water levels, as *E. vaginatum* can grow on microtopes which support surface water levels in the spring and lower water levels in

Figure 5.17 Walton Moss - Core 11. Humification data vs. depth.

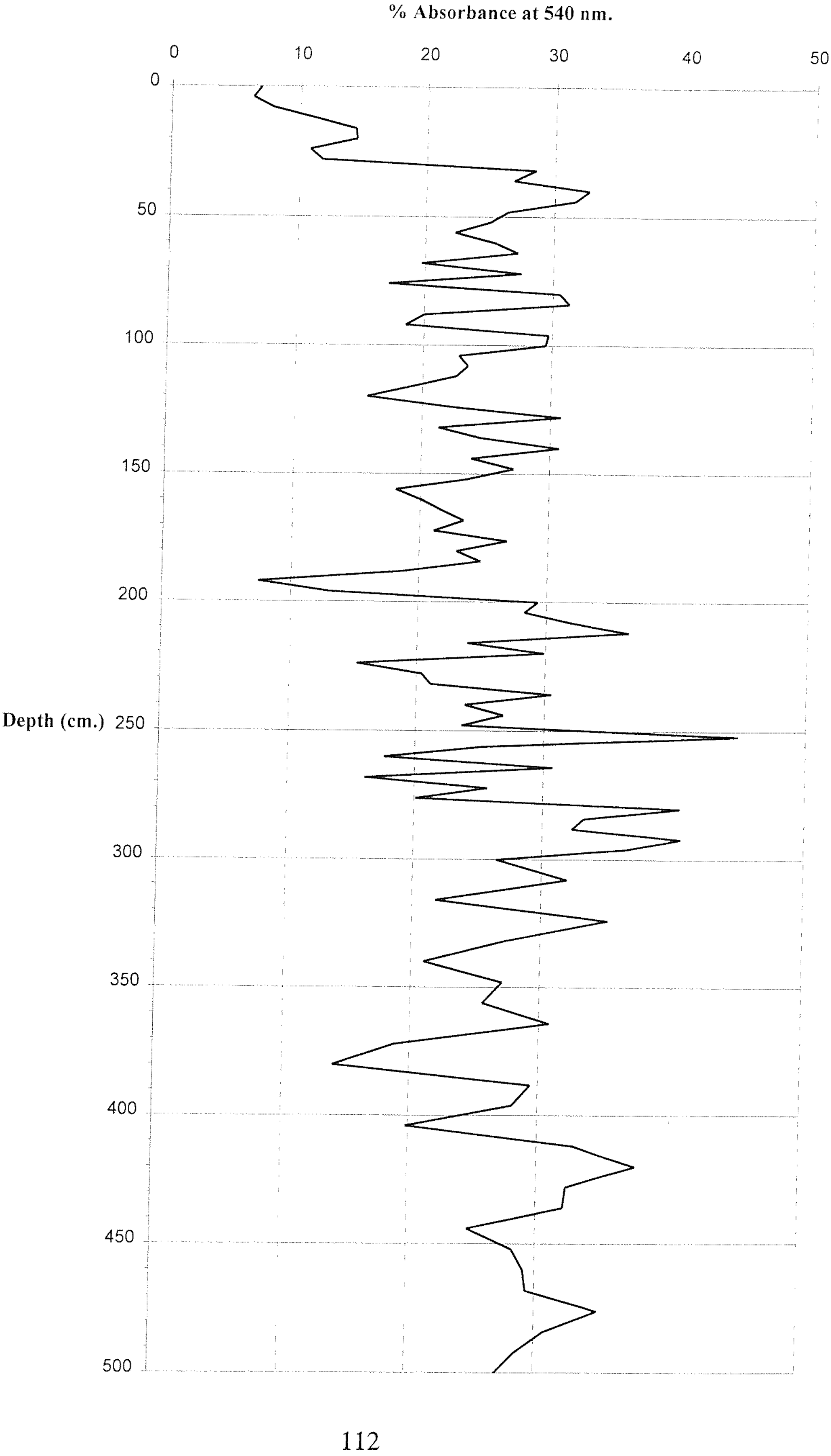
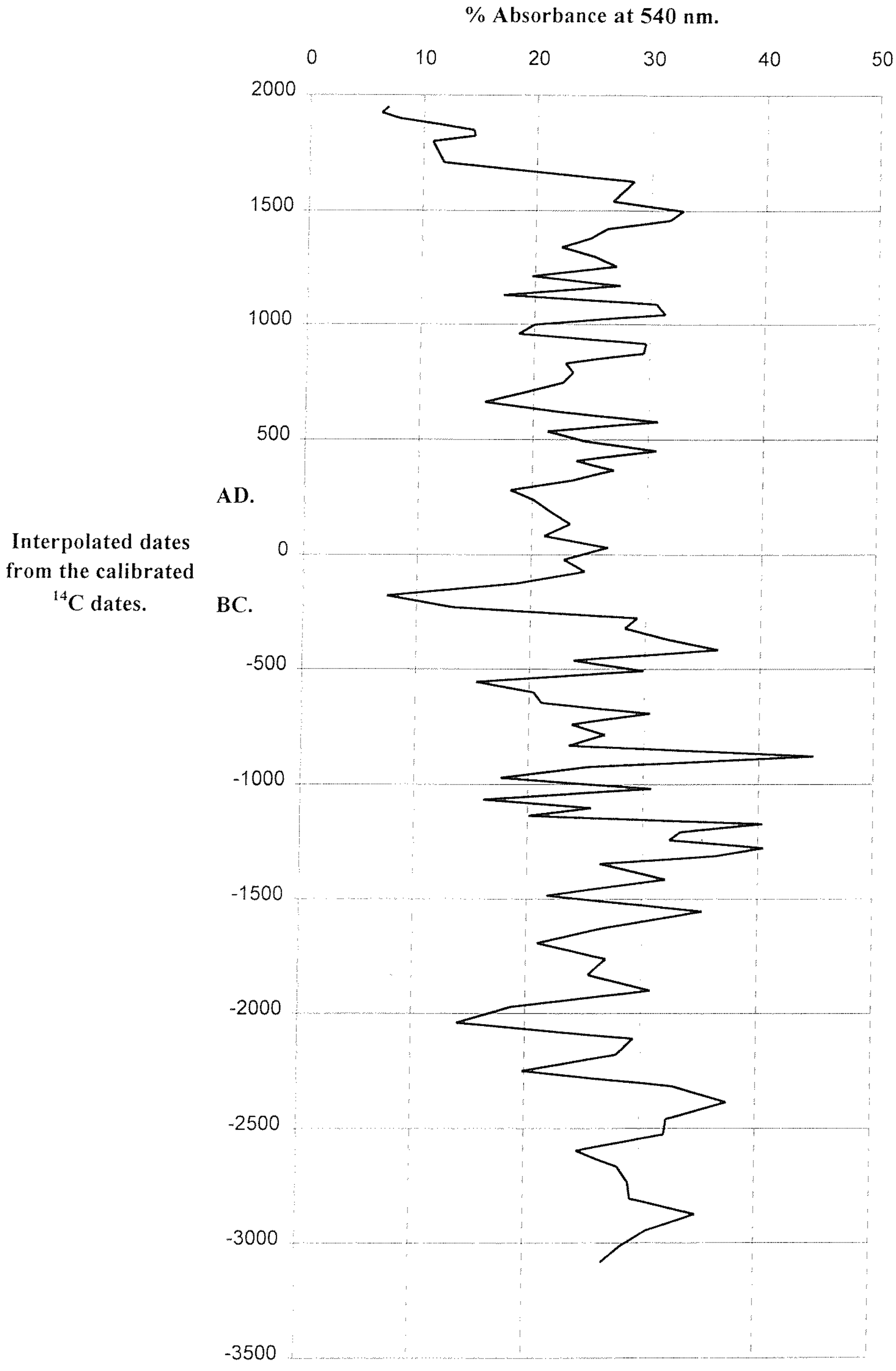


Figure 5.18 Walton Moss - Core 11 - Humification data vs. time.



the summer (Tansley, 1939; Gimingham, 1964; Wein, 1973). Clearly in this instance, it is difficult to assess mire surface wetness, but low U.O.M. values and the recovery of the hygrophilous sedge, *Rhynchospora alba* at 324 cm., does support the existence of a relatively wet mire surface.

Zone WLM - 11d. (samples 66-76, 258-304 cm.). The highest abundances of Ericaceae and *Aulacomnium palustre* are recorded in this zone (up to c. 32% and 19% respectively), and their presence in the peat matrix suggests possible hummock microtope conditions. Abundances of *Sphagnum* section *Acutifolia* are high, and there is a possibility they represent either *Sphagnum fuscum* or *Sphagnum capillifolium* var. *rubellum* leaves.

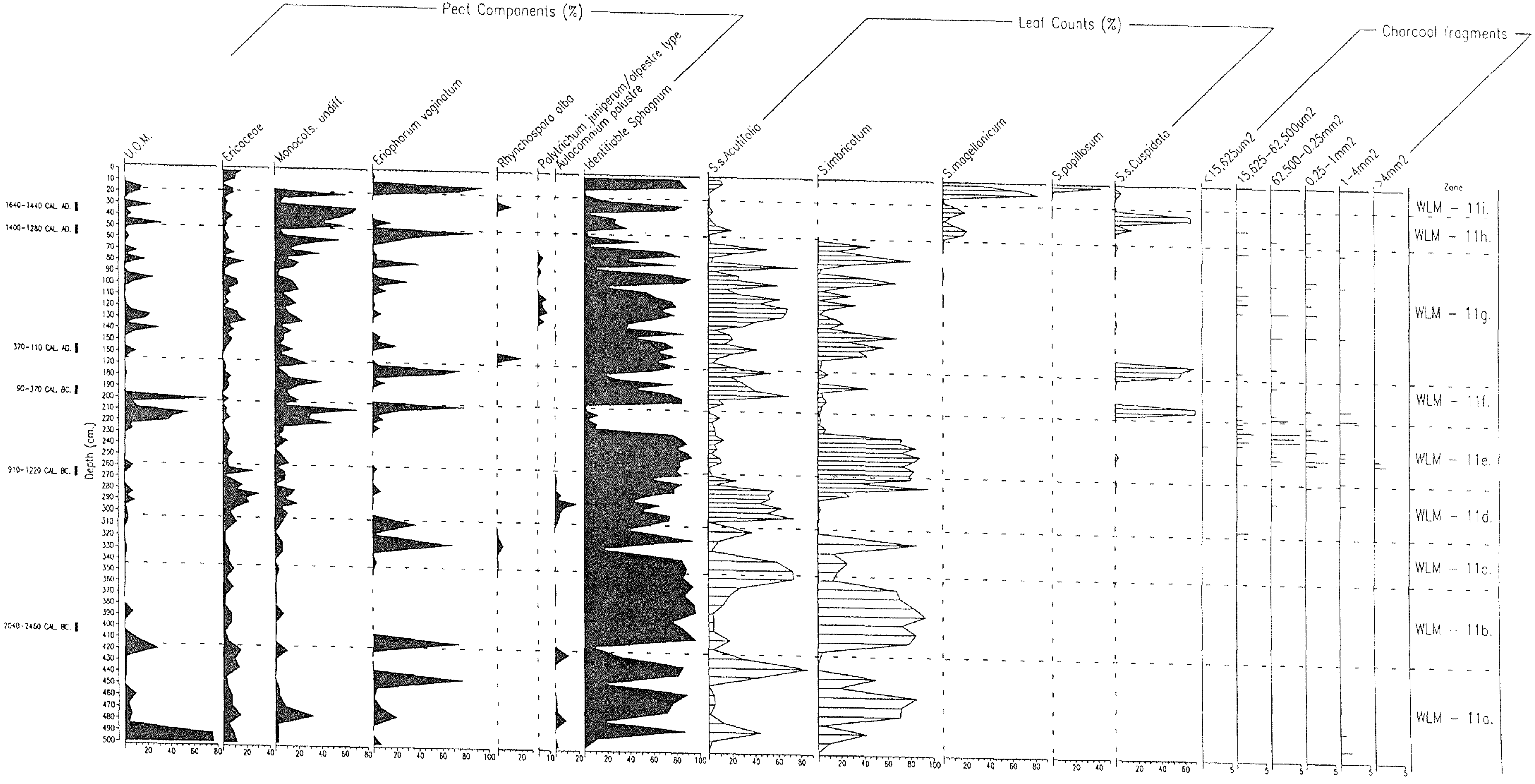
Zone WLM - 11e. (samples 52-65, 202-258 cm.). Sphagnum imbricatum dominates the entire zone with the exception of the top 20 cm., where there is abundant U.O.M. material. High frequencies of this decomposed, unidentifiable material offers evidence for low mire water levels, and is supported by the fusain stratigraphy. The highest frequencies and abundances of charcoal occur here, possibly as a result of the bog being more fire prone due to surface dryness. More charcoal is likely to be formed by the burning of drier vegetation, as less energy is needed to drive off moisture from the plant material, allowing ignition to occur more readily (Rhodes, 1996). Chance late summer fires may char an otherwise wet bog surface, weakening this argument, but it is certainly possible for *Sphagnum imbricatum* to grow in hummocks due to its inrolled cucullate leaves and compact growth form (Green, 1968; Flatberg, 1986). The virtual absence of *Sphagnum* section *Cuspidata* leaves (they comprise 3% of the peat matrix at 236 cm.) and the complete absence of any *Rhynchospora alba* epidermis, help to preclude the existence of raised local water tables, although it still remains difficult to ascertain just how dry the mire surface was.

Zone WLM - 11f. (samples 43-51, 166-202 cm.). The first high abundances of *Sphagnum* section *Cuspidata* leaves point to the unambiguous existence of higher mire water tables. U.O.M. and the quantity of charcoal fragments recovered declines appreciably, supporting this local water table reconstruction.

Zone WLM - 11g. (samples 14-42, 50 -166 cm.). A second clear wet phase in apparent in this zone, as high percentages of *Sphagnum* section *Cuspidata* leaves and the presence of *Rhynchospora alba,* indicate the existence of a former mire pool. Following this pool phase, which is dated to 370-110 CAL AD. (SRR-5869), increased U.O.M.. and Ericaceae representation, and the presence of both *Polytrichum juniperum/alpestre* type, *Sphagnum* section *Acutifolia,* and *Sphagnum imbricatum* leaves, invites the possibility that drier mire conditions were prevalent in this zone following the initial wet phase.

Zone WLM - 11h. (samples 6-13, 18-50 cm.). Another wet phase is recognisable in this zone, as a pool may have existed here, based on the high representation of *Sphagnum* section *Cuspidata* leaves (they form up to 66% of the peat matrix) and some epidermal tissues of *Rhynchospora alba*. There is, once again, a striking replacement of *Sphagnum imbricatum* by *Sphagnum magellanicum* associated with this wet shift, which has also consistently been demonstrated by Barber (1981), Smith (1985), Wimble (1986), Van Geel and Middledorp (1988), Stoneman (1993), and Stoneman *et al.* (1993). The extinction of *Sphagnum imbricatum*

Figure 5.19 Walton Moss - Core 11. Macrofossil diagram.



Analysis: Dmitri Mauquoy

occurs between CAL 1280-1400 AD. (SRR-5868), and overlaps with the date range for the extinction of this bryophyte from Bolton Fell Moss.

Zone WLM - 11i. (samples 1-5, 0-18 cm.). A tussock of *Eriophorum vaginatum* has been smothered by *Sphagnum magellanicum* and *Sphagnum papillosum*. The presence of these bryophytes suggest a low lawn microtope, and therefore a moderate degree of mire surface wetness in this topmost zone. The very fresh nature of these surficial peat deposits is reflected by the low U.O.M. values recorded.

5.4.3.3 Walton Moss Core 11 - Testate amoebae stratigraphy.

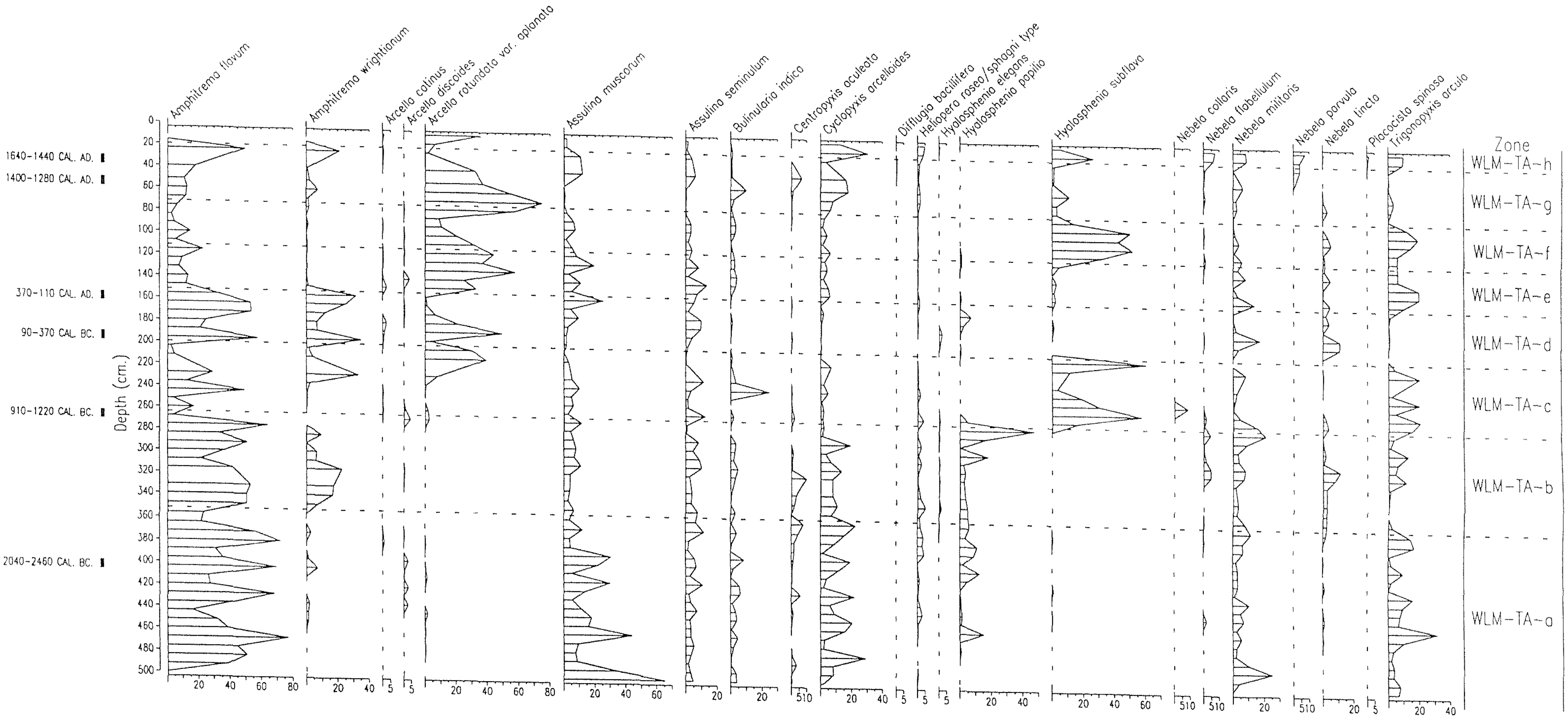
Zone WLM-TA-a. (samples 41-59, 352-500 cm.). There are large swings in the abundances of both *Amphitrema flavum* and *Assulina muscorum* in this zone, possibly suggesting fluctuations in mire surface wetness. *Amphitrema flavum* is a consistent indicator of elevated mire water tables (Tolonen *et al.*, 1992; Tolonen *et al.*, 1994; Warner and Charman, 1994), whilst sub-fossil thecae of *Assulina muscorum,* indicate relatively dry mire surface conditions (De Graaf, 1956; Heal, 1961; Tolonen *et al.*, 1994). Joosten (1985) has similarly proposed the existence of fluctuating mire water tables in peat stratigraphy, based on the presence of both *Amphitrema flavum* and *Sphagnum cuspidatum* leaves and the 'xeric' amoebae, *Hyalosphenia subflava* and *Trigonopyxis arcula.*

Zone WLM-TA-b. (samples 31-40, 264-352 cm.). Less marked fluctuations in *Amphitrema flavum* and increased numbers of *Amphitrema wrightianum* (up to 22% of the amoebae assemblage), combined with reduced *Assulina muscorum* abundances, suggest consistently high local water tables. Thecae of *Nebela tincta* and *Nebela flabellulum* suggest a degree of hydrological fluctuation again, as both these species inhabit drier microsites (Corbet, 1973; Tolonen *et al.*, 1994), although they are only present in small amounts (maximum values of 11% and 5% respectively). Because of this, any shifts to drier mire surfaces would possibly have been small.

Zone WLM-TA-c. (samples 24-30, 200-264 cm.). Much drier conditions seem to have been prevalent on the bog surface, as thecae of *Hyalosphenia subflava* are recovered in abundance for the first time, forming up to 60% of the thanatocoenose. *Trigonopyxis arcula* tests also increase in this zone, supporting the existence of lower mire water tables, as this species is a member of the 'tyrphoxene' mire taxa, which are found on drained peatlands or those overgrown with heather (Grospietsch, 1953). The macrofossil evidence does not support the existence of abundant heather at these depths (Figure 5.13), but large quantities of charcoal are present between 202-258 cm., and the disturbance this may have caused to the ecosystem, could possibly have allowed this species to increase in abundance, Joosten (1985).

Zone WLM-TA-d. (samples 18-23, 152-200 cm.). High abundances of *Amphitrema flavum* and *A. wrightianum*, and the presence of some *Hyalosphenia papilio* tests, point to increased mire surface wetness within this zone. Simultaneous declines (to very low levels), of *Hyalosphenia subflava* and *Trigonopyxis arcula*, support this reconstruction.

Figure 5.20 Walton Moss – Core 11. Testate amoebae.



Analysis: Dmitri Mauquoy

Zone WLM-TA-e. (samples 13-17, 112-152 cm.). Mire water levels appear to have dropped in this zone, as hygrophilous tests of *Amphitrema flavum* and *A. wrightianum* decline. In this instance, however, *Hyalosphenia subflava* thecae do not replace these species, suggesting there has not been a marked shift to increased dryness within this zone. *Trigonopyxis arcula* does increase in representation, but large numbers of *Arcella rotundata* var. *aplanata* tests, suggest, at least, moderately hydrophilous conditions, as both de Graaf (1956) and Joosten (1985) consider members of this genus to be indicative of elevated water tables. There is the possibility that *Arcella rotundata* var. *aplanata* has simply displaced *Amphitrema flavum* and *A. wrightianum* as the community dominant, or, the admixture of *Arcella rotundata* var. *aplanata* and *Trigonopyxis arcula* in the necrocoenose suggests possible fluctuating water levels.

Zone WLM-TA-f. (samples 8-12, 72-112 cm.). A clearer picture of mire surface wetness is apparent in this zone, as high abundances of *Hyalosphenia subflava* tests, a sustained presence of *Trigonopyxis arcula,* and further declines in *Amphitrema flavum,* offers strong support to the existence of a dry mire surface at these levels.

Zone WLM-TA-g. (samples 3-7, 20-72 cm.). The pattern of replacement, whereby *Amphitrema flavum* increases in abundance and *Hyalosphenia subflava* thecae decline, recurs, suggesting a further shift to wetter mire surface conditions within this zone.

Zone WLM-TA-h. (samples 1-2, 8-20 cm.). Increased numbers of *Hyalosphenia subflava, Trigonopyxis arcula, Cyclopyxis arcelloides* type, and *Nebela parvula,* offer evidence for a reduction in mire surface wetness. The latter three species had weighted average positions of 30.2 cm., 28.2 cm. and 15.1 cm. respectively, above the water table in the six Finnish mires investigated by Tolonen *et al.* (1992), which combined with the decline in *Amphitrema flavum* and *A. wrightianum* thecae, support the existence for lower local water tables.

5.4.3.4 Walton Moss - Core 11 - Summary of the humification, plant macrofossil and testate amoebae results.

The stratigraphy of Walton Moss - Core 11, shares similar features to its paired site, Bolton Fell Moss - Core L. Once again, *Sphagnum imbricatum* is replaced by *Sphagnum magellanicum* via a wet stage *(WLM - 11h.),* marked by the presence of *Sphagnum* section *Cuspidata* leaves and hygrophilous thecae of *Amphitrema flavum* and *A. wrightianum (zone WLM - TA -g.).* The extinction of *Sphagnum imbricatum* occurred between CAL 1280-1400 AD. (SRR-5868) in Core 11, which overlaps with the date range identified from Bolton Fell Moss. Stoneman (1993), however, dated this event to CAL 1668-1955 AD. (SRR-4529) in borehole 1, and CAL 1639-1955 AD. (SRR-4624) in borehole 2 from Walton Moss. A similar range of dates for the extinction of this species *within* a mire has been derived by Barber (1981), when the stratigraphy of 21 monoliths was analysed from Bolton Fell Moss. In 16 of the monoliths examined by Barber, the extinction of *Sphagnum imbricatum* occurred between 1300-1400 AD., but in four monoliths, it survived up to at least 1800 AD., provided it was growing in a hummock microtope. In these elevated positions it could resist the earlier climatic deteriorations which led to the demise of the species in lawn microtopes.

The marked increase in the abundance of *Sphagnum imbricatum* in zone *WLM - 11b.* has been dated to CAL 2040-2460 BC (SRR-5872). The humification values at 404 cm. (2250 BC.) are low, whilst the abundances of *Amphitrema flavum* are high, suggesting high local water tables. This is supported by decreases in the representation of the xeric amoebae, *Assulina muscorum* and *Trigonopyxis arcula* within zone *WLM-TA-a.*

A borehole (WLM15) taken by Hughes (1997), shows evidence for high mire surface wetness based on the presence of epidermal tissues of *Eriophorum angustifolium.* This level has been dated to CAL 390-190 BC. (SRR-5638). The stratigraphy of core 11 also shows evidence for increased mire surface wetness at this time, as a shift to pool *Sphagnum* section *Cuspidata* peat has been dated to CAL 370-90 BC. (SRR-5870). The two boreholes are positioned c. 1000 m. apart, yet they both offer evidence for a synchronous response to possible allogenic forcing.

The presence of relatively large amounts of charcoal in zone *WLM - 11e.*, high humification values at 370 BC., 415 BC., 690 BC. and 880 BC., and in addition, large amounts of *Hyalosphenia subflava* tests, offers strong evidence, certainly in this instance, that fires are associated with a dry mire surface. It is difficult, however, to determine whether burning occurred more frequently due to reductions in effective precipitation, promoting a drier, fire prone mire surface, or due to human agency.

5.4.4 Raeburn Flow.

5.4.4.1 Raeburn Flow - Humification data.

The humification curve from this site differs from Bolton Fell Moss - Core L, and Walton Moss - Core 11, in that there is a clear increase in absorbance values towards the base of the borehole (Figure 5.21). A 10 point running average curve has been fitted to the data, which helps to illustrate this. This trend was removed by calculating a regression line for the data points using Data Desk Version 5. The equation for the slope of the regression line (humification = 12.89-0.04 x depth) was subtracted from the original raw values to produce detrended curves (Figure 5.22 and 5.23). Inspection of this curve shows large increases in humification at 3030, 3220, 3610, 3800, and 3990 BC., but these values may simply be an artefact of the high *Eriophorum vaginatum* presence at these depths (Figure 5.24), rather than indicating periods of lower effective precipitation.

Low humification values were recorded at 1800, 1340, 1100 and 50 AD., and 270, 720, 1110, 1690, 2460, 2840, 3420 and 4480 BC., which offer possible evidence for high effective precipitation regimes. The 2 σ mid-point 1340 AD. date for the sample at 56 cm. (SRR-5873) needs to be interpreted cautiously however, since a level 20 cm. lower has a virtually identical 2 σ mid-point calibrated age range of 1335 AD. (SRR-5874). The lower sample may have been contaminated by younger intrusive sedge rhizomes which may possibly explain the same radiocarbon ages for these peat samples. Alternatively, the apparent age of the sample at 56 cm. may be too old, due to the presence of mycorrhizal fungi associated with fine Ericaceae

Figure 5.21 Raeburn Flow. Humification data vs. depth.

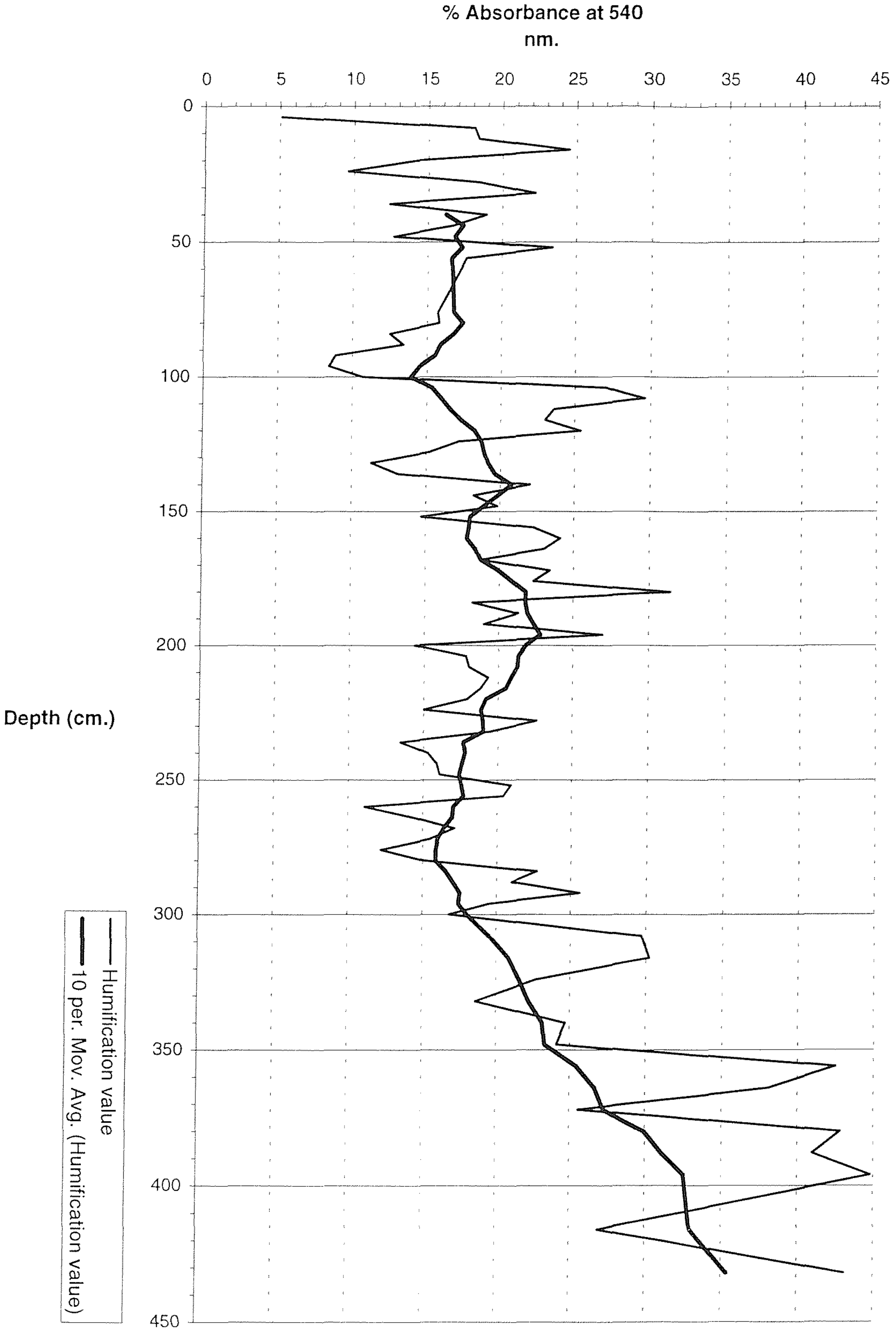


Figure 5.22 Raeburn Flow - Humification data vs. depth (detrended).

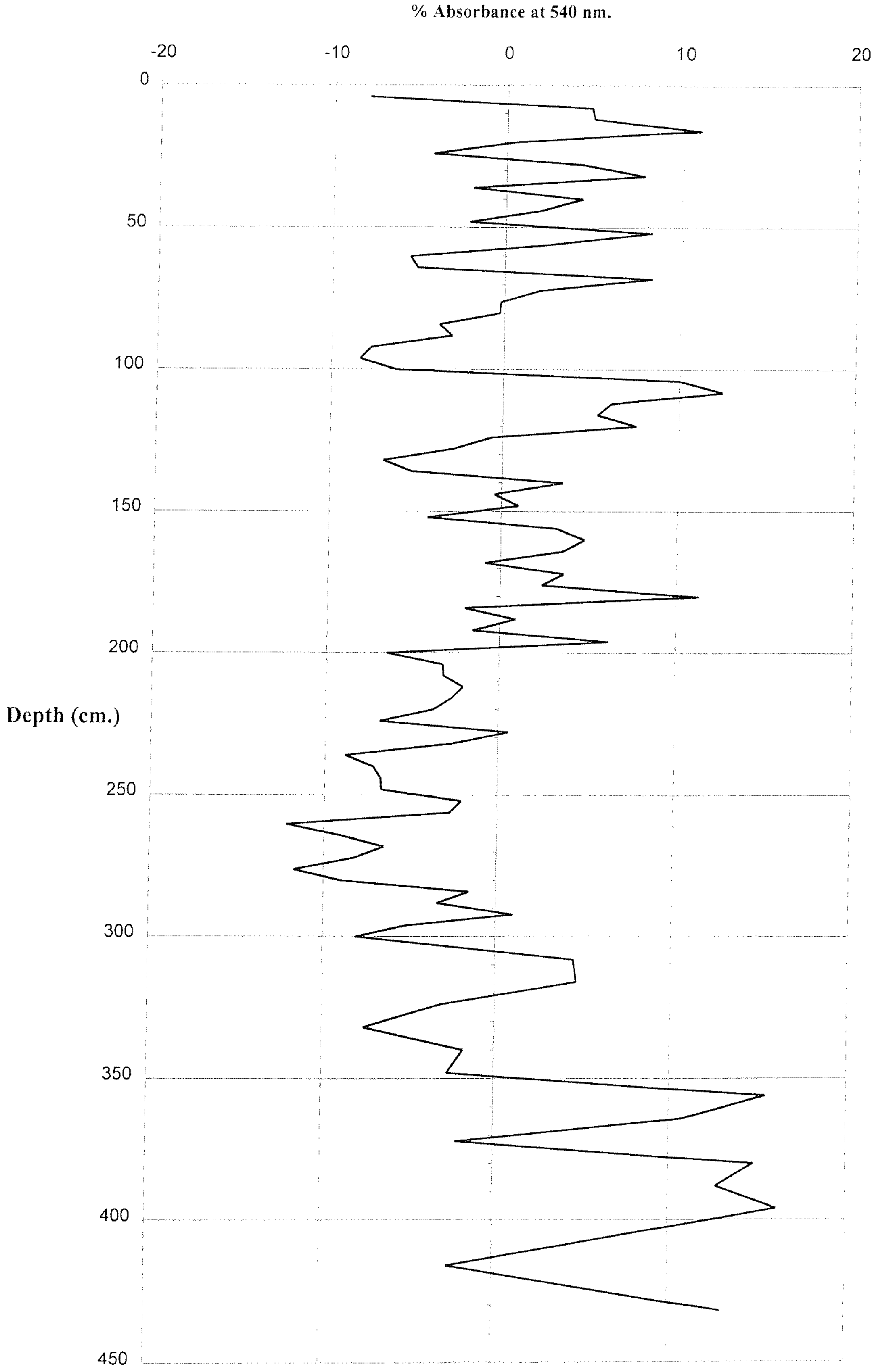
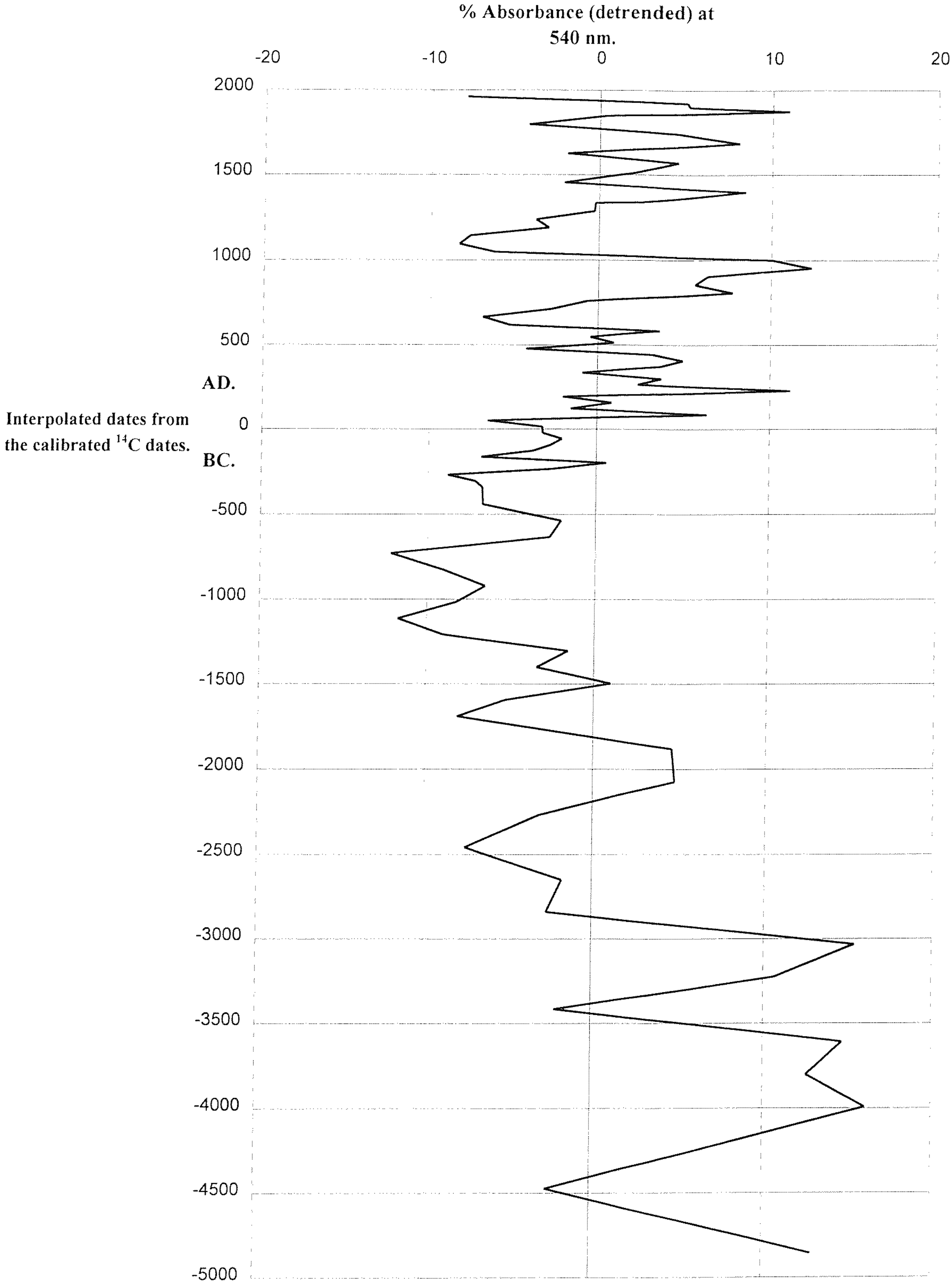


Figure 5.23 Raeburn Flow - Humification data vs. time (detrended).



rootlets. These fungi may fix old CO_2 produced from the bacterial oxidation of catotelmic methane (Kilian *et al.*, 1995).

5.4.4.2 Raeburn Flow - Macrofossils.

Zone RBF - a. (samples 83-89, 360-432 cm.). This zone contains abundant sedges and relatively little *Sphagnum*. *Eriophorum vaginatum* dominates the stratigraphy, which combined with a moderate presence of Ericaceae (up to 14% of the peat matrix), suggests relatively dry mire surface conditions between 3130-4850 BC. This zone certainly appears to be the driest on the basis of the presence of hygrophilous Sphagna, as it is the only one which does not contain *Sphagnum* section *Cuspidata* leaves. The detrended humification data in Figure 5.23 supports the plant macrofossil data, since the majority of the absorbance values are positive between 3130-4850 BC, also pointing to low local water tables.

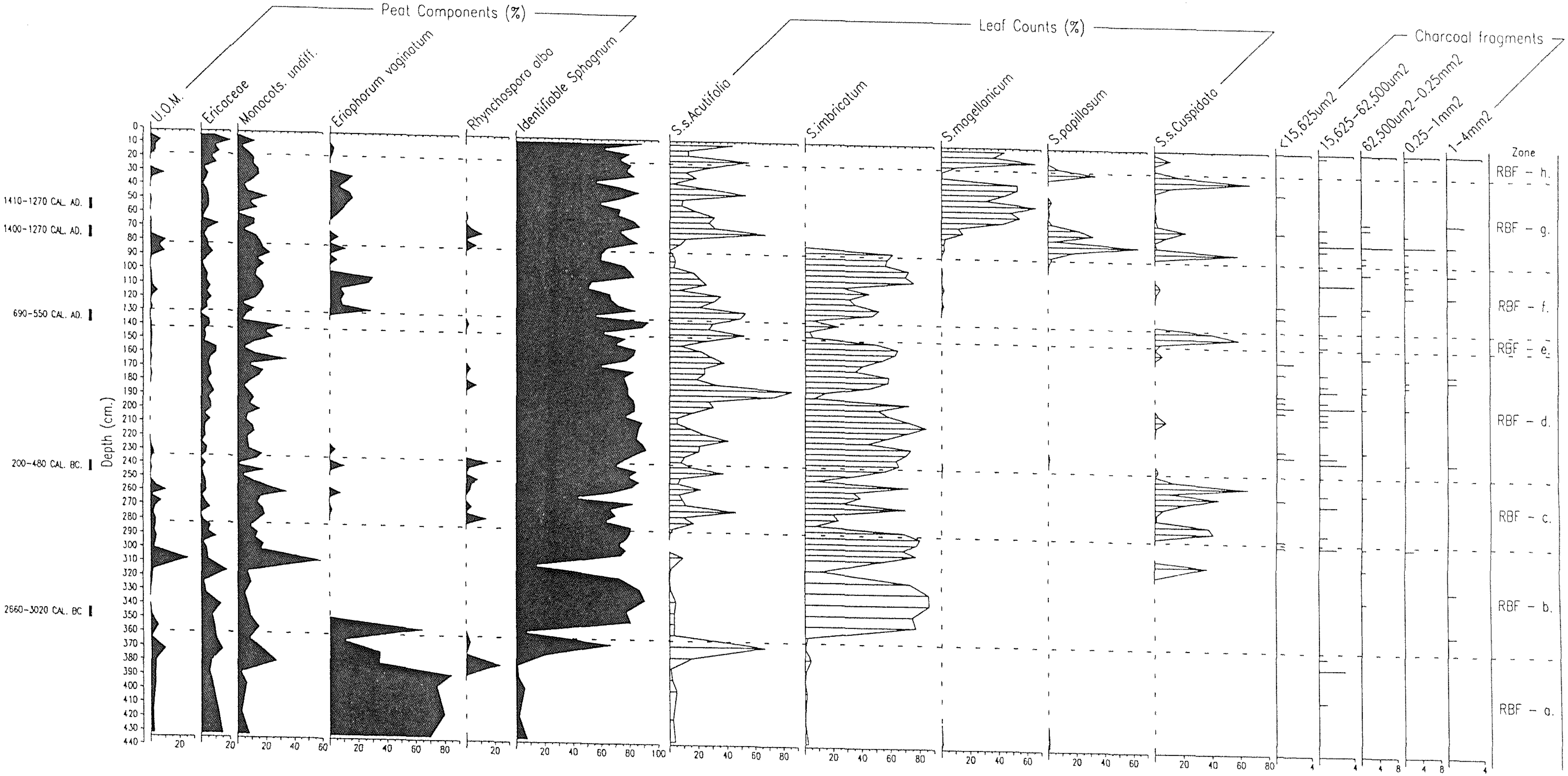
Zone RBF - b. (samples 71-82, 282-360 cm.). Sphagnum imbricatum dominates the peat stratigraphy, displacing the sedges which never regain their dominance. In this instance, Sphagna may be behaving as ecosystem engineers *sensu* Lawton (1994). The trigger for this expansion may have been increased mire surface wetness, as it would otherwise be difficult for this bryophyte to outgrow and smother the sedges in the community, especially if there were a dense above ground litter layer, which would shade the bryophytes in the autumn, and possibly reduce their growth (Malmer, 1992). The productivity of *Sphagnum* mosses is high compared to mire field layer species, which may then have given them a competitive advantage in this instance (Malmer, 1993). The presence of *Sphagnum* section *Cuspidata* leaves at the top of the zone does support the existence of elevated mire water levels.

Zone RBF - c. (samples 59-70, 234-282 cm.). This zone is appreciably wetter than the preceding zone, in that there are consistently high values of *Sphagnum* section *Cuspidata* leaves, and although abundances of *Rhynchospora alba* epidermal tissue are not high (maximum values are 15% of the peat matrix), they are also consistently present, supporting the existence of a shallow mire acrotelm. The continued presence of high abundances of *Sphagnum imbricatum*, attests to the ability of this bryophyte to grow under a wide range of mire water levels, and within this zone, leaves of the semi-aquatic ecad may be present in the stratigraphy (Green, 1968).

Zone RBF - d. (samples 36-58, 142-234 cm.). A reduction in local water tables is apparent in this zone, although low quantities of U.O.M., and the sporadic presence of *Rhynchospora alba* and *Sphagnum* section *Cuspidata* leaves, argue against a marked decrease in mire surface wetness. Increased quantities of charcoal are associated with the decline in mire surface wetness.

Zone RBF - e. (samples 33-35, 130-142 cm.). A short pool stage is distinguishable in this zone, as *Sphagnum* section *Cuspidata* leaves comprise 58% of the peat matrix. The interpolated dates for this period of increased mire surface wetness are 670-580 AD. Less burning of the mire surface occurred in this zone, possibly as a response to the increased wetness, which has also allowed *Rhynchospora alba* to recur.

Figure 5.24 Raeburn Flow. Macrofossil diagram.



Analysis: Dmitri Mauquoy

Zone RBF - f. (samples 21-32, 82-130 cm.). Mire water levels have lowered in this zone, since leaves of *Sphagnum* section *Cuspidata* occur only at 100 cm., and even here they comprise just 4% of the peat matrix. Sustained values of Ericaceae, however, argue against a marked decrease in mire surface wetness.

Zone RBF - g. (samples 5-20, 18-82 cm.). Sphagnum imbricatum becomes dramatically extinct between CAL 1270-1400 AD. (SRR-5874), and is replaced at first, by *Sphagnum* section *Cuspidata* and *Sphagnum papillosum*, suggesting this occurred during a phase of high mire water tables, and then by *Sphagnum magellanicum. S. magellanicum* largely dominates the zone, but it too is displaced by *S. papillosum* and *Sphagnum* section *Cuspidata* at 20 cm., where there is evidence for the existence of a former bog pool. The Pine rise for this site occurs at 24 cm., which suggests this last wet phase reflects the response of the Flow to the late Little Ice Age climatic deterioration.

Zone RBF - h. (samples 1-4, 4-18 cm.). Sphagnum magellanicum increases in importance once again, implying a change to a deeper mire acrotelm. Increased Ericaceae rootlets support the existence of a slightly drier mire surface, although the continued presence of some *Sphagnum* section *Cuspidata* leaves suggests there has not been a marked change to a drier mire surface. The inferred reduction in mire surface wetness and the marked increase in abundance of *Sphagnum magellanicum* appear to be a recent feature of the peat stratigraphy at this site, since it post-dates the c.1800 AD. Pine rise date recorded at 24 cm. depth.

5.4.4.3 Raeburn Flow - Testate amoebae stratigraphy.

Zone RBF-TA-a. (samples 58-64, 312-380 cm.). There are high abundances of both *Assulina muscorum* and *Amphitrema flavum* tests in this zone (43% and 67% respectively, Figure 5.25), which in a similar manner to *Zone WLM-TA-a.*, may indicate fluctuations in mire surface wetness. *A. flavum* tests are a consistent indicator of increased mire surface wetness (Tolonen *et al.*, 1992; Tolonen *et al.*, 1994; Warner and Charman, 1994), whilst the ability of *A. muscorum* to rapidly colonise (within two and a half years) drained peatlands (Warner and Chmielewski, 1992), points to the existence of drier phases within this zone. Abundances of *Trigonopyxis arcula* are also relatively high, further supporting the existence of xeric stages, under a fluctuating water table regime.

Zone RBF-TA-b. (samples 40-57, 234-312 cm.). Increases in *Amphitrema flavum*, *A. wrightianum*, and *Hyalosphenia papilio*, combined with declines in *Assulina muscorum* and *Trigonopyxis arcula*, point to a sustained wet period, with elevated local water tables affecting the mire surface. Isolated occurrences of *Difflugia bacillifera*, further support the existence of a shallow acrotelm, as they inhabit bog pools (Corbet, 1973).

Zone RBF-TA-c. (samples 25-39, 174-234 cm.). A slight reduction in mire surface wetness may have occurred here, as hygrophilous *Amphitrema wrightianum* tests decline, and are replaced by *Arcella rotundata* var. *aplanata,* which inhabit slightly less wet microsites (de Graaf, 1956; Joosten, 1985). There is very little

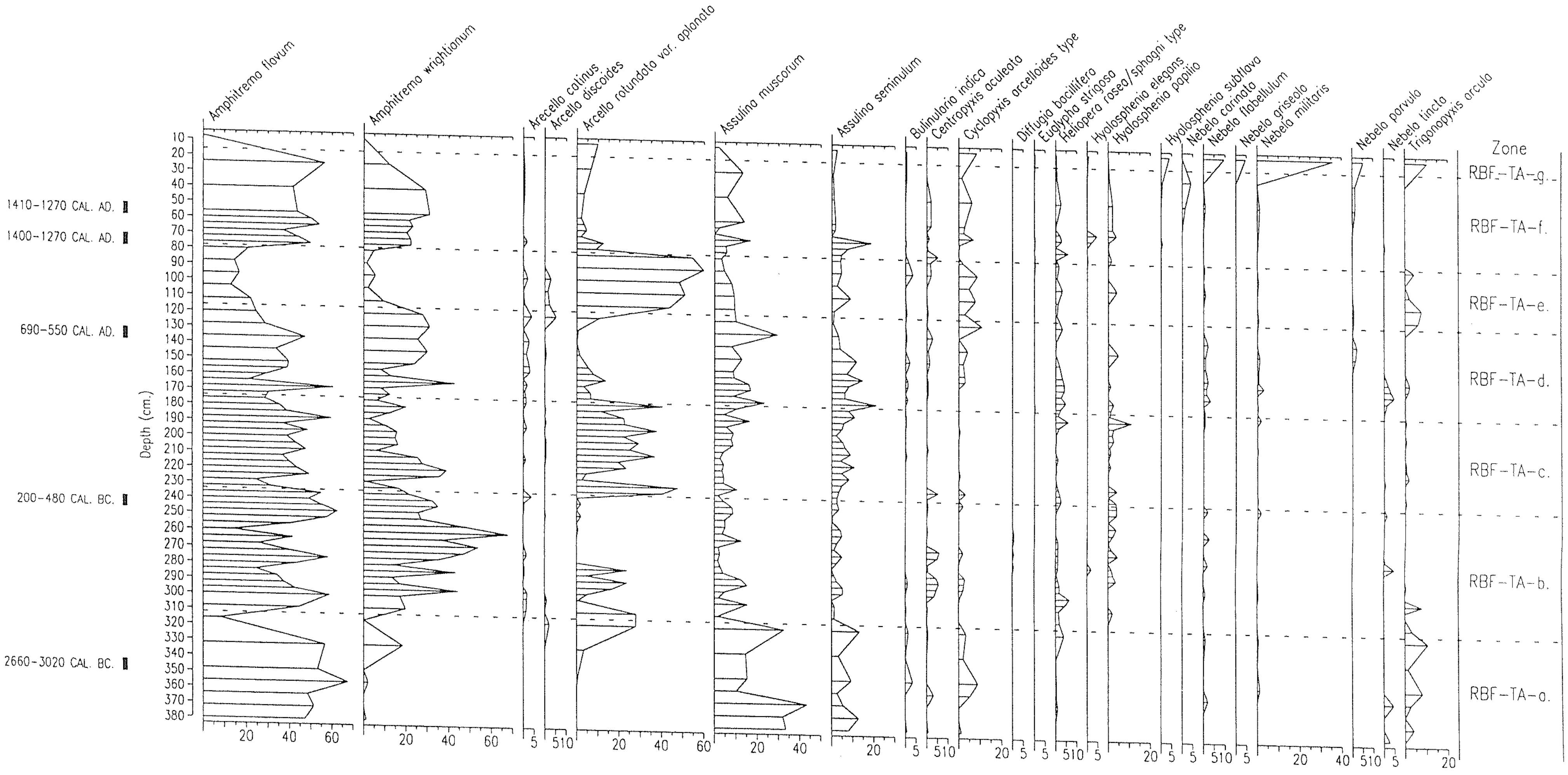


Figure 5.25 Raeburn Flow. Testate amoebae.

Analysis: Dmitri Mauquoy

change in the other testate amoebae species from this zone compared to the previous one, suggesting only a small reduction in local water tables.

Zone RBF-TA-d. (samples 15-24, 116-174 cm.). Mire water levels may have fluctuated in this zone again, as there is the same pattern of abundances of *Amphitrema flavum* and *Assulina muscorum,* which was also apparent in *Zone RBF-TA-a.* Oscillations to drier conditions may not have been so marked, as tests of *Trigonopyxis arcula* do not form a large part of the necrocoenose (2%), but increases in the percentage representation of *Cyclopyxis arcelloides,* suggests a moderate reduction in local water tables, as this species has a weighted average water table position of 20.6 cm. (Tolonen *et al.,* 1992).

Zone RBF-TA-e. (samples 10-14, 78-116 cm.). Arcella rotundata var. *aplanata* tests increase in abundance, replacing *Amphitrema flavum* and *A. wrightianum* as the community dominant. Since members of this genus are relatively hydrophilous (de Graff, 1956), mire water levels may not have changed appreciably in this zone. Abundance values of *Cyclopyxis arcelloides* do increase, which combined with increases in *Trigonopyxis arcula,* hint at slightly drier mire surface conditions.

Zone RBF-TA-f. (samples 2-9, 16-78 cm.). High local water tables return in this zone, as *Amphitrema flavum* and *A. wrightianum* increase in abundance. There may have been a degree of fluctuation in the water tables, as there are moderate amounts of *Assulina muscorum* and *Cyclopyxis arcelloides* type. Compared to *Zone RBF-TA-d.,* however, there are reduced abundances of *A. muscorum,* and no *Trigonopyxis arcula* thecae, which suggests that any fluctuation in the depth of the acrotelm may have been small.

Zone RBF-TA-g. (sample 1, 8-16 cm.). The rhizopod fauna in this zone indicates a degree of mire surface wetness which exceeds all those detectable in the other borehole zones. Dry mire surfaces, with a deep acrotelm, can be deduced from the complete absence of hygrophilous *Amphitrema flavum* and *A. wrightianum,* and their replacement by *Nebela militaris* tests. Heal (1961) and Corbet (1973) consider this species to be an indicator of hummock microtopes, which in this instance is supported by the presence of *Hyalosphenia subflava* thecae. Although it only comprises 4% of the thanatocoenose, it is absent from all the other zones, with the exception of *Zone RBF-TA-f.,* where only a single test was recovered. *Nebela flabellulum* and *N. parvula* thecae in this zone further support the existence of higher, hummock microtopes (Corbet, 1973; Tolonen *et al.,* 1992).

5.4.4.4 Raeburn Flow - Summary of the humification, plant macrofossil and testate amoebae results.

The macrofossil and testate amoebae assemblages of this mire consistently display high mire surface wetness. There are seven distinct bands of *Sphagnum* section *Cuspidata* leaves, whilst tests of dry indicator testate amoebae are markedly reduced in comparison to the other mires investigated. This is very much the case for *Hyalosphenia subflava*, which is scarcely recorded at all in the stratigraphy, with the exception of *Zone RBF-TA-g. (sample 1, 8-16 cm.).*

The base of the core appears to indicate a fluctuation in mire surface wetness conditions *(Zone RBF - a.),* with a marked reduction of *Sphagnum* species, high representation of *Eriophorum vaginatum*, and large numbers of *Amphitrema flavum* and *Assulina muscorum*. Other zones which may possibly indicate an oscillation in local water tables are, *Zone RBF-TA-d.* and *Zone RBF-TA-f.* The humification data within *Zone RBF - a.,* suggest very dry conditions, but the testate amoebae stratigraphy refutes this, as hygrophilous *Amphitrema flavum* tests are very numerous at these depths (they form 67% of the necrocoenose at 356 cm.). In this instance, there may well be a species dependent (*Eriophorum vaginatum*) humification signal.

Fires seem to have occurred regularly, as charcoal fragments are recorded in all of the designated zones. Compared to the stratigraphy of Walton Moss - Core 11 (*Zone WLM - 11e*), fires are not associated with a drier mire surface. Clearly, this proxy component needs to be interpreted cautiously, as charcoal rich levels need not necessarily indicate dry mire surfaces.

The extinction and replacement of *Sphagnum imbricatum* by *Sphagnum magellanicum (Zone RBF - f.),* is marked once again, by a wet phase with *Sphagnum papillosum* and section *Cuspidata* leaves. The testate amoebae assemblages further support the existence of elevated mire water levels, as tests of hygrophilous *Amphitrema flavum* are abundant.

5.4.5 Bell's Flow.

5.4.5.1 Bell's Flow - Humification data.

Relatively high absorbance values at 1100, 640, 470, and 280 AD. and 80, 720, 1120 and 1400 BC., suggest dry mire surface conditions (Figure 5.27), whilst those at 1420, 790, 560, 400, 300, and 100 AD., and 350 BC., indicate fresher, less humified peat, which may have been deposited rapidly under a high effective precipitation regime. Unlike Raeburn Flow, there are no sharp increases in the humification values derived from the peat stratigraphy, which may be explained by the dearth of *Eriophorum vaginatum* recovered from this borehole.

5.4.5.2 Bell's Flow - Macrofossils.

Zone BSF - a. (samples 62-76, 242-300 cm.). Compared to the rest of the borehole stratigraphy, there is a relatively large presence of Ericaceae (up to 33%), and up to 25% U.O.M. There is, additionally, a very high representation of *Sphagnum imbricatum* leaves, which combined with the other proxy evidence, points to drier mire surface conditions, as hummock dwelling ecads of this species are well adapted to xeric microsites (Flatberg, 1986).

Zone BSF - b. (samples 53-61, 206-242 cm.). This zone contains more identifiable *Sphagnum*, and a greater representation of *Sphagnum* section *Acutifolia* leaves. Ericaceae and U.O.M. values remain stable, and the absence of large swings in the humification data at these depths, and the continued presence of *Sphagnum imbricatum* leaves, suggest a further period of low local water tables.

Figure 5.26 Bell's Flow. Humification data vs. depth.

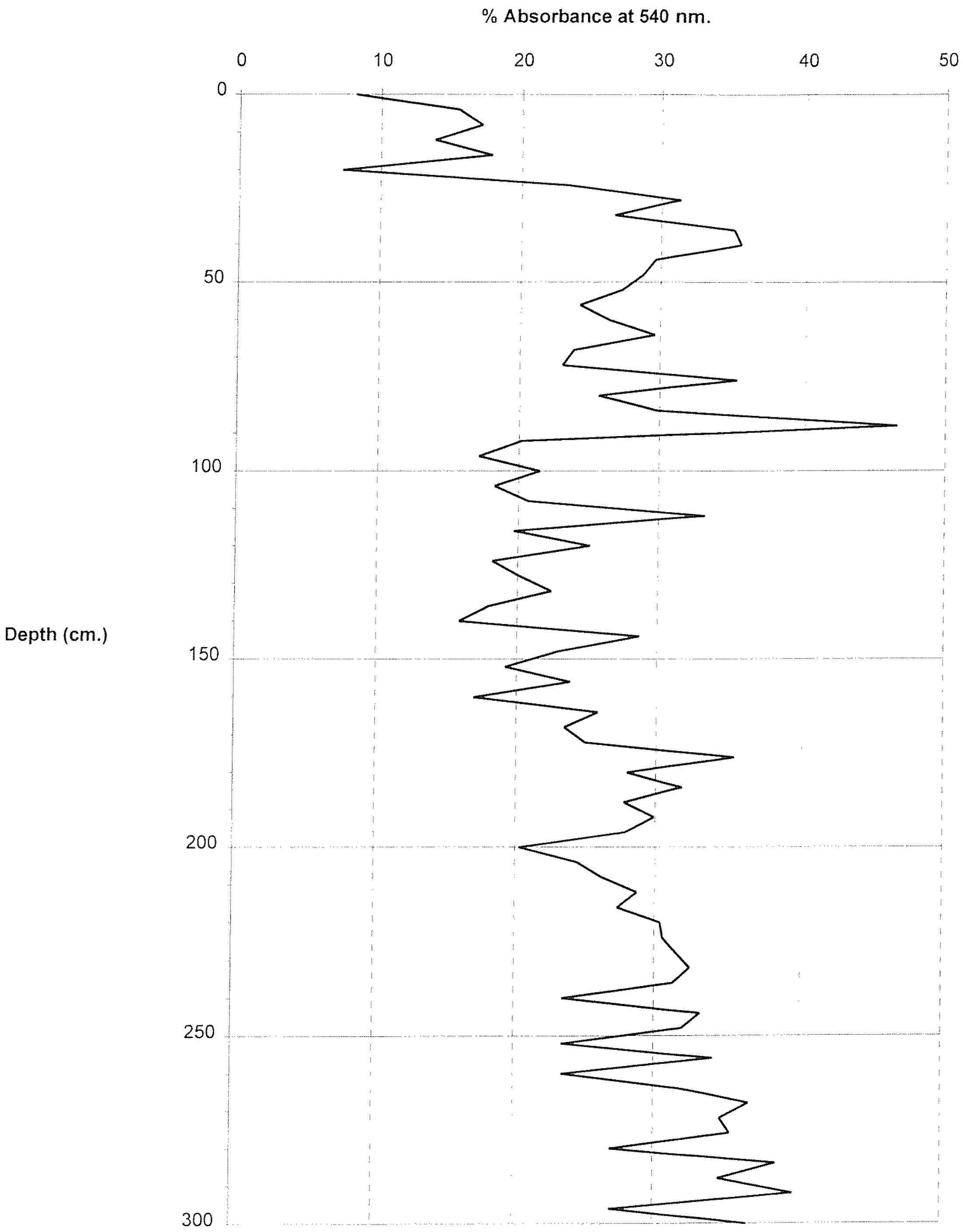
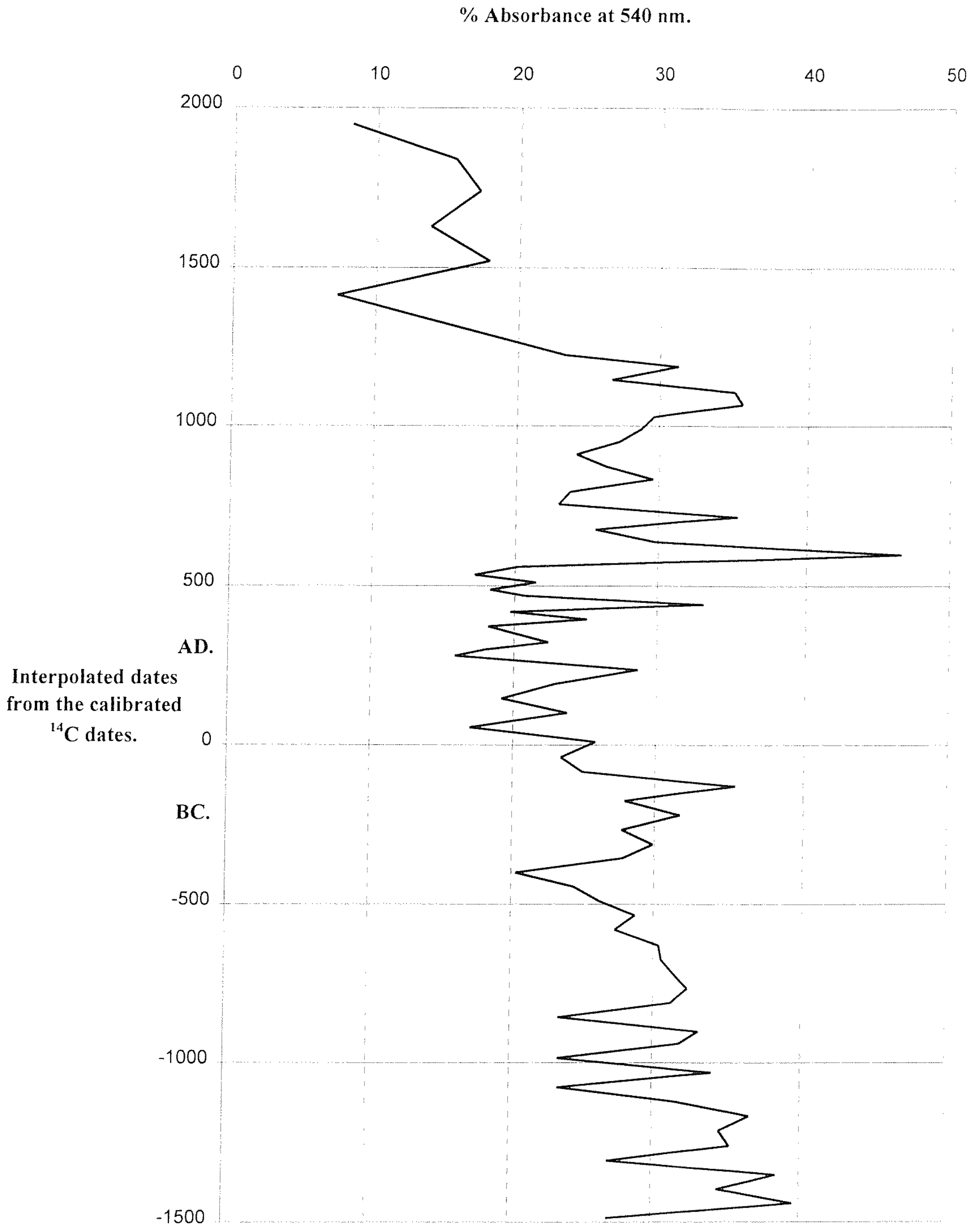


Figure 5.27 Bell's Flow - Humification data vs. time.



Zone BSF - c. (samples 49-52, 190-206 cm.). Sedges form a large part of the plant macrofossil assemblage, displacing *Sphagnum* section *Acutifolia* leaves, although it was not possible in this instance to identify them to species level. They may well be remains of *Eriophorum vaginatum*, which suggests a possible increase in mire surface wetness, given its ability to grow on wet mire surfaces with *Sphagnum* (Meade, 1992). This is of course very tentative, but low humification values between 310-440 BC. (Figure 5.27), do support the existence of a possible short wet phase, associated with this sedge expansion.

Zone BSF - d. (samples 38-48, 146-190 cm.). Sphagnum imbricatum and *Sphagnum* section *Acutifolia* leaves increase in abundance, whilst the representation of monocots. decline. The absence of *Rhynchospora alba* and *Sphagnum* section *Cuspidata* leaves, argue against any shift to a wetter mire surface, which invites the possibility that local water tables have remained low.

Zone BSF - e. (samples 26-37, 98-146 cm.). Sphagnum section *Acutifolia* markedly replaces *Sphagnum imbricatum.* The possibility that the *Acutifolia* leaves may belong to either hummock or lawn species (Section 5.2.14), makes any hydrological reconstruction difficult in this case. Low humification values at 300 AD. (140 cm.) suggest a possible increase in local water tables, although this would appear to have been small, as it was not sufficient to allow more hygrophilous vegetation to become established.

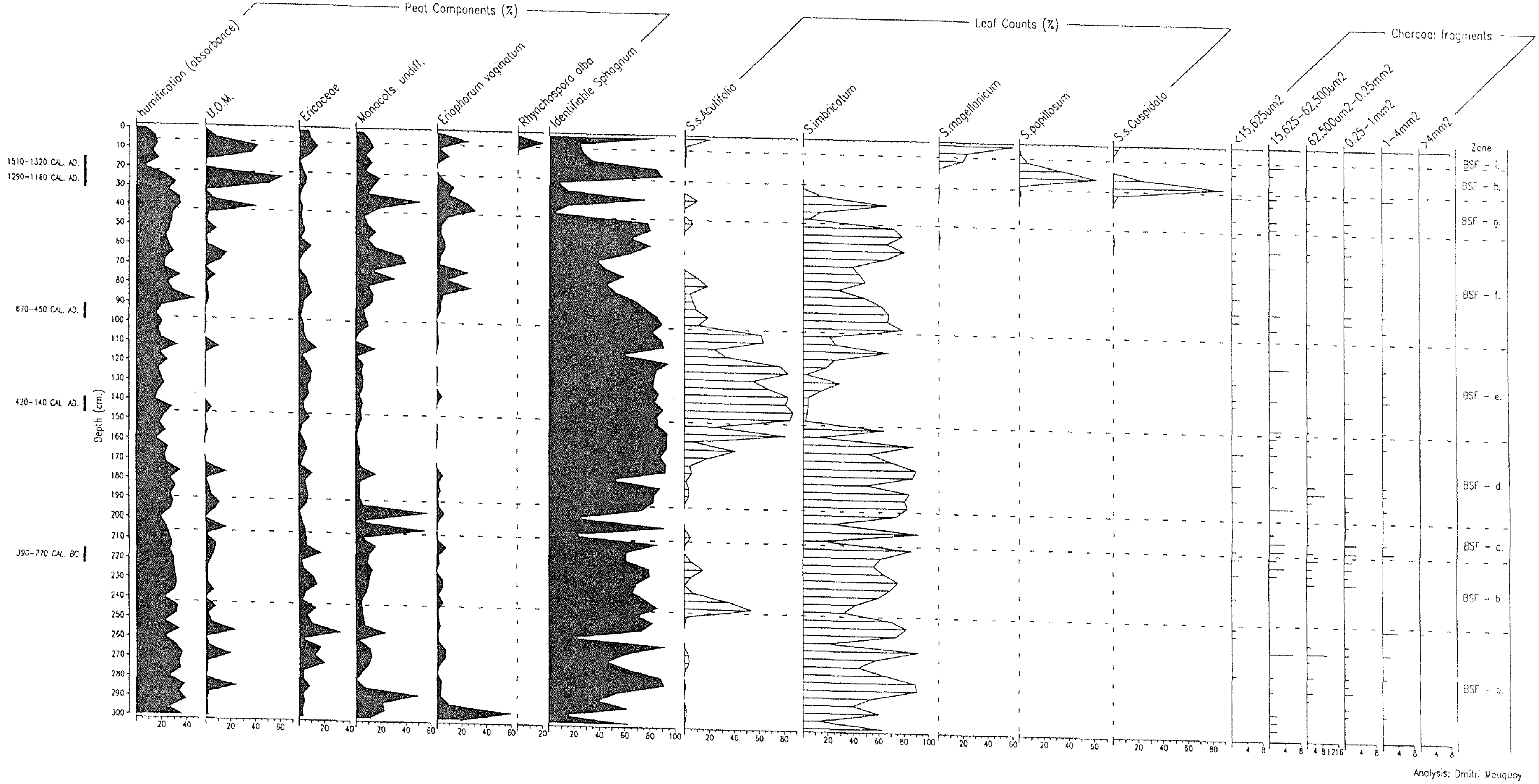
Zone BSF - f. (samples 12-25, 42-98 cm.). There is a prolonged phase of *Sphagnum imbricatum* dominance within this zone, with increased abundances of monocots. undiff. and *Eriophorum vaginatum.* It is difficult, once again, to ascertain the relative position of the local water table, although high absorbance values at 760 and 640 AD. (76 and 88 cm.), point to relatively dry conditions.

Zone BSF - g. (samples 7-11, 22-42 cm.). The homogeneous species composition of the stratigraphy makes it difficult to reconstruct with any confidence, the degree of mire surface wetness, since both *Sphagnum imbricatum* and *Eriophorum vaginatum* have a capacity to grow under a range of mire water levels. This problem has similarly been encountered by Casparie (1972) and Stoneman (1993), but the increased presence of U.O.M., and high absorbance values within the zone, point to increased dryness of the mire surface.

Zone BSF - h. (samples 3-6, 6-22 cm.). High abundances of *Sphagnum* section *Cuspidata*, which are succeeded by *Sphagnum papillosum* leaves, presents unambiguous evidence for the former existence of a bog pool/low lawn microtope. *Sphagnum imbricatum* displays a similar pattern to the other sites, in that it becomes extinct following this wet shift. High abundances of U.O.M. in this zone, may reflect the greater susceptibility of pool species to decay (Johnson *et al.*, 1990; Johnson and Damman, 1991).

Zone BSF - i. (samples 1-2, 0-6 cm.). The depth of the acrotelm appears to have increased, since *Sphagnum magellanicum* has replaced the hygrophilous Sphagna in the previous zone, although the presence of some *Rhynchospora alba*, suggests water levels have not significantly declined.

Figure 5.28 Bell's Flow. Macrofossil diagram.



5.4.5.3 Bell's Flow - Testate amoebae stratigraphy.

Zone BSF-TA-a. (samples 37-38, 288-300 cm.). Extremely high abundances of *Hyalosphenia subflava* (they form up to 83% of the rhizopod assemblage), point to dry mire surface conditions. The former water table of the mire, based on the presence of this species, may have been c. 50 cm. below the surface (Warner and Charman, 1994).

Zone BSF-TA-b. (samples 35-36, 272-288 cm.). A minor oscillation in water tables may have occurred in this zone, as limited tests of *Amphitrema flavum* and *A. wrightianum* occur (27 and 9% respectively) with reduced *Hyalosphenia subflava* thecae.

Zone BSF-TA-c. (samples 27-34, 208-272 cm.). Sustained high values of *Hyalosphenia subflava*, and increases in the representation of *Nebela militaris* and *Trigonopyxis arcula*, point to a recurrence of dry mire surfaces.

Zone BSF-TA-d. (samples 22-26, 176-208 cm.). A large reduction in *Hyalosphenia subflava* tests and increases in *Amphitrema flavum* and *A. wrightianum* in particular, combined with reductions in *Trigonopyxis arcula*, offers evidence for a rise in local water tables.

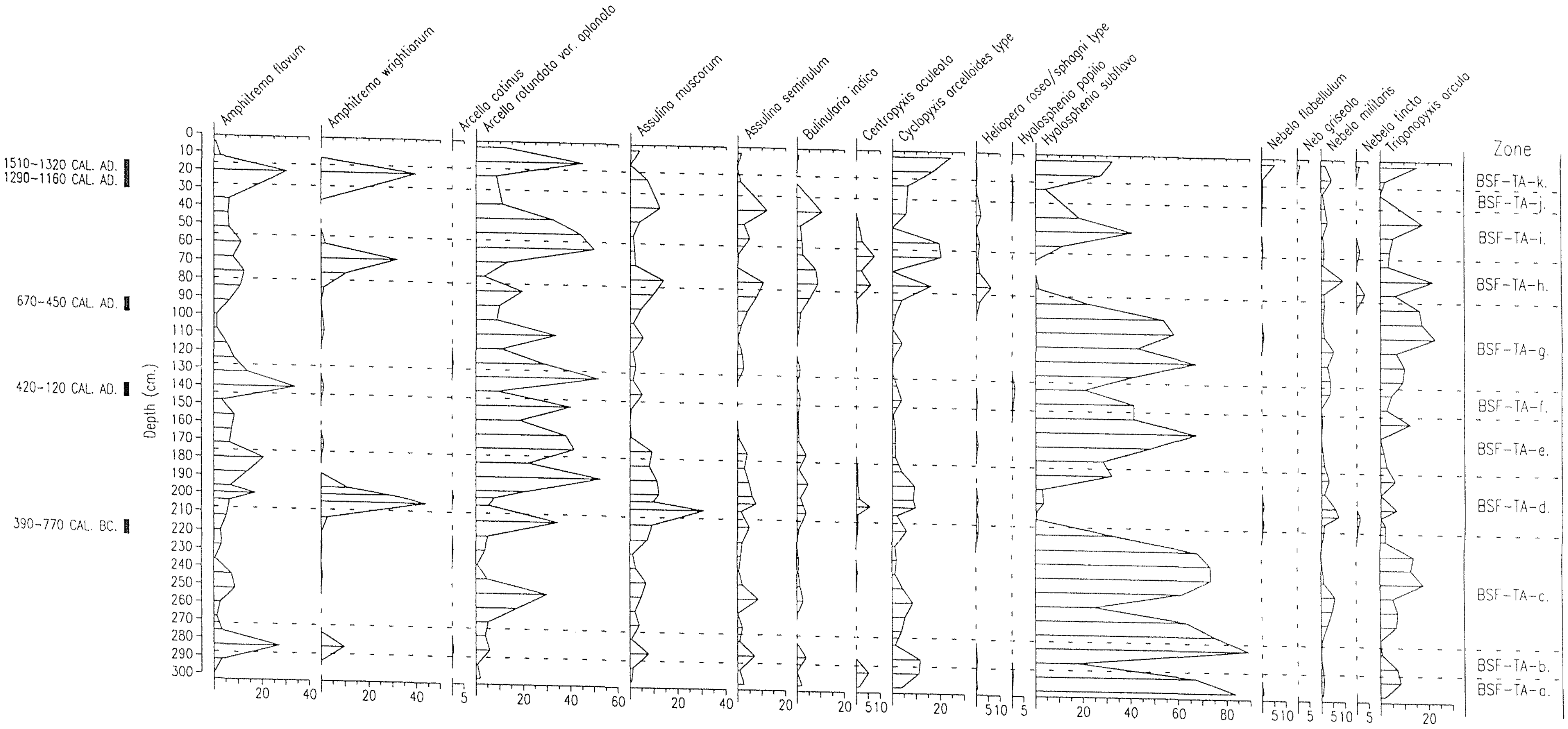
Zone BSF-TA-e. (samples 18-21, 144-176 cm.). Hyalosphenia subflava returns to dominate the necrocoenose, which combined with the simultaneous decline of *Amphitrema flavum* and *A. wrightianum,* suggests a return to drier conditions. The presence of up to 41% *Arcella rotundata* var. *aplanata* tests argues against a sharp decrease in local water tables however.

Zone BSF-TA-f. (samples 16-17, 128-144 cm.). The acrotelm may have fluctuated to a degree in this zone, since there are both increases in *Amphitrema flavum* and *Hyalosphenia papilio,* and relatively high abundances of *Hyalosphenia subflava* (up to 41%). The humification data supports this, as there are low absorbance values at these depths, suggesting possible wet swings in local water tables.

Zone BSF-TA-g. (samples 10-15, 80-128 cm.). Marked declines in the thecae of *Amphitrema flavum* and *Arcella rotundata* var *aplanata,* and increases once again in *Hyalosphenia subflava* and *Trigonopyxis arcula*, offer evidence for a very dry mire surface within this zone.

Zone BSF-TA-h. (samples 7-9, 56-80 cm.). A virtual absence of *Hyalosphenia subflava,* and high abundances of *Amphitrema wrightianum* and *Arcella rotundata* var. *aplanata* tests suggests a wetter mire surface with a shallower acrotelm. Relatively high values of *Trigonopyxis arcula* may point to a degree of water level fluctuation.

Figure 5.29 Bell's Flow. Testate amoebae.



Analysis: Dmitri Mauquoy

Zone BSF-TA-i. (samples 4-6, 28-56 cm.). There is a recurrence of drier conditions, as *Hyalosphenia subflava* tests become more numerous, whilst hygrophilous thecae of *Amphitrema flavum* and *A. wrightianum* are less frequently encountered.

Zone BSF-TA-j. (sample 3, 16-28 cm.). High values of both *Amphitrema flavum* and *A. wrightianum,* and markedly reduced *Hyalosphenia subflava* and *Trigonopyxis arcula* shells, highlight the existence of raised water tables, which on the basis of the testate amoebae species identified, make this the wettest local zone.

Zone BSF-TA-k. (samples 1-2, 4-16 cm.). Drier conditions, with a possible degree of water level fluctuation, seems to be characteristic of this topmost zone, as in the first instance, there are xeric tests of *Hyalosphenia subflava* and *Trigonopyxis arcula,* whilst a high representation of hydrophilous *Arcella rotundata* var. *aplanata* tests suggest, at the same time, a moderate degree of mire surface wetness.

5.4.5.4 Bell's Flow - Summary of the humification, plant macrofossil and testate amoebae results.

In comparison to Raeburn Flow, the stratigraphy of Bells Flow does not display the same degree of mire surface wetness. There is only a single peak of *Sphagnum* section *Cuspidata* leaves, which occurs immediately after *Sphagnum imbricatum* becomes extinct *(BSF - h.).* Following this wet phase, which is also clearly apparent in the testate amoebae stratigraphy *(BSF-TA-j.),* and the humification data, *Sphagnum papillosum* and then *Sphagnum magellanicum* replace the niche left by *Sphagnum imbricatum.*

With the exception of this wet phase, mire water levels, based on the plant macrofossil stratigraphy, do not seem to have risen high enough to induce a change to mire pool microtopes. The testate amoebae thanatocoenoses and humification absorbance values do, however, indicate areas where wetter mire surface conditions may have existed, highlighting the usefulness of a multi-proxy analysis. There are five areas where the testate amoebae indicate a shift to wetter conditions or possibly a fluctuation in water table depth, these are; *BSF-TA-b., d., f., h., and j.* In this case, testate amoebae may be more sensitive in recording hydrological changes, as the plant macrofossil record is very much dominated by both *Sphagnum imbricatum* and *Sphagnum* section *Acutifolia* leaves. Low absorbance values at 1415, and 300 AD., and 350 BC., offer further evidence for wetter shifts, which match the testate amoebae mire hydrological reconstructions. Without the testate amoebae and humification analysis, these changes would have remained unnoticed, because of the wide tolerances of *Sphagnum imbricatum* and *Sphagnum* section *Acutifolia* species to mire water levels.

The base of the core *(BSF - a.)* indicates dry surface conditions, based on the presence of up to 60% *Eriophorum vaginatum* and abundant thecae of *Hyalosphenia subflava.*

Fires appear to have occurred throughout the three metre span of the borehole, with the exception of the pool microtope in zone *BSF-h*, which is relatively charcoal poor.

5.4.6 Coom Rigg Moss.

5.4.6.1 Coom Rigg Moss - Humification data.

The humification signal from this site is similar to the one derived from Raeburn Flow, as there is a clear trend in the absorbance values with depth, illustrated by a ten point moving average trend line fitted to the data points (Figure 5.30). The gradual trend discernible in the data from Coom Rigg Moss, suggests there may be a depth/time dependent signal in the stratigraphy from this site, which has similarly been demonstrated in blanket peats by Blackford (1990). Concentrations of methane and carbon dioxide have been found to increase steadily down the catotelm, suggesting decay continues at all depths (Clymo, 1992), which may explain the depth trend in this instance, as the peat matrix becomes cumulatively more broken down. The humification values have been detrended (Figure 5.31 and 5.32) using the same techniques which were applied to the Raeburn Flow data points (Section 5.4.4.1).

Low humification values are found at 1610 AD. (interpolated ^{14}C date) and 1800 AD., (Pine rise date), 1190, 970, and 550-670 AD., and 180-130 and 760 BC., indicating unfavourable conditions for decay when this material passed through the litter layer. Middeldorp (1986), proposes that the main decomposition of organisms is accomplished within a few years, whilst they are resident in the acrotelm. In the light of this, the low humification values recorded here may reflect high mire water levels and possibly higher effective precipitation regimes, as this will inhibit aerobic decomposer micro-organisms.

5.4.6.2 Coom Rigg Moss - Macrofossils.

Zone CRG - a. (samples 53-73, 206-300 cm.). This zone is dominated by monocotyledon remains, with up to 41% *Eriophorum vaginatum* in the peat matrix. In addition to the predominant presence of sedges, high U.O.M. abundances and a dearth of *Sphagnum* leaves, point to dry mire surface conditions.

Zone CRG -b. (samples 36-52, 138-206 cm.). Increases in identifiable *Sphagnum,* principally *Sphagnum* section *Acutifolia* leaves, and a reciprocal decline in U.O.M. values, suggest a change to higher local water tables. *Eriophorum vaginatum* still forms a relatively large part of the peat matrix, which combined with a small quantity of *Rhynchospora alba* epidermis, points to fluctuating water levels. This zone commences at CAL 370-80 BC (SRR-5886).

Zone CRG -c. (samples 26-35, 98-138 cm.). The amount of U.O.M. and Ericaceae declines, which in addition to the first records of *Sphagnum* section *Cuspidata*, highlight the existence of wetter mire surface conditions.

Figure 5.30 Coom Rigg Moss. Humification data vs. depth.

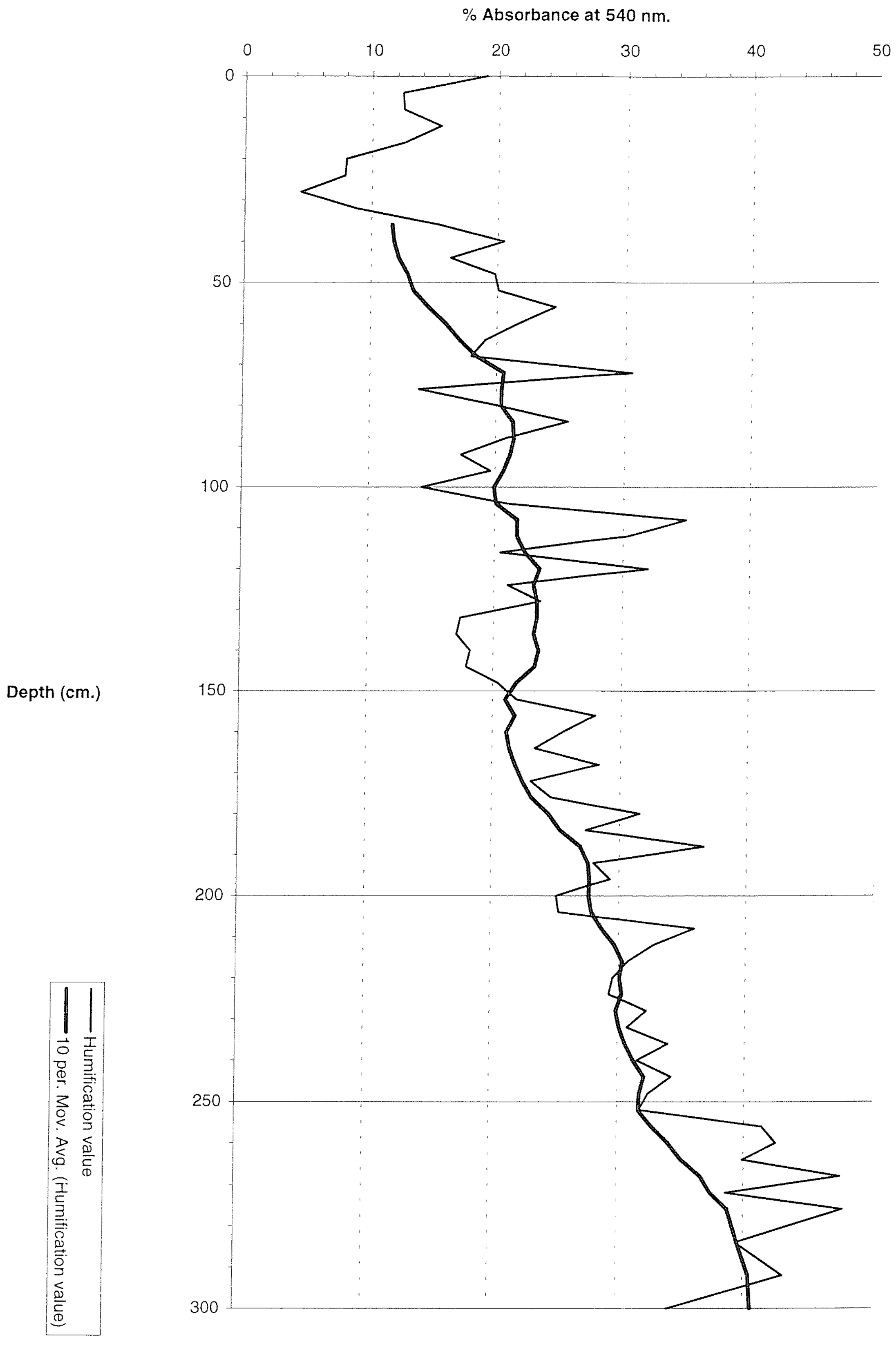


Figure 5.31 Coom Rigg Moss. Humification data vs. depth (detrended).

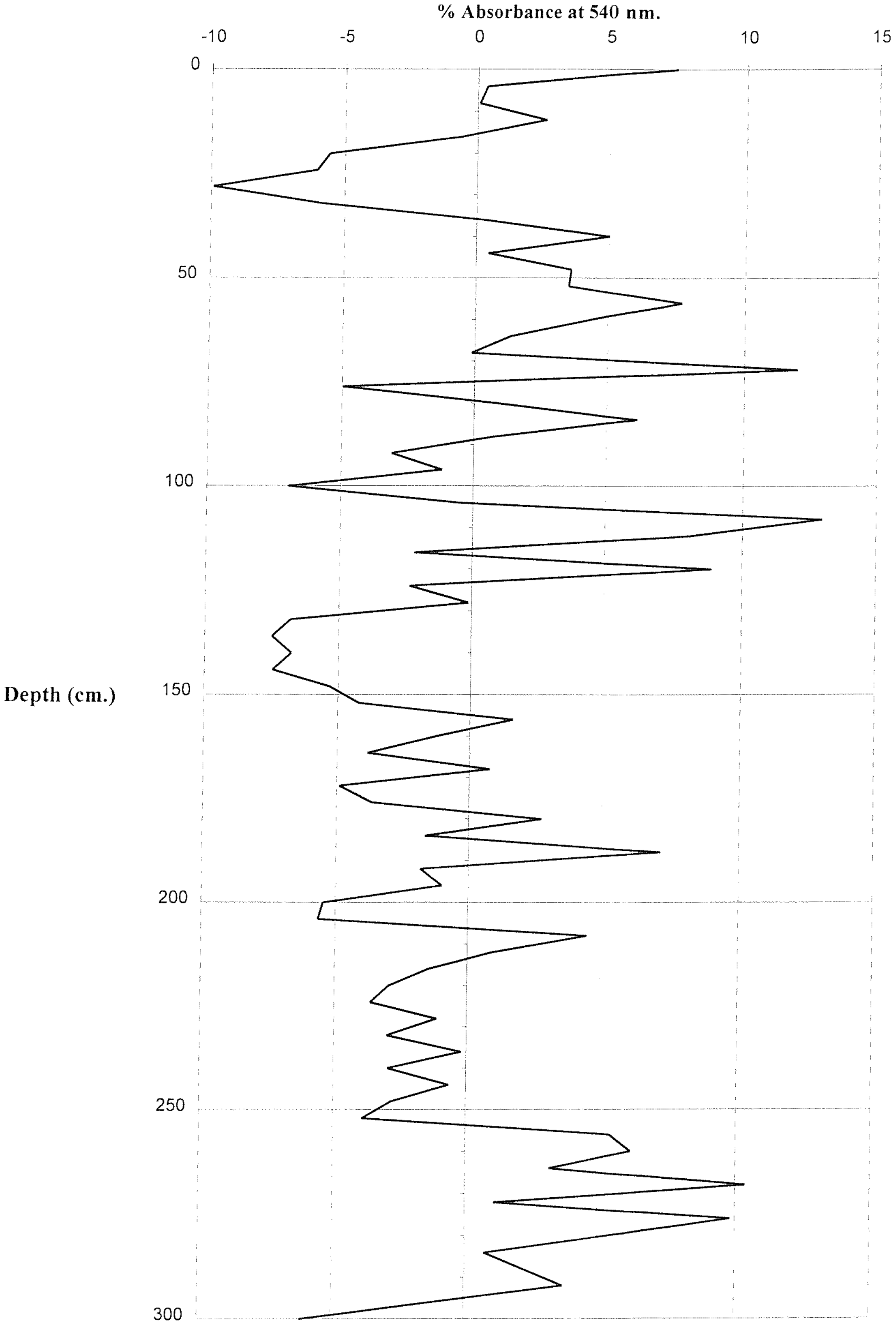


Figure 5.32 Coom Rigg Moss - Humification data vs. time (detrended).

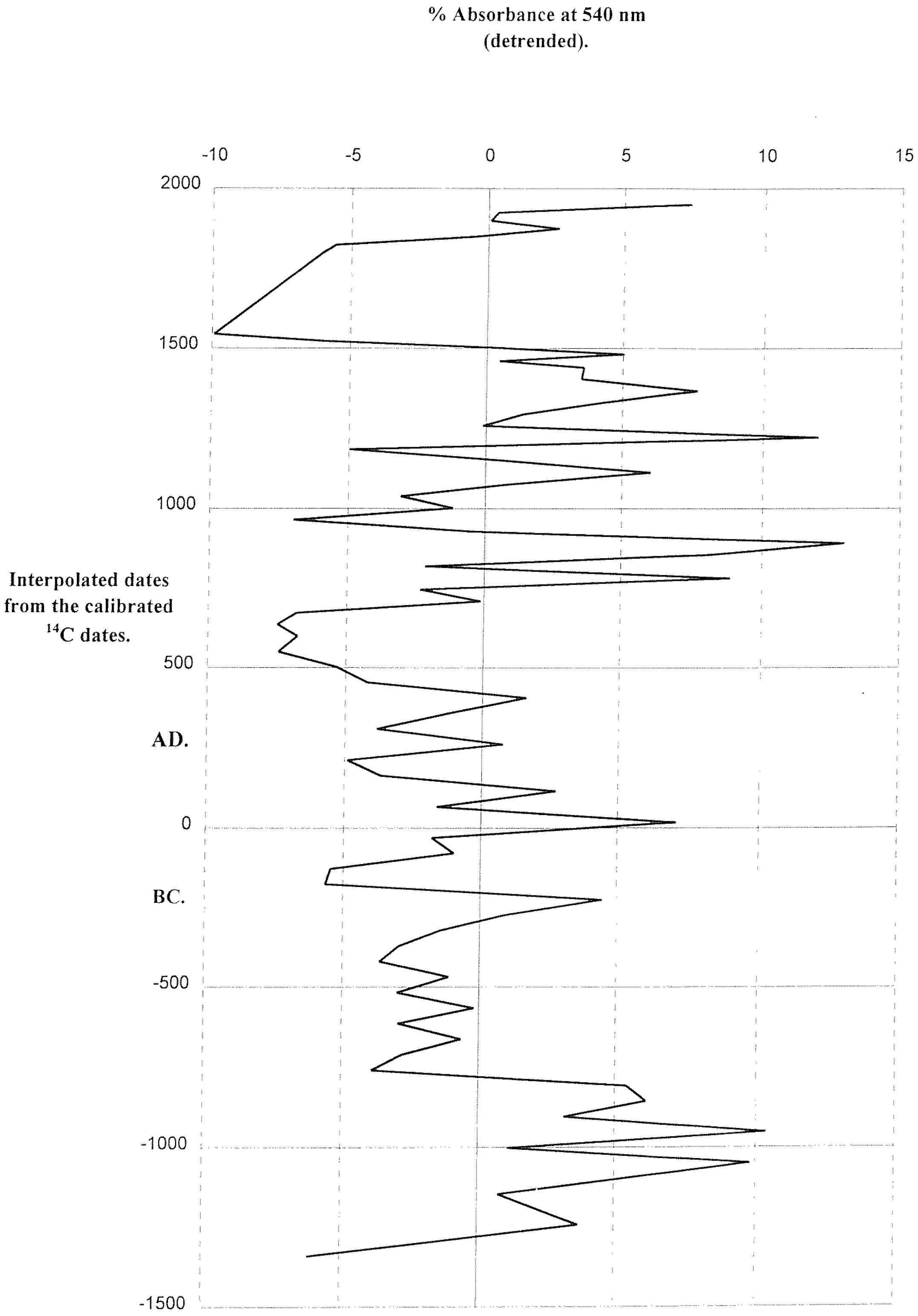
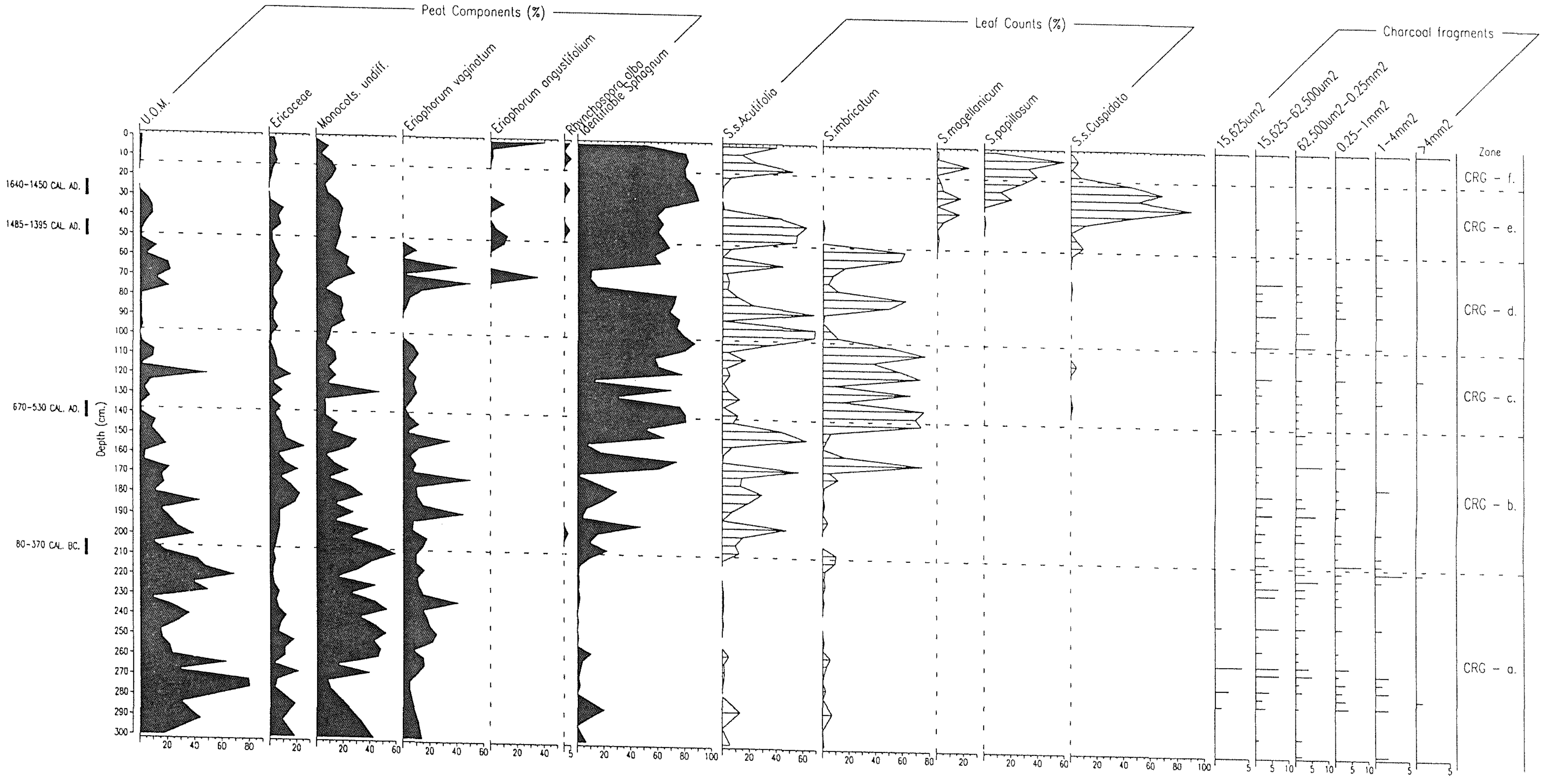


Figure 5.33 Coom Rigg Moss. Macrofossil diagram.



Analysis: Dmitri Mauquoy

Zone CRG -d. (samples 14-25, 50-98 cm.). The plant macrofossils display a high degree of variability in this zone, since there is evidence for both *Eriophorum vaginatum* and *E. angustifolium* displacing the *Sphagnum* sward. The latter species is relatively hygrophilous (Section 5.2.6), which combined with the presence of *E. vaginatum*, suggests a degree of local water table fluctuation. Relatively high U.O.M. values suggest possible swings to drier conditions, but stable values of Ericaceae argue against a marked shift to drier mire surface conditions. *Sphagnum imbricatum* becomes extinct between CAL 1395-1485 AD. (SRR-5884) at the top of the zone.

Zone CRG -e. (samples 5-13, 14-50 cm.). A very sharp increase in local water tables post-dating the extinction of *Sphagnum imbricatum* is readily apparent in this zone, as very high abundances of *Sphagnum* section *Cuspidata* leaves, and moderate amounts of *Eriophorum angustifolium* and *Rhynchospora alba*, are present in the peat stratigraphy.

Zone CRG -f. (samples 1-4, 0-14 cm.). In comparison to the stratigraphy of the other sites considered so far, *Sphagnum papillosum* continues to increase in abundance, whilst leaves of *Sphagnum* section *Cuspidata* decline. *Sphagnum magellanicum* forms only a relatively small part of the peat matrix (up to 23%). Mire hydrological conditions have become drier, but the presence of abundant *Sphagnum papillosum,* suggests effective precipitation is high enough to maintain low lawns (Section 5.2.17), which may be a reflection of the higher effective precipitation this site currently receives (Section 4.5.1).

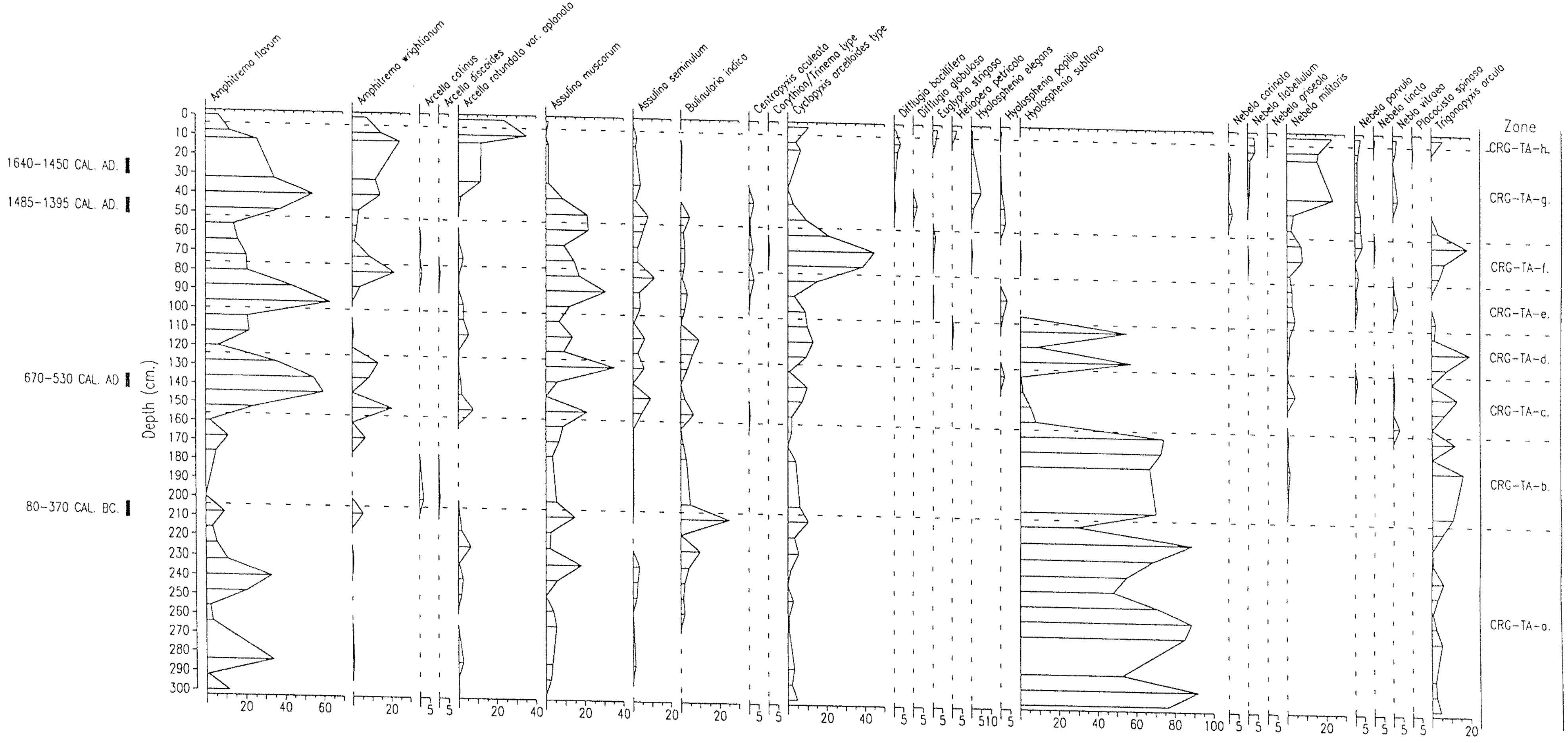
5.4.6.3 Coom Rigg Moss - Testate amoebae stratigraphy.

Zone CRG-TA-a. (samples 24-34, 204-300 cm.). Very high abundances of *Hyalosphenia subflava* point to the potential existence of a deep acrotelm, although fluctuations in the representation of *Amphitrema flavum* tests suggest a degree of fluctuation of the local water table, as they form up to 34% of the necrocoenose.

Zone CRG-TA-b. (samples 20-23, 156-204 cm.). Mire surface wetness is consistently low, as *Hyalosphenia subflava* thecae are consistently recorded in high numbers (up to 74%), *Trigonopyxis arcula* tests increase, and hygrophilous tests of *Amphitrema flavum* decline.

Zone CRG-TA-c. (samples 16-19, 124-156 cm.). A sharp decline in *Hyalosphenia subflava* tests, and increased representation of *Amphitrema flavum* and *A. wrightianum*, point to much wetter conditions spanning this zone.

Figure 5.34 Coom Rigg Moss. Testate amoebae.



Analysis: Dmitri Mauquoy

Zone CRG-TA-d. (samples 12-15, 100-124 cm.). Increases in *Hyalosphenia subflava* and *Trigonopyxis arcula*, and simultaneous declines in *Amphitrema flavum* shells, suggest a return to drier mire surface conditions.

Zone CRG-TA-e. (samples 10-12, 76-100 cm.). Hyalosphenia subflava tests completely disappear, and are replaced by *Amphitrema flavum* and *A. wrightianum.* Thecae of *Trigonopyxis arcula* also decline, which in addition to the presence of the *Amphitrema* species, highlight the existence of elevated water levels.

Zone CRG-TA-f. (samples 7-9, 52-76 cm.). The presence of increased *Cyclopyxis arcelloides* type and *Trigonopyxis arcula* shells, allied with a decline in *Amphitrema flavum* and *A. wrightianum* thecae, suggests a decrease in mire surface wetness.

Zone CRG-TA-g. (samples 2-6, 4-52 cm.). Assulina muscorum, *Cyclopyxis arcelloides* type, and *Trigonopyxis arcula* decline considerably, whilst increases in *Amphitrema flavum*, *A. wrightianum*, *Arcella rotundata* var. *aplanata* and *Difflugia bacillifera*, highlight a return to wetter conditions once again.

Zone CRG-TA-h. (sample 1, 0-4 cm.). This sample indicates a slight reduction in local water tables, but high abundances of *Arcella rotundata* var. *aplanata* (24%), still indicate relatively wet conditions.

5.4.6.4 Coom Rigg Moss - Summary of the humification, plant macrofossil and testate amoebae results.

Further evidence for wetness following the extinction of *Sphagnum imbricatum* is repeated in Coom Rigg Moss, since a wet phase is clearly demonstrated by the high numbers of *Sphagnum* section *Cuspidata* leaves recovered, increased abundances of *Amphitrema flavum and A. wrightianum*, and the low colorimetric absorbance values of the peat matrix within the macrofossil and thecamoebae zones *(CRG - e* and *CRG-TA-f). Sphagnum papillosum* and to a lesser extent, *Sphagnum magellanicum,* become the dominant section *Sphagnum* bryophytes after the demise of *Sphagnum imbricatum.*

This hydroclimatic event is the largest perturbation to the ecosystem based on the macrofossil and humification data, although the testate amoebae indicate two other periods of increased mire surface wetness in zones *CRG-TA-c.* and *e.* Low humification values between 710-550 AD. (128-144 cm.), corroborate the testate amoebae record in zone in *CRG-TA-c* (126-154 cm.). Testate amoebae analysis has indicated wetter and drier areas within the peat stratigraphy, which are otherwise 'masked' by the plant macrofossils, which although variable, are largely dominated by *Sphagnum imbricatum, Sphagnum* section *Acutifolia* and *Eriophorum vaginatum* between 76 and 156 cm.

5.4.7 Felecia Moss.

5.4.7.1 Felecia Moss - Humification data.

A ten point moving average trend line fitted to the data in Figure 5.35, has demonstrated a clear downcore increase in humification values, in a similar manner to Coom Rigg Moss, suggesting decomposition for these two paired sites has continued in the catotelm in accordance with Clymo (1992). Figure 5.36 and 5.37 present the humification data with the trend removed. Areas of higher and lower colorimetric values can be discerned on this diagram; low absorbance values occur at 1800, 1130, 640, and 320-350 AD., and 10, 160, 410, 530 and 710 BC., which may indicate periods of high effective precipitation. Conversely, high values at 1600, 850, 530, and 230 AD., and 40, 320,470, and 650 BC., point to possible drier mire surfaces and lower effective precipitation.

5.4.7.2 Felecia Moss - Macrofossils.

Zone FLC-a. (samples 59-76, 230-300 cm.). The presence of abundant *Sphagnum imbricatum* leaves and some *Sphagnum* section *Acutifolia* and *Eriophorum vaginatum* between 830-280 BC., precludes a straightforward hydrological reconstruction. There is only one sample (268 cm., 590 BC.), which contain hygrophilous species (*Rhynchospora alba* and *Sphagnum* section *Cuspidata*), and these are present in relatively small quantities. Van Geel (1978), notes that *Rhynchospora alba* may persist for some time following drainage of mires, which in combination with increased Ericaceae abundances and the generally high humification values, suggest relatively dry mire surfaces. Charcoal abundances are relatively high, but this need not indicate drier mire conditions (see Raeburn Flow).

Zone FLC-b. (samples 39-58, 150-230 cm.). There is much more variability of *Sphagnum imbricatum* and sedges within this zone. Ericaceae representation fluctuates, but does not differ appreciably from the former zone. Once again, the dominance of *Sphagnum imbricatum* and the relatively species poor macrofossil assemblage, makes any climatic reconstruction difficult. Increases in *Eriophorum vaginatum* at the top of the zone are also difficult to interpret, as this sedge can tolerate a range of mire water levels (Casparie, 1972; Van Geel, 1978; Barber, 1981; Jonasson and Chapin, 1985; Haslam, 1987). Within this zone there appears to have been a degree of water table oscillation, as low absorbance values between 80 AD.-10 BC., and 130-170 BC. point to wetter conditions, whilst higher values between 170-400 AD., suggest drier mire conditions, possibly due to a climatic amelioration.

Zone FLC-c. (samples 31-38, 118-150 cm.). Reduced Ericaceae and U.O.M. indicate a change to wetter conditions within this zone, which is also highlighted by the first consistent representation, albeit low, of *Sphagnum* section *Cuspidata* leaves.

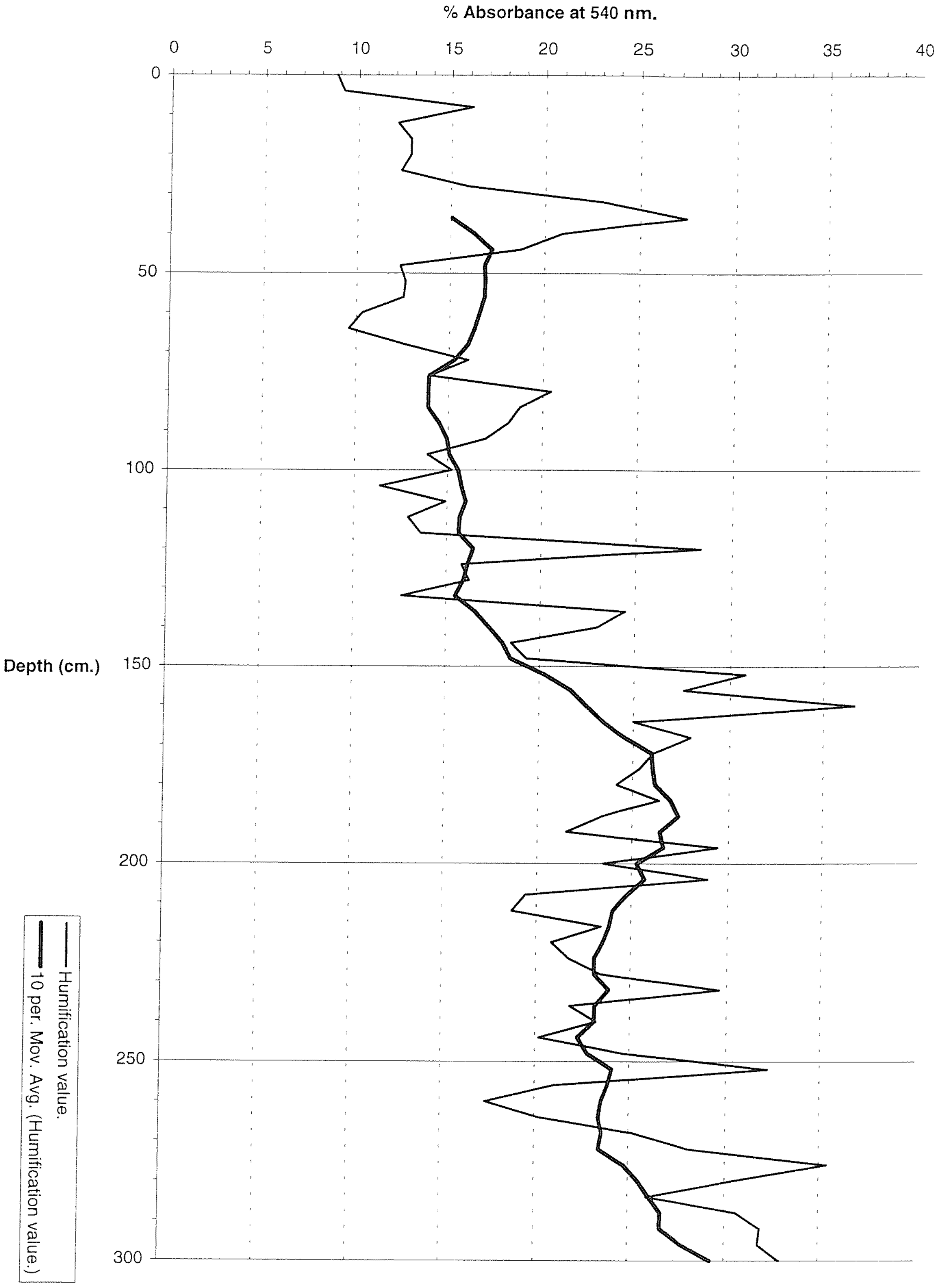


Figure 5.35 Felecia Moss. Humification data vs. depth.

Figure 5.36 Felecia Moss. Humification data vs. depth (detrended).

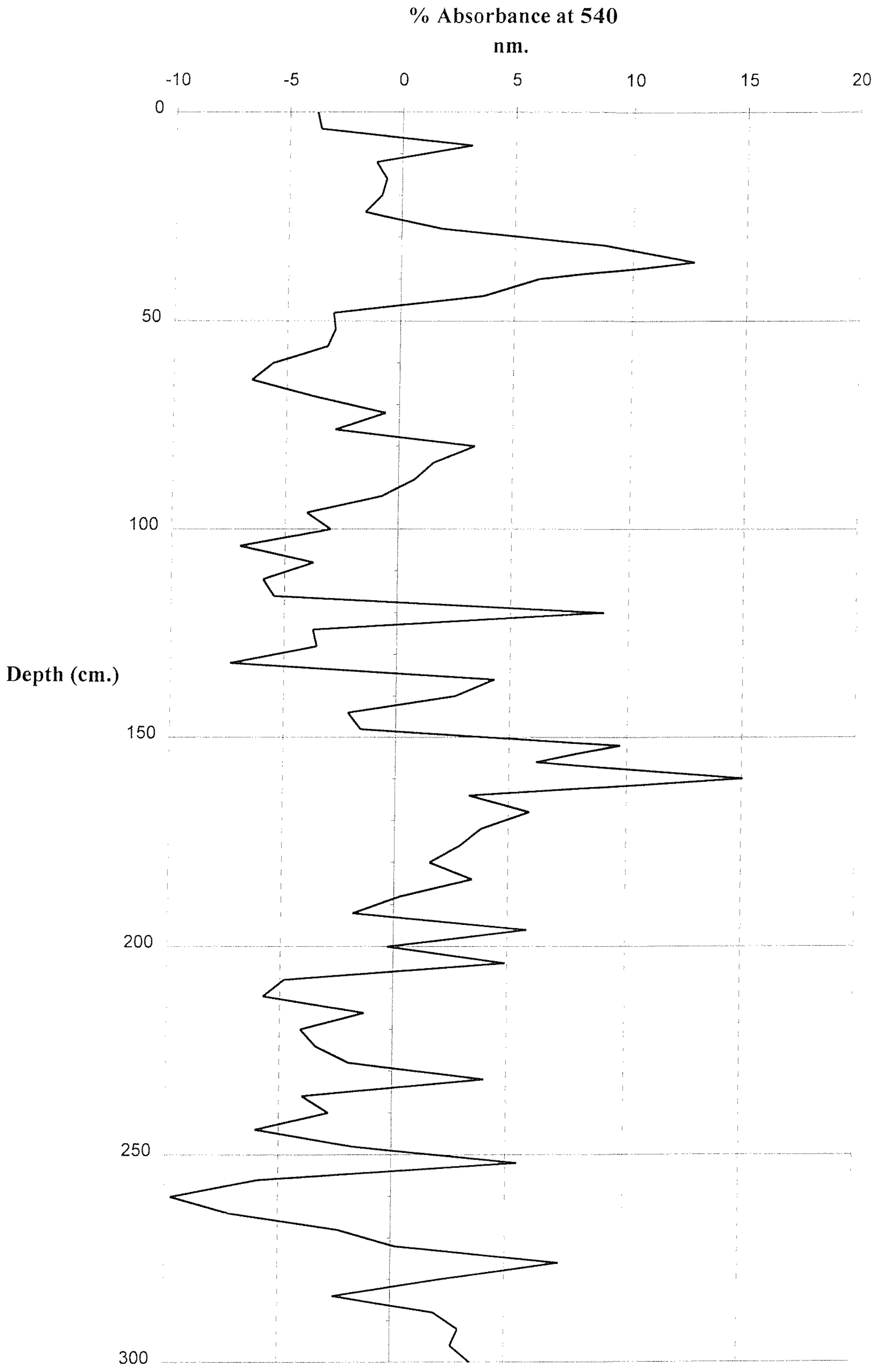


Figure 5.37 Felecia Moss - Humification data vs. time (detrended).

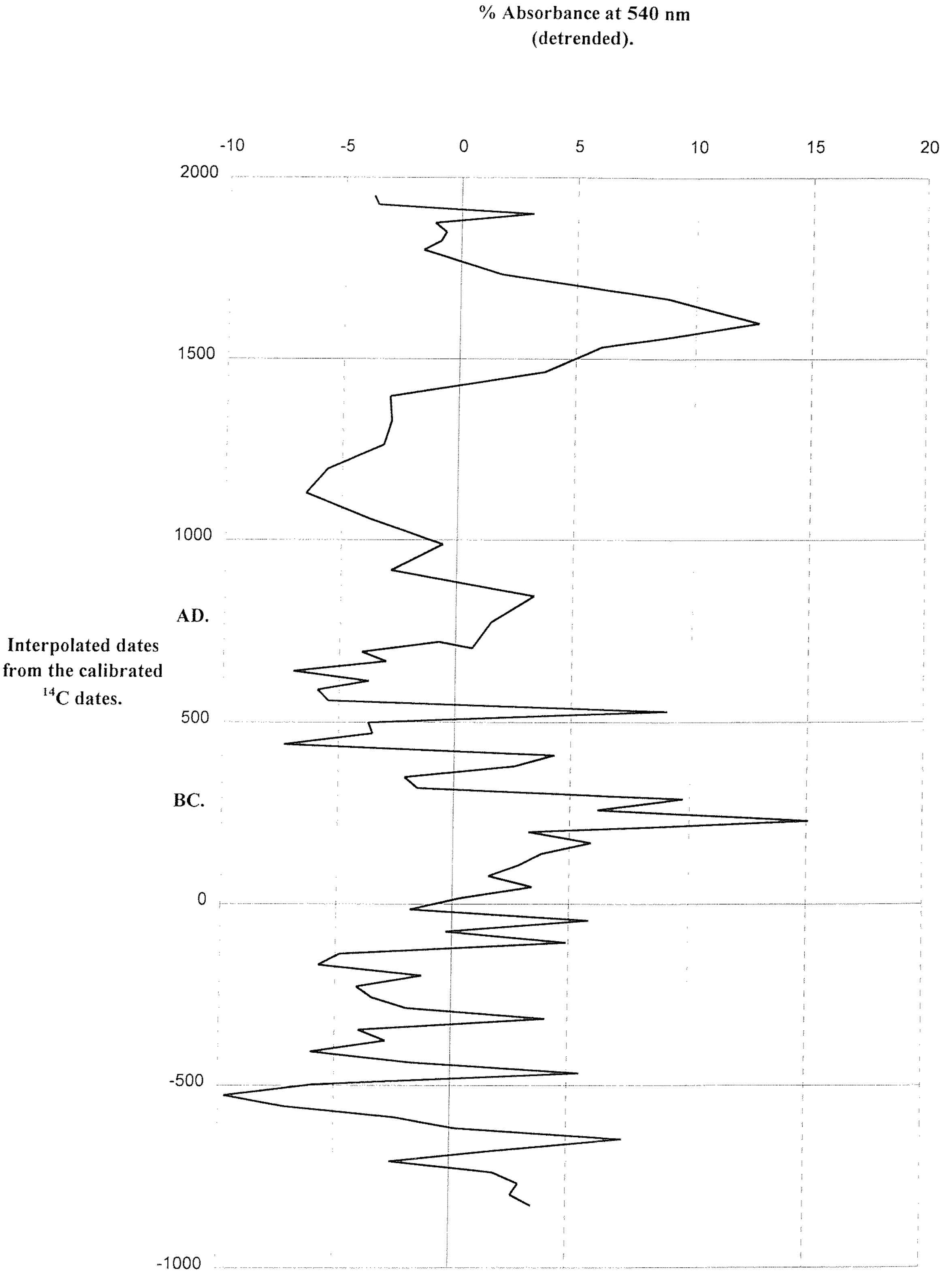
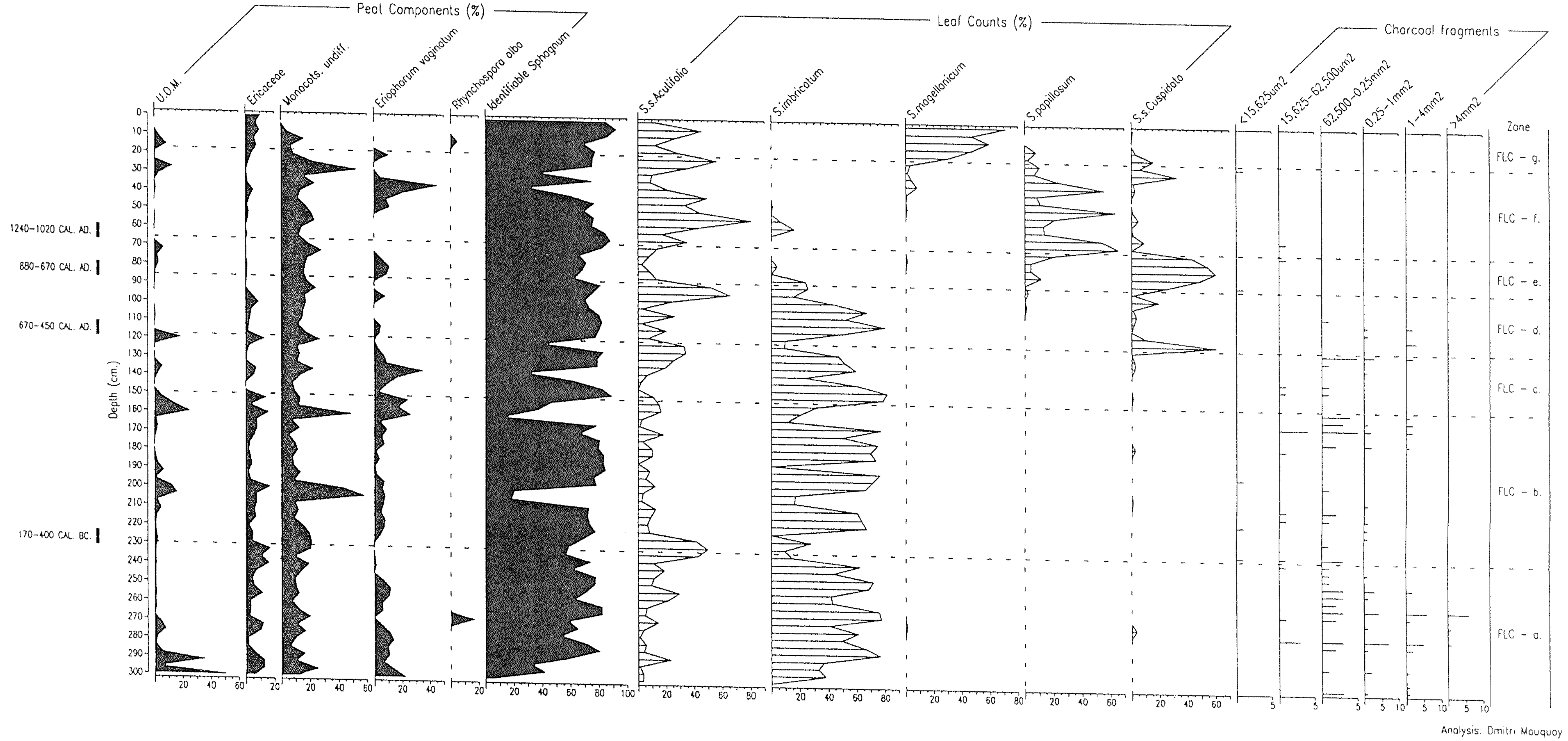


Figure 5.38 Felecio Moss. Macrofossil diagram.



Zone FLC-d. (samples 23-30, 86-118 cm.). Initially high values of *Sphagnum* section *Cuspidata* indicate the presence of a pool, which subsequently became infilled by *Sphagnum imbricatum*. The peak of *Sphagnum* section *Cuspidata* leaves within *Zone FLC-d.* has been dated to CAL 450-670 AD. (SRR-5893). Effective precipitation may well have remained high, however, as *Sphagnum* section *Cuspidata* maintains its presence, and the degree of U.O.M. falls to low values.

Zone FLC-e. (samples 18-22, 66-86 cm.). Hydroclimatological conditions deteriorate further, as a bog pool, comprising up to 60% *Sphagnum* section *Cuspidata,* is consistently present in this zone. Associated with this very wet phase there is a very sharp decline and disappearance of *Sphagnum imbricatum* from the borehole stratigraphy, which is replaced by both *Sphagnum* section *Cuspidata* and *Sphagnum papillosum*. This occurs between CAL 670-880 AD. (SRR-5892) and CAL 1020-1240 AD. (SRR-5891).

Zone FLC-f. (samples 6-17, 18-66 cm.). Mire surface wetness reduces, but remains relatively high, as *Sphagnum* section *Cuspidata* leaves are less frequently encountered in the peat matrix. *Sphagnum papillosum* increases in abundance, infilling the former pool to create a possible low lawn. *Sphagnum imbricatum* returns briefly, but finally becomes extinct, being replaced at first by *Sphagnum papillosum* and then by *Sphagnum magellanicum.* The extinction of *Sphagnum imbricatum* at Felecia Moss occurs at an interpolated date 1470 AD. High abundances of *Eriophorum vaginatum* may indicate water table oscillations, or may simply represent lateral spread from a pre-existing tussock of this species.

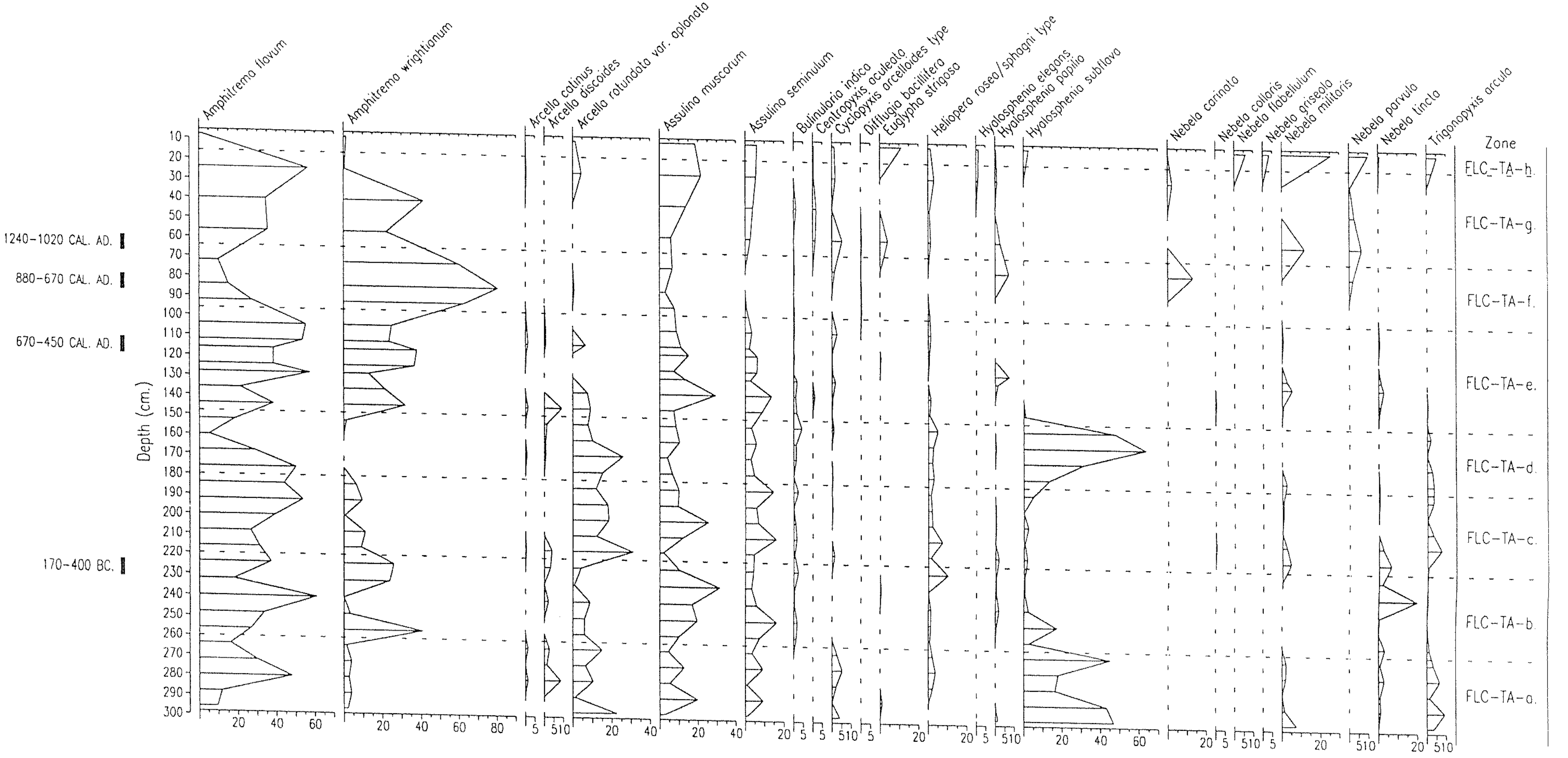
Zone FLC-g. (samples 1-5, 0-18 cm.). Local water tables decline further, as *Sphagnum* section *Cuspidata* leaves as less frequently encountered, Ericaceae representation increases, and *Sphagnum magellanicum* replaces *Sphagnum papillosum*. Wagner and Titus (1984) and Rydin (1985) suggest *Sphagnum magellanicum* is a better competitor for water than *Sphagnum papillosum* when drier conditions prevail, which in this instance, may explain the species replacement pattern.

5.4.7.3 Felecia Moss - Testate amoebae stratigraphy.

Zone FLC-TA-a. (samples 29-33, 260-296 cm.). High abundances of *Hyalosphenia subflava* and relatively high values of *Trigonopyxis arcula* tests, support the existence of low local water tables, although the presence of up to 48% *Amphitrema flavum* at 280 cm., suggests some fluctuation in mire surface wetness.

Zone FLC-TA-b. (samples 24-28, 220-260 cm.). Increases in *Amphitrema flavum* and *A. wrightianum*, combined with declines in xerophile *Hyalosphenia subflava* and *Trigonopyxis arcula,* suggest increases in mire surface wetness, following a possible climatic deterioration. *Nebela tincta* and

Figure 5.39 Felecia Moss. Testate amoebae.



Analysis: Dmitri Mauquoy

Assulina muscorum shells also increase in this zone, suggesting a degree of fluctuation in the local water tables, as these species inhabit drier microsites.

Zone FLC-TA-c. (samples 19-23, 180-220 cm.). Amphitrema flavum and hydrophilous *Arcella rotundata* var *aplanata* thecae increase, highlighting possible high mire water tables again. Tolonen *et al.* (1992), calculated the weighted average position of 38 mire fauna, and report values of 2.8 and 4.2 cm. above the local water table respectively for these rhizopods, supporting this water table reconstruction. Reduced *Assulina muscorum* and *Nebela tincta* tests point to less fluctuations in mire surface wetness.

Zone FLC-TA-d. (samples 15-18, 148-180 cm.). Very high abundances of *Hyalosphenia subflava*, and reductions in the thecae of *Amphitrema flavum, A. wrightianum,* and *Arcella rotundata* var *aplanata,* suggest a marked reduction in local water tables and a possible climatic amelioration.

Zone FLC-TA-e. (samples 8-14, 96-148 cm.). The complete disappearance of *Hyalosphenia subflava,* and its replacement by *Amphitrema flavum* and *A. wrightianum,* indicates a change to wetter conditions. Increases in *Hyalosphenia papilio* tests attest to this, but relatively high abundances of *Assulina muscorum*, may also point to a degree of fluctuation in the water tables.

Zone FLC-TA-f. (samples 5-7, 64-96 cm.). Extremely high abundances of *Amphitrema wrightianum*, and the first representation of *Nebela carinata,* and small quantities of *Difflugia bacillifera* in the peat stratigraphy, suggest very wet conditions occurred in this zone (Grospietsch, 1958; Tolonen *et al.*, 1992).

Zone FLC-TA-g. (samples 2-4, 16-64 cm.). There is a slight reduction in mire surface wetness, although water tables appear to have remained relatively high, as *Amphitrema flavum* and *A. wrightianum* shells are still numerous. Increases in *Assulina muscorum*, *Nebela militaris* and *Nebela parvula* thecae provide evidence for a reduction in mire surface wetness.

Zone FLC-TA-h. (sample 1, 8-16 cm.). Sharp declines in *Amphitrema flavum* and *A. wrightianum,* and concurrent increases in *Euglypha strigosa, Nebela flabellulum, Nebela griseola, Nebela militaris* and *Trigonopyxis arcula*, in addition to sustained high values of *Assulina muscorum,* point to drier conditions and low water tables in this modern peat.

5.4.7.4 Felecia Moss - Summary of the humification, plant macrofossil and testate amoebae results.

This mire differs from Coom Rigg Moss, in that there are three as opposed to one, distinct wet phases within the peat stratigraphy *(FLC - d., e., and f).* The humification data and testate amoebae assemblages (principally increased numbers of *Amphitrema flavum* and *A. wrightianum*), also support the existence of elevated mire water levels, within their respective zones (*FLC-TA- e., f.* and *g.*). This is very encouraging, as all three proxies appear to be able to detect the same direction of change in mire surface wetness.

The thecamoebae fauna in zone *FLC-TA-c.* and low colorimetric absorbance values between 180-192 cm. (80 AD.-10 BC.) and 208-212 cm. (130-160 BC.), however, point to a possible climatic deterioration, which is not readily detectable from the plant macrofossils. The dearth of tests of the xeric testate amoebae, *Hyalosphenia subflava*, suggest increases in local water tables, as this species is characteristically found in dry *Sphagnum* microsites with 76-89% water content (Warner, 1987). This zone is sandwiched between *FLC - d* and *b.*, where conversely, tests of the latter species are far more numerous (up to 63.5%), suggesting drier mire surface conditions.

5.4.8 Shaft Hill Monoliths.

Three peat monoliths *(SHL1, 2, 3),* were taken from this plateau blanket peat site, in order to test whether a climatic signal could be replicated in each. The second monolith *(SHL2)* was located 3 m. to the south of *SHL1,* whilst the third one *(SHL-3),* extended 15 m. to the east of *SHL1.*

Barber (1981), Stoneman (1993), Barber (1995), and Barber *et al.* (in prep.), have successfully demonstrated a replicable climatic signal in lowland raised peat stratigraphy. The replicability of the potential climatic signal in blanket peat stratigraphy, using plant macrofossil, thecamoebae and humification analysis, has not been so clearly demonstrated, with the exception of the pollen, microfossil and humification analyses undertaken by Blackford (1990), and the pollen and plant macrofossil work of Tallis (1994, 1995). The detailed analysis of three monoliths from the Moor House Reserve may help to fill this gap, and additionally, test the sensitivity of the ombrotrophic mire located here, to respond to changes in climate in an extreme climatological setting (Section 4.7).

The stratigraphy of each monolith is described first, then the differences and similarities of each of them will be considered together, to see if there is indeed a replicable species response to elevated water levels.

The humification curve for each monolith is plotted against depth, rather than time, to allow a comparison to be made between each of the monoliths. This approach had to be adopted, as none of the samples from Shaft Hill - Monolith 1 were submitted for radiocarbon dating, whilst only two radiocarbon assays were available for Monolith 2 (Table 5.5).

5.4.8.1 Shaft Hill - Monolith 1. - Humification data.

Low humification values which may indicate periods of climatic deterioration are located between 13 and 21.5 cm., and between 45.5 and 61.5 cm. (Figure 5.40). Conversely, absorbance values at the base of the monolith are very high (absorbance values reach 64%), suggesting the occurrence of low local water tables and dry mire surfaces. Although the humification values at the base of this blanket peat monolith exceed all those gathered from the raised mire sites, this must still be related in some way to effective precipitation, as this site is a water shedding one and therefore ombrotrophic.

5.4.8.2 Shaft Hill - Monolith 1. - Macrofossils.

Zone SHL1-a. (samples 29-37, 61.5-78 cm.). High values of Ericales roots, U.O.M., *Eriophorum vaginatum* and scattered leaves of *Racomitrium lanuginosum*, combined with a dearth of identifiable *Sphagnum*, point to dry mire surface conditions (Figure 5.41). Casparie (1972, p. 152), has similarly linked the appearance of both *E. vaginatum* and *Calluna* with 'desiccations', stressing the role of the former as a hummock coloniser. There is a great deal of evidence for burning in this zone, which may also be a reflection of the reconstructed drier mire surfaces.

Figure 5.40 Shaft Hill - Monolith 1 - Humification data vs. depth.

Analysis by Mark Garnett - Institute of Terrestrial Ecology.

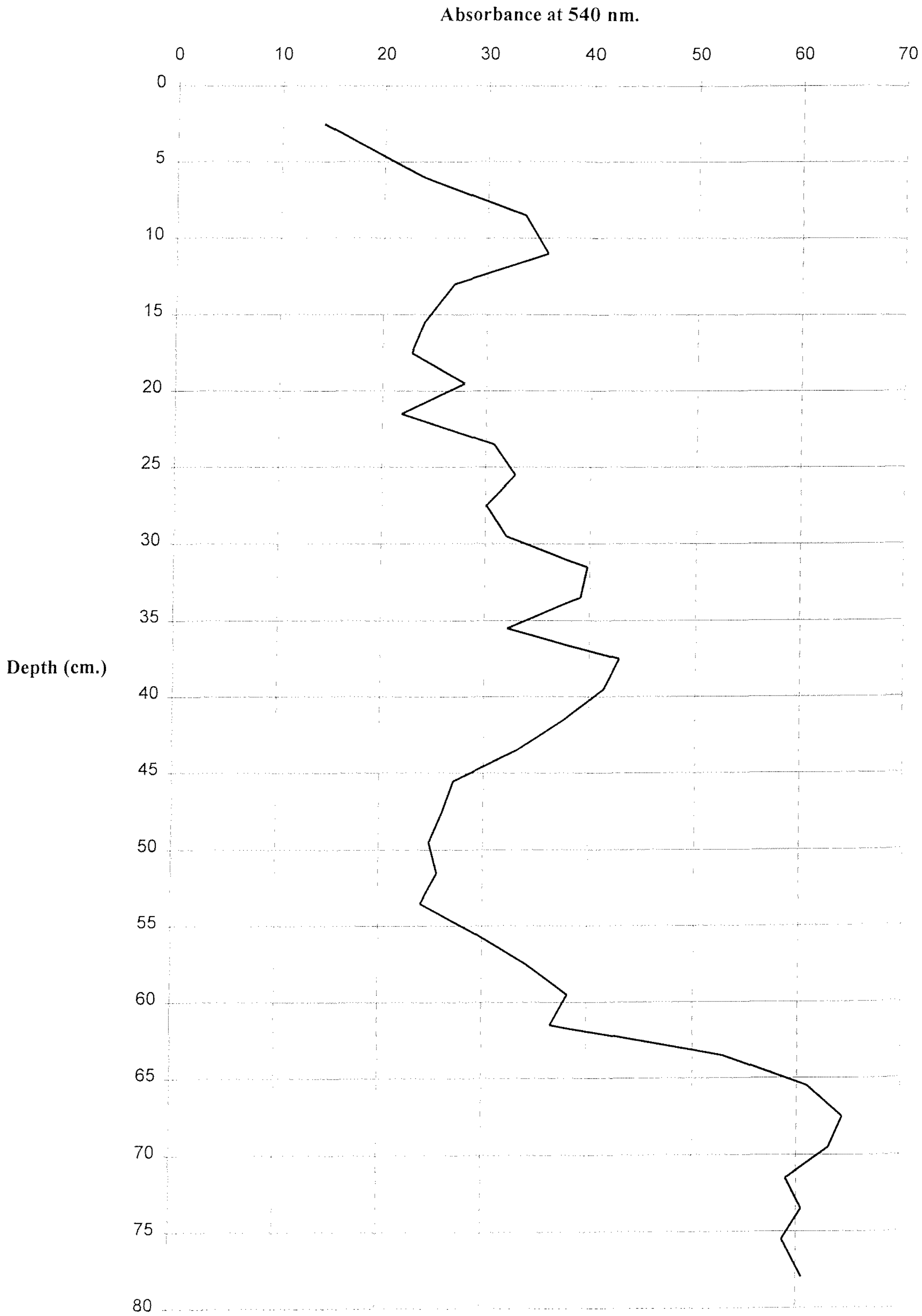
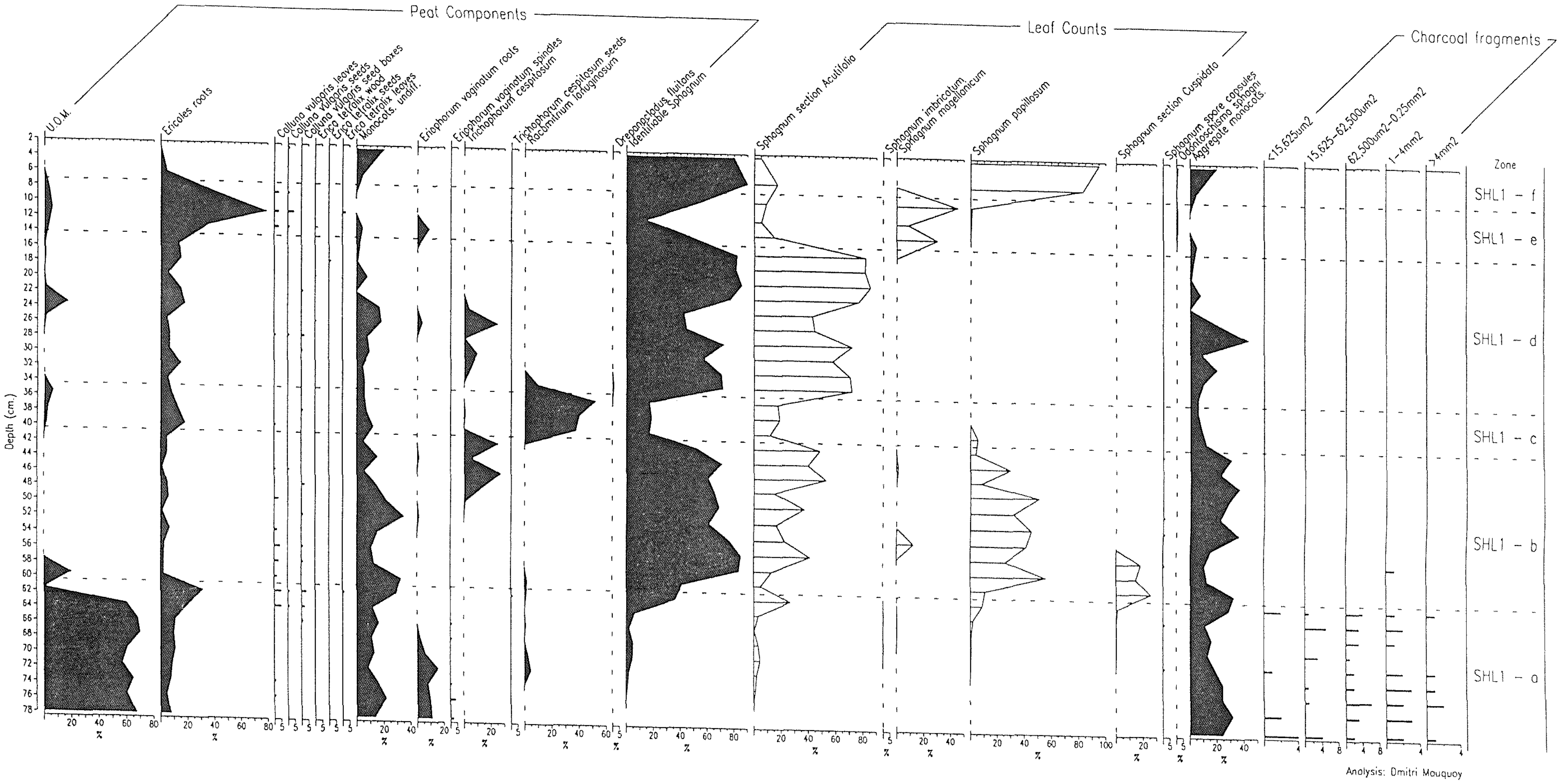


Figure 5.41 Shaft Hill – Monolith 1. Macrofossil diagram.



Zone SHL1-b. (samples 19-28, 40.5-61.5 cm.). A substantial increase in local water tables is indicated in this zone, as both *Sphagnum papillosum* and hygrophilous *Sphagnum* section *Cuspidata* leaves smother the hummock vegetation. Low U.O.M. values, and a reduction in Ericales roots, support the existence of a shallower acrotelm, whilst the presence of *Trichophorum cespitosum* epidermis may also indicate wetter surface conditions (Eddy *et al.*, 1969; Rodwell *et al.*, 1991).

Zone SHL1-c. (samples 16-18, 34.5-40.5 cm.). Racomitrium lanuginosum displaces the *Sphagna,* and U.O.M. and Ericales roots increase, suggesting a climatic amelioration. Tallis (1995), has similarly interpreted sub-fossil peat levels containing *R. lanuginosum* in southern Pennine blanket peat sites, and has suggested they indicate the period following the 'Early Medieval Warm Period'. The undoubted 'xeric' affinities of this bryophyte (Section 5.2.11), and the generally higher absorbance values within this zone, support the existence of a dry microsite.

Zone SHL1-d. (samples 6-15, 14.5-34.5 cm.). Racomitrium lanuginosum leaves decline and are replaced by *Sphagnum* section *Acutifolia*, which dominate the peat stratigraphy, suggesting a climatic deterioration. *Trichophorum cespitosum* epidermis and the U.O.M. record may also indicate wetter surface conditions, since with the exception of the sample at 24 cm. (17.5% of the peat matrix), U.O.M. values are low. The presence of *Drepanocladus fluitans* leaves, although small, may similarly point to wetter conditions (Section 5.2.12).

Zone SHL1-e. (samples 3-5, 7.5-14.5 cm.). Ericales roots, *Calluna vulgaris* leaves and seeds, and *Erica tetralix* seeds, are very prominent in this zone, displacing the *Sphagnum* spp., pointing to a reduction in mire surface wetness. *Sphagnum magellanicum* leaves reach their highest abundances in this zone, suggesting a lawn microtope may have existed (Section 5.2.16), implying the shift to drier conditions may not have been marked.

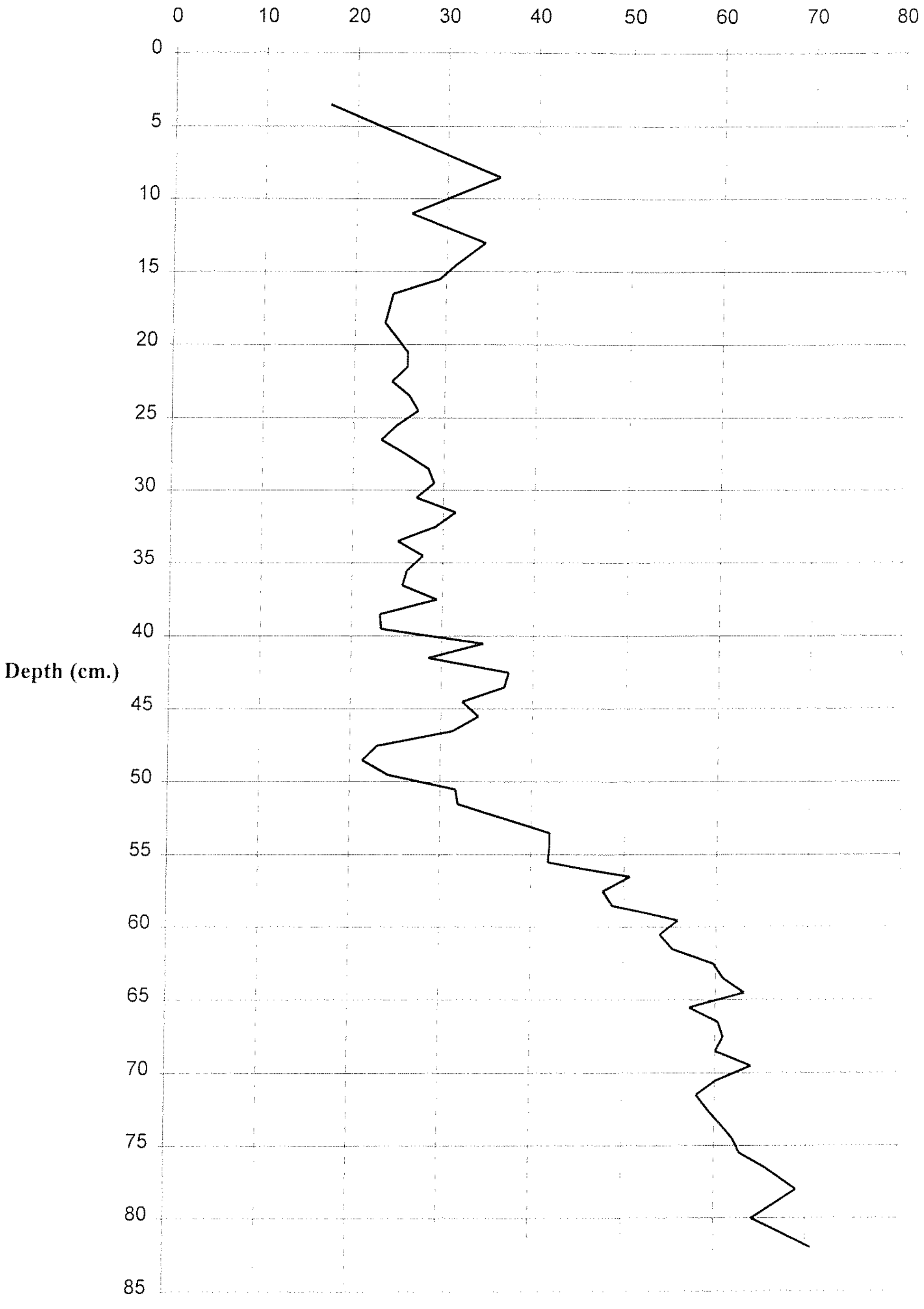
Zone SHL1-f. (samples 1-2, 1-7.5 cm.). Local water tables seem to have increased, as *Sphagnum papillosum* leaves occur abundantly in the peat stratigraphy, smothering the Ericaceae.

5.4.8.3 Shaft Hill - Monolith 2.- Humification data.

High absorbance values from the base of the monolith to 51-52 cm. (Figure 5.42), suggest low local water tables, and therefore low effective precipitation. Conversely, shifts indicating a low degree of humification occur between 47 and 51 cm., and from 38 to 41 cm. These levels may record some degree of climatic deterioration.

Figure 5.42 Shaft Hill - Monolith 2 - Humification data vs. depth.

Analysis by Mark Garnett - Institute of Terrestrial Ecology.



5.4.8.4 Shaft Hill - Monolith 2. - Macrofossils.

Zone SHL2 - a. (samples 30-37, 66.5-82 cm.). The peat matrix is dominated by U.O.M. material and sedges, whilst the representation of *Sphagna* is low. Leaves of *Sphagnum imbricatum*, in addition to those of *Sphagnum papillosum* and *Sphagnum* section *Cuspidata,* only comprise at most, 24% of the peat matrix. The joint occurrence of relatively abundant *Eriophorum vaginatum* roots, epidermis and spindles and *Calluna vulgaris* leaves, seeds and Ericales roots, combined with the dearth of *Sphagna*, suggests low local water tables. Relatively low abundances of Cladocera and Copepod zoofossils support this hydrological reconstruction, as they are normally associated with more hygrophilous plant macrofossils (Van Geel and Middeldorp, 1988).

Zone SHL2 - b. (samples 24-29, 54.5-66.5 cm.). Water levels appear to fluctuated to a degree in this zone, as hygrophilous *Sphagnum* section *Cuspidata* leaves are more frequently encountered, and epidermal tissue of *Eriophorum angustifolium* is recorded for the first time. The continued presence of U.O.M., *Calluna vulgaris* leaves, *Eriophorum vaginatum* spindles and *Racomitrium lanuginosum* leaves, also points to periods of low water tables, supporting the water level fluctuation hypothesis. Water levels appear to have been stable enough, however, to support Cladocera and Copepoda, as they were consistently recorded in the peat matrix. Macroscopic charcoal particles are frequently encountered in this zone, particularly larger fragments in the 1-4 mm.^{2} size range, pointing to the continued occurrence of fires on the mire surface.

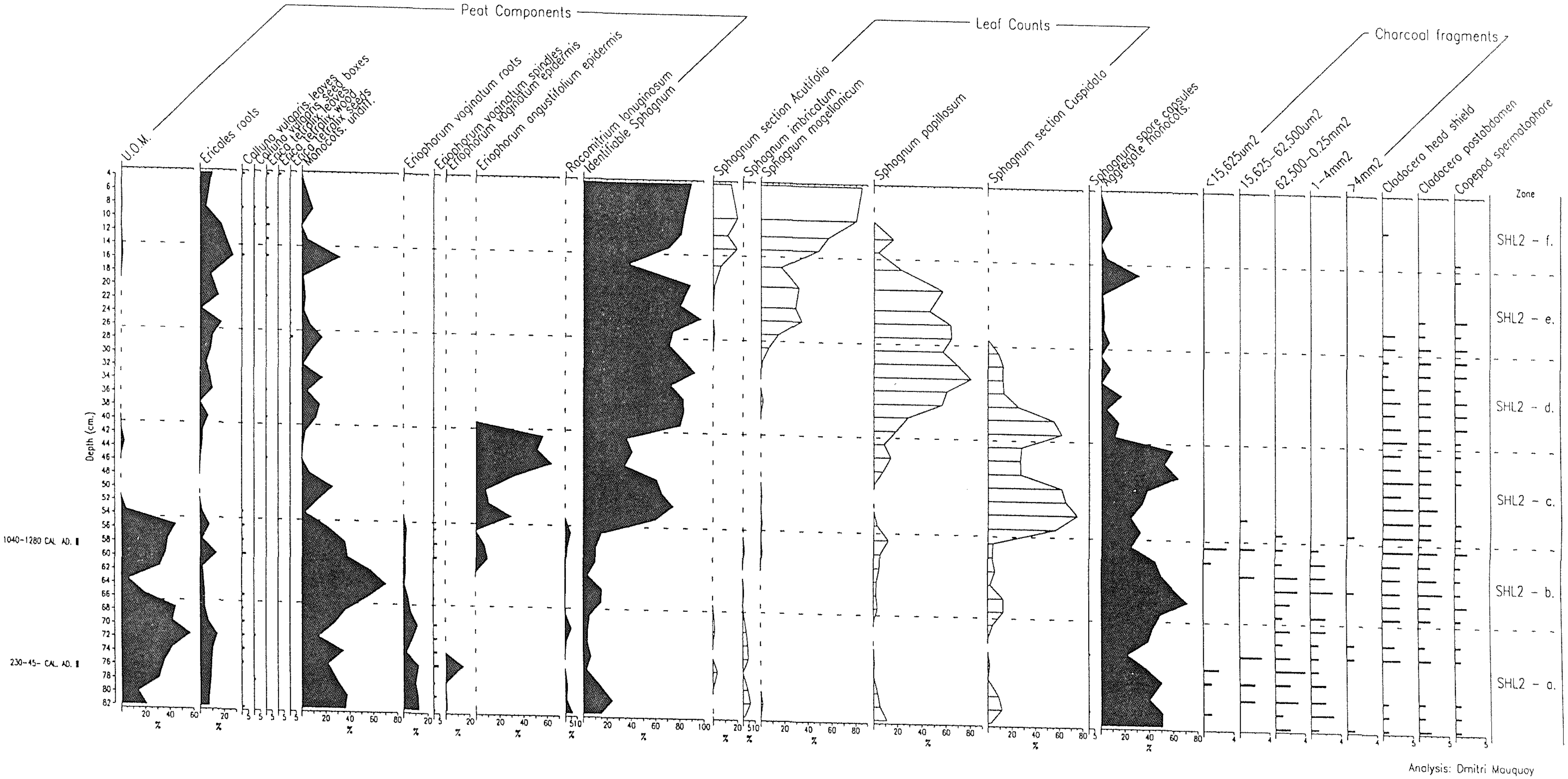
Zone SHL2 -c. (samples 17-23, 40.5-54.5 cm.). A very wet pool phase is readily detectable in this zone, as there are abundant *Sphagnum* section *Cuspidata* leaves and *Eriophorum angustifolium* epidermal tissues in the sub-sample. There is, allied to this, a sharp decline in the representation of U.O.M. and Ericaceae macrofossils, whilst *Racomitrium lanuginosum* and *Sphagnum imbricatum* disappear completely, further supporting a large increase in mire surface wetness.

Zone SHL2 -d. (samples 10-16, 26.5-40.5 cm.). Mire water levels reduce a degree, since Ericales roots recur, whilst the high representation of *Sphagnum papillosum* leaves highlight a change to a low lawn micro-environment.

Zone SHL2 -e. (samples 5-9, 14-26.5 cm.). A gradual decline in the representation of *Sphagnum papillosum,* and its replacement by *Sphagnum magellanicum* and increased Ericales roots, invites the possibility that local water tables have dropped further, possibly because of some climatic amelioration. After a lengthy period of consistent representation in the lower zones, Cladocera and Copepod zoofossils also diminish, lending support for increased desiccation in these samples.

Zone SHL2 -f. (samples 1-4, 3.5-14 cm.). Abundant *Sphagnum magellanicum* leaves indicate the presence of a lawn microtope which is sufficiently dry for *Sphagnum* section *Acutifolia* (cf. *Sphagnum capillifolium* var. *rubellum*), *Calluna vulgaris* and *Erica tetralix* to grow there.

Figure 5.43 Shaft Hill – Monolith 2. Macrofossil diagram.



5.4.8.5 Shaft Hill - Monolith 2. - Testate Amoebae Stratigraphy.

Zone SHL2-TA-a. (samples 30-37, 66.5-82 cm.). The thecamoebae stratigraphy in this zone are in accordance with the humification and macrofossil evidence, in that they indicate dry mire surfaces. Tests of the xerophilous taxon *Hyalosphenia subflava* (Tolonen, 1986; Warner, 1987), are numerous, whilst the representation of *Assulina muscorum* is also relatively high, further supporting the existence of low local water tables, as this is a hygrophilous/xerophilous species (Warner, 1987).

Zone SHL2-TA-b. (samples 24-29, 54.5-66.5 cm.). Water levels appear to have fluctuated between both relatively wet and dry mire surfaces, as xerophilous tests of *Assulina muscorum, Hyalosphenia subflava* and *Nebela parvula* are recorded along with hygrophilous *Amphitrema wrightianum, Difflugia bacillifera,* and *Nebela carinata* thecae.

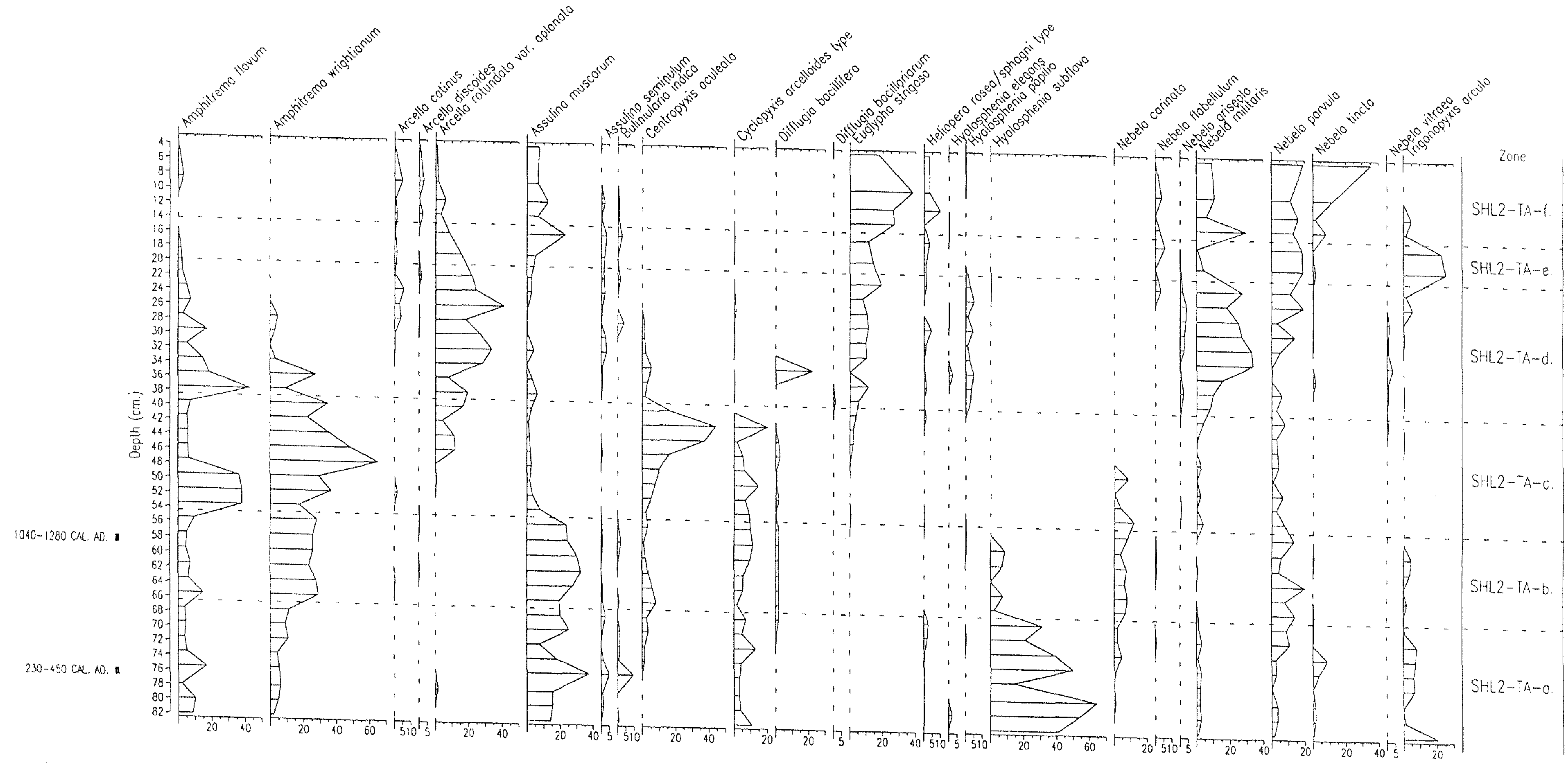
Zone SHL2-TA-c. (samples 16-23, 38.5-54.5 cm.). Very high mire surface wetness is indicated by the high representation of pool *Amphitrema wrightianum* thecae, and increased *Amphitrema flavum* and *Centropyxis aculeata* tests (Warner, 1987).

Zone SHL2-TA-d. (samples 7-15, 20-38.5 cm.). A deeper acrotelm may have existed in this zone, as thecae of *Amphitrema flavum* and *A. wrightianum* decline, and are replaced by hydrophilous *Arcella rotundata* var. *aplanata* type and *Euglypha strigosa* and *Nebela militaris*. The latter two species have xeric affinities (Bartos, 1940; De Graff, 1956; Grospietsch, 1958; Heal, 1961; Corbet, 1973), although Warner and Charman (1994), have demonstrated that *Euglypha* spp. in NW Ontario peatlands occur at different positions along hummock/hollow microtransects (low moisture values) than those in NE Ontario and Finland (middle to high mire moisture values). The presence of the bog pool species, *Difflugia bacillifera* and *D. bacillariarum* (Heal, 1961; Corbet, 1973), suggest hydrological conditions may have also fluctuated a degree within this largely drier zone.

Zone SHL2-TA-e. (samples 5-6, 14.5-20 cm.). Local water tables and effective precipitation seem to have reduced further in this zone, as hygrophilous *Amphitrema flavum* and *A. wrightianum* and hydrophilous *Arcella rotundata* var. *aplanata* type thecae decline further, to be replaced by *Assulina muscorum, Euglypha strigosa* and *Trigonopyxis arcula* shells.

Zone SHL2-TA-f. (samples 1-4, 3.5-14.5 cm.). The dominant species within this zone are *Euglypha strigosa* and *Nebela tincta*. The ecology of the former species needs to be interpreted with caution, as it appears to have been recorded over a large range of water table depths (Warner and Charman, 1994). The ecology of *Nebela tincta* is clearer, however, as it is associated with the driest parts of hummocks (Heal, 1961), and in high *Sphagnum fuscum* ridges, where it can comprise 26% of the thecamoebae

Figure 5.44 Shaft Hill – Monolith 2. Testate amoebae.



Analysis: Dmitri Mauquoy

assemblage (Tolonen, 1966). Allied to this, the continued paucity of *Amphitrema flavum* and *A. wrightianum* thecae, suggest local water tables have remained low, possibly due to a climatic amelioration.

5.4.8.6 Shaft Hill - Monolith 3.- Humification data.

Sustained high absorbance values from the base of the monolith to 36.5 cm. indicate a highly decomposed peat matrix, possibly resulting from a low effective precipitation regime (Figure 5.45). A sharp change to fresher, less humified peat occurs between 34.5 and 28.5 cm., which, conversely, may record a climatic deterioration. There is a slight increase in the humification signal from 20.5 cm. to the surface, suggesting a slight decrease in the depth of local water tables.

5.4.8.7 Shaft Hill - Monolith 3.- Macrofossils.

Zone SHL3 - a. (samples 30-35, 61-72 cm.). The peat matrix is almost exclusively composed of U.O.M. and Monocots. undiff., with some Ericales roots (up to 18% of the peat sub-sample). The additional presence of *Eriophorum vaginatum* macrofossils (roots and spindles), and the lack of *Sphagna*, highlight possible dry mire surface conditions. Zoofossils of Cladocera were frequently encountered in the 66 cm. sample, which may highlight a degree of water level fluctuation in the otherwise 'dry' peat stratigraphy.

Zone SHL3 - b. (samples 15-29, 31-61 cm.). Local water tables appear to have remained low, as there are consistently high values of U.O.M. and Ericales roots, and relatively low abundance values of Cladocera and Copepoda within this zone. The increased representation of *Sphagna (Sphagnum* section *Acutifolia,* cf. *Sphagnum capillifolium* var. *rubellum* and *Sphagnum imbricatum),* may highlight the existence of a hummock microtope, as both these species have xeric affinities. The increase in the abundance of *Sphagnum imbricatum* between 58-60 cm. is particularly marked, and has been dated to CAL 260-550 AD. (SRR-5866).

Zone SHL3 - c. (samples 7-14, 15-31 cm.). A very pronounced change to high mire surface wetness is immediately apparent in this zone, as leaves of *Sphagnum* section *Cuspidata* dominate the peat matrix. Epidermal tissues of *Eriophorum angustifolium* and consistently high values of Cladocera head shields, support this hydrological reconstruction. Macroscopic charcoal particles disappear from the peat matrix and are no longer recovered in any of the subsequent peat sub-samples, suggesting an absence of local surface fires.

Zone SHL3 - d. (samples 4-6, 9-15 cm.). Effective precipitation may have decreased, as *Sphagnum papillosum* and some *Sphagnum* section *Acutifolia* leaves replace hygrophilous *Sphagnum* section

Figure 5.45 Shaft Hill - Monolith 3 - Humification data vs. depth.

Analysis by Mark Garnett - Institute of Terrestrial Ecology.

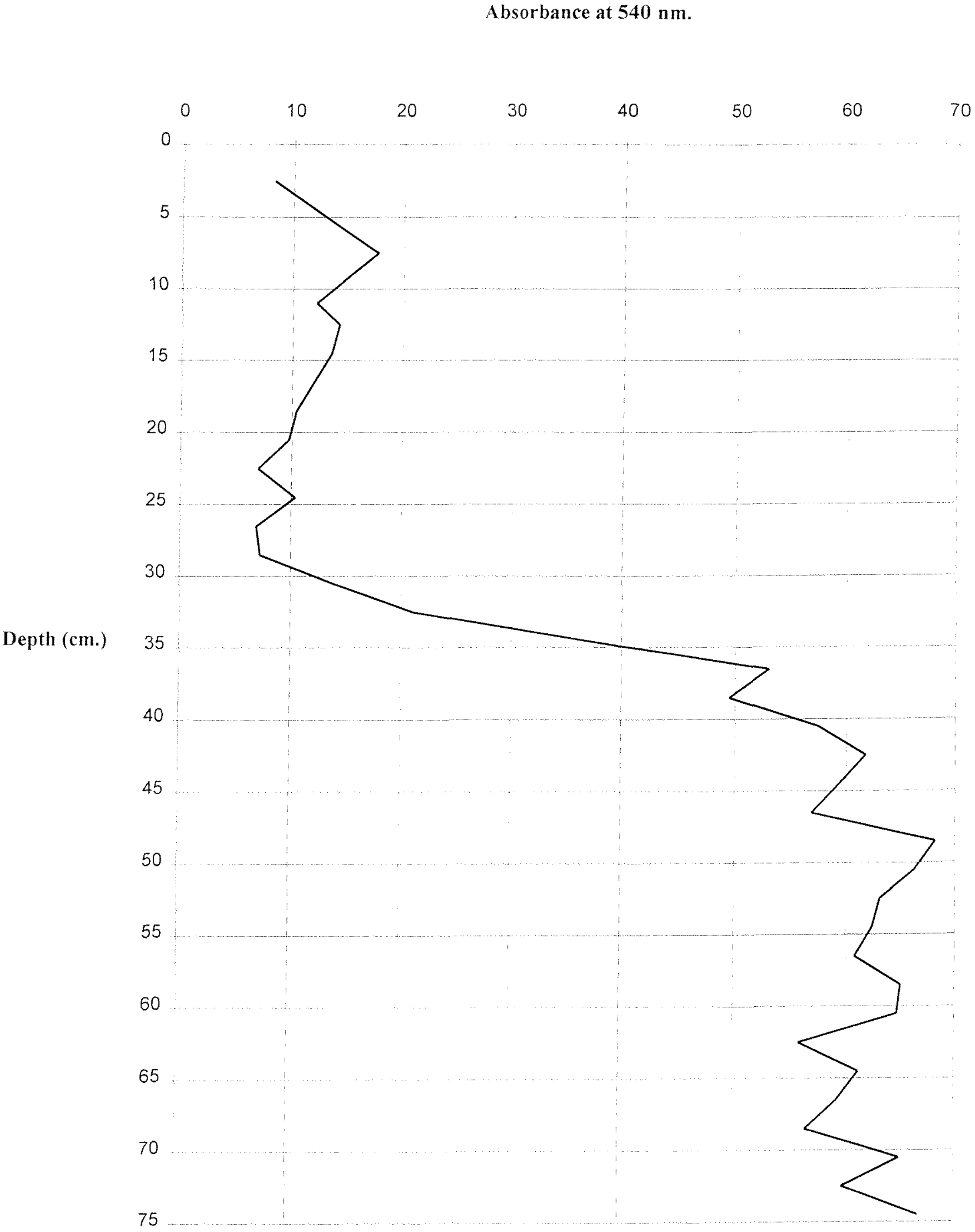
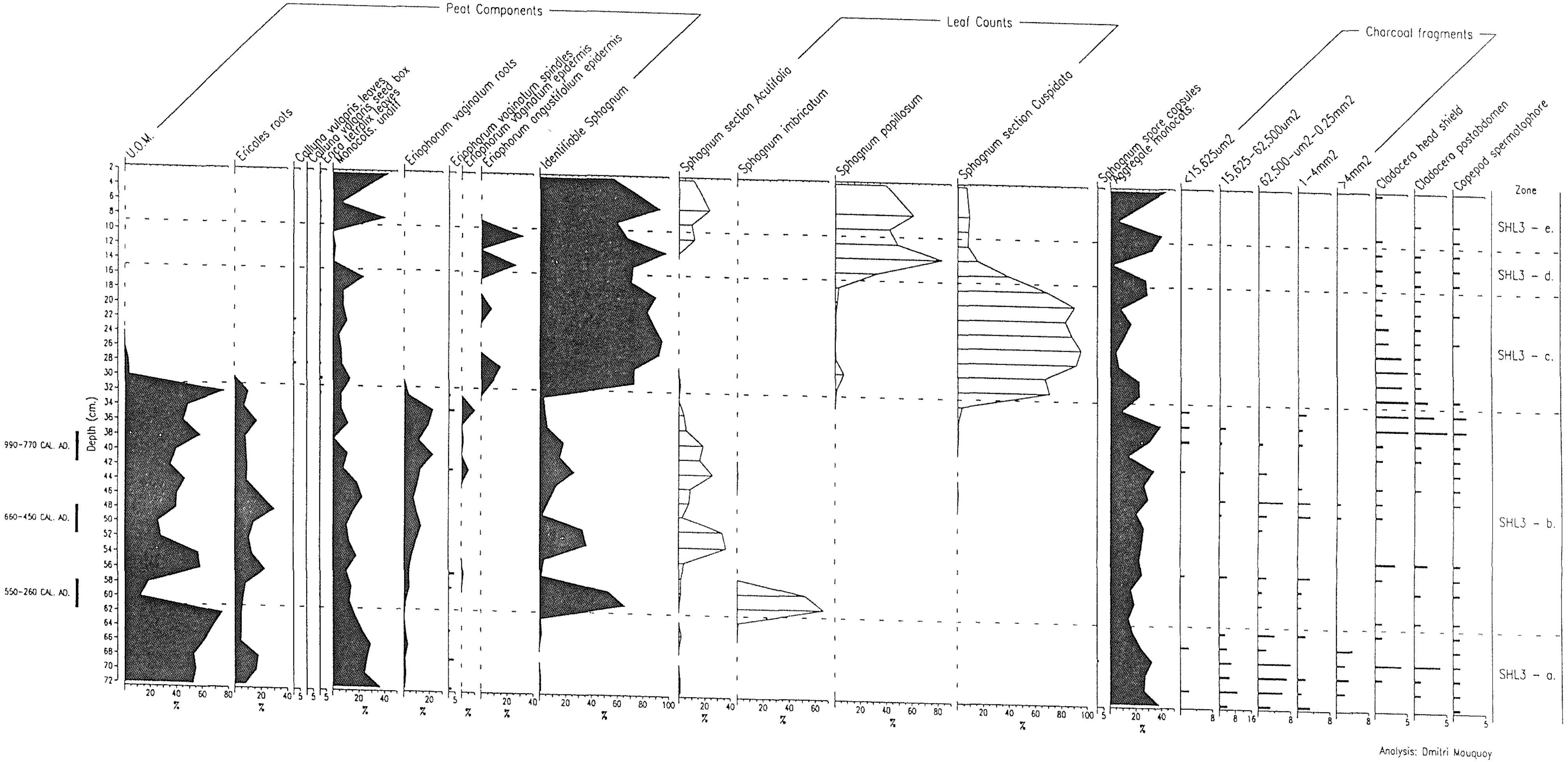


Figure 5.46 Shaft Hill – Monolith 3. Macrofossil diagram.



Cuspidata, whilst the increased representation of *Eriophorum angustifolium* may indicate a drying out of the former pool (Godwin and Conway, 1939; Phillips, 1954).

Zone SHL3 - e. (samples 1-3, 2-9 cm.). Local water tables may have declined further, as the abundance of *Sphagnum* section *Acutifolia* leaves increases, and the representation of *Sphagnum* section *Cuspidata* and Cladocera and Copepod zoofossils declines.

5.4.8.8 Shaft Hill - Monolith 3.- Testate amoebae stratigraphy.

SHL3-TA-a. (samples 32-35, 65-72 cm.). The necrocoenose is largely dominated by *Hyalosphenia subflava* thecae, pointing to overall dry mire conditions, although the presence of up to 38% *Amphitrema wrightianum* shells at 66 cm. may highlight a degree of former water level fluctuations at this depth, given this species hygrophilous affinities. Aside from this single large value, however, the representation of this species and *Amphitrema flavum* is low, supporting the existence of relatively low local water tables within this zone.

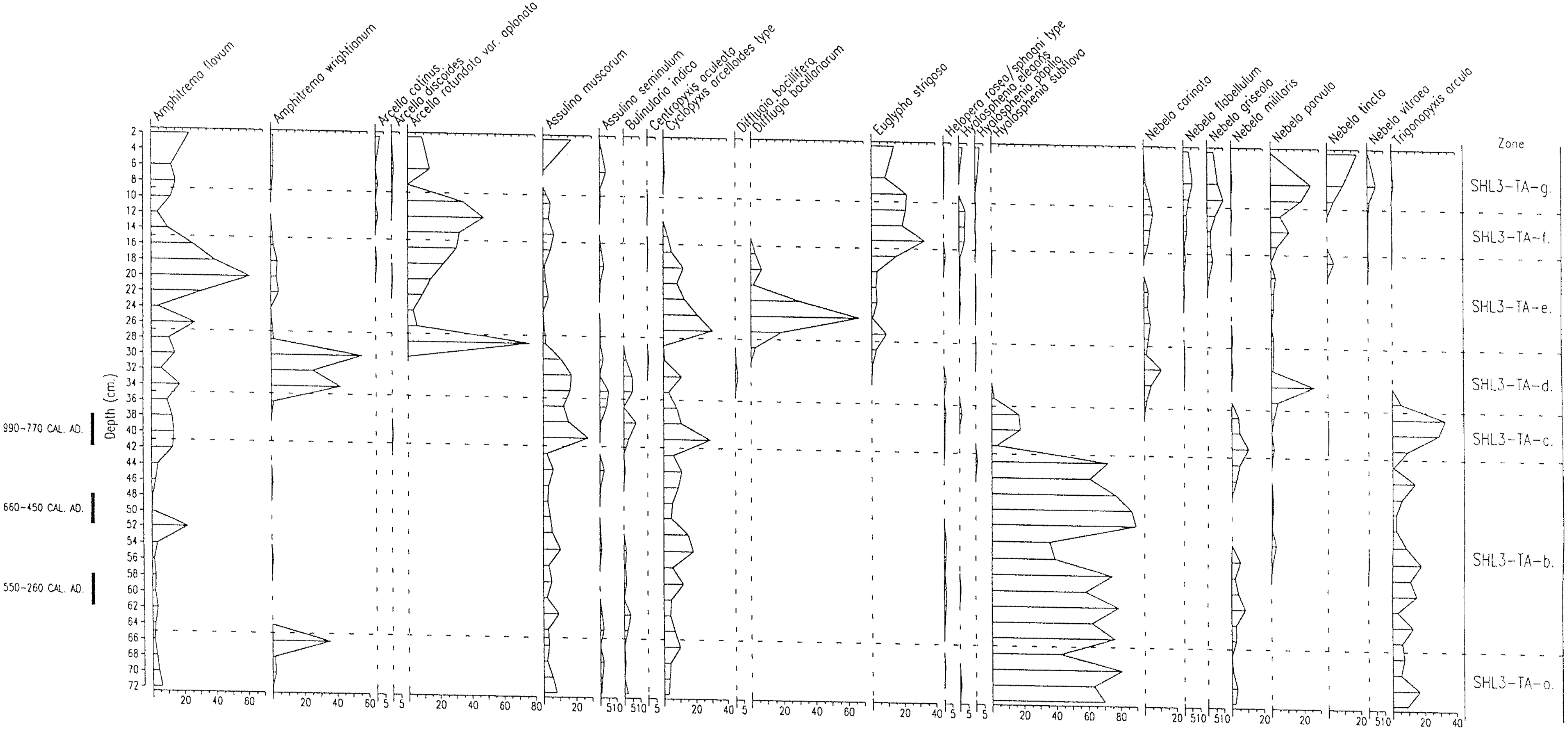
SHL3-TA-b. (samples 20-31, 41-65 cm.). High values of *Hyalosphenia subflava,* and the presence of the xeric rhizopods, *Assulina muscorum, Nebela militaris* and *Trigonopyxis arcula,* suggest continued low effective precipitation regimes, whilst the presence of a small peak of *Amphitrema flavum* thecea at 52 cm. (they form 22.5% of the thanatocoenose), may once again demonstrate a degree of water level fluctuation at this depth.

SHL3-TA-c. (samples 17-19, 35-41 cm.). Assulina muscorum, Cyclopyxis arcelloides type, *Nebela militaris* and *Trigonopyxis arcula* largely replace *Hyalosphenia subflava*, but local water tables must have remained low, as these species are found in relatively dry microsites (Section 5.2.19).

SHL3-TA-d. (samples 13-16, 27-35 cm.). The xerophile testate amoebae species, *Hyalosphenia subflava* and *Trigonopyxis arcula* decline and disappear in this zone, whilst the pool testate amoebae species, *Amphitrema wrightianum* increases dramatically in abundance, pointing to a large increase in mire surface wetness. The appearance of both *Arcella rotundata* var. *aplanata* and *Nebela carinata* also indicates an increase in local water table depth (De Graaf, 1956; Grospietsch, 1958; Tolonen *et al.*, 1992), possibly resulting from a climatic deterioration.

SHL3-TA-e. (samples 7-12, 15-27 cm.). The thecamoebae within this zone indicate continued high mire water levels and therefore sustained high effective precipitation, as hygrophilous *Amphitrema flavum* and *Difflugia bacillariarum,* and hydrophilous *Arcella rotundata* var. *aplanata,* largely dominate the necrocoenose.

Figure 5.47 Shaft Hill – Monolith 3. Testate amoebae.



Analysis: Dmitri Mauquoy

SHL3-TA-f. (samples 4-6, 9-15 cm.). A climatic amelioration may be recorded in this zone as the testate amoebae species indicate a reduction in the depth of local water tables, for example, *Amphitrema flavum* and *Amphitrema wrightianum* thecae are less commonly recorded, whilst *Eulglypha strigosa, Nebela flabellulum, Nebela griseola* and *Nebela parvula* increase in abundance. Sustained high values of *Arcella rotundata* var. *aplanata* suggest the decrease in local water tables was not a marked one.

SHL3-TA-g. (samples 1-3, 2-9 cm.). Assulina muscorum tests increase in abundance pointing to a further desiccation of the mire surface (Warner and Chmielewski, 1992), which is also supported by further increases in *Nebela flabellulum* and a marked rise in the representation of xerophile *Nebela tincta* shells (Tolonen *et al.*, 1992).

5.4.8.9 Shaft Hill Monoliths - Summary of the humification, plant macrofossil and testate amoebae results.

The three peat monoliths taken from this plateau blanket peat site display very similar changes in their stratigraphy, for example, each shows a change from humified peat containing a high degree of U.O.M., *Eriophorum vaginatum* and charcoal fragments to peat containing high abundances of *Sphagnum* leaves.

In both Monolith 2 and 3, there is a large discrepancy between the radiometric dates and the Pine pollen concentration 'dates'. For example the Pine rise occurs at 57.5 cm. in Monolith 2 (Figure 6.8), suggesting an 1800 AD. date, yet the range of dates from a radiocarbon assay taken just 1 cm. below this level spans CAL 1040-1280 AD. (SRR-5900). The Pine rise occurs at 32 cm. depth in Monolith 3 (Figure 6.9), but in this case the radiocarbon measurement for the peat sample spanning 28-32 cm. could not be used, since it was found to be contaminated with modern carbon. The next dated level at 38-42 cm. has a date of CAL 770-990 AD. (SRR-5864), yielding an accumulation rate of 115 yr. cm.$^{-1}$ (based on the mid-point of the sample and the 2 σ date range). This represents an extremely slow peat accumulation rate and also serves to highlight a problem with the geochronology. It is likely the stratigraphy from Monolith 1 will also display this mismatch, given the replicable changes in the humification, plant macrofossil, and testate amoebae stratigraphy between the monoliths. The possible reasons for the differences between the dating techniques are discussed in Chapter 6 (Section 6.2.1).

This change to bryophyte rich vegetation appears to have occurred as a response to increased mire surface wetness, as *Sphagnum* section *Cuspidata* leaves occur in each respective zone *(SHL1 - b, SHL2 - b, and SHL3 - c).* The testate amoebae assemblages and humification signals of *SHL2 and SHL3*, support this change to wetter conditions, as tests of *Amphitrema flavum* and *A. wrightianum* increase in zones *SHL2-TA-c and SHL3-TA-d,* and absorbance values reduce considerably between 47 and 51 cm. in *SHL2,* and between 28.5 and 34.5 cm. in *SHL3.*

Each of the peat monoliths registers a change to drier conditions within the surficial layers; humification increases between 9 and 13 cm. in Shaft Hill, Monolith 1, whilst xerophile *Euglypha strigosa* and *Nebela tincta* increase in zones *SHL2-TA-f* and *SHL3-TA-g.*

Sphagnum imbricatum leaves are very scarce in all three monoliths; in zones *SHL1-b,* and *SHL2-c,* the final disappearance of this species is associated with wetter mire surface conditions, whilst in *SHL3-b,* a 2 cm. thick band of *Sphagnum imbricatum* between 58-60 cm. depth is replaced by leaves of *Sphagnum* section *Acutifolia.* There is no real evidence for a change in mire surface wetness associated with this change, either from the humification or thecamoebae stratigraphy, so in this instance, the change may reflect competitive interactions with section *Acutifolia* species. The very final record of this species in *SHL3* occurs at 42 cm., which is significant, as tests of xeric *Hyalosphenia subflava* decline markedly in this zone. The reduction in the representation of this xerophile taxon suggests increased mire surface wetness, and a possible common trigger, in the form of a climatic deterioration, perhaps in combination with competitive interactions, for the extinction of *Sphagnum imbricatum* in all three monoliths.

5.5 Mire Surface Wetness Reconstructions.

5.5.1 Dupont Wetness Index - Plant macrofossils.

This simple technique was developed by Dupont (1986), in order to summarise water level fluctuations from plant macrofossils, and has been employed in its original form by Haslam (1987) and in a modified manner by Stoneman (1993). It employs weighted averaging, where each species is given a weight, which is a reflection of the hydrological conditions under which each species grows, multiplied by its abundance. These are simply added together and divided by the total abundance of species in the sample to derive an average mire wetness index value. The underlying assumption behind this rationale, is that the particular weight for each species represents an 'optimum' value or indicator value, *sensu* Ellenberg (1979), and that each species displays a unimodal response curve to the environmental gradient in question (Whittaker, 1956), which in this instance is a mire water level gradient. The validity of the unimodality assumption with regard to ombrogenous mire flora has been substantiated by Økland (1986). Weighted averaging implicitly requires that species conform to a species packing model, where, 'species evolve to occupy maximally separate niches with respect to a limiting resource', (ter Braak, 1995, p.85). This certainly applies to *Sphagnum* species which occupy hollows, for example, *Sphagnum cuspidatum,* (Lane and Dubois, 1981; Rydin, 1986) since they possess narrow ranges and have a clear upper limit on the hummock/hollow gradient (Rydin, 1993). For other species, however, the species packing model is not so relevant as *Sphagnum magellanicum* can grow over a wide range of water levels *within* a single mire (Vitt and Slack, 1975; Gignac, 1987), as can *Eriophorum vaginatum* (Meade, 1992).

Notwithstanding these potential problems, the incorporation of weighted averaging within the semi-quantitative Dupont wetness index does have its merits, in that it is simple, and allows direct comparison between sites.

The algorithm is defined as:

Equation 5.1.

$$u^* = (y_1x_1 = y_2x_2 + \ldots +y_nx_n)/(y_1+y_2+ \ldots +y_n)$$

where

u^* is the weighted average

$y_1, y_2, .., y_n$ are the abundances of the species

$x_1, x_2, ..,$ the values of the environmental variable (humidity value) at the sites 1,2 ...n

source: ter Braak , in Jongman *et al.* (1987).

The original weights assigned by Dupont (1986), are shown in Table 5.6. She left classes 7 and 4 empty to highlight the differences between Ericaceae and *Sphagnum* section *Acutifolia* leaves (classes 8 and 6), since

Ericaceae represent the driest end of the water level gradient, whilst the gap between humidity values 5 and 3, reflects the difference between hummock building *Sphagnum* and those which occupy low lawns.

Table 5.6 *Macrofossil weights/humidity values after Dupont (1986).*

Component.	Weight.
Ericaceae roots.	8
Sphagnum section *Acutifolia.*	6
Sphagnum imbricatum.	5
Sphagnum magellanicum.	3
Sphagnum papillosum.	2
Sphagnum section *Cuspidata.*	1

Stoneman (1993) altered the system of weights (Table 5.7), in an attempt to improve the potential accuracy of mire surface wetness reconstructions;

- The niche of *Sphagnum imbricatum* has been effectively taken over by *Sphagnum magellanicum* (Barber, 1981, Smith, 1985, Wimble, 1986 and Stoneman, 1993). Because of this, the two species were given the same weighting of 4.

- Leaves of *Sphagnum* section *Acutifolia* were assumed to be largely those of *Sphagnum capillifolium* var. *rubellum*, as low hummocks on contemporary raised mires are predominantly occupied with this species of section *Acutifolia.* A weight of 5 was therefore given, which reflects this microtopographic position. There is, however, the possibility that formerly, another species of section *Acutifolia* was more abundant in the past, which may lead to errors using this weight for this component.

- Monocotyledonous remains were recorded and a weight of 6 given to them. Where these are *Eriophorum vaginatum* sub-fossils, this will be a relatively accurate weight, but, equally, unidentified macrofossil *Eriophorum angustifolium* and *Rhynchospora alba* material will be wrongly assigned, and produce a spurious mire surface wetness reconstruction.

- *Sphagnum papillosum* leaves were given a weighting of 4, although *Sphagnum papillosum* does occupy slightly lower positions in the hummock-hollow water level gradient (Section 5.2.14). Because of this, 'complacent' water level reconstructions may ensue.

Table 5.7 *Macrofossil weights/humidity values after Stoneman (1993).*

Component.	Weight.
Unidentified organic matter.	7
Ericaceae roots.	7
Monocotyledonous remains.	6
Sphagnum section *Acutifolia.*	5
Sphagnum imbricatum.	4
Sphagnum magellanicum.	4
Sphagnum papillosum.	4
Sphagnum section *Cuspidata.*	2
Sphagnum section *Subsecunda.*	1

Despite the undoubted potential problems associated with the modified Dupont index adopted by Stoneman (1993), his weighting system was adopted unaltered with the exception of *Sphagnum papillosum*, which was given a weighting of 3, since this reflects the slightly lower position it occupies on the hummock/hollow gradient (section 5.2.14). Leaves of *Sphagnum* section *Cuspidata* were given the original Dupont weighting of 1, as no hygrophilous *Sphagnum* section *Subsecunda* leaves were recovered from any of the sites.

Additionally, further weighting indices had to be created for the sedge species and non-*Sphagnum* mosses identified, (Table 5.8), in order to make improved mire water level reconstructions from sub-fossil material. The identification of the sedges *Eriophorum angustifolium* and *Rhynchospora alba* for example, was particularly useful in this instance, as they both occupy pool/low lawn microtopes. Similarly, the remainder of the weights adopted in this instance, reflect the ecology (in terms of their optimum position along the hummock-hollow water level gradient) of the ombrogenous mire flora discussed in Section 5.2.

Table 5.8. *Revised weighting system.*

Component.	Weight.
Unidentified organic matter.	8
Ericaceae.	8
Monocotyledons undifferentiated.	7
Eriophorum vaginatum.	7
Trichophorum cespitosum.	6
Racomitrium lanuginosum.	6
Polytrichum juniperum/alpestre type.	6
Aulacomnium palustre.	5
Sphagnum section *Acutifolia.*	5
Sphagnum imbricatum.	4
Sphagnum magellanicum.	4
Rhynchospora alba.	3
Sphagnum papillosum.	3
Drepanocladus fluitans.	2
Eriophorum angustifolium.	2
Sphagnum section *Cuspidata.*	1

5.5.2 Dupont Wetness Index - Testate Amoebae.

The strong influence of mire water levels on the micro-distribution of thecamoebae (reviewed in Section 5.2.19), should render fossil assemblages of these protozoa readily amenable to weighted averaging, allowing the production of a wetness index. Van der Molen and Hoekstra (1988), used the same techniques employed by Dupont (1986) for plant macrofossils, and created humidity curves by applying a range of weights to 11 sub-fossil rhizopod species identified in peat samples from the Engbertsdijksveen, The Netherlands. Only three weights were assigned to the 11 rhizopod species encountered (Table 5.9), which in the light of the new quantitative ecological investigations of Charman and Warner (1992), Tolonen *et al* (1992; 1994), Warner and Charman (1994) and Woodland (1996), may misrepresent or mask changes in mire water levels. The weighting of *Amphitrema flavum* in particular is a case in point, as the latest testate amoebae literature consistently shows this species to be a faithful indicator of elevated mire water tables (Woodland, 1996, Table 5.2). Because of these problems, a revised weighting system was adopted, based on the hydrological optima of each species discussed in Section 5.2.19, which will allow a comparison of the Dupont wetness index curves derived from both the thecamoebae and plant macrofossils. Classes 2 and 7 have been omitted to highlight the differences between the xeric and hygrophilous testate amoebae taxa, and the results of the Dupont index for each site are presented with the curves generated from the macrofossil flora, to compare areas where they are similar/differ.

Table 5.9 *Testate Amoebae weights, after Van der Molen and Hoekstra (1988).*

Habitat.	**Species.**	**Weight.**
Pool or hollow.	*Arcella* cf. *vulgaris.*	1.
	Arcella rotundata var. *aplanata.*	1.
	Centropyxis aculeata.	1.
	Amphitrema wrightianum.	1.
Slope or lawn.	*Hyalosphenia papilio*	4.
Hummock.	*Amphitrema flavum.*	8.
	Assulina muscorum.	8.
	Assulina seminulum.	8.
	Bullinularia indica.	8.
	Heleopera sphagni.	8.
	Nebela collaris.	8.

Table 5.10 Revised Testate Amoebae weights.

Species.	Weight.
Amphitrema flavum.	1.
Amphitrema wrightianum.	1.
Arcella discoides.	1.
Arcella rotundata var. *aplanata.*	1.
Difflugia bacillariarum	1.
Difflugia bacillifera.	1.
Difflugia globulosa.	1.
Nebela carinata.	1.
Centropyxis aculeata.	3.
Euglypha strigosa.	4.
Hyalosphenia elegans.	4.
Hyalosphenia papilio.	4.
Nebela marginata.	4.
Placocista spinosa.	4.
Arcella catinus.	5.
Cyclopyxis arcelloides type.	5.
Heliopera petricola.	5.
Heliopera rosea/sphagni type.	5.
Nebela collaris.	5.
Nebela griseola.	5.
Nebela militaris.	5.
Nebela parvula.	5.
Nebela tincta.	5.
Assulina muscorum.	6.
Assulina seminulum.	6.
Corythion/Trinema type.	6.
Cyclopyxis arcelloides type.	6.
Nebela flabellulum.	6.
Bullinularia indica.	8.
Hyalosphenia subflava.	8.
Trigonopyxis arcula.	8.

5.5.3 Results of the Dupont weighted averaging.

5.5.3.1 Bolton Fell Moss - Core L (BFML).

The curves derived from the testate amoebae do not display the same degree of hydrological information as those derived from the plant macrofossils (this applies to all the combined Dupont index plots), since the closest sampling interval for the testate amoebae was 8 cm. compared to the 4 cm. interval (down to 3 m. depth) for the plant macrofossils (Figure 5.48 and 5.49). Testate amoebae were principally sampled from levels rich in *Sphagnum imbricatum,* since this species can grow over a range of water levels and may mask changes in the position of the acrotelm/catotelm boundary (Section 5.2.15). Outwith of these areas of the peat stratigraphy, the testate amoebae assemblages were sampled at a coarser resolution (up to a maximum 16 cm. between levels), due to time limitations. This may account for some of the divergences between the two indices displayed in this site, and from the other mires investigated.

There are clearly areas in the stratigraphy where both the testate amoebae and plant macrofossils display the same direction of hydrological change. For example, at 108, 132, 216-212, 328-320, 352, and 448 cm., both the plant macrofossils and testate amoebae indicate a change to increased mire surface wetness. This is certainly encouraging.

There are also areas where the testate amoebae and plant macrofossils appear to give conflicting evidence, particularly at 204 and 240 cm. The ability of testate amoebae to encyst during periods of desiccation, anaerobiosis and depletion of food supplies (Section 2.3.4), may explain this divergence between the two biological proxies, since the presence of *encysted* tests of a particular species will not reflect the hydrological conditions under which the organism is normally found. Interpreting water level changes in these levels is difficult, but can be overcome by recourse to the humification analysis, since it offers an independent means to reconstruct the degree of mire surface wetness. The levels at 204 and 240 cm. appear to be dry based on the humification analysis (Figure 5.13), suggesting the testate amoebae Dupont indices give a true reflection of mire surface wetness at these depths, since the species assemblages point to deep water tables. The failure of the plant macrofossil derived Dupont indices to register this dry phase may be due to the dominant presence (up to c. 80%) of *Sphagnum imbricatum* in the peat matrices at 204 and 240 cm. (Figure 5.15). In the absence of more hygrophilous mire vegetation, it is difficult to determine the degree of mire surface wetness with this bryophyte alone, since it is able to grow over a range of mire water table depths (Section 5.2.15).

This serves to highlight the value of a multi-proxy approach to reconstruct effective precipitation, given the differential sensitivities of each of the peat components to record changes in mire hydrology.

Figure 5.48 Bolton Fell Moss - Core L. Dupont indices vs. depth.

Key to Dupont diagram: solid line=plant macrofossils, dotted line=testate amoebae.

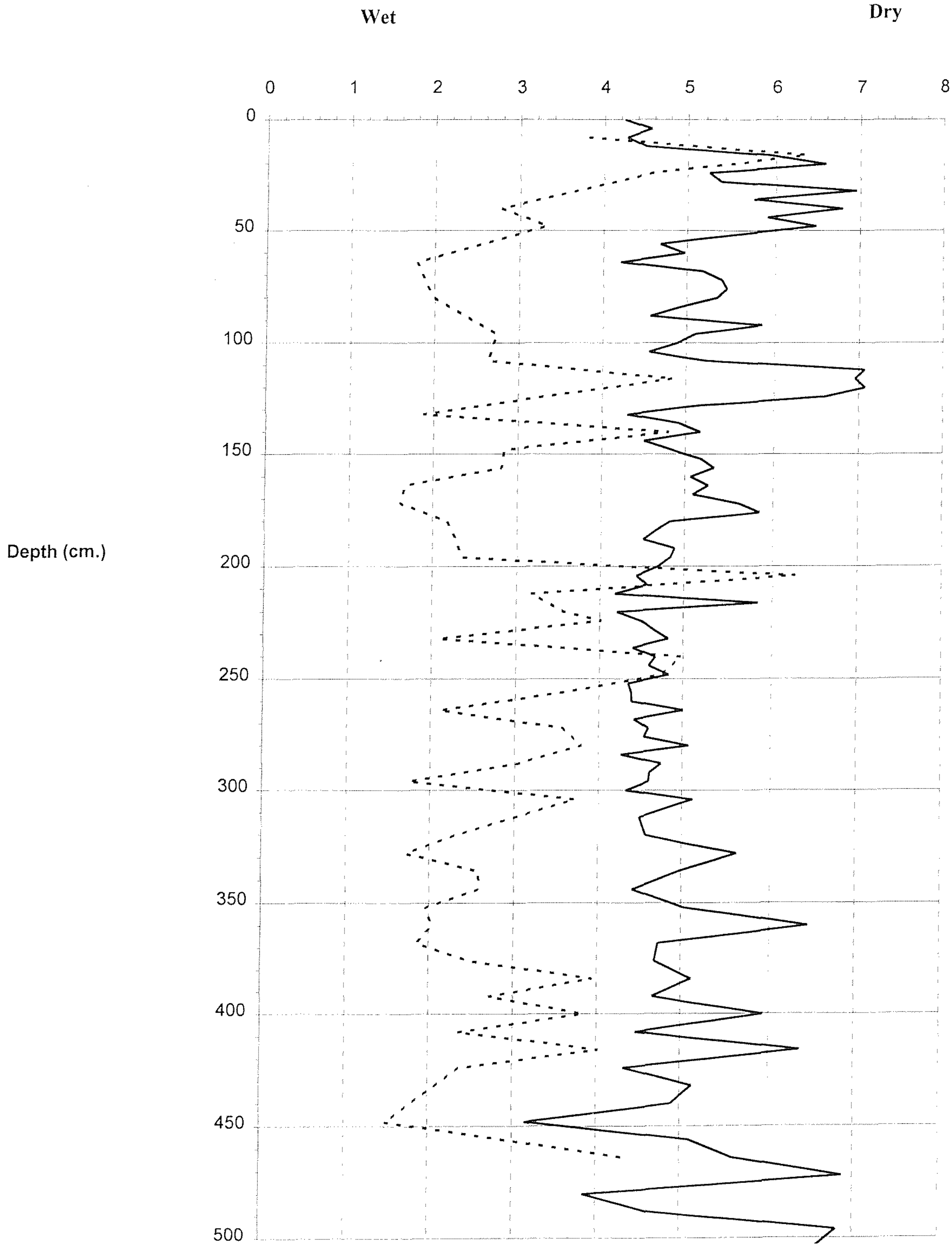
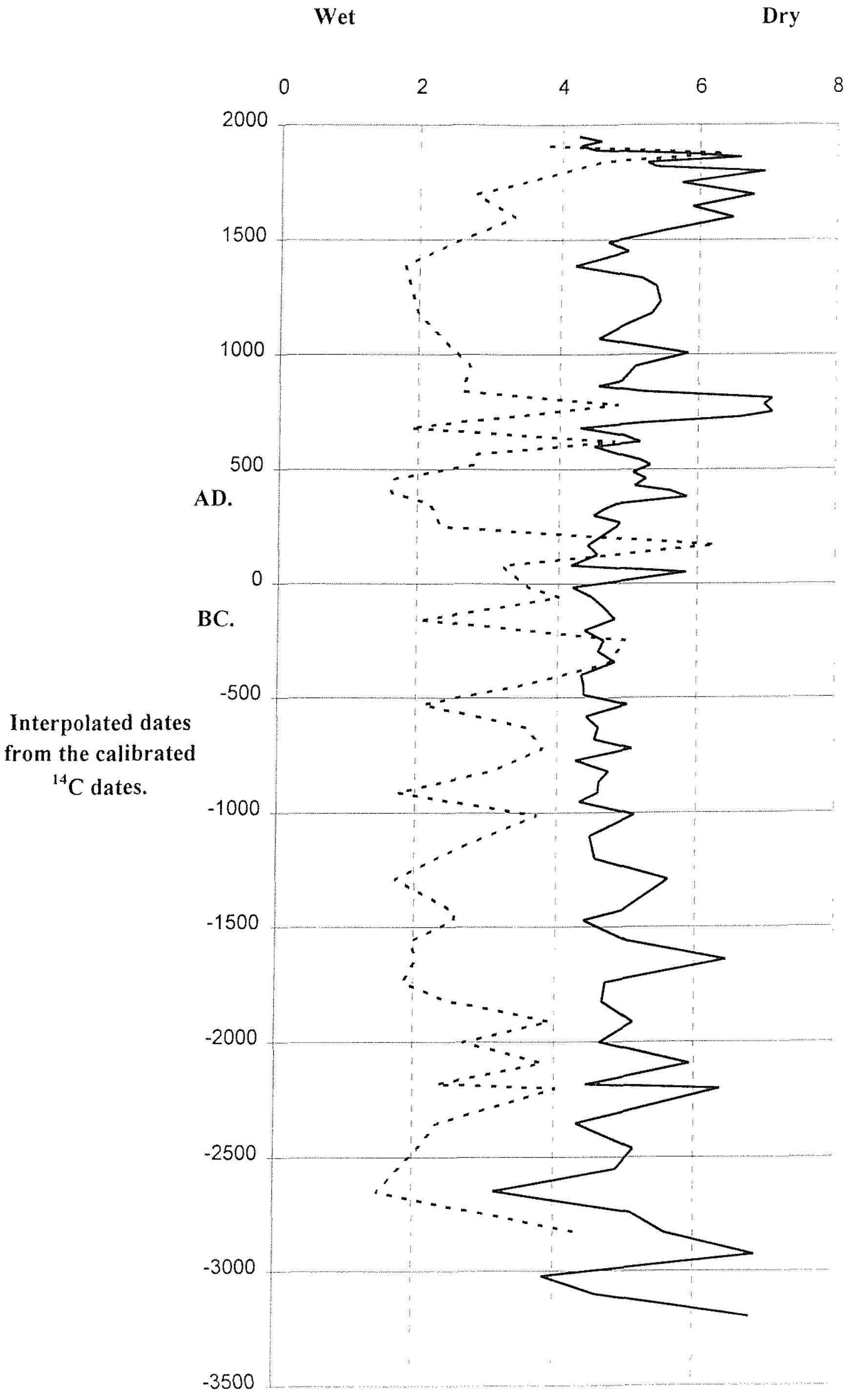


Figure 5.49 Bolton Fell Moss - Core L - Dupont indices vs. time.
Solid line =plant macrofossils, grey line = testate amoebae.



5.5.3.2 Walton Moss - Core 11 (WLM11).

Building on the results from BFML, there are multiple levels where the Dupont plant macrofossil and testate amoebae indices display the same direction of change in mire surface wetness. Close agreements between the two proxies (Figures 5.50 and 5.51) can be found at 28-24, 68, 120-116, 136-132, 196-192, 244, 380, 404, and 484 cm.

There are again, however, areas where the two curves diverge widely, particularly between 220-228 cm. and 332 cm. (Figure 5.50). Examination of the humification and plant macrofossil data suggests the testate amoebae curve is more likely to be correct, as the inferred change to wetter mire surface conditions derived from the testate amoebae is corroborated by the humification data, since these fall between 332-340 and 220-228 cm. (Figure 5.17). The Dupont curve for the plant macrofossils at these levels of the peat stratigraphy is inadequate and possibly oversimplistic, as the peat matrices at 332 cm. contain abundant *Eriophorum vaginatum,* whilst those at 220-228 cm. also contain high percentages of Monocots. undiff. (up to 49% of the peat matrix, Figure 5.19). The former species can grow over a range of local water table depths, whilst assigning a single weight (7) to the latter vegetative macrofossil is open to error, as there are a range of sedges which can grow on the surfaces of mires, often in wet microsites (*Rhynchospora alba* and *Eriophorum angustifolium*, Section 5.2.6, 5.2.7).

5.5.3.3 Raeburn Flow.

A clear feature of the diagrams presented in Figures 5.52 and 5.53 is the insensitive nature of the testate amoebae Dupont curve, since with the exception of the changes recorded between 300-380 cm., only small oscillations occur in the index. This is a reflection of the testate amoebae assemblages, as the borehole stratigraphy is dominated by hygroscopic *Amphitrema flavum, Amphitrema wrightianum* and *Arcella rotundata* var. *aplanata* tests, whilst xerophile *Hyalosphenia subflava* tests are infrequently encountered.

Levels where the two indices display shifts to increased mire surface wetness can be found at 80, 136, 168, 196, 244-248, 276, 296-300 and 332 cm. (Figure 5.52).

Divergent water level reconstructions occur at 356 and 308 cm. At these levels, the plant macrofossil curve suggests dry mire surface conditions were prevalent, whilst the testate amoebae derived curve points to a wet mire surface with a shallow acrotelm. High humification values at both these depths support the plant macrofossil data, and suggests the testate amoebae curve at this level does not reflect the former degree of mire surface wetness. This may be a reflection of the high abundances of *Amphitrema flavum* within these two levels (Figure 5.25). Although this species is a good indicator of wet mire surfaces (Table 5.2), particularly in terms of depth to the water table, it is relatively xerophilous in terms of moisture content of the peat substrate, since it can exist where moisture is less than 70% (Woodland, 1996). The small size of this protist (less than 77 μm., Corbet, 1973), allows it to survive in shrinking water films (Woodland, 1996), and again highlights

Figure 5.50 Walton Moss - Core 11. Dupont indices vs. depth.

Solid line=plant macrofossils, dotted line=testate amoebae.

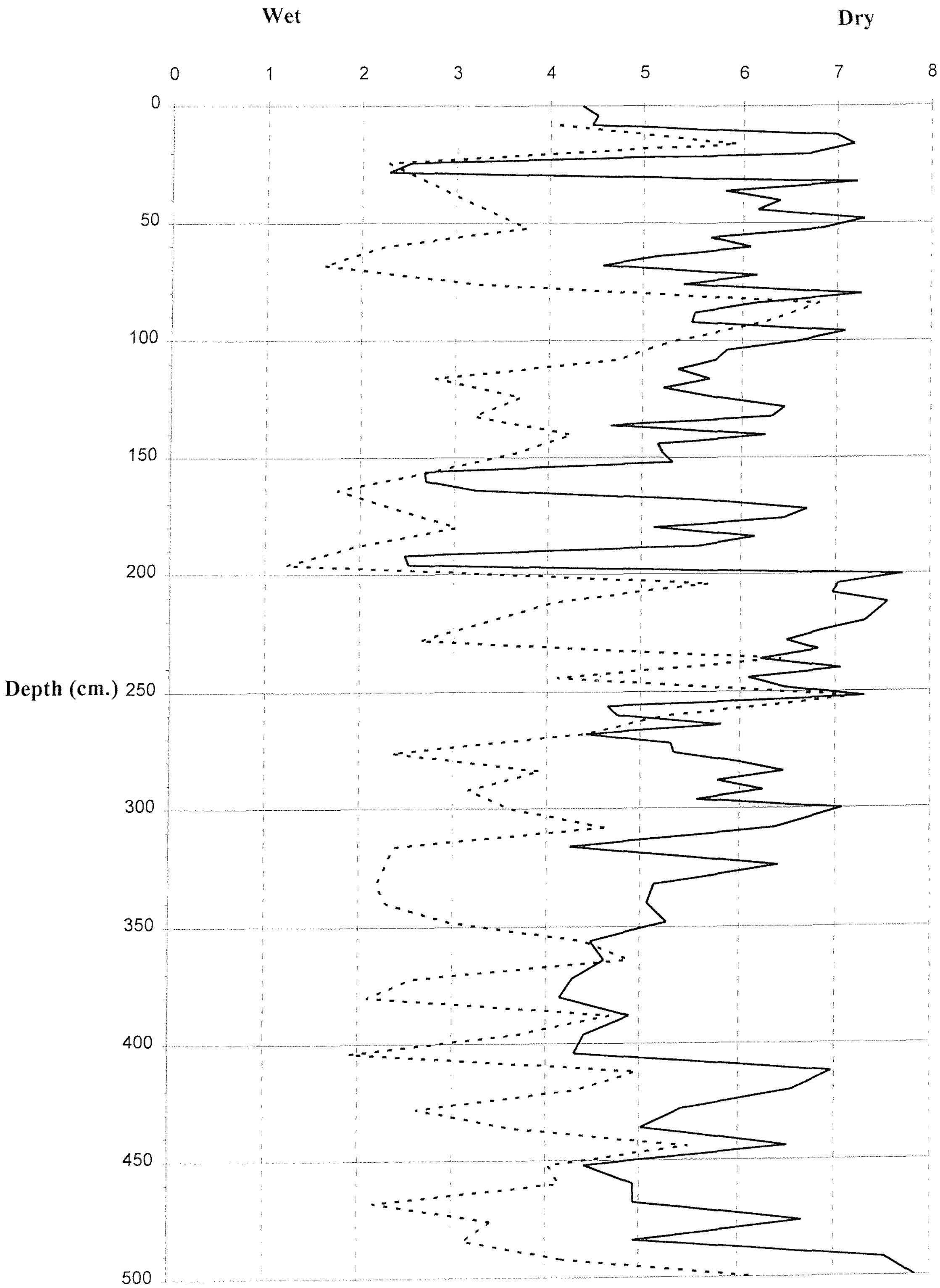


Figure 5.51 Walton Moss - Core 11 - Dupont indices vs. time.

Solid line=plant macrofossils, dotted line=testate amoebae.

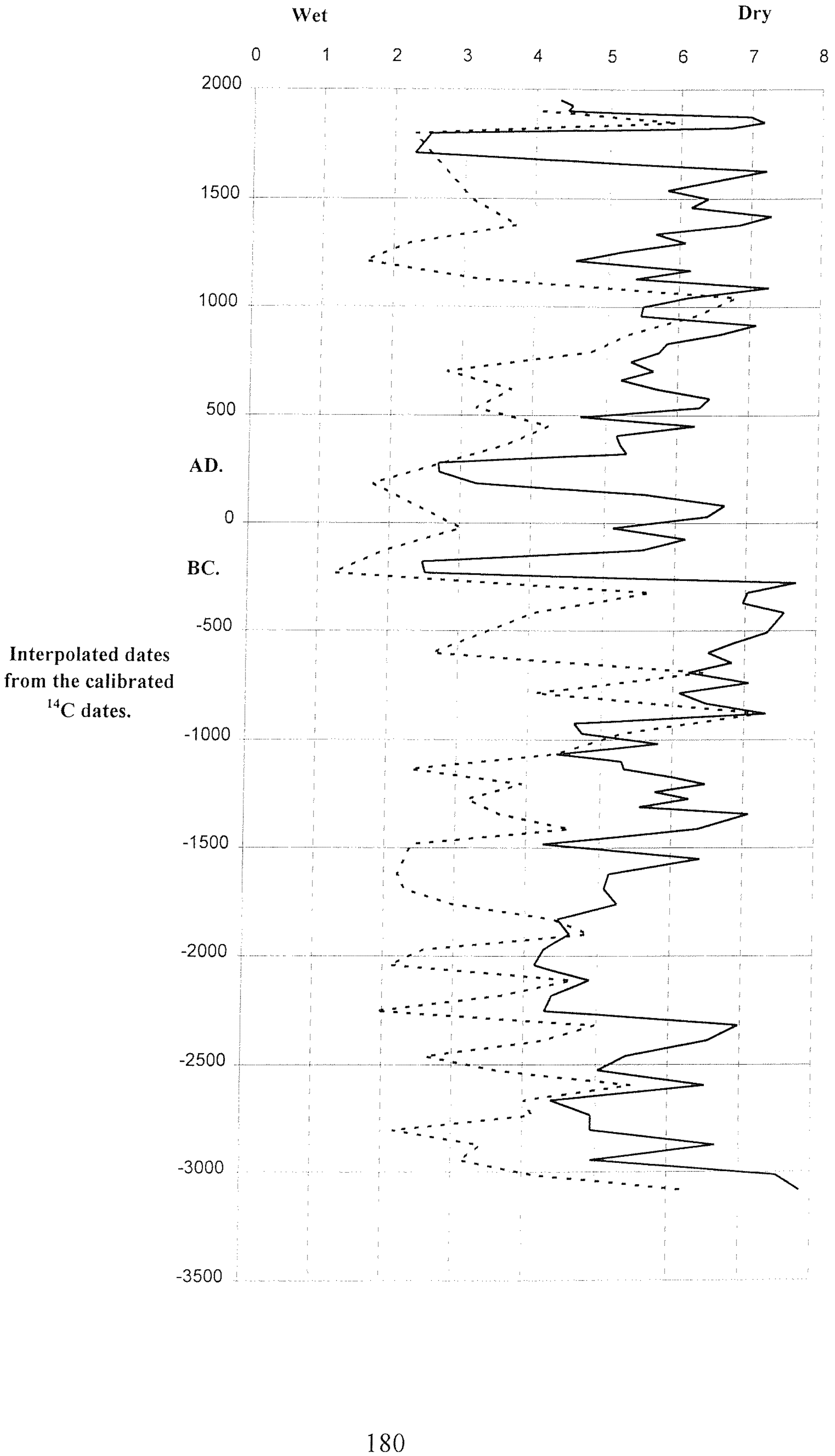


Figure 5.52 Raeburn Flow. Dupont indices vs. depth.

Solid line=plant macrofossils, dotted line=testate amoebae.

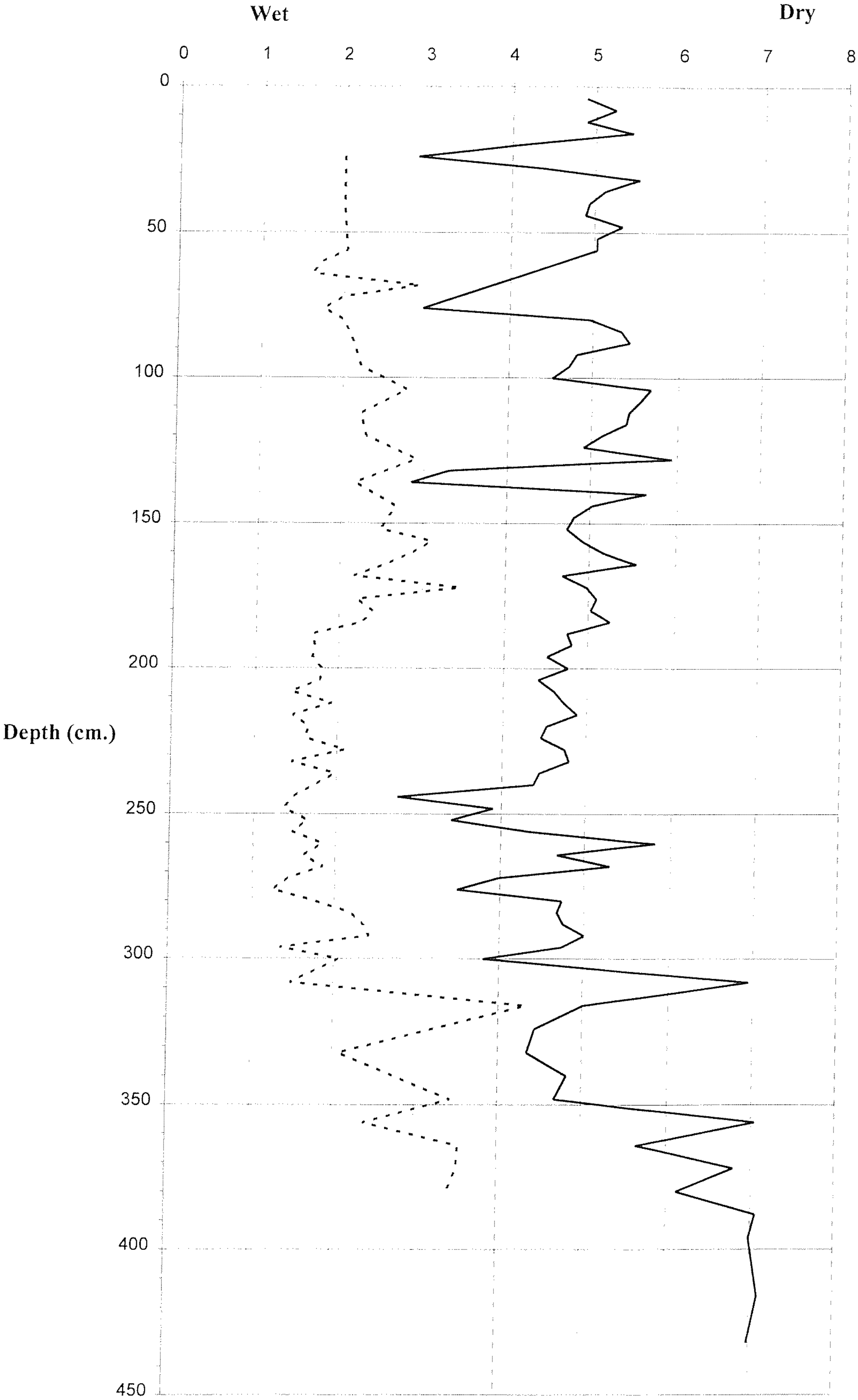
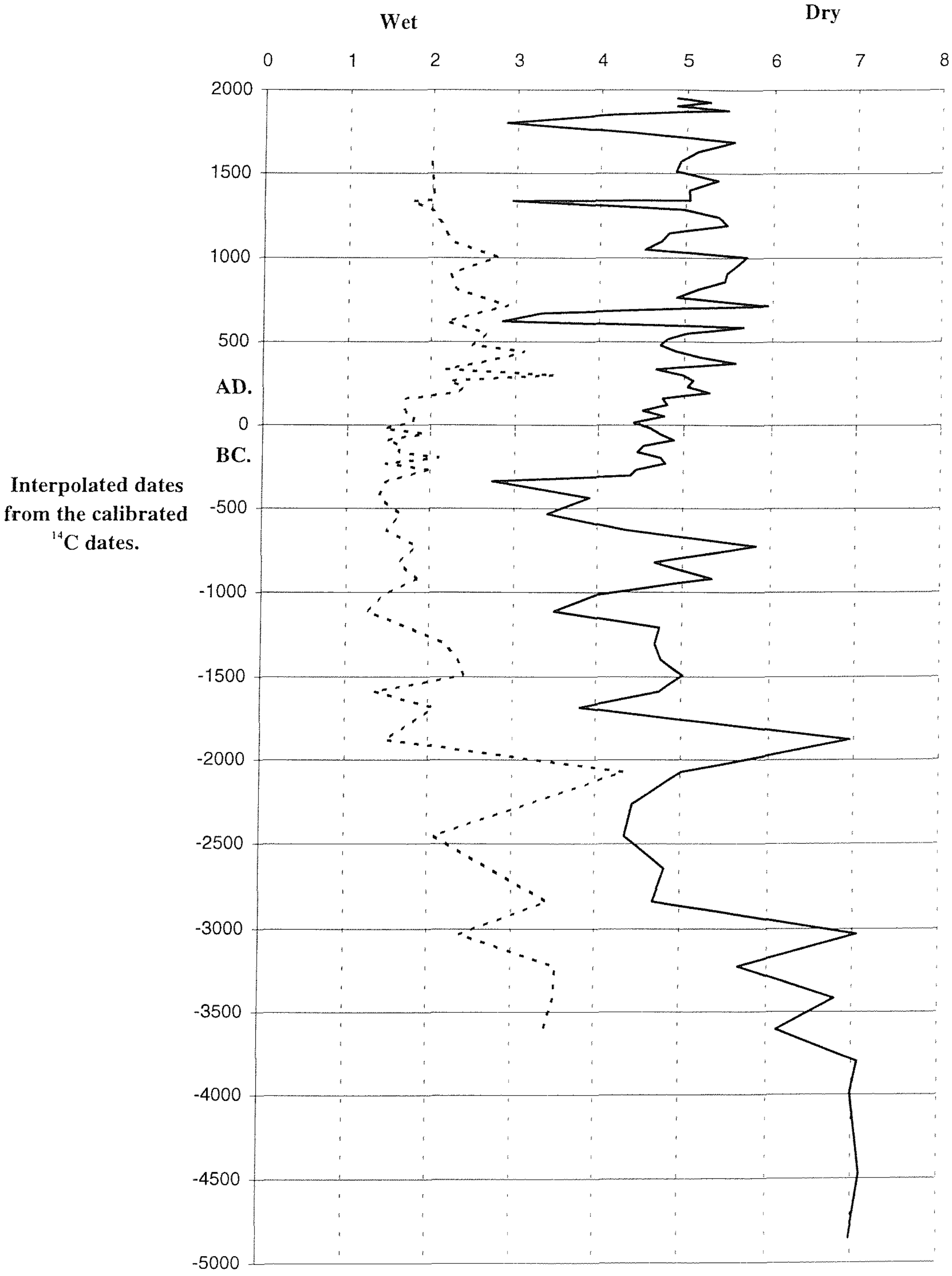


Figure 5.53 Raeburn Flow - Dupont indices vs. time.

Solid line=plant macrofossils, dotted line=testate amoebae.



the difficulty of applying a single weighting factor to each of the biological proxy data, and may explain the differences between the Dupont plant macrofossil and testate amoebae curves at these depths.

5.5.3.4 Bell's Flow.

The Dupont wetness curve for the testate amoebae (Figures 5.54 and 5.55) shows more marked fluctuations than the plant macrofossils. This reflects the relatively 'dry' stratigraphy of the borehole, since there is only a single level of *Sphagnum* section *Cuspidata* leaves between 16 and 20 cm. (Figure 5.28). The Dupont testate amoebae index records this wet shift, whilst changes to increased mire surface wetness are recorded by both techniques at 1420, 950-910 AD. and 10 AD.-40 BC., and 350, 1030-940 and 1260-1300 BC. (Figure 5.55).

The Dupont testate amoebae index indicates a marked change to increased mire surface wetness at 60 and 132 cm. Humification absorbance values are relatively low at these levels, supporting this hydrological reconstruction (Figure 5.26), although another inferred testate amoebae wet shift at 188 cm., is not supported by the humification data. This again highlights the need to look at alternative evidence before one can more firmly establish the occurrence of a wet shift, since each technique on its own, does not appear to give a 100% reliable indication of mire surface wetness.

5.5.3.5 Coom Rigg Moss.

There is evidence to suggest both the Dupont plant macrofossil and testate amoebae indices are capable of registering both wet and dry shifts synchronously in the borehole stratigraphy from this site. Wet shifts are registered by both techniques between 600-670 AD. (plant macrofossils) and 550-640 AD (testate amoebae) (Figure 5.57). Dry shifts are also registered at 780 AD., and between 930-1080 AD.

There are also, unfortunately, areas where the two indices give conflicting water level reconstructions, for example at 40 cm. (1480 AD.), the plant macrofossils indicate dryness (Figure 5.57), whilst the testate amoebae suggest local water tables were high. Conversely, the plant macrofossils at 160 cm. (360 AD.) suggest a wet mire surface, conflicting with the dry index value derived from the testate amoebae. The detrended colorimetric humification data in Figure 5.31 points to a deep acrotelm at 40 cm., which implies the testate amoebae reconstruction is in error at this depth. This is possibly again due to the low weighting given to *Amphitrema flavum,* since it is clearly capable of surviving in relatively thin water films on *Sphagnum* leaves. The humification value at 160 cm. supports the testate amoebae hydrological reconstruction, and highlights a problem with the plant macrofossil index. This is due to the dominance of *Sphagnum imbricatum* at this level (Figure 5.33), as a weight of 4 (Table 5.8), will clearly not always accurately reflect the microsite position of this bryophyte, given its ability to grow over a wide range of water table depths (Section 5.2.15).

Figure 5.54 Bell's Flow. Dupont indices vs. depth.

Solid line=plant macrofossils, dotted line=testate amoebae.

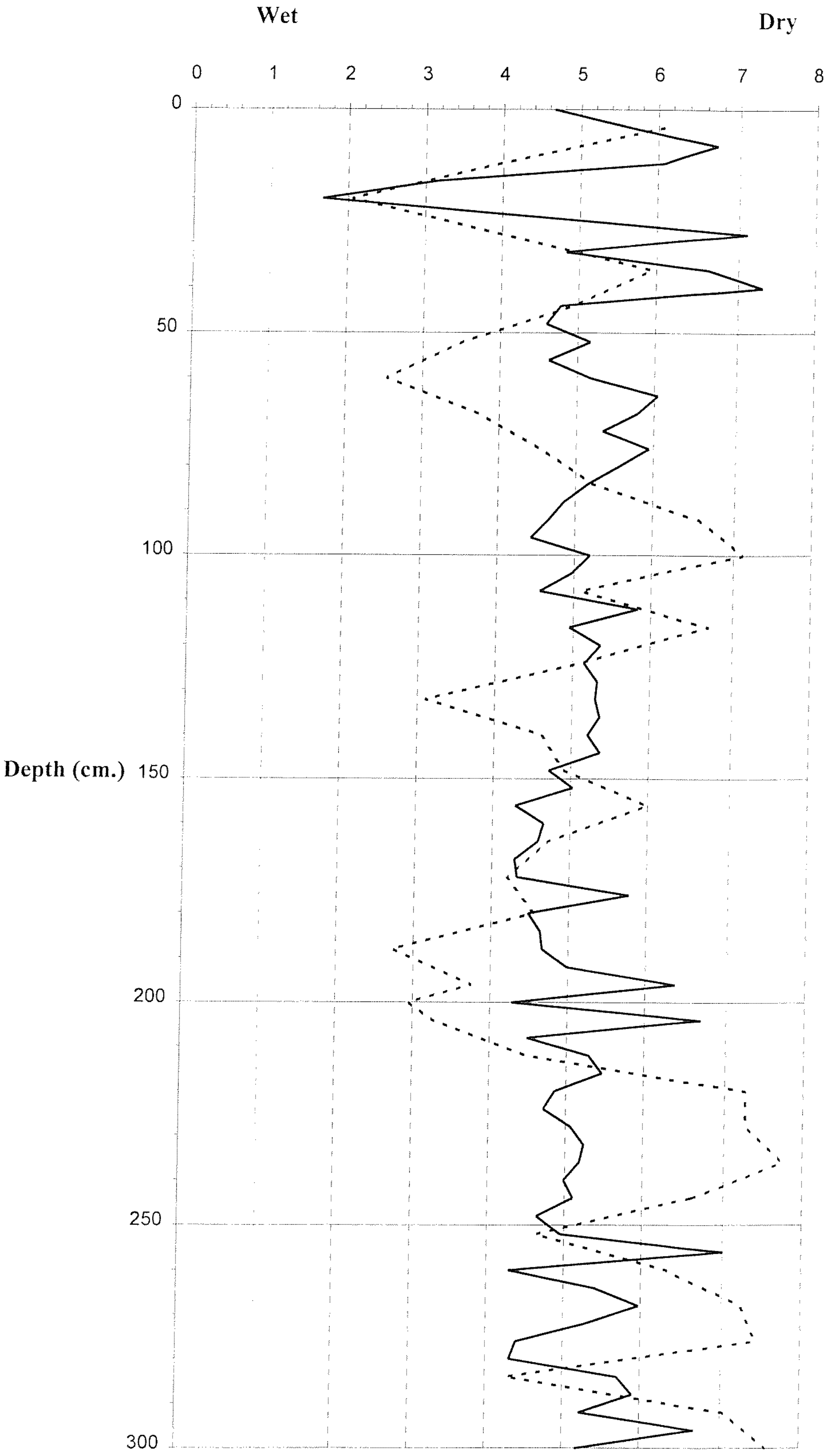


Figure 5.55 Bell's Flow - Dupont indices vs. time.

Solid line=plant macrofossils, dotted line=testate amoebae.

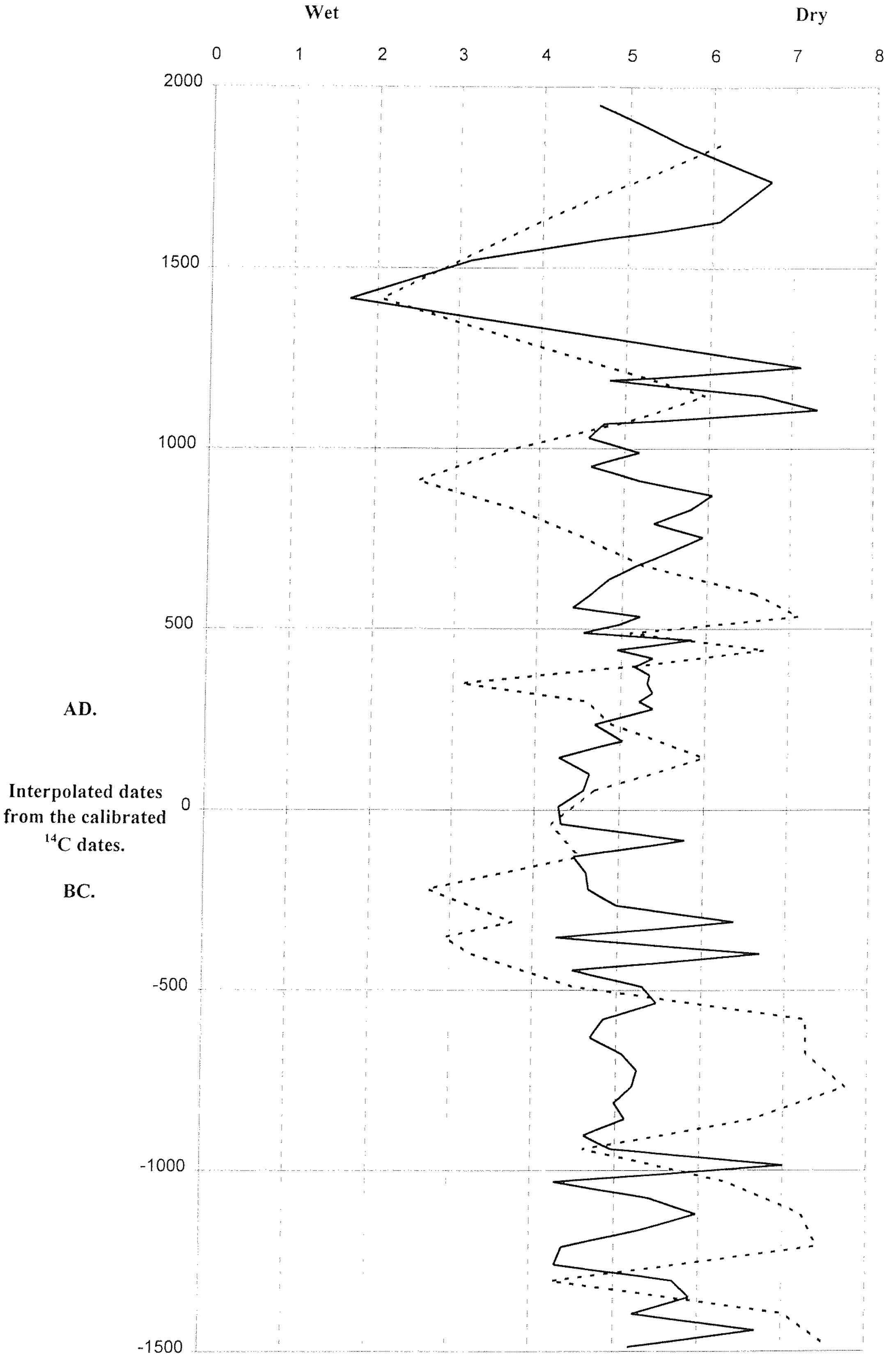


Figure 5.56 Coom Rigg Moss. Dupont indices vs. depth.

Solid lines=plant macrofossils, dotted line=testate amoebae.

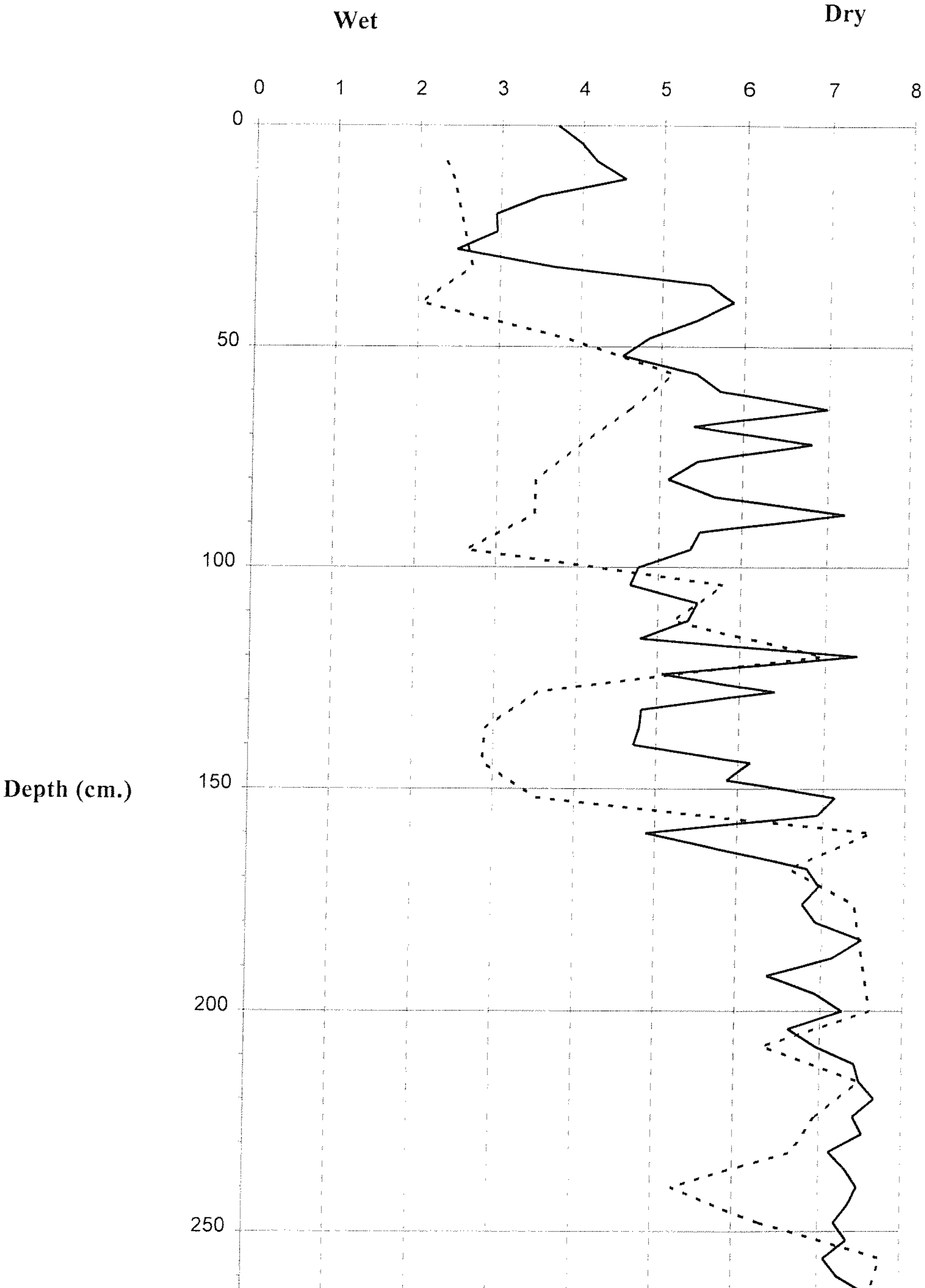
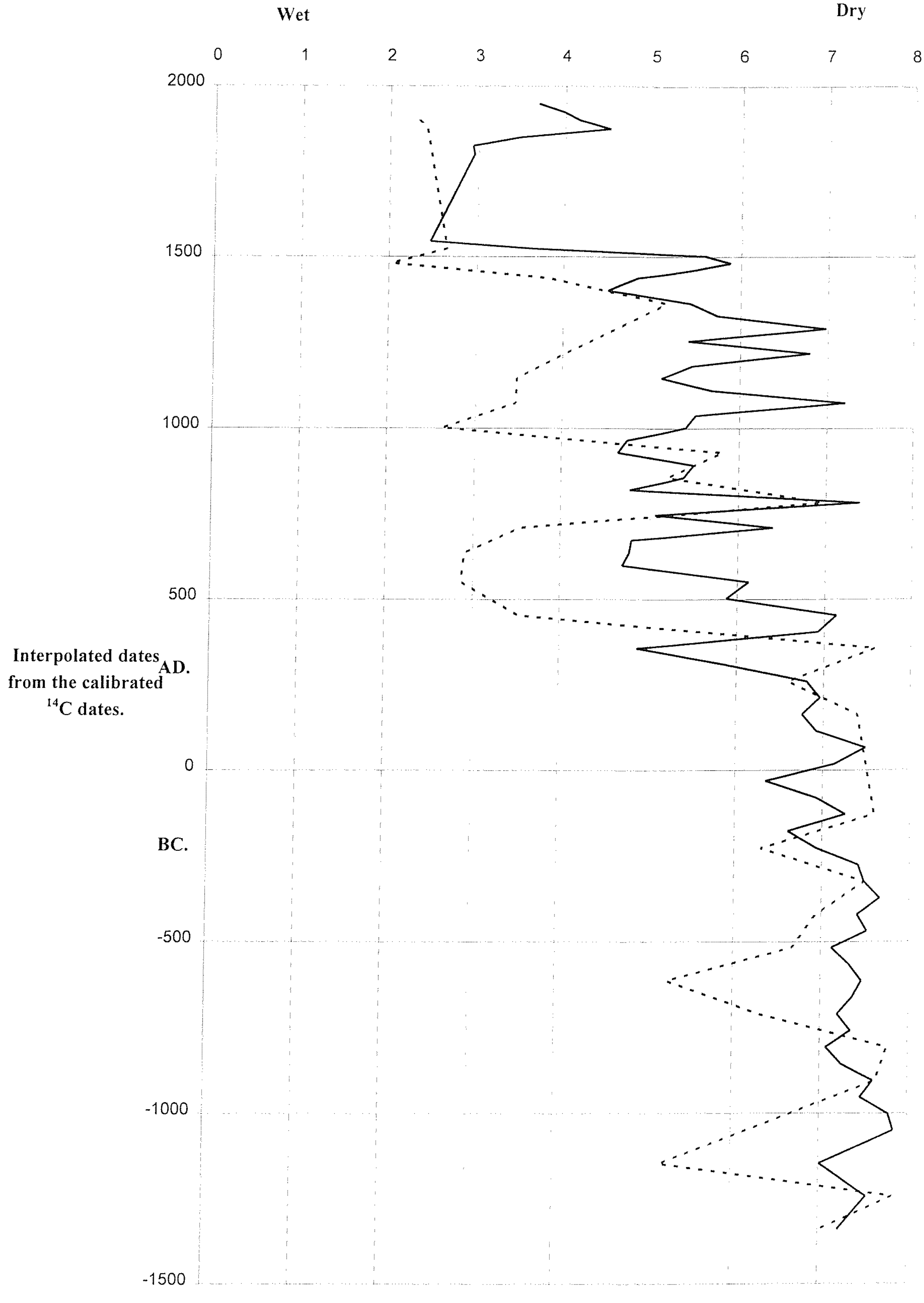


Figure 5.57 Coom Rigg Moss - Dupont indices vs. time.

Solid line=plant macrofossils, dotted line=testate amoebae.



5.5.3.6 Felecia Moss.

The results from this site are very encouraging, as changes to increased mire surface wetness are registered by both techniques between 320-350 AD., and 20 AD.-10 BC., 200, 590-500 and 710 BC. (Figure 5.59). Dry shifts are also recorded by both the plant macrofossils and testate amoebae at 230 AD., 130-100 and 830-740 BC.

There is a contradictory water level reconstruction at 500 BC., where the plant macrofossils indicate a relatively dry mire surface, whilst the testate amoebae assemblage suggests local water tables were high at this depth. The peat matrix at this depth is fresh, and possibly passed through the acrotelm quickly, possibly as a result of high peat accumulation rates (Figure 5.36). The detrended humification data supports the testate amoebae assemblage, and highlights a potential period of high effective precipitation at 256 cm. The failure of the plant macrofossils to detect this can be ascribed to the dominance of *Sphagnum imbricatum* once again, and highlights the ability of this moss to 'mask' hydroclimatological changes on the mire surface.

5.5.3.7 Shaft Hill Monoliths.

The largest change in the Dupont macrofossil index for Monolith 1 occurs at 57.5 cm. (Figure 5.60) and coincides with a reduction in the colorimetric humification absorbance values which decline at 59.5 cm.(Figure 5.40). In this instance, both techniques point to a reduction in the depth of local water tables at this position on the blanket mire surface. There is close agreement between the Dupont plant macrofossil and testate amoebae indices for both Monoliths 2 and 3 from Shaft Hill (Figure 5.61 and 5.62), which is very encouraging. The main change from humified, monocotyledon, charcoal rich peat matrices to *Sphagnum* rich peat stratigraphy, is registered by both techniques in each of the peat monoliths. For Monolith 2 this occurs at 51.5 cm., and at 30 cm. in Monolith 3.

5.5.3.8 Summary of the Dupont ordinations.

The Dupont indices are clearly capable of simplifying the complex plant macrofossil and testate amoebae species assemblages in order to produce a single index of mire surface wetness at any one level. Changes in reconstructed mire surface wetness which occur at the same depth/time, have been demonstrated using both the plant macrofossil and testate amoebae moisture curves.

The shortcomings of the Dupont indices are also apparent from the diagrams. Assigning a single weight to plant macrofossils and testate amoebae can be unrealistic, since recourse to the humification data has shown that some of the Dupont index water level reconstructions are quite possibly incorrect. This is due to the broad niche lengths of some of the plant macrofossil and testate amoebae species. Because of this, a more sophisticated, alternative technique to reconstruct mire surface wetness is required. The statistical technique chosen to offer an independent means of reconstructing local water tables is Detrended Correspondence Analysis (DCA), since this does not does not assign a single subjective weight to each of the plant macrofossil components and testate amoebae species.

Figure 5.58 Felecia Moss. Dupont indices vs. depth.

Solid line=plant macrofossils, dotted line=testate amoebae.

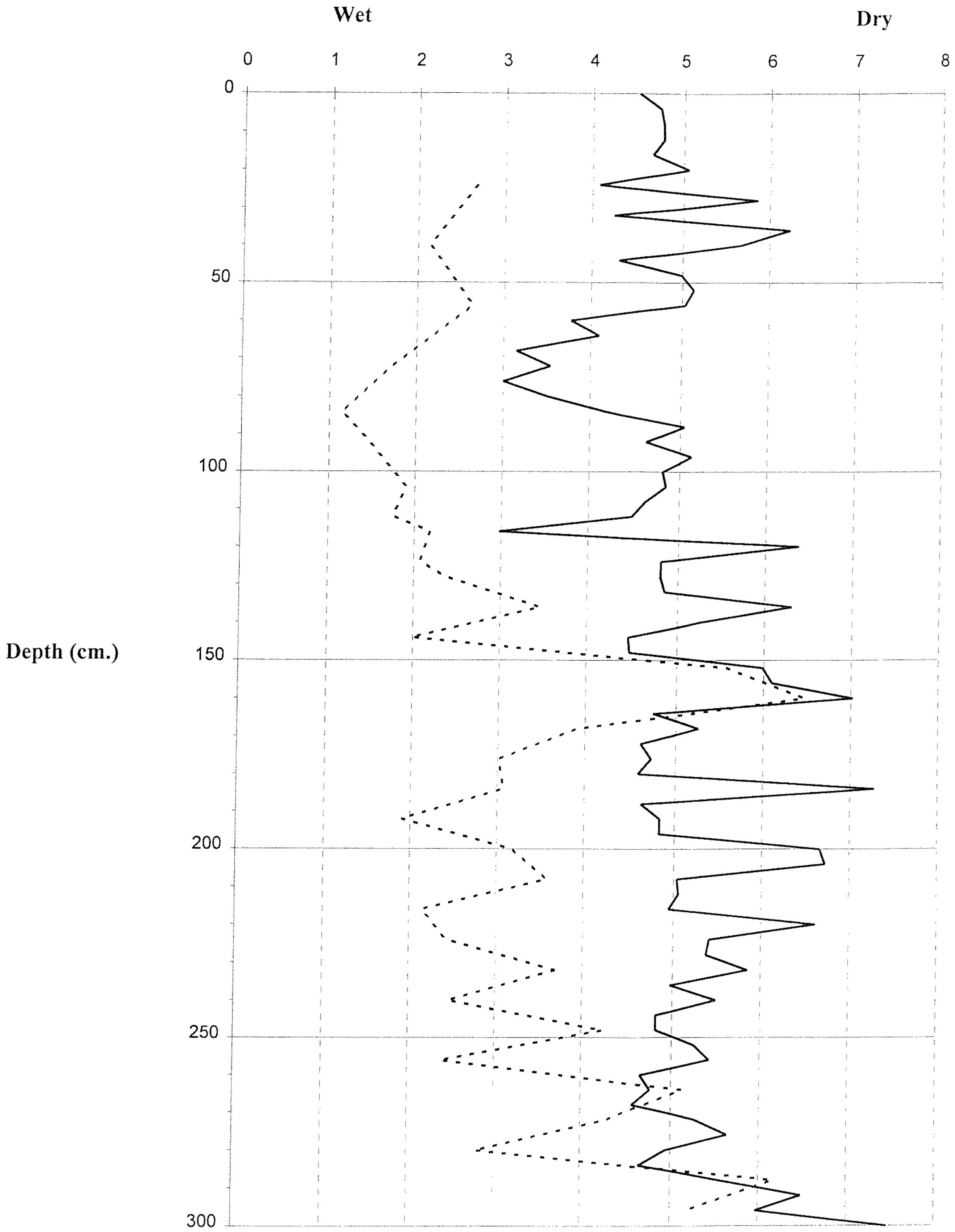


Figure 5.59 Felecia Moss - Dupont indices vs. time.

Solid line=plant macrofossils, dotted line=testate amoebae.

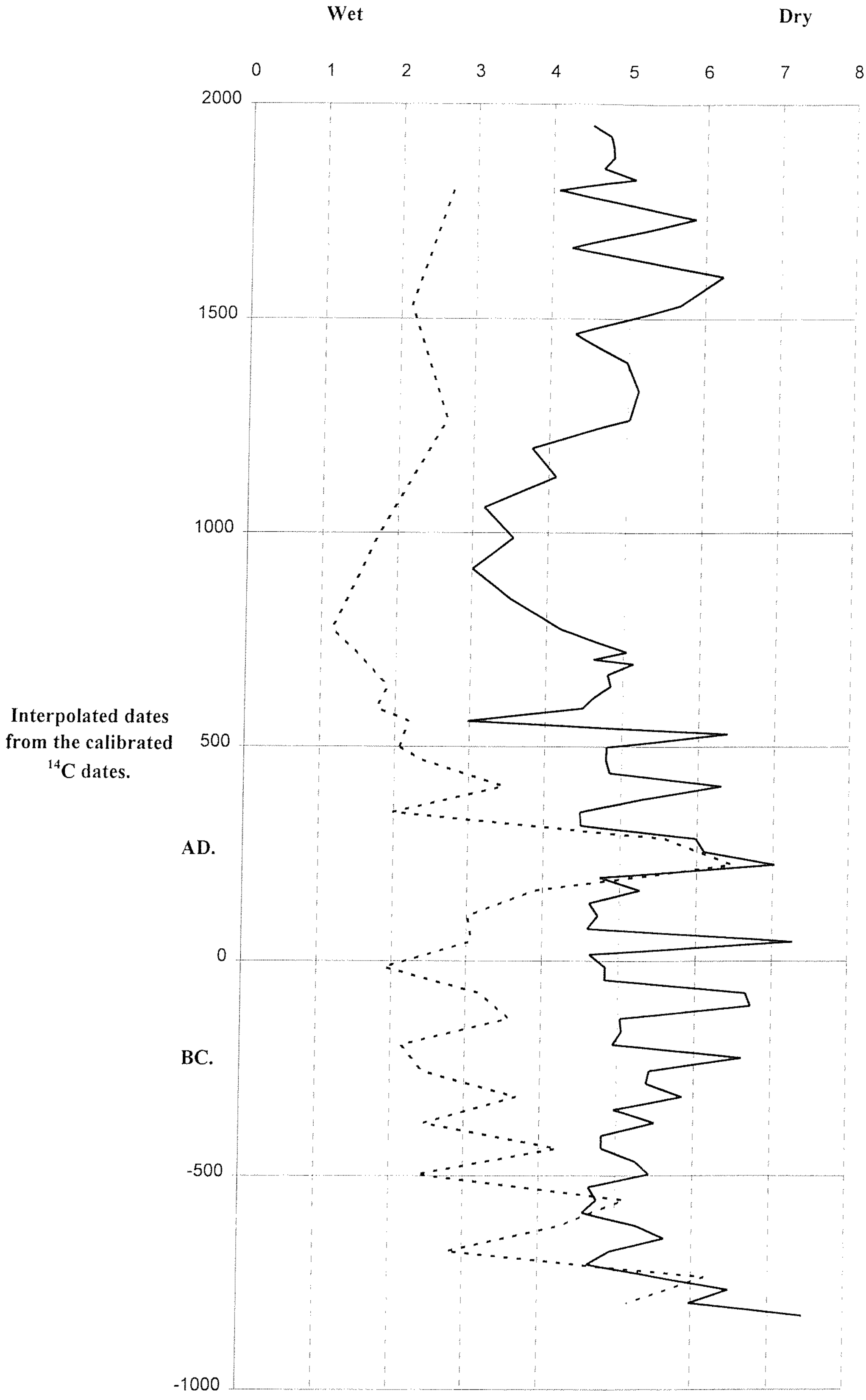


Figure 5.60 Shaft Hill - Monolith 1 - Dupont index vs. depth (Plant Macrofossils only).

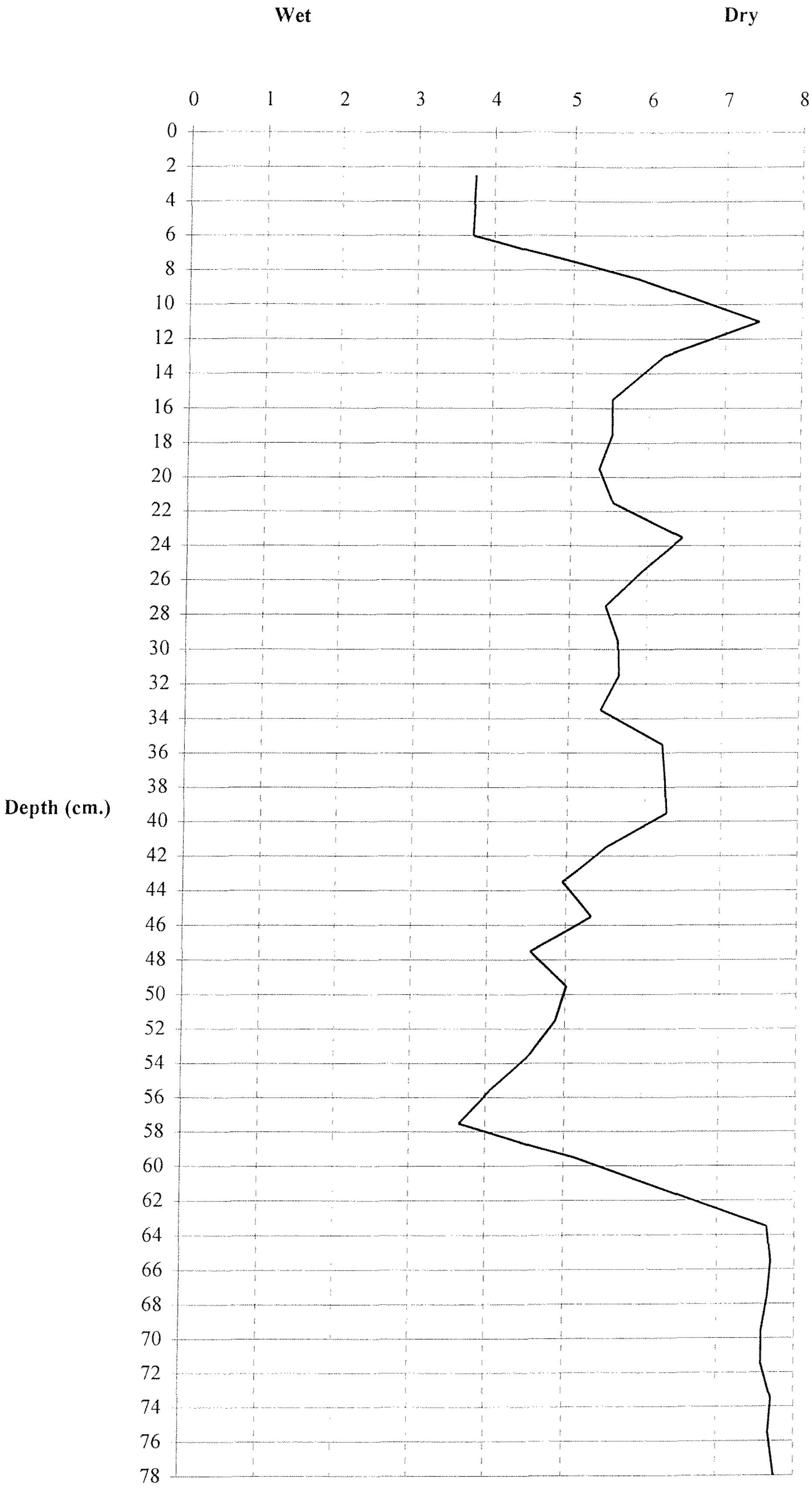


Figure 5.61 Shaft Hill - Monolith 2 - Dupont indices vs depth.

Solid line=plant macrofossils, dotted line=testate amoebae.

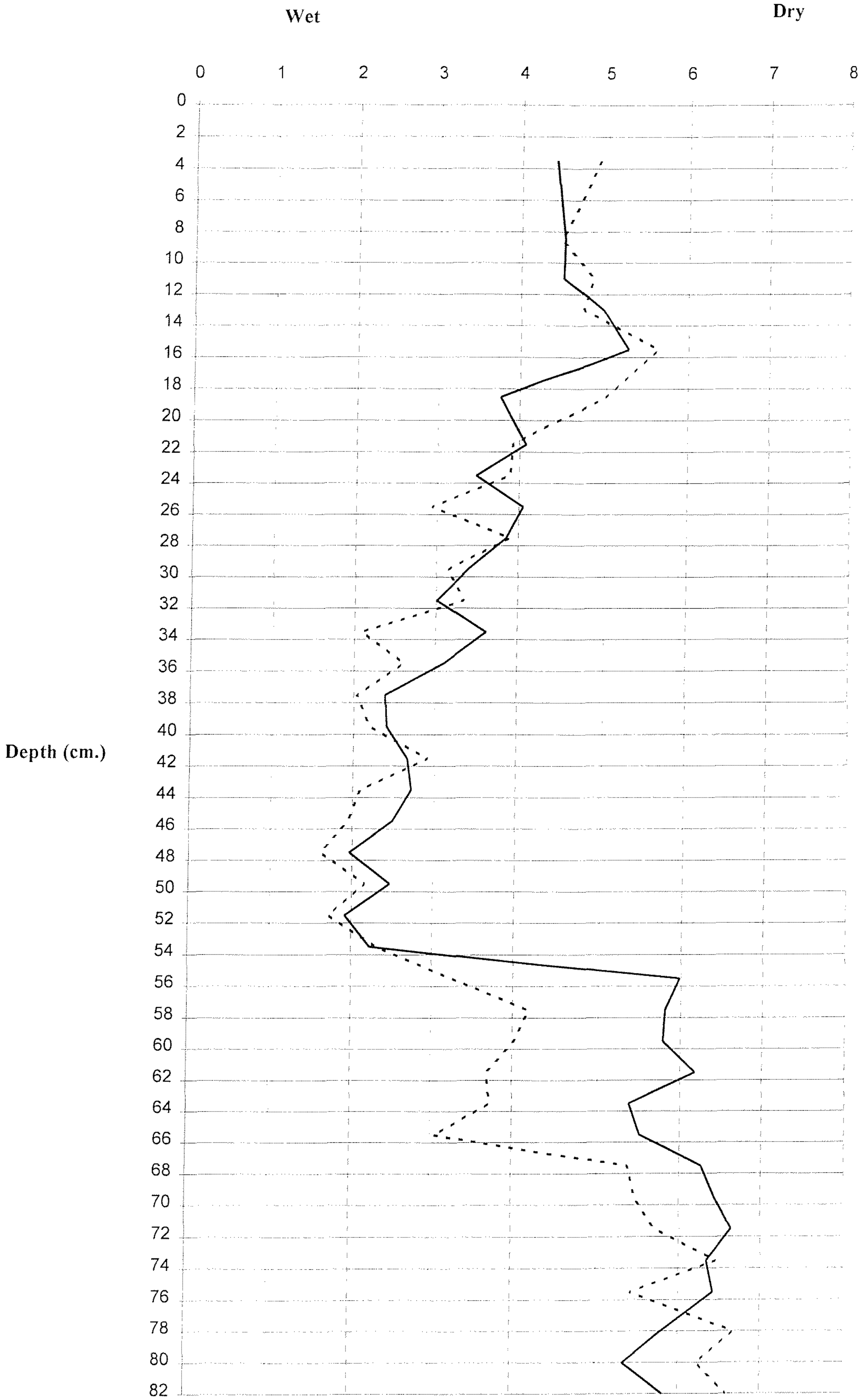
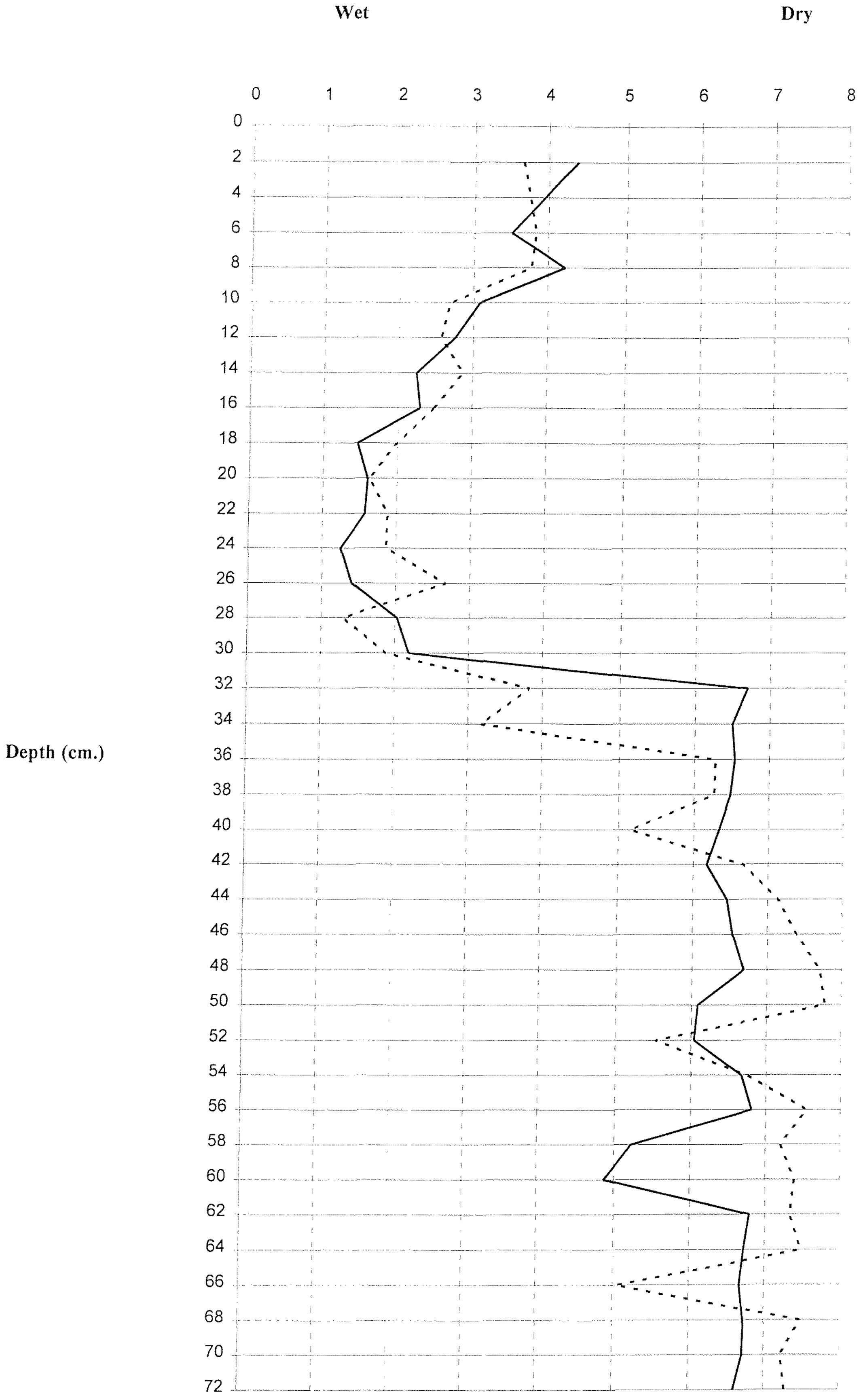


Figure 5.62 Shaft Hill - Monolith 3 - Dupont indices vs. depth.

Solid line=plant macrofossils, dotted line=testate amoebae.



5.5.4 Detrended Correspondence Analysis (DCA).

5.5.4.1 Introduction.

The process of assigning weights for each of the species in order to construct a wetness index, whilst remaining ecologically plausible, is subjective. The adoption of an alternative, more objective process, where data sets can be statistically decoded, and environmental gradients detected, would be an improvement, since it offers the possibility of corroborating the Dupont wetness index and humification data.

A standard technique which offers this potential is Detrended Correspondence Analysis or DCA. DCA is an ordination technique developed by Hill and Gauch (1980), and is a modification of Correspondence Analysis (Hill, 1973). An excellent review of ordination techniques can be found in ter Braak, (1995), whilst Gauch (1982), Pielou (1984), Birks and Gordon (1985), Manly (1994), and Kovach (1995) and Maddy and Brew (1995), also thoroughly review the subject.

Ordination techniques simplify large data sets by reducing their dimensionality, for example:

> "three samples give you a three dimensional data set; 100 samples give you a 100 dimensional data set. It is easy to visualise a three dimensional space but it is impossible to spatially comprehend a 100 dimensional space." (Kovach, 1995, p 20).

Similarly:

> "Ordination is a procedure for adapting a multidimensional swarm of data points in such a way that when it is projected onto a two-space (such as a sheet of paper), any intrinsic pattern the swarm may possess becomes apparent." (Pielou, 1984).

The mechanics of DCA, and its development from Correspondence Analysis (CA), along with worked examples, are thoroughly explained in ter Braak (1995), therefore in this instance, only the key fundamentals are considered here, which for DCA, is the process of weighted averaging (introduced in equation 5.10), and the Gaussian, unimodal response model.

DCA transforms multidimensional data sets by performing *eigenanalysis*. The new axes this process produces have *eigenvalues*, which describes the amount of variation each axis contains. Each axis is composed of *eigenvectors*, which are a set of new scores for each original data point. The original eigenanalysis technique which CA employs is termed reciprocal averaging, after (Hill, 1973), and is essentially a double weighted averaging procedure or two-way weighted averaging.

Initially unequal, arbitrary trial site scores are selected, and new species scores (u_k, Equation 5.2), are calculated by weighted averaging of the site scores, where y_{ki} denotes the abundance of species k at site i, x_i, the score of site i, and u_k represents the score of species k.

Equation 5.2. $$u_k = \sum_{i=1}^{n} y_{ki}x_i / \sum_{i=1}^{n} y_{ki}$$

From the new species scores created in this step, new site scores (x_i, Equation 5.3) are recalculated by weighted averaging of the species scores.

Equation 5.3. $$x_i = \sum_{k=1}^{m} y_{ki}u_k / \sum_{k=1}^{m} y_{ki}$$

New species scores are once again recalculated from the preceding site scores, and the process is repeated until the values for the species scores and samples stabilise. This produces the first ordination axis, which has the maximum eigenvalue and maximum dispersion for each site. Since the technique involves taking averages, at each iteration stage, the range of scores gets smaller and smaller each time. In order to overcome this, site scores are standardised after the first iteration to maintain dispersion between the scores (details of the procedure can be found in ter Braak, 1995, pp. 100-101). 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. The original CA method is subject to two problems, which potentially reduce its analytical precision; the first of these is the arch effect, where an arched pattern of points occurs along the first two axes. Rather than the axes remaining independent of each other, this represents a mathematical artefact between the two axes. The second problem arising from this is that data points at the end of the axes are compressed, and therefore misrepresent the degree of similarity between them. DCA (Hill and Gauch, 1982), corrects these faults, by 'detrending', where "at any point along the first axis, the mean value of the site scores on the subsequent axes is about zero", (ter Braak, 1995, p106). Non-linear rescaling (Hill and Gauch, 1980) is employed 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 uses to detrend the arch effect is given in ter Braak (1995), with further discussion by Kovach (1995).

Each axis produced by DCA is scaled in standard deviation (SD) units, and reflects the amount of biological turnover within that axis. The underlying ecological gradients which drive the dispersion of species and sites can then be considered *indirectly*. Where DCA has been applied to mire macrofossil datasets, the existence of a water-level gradient has been successfully demonstrated on either axis 1 or 2 of a DCA biplot (Haslam, 1987; Stoneman, 1993; Barber *et al.,* 1994e).

DCA assumes species display a unimodal response curve to environmental gradients, with a bell shaped curve of abundance rising, peaking and subsiding over 4 SD units (Figure 5.47). Because of this, samples which differ by more than 4 SD have little taxa in common, whilst a change of 1 SD units reflects a 50% change in sample composition.

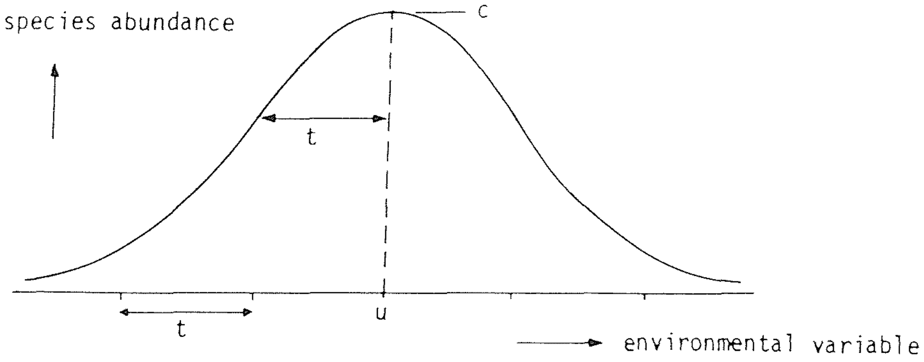


Figure 5.63 Gaussian unimodal response curve. The three ecological parameters are: maximum (c), optimum (u), and tolerance (t). The vertical axis represents species abundance, and the horizontal the environmental variable. The range of occurrences of the species is about 4t (4 SD). Source: ter Braak and Looman (1995).

Kovach (1995), Birks (1995) and ter Braak (1995), explain the development of DCA from CA fully, and discuss the merits of the unimodal species response model and weighted averaging. Weighted averaging is a highly regarded technique (ter Braak and Juggins, 1993), since it is simple, has good predictive power and the underlying assumption of a unimodal species response carries ecological plausibility. Species response curves may certainly be more complex than the Gaussian curve (Austin and Gaywood, 1994), but the unimodal Gaussian curve does serve as a convenient and robust approximation (Birks, 1995).

5.5.4.2 Data transformation and interpretation of the bi-plots.

Tilia spreadsheets were converted into .WKS files and then exported into TRAN, where the formatting was changed into Cornell Free Format, in order to allow the programme CANOCO (ter Braak, 1987), to run. Output files from CANOCO, were then exported back into Excel, in order to produce biplots of the species and sample scores. These are relatively easy to interpret. Site scores are weighted averages of the species scores. Because of this, sites scores that lie close to the position of a species score very likely contain high abundances of that particular species.

Within CANOCO, there is the option to either downweight or delete rare species, as DCA places them at the far edges of the biplot. Where extreme outliers occurred, they were deleted, since they only represent a small part of the data, and would otherwise dominate the first axis, making interpretation of underlying environmental gradients difficult.

The largest change in species composition in all of the raised mires investigated, and in 7 of the 11 bogs investigated by Stoneman (1993) is the extinction of *Sphagnum imbricatum*, and its replacement by *Sphagnum magellanicum*. DCA unfailingly picks up this change, so that axis 1 (with the exception of the Bells Flow and Raeburn Flow cores) is dominated by the two species placed at either end, and represents a species replacement gradient. Subordinate axes explain less of the variance in the data, rendering detection of latent mire surface wetness gradients difficult. Stoneman *et al.* (1993), concluded that the niche of *Sphagnum imbricatum* has been replaced by *Sphagnum magellanicum*, therefore the two can be considered together as one species unit. This approach has been adopted by Barber *et al.* (1994e), and is adopted here, with the exception of Bell's Flow and Raeburn Flow (the extinction of *Sphagnum imbricatum* at these two sites is represented on axis 2), in order to increase the chances of detecting a mire surface wetness gradient.

5.5.4.3 DCA of Bolton Fell Moss - Core L.

Figure 5.65 represents the best species separation for the Bolton Fell Moss macrofossil data set. The ordination was produced with the detrending by segments option. Detrending by segments may lead to some loss of information, as the variation associated with one of the underlying environmental gradients may be attenuated (Minchin, 1987, ter Braak, 1995). To overcome this potential problem, there is the option to detrend by polynomials, for example one can detrend using second order polynomials, where the second CA axis is made not only uncorrelated with the first axis, but also uncorrelated with its square. However, trial analysis of the data set using detrending by first, second and third order polynomials failed to separate the species as well as detrending by segments, therefore the latter option was adopted. The number of segments used in the detrending process was held constant at the default setting of 26, and will allow comparisons between the results of this ordination and those from the other sites.

Trial ordinations of the plant macrofossil stratigraphy from this site (Figure 5.64) resulted in the placement of *Eriophorum vaginatum* with the hygrophilous mire vegetation (*Rhynchospora alba and Sphagnum section Cuspidata*). Although this species can clearly grow over a range of water levels (Section 5.2.5), its position at this end of the axis may also reflect a species replacement gradient between this sedge and *Sphagnum imbricatum/magellanicum,* possibly representing an outgrowth of a tussock, and not changes in mire water level. With this possibility in mind, a second ordination run was performed in CANOCO, with *Eriophorum vaginatum* excluded. The results of this ordination are presented in Figure 5.65. Although axes 1 and 2 in this diagram represent less of the variation in the data set (22.3 and 8.7%, respectively) compared to that in Figure 5.64 (42.9 and 17.2%), a distinction between the hygrophilous flora (*Rhynchospora alba, Sphagnum*

Figure 5.64 Bolton Fell Moss - Core L - Detrending by segments.

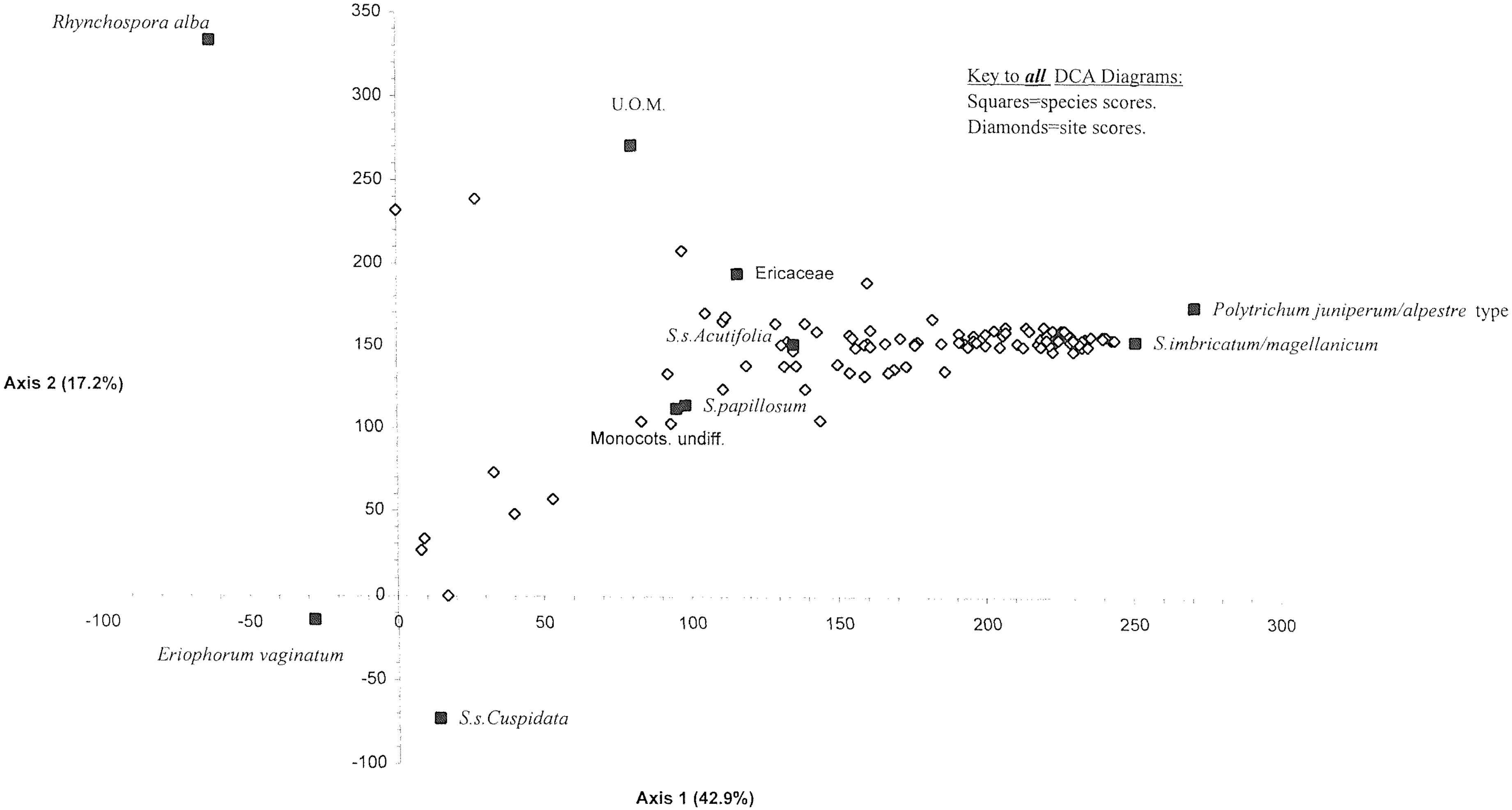


Figure 5.65 Bolton Fell Moss - Core L - Detrending by segments.

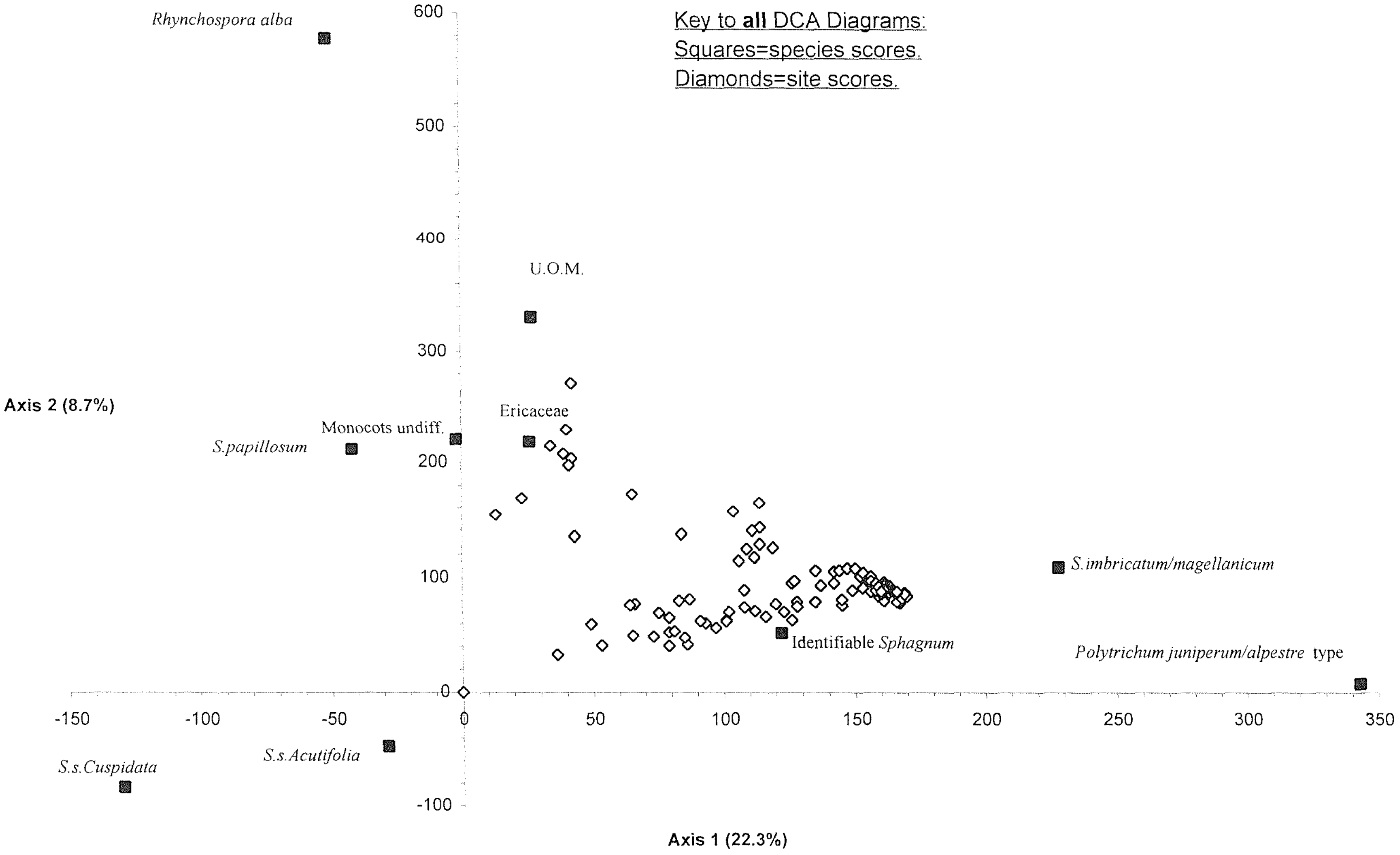


Figure 5.66 Bolton Fell Moss - Core L. DCA axis 1 scores vs depth.

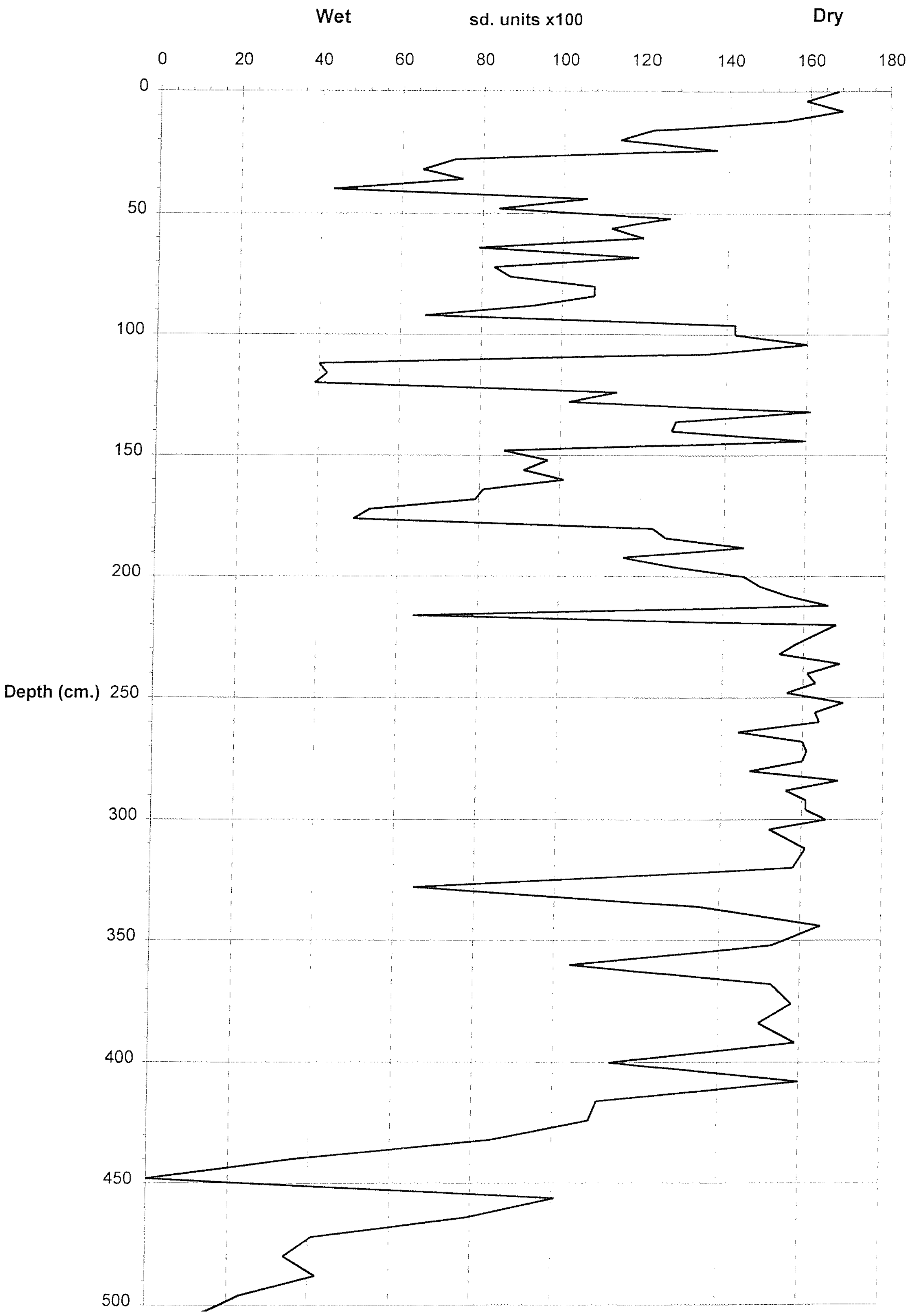
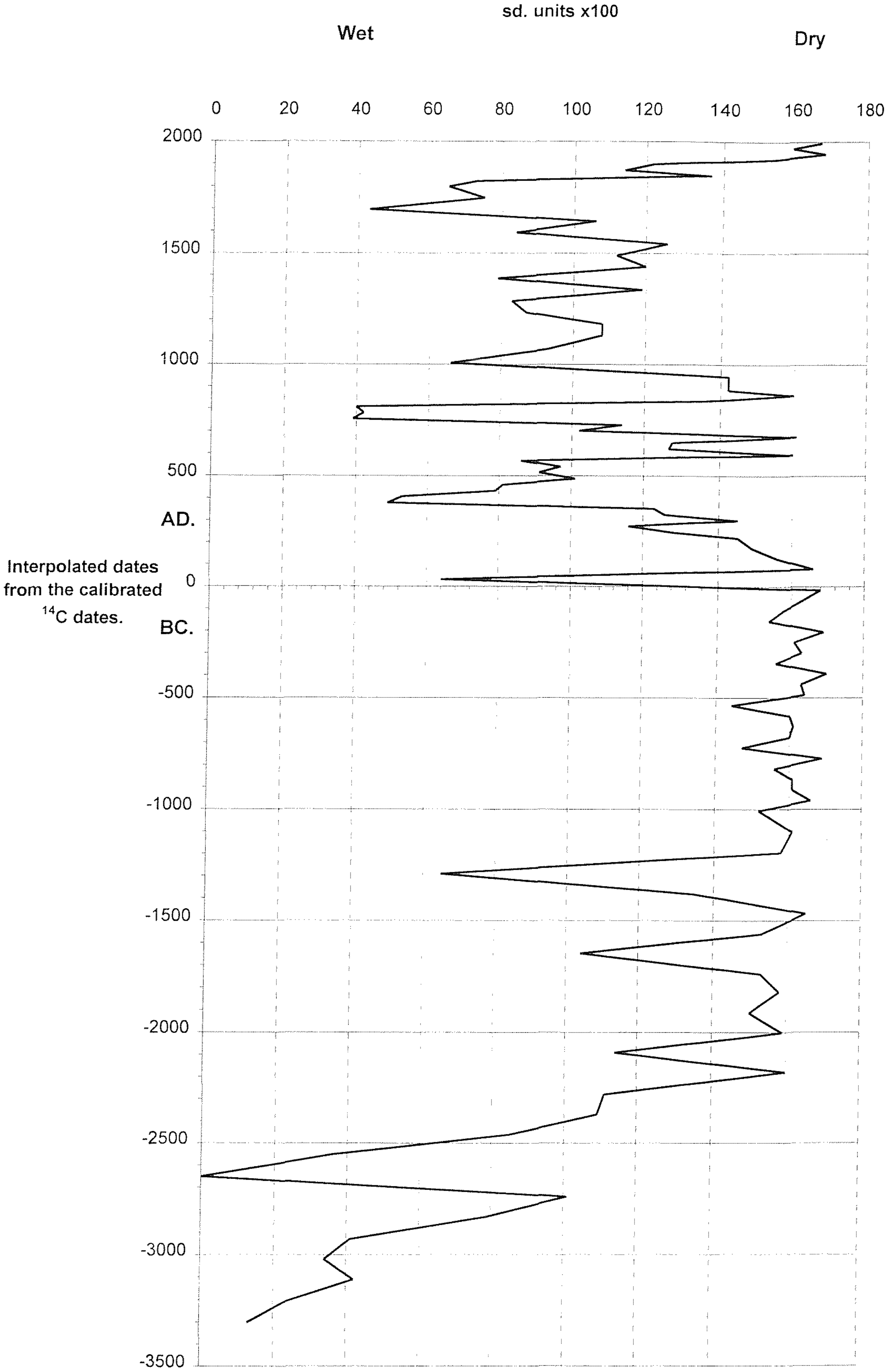


Figure 5.67 Bolton Fell Moss - Core L. DCA axis 1 scores vs. time.



papillosum and *Sphagnum* section *Cuspidata*) and the drier mire components (Ericaceae and U.O.M.) can be made on axis 1. *Sphagnum imbricatum/magellanicum* also appears to be associated with dry mire surface conditions, since it is located at the extreme right of the diagram. There is certainly plant macrofossil and testate amoebae evidence to suggest that *Sphagnum imbricatum/magellanicum* has grown on peat surfaces with a deep acrotelm, as *Polytrichum juniperum/alpestre* type is associated with *Sphagnum magellanicum* in zone *BFML-g.* (Figure 5.15), whilst in zones *BFML-b* and *c.* (412-174 cm.), where *Sphagnum imbricatum* forms the dominant floral component, thecae of *Hyalosphenia subflava* and *Trigonopyxis arcula* are relatively abundant *(BFML-TA-b. and c.).* The position of *Sphagnum* section *Acutifolia* with relatively hygrophilous species, may imply leaves of *Sphagnum tenellum* are present in the peat stratigraphy. This species can be misidentified as a *Sphagnum* section *Acutifolia* species due to its small size, (Section 5.2.14), and its ability to grow over a wide range of water levels (up to 2 cm. above the water table, Økland, 1990), may explain its position at this point in the scatter plot.

In Figure 5.66 and 5.67, axis 1 scores are plotted against depth and the interpolated dates derived from the calibrated ^{14}C dates. Since these axes represent a water level gradient, the site scores for each level reflects reconstructed mire surface wetness, and serves to indicate the degree of effective precipitation.

5.5.4.4 DCA of Walton Moss - Core 11.

Axis one and two scores are plotted against each other in Figure 5.68. Along axis 1 of this diagram there is evidence of a hummock/hollow gradient, as taxa indicative of wet mire surface conditions (*Rhynchospora alba* and *Sphagnum* section *Cuspidata*) are positioned at the opposite end of the scale to the dry mire indicator components (*Eriophorum vaginatum, Polytrichum juniperum/alpestre* type and Ericaceae). This axis accounts for 64.1% of the dispersion in the ordination points, and spans 3.7 standard deviation (sd.) units. In the unimodal species response model, species abundances rise and fall over 4 sd. units along an environmental gradient (ter Braak and Prentice, 1987), therefore in this instance species at the opposite ends of axis 1 are mutually exclusive of each other. The position of the monocots. undiff. towards the 'wet' end of axis 1, suggests that this material is possibly *Rhynchospora alba* or *Eriophorum angustifolium.*

In Figure 5.69 and 5.70, axis 1 scores are plotted against depth and time. These again serve as an effective precipitation proxy curve, as the site scores for each level represent a water level gradient.

Figure 5.68 Walton Moss - Core 11 - Detrending by segments.

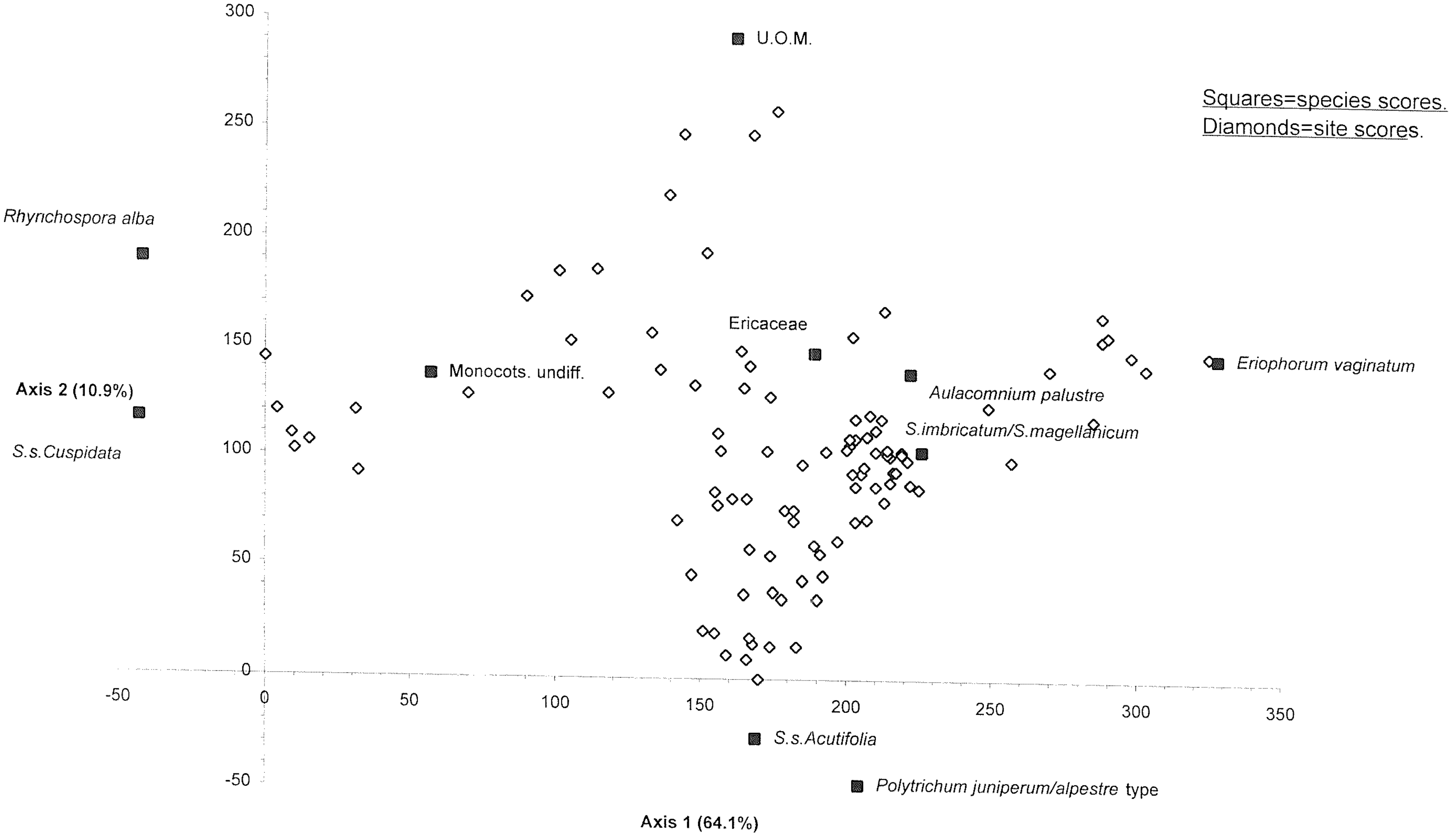


Figure 5.69 Walton Moss - Core 11. DCA axis 1 scores vs. depth.

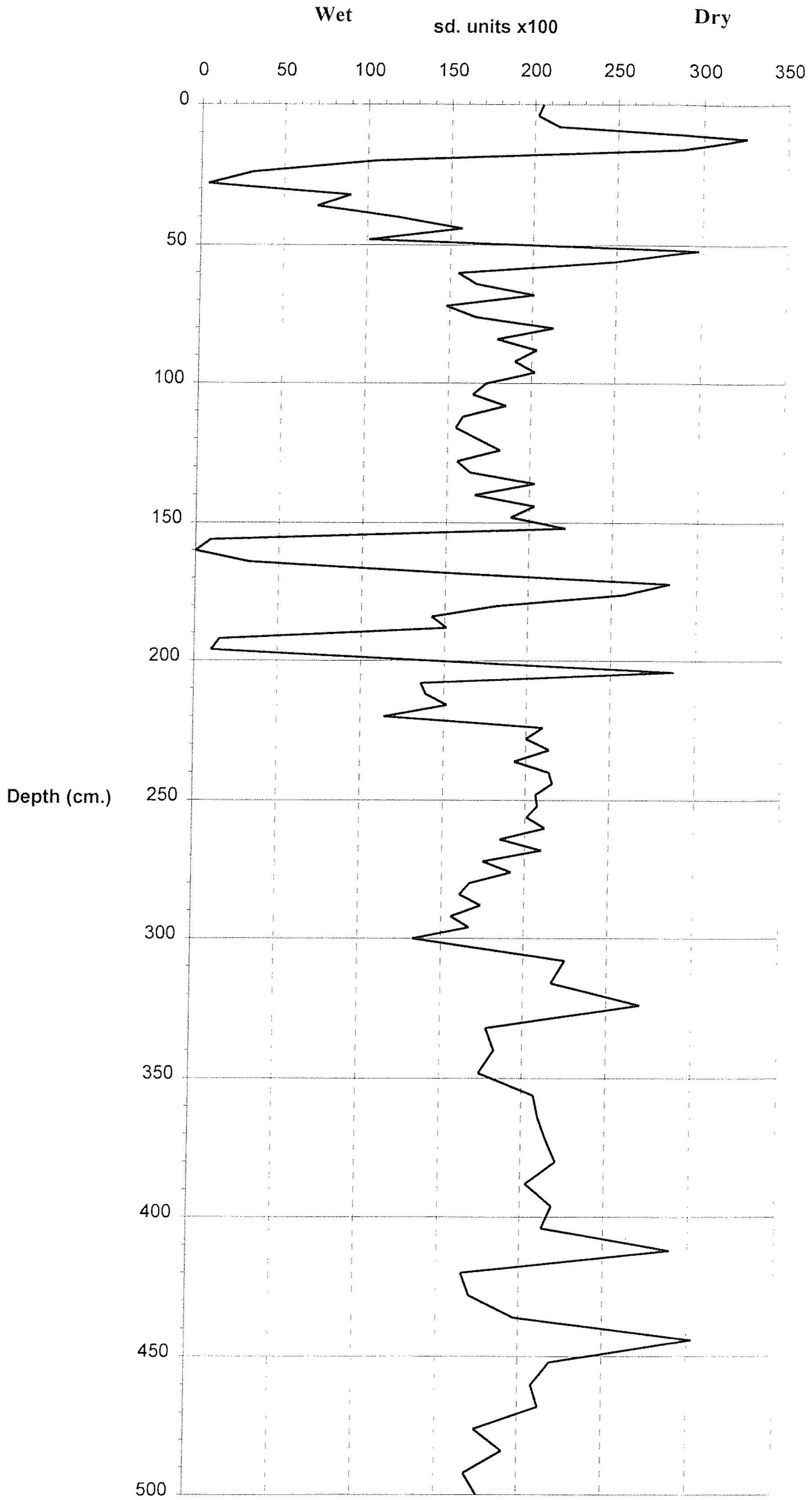
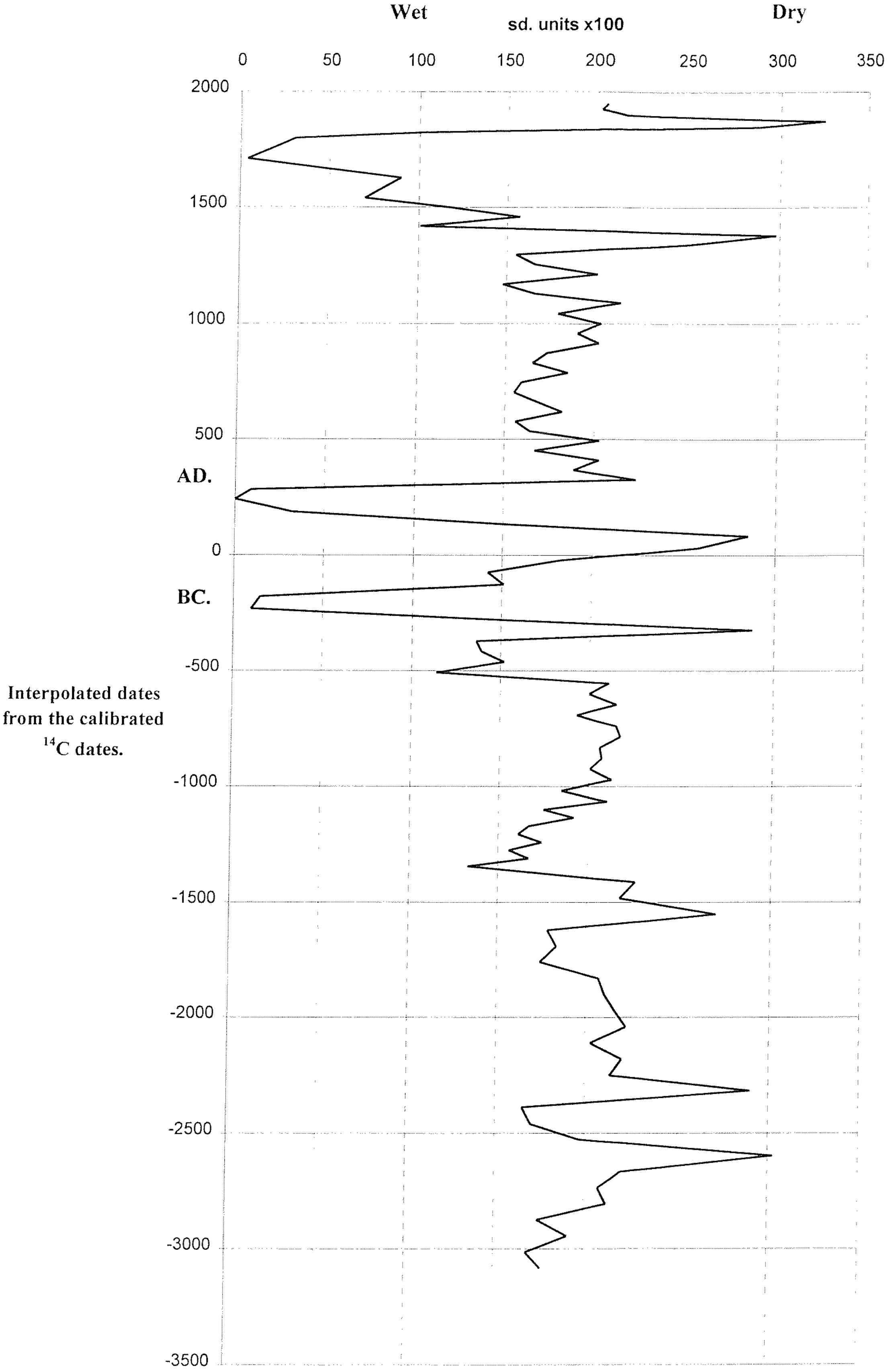


Figure 5.70 Walton Moss - Core 11. DCA axis 1 scores vs. time.



5.5.4.5 DCA of Raeburn Flow.

A very clear mire surface wetness gradient is again apparent along axis 1 of Figure 5.71, with, once again, a clear separation of components indicative of wetter microtopes (*Sphagnum* section *Cuspidata*, *Rhynchospora alba* and *Sphagnum papillosum*) from those indicating drier microsites (*Eriophorum vaginatum,* Ericaceae and U.O.M.). This axis is 3.9 sd. units long, and represents 80.7% of the variation in the core. Leaves of *Sphagnum magellanicum* from this site appear to be associated with the drier hummock end of the moisture gradient, which contrasts with the low lawn position this species possibly adopted in the Bell's Flow site. This could well be a reflection of the broad habitat niche this species is capable of occupying (Økland, 1990).

The replacement of *Sphagnum imbricatum*/U.O.M. association by *Sphagnum magellanicum* on DCA axis 2 (7.3% of the variation in the data set), is again readily apparent from the ordination biplot.
The DCA axis 1 scores in Figure 5.73, again show a large at change at 1800 AD. (*Pinus* rise 'date'), and a further large change in reconstructed mire surface wetness is evident at 1340 AD.

5.5.4.6 DCA of Bell's Flow.

A latent hummock/hollow gradient is discernible in the macrofossil ordination for this site (Figure 5.74). This is represented on axis 1, which represents 78.1% of the dispersion of the data points. The taxa are widely separated along this axis, since it is 4.35 sd. units in length. *Sphagnum* section *Acutifolia*, *Sphagnum imbricatum*, Ericaceae and *Eriophorum vaginatum* are located at the opposite end of axis 1 in relation to the hygrophilous *Sphagnum* section *Cuspidata*, *Sphagnum papillosum* and *Rhynchospora alba* components.

Sphagnum capillifolium leaves may be present in the peat core, as the position of Section *Acutifolia* in the ordination plot suggests a hummock microtope. *Sphagnum magellanicum* in this instance, appears to lie in a low lawn position, since it occurs in ordination space with *Rhynchospora alba.* The 'generalist' nature of *Sphagnum magellanicum* (Van der Molen and Wijmstra, 1994), with respect to mire water level (section 5.2.15), may allow it to have grown in this relatively wet environment. *Sphagnum imbricatum*, by comparison, appears to have been restricted to hummock environments. This is certainly supported by the testate amoebae evidence, as this species is predominantly associated with zones *BSF-a.* and *c.* (300-146 cm.) which contain relatively high amounts of the xeric rhizopod, *Hyalosphenia subflava (BSF-TA-a.-c.).*

Within axis 2, the replacement of *Sphagnum imbricatum* by *Sphagnum magellanicum* is apparent, although this change is subordinate to the water level gradient identified in axis 1 (axis 2 only accounts for 5.5% of the dispersion in the ordination data).

Figures 5.75 and 5.76 show the changes in DCA axis 1 scores downcore, and what is immediately apparent is the very large change in reconstructed mire surface wetness which occurs at 20 cm. depth.

Figure 5.71 Raeburn Flow - Detrending by segments.

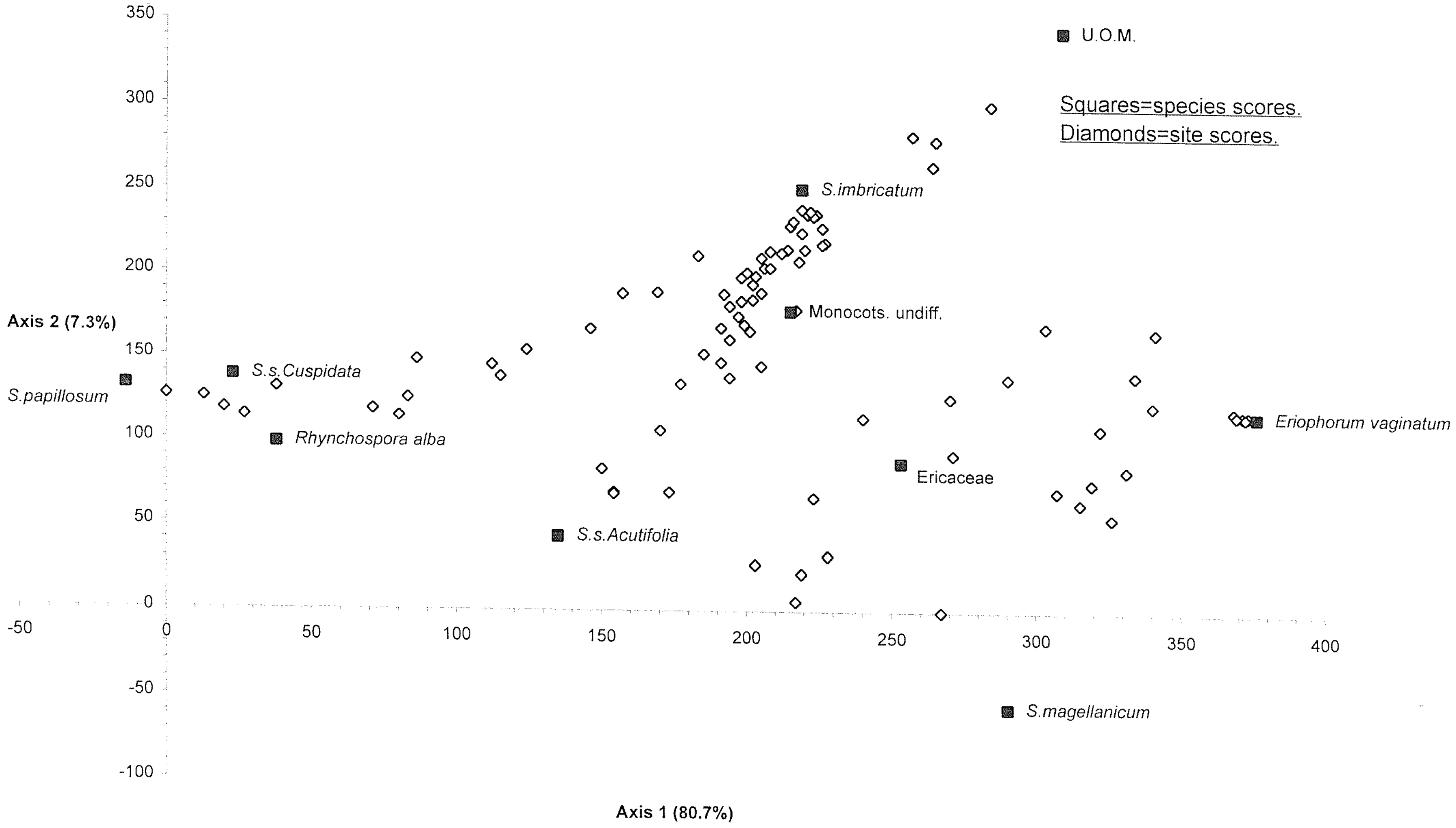


Figure 5.72 Raeburn Flow. DCA axis 1 scores vs. depth.

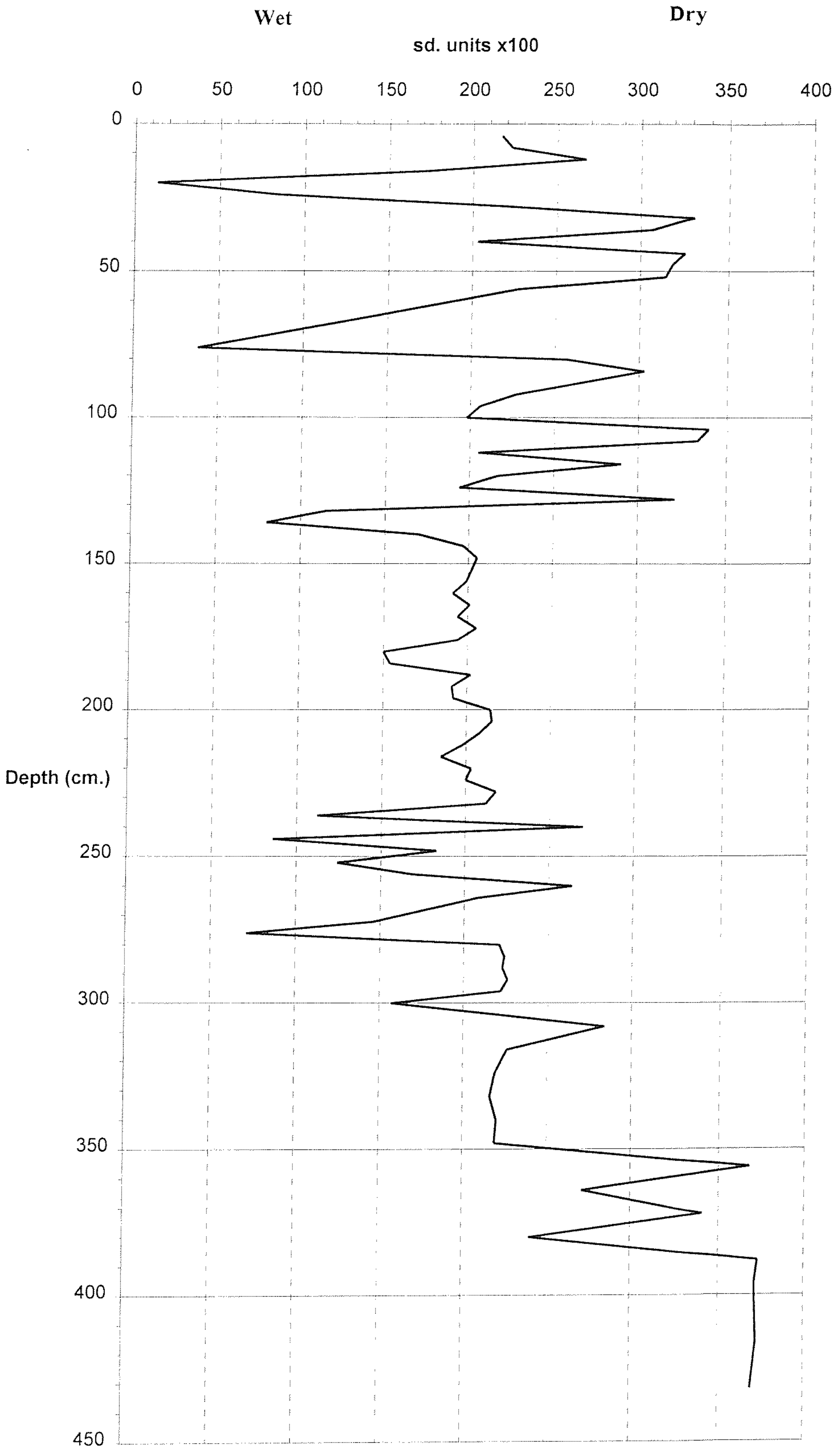


Figure 5.73 Raeburn Flow. DCA axis 1 scores vs. time.

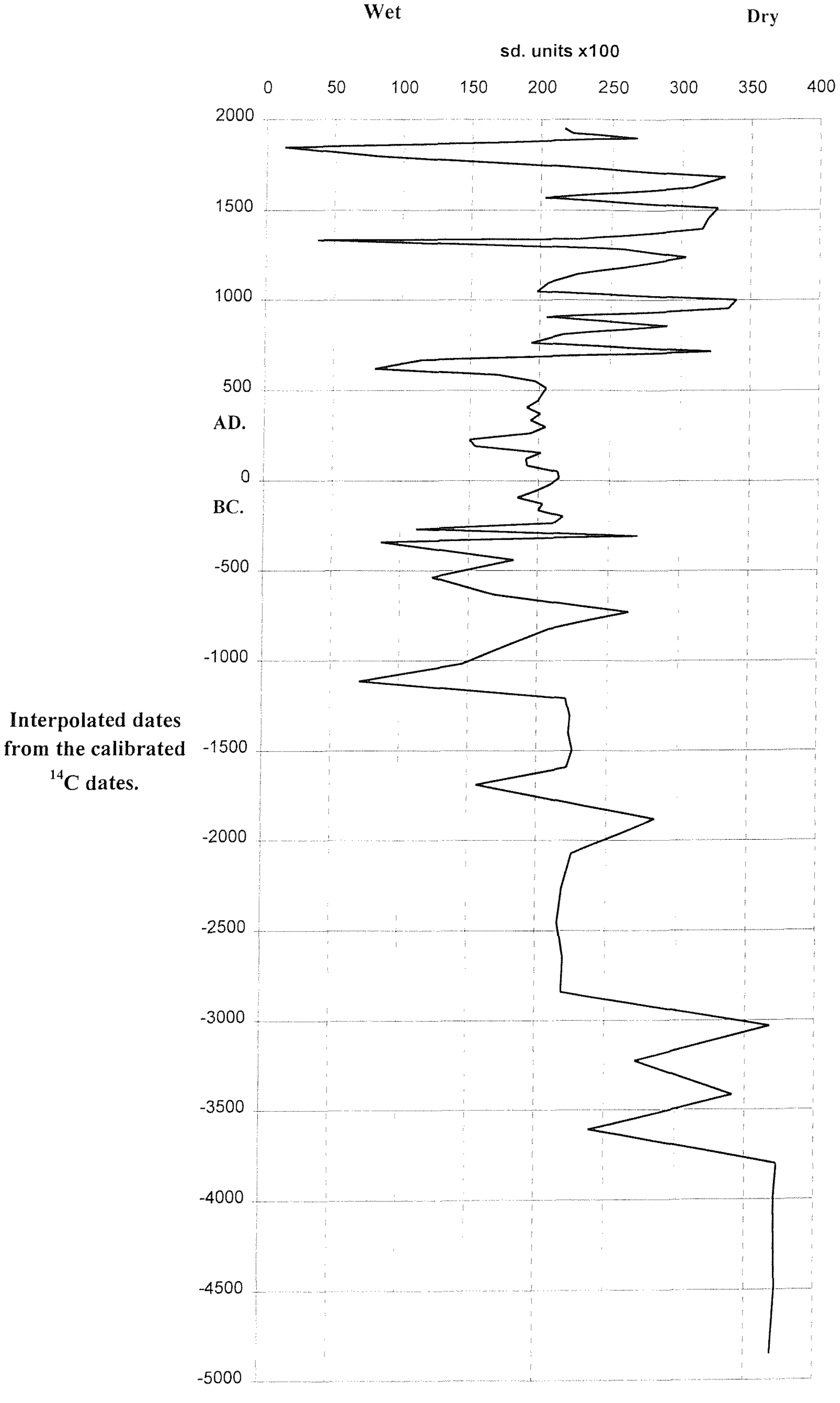


Figure 5.74 Bell's Flow - Detrending by segments.

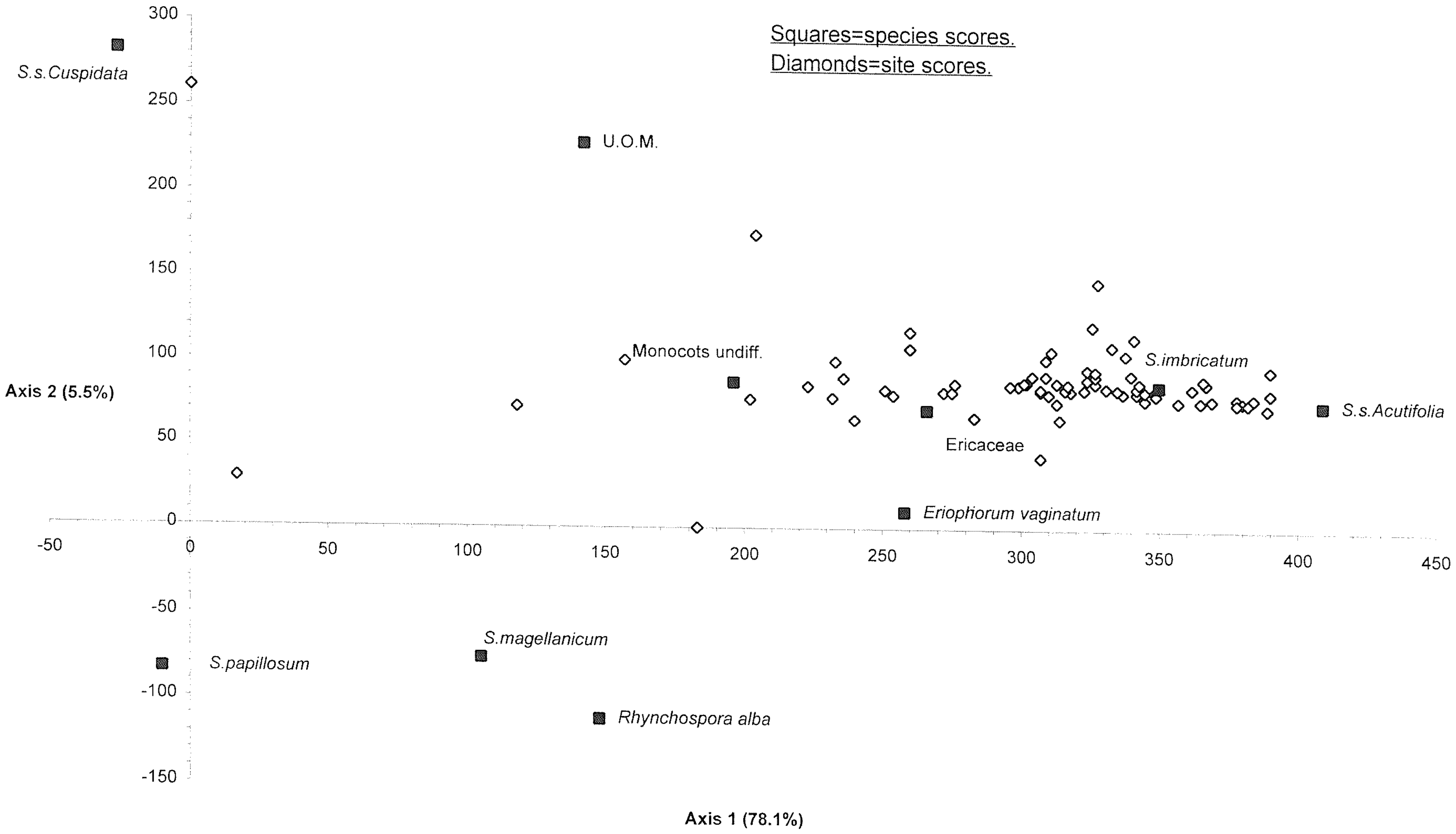


Figure 5.75 Bell's Flow. DCA axis 1 scores vs. depth.

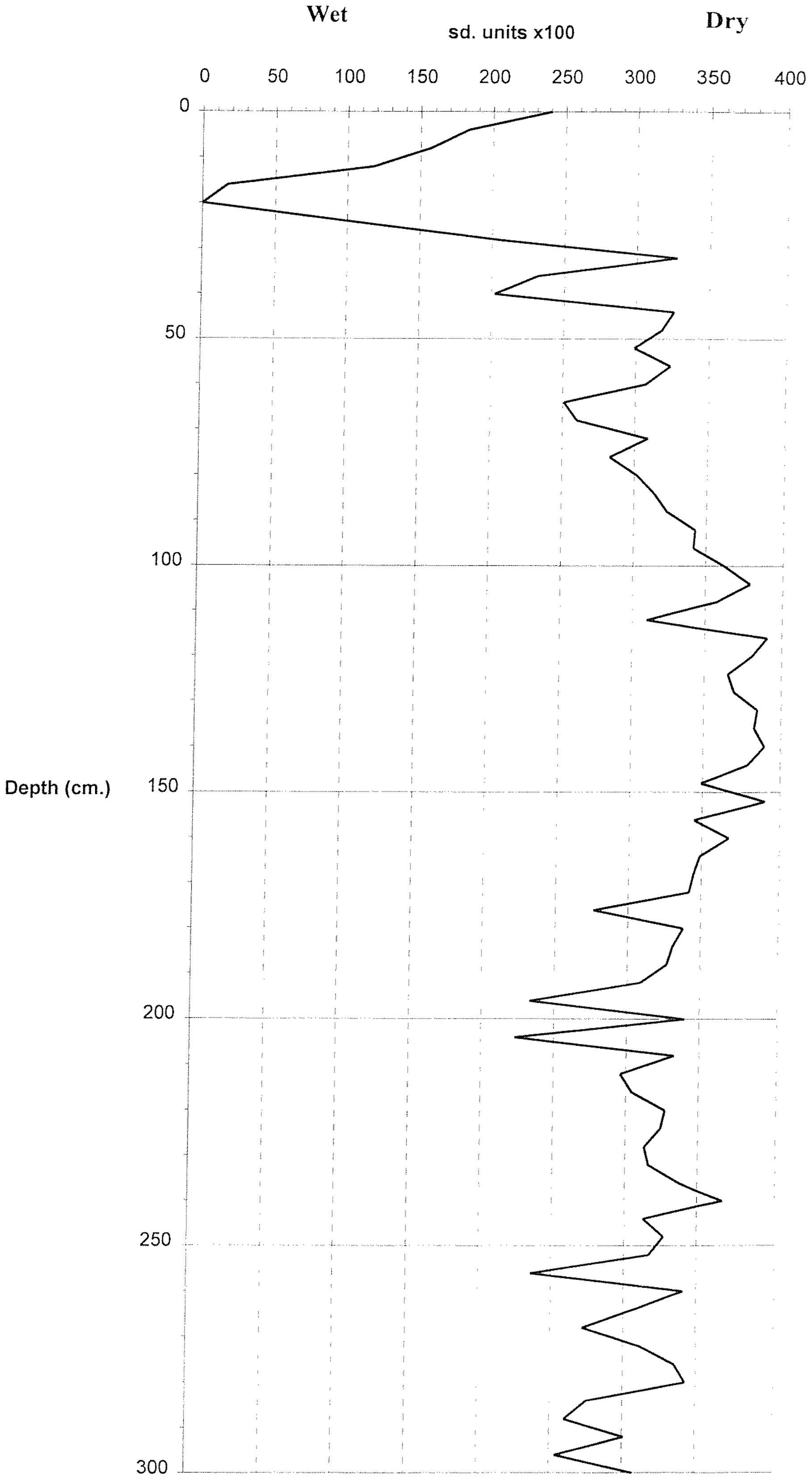
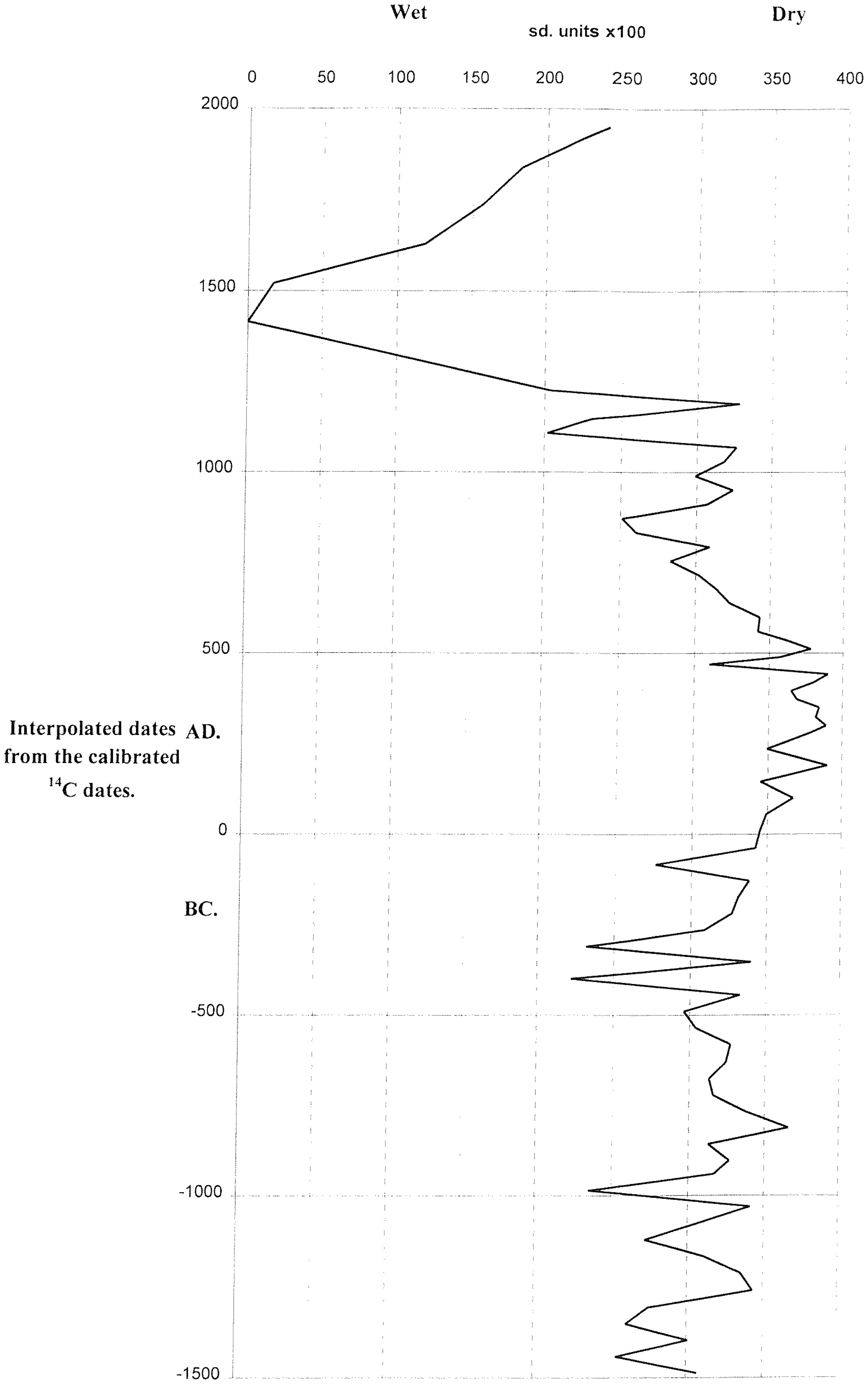


Figure 5.76 Bell's Flow. DCA axis 1 scores vs time.



5.5.4.7 DCA of Coom Rigg Moss.

Axis 1 on Figure 5.77 indicates an unambiguous hummock/hollow gradient, which extends 3.5 sd. units (68.8% of the dispersion of the data points). *Eriophorum angustifolium* epidermis was identified in the stratigraphy of this borehole (Figure 5.33), and has been objectively placed with the other 'wet' mire taxa (*Sphagnum* section *Cuspidata, Sphagnum papillosum* and *Rhynchospora alba*). Leaves of *Sphagnum* section *Acutifolia* are placed near to these pool/low lawn species on the ordination biplot, which suggests they possibly originate from *Sphagnum subnitens* sporophytes. At the opposite end of the axis, U.O.M., Ericaceae and *Eriophorum vaginatum* support the existence of a dry hummock top microtope.

The largest swing in reconstructed mire surface wetness occurs near the surface at 28 cm. (Figure 5.78). In a similar manner to the stratigraphy of Bell's Flow, dating this level is difficult, since the c. 1800 AD. Pine rise date occurs at 24 cm., whilst the mid point of the two 2 σ calibrated range is 1545 AD. for the sample spanning 24-32 cm. (SRR-5883). The possible reasons for this discrepancy are discussed in Section 6.2.1, but there is a possibility this large wet shift is a response of the mire flora to the LIA.

5.5.4.8 DCA of Felecia Moss.

A clear mire surface wetness gradient is evident in the ordination biplot (Figure 5.80). This is very encouraging, as DCA appears to have consistently picked up hummock/hollow gradients from the macrofossil components of all of the raised mires sites investigated. Axis 1 on Figure 5.80 is 3.45 sd. units long and has a relatively high eigenvalue (axis 1 represents 50% of the variation within the core). Peat components indicative of a deeper acrotelm (*Eriophorum vaginatum*, U.O.M., and Ericaceae) are located at the opposite end of axis 1 to those taxa which indicate a shallow acrotelm (*Sphagnum* section *Cuspidata*, *Sphagnum papillosum* and *Rhynchospora alba*). The position of *Sphagnum* section *Acutifolia* leaves near to the hygrophilous taxa, may once again indicate the presence of *Sphagnum subnitens* in the sample borehole.

The largest change in inferred mire surface wetness on Figure 5.82 appears to have taken place at CAL 1020-1240 AD. (SRR-5891).

Figure 5.77 Coom Rigg Moss - Detrending by segments.

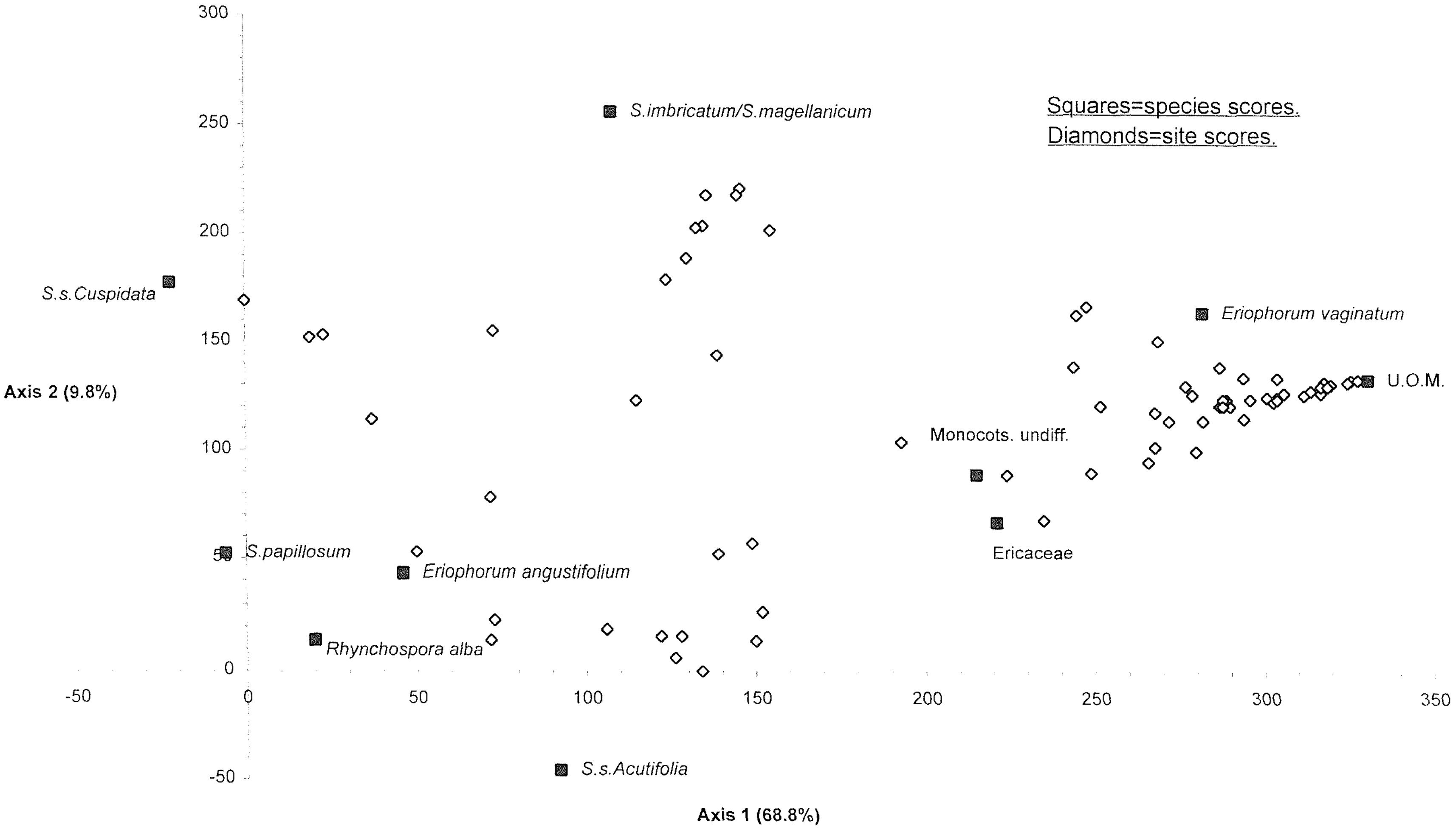


Figure 5.78 Coom Rigg Moss. DCA axis 1 scores vs. depth.

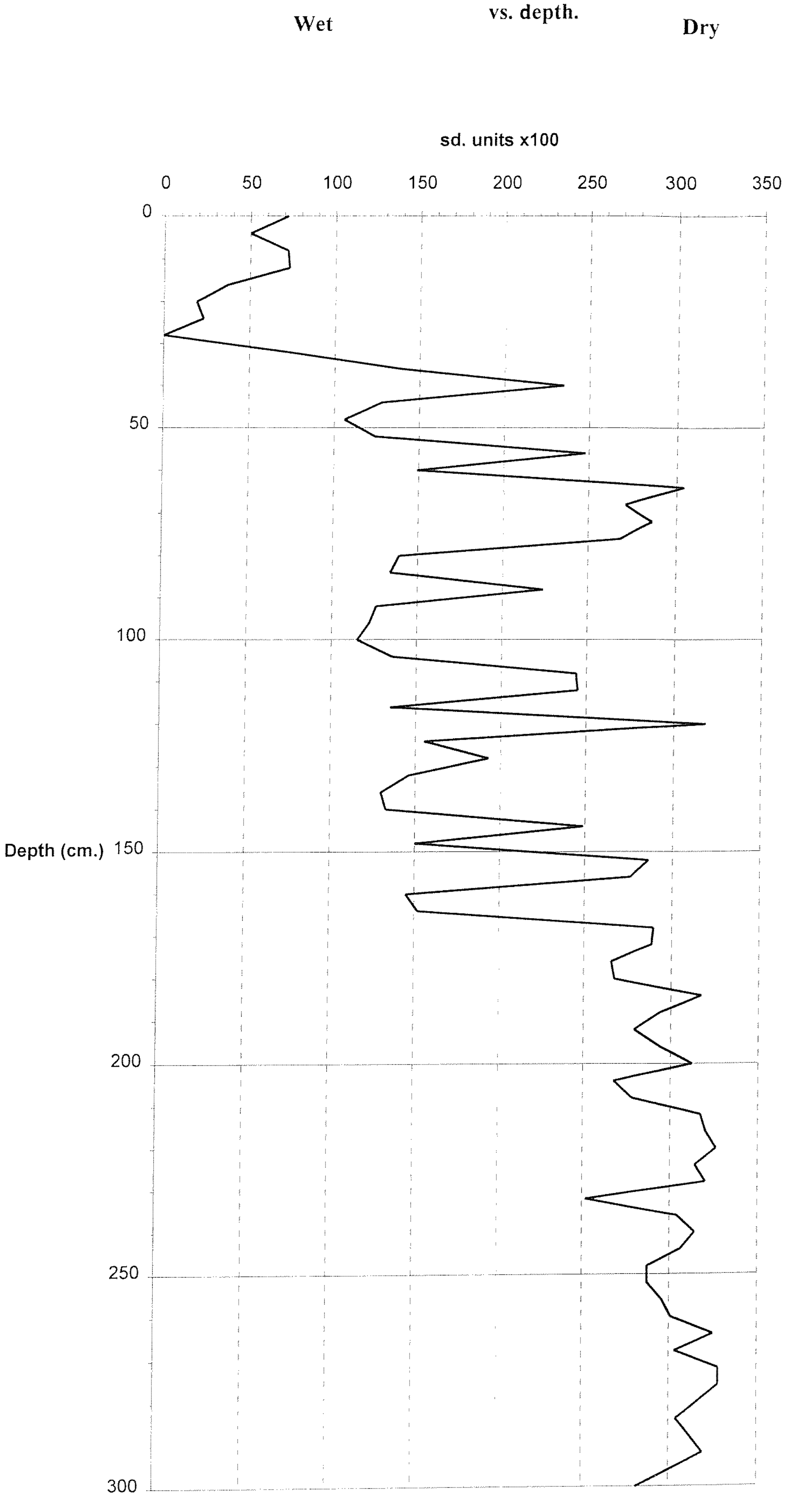


Figure 5.79 Coom Rigg Moss. DCA axis 1 scores vs. time.

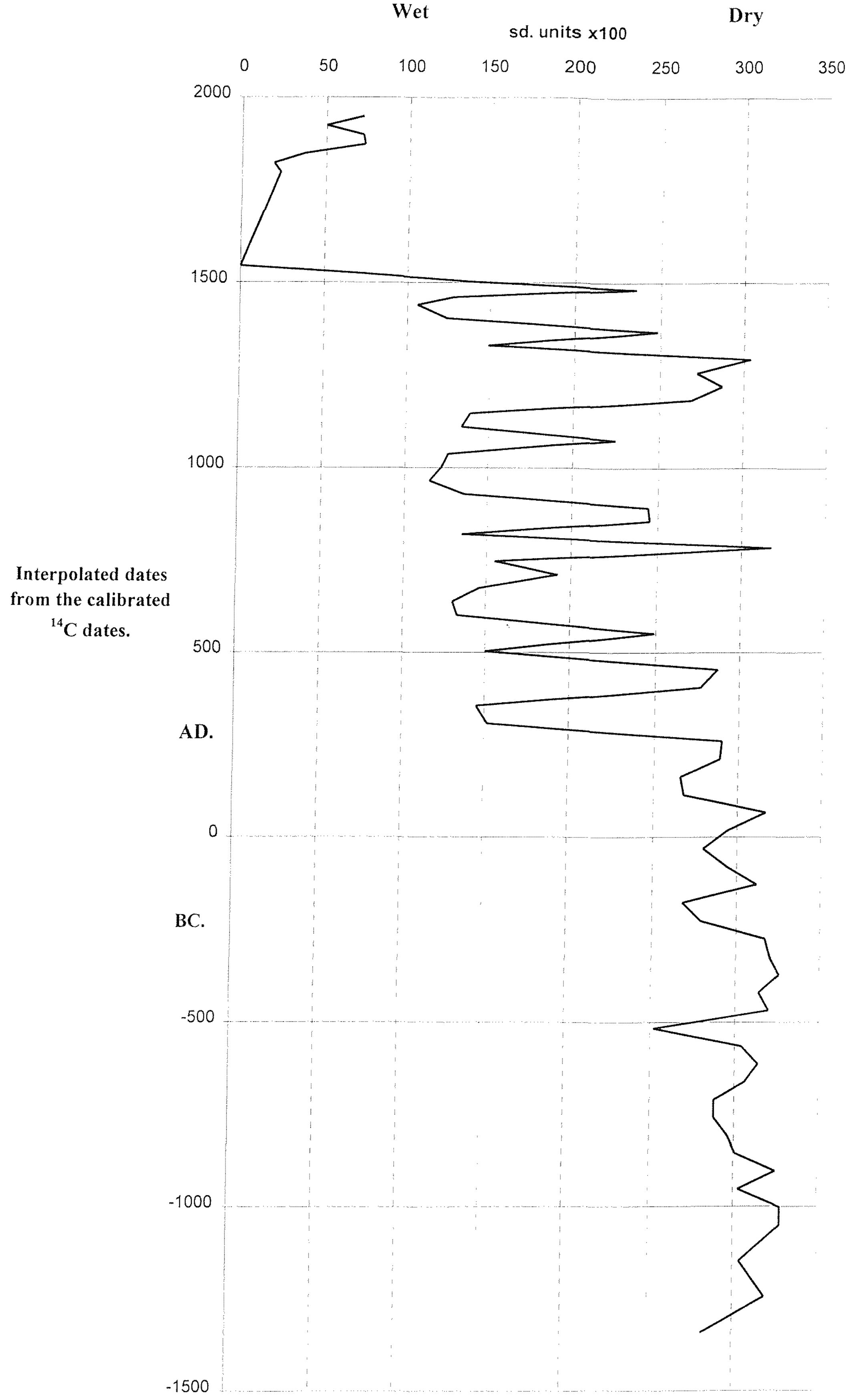


Figure 5.80 Felecia Moss - Detrending by segments.

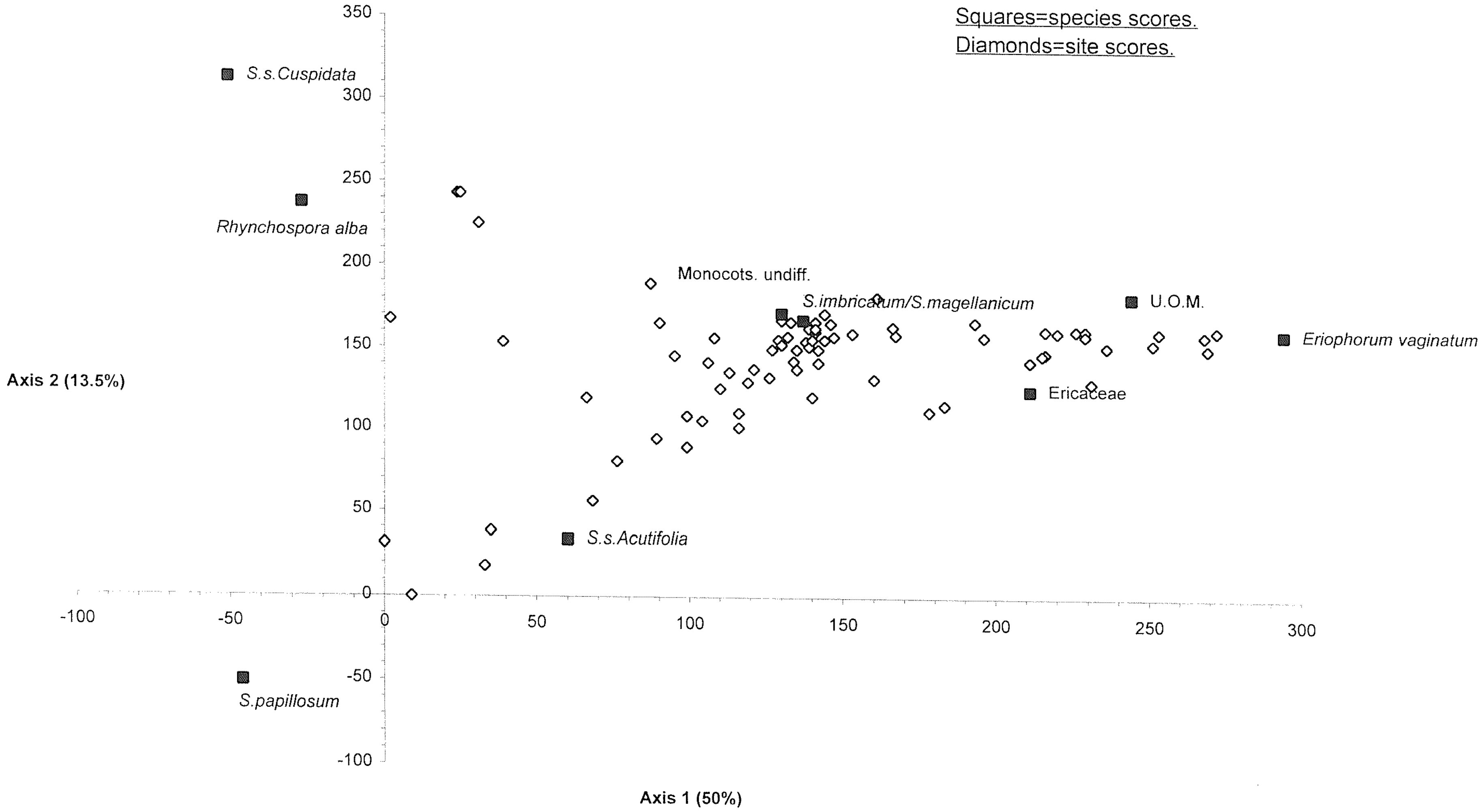


Figure 5.81 Felecia Moss. DCA axis 1 scores vs. depth.

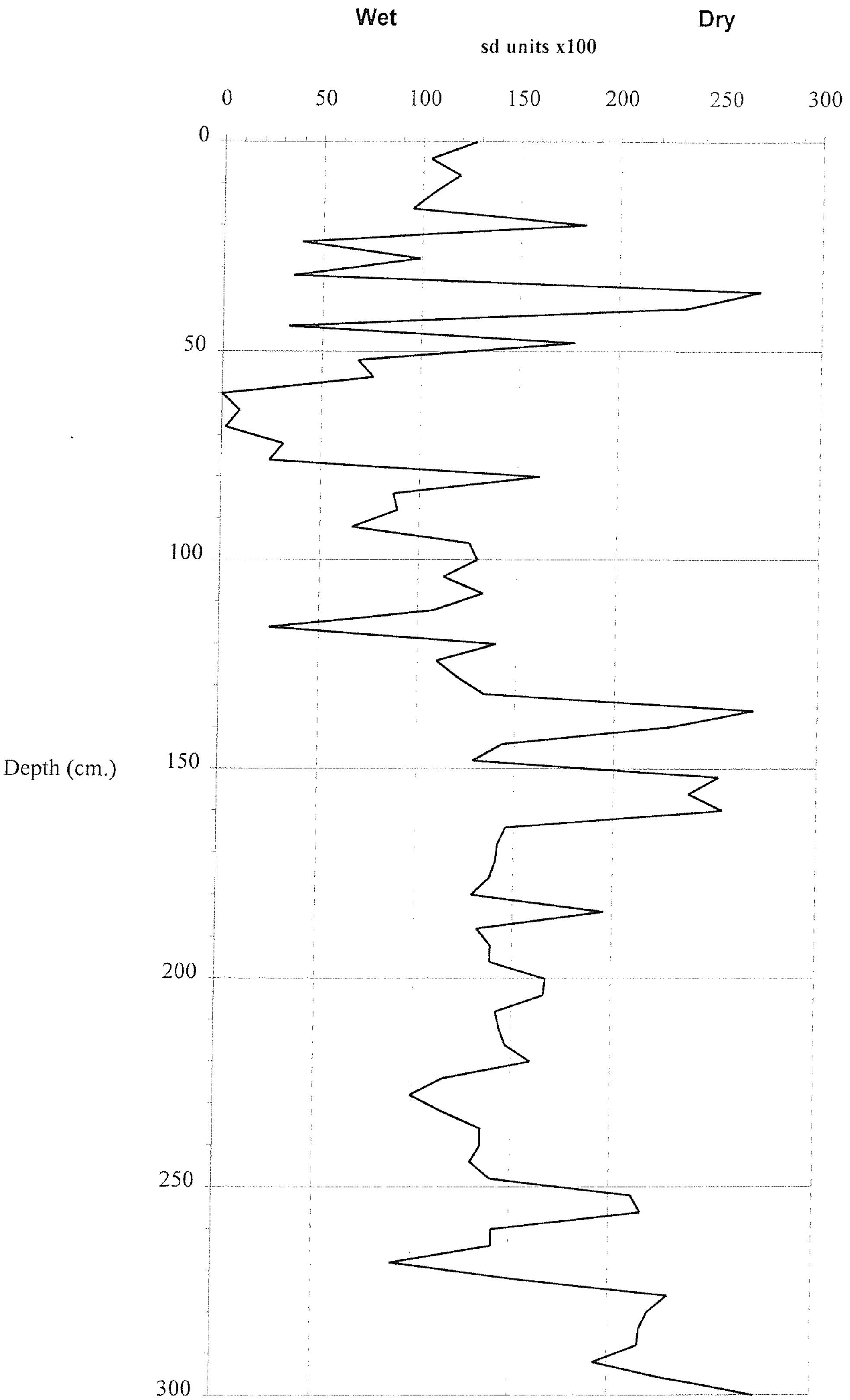
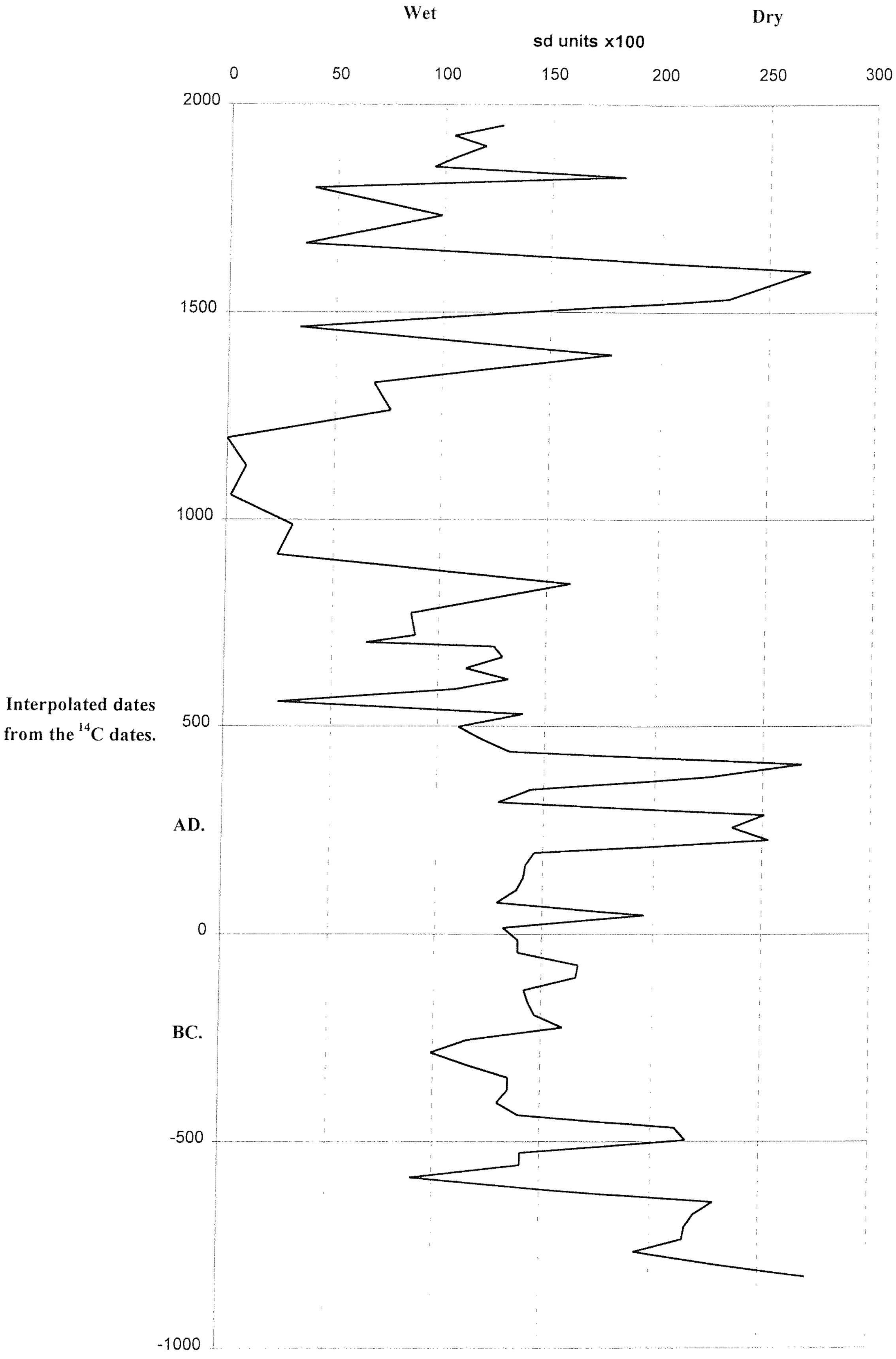


Figure 5.82 Felecia Moss. DCA axis 1 scores vs. time.



5.5.4.9 DCA of Shaft Hill - Monolith 1.

The best ordination biplot for this site (Figure 5.83) was produced by using the detrending by segments option. In comparison to the raised peat bogs, the existence of a latent hummock/hollow gradient from this blanket peat monolith is not as clear cut, as remains of *Eriophorum angustifolium* and *Rhynchospora alba* were not recovered. Despite this, drier mire components (U.O.M., *Eriophorum vaginatum,* Ericaceae and *Racomitrium lanuginosum* leaves), do plot out at opposite positions on axis 2 in relation to the 'wetter' vegetation (*Sphagnum* section *Cuspidata* and *Sphagnum papillosum* leaves), which is encouraging. The scores from Axis 2 have been plotted on Figure 5.84, where it is important to note that high sd. unit values represent *increased* mire surface wetness. Axis 1 on this diagram does not appear to represent a water-level gradient, but instead a species replacement gradient from *Eriophorum vaginatum* and U.O.M. to *Sphagnum papillosum, Sphagnum* section *Acutifolia* and *Trichophorum cespitosum.* This axis accounts for 63.6% of the macrofossil variation, and spans 3.53 sd. units. The second axis, which best represents a water-level gradient, accounts for 11.7% of the dispersion of the data points, and spans 4.34 sd. units. From the ordination diagram, epidermal tissues of *Trichophorum cespitosum* appear to be associated with the drier mire components (*Sphagnum* section *Acutifolia* and *Racomitrium lanuginosum).* This is supported by Rodwell *et al.* (1991), since they suggest it can survive in drier hummocks. In the light of this, the position of this sedge on axis 2 does seem appropriate.

5.5.4.10 DCA of Shaft Hill - Monolith 2.

Axis 1 of Figure 5.85 is 4.3 sd. units long, and encompasses 59.2% of the dispersion of the data points. Along this axis there is a separation of pool/lawn components from hummock taxa, as the former (*Eriophorum angustifolium, Sphagnum papillosum* and *S. magellanicum*) are found at the opposite end of the axis to the *Eriophorum vaginatum* macrofossils, Ericaceae, U.O.M., and *Racomitrium lanuginosum* leaves. In addition to representing a water level gradient, axis 1 may also reflect to some extent, the degree of burning of the vegetation, and the curve presented in Figure 5.86 may be a composite mire water level/burning history curve. Fires may have allowed *R. lanuginosum* and *E. vaginatum* to become more abundant (Ratcliffe, 1964; Barber, 1981; Lindsay *et al.*, 1988; Rodwell, 1991). This is supported by the monolith macrofossil evidence (Figure 5.33), as there is a dearth of *Sphagnum* species and charcoal fragments are relatively abundant in the levels where *Racomitrium* leaves and *E. vaginatum* macrofossils occur.

The position of *Sphagnum* section *Acutifolia* juxtaposed with the relatively hygrophilous species, may once again suggest leaves of *Sphagnum tenellum* are present in the peat stratigraphy (Section 5.5.2.3). Leaves of *Sphagnum imbricatum* were excluded from the final ordination as they represent at most 6% of the peat matrix, and are largely absent from the majority of the sub-fossil samples. Because CA is

Figure 5.83 Shaft Hill - Monolith 1 - Detrending by segments.

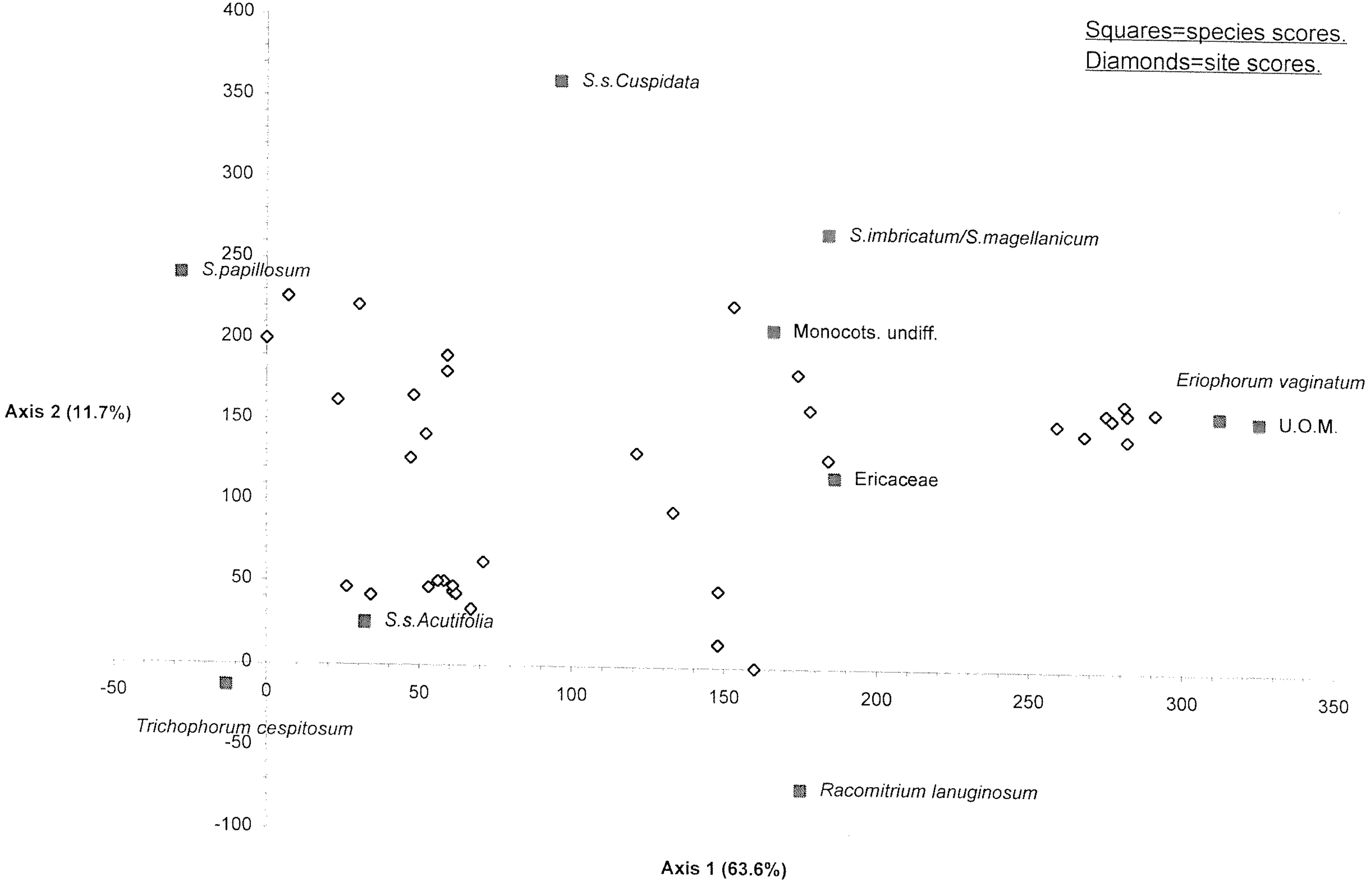
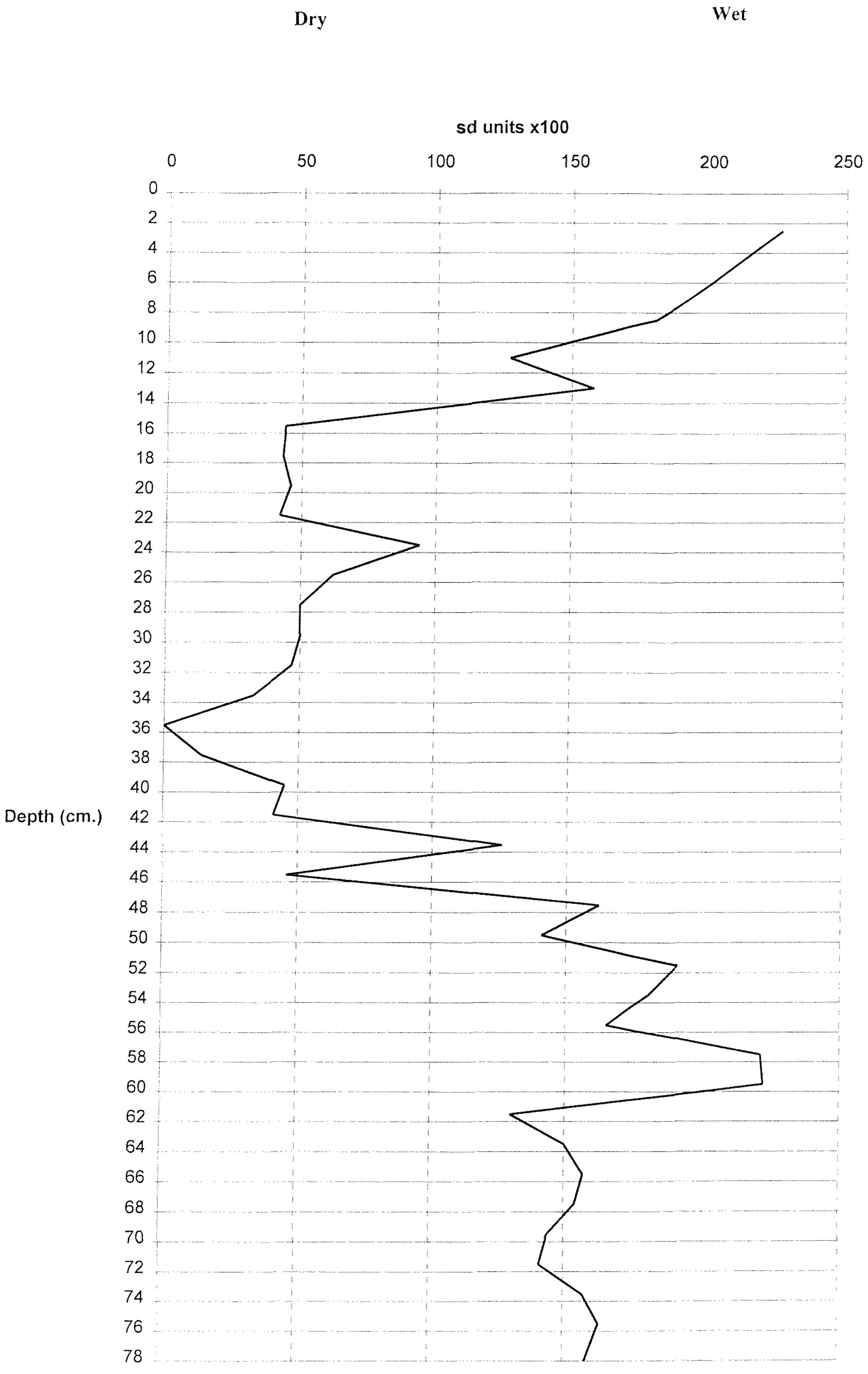


Figure 5.84 Shaft Hill - Monolith 1 - DCA axis 2 scores vs. depth.



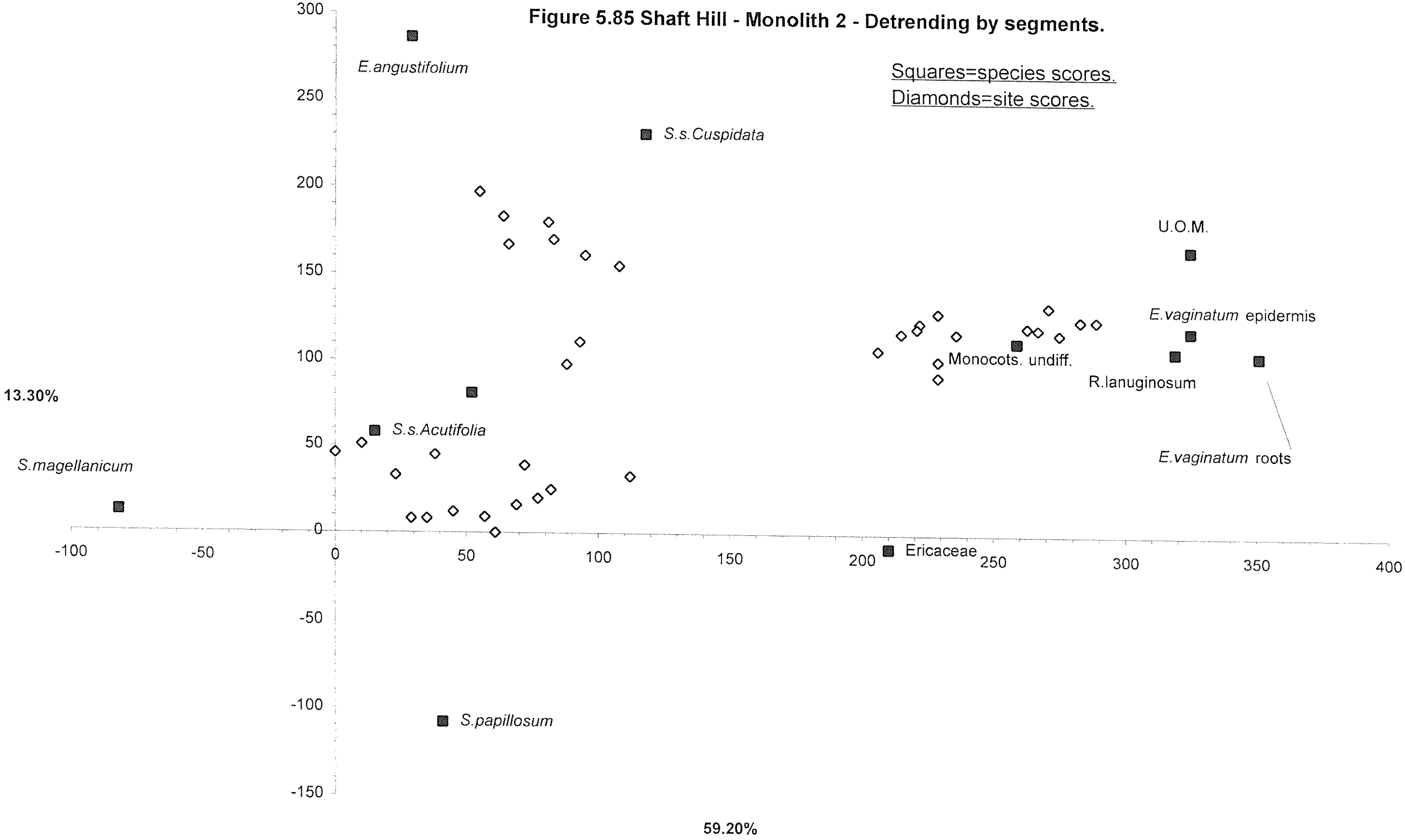
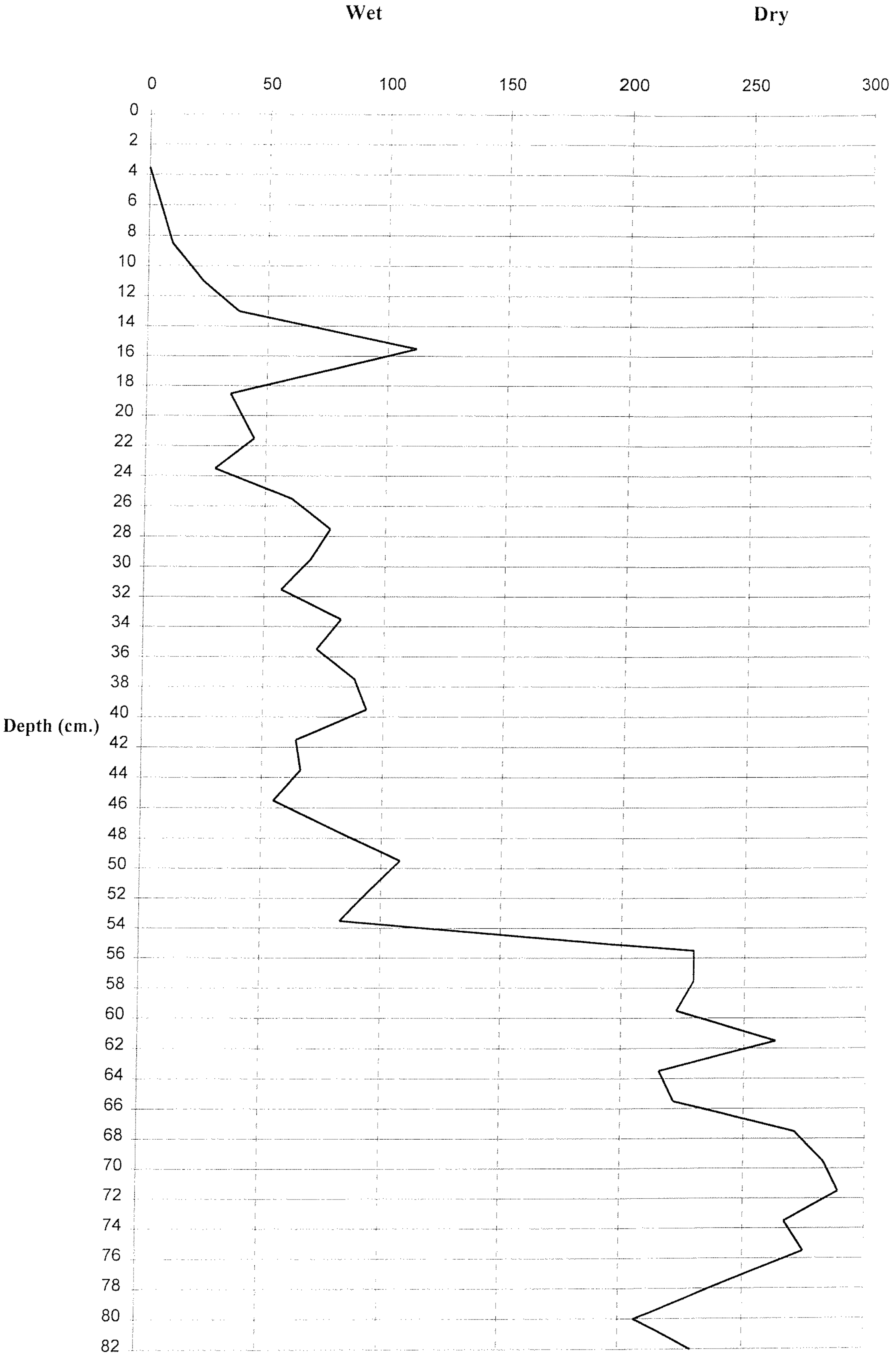


Figure 5.85 Shaft Hill - Monolith 2 - Detrending by segments.

Figure 5.86 Shaft Hill - Monolith 2 - DCA axis 1 scores.



sensitive to rare species within species poor data sets (n=11 in this example, ter Braak, 1995), this exclusion was necessary in order to construct an ecologically meaningful ordination diagram.

5.5.4.11 DCA of Shaft Hill - Monolith 3.

The ordination biplot for this monolith resembles those produced from the raised mires. Axis 1 represents 82.7% of the dispersion of the data points, and in addition to this high eigenvalue, the axis is 4.48 sd. units long (Figure 5.87). Clearly, the mire taxa are widely separated along this latent environmental gradient and are mutually exclusive of each other. The position of the mire components along axis 1 strongly suggests the presence of a hummock/hollow gradient, as once again, the hygrophilous taxa (*Sphagnum* section *Cuspidata* and *Eriophorum angustifolium*), are positioned at the extreme end of axis 1 in relation to the hummock top components (U.O.M., Ericaceae, *Eriophorum vaginatum* and *Sphagnum imbricatum*). The robust hummock ecad of *Sphagnum imbricatum, sensu* Green (1968), is most probably present in the peat matrix, as relatively abundant tests of *Hyalosphenia subflava* and to a lesser degree, *Trigonopyxis arcula*, occur in zone *SHL3-TA-b.* (Figure 5.47), spanning the levels where this bryophyte occurs. These rhizopods are characteristic of dry hummock sites (Grospietsch, 1958; Heal, 1961; Warner, 1990), and complement the vegetative macrofossil data.

5.5.4.12 Summary of the DCA results.

The DCA ordinations display a clear separation of the wet/dry macrofossil components, and offer strong evidence for a water level gradient along DCA axis 1. This axis represents between 42.9% and 82.7% of the dispersion of the data points, and ranges in length from 3.3 to 4.48 standard deviation (sd) units. Clearly in this instance, the Gaussian model upon which DCA is based is robust (Figure 5.63), and appears to adequately portray the response of the mire flora to mire water levels. In the light of these very encouraging results, the objectively reconstructed curves of mire surface wetness offer a further climate proxy to complement the humification and Dupont indices.

Figure 5.87 Shaft Hill - Monolith 3 - Detrending by segments.

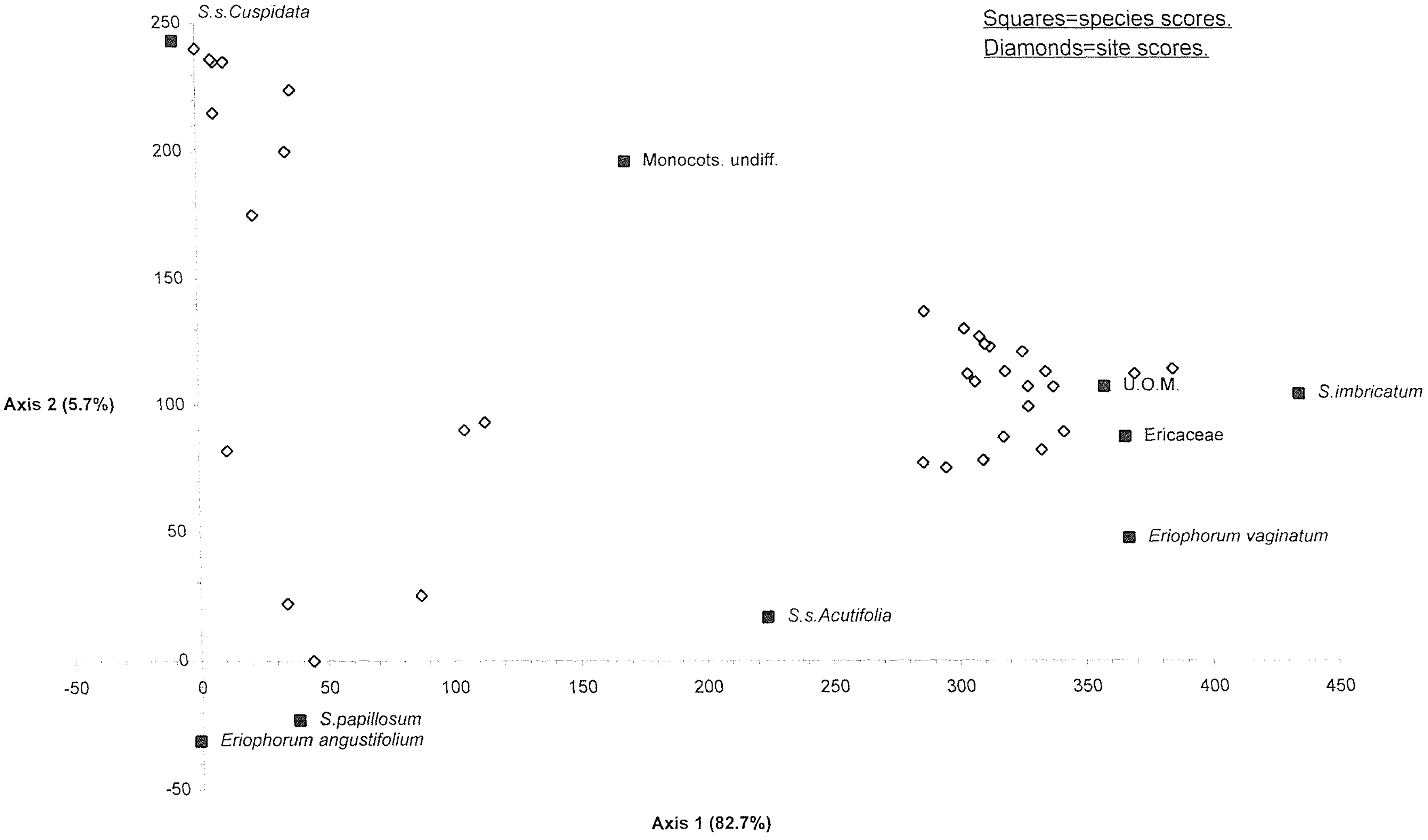
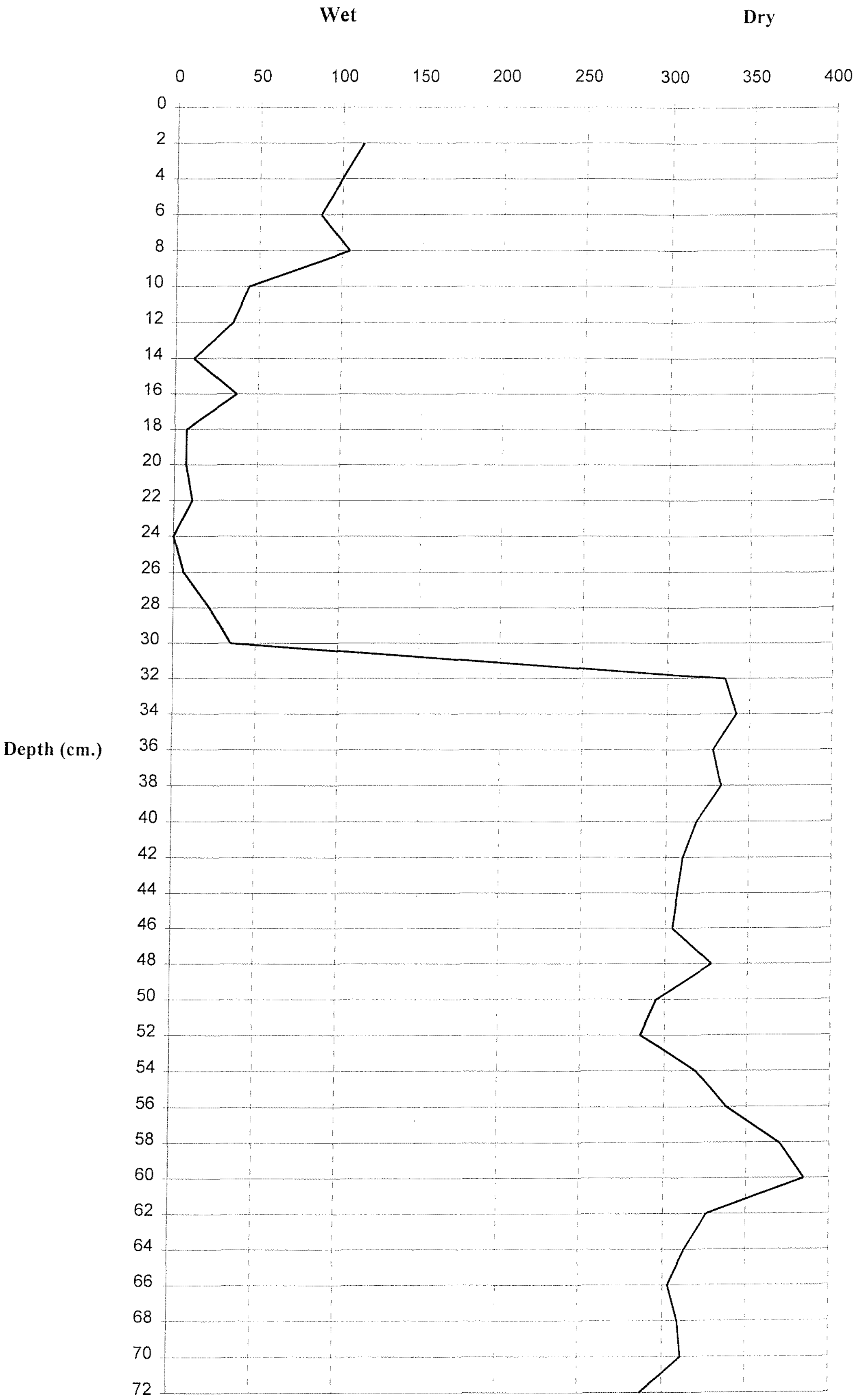


Figure 5.88 Shaft Hill - Monolith 3 - DCA axis 1 scores.



5.5.5 DCA of the testate amoebae assemblages.

In comparison to the plant macrofossil DCA ordinations, those performed on the thecamoebae datasets were not as successful. The position of species on the inferred environmental gradient axes do not appear to reflect the prime importance of mire water levels on the microdistributions of these protozoa (Warner and Charman, 1994).

The testate amoebae plot out at anomalous positions on axis 1 of the DCA biplot for Bolton Fell Moss - Core L (Figure 5.89). Hygrophilous *Amphitrema wrightianum* (species 3) and *Difflugia bacillifera* (species 21) plot out at opposite ends of axis 1, whilst on both axes 1 and 2, hygrophilous *Amphitrema flavum* (species 11), is positioned next to *Cyclopyxis arcelloides* type (species 12). This latter species is indicative of drier mire surfaces (Table 5.4). The seemingly anomalous positions of *Amphitrema flavum* and *Cyclopyxis arcelloides* type on Figure 5.89 may be due to the small size of the former species (50-75 μm, Grospietsch, 1958; 45-77 μm, Corbet, 1973; 45-70 μm, Woodland, 1996). By virtue of its diminutive size, it can continue to live in shrinking water films surrounding *Sphagnum* leaves (Woodland, 1996), and may not in this instance represent a good indicator of mire surface wetness.

A similar problem was encountered with the testate amoebae ordination for Shaft Hill - Monolith 2 (Figure 5.90), as hygrophilous *Amphitrema wrightianum* and *Nebela carinata* are positioned alongside xerophilous *Hyalosphenia subflava* tests. There is the possibility this axis represents a species replacement axis rather than a water level gradient, as *Hyalosphenia subflava* dominated communities are replaced by an assemblage dominated by *Arcella rotundata* var. *aplanata* and *Nebela militaris* via a thanatocoenose containing abundant *Amphitrema wrightianum*. Weighted averaging regression within DCA works best where species may be absent in many of the samples (ter Braak and Juggins, 1993). Within the Shaft Hill - Monolith 2 data-set (Figure 5.44), the abundances of *Amphitrema wrightianum* and *Hyalosphenia subflava* do overlap to a small degree, which may explain their proximal location to each other on axis 1.

DCA axis 1 of Walton Moss - Core 11 (Figure 5.91), by comparison, appears to clearly represent a water level gradient, since hygrophilous taxa such as *Difflugia bacillifera, Amphitrema wrightianum* and *Amphitrema flavum* are positioned at the opposite end of axis 1 in relation to the xeric rhizopods, *Hyalosphenia subflava* and *Trigonopyxis arcula*. The length of DCA axis 1 for Walton Moss stands at 4.18 sd. units, and therefore conforms to the Gaussian species response model inherent in Correspondence Analysis.

Despite this encouraging result, the inconsistent nature of the testate amoebae DCA ordinations prevents the construction of an ecologically sound mire water level reconstruction for all the study sites. In this instance, DCA does not appear to be a suitable technique to reliably ordinate the thecamoebae assemblages, and further analysis of the remaining sites was not undertaken.

Figure 5.89 Bolton Fell Moss - Core L - DCA - Testate Amoebae - Detrending by segments.

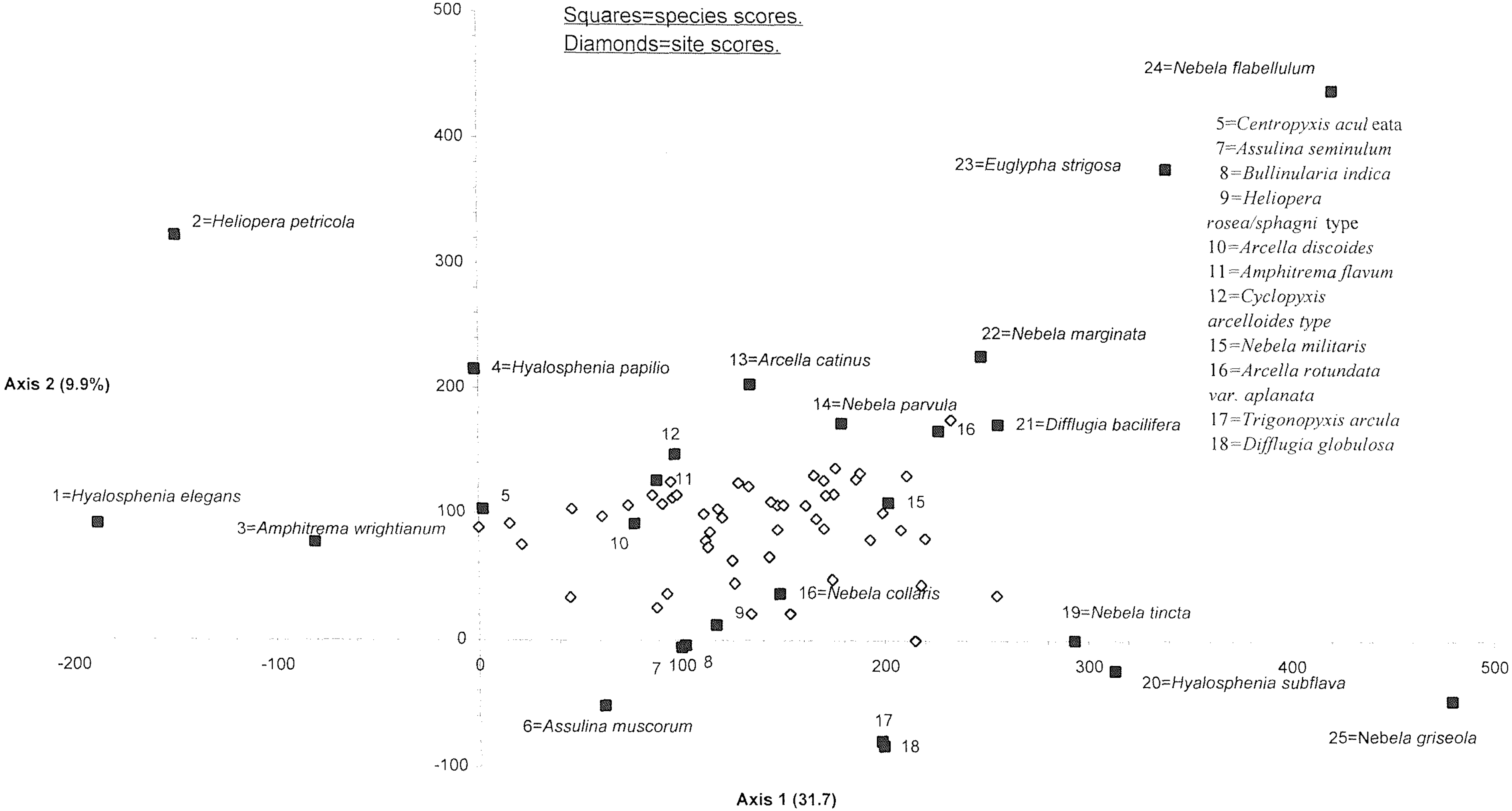


Figure 5.90 Shaft Hill - Monolith 2 - Testate Amoebae - Detrending by segments.

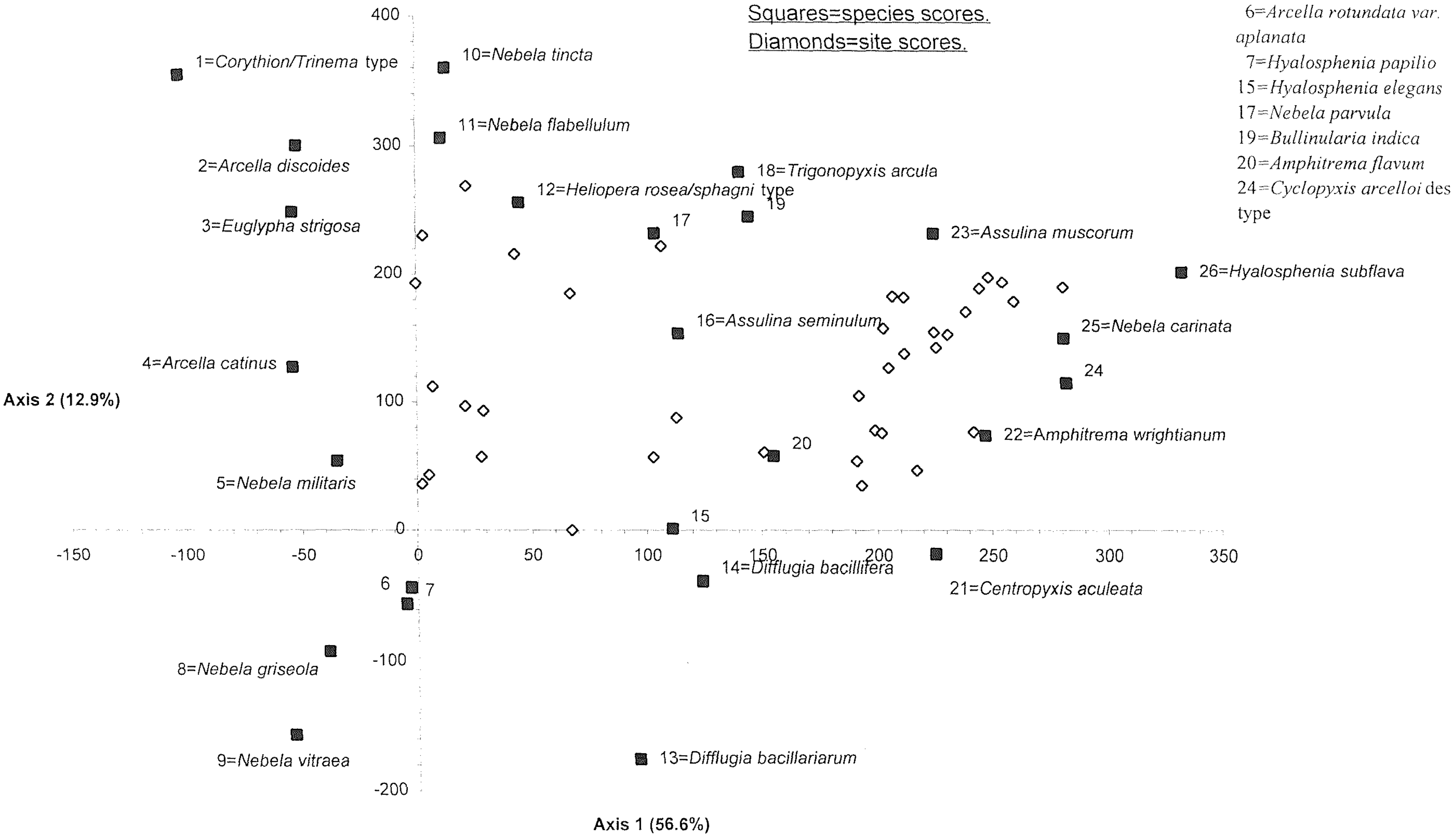
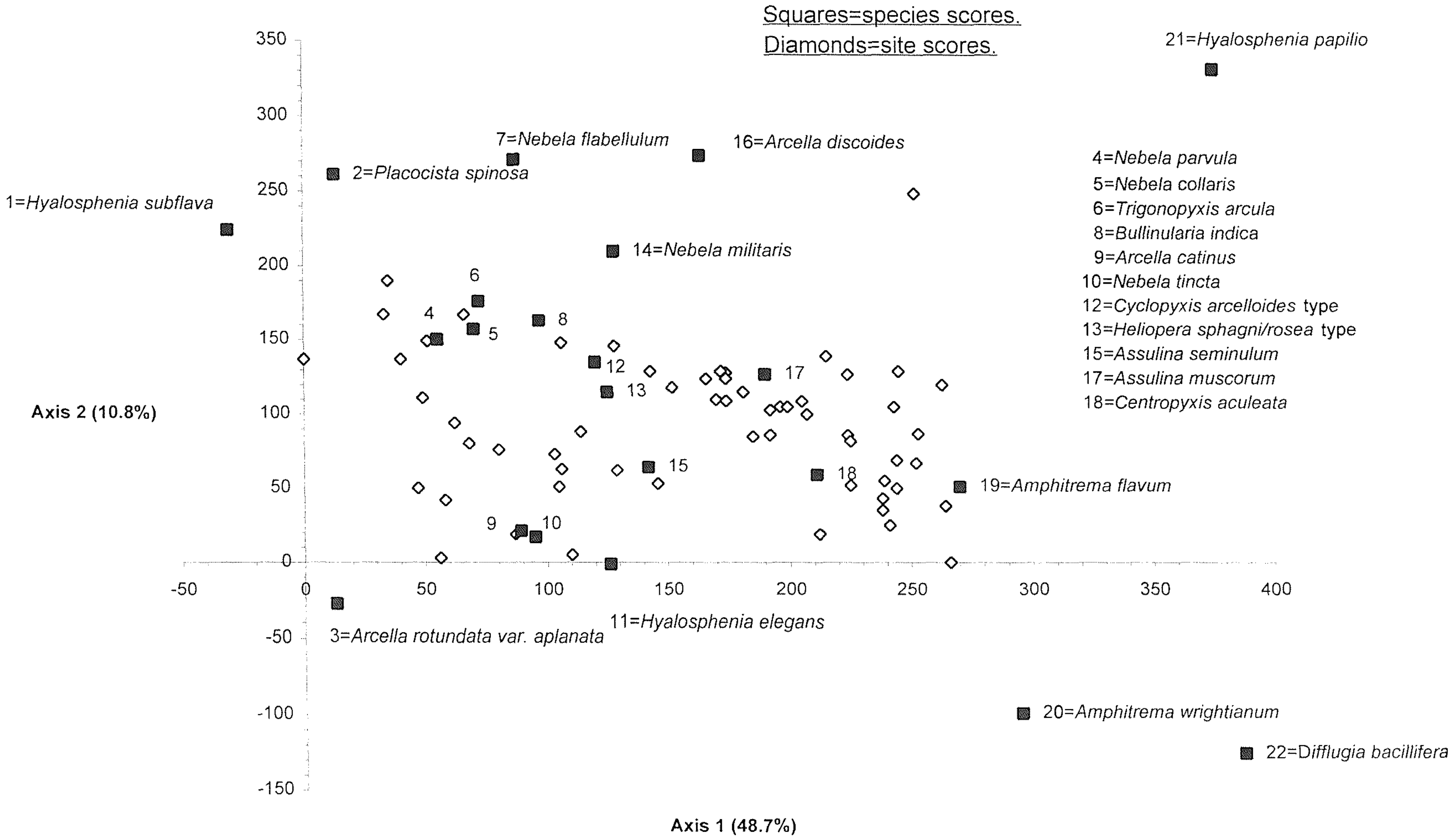


Figure 5.91 Walton Moss - Core 11 - DCA - Testate Amoebae - Detrending by segments.



5.6 CCA of the testate amoebae assemblages.

5.6.1 Introduction.

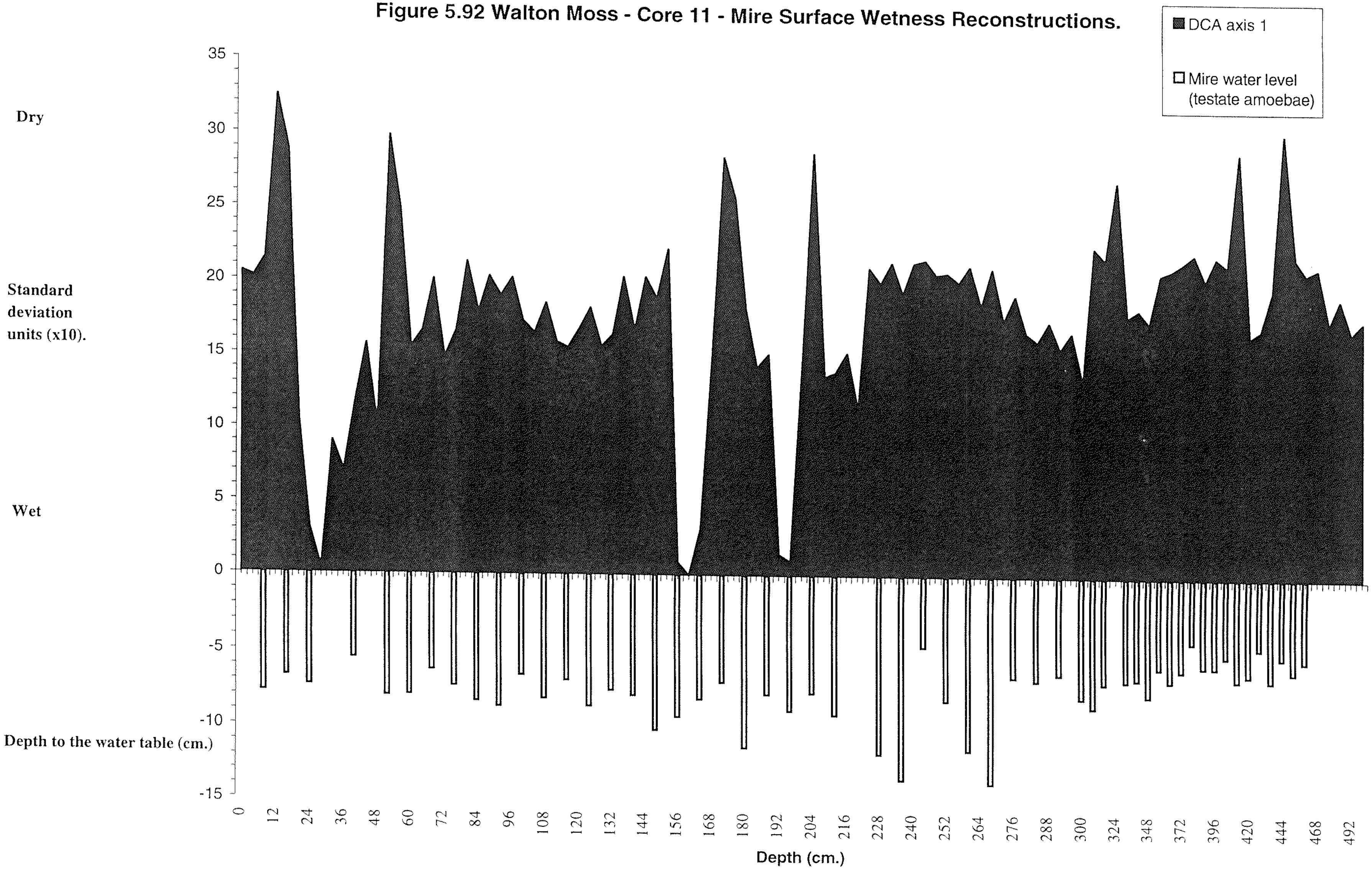
The relationship between testate amoebae and plant macrofossils has been investigated further, by performing a quantitative reconstruction of mire surface wetness using transfer functions developed by Woodland (1996), and Charman (pers. com.). The term "transfer function" represents a quantifiable relationship between a selected environmental parameter and a species distribution (Birks, 1995; Woodland, 1996). The hydrological optima of British testate amoebae species sampled from nine bogs has been determined by Woodland (1996), using Canonical Correspondence Analysis (CCA). This direct ordination technique (a full description of CCA is available in Kent and Coker, 1992), incorporates correlation and regression between species data and environmental factors. The relationship between testate amoebae species and selected environmental data (mean water table depth summer 1993, autumn 1993, winter 1993-94, spring 1994, summer 1994, mean annual water table depth, % moisture content, dissolved organic carbon, SO_4^{2-}, Cl^-, Ca^{2+}, conductivity, Mg^{2+}, pH, and temperature) was explored by Woodland (1996), using this ordination technique. Water availability (water table depth and % moisture) was confirmed as the most important environmental variable affecting the distribution and abundance of testate amoebae populations, in line with the work of Warner (1989), Charman and Warner (1992), Tolonen *et al.* (1992, 1994); and Warner and Charman (1994). Weighted averaging was then employed to derive the optimum species water table depth using the regression equation of Oksanen *et al.* (1988).

Equation 5.4. (from Woodland, 1996) $w_i = \sum y_{ij} x_j / \sum y_{ij}$:

Where w_i is the weighted average of % moisture or depth to water table for species i, which occurs at y% abundance at site j, which has the moisture content or depth to water table x_j (this is identical to the weighted averaging incorporated in equations 5.2 and 5.3 for DCA ordination). Using the weighted average water table depth/% moisture content for each species, an estimate of local water table depth or moisture content for each site can be made by averaging the optima of the species present (Juggins, 1992). Woodland (1996) compared the predicted to the observed hydrological variables measured from her research sites, and found that the weighted averaging model could be used to predict water table depth with a prediction error (root mean square of the error) of 5.62 cm., whilst the error term for moisture content was 7.79. These two error terms are a measurement of random differences in model predictions.

In view of these encouraging results, Dr. Dan Charman (Plymouth University), ran a water table reconstruction on the fossil testate amoebae stratigraphy from WLM11, using the testate amoebae transfer functions derived from the modern British fauna by Woodland (1996). The results of this trial water level reconstruction for WLM11, along with the DCA axis 1 scores determined from the plant macrofossils, are presented in Figure 5.92.

Figure 5.92 Walton Moss - Core 11 - Mire Surface Wetness Reconstructions.



5.6.2 Palaeohydrology - plant macrofossils versus testate amoebae.

A comparison of the two mire surface wetness reconstruction techniques is difficult, since each one is expressed in different units (standard deviation units for the plant macrofossil data and depth to the water table in cm. for the testate amoebae). What is apparent, however, from Figure 5.92, is a more marked and rapid response of the plant macrofossil DCA derived palaeohydrological curve to possible environmental change. A similar observation has been made by Woodland (1996), when she compared the moisture curves generated from testate amoebae taken from Bolton Fell Moss - monolith J2 and plant macrofossils identified from an adjacent monolith (J1) from Bolton Fell Moss (Barber *et al.,* 1994e). She suggests the more rapid and frequent variations in the plant macrofossil curve in comparison to the testate amoebae water level curve may be explicable in terms of the species-poor nature of the former. For example, a gradual change in local water tables may be registered by the plant macrofossils as a sudden change, when local water levels rise to a sufficient level to force a change in species composition.

There is however, in line with the results of Woodland (1996), some agreement in the trends of mire surface wetness changes identified using each technique in Figure 5.92. For example, the DCA axis 1 curve indicates high mire surface wetness at 428 cm., 292 cm., and 52 cm. The testate amoebae hydrological reconstructions also point to increases in the height of local water tables at these depths, although these are not marked. This is possibly, again, a reflection of the different units employed by each of the water-level reconstruction techniques.

At two levels, the testate amoebae appear to have responded earlier to possible increases in effective precipitation. The rhizopods point to a rise, albeit of low magnitude, in the acrotelm/catotelm boundary at 204 cm. (320 BC.), whilst the plant macrofossils indicate this change later, at 196 cm. (230 BC.). Similarly, the testate amoebae stratigraphy at 172 cm. (80 AD.) highlights a potential increase in local water tables, which is recorded by the plant macrofossils at 160 cm. (240 AD.). Woodland (1996), has also noted an earlier response of testate amoebae to possible increases in effective precipitation, although there was only a 4 cm. difference between the testate amoebae and plant macrofossil records, rather than the maximum 12 cm. difference noted here. This, however, is quite possibly a reflection of the coarse 8 cm. sampling resolution of the testate amoebae analysis, since the technique was only adopted to support the plant macrofossil and humification analyses. Notwithstanding this, rhizopods may be more sensitive in recording changes in mire hydrology (Woodland, 1996), due to their established ability to rapidly double their population sizes (Section 2.3.4).

There are certainly sections on Figure 5.92, where there is a poor correspondence between the testate amoebae and plant macrofossil curves. Although a dry phase can be discerned using both techniques at 180 cm., the two lowest reconstructed water-tables derived from the testate amoebae stratigraphy of WLM11 are at 236 and 268 cm. (reconstructed water table depths = -13.6 and -13.9 cm. respectively). The DCA axis 1 scores for these levels are not as extreme as other levels derived from the plant macrofossil components, suggesting a mismatch between the two surface wetness reconstruction techniques at these points. Mire surface wetness must have been high between 196-192 cm. and 164-156 cm., as the peat matrices contain abundant *Sphagnum* section

Cuspidata leaves and some *Rhynchospora alba* (Figure 5.19), and are also weakly humified (Figure 5.17). Although there may be an earlier response of the testate amoebae to this undoubted increase in local water tables, the magnitude of the change is small. The maximum modelled increase in water table depth was 4.4 cm. between 180 and 172 cm., yet the plant macrofossils point to the presence of mire pools. This may highlight a possible problem with the testate amoebae transfer functions (these are still being refined by Dr. Dan Charman (pers com.). Alternatively, some of the problems may lie with the DCA water level reconstructions, since the peat matrices at 236 and 268 cm. are largely composed of *Sphagnum imbricatum* leaves (71 and 96% respectively). This *Sphagnum* species can resist mire hydroclimatic changes through phenotypic plasticity (Section 5.2.15), which may explain the absence of a clear dry phase in the plant macrofossil stratigraphy at these depths.

Further CCA reconstructions using testate amoebae was not attempted, since improvement of the testate amoebae transfer functions is ongoing. Because of this, the mire water table reconstruction presented in Figure 5.92 may be obsolete in as little as six months time (Dr. Dan Charman, pers. com.).

This work, however, has served to illustrate where the two techniques agree and diverge, and highlights the need for alternative proxy evidence (humification analysis), to help resolve conflicts between the testate amoebae and plant macrofossil data. For example, peat humification is relatively high at 236 cm. (690 BC.), which suggests the water-table reconstruction derived from the testate amoebae is correct at this level.

5.7 Similarities/differences between the humification, plant macrofossil (Dupont and DCA Axis 1) and testate amoebae (Dupont) proxy-climate curves.

5.7.1 Introduction.

In the following sections, tables and diagrams are presented displaying the depths and dates of inferred wet and dry shifts. The criteria for selecting these shifts are simply related to the position of the peaks (dry mire surfaces with low water tables) and troughs (wet mire surfaces) for each proxy-climate curve diagram. Stoneman (1993) used a strict set of criteria to select shifts in his proxy climate curves, by imposing a minimum change of 2 weighted average units for the Dupont indices and 1 sd. unit for the DCA Axis 1 scores. These values were not applied here, because in the first instance, they are arbitrarily defined and may not relate to real changes in mire surface wetness, and secondly, because many of the proxy-climate indices fell just short of these cut-off points. Clearly the magnitude of change is important, but equally, the direction of change is also an important factor.

A comparison of the inferred wet and dry shifts between the sites will be presented and discussed in Chapter 6.

5.7.2 Bolton Fell Moss - Core L.

Inferred wet shifts reconstructed using the four proxies are presented in Table 5.11. There are depths/periods of time when all 4 hydro-climatological proxies display the same shifts (direction of change) in mire surface wetness, for example wet shifts appear to have occurred between 680-810 AD., and between 30-270 AD. (Figure 5.93).

In comparison to the plant macrofossil derived indices, more wet shifts are registered by the humification and Dupont-TA techniques, which may suggest these climate proxies are more sensitive indicators of changes in mire water levels and therefore effective precipitation. The dominance of *Sphagnum imbricatum* in the borehole stratigraphy, and the virtual absence of hygrophilous mire vegetation between zones *BFML-b* through to *BFML-e* (Figure 5.15), may explain this insensitivity, given the ability of *Sphagnum imbricatum* to grow over a range of water table depths (Section 5.2.15).

There are detailed differences in the timing of hydrological changes between the different proxies, but no readily apparent pattern. For example, the testate amoebae register a slightly earlier wet shift at 160 BC. (232 cm.) than the humification data (60 BC., 224 cm.), yet they appear to lag behind the plant macrofossil and humification stratigraphy at other levels. For example, the colorimetric absorption and DCA indices record a possible climatic deterioration between 1010-1070 AD. This is also recorded by the testate amoebae, but at a later date (1180 AD.).

It is possible, again, to highlight mire hydroclimatic changes which are registered by all four techniques, as dry shifts seem to have occurred between 2930-2740 BC., and 760-860 AD. Inspection of Figure 5.94 again reveals no readily apparent pattern to suggest any of the techniques is consistently more or less sensitive in recording changes in mire water levels.

5.7.3 Walton Moss - Core 11.

In a similar manner to the Bolton Fell Moss data, the vegetative macrofossil derived wet shifts identified using the Dupont index and DCA fail in some cases to show changes in inferred mire surface wetness. A possible reason for the ‘complacency’ of the plant macrofossil record at these levels, may again be due to the abundance of *Sphagnum imbricatum* within the peat matrices, given the water level induced phenotypic plasticity of this species (Section 5.2.15). This bryophyte is the dominant floral component (Figure 5.19) between 260-268 cm. (mean abundance 69%), and at 380 cm. (mean 93%), and may account for the absence of a climate signature within these levels.

Despite this, the four techniques register similar changes in mire water tables, for example both the Little Ice Age and a wet period between 1130-1210 AD. (76-68 cm.) are readily identified using all four climate proxies (Figure 5.95). It is also possible to identify potential dry shifts using all four techniques (Table 5.14 and Figure 5.96), for example there is evidence for low local water tables between 420-280 BC. (212-200 cm.), and 2390-2320 BC. (420-412 cm.).

Table 5.11 Bolton Fell Moss - Core L - Inferred wet shifts (depth cm./interpolated pollen/^{14}C dates dates [rounded to the nearest decade]).

Humification.	Dupont index.	DCA Axis 1.	Dupont index - Testate Amoebae
1850 AD. 24 cm.	1820 AD. 28 cm.	1750-1800 AD. 36-32 cm.	1800 AD. 32 cm.
*	*	*	1390 AD. 64 cm.
1070 AD. 88 cm.	*	1010 AD. 92 cm.	1180 AD. 80 cm.
*	840 AD. 108 cm.	*	840 AD. 108 cm.
680 AD. 132 cm.	680 AD. 132 cm.	810-760 AD. 112-120 cm.	680 AD. 132 cm.
*	*	380 AD. 176 cm.	*
220-270 AD. 200-192 cm.	30-170 AD. 204-216 cm.	30 AD. 216 cm.	80 AD. 212 cm.
60 BC. 224 cm.	*	*	160 BC. 232 cm.
490-440 BC. 260-256 cm.	*	*	530 BC. 264 cm.
1290-1010 BC. 328-304 cm.	1200 BC. 320 cm.	1290 BC. 328 cm.	1290 BC. 328 cm.
*	1560 BC. 352 cm.	*	1560 BC. 352 cm.
1820-1740 BC. 376-368 cm.	*	*	1740 BC. 368 cm.
*	2650 BC. 448 cm.	2650 BC. 448 cm.	2650 BC. 448 cm.
3110 BC. 488 cm.	3020 BC. 480 cm.	3020 BC. 480 cm.	*Testate amoebae not sampled.*

Table 5.12 Bolton Fell Moss - Core L - Inferred dry shifts (depth cm./interpolated pollen/^{14}C dates dates [rounded to the nearest decade]).

Humification.	Dupont index.	DCA Axis 1.	Dupont index - Testate Amoebae
1900 AD. 16 cm.	1870 AD. 20 cm.	1950 AD. 8 cm.	1900 AD. 16 cm.
760 AD. 120 cm.	760-810 AD. 120-112 cm.	860 AD. 104 cm.	780 AD. 116 cm.
620 AD. 140 cm.	*	680 AD. 132 cm.	620 AD. 140 cm.
410 AD. 172 cm.	*	*	*
170 AD. 204 cm.	*	80 AD. 212 cm.	170 AD. 204 cm.
350 BC. 248 cm.	*	200 BC. 236 cm.	250 BC. 240 cm.
580 BC. 268 cm.	*	770 BC. 284 cm.	720 BC. 280 cm.
*	*	1470 BC. 344 cm.	*
*	1740 BC. 368 cm.	*	*
1910 BC. 384 cm.	*	2000 BC. 392 cm.	1910 BC. 384 cm.
*	2370 BC. 424 cm.	2180 BC. 408 cm.	2280 BC. 416 cm.
2830 BC. 464 cm.	2930 BC. 472 cm.	2740 BC. 456 cm.	2830 BC. 464 cm.

* Change not recorded.

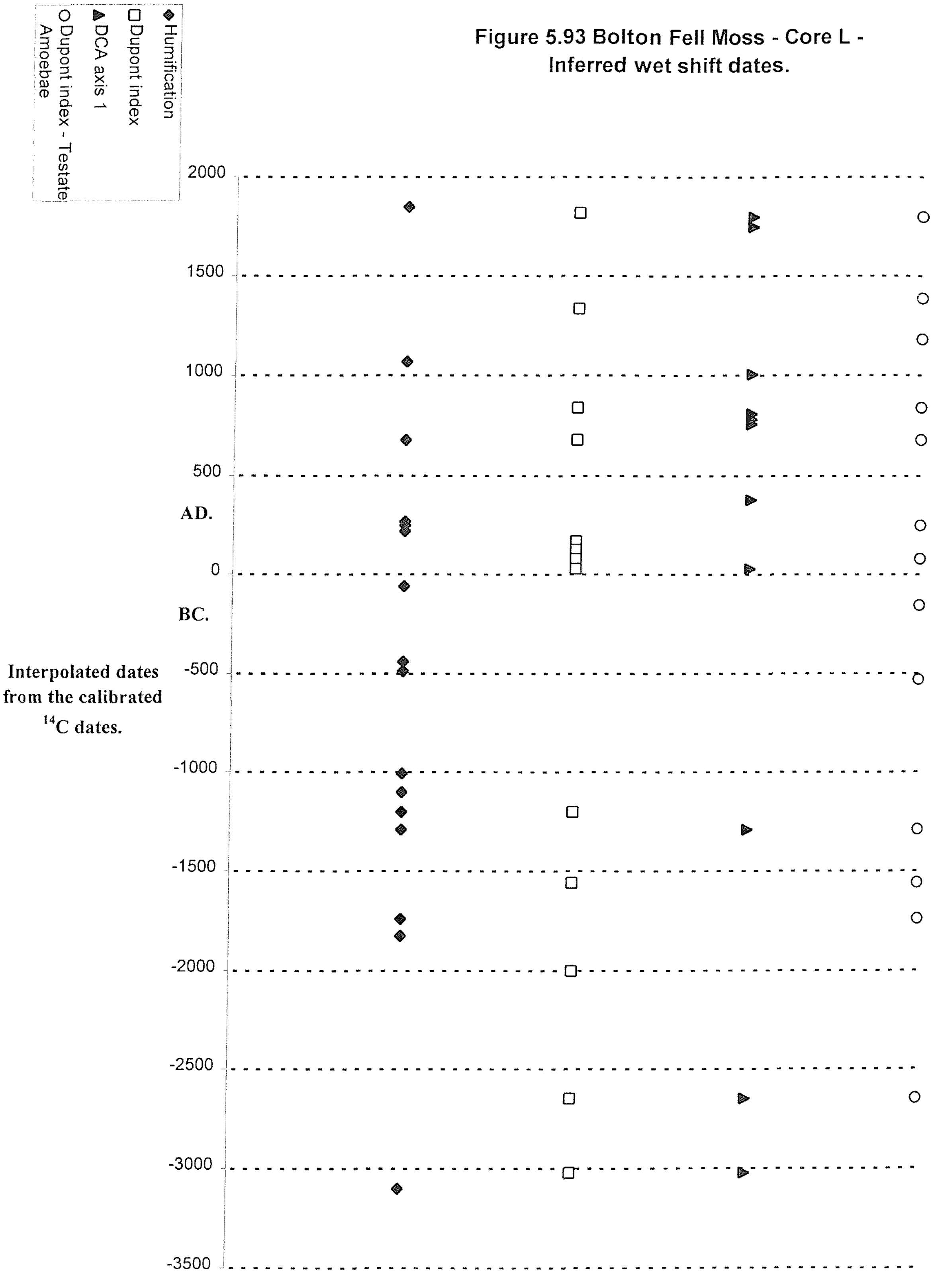


Figure 5.93 Bolton Fell Moss - Core L - Inferred wet shift dates.

Figure 5.94 Bolton Fell Moss - Core L - Inferred dry shift dates.

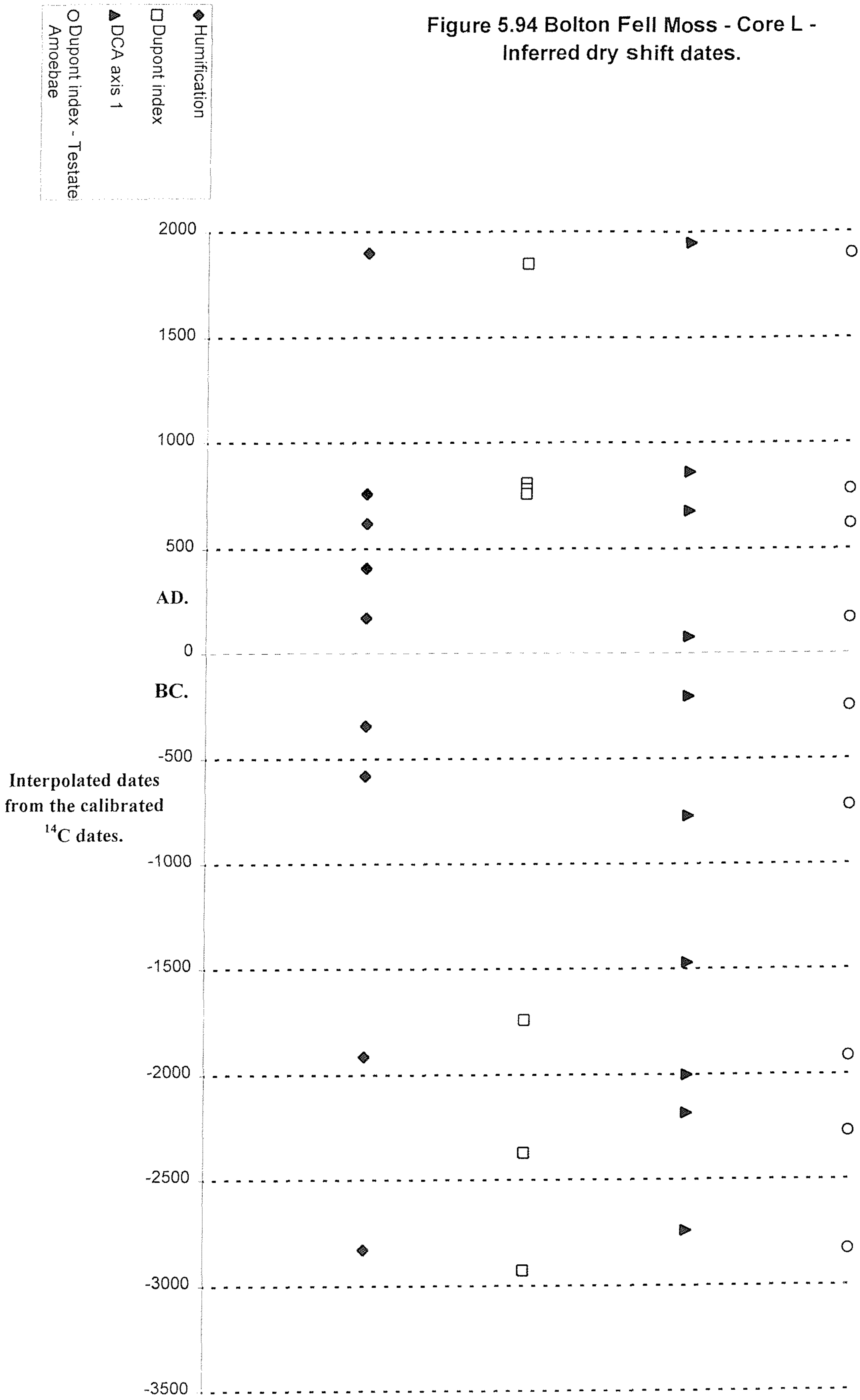


Table 5.13 Walton Moss - Core 11 - Inferred wet shifts (depth cm./interpolated pollen/^{14}C dates dates [rounded to the nearest decade]).

Humification.	Dupont index.	DCA Axis 1.	Dupont index - Testate Amoebae
1800 AD. 24 cm.	1710-1800 AD. 28-24 cm.	1710 AD. 28 cm.	1800 AD. 24 cm.
1130 AD. 76 cm.	1210 AD. 68 cm.	1170 AD. 72 cm.	1210 AD. 68 cm.
660 AD. 120 cm.	660 AD. 120 cm.	*	710 AD. 116 cm.
*	490 AD. 136 cm.	*	540 AD. 132 cm.
280 AD. 156 cm.	280 AD. 156 cm.	240 AD. 160 cm.	190 AD. 164cm.
180 BC. 192 cm.	230-180 BC. 196-192 cm.	230-180 BC. 196-192 cm.	230 BC. 196 cm.
550 BC. 224 cm.	*	510 BC. 220 cm.	600 BC. 228 cm.
*	790 BC. 244 cm.	*	790 BC. 244 cm.
1070 BC. 268 cm.	970-920 BC. 260-256 cm.	*	1130 BC. 276 cm.
1690 BC. 340 cm.	1480 BC. 316 cm.	1340 BC. 300 cm.	1620 BC. 332 cm.
2040 BC. 380 cm.	2040 BC. 380 cm.	*	2040 BC. 380 cm.
*	2250 BC. 404 cm.	*	2250 BC. 404 cm.
2600 BC. 444 cm.	2670 BC. 452 cm.	2460-2390 BC. 428-420 cm.	2460 BC. 428 cm.
*	*	2880 BC. 476 cm.	2810 BC. 468 cm.
*	2950 BC. 484 cm.	*	2950 BC. 484 cm.

Table 5.14 Walton Moss - Core 11 - Inferred dry shifts (depth cm./interpolated pollen/^{14}C dates dates [rounded to the nearest decade]).

Humification.	Dupont index.	DCA Axis 1.	Dupont index - Testate Amoebae
*	1870 AD. 16 cm.	1900 AD. 12 cm.	1870 AD. 16 cm.
1500 AD. 40 cm.	1630 AD. 32 cm.	*	*
*	1420 AD. 48 cm.	1380 AD. 52 cm.	*
1040 AD. 84 cm.	1090 AD. 80 cm.	*	1040 AD. 84 cm.
920 AD. 96 cm.	920 AD. 96 cm.	*	*
450 AD. 140 cm.	450 AD. 140 cm.	*	450 AD. 140 cm.
30 AD. 176 cm.	80 AD. 172 cm.	80 AD. 172 cm.	*
420 BC. 212 cm.	280 BC. 200 cm.	320 BC. 204 cm.	320 BC. 204 cm.
880 BC. 252 cm.	880 BC. 252 cm.	*	880 BC. 252 cm.
1170 BC. 280 cm.	*	*	*
1270 BC. 292 cm.	1340 BC. 300 cm.	1550 BC. 324 cm.	1410 BC. 308 cm.
*	*	*	1900 BC. 364 cm.
*	*	*	2110 BC. 388 cm.
2390 BC. 420 cm.	2320 BC. 412 cm.	2320 BC. 412 cm.	2320 BC. 412 cm.
*	*	2600 BC. 444 cm.	2600 BC. 444 cm.

* Change not recorded.

Figure 5.95 Walton Moss - Core 11 - Inferred wet shift dates.

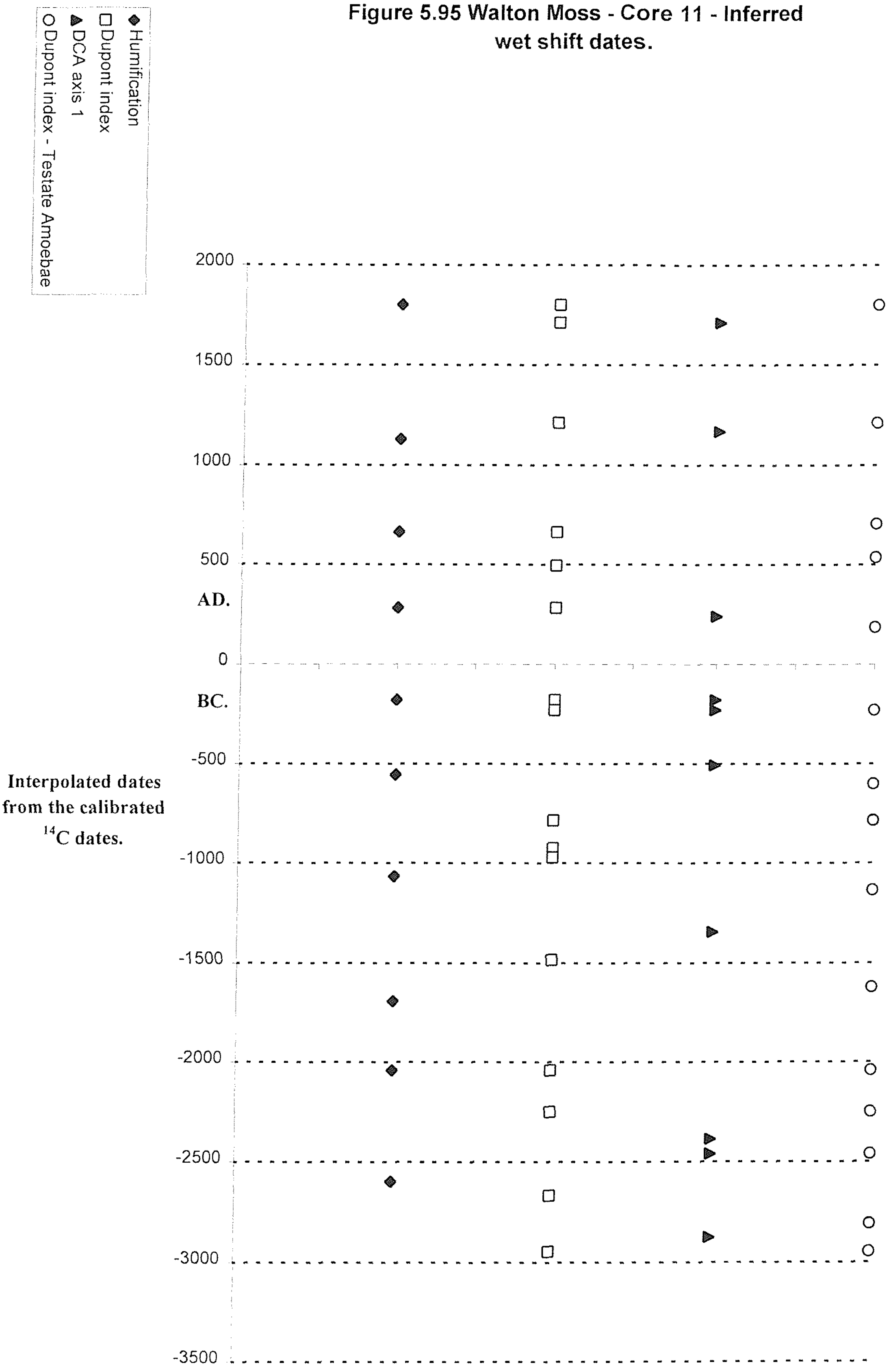
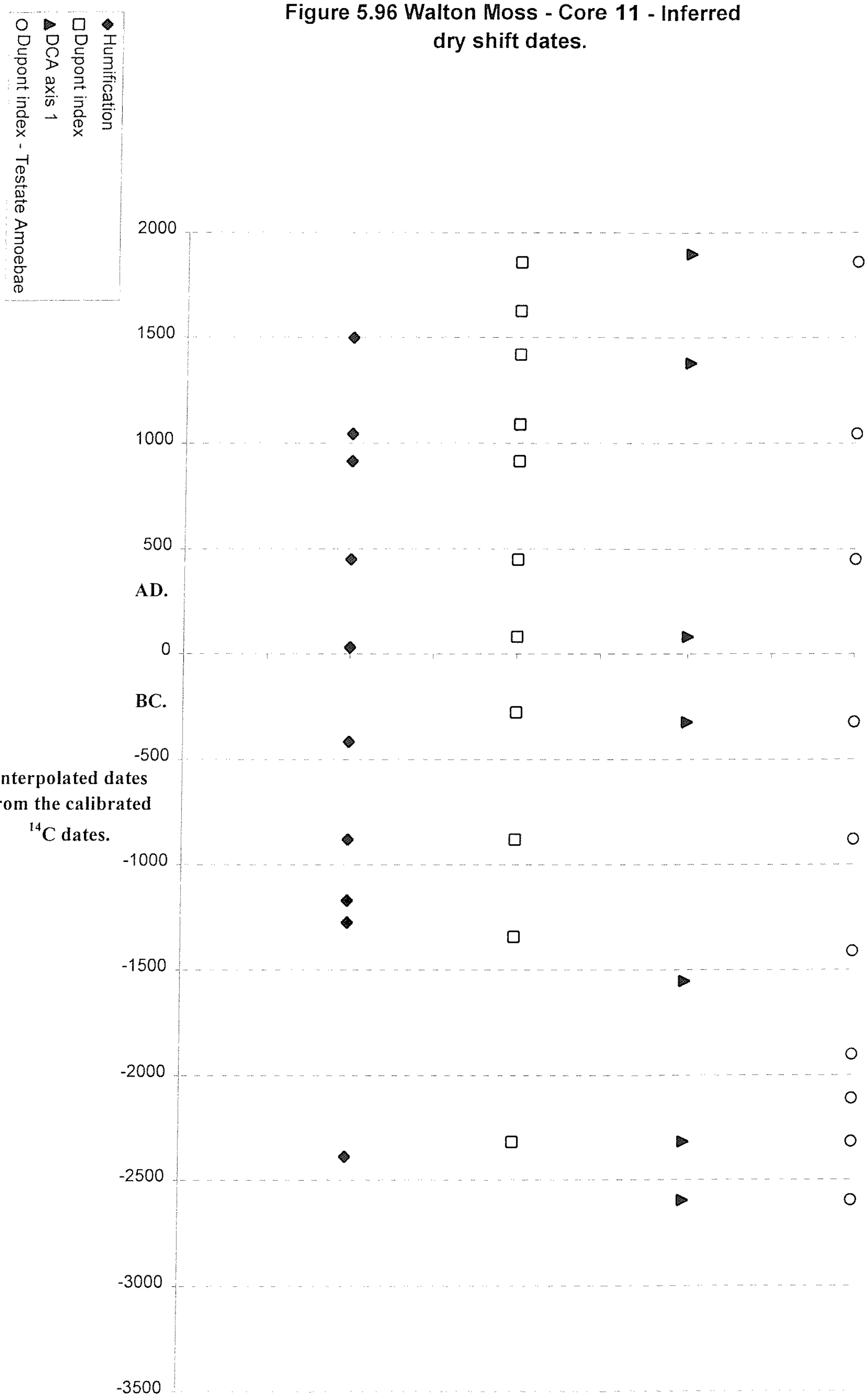


Figure 5.96 Walton Moss - Core 11 - Inferred dry shift dates.



5.7.4 Raeburn Flow.

The pattern of dry shifts identified using testate amoebae from this site is interesting, as compared to Bolton Fell Moss and Walton Moss, they seem insensitive to changes in mire water tables. This is evident from the thecamoebae stratigraphy (Figure 5.25), as xeric species, particularly *Hyalosphenia subflava*, and *Trigonopyxis arcula*, are present in small amounts. Because of this, the range of values for the weighted averaging algorithm is limited, and the changes in the index are necessarily small (Figure 5.98). Changes in the humification stratigraphy (Figure 5.23), plant macrofossil Dupont index (Figure 5.53), and DCA axis 1 scores (Figure 5.73) are marked, offering alternative evidence for mire hydro-climatological changes. Periods of low local water tables appear to have occurred at 1690, 950-1000, and 230-370 AD. and 2070-1880 and 3030 BC.

Wet shifts are readily identified using all four techniques, for example between 1290-1340, and 620-670 AD., and 440-270, 1110, and 1690-1590 BC.

5.7.5 Bell's Flow.

The DCA axis 1 scores do not change markedly downcore from this site (Figure 5.75), with the exception of the possible climatic deterioration which occurred at 20 cm. depth. The climatically insensitive nature of the DCA axis 1 scores has clearly resulted from the species poor flora recovered from this site, since very little *Rhynchospora alba* and no *Eriophorum angustifolium* epidermis was identified (these sedges are useful indicators of increased surface wetness). Additionally, the dominance of *Sphagnum imbricatum* and *Sphagnum* section *Acutifolia* leaves within the peat matrices, may have masked hydrological changes, given the wide tolerances of these taxa to mire water tables in an undisturbed ecosystem.

Testate amoebae are clearly useful climate proxies and are capable of complementing the other water level reconstruction techniques. A wet shift identified using the testate amoebae stratigraphy at 910 AD (Table 5.17, Figure 5.99), is also recorded by the plant macrofossil derived Dupont index (950 AD.) and the DCA axis 1 scores (870 AD.), whilst all four techniques point to increased mire surface wetness between 400-350 BC. Thecamoebae, are however, again incapable of recording some changes which have been picked up by the humification and plant macrofossil derived indices, for example a wet shift at 560 AD. Clearly in the light of this, proposing changes in palaeoclimates based on a single proxy alone is hazardous (Tipping, 1995), and argues for a need to look at the same direction of change in at least two indices. This may reduce the importance of ecological noise.

Table 5.15 Raeburn Flow - Inferred wet shifts (depth cm./interpolated pollen/^{14}C dates dates [rounded to the nearest decade]).

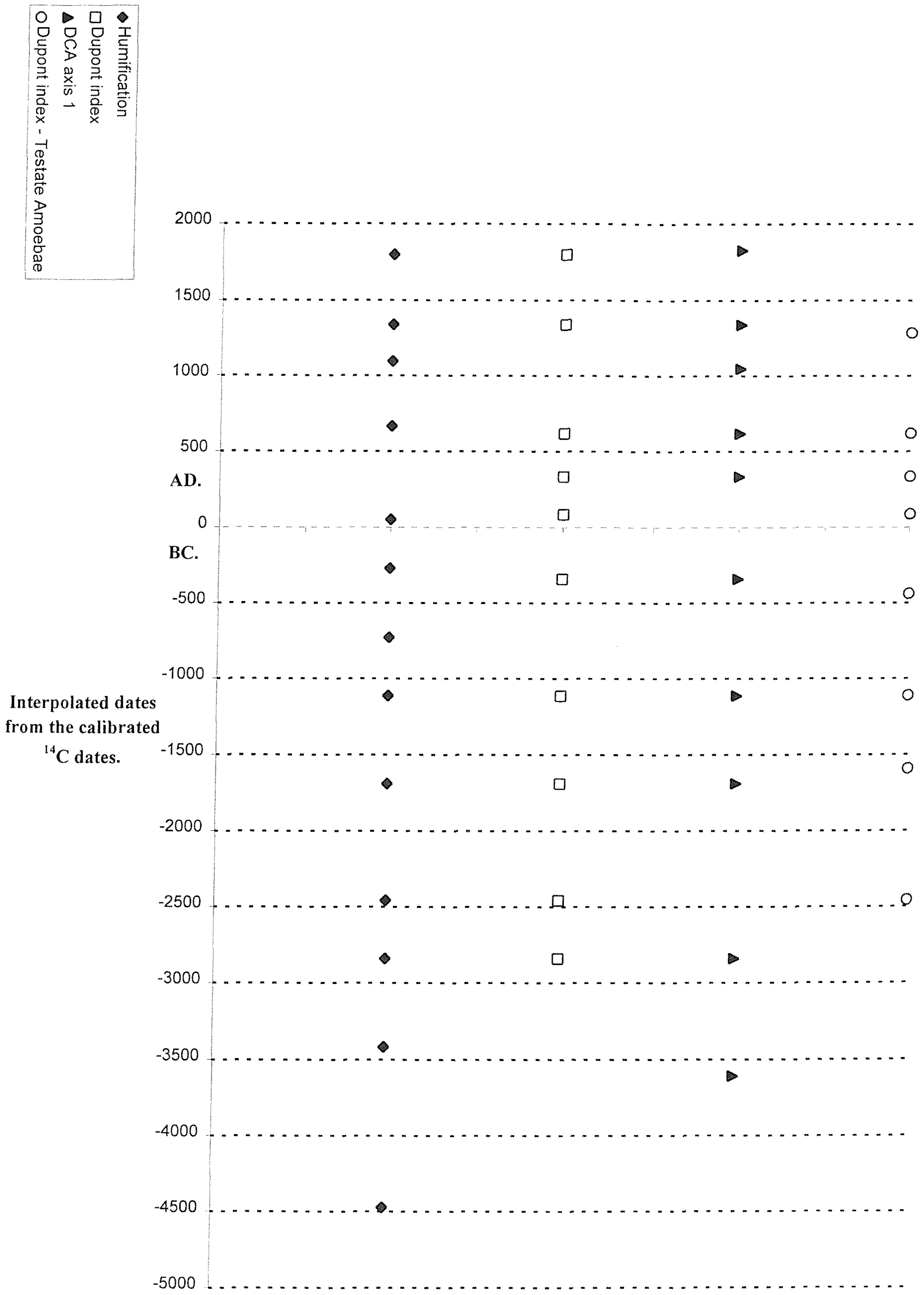
Humification.	Dupont index.	DCA Axis 1.	Dupont index - Testate Amoebae
1800 AD. 24 cm.	1800 AD. 24 cm.	1830 AD. 20 cm.	*
1340 AD. 56 cm.	1340 AD. 76 cm.	1340 AD. 76 cm.	1290 AD. 80 cm.
1100 AD. 96 cm.	*	1050 AD. 100 cm.	*
670 AD. 132 cm.	620 AD. 136 cm.	620 AD. 136 cm.	620 AD. 136 cm.
*	340 AD. 168 cm.	*	340 AD. 168 cm.
50 AD. 200 cm.	90 AD. 196 cm.	*	90 AD. 196 cm.
270 BC. 236 cm.	340 BC. 244 cm.	340 BC. 244 cm.	440 BC. 248 cm.
720 BC. 260 cm.	*	*	*
1110 BC. 276 cm.	1110 BC. 276 cm.	1110 BC. 276 cm.	1110 BC. 276 cm.
1690 BC. 300 cm.	1690 BC. 300 cm.	1690 BC. 300 cm.	1590 BC. 296 cm.
2460 BC. 332 cm.	2460 BC. 332 cm.	*	2460 BC. 332 cm.
2840 BC. 348 cm.	2840 BC. 348 cm.	2840 BC. 348 cm.	*
3420 BC. 372 cm.	*	3610 BC. 380 cm.	*
4480 BC. 416 cm.	*	*	*

Table 5.16 Raeburn Flow - Inferred dry shifts (depth cm./interpolated pollen/^{14}C dates dates [rounded to the nearest decade]).

Humification.	Dupont index.	DCA Axis 1.	Dupont index - Testate Amoebae
1870 AD. 16 cm.	1870 AD. 16 cm.	1900 AD. 12 cm.	*
1690 AD. 32 cm.	1690 AD. 32 cm.	1690 AD. 32 cm.	*
950 AD. 108 cm.	1000 AD. 104 cm.	1000 AD. 104 cm.	*
*	580 AD. 140 cm.	*	*
230 AD. 180 cm.	370 AD. 164 cm.	300 AD. 172 cm.	300 AD. 172 cm.
90 AD. 196 cm.	*	*	*
*	310 BC. 240 cm.	310 BC. 240 cm.	*
*	720 BC. 260 cm.	720 BC. 260 cm.	*
2070 BC. 316 cm.	1880 BC. 308 cm.	1880 BC. 308 cm.	2070 BC. 316 cm.
3030 BC. 356 cm.	3030 BC. 356 cm.	3030 BC. 356 cm.	*
3610 BC. 380 cm.	*	3800 BC. 388 cm.	*
4000 BC. 396 cm.	*	*	*

* Change not recorded.

Figure 5.97 Raeburn Flow - Inferred wet shift dates.



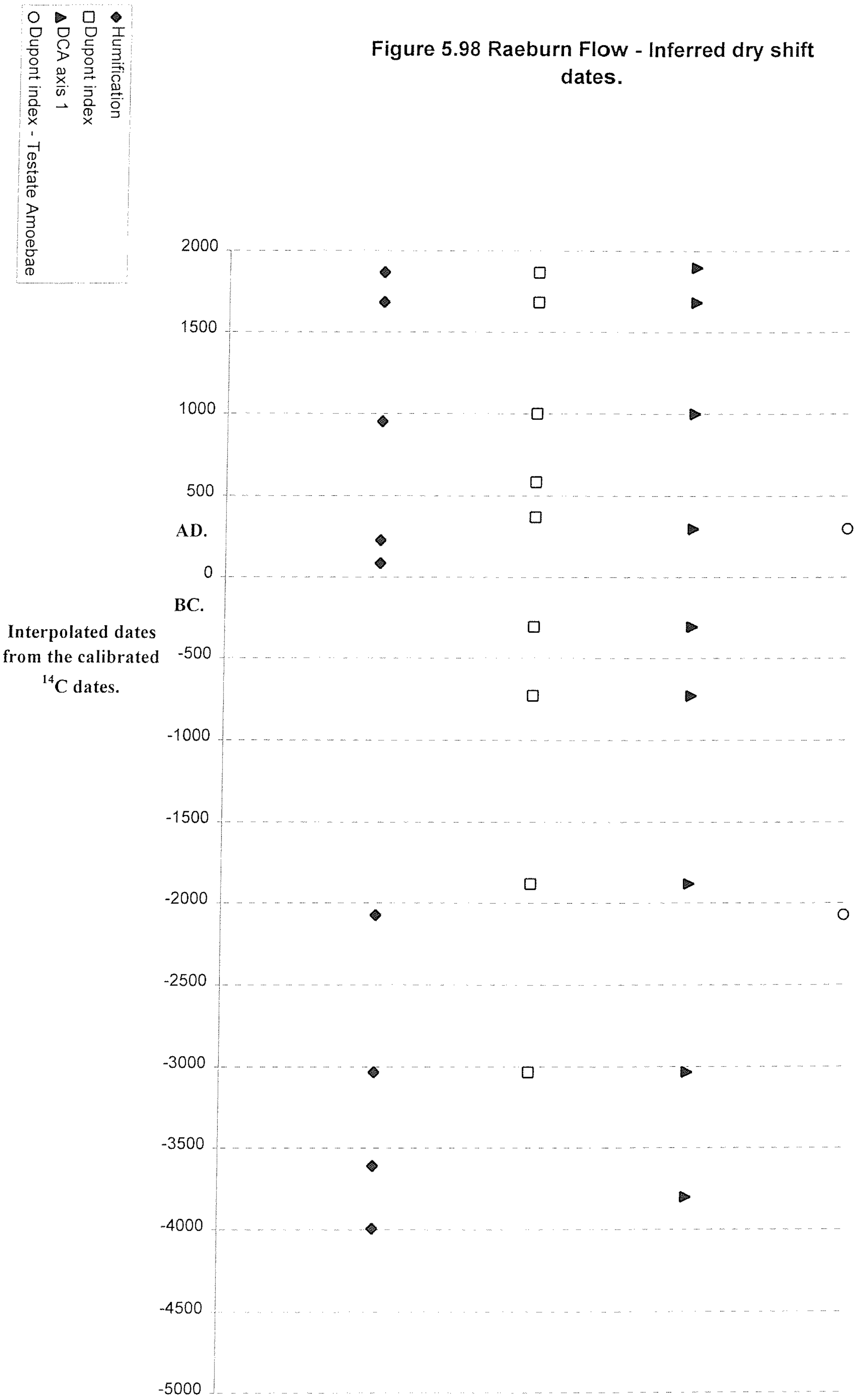


Figure 5.98 Raeburn Flow - Inferred dry shift dates.

Table 5.17 Bell's Flow - Inferred wet shifts (depth cm./interpolated pollen/^{14}C dates [rounded to the nearest decade]).

Humification.	Dupont index.	DCA Axis 1.	Dupont index - Testate Amoebae
1800 AD.# 20 cm. 1420 AD.‡ 20 cm.	1800 AD.# 20 cm. 1420 AD.‡ 20 cm.	1800 AD.# 20 cm. 1420 AD.‡ 20 cm.	1800 AD.# 20 cm. 1420 AD.‡ 20 cm.
*	1070 AD. 44 cm.	1110 AD. 40 cm.	*
790 AD. 72 cm.	950 AD. 56 cm.	870 AD. 64 cm.	910 AD. 60 cm.
560 AD. 96 cm.	560 AD. 96 cm.	*	*
400 AD. 124 cm.	*	*	350 AD. 132 cm.
300 AD. 140 cm.	*	*	*
100 AD. 160 cm.	10 AD. 168 cm.	*	40 BC. 172 cm.
350 BC. 200 cm.	350 BC. 200 cm.	400 BC. 204 cm.	350 BC. 200 cm.
*	1030 BC. 260 cm.	990 BC. 256 cm.	940 BC. 252 cm.
*	1260 BC. 280 cm.	*	1300 BC. 284 cm.

Table 5.18 Bell's Flow - Inferred dry shifts (depth cm./interpolated pollen/^{14}C dates [rounded to the nearest decade]).

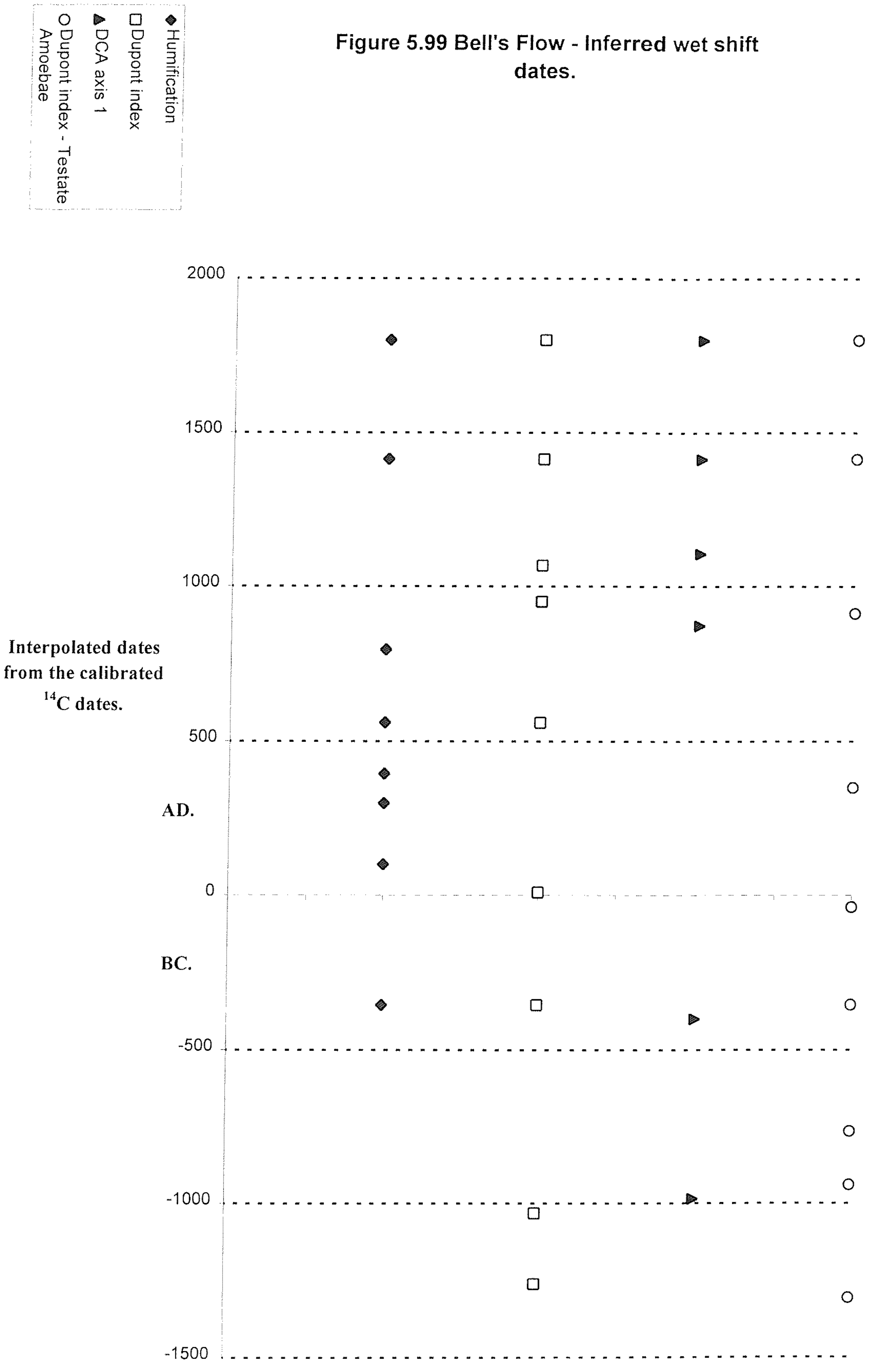
Humification.	Dupont index.	DCA Axis 1.	Dupont index - Testate Amoebae
*	1930 AD. # 8 cm.	*	1960 AD. # 4 cm.
1110 AD. 40 cm.	1110 AD. 40 cm.	1190 AD. 32 cm.	1150 AD. 36 cm.
640 AD. 88 cm.	870 AD. 64 cm.	*	*
*	*	*	540 AD. 100 cm.
470 AD. 112 cm.	470 AD. 112 cm.	440 AD. 116 cm.	440 AD. 116 cm.
280 AD. 144 cm.	*	*	*
80 BC. 176 cm.	80 BC. 176 cm.	*	140 AD. 156 cm.
*	400 BC. 204 cm.	400 BC. 204 cm.	580 BC. 220 cm.
720 BC. 232 cm.	*	810 BC. 240 cm.	760 BC. 236 cm.
1120 BC. 268 cm.	990 BC. 256 cm.	1030 BC. 260 cm.	*
*	*	*	1210 BC. 276 cm.
1400 BC. 292 cm.	1440 BC. 296 cm.	1260 BC. 280 cm.	1490 BC. 300 cm.

* Change not recorded.

‡= date interpolated from the ^{14}C chronology.

#= date interpolated from the Pine chronology.

Figure 5.99 Bell's Flow - Inferred wet shift dates.



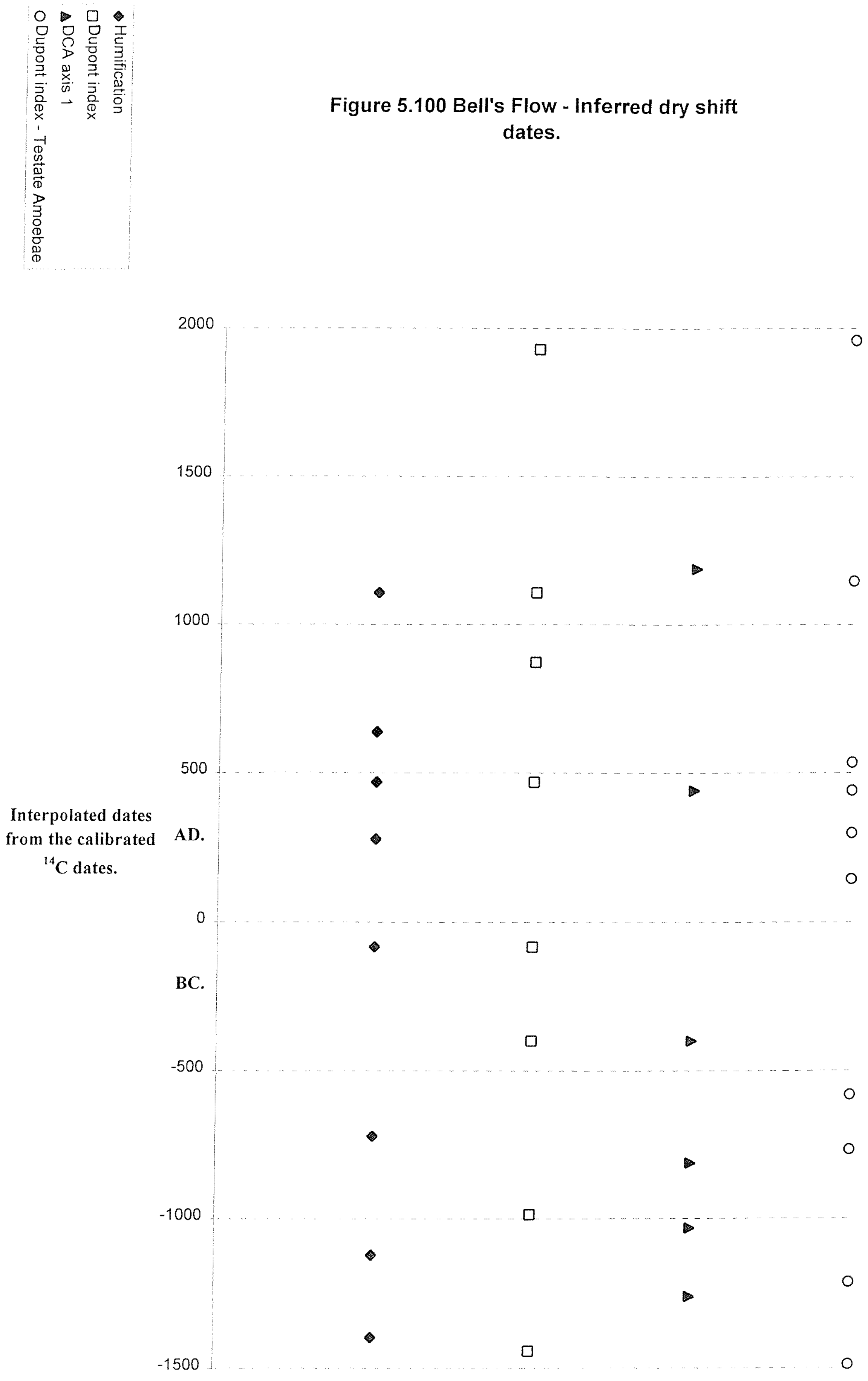


Figure 5.100 Bell's Flow - Inferred dry shift dates.

5.7.6 Coom Rigg Moss.

The absence of Dupont index and DCA Axis 1 wet shifts pre-dating 130 BC. can be readily attributed to the plant macrofossil stratigraphy of the borehole, since it is dominated by U.O.M. and *Eriophorum vaginatum* from 130 BC. to 1340 BC. (200-300 cm.). Despite this, the peat matrices from these depths still appear to record climate signals. Wet-shifts can be identified using colorimetric humification analysis and testate amoebae between 760-610 BC.

Between 1480 AD. and 70 AD., both the Dupont index and DCA Axis 1 Scores display inferred dry shifts at exactly the same depths/ages (Table 5.20, Figure 5.102), which is very encouraging, as both techniques appear capable of detecting mire hydro-climatic changes.

5.7.7 Felecia Moss.

This bog displays more wet shifts than Coom Rigg Moss, and the plant macrofossil Dupont index and DCA Axis 1 scores appear to be more sensitive in recording changes in mire water levels. Unlike Coom Rigg Moss, which does not contain a *Sphagnum* rich flora pre-dating 80-370 CAL. BC., the stratigraphy of Felecia Moss is dominated by sub-fossil *Sphagnum* species and consequently is better able to respond to and record changes in the depth of the acrotelm/catotelm boundary. The registration of inferred wet shifts using each technique is broadly synchronous, and between 320-350 AD., and 20 AD.-10 BC., 290-160, and 590-500 BC., increased mire surface wetness can be inferred using all four proxies (Table 5.21, Figure 5.103). An equally noteworthy synchronous response of the mire flora, fauna, and colorimetric humification signal to increased dryness can be detected at 230 AD. and between 530-410 AD. (Table 5.22, Figure 5.104).

Table 5.19 Coom Rigg Moss - Inferred wet shifts (depth cm./interpolated pollen/^{14}C dates [rounded to the nearest decade]).

Humification.	Dupont index.	DCA Axis 1.	Dupont index - Testate Amoebae
1800 AD.# 24 cm. 1610 AD.‡ 24 cm.	1800 AD.# 24 cm. 1610 AD.‡ 24 cm.	1770 AD.# 28 cm. 1550 AD.‡ 28 cm.	*
*	1400 AD. 52 cm.	1440 AD. 48 cm.	1480 AD. 40 cm.
1190 AD. 76 cm.	1150 AD. 80 cm.	1110 AD. 84 cm.	*
970 AD. 100 cm.	930 AD. 104 cm.	930-1040 AD. 104-92 cm.	1000 AD. 96 cm.
550-670 AD. 144-132 cm.	600-670 AD. 140-132 cm.	600-640 AD. 140-136 cm.	550-640 AD. 144-136 cm.
210 AD. 172 cm.	360 AD. 160 cm.	360 AD. 160 cm.	*
180-130 BC. 204-200 cm.	*	*	*
760 BC. 252 cm.	*	*	610 BC. 240 cm.
*	*	*	1150 BC. 284 cm.

Table 5.20 Coom Rigg Moss - Inferred dry shifts (depth cm./interpolated pollen/^{14}C dates [rounded to the nearest decade]).

Humification.	Dupont index.	DCA Axis 1.	Dupont index - Testate Amoebae
*	1900 AD.# 12 cm.	*	*
1480 AD. 40 cm.	1480 AD. 40 cm.	1480 AD. 40 cm.	1370 AD. 56 cm.
1220 AD. 72 cm.	1290 AD. 64 cm.	1290 AD. 64 cm.	*
*	1080 AD. 88 cm.	1080 AD. 88 cm.	930 AD. 104 cm.
890 AD. 108 cm.	780 AD. 120 cm.	780 AD. 120 cm.	780 AD. 120 cm.
*	450 AD. 152 cm.	450 AD. 152 cm.	360 AD. 160 cm.
20 AD. 188 cm.	70 AD. 184 cm.	70 AD. 184 cm.	*
230 BC. 208 cm.	*	370 BC. 220 cm.	130 BC. 200 cm.
*	*	*	810 BC. 256 cm.
950 BC. 268 cm.	*	*	*
1050 BC. 276 cm.	1050 BC. 276 cm.	1050 BC. 276 cm.	*
*	*	*	1240 BC. 292 cm.

* Change not recorded.

‡= date interpolated from the ^{14}C chronology. #= date interpolated from the Pine chronology.

Figure 5.101 Coom Rigg Moss - Inferred wet shift dates.

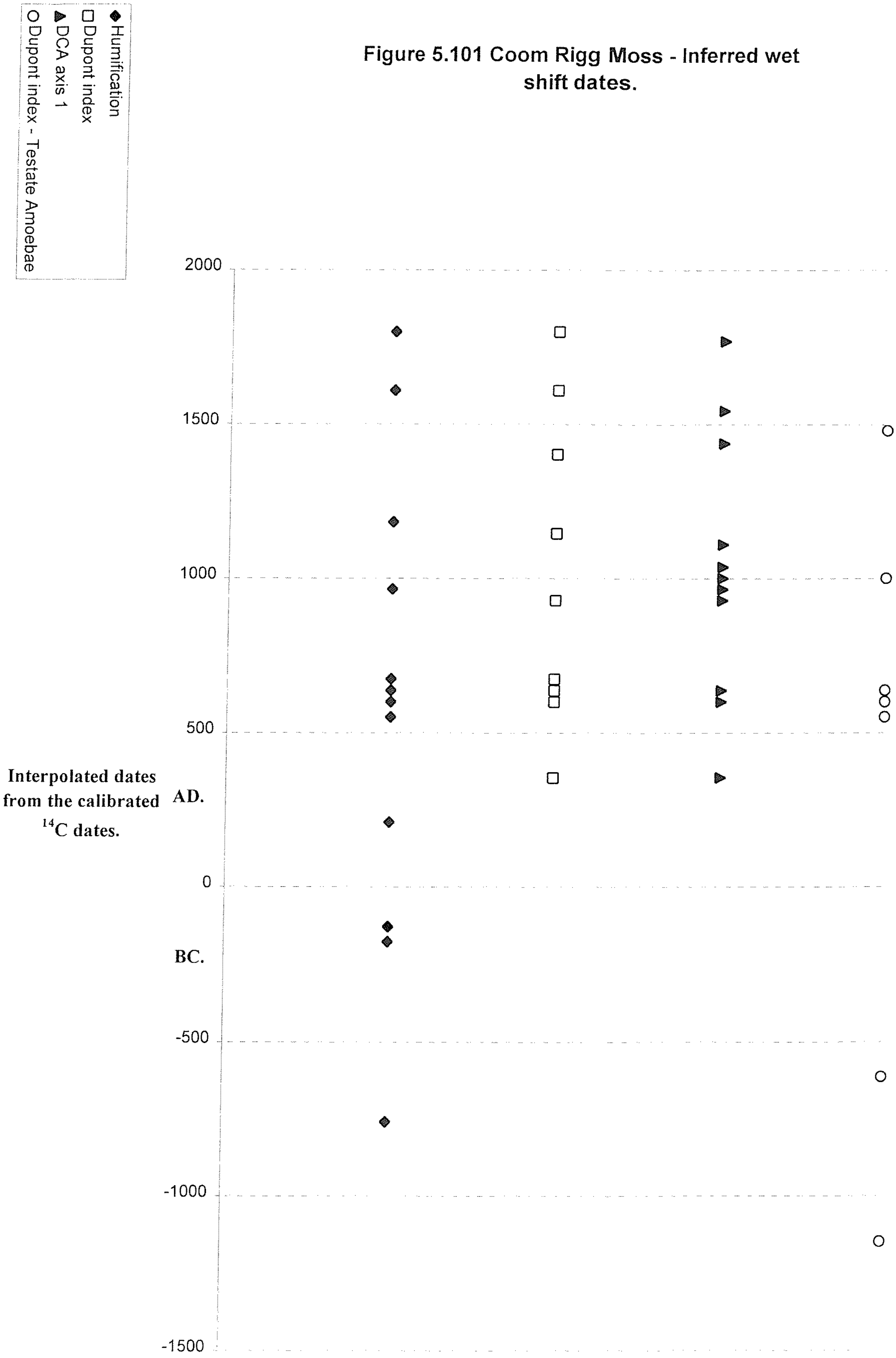


Figure 5.102 Coom Rigg Moss - Inferred dry shift dates.

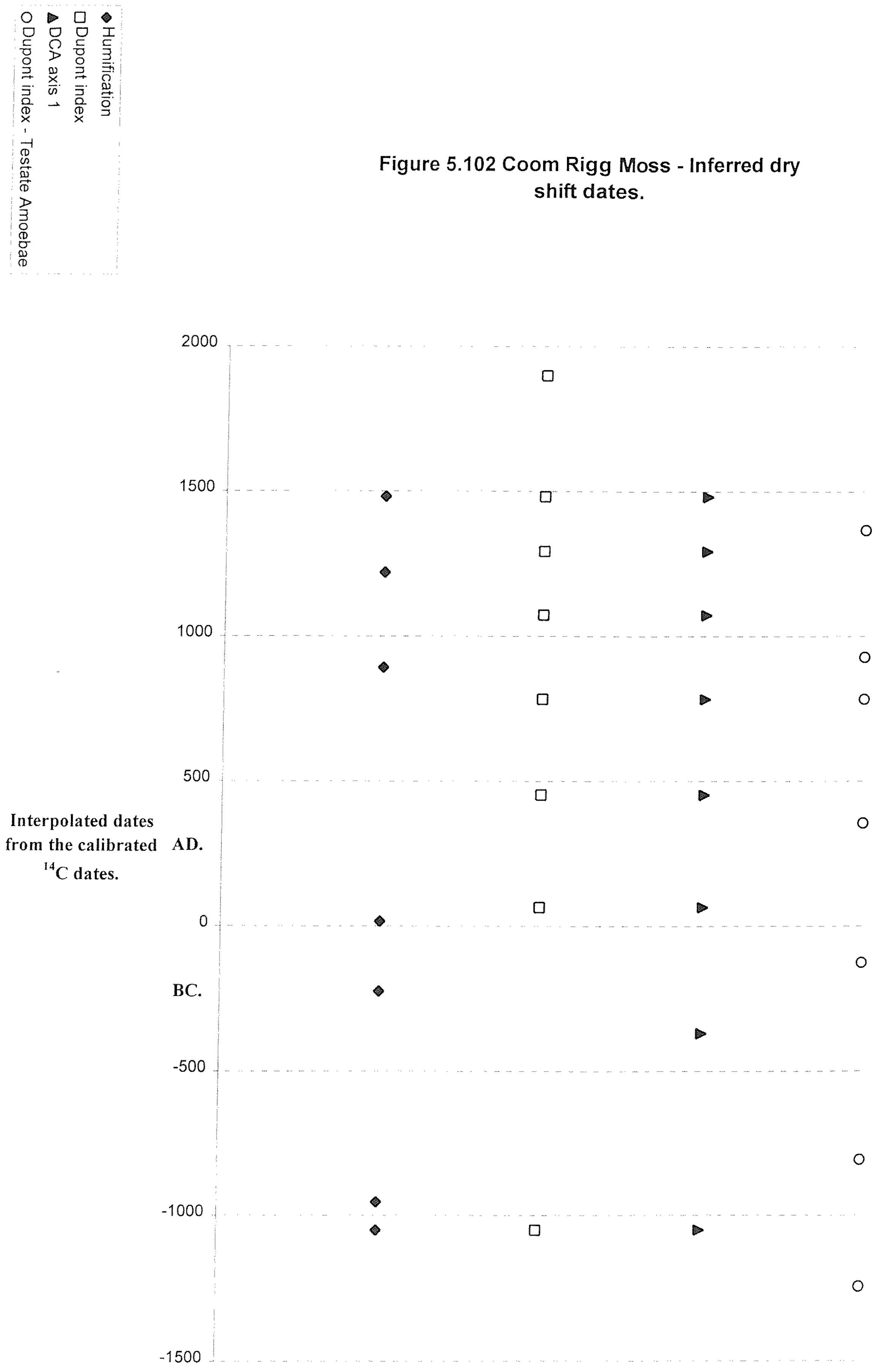


Table 5.21 Felecia Moss - Inferred wet shifts (depth cm./interpolated pollen/^{14}C dates [rounded to the nearest decade]).

Humification.	Dupont index.	DCA Axis 1.	Dupont index - Testate Amoebae
1800 AD. 24 cm.	1800 AD. 24 cm.	1800 AD. 24 cm.	*
*	1700 AD. 32 cm.	1700 AD. 32 cm.	*
*	1470 AD. 44 cm.	1470 AD. 44 cm.	1530 AD. 40 cm.
1130 AD. 64 cm.	*	1200 AD. 60 cm.	*
*	920 AD. 76 cm.	1060 AD. 68 cm.	*
*	*	*	780 AD. 84 cm.
640 AD. 104 cm.	560 AD. 116 cm.	560 AD. 116 cm.	*
320-350 AD. 148-144 cm.	320-350 AD. 148-144 cm.	350 AD. 144 cm.	350 AD. 144 cm.
10 BC. 192 cm.	20 AD. 188 cm.	20 AD. 188 cm.	10 BC. 192 cm.
160 BC. 212 cm.	200 BC. 216 cm.	290 BC. 228 cm.	200 BC. 216 cm.
410 BC. 244 cm.	*	*	380 BC. 240 cm.
530 BC. 260 cm.	590 BC. 268 cm.	590 BC. 268 cm.	500 BC. 256 cm.
710 BC. 284 cm.	710 BC. 284 cm.	*	710 BC. 284 cm.

Table 5.22 Felecia Moss - Inferred dry shifts (depth cm./interpolated pollen/^{14}C dates [rounded to the nearest decade]).

Humification.	Dupont index.	DCA Axis 1.	Dupont index - Testate Amoebae
*	*	*	1930 AD. 8 cm.
1600 AD. 36 cm.	1600 AD. 36 cm.	1600 AD. 36 cm.	*
*	*	1400 AD. 48 cm.	*
850 AD. 80 cm.	*	850 AD. 80 cm.	*
530 AD. 120 cm.	530 AD. 120 cm.	410 AD. 136 cm.	410 AD. 136 cm.
230 AD. 160 cm.	230 AD. 160 cm.	230 AD. 160 cm.	230 AD. 160 cm.
*	50 AD. 184 cm.	50 AD. 184 cm.	*
40 BC. 196 cm.	100 BC. 204 cm.	*	130 BC. 208 cm.
320 BC. 232 cm.	230 BC. 220 cm.	*	*
470 BC. 252 cm.	*	500 BC. 256 cm.	440 BC. 248 cm.
650 BC. 276 cm.	*	680 BC. 280 cm.	560 BC. 264 cm.
*	830 BC. 300 cm.	830 BC. 300 cm.	740 BC. 288 cm.

* Change not recorded.

Figure 5.103 Felecia Moss - Inferred wet shift dates.

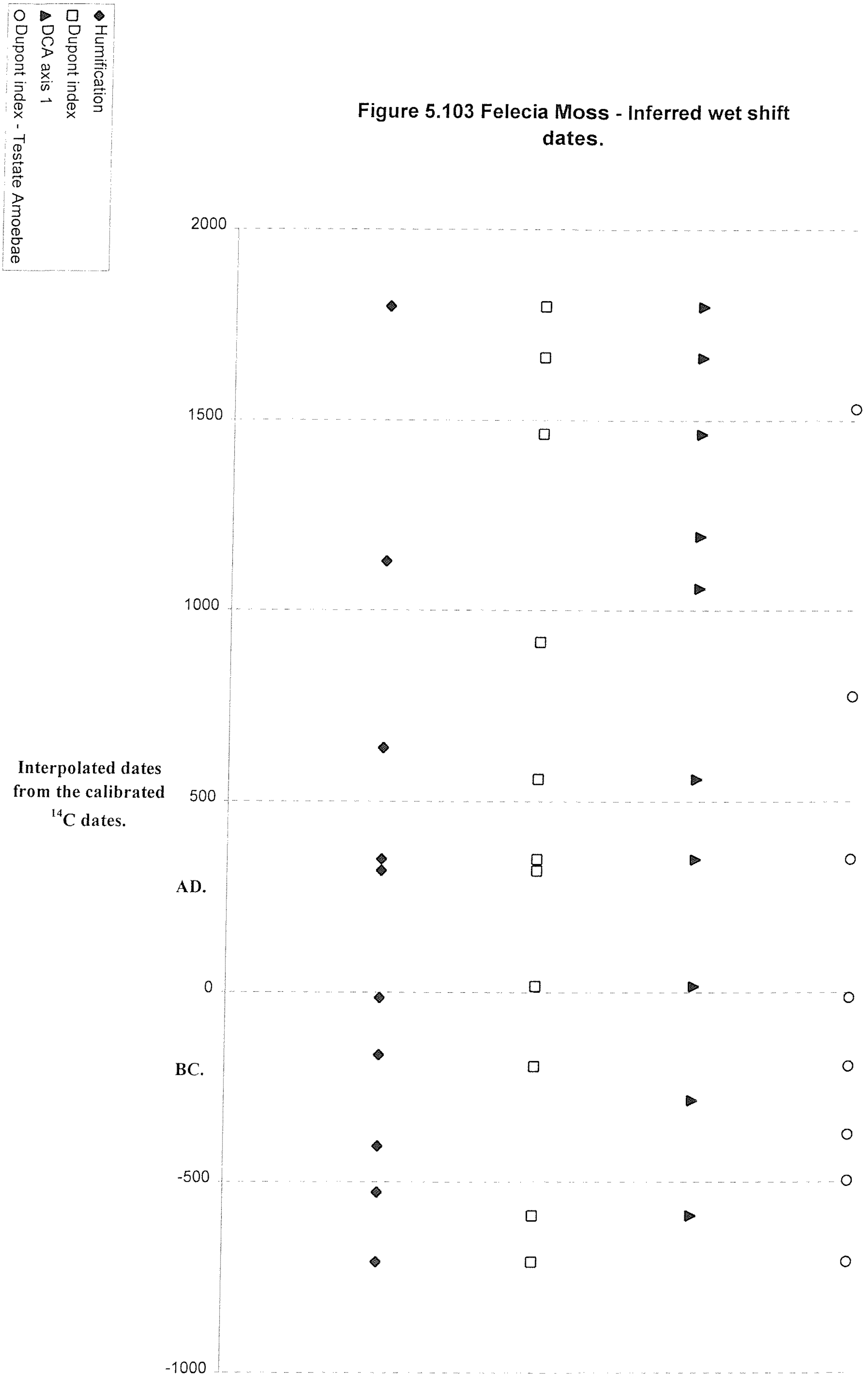
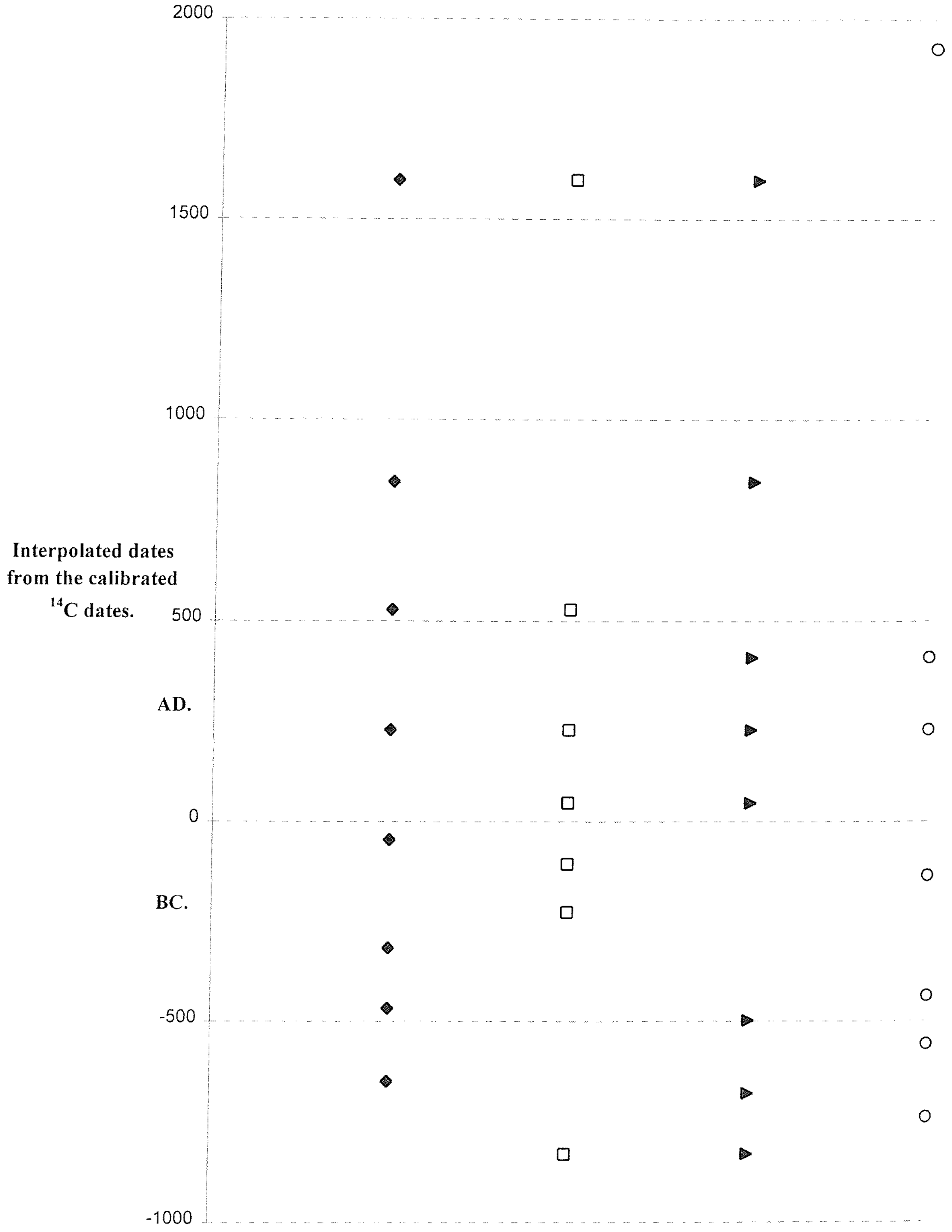


Figure 5.104 Felecia Moss - Inferred dry shift dates.



5.8 Time Series Analysis.

5.8.1 Introduction.

The measurements or numerical values of any variable that changes with time constitutes a time series (Shaw, 1983). The mathematical description and identification of the components contributing to the structure of a time series forms the basis of time series analysis. Through this, a search can be made for significant cycles and their periods, and these can then be compared to other published periodicities derived from palaeoecological datasets, to see if a common signal is present. Cycles have been detected in ombrogenous mire stratigraphy (Section 2.3.3) by Aaby (1976), Wijmstra *et al.* (1984) and Barber *et al.* (1994), therefore their analysis here will serve to corroborate this work, and possibly reveal new periodicities. The colorimetric absorbance values from Bolton Fell Moss - Core L (BFML) and Walton Moss - Core 11 (WLM11, Figures 5.14 and 5.18), and the DCA axis 1 scores from WLM11 (Figure 5.70), appear to show cyclical changes, although this is less clear in the DCA axis 1 scores from BFML (Figure 5.67).

Spectral analysis, where data is plotted in the frequency or wavelength domain will show how much variance (and therefore variability), is explained by different frequencies or wavelength bands. Analysis of this variance will allow the identification of systematic behaviour as periodicities, in order to determine whether there are indeed cyclical signals within the peat stratigraphy of the study sites.

5.8.2 Spectral Analysis of Bolton Fell Moss - Core L and Walton Moss - Core 11.

The DCA axis 1 scores and colorimetric humification values from BFML and WLM11 only, were subjected to spectral analysis. The Dupont index values derived from the plant macrofossils were not utilised, since unlike the DCA axis 1 scores, these values have been constructed subjectively. The Dupont indices derived from the Testate Amoebae were also excluded for the same reason, and also because the thecamoebae were sampled at a coarser resolution to the plant macrofossil and colorimetric humification data. BFML and WLM11 had the best chronologies of all the sites investigated (six ^{14}C assays were available for each site), and were chosen for this reason. The age depth curves derived from the radiocarbon dates revealed an almost linear accumulation of peat within these ecosystems (Figures 5.2 and 5.3). The age models constructed from the calibrated radiocarbon dates are based simply on linear interpolations between each dated horizon. Given the relatively constant rates of peat accumulation within these two raised mires, this will not be too gross an oversimplification. This is corroborated by the peat stratigraphy from Core J, Bolton Fell Moss, as it also appears to have accumulated linearly between 50 cm. and 5 m. (Barber *et al.,* 1994e).

The humification and plant macrofossil data from BFML and WLM11 have been sampled unevenly. An appropriate spectral analysis method to use on unevenly sampled data has been developed by Lomb (1976), based on earlier work by Barning (1963) and Vanicek (1971), and later expanded by Scargle (1982). Signals in the data are detected by estimating a power spectrum derived from a periodogram. A full mathematical description of the algorithms employed in the periodogram analysis are presented in Scargle (1982), where it is also shown that the statistical behaviour of the periodogram for unevenly spaced data is virtually identical to that derived from evenly spaced data.

Analysis of the data and construction of the periodograms was performed using the LOMB program (Press *et al.*, 1992) and DOODLER plotting software written and very kindly made available by Dr. M. Kelly, The Climatic Research Unit, University of East Anglia. Within the LOMB program, there is no facility to calculate confidence bands, so the results must be viewed only as a guide as to the amount of variance each peak actually shows, and which peaks are statistically significant.

The results of the time series analysis, and the identification of potentially significant periods within the data are marked on the diagrams (Figures 5.105 to 5.108) and presented in Table 5.23. On the BFML humification data periodogram (Figure 5.105) it is immediately apparent that the data set is noisy, and additionally, there appear to be other significant cycles which have not been marked. For example there is a large power value (6.1) at 13.1 cycles per thousand years. This translates into a periodicity of 76 years (1000/13.1280). This cannot be considered to be significant, however, since it does not exceed x2 the sampling interval of the data (pers. comm., Dr. Tony Payne). The closest peat sampling interval of 4 cm. equates to a time period of 43 years per sample (the mean accumulation rate for BFML is c.10.8 years cm.$^{-1}$). Double this interval equates to a time period of c. 86 years, which is the shortest period which can be considered significant for the data set. In this case, high frequency changes with a period smaller than this value can be dismissed, since they are not statistically significant. A further restriction of the periodogram analysis, is the requirement that a record must be at least seven to ten times as long as the period of the cycle, before a period can be considered as significant. Because of this stipulation, high power values on the BFML DCA periodogram (Figure 5.106), for example the peak at 0.236 cycles per 1000 years, can be excluded, since this value corresponds to a period of 4237 years, yet the entire record for BFML extends no further back in time than CAL 3500-3100 BC. The same restrictions apply to the WLM11 data, as there are similar, potentially spurious, high and low frequency periods visible on the periodograms.

Despite these caveats, recurrent periods appear to be present in the peat humification data and DCA axis 1 scores for each site (Table 5.23). The consistent registration of a period ranging in length from 261-282 years, using both two techniques and between two sites, is very encouraging, although the power of the WLM11 humification period (274 years) is low (3.1), in comparison to the 430 year (power=5.9) and 155 year periods (power=3.79) identified. The strongest periods identified in the periodograms have a greater dispersion of periods and range from 338-516 years, although both BFML and WLM11 share similar periods in the DCA data (341 and 338 years respectively).

The identification of 260 and 520 year cyclicity in the peat humification stratigraphy of Draved Mose by Aaby (1976), match some of the results of this time series analysis, whilst some of the periods identified by Wijmstra *et al.* (1984) from a peat section in the Engbertsdijksveen, The Netherlands (500, 350, 200 and 145 periods), also overlap with the range of values determined in this instance. The strongest spectral peak identified by Barber *et al.* (1994e) from the peat stratigraphy of Bolton Fell Moss - Core J, had a frequency of 800 years, which diverges from the frequencies identified here. Conversely, the loss-on-ignition curve generated by

Barber *et al.* (in press) from Lochan Uaine, in the Scottish Cairngorms, shows possible cyclical changes which have a frequency of c. 200 years, which overlap the lower range of periodicites identified in this research project. Insolation variations driving increases in lake primary productivity have been proposed by Barber *et al.* (in press) as a possible cause of this cyclicity. The significance and further consideration of the time series analysis results will be discussed in Chapter 6.

Figure 5.105 Spectral Analysis of Bolton Fell Moss - Core L - Humification data.

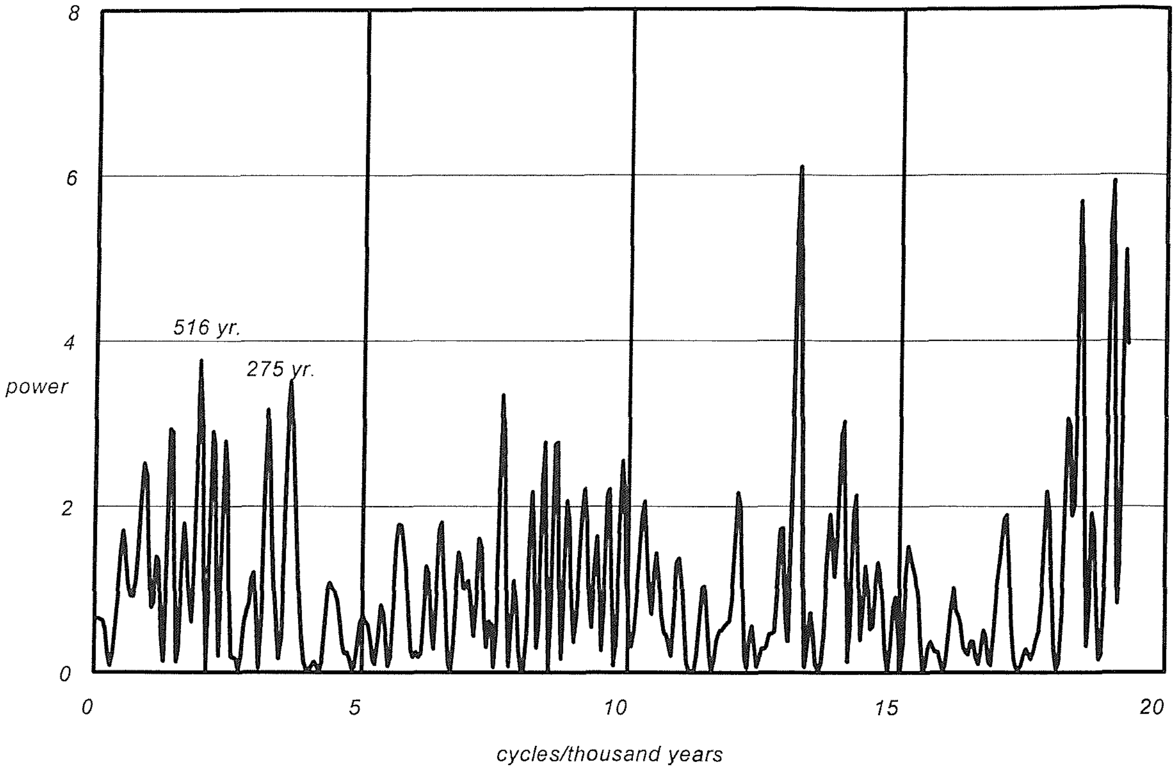


Table 5.23 *Periods identified using LOMB.*

Site	*Period (Humification data)*	*Period (DCA data).*
Bolton Fell Moss - Core L.	516 years.	341 years.
	275 years.	261 years.
Walton Moss - Core 11.	430 years.	338 years.
	274 years.	282 years.
	155 years.	

Figure 5.106 Spectral Analysis of Bolton Fell Moss - Core L - DCA.

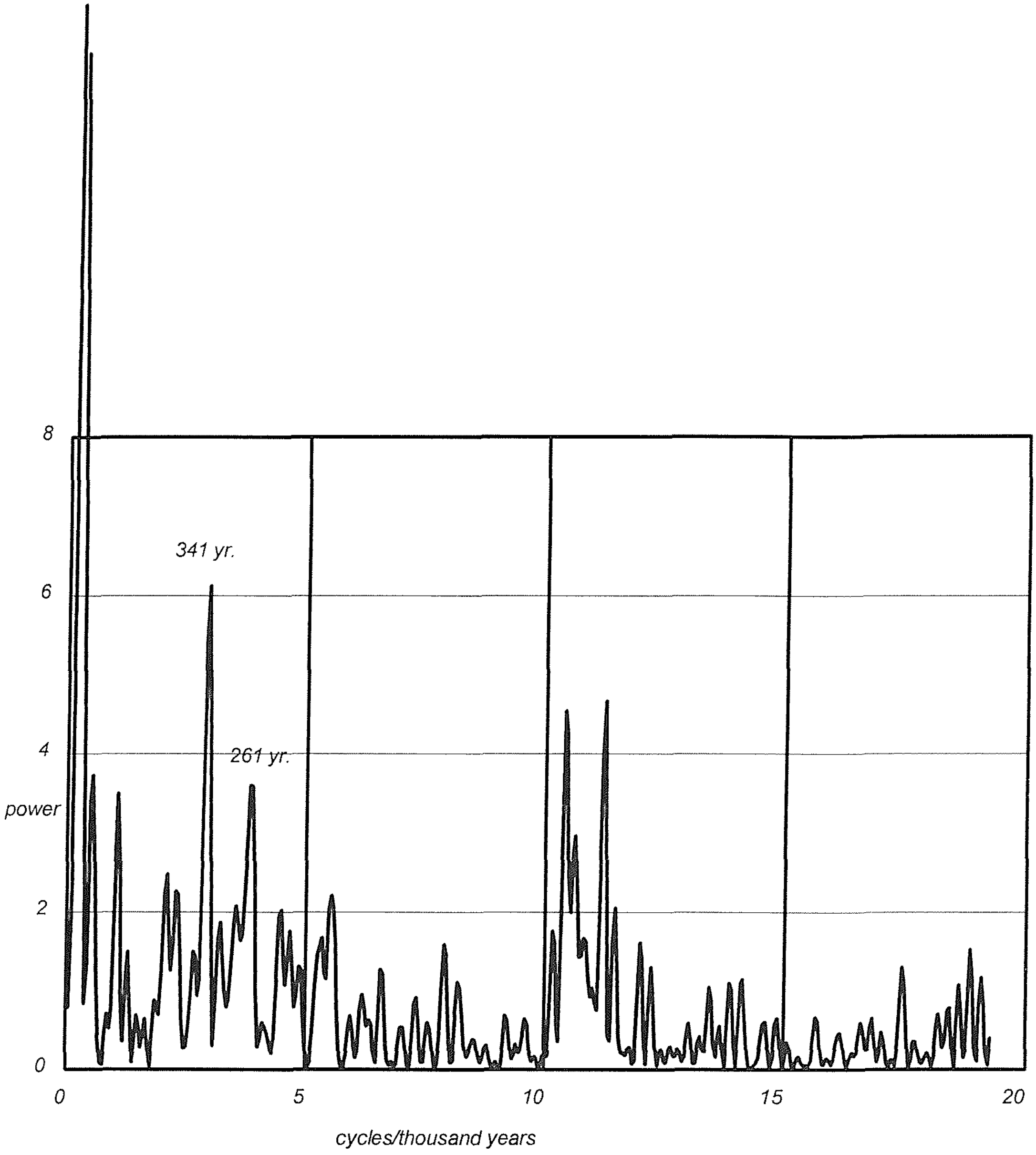


Figure 5.107 Spectral Analysis of Walton Moss - Core 11 - Humification data.

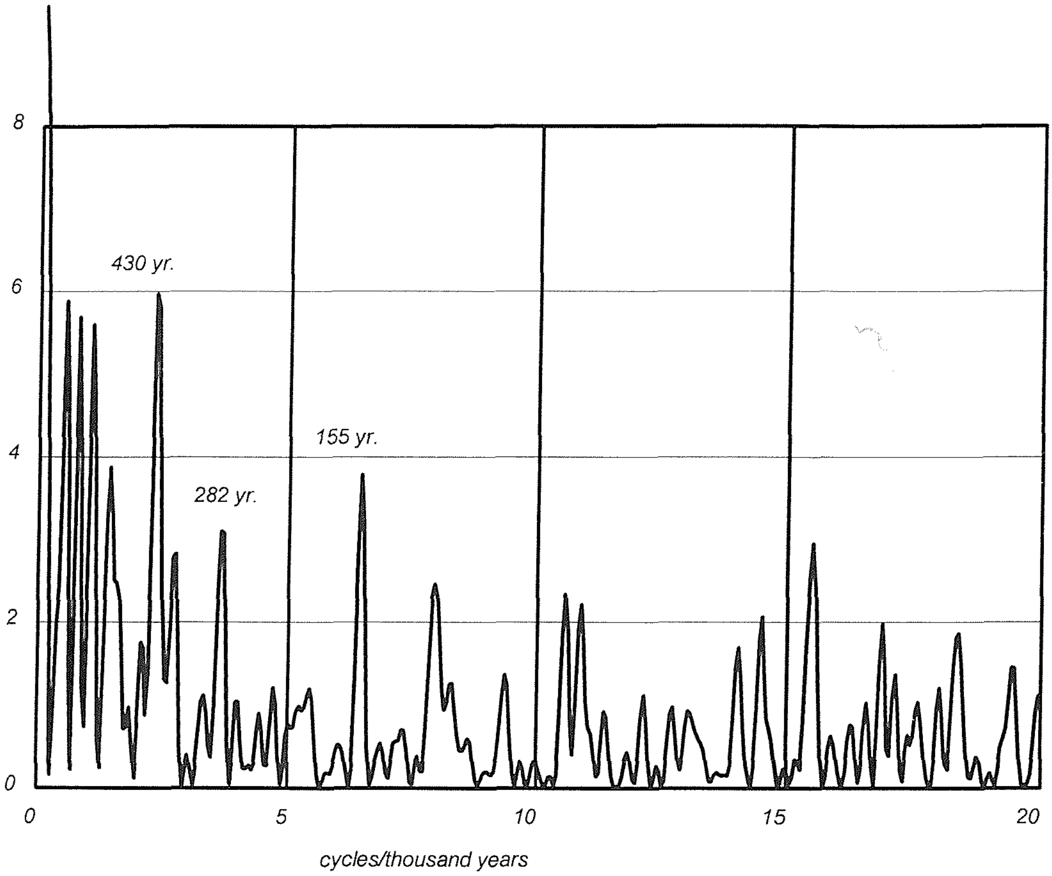
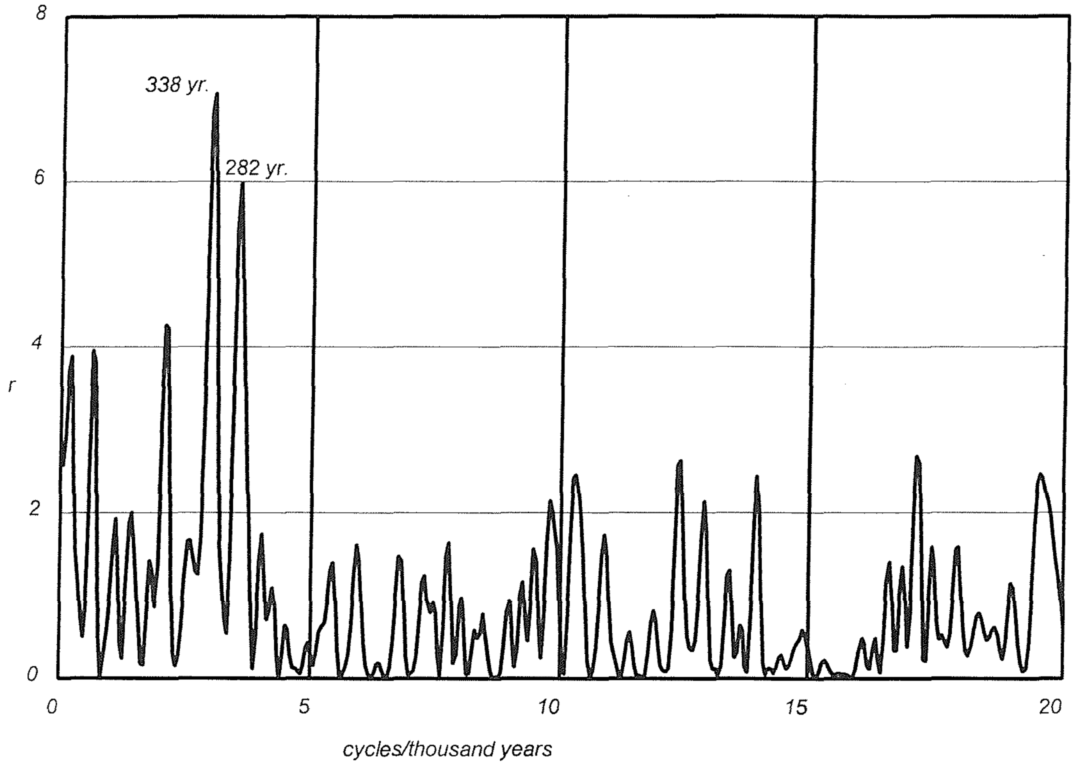


Figure 5.108 Spectral Analysis of Walton Moss - Core 11 - DCA data.



5.9 Summary.

The results of the humification, plant macrofossil and testate amoebae analyses demonstrate, on the whole, consistent changes in inferred mire surface wetness using each proxy. For some of the sites, however, each proxy technique displays differential sensitivities to record changes in local water tables. For example, the plant macrofossils in the stratigraphy of Bell's Flow (Section 5.7.5), are relatively homogeneous and species poor, yet changes in effective precipitation can be inferred using both the humification and testate amoebae zoofossils. These proxies are not a universal panacea, however, as the testate amoebae stratigraphy of Raeburn Flow (Section 5.7.4), is complacent in comparison to the humification and plant macrofossil record, whilst some of the colorimetric absorbance signal may be dependent on the composition of the peat matrix, particularly where *Eriophorum vaginatum* is abundant (Section 5.7.2).

A multi-proxy approach clearly has a better chance of detecting changes in mire surface wetness, but the irregular lead and lag times each proxy can display before registering a change in local water tables can 'smear' *sensu* Baillie (1991), the time span over which climatic deteriorations and ameliorations occurred. Exploratory use of CCA to quantitatively reconstruct mire water tables (Section 5.7), has also shown the differential sensitivity of peat stratigraphic components, with in this instance, a possible earlier response of testate amoebae to hydrological change. This is a very tentative finding, since the transfer functions developed by the Plymouth University team may not accurately model the height of local water tables.

Despite these problems, analysis of multiple proxies has served to highlight periods of higher and lower local water tables within each of the bogs studied.

A regional palaeoclimatic reconstruction will be made in the next chapter, based on the results presented here, and an attempt will be made to validate the record obtained from this research project with other documentary and palaeoecological evidence. This information will then serve to answer the key question of this research project, namely, to indicate which of the mires investigated is the most sensitive in recording changes in climate.

Chapter 6 Discussion.

6.1 Introduction.

In Chapter 5, a suite of dates for inferred wet and dry shifts was identified for each site (Tables 5.11 to 5.22). A 'time envelope' which encompasses the range of wet and dry shifts detected using humification, plant macrofossil and testate amoebae analyses between the sites is presented in Tables 6.1 and 6.2. Common periods of possible climatic change both between the paired, and other sites spanning the climatic gradient over which they are situated are readily visible on these Tables, and on Figures 6.1 and 6.2, where the results of the humification and DCA analyses are plotted against time. These are highly likely to represent periods of allogenic forcing within the region. There are clearly periods of time in which the hydroclimatic changes identified in the ombrogenous peat stratigraphy from each site coincide (see Section 6.2.1) for a realistic qualification of the ^{14}C chronology) with those derived from other sites (these are marked by shading on tables 6.1 and 6.2).

In comparison to the wet-phase shifts identified here, interpreting and dating dry stratigraphic events is more hazardous. Aaby (1976) ignored dry shifts derived from peat humification changes, because of the possibility of secondary decomposition, and interpreted wet-shifts only in his climatic reconstruction. Pool infilling by 'dry' indicator species can occur in a constantly wet climate (Barber, 1981), whilst peat accumulation rates can slow down, as there is more decomposition of peat as the depth of the acrotelm increases. For these reasons, Barber (1981), did not systematically use the dry marker phases he identified. Haslam (1987) reviews this problem, and discusses a range of inferred peat accumulation rates extending from the Atlantic to the Subatlantic climatic deterioration. Haslam argues that during periods of low local water tables, a single centimetre of peat can represent several centuries of accumulation, due to enhanced aerobic decomposition, catotelmic decay and autocompaction, making it difficult to pinpoint the start of a dry phase. The presence of *Calluna vulgaris*, whilst certainly indicating lowered water tables (Section 5.2.3), introduces a further problem in establishing the longevity of a dry phase, since once established it is 'potentially immortal', (Barber, 1981), as it can root adventitiously as it is overgrown by *Sphagnum* (Forest, 1971; Gimingham, 1988; Macdonald *et al.*, 1995). Wallén (1980) and Christensen (1989) have shown that a *Calluna* stand can maintain cover, probably as a result of layering (adventitious rooting of stems), for over 60 years. These dwarf shrubs can, therefore, clearly resist swamping by *Sphagnum* species, and are able to keep pace with increases in local water tables (Barber, 1981), masking the detection of wet shifts and possibly extending the real age of a dry phase.

For some, or possibly all of these reasons, linking dry stratigraphic levels both within and between sites is hazardous and has been investigated by Wimble (1986). 'Retardation layers', that is to say more humified bands of peat, were found to show asynchronous changes in the Cumbrian raised mires investigated, for example one site, Helsington Moss, contained prominent retardation layers after c. 3000 BP, whilst in White Moss, they only occurred after c. 1200 BP. By comparison, the wet shift or recurrence surface indicators detected by Wimble showed a high degree of synchroneity within the south Cumbria study region. The

Table 6.1 *Wet Shift Dates.*

Sites. → **Wet shift dates.** ***H=Humification data, Pdu= Plant Macrofossil-Dupont, Pdca= Plant macrofossil DCA, TA= Testate Amoebae.*** ↓	**Bolton Fell Moss - Core L.**	**Walton Moss - Core 11.**	**Raeburn Flow.**	**Bell's Flow.**	**Coom Rigg Moss.**	**Felecia Moss.**	**Shaft Hill - Monolith 1.**	**Shaft Hill - Monolith 2.**	**Shaft Hill - Monolith 3.**
Pollen date.	**1750-1850 AD. (H, Pdu, Pdca, TA).**	**1710-1800 AD. (H, Pdu, Pdca, TA).**	**1800-1830 AD. (H, Pdu, Pdca, TA).**	**1800 AD. (H, Pdu, Pdca, TA).**	**1800-1770 AD. (H, Pdu, Pdca, TA).**	**1800 AD. (H, Pdu, Pdca,).**		**1800 AD. (H, Pdu, Pdca, TA).**	
						1700 AD. (Pdu, Pdca).			
Interpolated radiocarbon date. → ↓					**1550-1610 AD. (H, Pdu, Pdca).**				
	1390 AD. (TA).		**1290-1340AD. (H, Pdu, Pdca, TA).**	**1420 AD. (H, Pdu, Pdca, TA).**	**1400-1480 AD. (Pdu, Pdca, TA).**	**1470-1530 AD. (Pdu, Pdca, TA).**			
	1010-1180 AD. (H, Pdca, TA).	**1130-1210 AD. (H, Pdu, Pdca, TA).**	**1050-1100 AD. (H, Pdca).**	**1070-1110 AD. (Pdu, Pdca).**	**1110-1190 AD. (H, Pdu, Pdca).**	**1130-1200 AD. (H, Pdca).**			
	840 AD. (Pdu, TA).			**790-950 AD. (H, Pdu, Pdca, TA).**	**930-1040 AD. (H, Pdu, Pdca, TA).**	**920-1060 AD. (Pdu, Pdca).**			
	680-810 AD. (H, Pdu, Pdca, TA).	**660-710 AD. (H, Pdu, TA).**	**620-670 AD. (H, Pdu, Pdca, TA).**	**560 AD. (H, Pdu).**	**550-670 AD. (H, Pdu, Pdca, TA).**	**560-640 AD. (H, Pdu, Pdca).**			
	380. AD. (Pdca).		**340 AD. (Pdu, TA).**	**350-400 AD. (H, TA).**	**210-360 AD. (H, Pdu, Pdca).**	**320-350 AD. (H, Pdu, Pdca, TA).**			
		490-540 AD. (Pdu, TA).							
	30-270 AD. (H, Pdu, Pdca, TA).	**190-280 AD. (H, Pdu, Pdca, TA).**		**300 AD. (H).**					
	160-60 BC. (H, TA).	**230-180 BC. (H, Pdu, Pdca, TA).**	**50-90 AD. (H, Pdu, TA).**	**40 BC.-100 AD. (H, Pdu, TA).**		**10 BC.-20 AD. (H, Pdu, Pdca, TA).**			
			440-270 BC. (H, Pdu, Pdca, TA).	**400-350 BC. (H, Pdu, Pdca, TA).**	**180-130 BC. (H).**	**410-160 BC. (H, Pdu, Pdca, TA).**			
	530-440 BC. (H, TA).	**790-510 BC. (H, Pdu, Pdca, TA).**	**720 BC. (H).**		**760-610 BC. (H, TA).**	**710-500 BC. (H, Pdu, Pdca, TA).**			
	1290-1010 BC. (H, Pdu, Pdca, TA).	**1130-920 BC. (H, Pdu, TA).**	**1110 BC. (H, Pdu, Pdca, TA).**	**1030-940 BC. (Pdu, Pdca, TA).**	**1150 BC. (TA).**				
				1300-1260 BC. (Pdu, TA).					
	1560 BC. (Pdu, TA).	**1690-1340 BC. (H, Pdu, Pdca, TA).**	**1690-1590 BC. (H, Pdu, Pdca, TA).**						
	1820-1740 BC. (H,TA).								
		2040 BC. (H, Pdu, TA).							
		2250 BC. (Pdu, TA).							
	2650 BC. (Pdu, Pdca, TA).	**2670-2390 BC. (H, Pdu, Pdca, TA).**	**2460 BC. (H, Pdu, TA).**						
		2880-2810 BC. (Pdca, TA).	**2840 BC. (H, Pdu, Pdca).**						
	3110-3020 BC. (H, Pdu, Pdca).	**2950 BC. (Pdu, TA).**							
			3610-3420 BC. (H, Pdca).						
			4480 BC. (H).						

Table 6.2 ***Dry Shift dates.***

Sites → **Dry shift dates.** ***H=Humification data, Pdu= Plant Macrofossil-Dupont, Pdca= Plant macrofossil DCA, TA= Testate Amoebae.*** ↓	**Bolton Fell Moss - Core L.**	**Walton Moss - Core 11.**	**Raeburn Flow.**	**Bell's Flow.**	**Coom Rigg Moss.**	**Felecia Moss.**
Pollen date.	**1870-1950 AD. (H, Pdu, Pdca, TA).**	**1870-1900 AD. (Pdu, Pdca, TA).**	**1870-1900 AD. (H, Pdu, Pdca).**	**1930-1960 AD. (Pdu, TA).**	**1900 AD. (Pdu).**	**1930 AD. (TA).**
Interpolated radiocarbon dates. → ↓		**1500-1630 AD. (H, Pdu).**	**1690 AD. (H, Pdu, Pdca).**			**1600 AD. (H, Pdu, Pdca).**
		1380-1420 AD. (Pdu, Pdca).			**1370-1480 AD. (H, Pdu, Pdca, TA).**	**1400 AD. (Pdca).**
				1110-1190 AD. (H, Pdu, Pdca, TA).	**1220-1290 AD. (H, Pdu, Pdca).**	
		1040-1090 AD. (H, Pdu, TA).	**950-1000 AD. (H, Pdu, Pdca).**		**930-1080 AD. (H, Pdu, Pdca).**	
	760-860 AD. (H, Pdu, Pdca, TA).			**640-870 AD. (H, Pdu).**	**780-890 AD. (H, Pdu, Pdca, TA).**	**850 AD.** (H, Pdca).
	620-680 AD. (H, Pdca, TA).		**580 AD. (Pdu).**	**540 AD. (TA).**		
	410 AD. (H).	**450 AD. (H, Pdu, TA).**		**440-470 AD. (H, Pdu, Pdca, TA).**	**360-450 AD. (Pdu, Pdca, TA).**	**410-530 AD.** (H, Pdu, Pdca, TA).
			230-370 AD. (H, Pdu, Pdca, TA).	**280 AD. (H).**		**230 AD.** (H, Pdu, Pdca, TA).
	80-170 AD. (H, Pdca, TA).	**30-80 AD. (H, Pdu, Pdca).**	**90 AD. (H).**		**20-70 AD. (H, Pdu, Pdca).**	**50 AD.** (Pdu, Pdca).
				80 BC.-140 AD. (H, Pdu, TA).		**130-40 BC.** (H, Pdu, TA).
	350-200BC. (H, Pdca, TA).	**420-280 BC. (H, Pdu, Pdca, TA).**	**310 BC. (Pdu, Pdca).**		**370-130 BC. (H, Pdca, TA).**	**320-230 BC.** (H, Pdu).
				580-400 BC. (Pdu, Pdca, TA).		**500-440 BC.** (H, Pdca, TA).
						680-560 BC. H, Pdca, TA).
	770-580 BC. (H, Pdca, TA).		**720 BC. (Pdu, Pdca).**	**810-720 BC. (H, Pdca, TA).**	**810 BC. (TA).**	**830-740 BC.** (Pdu, Pdca, TA).
		880 BC. (H, Pdu, TA).			**950 BC. (H).**	
		1170 BC. (H).		**1120-990 BC. (H, Pdu, Pdca, TA).**	**1050 BC. (H, Pdu, Pdca).**	
	1470 BC. (Pdca).	**1550-1270 BC. (H, Pdu, Pdca, TA).**		**1440-1260 BC. (H, Pdu, Pdca, TA).**	**1240 BC. (TA).**	
	1740 BC. (Pdu).	**1900 BC. (TA).**				
	2000-1910 BC. (H, Pdca, TA).	**2110 BC. (TA).**	**2070-1880 BC. (H, Pdu, Pdca, TA).**			
	2370-2180 BC. (Pdu, Pdca, TA).	**2390-2320 BC. (H, Pdu, Pdca, TA).**				
		2600 BC. (Pdca, TA).				
	2930-2740 BC. (H, Pdu, Pdca, TA).		**3030 BC. (H, Pdu, Pdca).**			
			3800-3610 BC. (H, Pdca). **4000 BC. (H).**			

Figure 6.1 Humification data vs. time

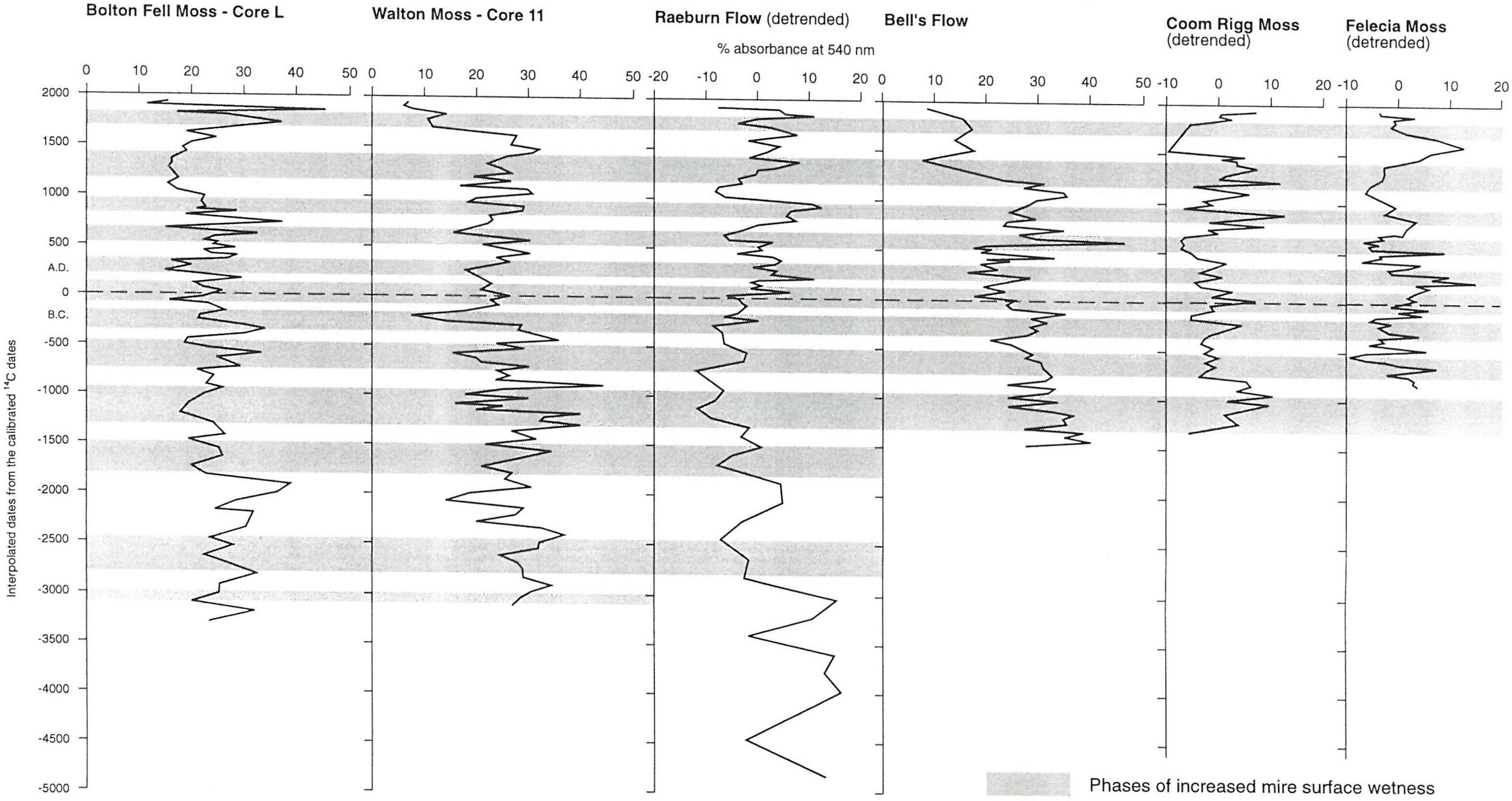
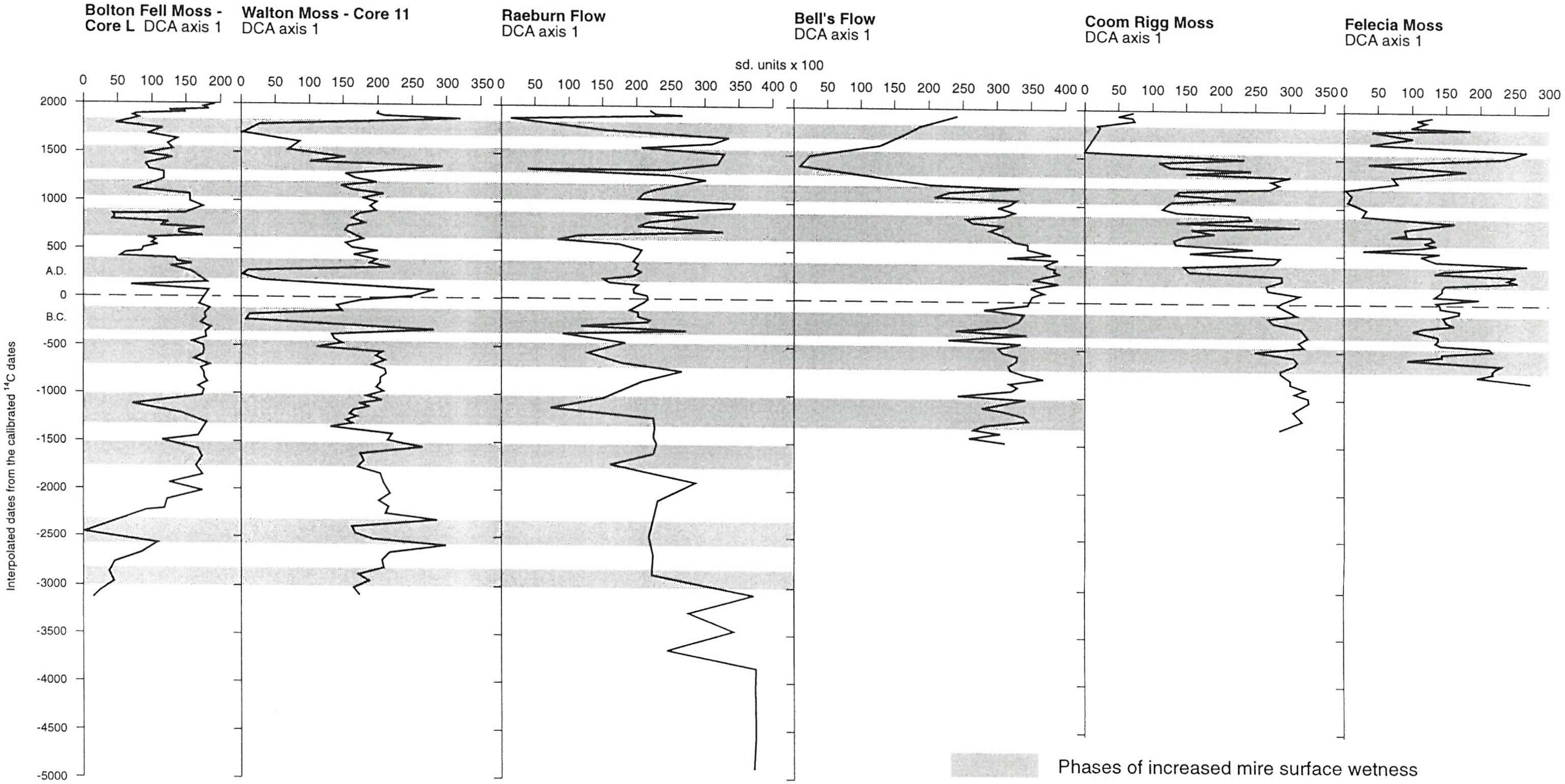


Figure 6.2 DCA axis 1 scores vs. time



analysis of peat humification and testate amoebae has the potential to overcome some of these problems, as each technique is independently capable of detecting dry mire surfaces. These techniques are also subject to potential errors, but identification of a dry phase using at least two techniques should allow the accurate registration of peat samples formed during periods of low effective precipitation. These have been readily identified in Tables 5.12 to 5.22, therefore the significance of both the wet shifts and the drier phases, are discussed below, by comparing them to other inferred climate change dates proposed in the palaeoclimatological literature, and to the documentary evidence for the more recent climatic changes, in order to validate them.

Following this evidence for palaeoclimatic changes, the second part of the discussion will focus on the possible differential sensitivities of the ombrotrophic raised and blanket mire sites to record changes in effective precipitation.

6.2 The Little Ice Age.

The longest instrumental climatic record for the British Isles extends from 1650 AD. (Manley, 1974), which although of short duration in palaeoecological terms, allows some of the climatic deteriorations within the Little Ice Age (LIA) to be placed into context. This term was first introduced by Matthes (1939), and has been described as a world-wide, synchronous cold interval. Grove (1988) highlighted the broad span of dates the LIA can span, since in Europe it started between the twelfth to sixteenth centuries. In addition to this time transgressive nature of the LIA, Bradley and Jones (1993), using a variety of record types ranging from instrumental, documentary and tree-ring densities to reconstruct summer temperatures, suggest the LIA was a more variable period of climatic anomalies, comprising both warm and cold phases, which may have varied geographically on a global basis. For the composite European record, they propose a decline in summer temperatures between the 1570's and 1690's, with a further decline in the 1810's and 1880's. Similar changes have been identified within the Manley data series, for example the time period 1690-1730 AD. demonstrated the most rapid variation in annual to hemi-decadal temperature change (Barber *et al.*, in press).

Palaeoecological evidence which supports the later and most severe stages of the LIA has been presented by Barber (1981). Wet shifts identified using macrofossil *Sphagnum* section *Subsecunda* and *Sphagnum cuspidatum* and algal muds from multiple monoliths were dated pollen analytically to c. 1800 AD. Corroborative work on the same bog (Bolton Fell Moss, Barber, 1995) and Walton Moss (Barber *et al.*, in press), has revealed similar replicable climatic signals using bryophyte evidence within each raised mire, which on the basis of their pollen stratigraphy, reveal uniform increases in local water tables coeval with the later phase (c. 1800 AD.) of the LIA. This section of the LIA can also be detected in the raised mires of Eire, as Abbeyknockmoy Bog, Co. Galway, displayed a wet period c. 1740 AD. (Barber *et al.*, 1994). In addition to this palaeoclimatic evidence from raised peat bogs, signals from blanket peat ecosystems also reveal hydro-climatological changes consistent with the instrumental and documentary evidence. Three of the water shedding blanket peat sites investigated by Blackford (1990 [Harold's Bog, North Yorkshire Moors, Migneint mountain, North Wales, and Letterfrack, Co. Galway, Eire]), displayed wet shifts between 1750-1810 AD., based on interpolated ^{14}C dates. Barber *et al.* (in press), examined the stratigraphy of a water-shedding site within a montane blanket bog ecosystem (Moine Mhor, the Cairngorm mountains), and was also able to date hydroclimatic changes in the plant macrofossil stratigraphy (a switch from relatively xeric *Racomitrium* dominated peat to hygrophilous *Sphagnum* rich peat) to 1680-1850 AD. using both radiocarbon and spheroidal carbonaceous particle (SCP) chronologies (Rose *et al.,* 1995).

Before discussing the possible magnitude of the hydro-climatic changes registered in the study sites, the *Pinus* pollen chronology for each site will be briefly reviewed to assess the accuracy of the pollen correlation's.

6.2.1 *Pinus* Pollen Chronology.

The resolution of the *Pinus* chronology was relatively coarse (samples were taken at 8 cm. intervals from the raised peat bogs and 4 cm. intervals from the blanket peat monoliths). A possible consequence of this is the registration of the *Pinus* rise at the same depth (24 cm.) in 5 of the raised mires investigated (Walton Moss, Raeburn Flow, Bell's Flow, Coom Rigg and Felecia Moss), giving an accumulation rate (these sites were cored in 1995) of 8.1 yr. cm.$^{-1}$ (Figures 6.2 - 6.6). Clearly, sampling at a higher resolution would have more firmly established the occurrence of the *Pinus* rise for each site, as accumulation rates are likely to have varied between the bogs, but time limitations prevented this. Nevertheless, the inferred peat accumulation rate for these mires compares favourably with the pollen derived accumulation rate of 8.33 yr. cm.$^{-1}$ calculated by Barber (1981) for Bolton Fell Moss - Monolith HI9. The slightly faster estimated peat accumulation rate for Bolton Fell Moss - Core L was 6.1 yr. cm.$^{-1}$ (this mire was cored in 1994), since the Pine rise occurs at 32 cm.

Although the Pine rise dates appear to be correct (Section 3.8), pinpointing the date of the LIA using them is difficult, however, as the relatively large sample intervals for both the pollen and radiocarbon dates can 'smear' the period of time over which it occurred. For Bell's Flow, on the basis of both the radiocarbon and pollen chronologies, the LIA occurred between c. 1800 AD. and CAL 1320-1510 AD. Similarly, the range of dates for Coom Rigg Moss is c. 1800 AD. and CAL 1450-1640 AD. There are further potential problems with the blanket peat samples. The Pine rise occurs at 57.5 cm. in Shaft Hill - Monolith 2 (SHL2) and 32 cm. in Shaft Hill - Monolith 3 (SHL3), giving peat accumulation rates of 3.4 and 6.1 yr. cm.$^{-1}$ (the sites were cored in 1996). These inferred accumulation rates are rapid, but not unremarkable, as Barber (1982) calculated peat accumulation rates from the radiocarbon dated pollen profiles of Turner (1965), which approach 3.3 yr cm.$^{-1}$ (Bloak Moss, Ayrshire, between 2646-2354 BP). The pollen derived dates of c. 1800 AD. for these two blanket peat monoliths do, however, *conflict* with the radiocarbon dates. The peat matrix for SHL2 (58-59 cm.) has a 2 σ calibrated date of CAL 1040-1280 AD. (SRR-5900), whilst the sample in SHL3 (28-32 cm.) contains 0.47% modern carbon (SRR-5863), and was out of the calibration range of OXCAL. The sample at 38-42 cm. however, has a 2 σ date of CAL 770-990 AD. (SRR-5964), which again conflicts with the *Pinus* pollen date, since the radiocarbon date appears to be too old. This is unlikely, however, as both SRR-5900 and

SRR-5964 both consistently reveal dates older than those inferred from extrapolations based on the *Pinus* dates. The Pine dates for SHL1 and SHL2 appear to be correct, as analysis of the SCP's within the peat stratigraphy (Figures 5.10 - 5.11), suggests the fresh peat stratigraphy above the U.O.M./*Eriophorum vaginatum* dominated matrices (Figures 5.33 and 5.36) is of recent origin. The c. 1800 AD. Pine rise date in Monolith 1 occurs at 44 cm., whilst SCP's triple in abundance at 45.5 cm.. In Monolith 2, the Pine rise occurs at 57.5 cm., whilst SCP's are also present at this depth. In Monolith 3, *Pinus* pollen concentrations increase at 32 cm., whilst the first continuous increase in SCP's occurs at 35.5 cm. The juxtaposition of very high *Pinus* pollen concentration values in SHL3 (Figure 6.9), with rapid increases in SCP spherules (Figure 5.12), invites the possibility that the peat matrices containing the Pine rise pollen post date c. 1800 AD.

The Pine pollen and SCP stratigraphy from SHL2 may reflect an early nineteenth century/late eighteenth century date for the inception of a wet shift marked by high abundances of *Sphagnum* section *Cuspidata* leaves at 54.5 cm. in SHL2 (Figure 6.8). Peat matrices containing *Sphagnum* section *Cuspidata* in SHL1 however, (54.5-59.5 cm.), pre-date the *Pinus* (44 cm., Figure 6.7) and SCP (45.5 cm., Figure 5.10) take-off levels. Increased mire surface wetness does not, therefore, appear to have occurred around c. 1800 AD. at this position on the blanket peat surface. Unfortunately, there are no radiometric dates available for this monolith, and therefore it is difficult to gauge the age of this hydro-climatic event. The stratigraphy from SHL3 which contains hygrophilous *Sphagnum* section *Cuspidata* (30 cm., Figure 6.9), may date to c. 1940-1950 AD., since there is a very large increase in SCP's at 35.5 cm., which could possibly relate to the same feature identified in lake sediments by Rose *et al.* (1995).

If the radiocarbon dates are indeed plausible, an explanation needs to be found to explain their divergence from the pollen and SCP 'dates' derived for SHL2 and 3. One possible reason for the anomaly could simply be that peat accumulation rates were very low in the radiometrically dated samples, possibly due to high rates of decomposition because of a climatic amelioration. This is supported by the work of Barber (1981), as he found evidence for reductions in peat growth rates in more humified peat matrices from Bolton Fell Moss - Monolith HI9 (33.9 yr. cm.$^{-1}$ for peat pre-dating the main humification change, and 13.3 yr. cm.$^{-1}$, following this stratigraphic marker).

The humification, plant macrofossil and testate amoebae stratigraphy in SHL2 and 3 indicate low local water tables in the radiometrically dated samples, which may help to explain the low rates of accumulation in the samples pre-dating the 'rejuvenation ' layer, which in its turn, may have been triggered by an increase in effective precipitation at c. 1800 AD.

It is unlikely, however, that changes in accumulation rates have led to the demonstrated maximum 760 year age difference between the 1800 AD. date for SHL2 (57.5 cm. depth) with the ^{14}C date for a level just 1 cm. lower (CAL 1040-1280 AD). Given this, there is the distinct possibility that a hiatus has occurred between these two levels, possibly as a result of burning. A severe fire, either natural or human initiated, could have

Figure 6.3 Bolton Fell Moss - Core L. Selected taxa.

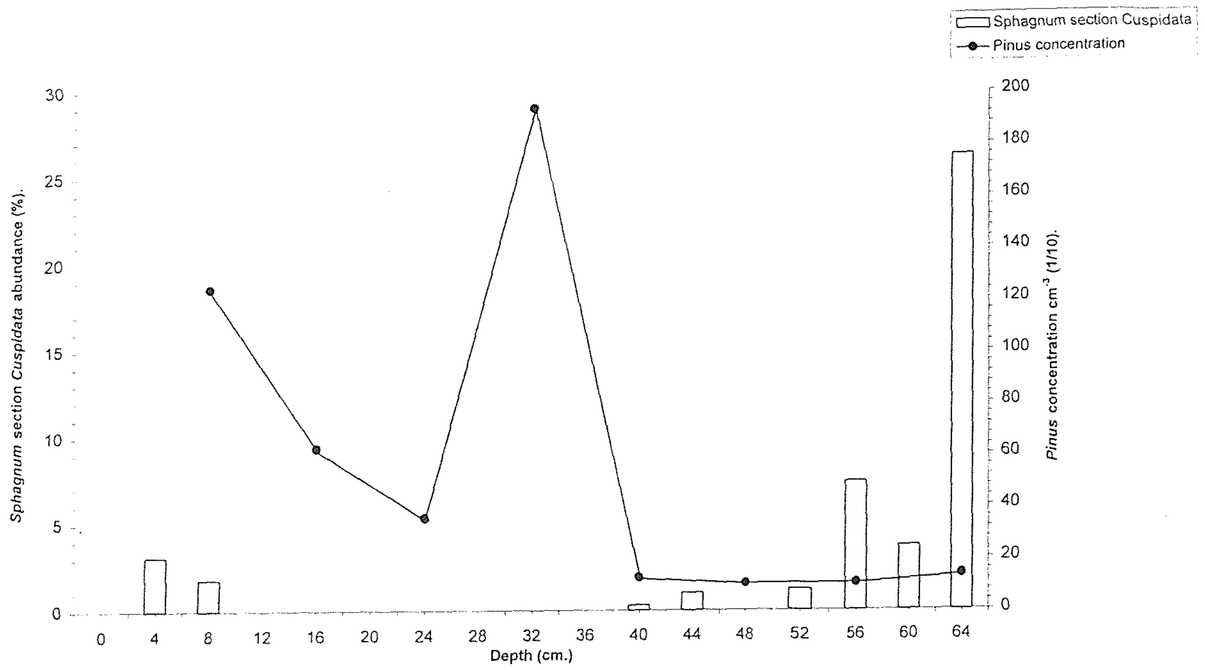


Figure 6.4 Walton Moss - Core 11. Selected taxa.

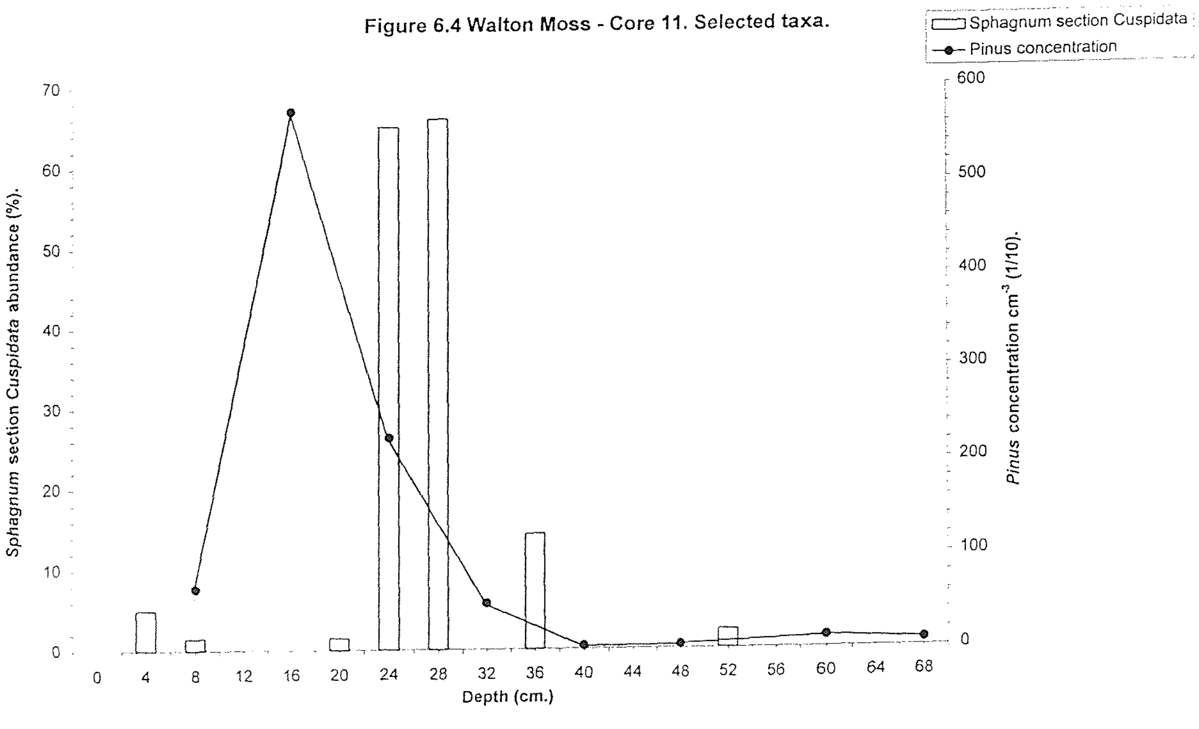


Figure 6.5
Raeburn Flow - Selected taxa.

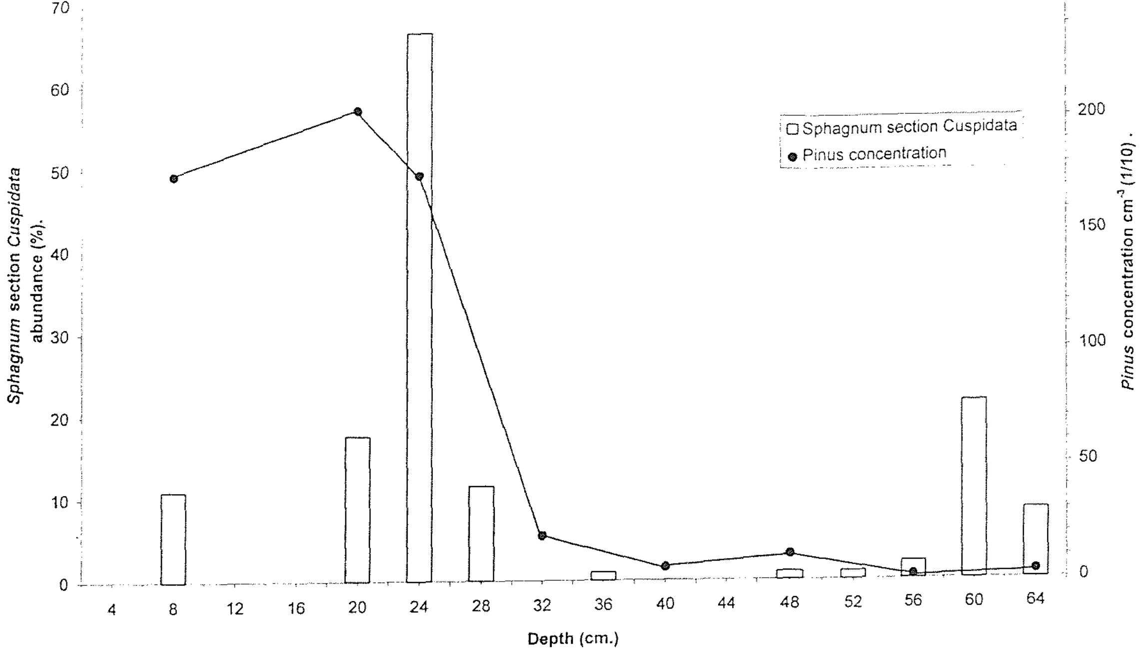


Figure 6.6 Bell's Flow - Selected taxa.

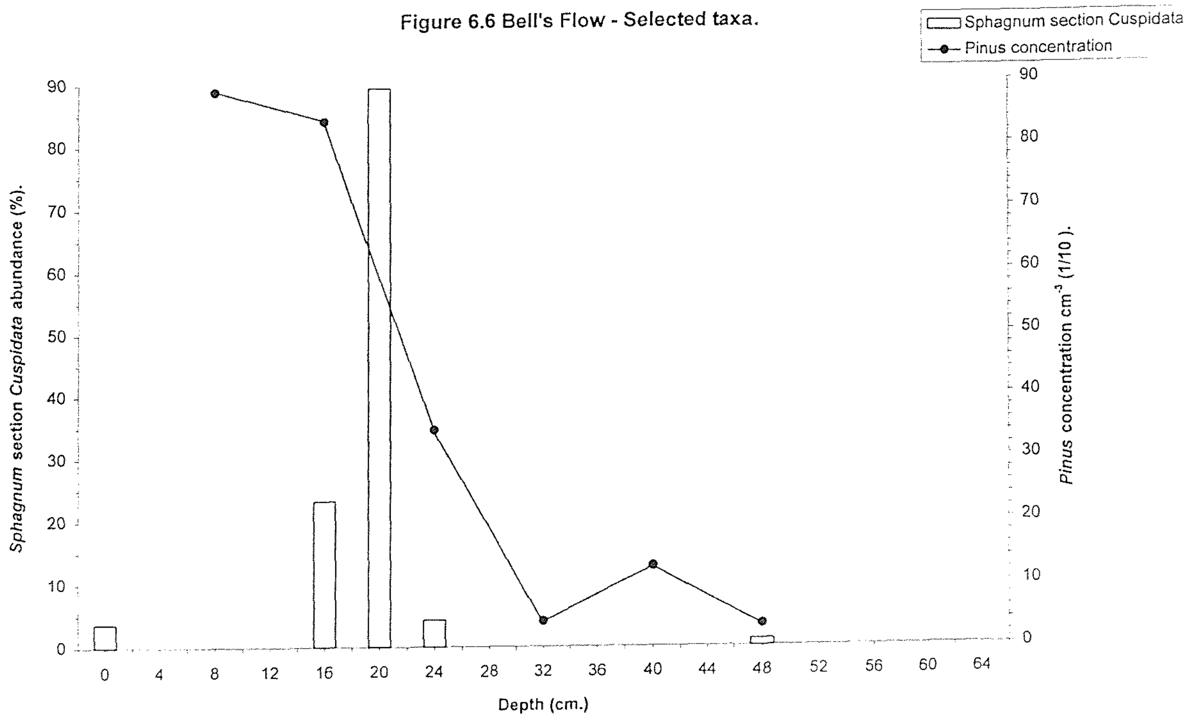


Figure 6.7 Coom Rigg Moss - Selected taxa.

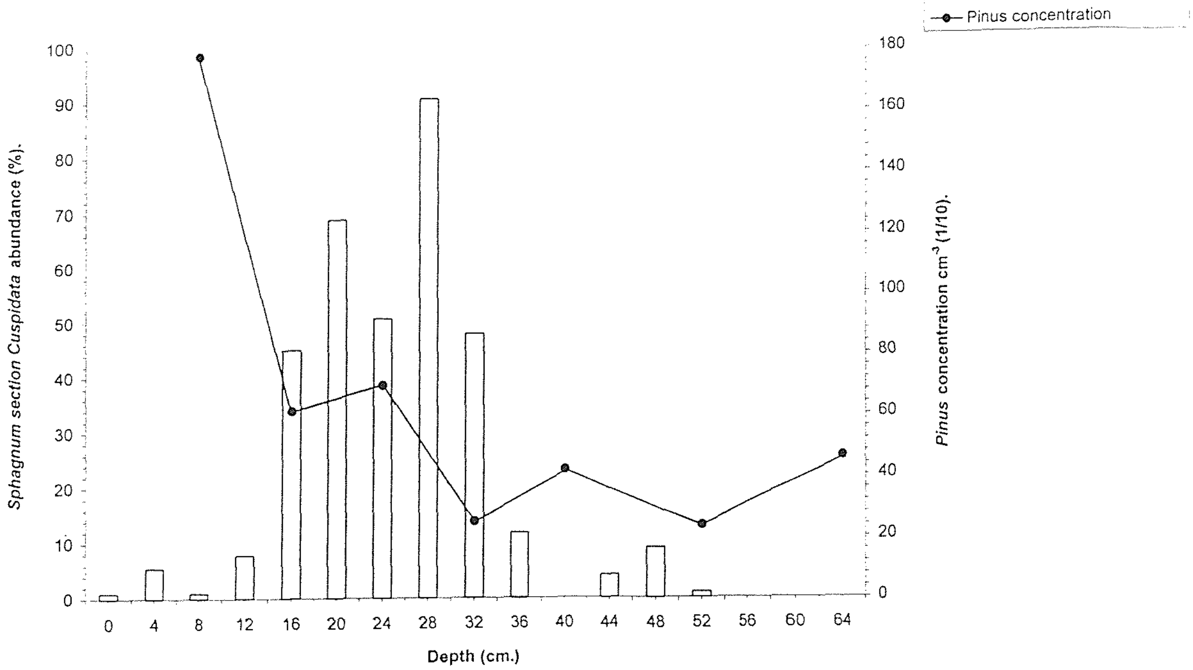


Figure 6.8 Felecia Moss - Selected taxa.

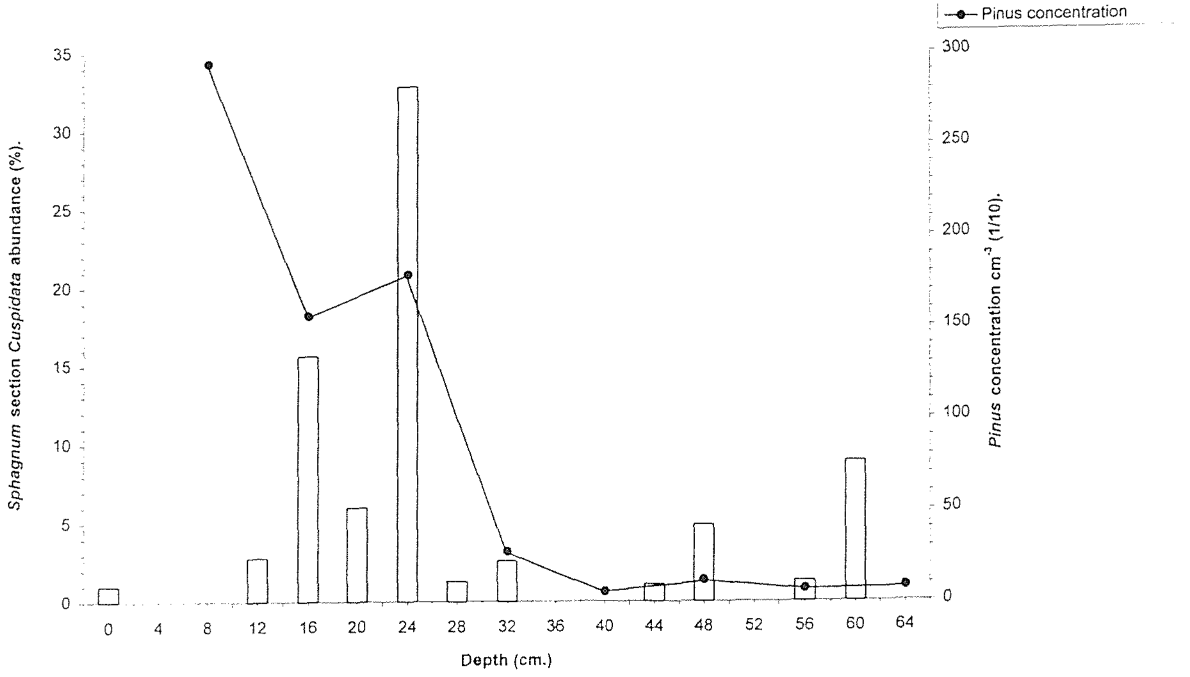


Figure 6.9 Shaft Hill - Monolith 1 - Selected taxa.

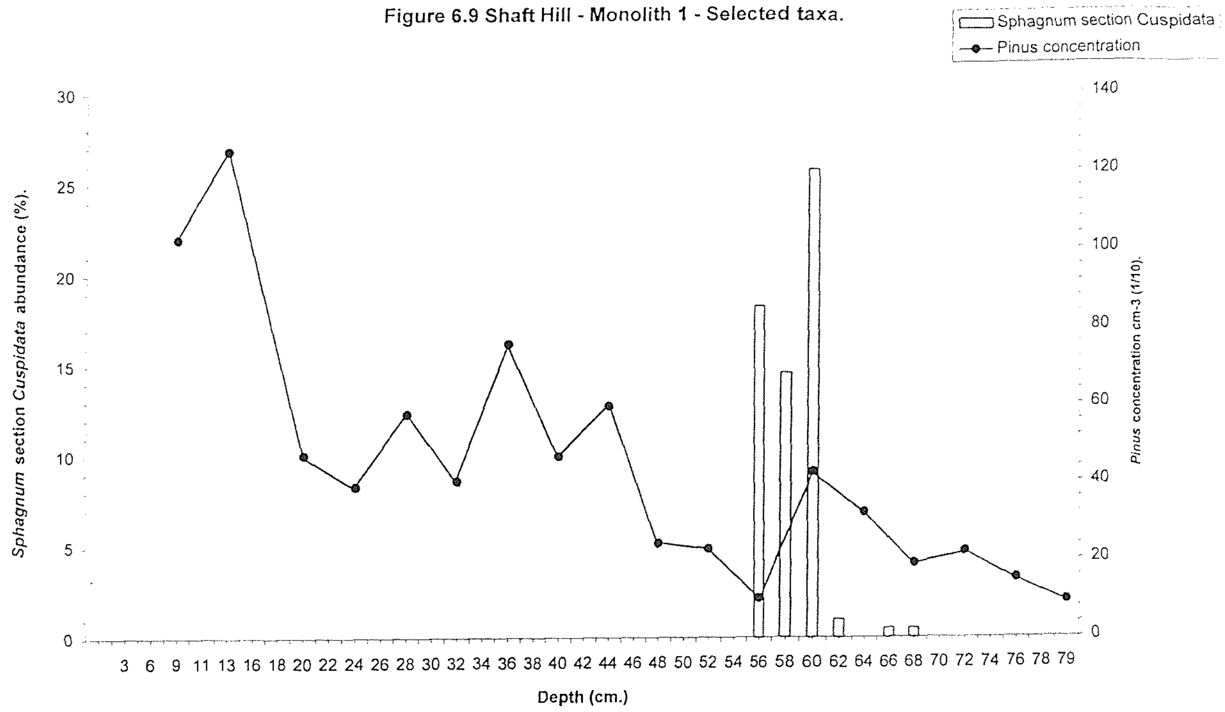


Figure 6.10 Shaft Hill - Monolith 2 - Selected taxa.

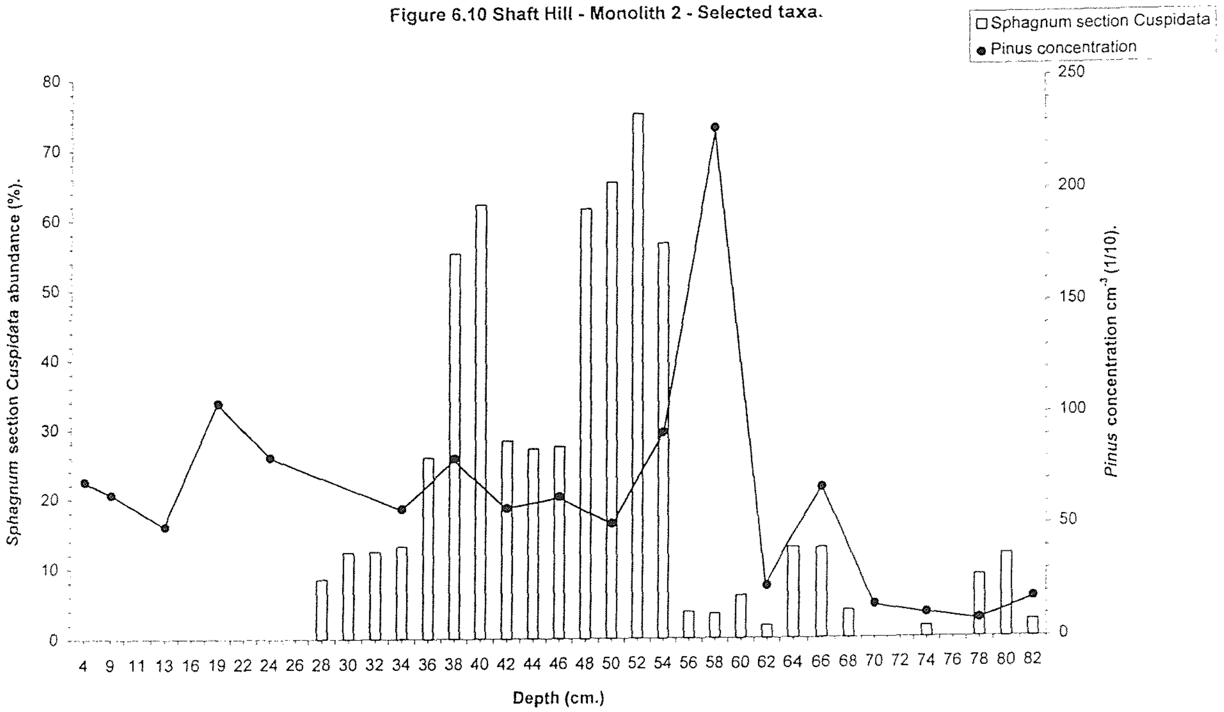
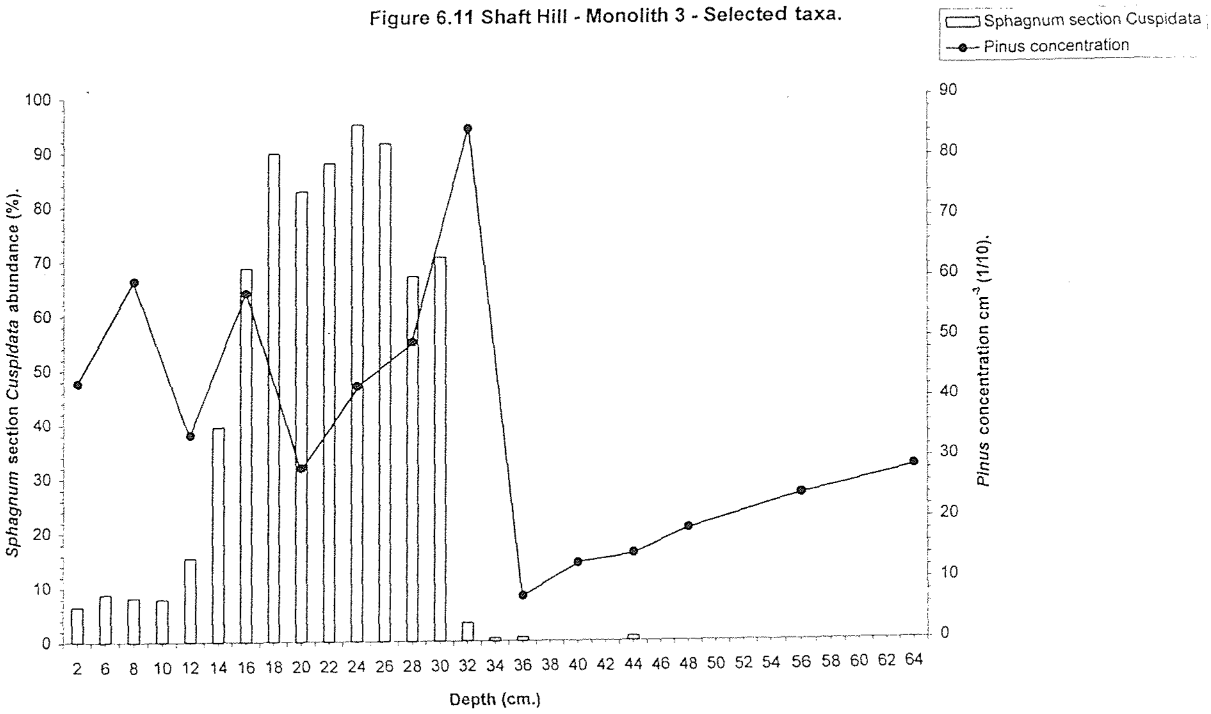


Figure 6.11 Shaft Hill - Monolith 3 - Selected taxa.



burnt down into the peat matrix and destroyed the record of peat spanning the time period between the two dates. Summer fires during drought conditions can generate sufficiently high temperatures to ignite the surface organic horizons (Legg *et al.*, 1992). These fires can smoulder for weeks destroying up to several decimetres of peat (Radley, 1965). There is certainly macroscopic evidence for the local burning of the vegetation (Figures 5.33 and 5.36), and given the extreme sub-arctic climatological conditions the Moor House Reserve experiences, the impacts could have been long lasting. Miller and Cummins (1987), have shown that *Calluna* seedling mortality is high in upland areas because of desiccation caused by frost-heave and wind blast, which in combination with the physical removal of peat by combustion, may account for the possible hiatus in each of the monoliths from Shaft Hill.

Variations in accumulation rates may explain the divergence between the radiocarbon and Pine rise dates for Bell's Flow and Coom Rigg Moss (Figure 5.5 and 5.6), since there is no discernible increase in the adundances of charcoal in these boreholes. Peat growth may have stagnated on Bell's Flow between 1415 AD. (SRR-5878) and 1225 AD. (SRR-5879), and a retardation layer may be present between the two dated levels. This is supported by the humification and plant macrofossil stratigraphy of Bell's Flow, since absorbance values (Figure 5.27) and the abundances of U.O.M. (Figure 5.28) are high. This time period corresponds to the 'High Middle Ages' (Section 6.2.4), and a climatic amelioration may have caused a slowing down of peat accumulation. Peat may not have actively accumulated again until a sufficiently severe climatic deterioration occurred to increase the productivity of the mire flora, and retard decomposer micro-organisms. The juxtaposition of the high Pine pollen values with the 1415 AD. radiocarbon measurement, suggests the latter stage of the Little Ice Age may have provided the necessary increased effective precipitation to facilitate this on Bell's Flow. There is a similar, though less extreme juxtaposition of radiocarbon and Pine rise dates for Coom Rigg Moss (Figure 5.6). The *Pinus* rise for this site occurs at 24 cm., whilst the radiocarbon assay taken from 28 cm. (mid point of the sample), has a 2 σ calibrated date of 1450-1640 AD. (SRR-5883). Peat accumulation rates may have again slowed prior to the wet shift post-dating the radiocarbon measurement (evidence for possible climatic ameliorations is presented in Section 6.2.3), in a similar manner to Bell's Flow, as peat humification is relatively high at 1545 AD. (Figure 5.32). The radiocarbon measurement was also taken from a bulk sample containing abundant *Sphagnum* section *Cuspidata* leaves. *Sphagnum* species in pool environments decay faster than those in hummock microtopes, possibly due to both pool oxygenation promoting microbial decomposition, and the reduced decay resistance of *Sphagnum* pool species (Johnson *et al.*, 1990; Rochefort *et al.,* 1990; Johnson and Damman, 1991, Hogg, 1993). This may have again led to a reduction in peat growth rates.

The similarities between the pollen and SCP chronologies constructed for SHL1, 2 and 3, suggests the Pine pollen dates provide an approximation for the ages of peat samples post-dating c. 1800 AD. With the exception of BFML and SHL1 and 3, increases in hygrophilous *Sphagnum* section *Cuspidata* leaves in six boreholes occur coevally with the Pine rise, offering strong support for the existence of high effective precipitation regimes during the late LIA. (Figures 6.1 to 6.9). Other changes within the LIA period pre-dating this pollen chronostratigraphic marker date may be more difficult to detect, given the possibility that climatic fluctuations within the LIA may have occurred on a decadal time-scale (Meese *et al.*, 1994). Because of this rapidity, it is difficult to accurately correlate periods of climatic severity during the LIA within the peat stratigraphy using the relatively large 2 σ age ranges of the bulk ^{14}C dated samples.

Despite these chronological shortcomings, a provisional assessment of the magnitude of the LIA has been attempted in Section 6.2.3. The registration and possible magnitude of other periods of increased and decreased effective precipitation (identified in Tables 6.1 and 6.2) has also been made in the ensuing sections. An attempt has been made to group the periods of hydroclimatic changes identified in Tables 6.1 and 6.2 into a contiguous time series.The different lead and lagg response of each of the peat components to environmental change (Section 5.7), can potentially extend the range of dates over which a single change in effective precipitation is registered. Allied to this, the date ranges displayed in Tables 6.1 and 6.2 are based on linear interpolations of calibrated ^{14}C dates, and are rounded to the nearest decade. Because of this, the date ranges identified in the following sections may extend beyond the section title age range and overlap with other section date ranges.

At this juncture, the limitations of the ^{14}C chronology are clearly evident, and need to be reiterated, since the palaeoclimatic changes identified here are based, at best, on six bulk high precision dates for a five metre borehole (Bolton Fell Moss - Core L and Walton Moss - Core 11). The age depth models constructed for these two sites appear to show relatively constant rates of peat accumulation (Figures 5.2 and 5.3), but these features may be more apparent than real. In the first instance the bulk radiocarbon dates may be imprecise (Section 3.9), possibly due to areas where the calibration curve is flat (Pearson *et al.*, 1986). Allied to this, the possible presence of 'old' methane, and its fixation by mycorrhizal fungi associated with *Calluna vulgaris* roots, may mean some of the radiometric dates are too old, if the theory of Kilian *et al.* (1995) is correct.

The high precision (HP) radiometric dates for this research project were derived from 8 cm. slices of peat. There is a possibility some of the samples may have been contaminated by rootlets, particularly by roots of *Eriophorum* species, since their roots can grow up to c. 1 m. below the peat surface (Heal *et al.,* 1978). The large sample sizes of peat required for the HP dates may have also led to further uncontrolled environmental errors (Oldfield *et al.*, 1997), as some of the samples may have contained a contact between a hummock and a pool microtope. These two areas of microrelief on the mire surface can accumulate at very different rates. The rate of peat accumulation in hummock communities has been found to be twice that displayed by lawn communities (Ohlson and Dahlberg, 1991). This may be due to the higher decay resistance of hummock species compared to lawn and hollow species (Johnson *et al.,* 1990; Rochefort *et al.*, 1990; Johnson and Damman, 1991; Hogg, 1993). The low decay resistance of *Sphagnum* pool species will clearly violate the assumption of an even rate of accumulation between radiometrically dated points of the peat stratigraphy, and the age/depth model constructed for each of the sites is an oversimplification of possible peat accumulation rates.

In the light of these shortcomings, the rounding off of sample points between dated levels to the nearest decade is a gross oversimplification and is recognised here. A more realistic figure would be to the nearest century (Prof. Frank Oldfield, pers. com.). Despite this, having clearly stated the deficiencies of the radiocarbon chronology, the decadal timescale has been employed, with a key understanding that the time periods of climatic change identified using the chronology will only serve to indicate the possible age range over which these climatic departures occurred. A more sophisticated 'wiggle match' in future research will pinpoint to a far higher degree of certainty, the timing and rapidity of palaeoclimatic changes. Analysis of this nature has already been undertaken by Van Geel *et al.* (1996), and the option of AMS dating is considered further in Chapter 7.

On a more encouraging note, the Pine rise date of c. 1800 AD., in Northern England and the Scottish Borders (Section 3.8), offers a reliable 'pinning point', to each of the age/depth models, and for this period of time, at least, the age/depth models will be potentially accurate to a few decades either side of c. 1800 AD. (Professor Frank Oldfield, pers. com.).

6.2.2 1990-1850 AD.

Within this time period, the six raised peat bog study sites register dry shifts. Attributing this to a climatic amelioration is dangerous, however, as both Coom Rigg and Felecia Moss have been afforested, whilst Bolton Fell Moss has been subject to disturbance through peat cutting operations (Section 4.1, 4.5 and 4.6). Because of the increasing scale of modern disturbances to raised mires, it may be pure coincidence that evidence for drier mire surfaces detected in the stratigraphy of Bell's Flow and Felecia Moss between 1930-1960 AD., matches the findings of the IPCC (1996), since global temperatures were relatively warm in the 1930's and 1940's. Barber *et al.* (in press), suggests there has been a gradual rise in air temperatures in the UK during the last 350 years, with a rise of $0.2^{\circ}C. \pm 0.06\ ^{\circ}C.\ century^{-1}$. The registration of dry shifts by the mire flora and fauna may represent a culmination of this warming trend, but again, human disturbances may equally be responsible for this drying trend, through alterations in mire hydrology.

6.2.3 1700-1850 AD.

The registration of the latter stage of the LIA (c. 1800 AD.) in SHL2, represents the wettest phase detectable in this blanket peat stratigraphy. The oldest dated sample from SHL2 (SRR-5901) has a 2 σ calibrated date of 230-450 AD., therefore the record of this blanket peat monolith is short in relation to that derived from the raised peat bogs. These extend back to CAL 3500-3100 BC. (Bolton Fell Moss - Core L, SRR-4937), whilst the interpolated radiocarbon dates extend back to 4860 BC. for Raeburn Flow. Despite this, for two of the raised peat bogs (Bell's Flow and Coom Rigg Moss), the Pine rise chronology suggests the LIA represents the *largest* change based on the humification, Dupont indices (calculated from both the plant macrofossil and testate amoebae components), and the DCA ordinations. The high magnitude of this hydro-climatic signal in three of the research sites, and its registration in seven boreholes from seven of the study sites, suggests the

LIA was a significant climatic deterioration. This supports the conclusions of Barber *et al.* (1994a, b, 1995), Huntley (1994) and Chambers *et al* (in press). Barber et *al.* (1996, in press) have developed this further and suggest, 'the Little Ice Age is the coolest period of the last 2000 years', based on the results of multi-climate proxy data (plant macrofossils, diatoms, magnetic records and L.O.I. data). This is supported by ice-core data, as O'Brien *et al.* (1995), noted the modern day peak abundance of sea salt in Greenland snow occurs in winter when the atmospheric circulation is intensified because of expansion of the north polar vortex or enhanced meridional flow. By interpreting changes in the flux values of sea salt species within the GISP2 Summit Ice Core, O'Brien *et al.* matched the most recent and abrupt increase in sea salt concentration to the LIA Event.

6.2.4 1500 AD. - 1700 AD.

Drier mire surface conditions are registered by Walton Moss - Core L, Raeburn Flow and Felecia Moss during this time period (Table 6.2). According to Lamb (1995), the climate of the time interval 1500-1550 was 'mostly genial'. Lamb develops this further by exploring the work of Hoskins (1964), quoting examples of good harvests between 1537-1548. Barber (1981) offers palaeoecological evidence supporting this work, since he noted evidence for temporary drying out in monolith DI1 between 1510 and 1610 AD. Stoneman (1993) also found plant macrofossil evidence for a climatic amelioration between 1480 and 1645 AD. The later seventeenth century dates for dry mire surface conditions identified here may reflect the great variability of weather in the LIA, as Lamb points to the hot summer weather London experienced in 1665 and 1666, or alternatively the dating control may not be precise enough.

6.2.5 1150 AD. - 1500 AD.

Paradoxically both drier phases (1110-1290 AD., 1370-1480 AD.) and wet shifts (1290-1530 AD.) are identified in the study sites. This may be an artefact of the potentially imprecise interpolations made from the radiocarbon dates, which themselves contain errors of ± 45 years before calibration, and may also highlight the difficulty of accurately dating dry phases discussed in section 6.1. Equally, however, the registration of both wet and dry phases may reflect the great climatic variability during these centuries (Section 6.2).

Aaby (1976), identified a change in peat humification in the stratigraphy of Draved Mose, which is dated to 1500 AD., whilst Barber (1981), using the tables in Lamb (1966), proposed there was a period of excessively wet summers during the period 1320-1500 AD. The *Sphagnum* macrofossils identified in seven monoliths by Barber (1981) clearly demonstrated a wet shift starting at 1425 AD., whilst the characterisation of storm surges around 1449-1452 AD. along the Lancashire coast using monastic records of dune instability (Tooley, 1985), also supports the existence of a climatic deterioration at this time. Organic material has been used to date outermost moraines delimiting the neoglacial maximum extent of four glaciers in the Jotunheimen-Jostedalsbreen region of southern Norway (Matthews, 1991). The maximum 2 σ dates for the burial of organic material range from 1424-1516 AD., strongly suggesting a climatic deterioration occurred during the early LIA. Matthews (1991) proposes the severity of the LIA was sufficient to allow the largest Norwegian glacier expansion since regional deglaciation c. 9000 BP, and 'the most southerly migration of oceanic and atmospheric polar fronts since the early Holocene'.

Stoneman (1993), further corroborates the record and suggests the period 1335-1615 AD. was a period of climatic deterioration, based on plant macrofossil results from 10 raised peat bogs.

Palaeoclimatic reconstructions can also be found in the literature which support the earlier records for dry shifts from the study sites, which commences from 1110 AD. and extends to 1480 AD. Parry (1975), examined the cultivation of oats and the abandonment of farmland in south-east Scotland, and found the optimum limit of cultivation in the Lammermuir hills occurred around 1150-1250 AD. at 450 m. OD. In comparison to this climatically optimal period, the deteriorations of the LIA around 1600 AD., forced a 140 m. fall in the limit to cultivation. Lamb (1995) discussed documentary and parameteorological phenomena which attest to the warmth of the High Middle Ages (1050-1310 AD.), drawing attention in particular to the distribution of medieval vineyard sites. Using data from the modern limits of wine production, Lamb suggested average summer temperatures during this period were 0.7 to 1.0 °C warmer than the twentieth-century average. Highly humified peat matrices containing abundant *Empetrum* and *Vaccinium* pollen below a zone containing abundant *Racomitrium lanuginosum* leaves, have been identified from Over Wood Moss, an uneroded Southern Pennine blanket peat site, and dated to 1150-1300 AD. by Tallis (1995), offering further palaeoecological evidence for dry conditions which match those periods (1110-1290 AD., 1370-1480 AD.) identified here.

6.2.6 800 AD. - 1150 AD.

The age ranges of the reconstructed dry (930-1090 AD.) and wet shifts (790-1060 AD. and 1010-1210 AD.), overlap once more, pointing to the potential occurrence of highly variable regional climates.

Within the 790-1210 AD. wet shift range identified in the study region, some of the inferred dates match those recorded by Dickinson (1975), where a date of 805 BP (1145 AD.) was estimated for a peat sample taken above a recurrence surface from Rusland Moss, Cumbria. Aaby (1976, 1978) supported the existence for wetter conditions at this time further, by presenting evidence for declines in peat humification values at 1000 AD. and 1250 AD. Barber (1981), noted pools expanded across the surface of Bolton Fell Moss around 900 AD., followed by a drying phase, then a second wet-shift recorded at 1150 AD. Blanket peat profiles examined by Chambers (1984) show changes to wetter conditions around 1150-1200 AD., whilst Stoneman (1993) identified a climatic deterioration between 930-1120 AD. in the aggregate peat stratigraphy of Cumbrian and Scottish raised bogs, which further supports the wet shift dates identified in this research project.

Within the 160 year 930-1090 AD. period, the high humification values of Raeburn Flow at 108 cm. (950 AD., Figure 5.26) and a marked change in the thecamoebae stratigraphy in Walton Moss at 84 cm. (1040 AD., Figure 5.20), certainly point to drier mire surface conditions within these sites, although only three mires demonstrate this (Walton and Coom Rigg Moss and Raeburn Flow). Barber (1981) identified a dry phase in the stratigraphy of Bolton Fell Moss between 900-1150 AD., which compares favourably with the 920-1080 AD. episode identified here. The failure of the other sites to record a similar change possibly suggests the dry phase identified here may not have been severe enough to induce a change in their stratigraphy, given the ability of mires to resist hydro-climatological changes through negative feedback processes. For example, where water tables fall, the permeability of the acrotelm diminishes, reducing the seepage of water to the lagg (Section 2.2.3). This reduction in permeability has been attributed to collapsed plant structures induced by higher overburden pressures (Clymo, 1992), and may prevent a marked decline in local water tables.

6.2.7 650 AD. - 800 AD.

Clearer evidence for dry mire surfaces is presented in this time period, since BFML, Bell's Flow, Coom Rigg and Felecia Moss offer evidence for climatic ameliorations between 640-890 AD. Corroborative matching evidence can be found once again in the surface wetness curve of Barber (1981), as the century 800 AD. appears to have been dry, whilst the 765-970 AD. climatic amelioration period identified by Stoneman (1993) offers further encouraging evidence for the recognition of a common period of low effective precipitation within the study region.

6.2.8 550 AD. - 650 AD.

A wet phase spanning this time interval can be detected in all six of the raised mires investigated, although its registration in BFML extends from 680-810 AD. and 660-710 AD. in WLM11. The radiocarbon dated blanket peat monoliths, however, do not register this, and other changes, with the exception of the late LIA in SHL2. Wide ranging regional and supra-regional palaeoecological evidence supporting this time period has been found by a suite of researchers. For example Mitchell (1956), identified a recurrence surface (a change from humified to unhumified peat), around 500 AD. in Irish raised bogs. Nilsson (1964), recorded a wet-shift at 650 AD. in Agerods Mosse, Sweden, whilst Aaby (1976), noted a change in peat matrix humification at 500 AD. (Draved Mose, Denmark). Lamb (1977b), pointed to the existence of cool summers between 500-700 AD., which compared favourably with the plant macrofossil evidence presented by Barber (1981), and the peat humification change of c. 650 AD. identified by Chambers (1984) from a blanket peat sample in the Brecon Beacons, South Wales. Narrow Belfast tree rings which may represent a response to adverse summer growing conditions, have been identified by Baillie and Munro (1988) and dated to 541 AD., whilst Blackford (1990) and Blackford and Chambers (1991), highlight the existence of a change to wetter conditions around 550 AD. The blanket peat stratigraphy of Letterfrack, Eire shows changes in humification between 620-655 AD., in addition to those inferred from Harold's Bog, and Migneint Mountain North Wales (525-530 AD.). Stoneman (1993) identified a phase of increased mire surface wetness between 470-660 AD., which in addition to the other evidence, provides strong evidence for increases in effective precipitation both for the study region and the quoted North European sites.

6.2.9 200 AD. - 550 AD.

Both wet and dry changes appear to have occurred during this time interval. Given the difficulties of dating dry episodes and the range of dates obtained from each site using multi-proxy evidence, the inferred wet and dry time intervals overlap a great deal again. Dry phases seem to have lasted from 230-370 AD. and 360-530 AD., whilst wetter conditions may have prevailed from 210-380 AD. There is up to a 140 year difference between the humification and Dupont index dates for the inception of dry mire surface conditions within the research sites (Raeburn Flow, Table 5.16), which may partly explain this overlap. This may possibly reflect the lead and lagg response of these proxy-climate components. A 300 year difference in timing between local pollen assemblages and peat humification signals has been noted by Tipping (1995). These variations between the different hydro-climatic proxies may blur the consistent registration of allogenic forcing over short (less than 250 year) intervals, and renders detection of hydro-climatic events difficult for this time period.

Conway (1948), suggests each mire has a *threshold* 'moisture factor' value which must be exceeded before a climatic shift is expressed by the flora. Aaby (1976), and Barber (1982) have used this idea to explain temporal variation in the registration of climatic signals, whilst Haslam (1987), has developed this idea further, and suggests hydrological variations in average seepage rates, storage capacities and the fronts of efflux between mires, may partly explain their diachronous response to changes in effective precipitation. These factors on their own or in combination, may account for the overlapping date ranges for the wet and dry shifts.

Godwin and Willis (1960) detected a recurrence surface in Helsington Moss, Cumbria, and the radiocarbon date for the unhumified peat above the recurrence surface was 1514 ± 100 BP ([436 AD.] Q-83). Another raised mire, Rusland Moss, (Dickinson, 1975), also had a recurrence surface which was dated between 1552-1511 BP (398-439 AD.). The bogs investigated by Smith (1985) in Humberside revealed a range of dates for the formation of their recurrence surfaces, spanning 1680-1460 BP (270-490 AD.), whilst the blanket peat stratigraphy investigated by Blackford (1990) showed wet shifts between 230-260 AD. and 410-530 AD. This data fits in with the 210-380 AD. wet shift range identified from the project sites, offering evidence for regional climatic changes.

There is a dearth of palaeoclimatological evidence for dry phases at this time, but peat samples intercalating sand have been dated to 155 AD. and 580 AD., and highlight a period of dune stability in Ainsdale, Lancashire (Tooley, 1990). The repetition of dune stability during the Medieval Warm Period, suggests this earlier phase of dune stability may also reflect a period of climatic amelioration, with a low incidence of storms.

There does on balance appear to be evidence for both wet and dry shifts, but once again the timing of the dry shifts need to be interpreted cautiously, given the problems discussed in Section 6.1.

6.2.10 150 BC. - 200 AD.

Wet shifts extend from 160 BC. to 100 AD. (2100-1850 BP), and match the periods identified by Stoneman (1993, 130 BC.-150 AD.) and Tipping (1995, 2050-1950 BP). There are overlapping dates once again for inferred periods of dryness, which extend from 130-40 BC. and 20-170 AD., but in this instance, there is a lack of proxy evidence with which to compare and provisionally validate them.

6.2.11 850 BC. -150 BC.

Wet shifts are registered between 790-440 BC. (2740-2390 BP) and 440-130 BC. (2390-2080 BP). There is a large amount of published palaeoecological material to substantiate this. Recurrence surface dates derived by Godwin and Willis (1960) from Flanders Moss, the Forth Valley (2712 ± 120 BP, Q-541-3) and Pilling Moss, Lancashire (2760 ± 120 BP, Q-68) correspond to the earlier wet shifts identified here. Godwin and Willis (1960) and Godwin and Switsur (1966), also dated recurrence surfaces in Tregaron Bog, Wales and Chat Moss, Cheshire to 2646 ± 100 BP (Q-863) and 2645 ± 70 BP (Q-863) respectively. Blanket peat ecosystems analysed by Tallis and Switsur (1973) in the southern Pennines (Featherbed Moss) yield a similar date for the start of *Sphagnum* growth at 2685 ± 50 BP (Q-855). Coles *et al.* (1975) published a range of dates for buried tracks in the Somerset Levels, which extend from 2685-2410 BP, whilst Dickinson (1975) found 2686 ± 50 BP (SRR-128) to be the earliest date for the initiation of unhumified peat in Rusland Moss, Cumbria. Humification values declined markedly in Draved Mose, Denmark at 620 BC. (Aaby, 1976). Van Geel (1978) and Brenninkmeijer *et al.* (1982) highlighted a marked change in the plant macrofossil, *Corylus avellana* pollen percentages and $\delta\ ^{18}O$ and Deuterium percentages at c. 800 BC., from a raised bog core taken from the Engbertsdijksveen, the Netherlands. Barber (1982) suggests cooler and wetter climates prevailed between 2850-2550 BP, whilst recurrence surface formation in the Humberside raised bogs analysed by Smith (1985), occurred between 2470-2260 BP. Finally, Charman (1990; 1995) places a change to a *Sphagnum* rich stratigraphy in the Cross Lochs area, the Flow Country to c. 2700 BP.

The similarity in timing of these events, given the errors in radiometric dating, suggest the climatic deterioration detected here occurred over a large area of Britain and extended into Denmark. The registration of palaeoclimatic changes in these sites which all experience maritime climates, could have arisen because of the possible operation of a common forcing mechanism, perhaps ocean-driven, which has been suggested by Barber *et al.* (1994). Both BFML and WLM11 share common proxy climate periodicities (Section 5.7.2) between 261 and 275 years (Table 5.23), which match some of the periods identified by Aaby (1976) in Danish mires, and those detected by Wijmstra *et al.* (1984) in the Engbertsdijksveen, the Netherlands. There does therefore appear to be a common periodicity in the climate proxies reconstructed from a range of maritime European sites, which could possibly highlight the existence of a common ocean driven trigger mechanism.

Dry phases can also be detected spanning 830-580 BC. (2780-2530 BP) and 580-400 BC. (2530-2350 BP), which overlap the dates identified by Stoneman (1993) of 625-510 BC. Van Geel *et al.* (1996) discusses the possibility of climatic deteriorations occurring in a stepwise manner with 'alternations of two steps forward and one step backward', during the period c. 3350-2550 BP, which may explain the existence of both wet and dry phases within this 830-130 BC. time frame.

6.2.12 1250 BC.-850 BC.

Elevated mire surface wetness and therefore increased effective precipitation occurred between 1290-920 BC. (3240-2870 BP). This hydro-climatic reconstruction is supported by the deuterium/hydrogen ratios determined by Dubois and Ferguson (1985) for sub-fossil Pine. Using this technique they suggest there was a 'pluvial' phase of wet conditions in the Cairngorms at c. 3300 BP. Further afield in Eire, Mongan Bog changed from a sedge to a *Sphagnum* dominated mire between 3500-3000 BP (Barber *et al.*, 1994). The stratigraphy of Burnfoothill Moss, in the Scottish Borders, also contained more *Sphagnum* between c. 3200 and 3100 BP, highlighting the increased wetness of this time period (Tipping, 1995a).

6.2.13 1550 BC.-1250 BC.

Drier conditions return to the study sites between 1550-1240 BC. (3500-3190 BP). Turner *et al.* (1973) dated a peat sample below a recurrence surface to 3150 ± 100 BP (GaK-2913), at Wheelhead Moss, the Northern Pennines. Outside the study region, Barber *et al.* (1994) point to the existence of relatively dry, sedge dominated bogs prior to c. 3500 BP in Eire (Abbeyknockmoy and Mongan Bog). The colorimetric humification analyses undertaken by Tipping (1995), suggest dry mire surface conditions were sustained until 3600-3500 BP at Burnfoothill Moss, the Scottish Borders.

6.2.14 1700 BC.-1550 BC.

A wet shift is recorded between 1690-1560 BC. (3640-3510 BP) in BFML and Raeburn Flow. It is also registered using all four water level reconstruction techniques in the stratigraphy of WLM11, but extends from 1690-1340 BC. The other raised mires may well have recorded this change, but they were not sampled at a sufficient depth to test this. It is unlikely, however, that Coom Rigg Moss would have registered this change, as it only developed a water-level sensitive *Sphagnum* flora at CAL 80-370 BC.

The dates for increased mire surface wetness presented by Hughes (1997) suggest a close parallel to the wet shifts identified here. For example in Mongan Bog, Eire, the first arrival of hygrophilous *Rhynchospora alba* has been dated to 3770 BP.

A similarity in the timing between this 1690-1340 BC. wet phase (3640-3290 BP) and those identified by Dupont (1986), offers further supporting evidence for palaeoclimatic changes. She presented plant macrofossil evidence for wet mire surface conditions in four sequences from the Meerstalblok, The Netherlands, which extended from 3700 to 3500 BP. The plant macrofossil derived reconstructions of Stoneman (1993) revealed a period of climatic deterioration between 1690-1600 BC., whilst the $\delta\ ^{18}O$ and accumulation record of the GISP2 ice core (Meese *et al.,* 1994) reveal 'LIA type events' between 3750-3550 BP. The hydro-climatic reconstructions of Tipping (1995), adds further validity to the existence of climatic deterioration's during this time, since wet phases were detected between 3600-3500 BP., using colorimetric absorbance analysis.

6.2.15 2400 BC.-1700 BC.

The boreholes from Bolton Fell/Walton Moss and Raeburn Flow, point to the former potential existence of low local water tables and a deep acrotelm from 2390-2180 BC. (4340-4130 BP, BFML and WLM11) and 2110-1880 BC. (4060-3830 BP, BFML, WLM11 and Raeburn Flow). Irish and Scottish pine megafossils also offer evidence for decreased effective precipitation and possibly warmer summers at this time. Prior to 4200 BP, pine trees were growing in the Wicklow Mountains, Eire (Bradshaw and Browne, 1987), whilst Gear and Huntley (1991) noted a c. 80 km. expansion of *Pinus sylvestris* in Northern Scotland between c. 4400-4000 BP, and suggest it may have occurred as a response to drying blanket mire surfaces. Within the study area, Tipping (1995) noted high colorimetric absorbance values between 4050 and 3950 BP, whilst the extensive peat stratigraphic investigations of Casparie (1972), on the Bourtanger Moor, the Netherlands, revealed matching periods of dryness between 2500-2000 BC., based on the presence of extensive highly humified peat. These peat matrices contained abundant *Sphagnum rubellum, Calluna vulgaris* and *Eriophorum vaginatum* macrofossils.

6.2.16 3100 BC.-2400 BC.

Wet shifts are registered by BFML and WLM11 between 3110-2950 BC. (5060-4900 BP). WLM11 and Raeburn Flow also record wet shifts between 2880-2810 BC. (4830-4760 BP), whilst all three mires register a wet shift between 2670-2390 BC. (4620-4340 BP). The latter wet shift may overlap with the 'pluvial' phase (4200-3940 BP) inferred by Dubois and Ferguson (1985), based on the analyses of deuterium/hydrogen ratios in sub-fossil Pine stumps from the Cairngorms. The detailed mire stratigraphic analyses undertaken by Hughes (1997), also suggests wet shifts occurred during this time interval. He found the first major colonization of *Sphagnum imbricatum* on Tregaron Bog, Wales, occurred at 4605 CAL BP (SRR-5642), whilst a similar change in the stratigraphy of Abbeyknockmoy Bog, Eire, was dated to 4575 CAL BP (SRR-5732). *Pinus sylvestris* was displaced by *Eriophorum vaginatum/Calluna vulgaris* on Mongan Bog at 4625 CAL BP (SRR-5730). Hughes (1997), attributes the death of *P. sylvestris* to increased mire surface wetness, following a possible climatic deterioration at this time. The raised peat bogs from Cumbria and the Scottish Borders corroborate the research of Hughes, and support the existence of high effective precipitation regimes during these time intervals.

6.3 Summary of the Palaeoclimatic Reconstructions.

The registration of the later stage of the LIA at c. 1800 AD., in seven boreholes from seven ombrotrophic mires fulfils a *key* requirement, in that documented evidence for real climatic changes can be detected using the humification, plant macrofossil and testate amoebae analyses. A replicable sequence of changes in the humification, plant macrofossil and testate amoebae assemblages from Shaft Hill has been detected. In one of the monoliths (SHL2), a change to increased mire surface wetness occurred at c. 1800 AD., supported by two independent chronologies (*Pinus* pollen and SCP's).The loss of peat through fires, may account for the failure of SHL3 to record the later stage of the LIA.

The high magnitude of this hydro-climatic signal in Bell's Flow, Coom Rigg Moss and Shaft Hill Monolith 2, and its registration in seven boreholes from seven of the study sites, suggests the LIA was a significant climatic deterioration. If the Pine rise/SCP 'dates' are correct, it is the only climatic deterioration which can be detected in all seven of the mires investigated, and the only climatic departure of sufficient magnitude to force an increase in the height of local water tables in all of the study sites, despite the existence of an altitudinally imposed climatic gradient in the study region.

Palaeoclimatic changes which exceed the date ranges of the instrumental and documentary records can be placed less firmly into context, as many of the time periods identified here have been compared to other dates, which have also been derived from proxy-climatic evidence. There is clearly a risk of mutual reinforcement when attempting to validate these more ancient inferred palaeoclimatological changes (Oldfield, 1993). Allied to this, inherent errors within the ^{14}C chronology, and the existence of differential sensitivities of each of the climate proxies to record both changes in increased and decreased effective precipitation (Section 6.2.5 and 6.2.8), reduces the precision of the palaeoclimatic reconstructions. This latter problem is difficult to redress, since there appears to be no systematic variation in the differential sensitivity of each component to record changes in effective precipitation (Section 5.5.3, 5.5.4 and 5.7).

Despite this, there appears to be a high degree of synchroneity for the inferred hydro-climatic changes recognised here using the multi-proxy techniques, and with other proxy-climatic data generated from within the study region, and farther afield, extending to Eire, Sweden, Denmark and the Netherlands, particularly for the time periods 550-650 AD. (Section 6.2.8) and 850-150 BC. (Section 6.2.11). Changes in the $\delta\ ^{18}O$ and sea salt species within Greenland ice cores (Meese *et al.*, 1994 and O'Brien *et al.*, 1995) match some of the palaeoclimatic change periods identified here and from the other north-west European sites, suggesting the geographical spread of these inferred climatic changes were possibly far reaching.

Van Geel *et al.* (1996) suggested changes in heat transportation by ocean currents and atmospheric circulation patterns may be responsible for some of the climatic changes during the Holocene, particularly the time period 2650 BP. There appear to be recurring periodicities (Table 5.23) in the proxy climatic data generated from two sites (BFML and WLM11), using two effective precipitation reconstruction techniques (colorimetric humification analysis and DCA), which match the 520 and 260 year periodicity identified by Aaby (1976) from Danish Mires. 500 and 200 year cycles have also been identified in Dutch peat stratigraphy by Wijmstra *et al.* (1984), which serves to strengthen the existence of a common forcing mechanism affecting these North-West European sites. The implication is clear. Some of the palaeoclimatic changes registered in the ombrotrophic mires may be driven by changes in ocean circulation (Barber *et al.,* 1994; Van Geel *et al.*, 1996).

Analysis of marine sediments, banded corals and planktonic foraminifera by Druffel (1982) and Keigwin (1996), offer encouraging evidence for changes in this component of the ocean/atmosphere system. The carbon-14/ carbon-12 ratios, and $\delta\ ^{18}O$ isotopes within banded corals in the Florida Straits (Druffel, 1982), suggest a possible 1°C decrease in the water temperature of the Gulf Stream occurred during the LIA. Druffel suggests this cooling may have arisen from changes in ocean mixing patterns. Carbonate minima and increased inputs of terrigenous clay and silt occurred during the LIA in the Bermuda Rise region, which Keigwin (1996), attributed to increased atmospheric storminess driving the Gulf Stream, which in turn may have increased the kinetic energy of the linked deep recirculating gyres. It is these gyres which deliver the fluxes of terrigenous sediment to this region of the northern Sargasso Sea. Based on this evidence, there could be a link between the terrestrial and marine palaeoclimatic archives, as they both provide evidence for climatic deteriorations within the North Atlantic Region during the LIA. The identification of common periodicities within the peat stratigraphy of maritime European raised peat bogs using time series analysis, may serve to highlight a possible ancient link between these ecosystems and changes in ocean circulation.

6.4 The extinction of *Sphagnum imbricatum.*

The disappearance of this bryophyte from the stratigraphy of British and Irish peatlands is a dramatic feature and has been noted by Godwin and Conway (1939), Green (1968), Dickson (1973), Barber (1981), Smith (1985), Wimble (1986), Van Geel and Middeldorp (1988) and Stoneman (1993). Ascribing possible causes for this extinction, however, is more difficult.

Barber (1981) suggests the demise of this species is climatically induced, and may have been aided by competition from *Sphagnum magellanicum* and *Sphagnum papillosum*. On Bolton Fell Moss, *S. imbricatum* became extinct at many points on the mire surface during a period of increased mire surface wetness between 1300-1400 AD. The evidence for climatic forcing is strong from this site, as a change from *Sphagnum imbricatum* dominated communities to those dominated by *Sphagnum magellanicum* via a *Sphagnum* section *Cuspidata/Sphagnum papillosum* stage is repeated in 16 of the 21 monoliths examined. Although *Sphagnum imbricatum* can grow in both wet and dry microsites (Section 5.2.15), Barber (1981), suggests it may have been unable to change rapidly enough from the 'robust' hummock ecad to the 'lax' lawn ecad in response to climatic forcing and interspecific competition.

The demise of *Sphagnum imbricatum* is also associated with a change to increased mire surface wetness in three of the raised peat bogs (Walton Moss, Core 1, Dogden and Drone Moss) investigated by Stoneman (1993). Its extinction from the stratigraphy of Walton Moss, Core 2, Carsegowan and Blairbech Moss, may also have been due to climatic change, as its disappearance is associated with large fluctuations of water tables, followed by a phase of increased mire surface wetness (Stoneman, 1993). The time period over which these extinctions occur (1200-1890 AD.) is also marked by a high degree of climatic fluctuations (Lamb, 1977; Bradley and Jones, 1993). Independent evidence in the form of testate amoebae, also highlight a possible climatic deterioration which occurred during the extinction of *Sphagnum imbricatum* on Bolton Fell Moss - Core J2 (Woodland, 1996). This matches the plant macrofossil evidence in Core J1, since the extinction of *Sphagnum imbricatum* is marked by the presence of hygrophilous *Sphagnum papillosum* and *Sphagnum* section *Cuspidata* leaves (Barber *et al.,* 1994e).

In all six of the raised peat bogs examined for this research project there are wet shifts (determined from the humification, plant macrofossil and testate amoebae indices) associated with the decline and extinction of *Sphagnum imbricatum* (Tables 5.11-5.21). The vegetation changes, inferred wet shift date ranges and extinction dates are presented in Table 6.3. Following Barber (1981), competition from faster growing *Sphagnum magellanicum* and *Sphagnum papillosum* (Green, 1968; Flatberg, 1986) may have also been an important factor in the extinction of *Sphagnum imbricatum*, as these species consistently replace the latter species, often via a pool phase of *Sphagnum* section *Cuspidata.*

The three blanket peat monoliths taken from Shaft Hill (Figures 5.31, 5.33, and 5.36), particularly monoliths one and two, contain negligible sub-fossil *Sphagnum imbricatum* leaves (maximum abundance 5%). Despite this, the final disappearance of *Sphagnum imbricatum* in monoliths one and two occurs following a wet shift, again marked by the presence of *Sphagnum* section *Cuspidata* leaves (zone *SHL1 - b*, Figure 5.31, and zone *SHL2 - b.*, Figure 5.33). Conversely, the extinction of *Sphagnum imbricatum* in monolith 3 from Shaft Hill (Figure 5.36), does not appear to be related to an increase in mire surface wetness, since it precedes a large pool phase containing abundant *Sphagnum* section *Cuspidata* leaves. The humification and testate amoebae stratigraphy (Figures 5.35 and 5.37), also suggests the demise of this bryophyte at 56 cm. does not appear to be related to increases in local water tables, and therefore climate change may not be responsible for its extinction in this instance.

With the exception of the blanket peat monoliths, where *Sphagnum imbricatum* only comprises a small percentage of the peat matrices, there is strong evidence to suggest the extinction of *Sphagnum imbricatum* in lowland raised mires occurred during climatic deteriorations. This supports the work of Barber (1981), Smith (1985), and Stoneman (1993). The replacement of this section *Sphagnum* species by *Sphagnum magellanicum* and *Sphagnum papillosum* suggests competitive interactions may also have been important. Both these factors, however, fail to account for the 'great unbroken accumulations of peat' (Green, 1968), in which *Sphagnum imbricatum* is found, where it appears to have survived earlier periods of both climatic forcing and competition from the vascular and bryophyte flora. For example, *Sphagnum imbricatum* dominates the peat stratigraphy in

Table 6.3. The extinction of *Sphagnum imbricatum* in six raised peat bogs.

Site.	**Vegetation change.**	**Wet shift date range (interpolated dates from the mid-point of the calibrated ^{14} C dates.**	**Extinction date.**
Bolton Fell Moss - Core L.	*Sphagnum imbricatum* is replaced by *Sphagnum* section *Cuspidata* and then by *Sphagnum magellanicum*.	1010-1180 AD.	CAL 1030-1230 AD. (SRR-5887).
Walton Moss - Core 11.	*Sphagnum magellanicum* replaces *Sphagnum imbricatum*. This is then followed by a pool phase with abundant *Sphagnum* section *Cuspidata* and some *Rhynchospora alba*.	1130-1210 AD.	CAL 1280-1400 AD. (SRR-5868).
Raeburn Flow.	*Sphagnum imbricatum* is replaced by *Sphagnum* section *Cuspidata* at first, then by *Sphagnum papillosum* and finally by *Sphagnum magellanicum*.	1290-1340 AD.	CAL 1270-1400 AD. (SRR-5874).
Bell's Flow.	*Sphagnum* section *Cuspidata* is the first species to replace *Sphagnum imbricatum* followed by *Sphagnum papillosum* and *Sphagnum magellanicum*.	1070-1110 AD.	CAL 1160-1290 AD. (SRR-5879).
Coom Rigg Moss.	*Sphagnum imbricatum* disappears during a pool phase containing abundant *Sphagnum* section *Cuspidata* leaves with some *Rhynchospora alba*. This pool is then infilled by *Sphagnum papillosum* and *Sphagnum magellanicum*.	1400-1480 AD.	CAL 1395-1485 AD. (SRR-5884).
Felecia Moss.	1. A sharp reduction in the abundance of *Sphagnum imbricatum* occurs at 84 cm. It is replaced by both *Sphagnum papillosum* and *Sphagnum* section *Cuspidata*. 2. *Sphagnum imbricatum* reappears at 60 cm., but finally becomes extinct at 44 cm. It is replaced by *Sphagnum papillosum* and some *Sphagnum* section *Cuspidata*.	570-780 AD. 1470-1520 AD.	CAL 670-880 AD. (SRR-5892). 1470 AD. (interpolated dates from the mid-point of the calibrated ^{14} C dates.

Bell's Flow (Figure 5.22), and it has been able to recover from former pool phases in Bolton Fell Moss (zone *BFML-a*, Figure 5.12) and Walton Moss (zone *WLM-11g*, Figure 5.15).

Alternative theories which have been offered to explain the widespread extinction of this species have been reviewed by Stoneman *et al.* (1993). Direct human interference (burning, cutting, drainage or grazing) has been proposed by Pearsall, (1956) and Piggot and Piggot (1963) as a possible trigger for the decline of *Sphagnum imbricatum*. Stoneman (1993), however, could not find a correlation between the charcoal stratigraphy and the abundances of *Sphagnum imbricatum* in eight of his research sites. The plant macrofossil diagrams produced for this research project also fail to show a consistent correlation between these two components, which also suggests burning is not responsible for the demise of *Sphagnum imbricatum*. The effects of cutting, drainage and grazing are unlikely to have had a serious effect on the local water tables of the research project sites, as they are all intact, and have only suffered from peripheral drainage and peat cutting. More subtle indirect human disturbance through airborne contamination of nutrients may be more significant. Van Geel and Middeldorp (1988) suggest the decline of *Sphagnum imbricatum* on Carbury Bog, Eire, (c. 1400 AD.) is related to the deposition of agriculturally derived dust and charcoal particles. The high tolerance of *Sphagnum magellanicum* to nitrate concentrations (Rudolph and Voigt, 1986), may therefore have allowed it to replace *Sphagnum imbricatum*, although the evidence for this is purely speculative, since the sand particles observed in the peat matrices which mark the decline of *Sphagnum imbricatum* may not have been derived from agricultural activities. The extinction of *Sphagnum imbricatum* at Bolton Fell Moss - Core L., Walton Moss - Core 11, Raeburn Flow and Bell's Flow, occurred between 1030-1400 AD. (this age range encompasses the calibrated two sigma date ranges of the radiocarbon assays). *Sphagnum imbricatum* became extinct between 1300-1400 AD., in 16 peat monoliths examined by Barber (1981). These extinction dates were calculated using a radiocarbon dated master core and detailed pollen correlations. The information generated from these pollen diagrams, and a detailed review of the land use/historical literature by Barber (1981), show that agricultural activities during this period may not have been responsible for the extinction of *Sphagnum imbricatum,* either directly through drainage of mires, or indirectly through deposition of nutrients. This is because agriculture was in decline in Cumberland between 1190-1380 AD., due to 'warfare, pestilence and famine', (p116, Barber, 1981). For example, Barber details the Anglo-Scottish wars which began in 1296 AD., the failure of harvests between 1315-1317 AD., which may have been climatically induced, and the Black Death which occurred between 1348-50 AD. This documented agricultural retrogression is detectable in the pollen stratigraphy of Bolton Fell Moss, as there is extensive regeneration of woodland at this time (60-80% non-mire pollen, zone 'F', Barber, 1981). Deposition of agriculturally derived nutrients on the surfaces of the raised bogs in the study region may not therefore be responsible for the decline of *Sphagnum imbricatum*, although the lack of precision with the radiocarbon dates, precludes an exact comparison with the documentary and palaeoecological evidence.

Pinning down the specific cause of the *Sphagnum imbricatum* decline remains elusive, and is perhaps beyond the scope of this research project. On a more positive note, its extinction in the research sites is associated with elevated mire surface wetness. Its extinction, therefore, may be related to climatic change. Competitive interactions in addition to climatic change, may have also played a rôle in its demise, as it is replaced by faster growing *Sphagnum magellanicum* and *Sphagnum papillosum* in the peat stratigraphy, often via a stage of *Sphagnum* section *Cuspidata* abundance.

6.5 Site sensitivity.

6.5.1 Introduction.

The study sites have responded to known environmental changes during the late stages of the LIA, and the time parallel nature of many of the wet and dry shifts identified in the preceding sections, within the limitations of the ^{14}C chronology, offer strong evidence for potential climatic changes extending to 3110 BC.

When both paired sites display a change in inferred mire surface wetness in the same direction, and at the same time, it is highly likely that this represents allogenic (climatic) forcing. Analysis of Table 6.1, clearly demonstrates the climatic *insensitivity* of the blanket peat stratigraphy at Shaft Hill within the Moor House Reserve, since only a single wet shift (at c. 1800 AD.) is recorded in one monolith (SHL2). In comparison to this site, the *sensitivity* (in terms of the amount of palaeoclimatic changes registered), of Coom Rigg Moss and Felecia Moss is far higher, as eight wet shifts can be detected. Although eight wet shifts can also be identified in the stratigraphy of Raeburn Flow and Bell's Flow, the palaeoclimatic record from the former paired mires appears to be more sensitive, as eight wet shifts were recorded post-dating 760 BC. By comparison, only seven wet shifts were registered by Raeburn /Bell's Flow in the same time period, whilst the magnitude of change in the DCA axis 1 scores (Figure 6.2) of these mires, particularly Bell's Flow, is low, compared to Coom Rigg and Felecia Moss. These latter bogs, appear therefore, to be more sensitive both in terms of the number of climatic deteriorations they have recorded, and also in the way their flora have responded to possible increases in effective precipitation.

Although ten phases of increased mire surface wetness can be detected using the colorimetric humification, plant macrofossil and testate amoebae analyses from BFML and WLM11 (Table 6.1), these sites still appear to be less sensitive than Coom Rigg and Felecia Moss, since the peat matrices sampled from the former sites were much older (up to CAL 3500-3100 BC., SRR-4937). Prior to CAL 370-80 BC. (SRR-5886), the vegetation of Coom Rigg Moss would have not been able to respond to changes in mire water levels, since it did not possess a water-level sensitive *Sphagnum* flora (Section 6.2.14). Yet despite this, the stratigraphy of this site and its paired site, Felecia Moss, show consistent time parallel changes to increased mire surface wetness, which match the instrumental/documentary and palaeoclimatological record and exceed the number of wet shifts recorded in a similar time span by the other sites.

Exploring the possible reasons why the raised and blanket peat bogs in the study region display differential sensitivity to record changes in climate is difficult, but the visionary paper of Conway (1948), offers potential answers. She suggests (p 227), that variations in the rainfall/evaporation ratio are likely to be the most influential 'moisture factor' determining the growth of *Sphagnum* species. She develops this further, and writes,

> "It is postulated that any given stage in the course of the climatic fluctuations over a large area will give a value of the moisture factor which will vary from locality to locality according to the altitude, the general situation, and the topographic characteristics of each locality."

Following on from these ideas, variations in effective precipitation, mire size, shape and hydrology, may have a bearing upon site sensitivity, and are considered in the ensuing sections.

The possible reasons for the climatic insensitivity of the blanket peat samples will be considered first in the next section, whilst subsequent sections will consider the possible reasons for the greater sensitivity of Coom Rigg Moss and Felecia Moss to respond to increases in effective precipitation. Because of the difficulties associated with consistently identifying dry phases (Section 6.1), these will be considered no further.

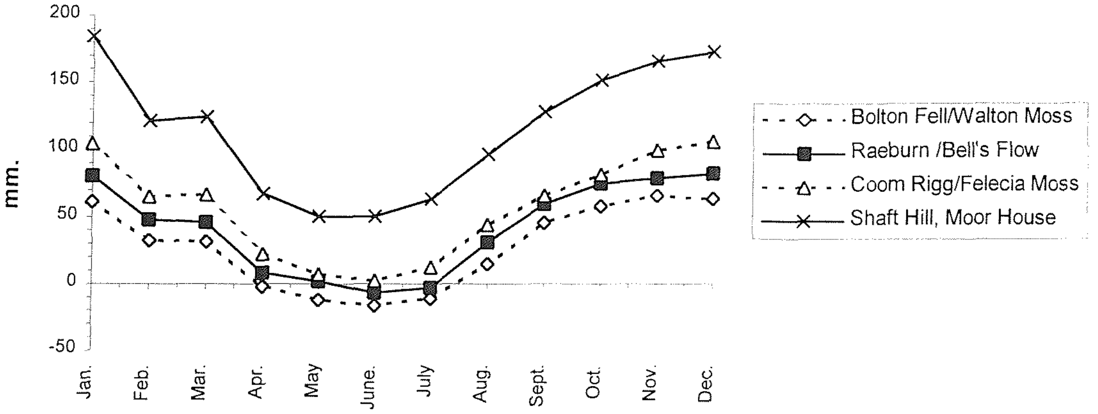
6.5.2 Shaft Hill monoliths - climatically insensitive ?

This site within the Moor House Reserve experiences the highest annual effective precipitation regime (1372.5 mm, Figure 6.12), yet it contains the driest stratigraphy of all the study sites, with evidence for only one replicable wet shift. The monoliths do not span as long a time interval as the raised peat sites (Shaft Hill Monolith 2 has a date of CAL 230-450 AD.), but the raised mires show multiple evidence for wet shifts post-dating this time, whilst the blanket peat site does not. The absence of raised peat bogs within the Moor House Reserve prevented a like comparison between the same type of ecosystem, but blanket peat bogs do appear to hold a sensitive climatic record, as demonstrated by the work of Blackford (1990), Blackford and Chambers (1995), Tallis (1995) and Barber *et al* (in press), and therefore the insensitive nature of the blanket peat stratigraphy is surprising.

Stoneman (1993), found that a raised mire within the Silver Flowe, Scotland (Ellergower Moss), possessed a relatively dry peat stratigraphy (high U.O.M. content, *Racomitrium* leaves were present, and abundances of hygrophilous *Sphagnum* section *Cuspidata* leaves were low), yet it experienced the highest rainfall by far of his study sites (1900 mm. yr.$^{-1}$ compared to 555 mm. yr.$^{-1}$ received by Drone Moss, Berwickshire). In this instance Stoneman suggests mire hydrological negative feedback processes (Section 2.2.3) may operate to remove excess water under high rainfall regimes, through drainage channels, water sinks and peripheral gullies, which were visible at the site.

These features were not visible at Shaft Hill, but alternative mechanisms to remove excess water via throughflow and overland flow may be in operation to remove the considerable effective precipitation this site receives. Overland flow in mires may occur preferentially along well defined paths termed water tracks (Hobbs, 1986). Burt *et al.* (1990) highlights the dearth of hydrological work undertaken to investigate run-off production from peatlands, but despite this, suggests their low gradient and near saturated state, may make them very conducive to saturation-excess overland flow, particularly during periods of heavy rainfall and from snowmelt (Eggelsmann *et al.,* 1993). Infiltration-excess overland runoff may also occur during high intensity rainstorms. These mechanisms have been investigated in a moorland catchment at Plynlimon, Wales, where peat deposits form 30% of the catchment (Muscutt *et al.,* 1993). Peak overland flow can exceed 40 l s^{-1}, which if it operates in a similar manner to Plynlimon (both sites receive similar, high precipitation [2500 mm. for Plynlimon and up to 2400 mm. for the Moor House Reserve]), precipitation on the Shaft Hill site, particularly high intensity rainfall, may be routed away, preventing the development of a hygrophilous flora and fauna. Another mechanism for drainage under high effective precipitation regimes is through subsurface piping of water (Hobbs, 1986; Foster and Fritz, 1987). At Stor Kräckelbäcken, Central Sweden, Foster and Fritz report pipes 20-30 cm. across and over 2 m. in length connecting two large pools. They suggest their formation may be due to hydrostatic pressure on the peat floor which follows lines of weakness in the subsurface peat. Via these pipes, a 40 cm. drop in the level of an upper pool occurred.

Figure 6.12 Study site effective precipitation regimes.



There does seem to be the potential, based on hydrological work in other areas, that these processes can lower mire water levels. Whether they can be invoked to explain the 'dry' stratigraphy of the Shaft Hill monoliths is more difficult to determine, however, given the lack of comparable experimental work undertaken within the Moor House Reserve.

The prolonged presence of snowcover may also contribute to the generally dry stratigraphy of the Shaft Hill sites. The average value for the number of days with snow (1953-1972) within the Moor House Reserve is 66.7 days $year^{-1}$, which may cause physiological drought to the flora, given that water is locked up within the snow crystals.

In Section 6.2.1 the existence of a possible hiatus in the Shaft Hill stratigraphy was suggested, given the large 760 year difference between the pollen/SCP dates and the ^{14}C dates. The removal of this material triggered by possible fire events, may account for the insensitive record from this site, as peat matrices which may possibly have contained a climatic record were lost from the blanket peat ecosystem. The detection of humification changes in the blanket peat stratigraphy of two monoliths taken from Migneint Mountain, Snowdonia (Blackford, 1990), shows that sites which receive very high precipitation (up to 2500 mm. $yr.^{-1}$) can yield evidence for climatic change. The failure of the Shaft Hill monoliths to show evidence for changes in effective precipitation, under a similar high rainfall regime, suggests both hydrological negative feedback processes and prolonged snowcover need not be invoked to explain the relatively xeric peat stratigraphy of the Shaft Hill sites. There may well be a hiatus in the blanket peat stratigraphy examined from Shaft Hill.

6.5.3 Raised peat bogs and differential climatic sensitivities.

6.5.3.1 Summer water deficits.

Both Bolton Fell /Walton Moss and Raeburn/Bell's Flow experience summer water deficits based on the 30 year mean values for precipitation and potential evaporation (Figure 6.12). For Bolton Fell and Walton Moss the deficit extends from April to July, whilst for Raeburn and Bell's Flow it appears to extend from June to July. For Coom Rigg/Felecia Moss precipitation exceeds potential evaporation for every month (even during May where P=69.6 mm., compared to 62.6 mm. of potential evaporation). Could this explain the greater climatic sensitivity of these two sites? The length of growth in *Sphagnum* species is dependent upon the distribution of precipitation through the year, particularly the August of the preceding year and June to August of the current year (Backéus, 1988). Based on this work, the current conditions for *Sphagnum* growth are supra-optimal on Coom Rigg/Felecia Moss using the average values of the 30 year climatic data set. Any increase in these values, through a climatic deterioration for example, may have initiated a rapid species response, which may account for the high representation of recorded wet shifts, as hygrophilous vegetation could extend from pools and low lawns and swamp lawn and possibly low hummock vegetation. For the remaining raised peat bog sites, however, given the potential for them to experience summer water table deficits, their response to any climatic deterioration may have been damped, as increases in effective precipitation would have to at first negate the summer water table deficit, before a change to more hygrophilous vegetation could occur. If this is the case, it may explain the greater sensitivity of Coom Rigg/Felecia Moss to record changes in effective precipitation. This again draws from Conway (1948), since she suggests hydrological *thresholds* within mires may account for the differential registration of climatic shifts by them.

The 30 year climatic data for the research sites can only serve as a guide to the effective precipitation each ombrotrophic mire has received in the past. This is because the boundary conditions which control climates have most probably altered during the course of the Holocene, for example, changes in terrestrial geography (ice-sheet size, land-sea distribution), are highly likely to have caused changes to the atmospheric circulation

(Yu and Harrison, 1995). Yu and Harrison suggest fluctuations in European lake levels during the early and mid-Holocene may have been due to changes in the size of the Baltic Sea and the Scandinavian Ice Sheet. They point to the regional summer cooling effect any large water body can have, and suggest blocking anticyclones were strengthened over the Baltic Sea in summer, until it attained its modern size at c. 2500 BP. Changes in solar irradiance from 9000 BP may have also altered boundary conditions, as seventeen out of nineteen low solar activity events identified by Wigley and Kelly (1990) correspond to cold events, identified through pine tree-line reconstructions in Scandinavia (Karlén and Kuylenstierna, 1996). In addition to possible changes in boundary conditions, precipitation amounts and frequencies may have also altered over the course of the Holocene, as the frequency, intensity and tracks of rain-bearing systems may have changed (Barrow and Hulme, 1997). Based on a 30 year run of data, Coom Rigg and Felecia Moss appear to possess the most favourable water-balance. Ascribing the climatic sensitivity of these sites to this feature however, may be over-simplistic, as the above examples suggest boundary conditions may have changed during the course of the Holocene. Despite this, the *relative* effective precipitation of Coom Rigg and Felecia Moss is likely to have been higher than the other raised peat bogs, since the former sites are located at a higher elevation (Section 4.5.1). They are certain, therefore, to have been cooler than the less sensitive sites due to lapse rate temperature declines (0.6-0.9 °C. 100 m.$^{-1}$, Manley, 1969; Chandler and Gregory, 1976; Harding, 1979; Ballantyne, 1983), and to have been more prone to orographic precipitation, through forced uplift of air masses. Forced uplift by orography may also intensify or trigger the other two principal precipitation mechanisms which occur in the British Isles, namely low level convergence and buoyancy/local atmospheric instability (Chandler and Gregory, 1976).

Factors other than the distribution of rainfall throughout the year, however, may also affect the sensitivity of each site to record climatic changes. The hydrology and morphology of each raised mire may also play an important role.

6.5.3.2 Mire size, shape and hydrology.

The importance of mire area, wetted perimeter, convexity and effective rainfall, and their bearing on hydrology, has been investigated by Ivanov (1975), Ingram (1982), Dupont (1985; 1986), Haslam (1987), and Kneale (1987). Haslam, drawing from the earlier work of Dupont (1985; 1986), was able to demonstrate a link between the hydrological stability, storage capabilities and effective precipitation regimes for each of his study sites, and suggested sites which have limited abilities to absorb increases in effective precipitation are the first to respond to climatic deteriorations, allowing (in this case) the formation of diachronous recurrence surfaces. The key premise of this work was the stable water balance equations of Ivanov (1975) and Dupont (1985), where 'the total discharge of water across the front of efflux equals the total internal water exchange', (Haslam, 1987, p 231):

Equation 6.1:

$$\bar{q}_n L_2 = \bar{p}_p - \bar{p}_e) \omega$$

where L_2 = the boundary of the bog in kilometres; $\bar{q}_n$ = the average natural component of the seepage in the direction of the boundary in $dm^3 s^{-1} km^{-1}$; $\bar{p}_p$ = rainfall in mm. yr^{-1}; $\bar{p}_e$ = mean evapotranspiration in mm. yr^{-1}; ω = the area of the bog in km^2.

This simple equation predicts that a rise in effective precipitation will require increased rates of seepage to maintain hydrological stability. If seepage rates are not high enough to remove the increased water inputs, an increase in local water tables and a possible increase in hygrophilous flora and microfauna may ensue. This equation can be used to calculate possible seepage rates for each of the raised mires investigated. Haslam (1987) suggested sites which displayed higher rates of seepage to the mire boundary under modern boundary conditions (Tregaron Bog, Wales and Totes Moor, Germany) responded earlier to palaeoclimatic deteriorations, since it was more difficult for these sites to maintain hydrological stability following increases in effective precipitation. The identification of similar mires in this research project may also serve to explain the pattern of differential climatic sensitivity discussed in Section 6.3.1.

Application of equation 6.1 to the study sites was straightforward. The mire boundaries (L_2) and areas (ω) were calculated by using a Tamaya digital planimeter. Evapotranspiration data for each of the study sites is lacking, but this should not be a problem, since the widespread wet surfaces of *Sphagnum* mires allow potential evaporation (data for this climatic parameter is available for each of the sites), to equal potential evapotranspiration (Ingram, 1983; Dupont, 1986). Inserting a $\bar{q}_n$ value for each of the sites is difficult, however, as annual average seepage rates vary between different microtopes. For example the respective seepage rates for mire surfaces containing 80, 50 and 20% hummocks (and conversely, 20, 50 and 80% hollows), are 2, 4 and 10 $dm^3 km^{-1} s^{-1}$, based on the analysis of western Siberian peatlands by Ivanov (1975). Following Haslam (1987), a range of possible seepage rates have been fed into equation 6.1 and the computed effective precipitation values for each site are presented in Table 6.3. The values at the foot of the table were calculated using modern day effective precipitation data, allowing a comparison to be made with the other potential seepage rates.

From Table 6.3, it is clear there is not much variation in the inferred average seepage rates for each site to maintain hydrological stability. Indeed for Raeburn/Bell's Flow and Felecia/Coom Rigg Moss, the inferred seepage rates calculated using the 30 year mean effective precipitation data are very similar (3.3 and 3.8 $dm^3 km^{-1} s^{-1}$ respectively). For Bolton Fell and Walton Moss, whose areas are larger in relation to their perimeters (reflected in the lower mire boundary/area ratios), slightly higher seepage rates need to occur in order to maintain hydrological stability (5.5 and 4.96 $dm^3 km^{-1} s^{-1}$). The conservative variation in potential average

Table 6.4. Computed effective precipitation values for a stable mire water balance using 10 values of average seepage ($\bar{q}_n$).

Average seepage ($\bar{q}_n$).	***Effective precipitation*** ($\bar{p}_p - \bar{p}_e$).					
$dm^3\ s^{-1}\ km^{-1}$.	BFML.	WLM11.	Raeburn Flow.	Bell's Flow.	Felecia Moss.	Coom Rigg Moss.
1	61.6 mm.	66.7 mm.	151.2 mm.	135.4 mm.	205.2 mm.	176.2 mm.
2	123.2 mm.	133.4 mm.	302.3 mm.	270.7 mm.	410.4 mm.	352.4 mm.
3	184.8 mm.	200.1 mm.	453.5 mm.	406.1 mm.	615.7 mm.	528.6 mm.
4	246.4 mm.	266.8 mm.	604.7 mm.	541.5 mm.	820.9 mm.	704.8 mm.
5	308 mm.	333.5 mm.	755.8 mm.	676.9 mm.	1026.2 mm.	881 mm.
6	369.6 mm.	400.2 mm.	907 mm.	812.2 mm.	1231.4 mm.	1057 mm.
7	431.2 mm.	466.9 mm.	1058 mm.	947.6 mm.	1436.7 mm.	1233 mm.
8	492.8 mm.	533.6 mm.	1209.3 mm.	1083 mm.	1641.9 mm.	1409.5 mm.
9	554.4 mm.	600.3 mm.	1360.5 mm.	1218.3 mm.	1847 mm.	1585.7 mm.
10	616 mm.	667 mm.	1511.7 mm.	1353.7 mm.	2052 mm.	1761.9 mm.
Area (km^2).	3.88	4.76	0.719	1.147	0.386	0.732
Boundary (km).	7.55	10.02	3.43	4.9	2.5	4.07
Ratio between Boundary and area.	1.95	2.1	4.8	4.3	6.5	5.5
Effective P.	330.9 mm.	330.9 mm.	500 mm.	500 mm.	676.5 mm.	676.5 mm.
	Inferred seepage rates which match the 30 year effective precipitation data ($dm^3\ km^{-1}\ s^{-1}$).					
	5.3	**4.96**	**3.3**	**3.7**	**3.3**	**3.8**

seepage rates, however, suggests this hydrological parameter is not responsible for the differential climatic sensitivity of the study sites. Unlike the sites investigated by Haslam (1987), the research project sites do not demonstrate large variations in average seepage rates, boundary length, area and effective precipitation. For example, Tregaron Bog, Wales was deemed to be more climatically sensitive than Machnacz, Poland, using equation 6.1, because of the higher inferred rates of average seepage for the Welsh mire (12 $dm^3\ s^{-1}\ km^{-1}$), compared to 1 $dm^3\ s^{-1}\ km^{-1}$ for the Polish site (Haslam, 1987). The reason for this large difference was the high effective precipitation (868 mm.) that Tregaron Bog receives, compared to the far lower value of 106 mm. falling on Machnacz. Such large extremes as this do not exist between the study region sites, which is unsurprising, given that Haslam (1987), examined raised peat bogs spanning a 2200 km. transect from Western maritime Ireland to Eastern continental Poland.

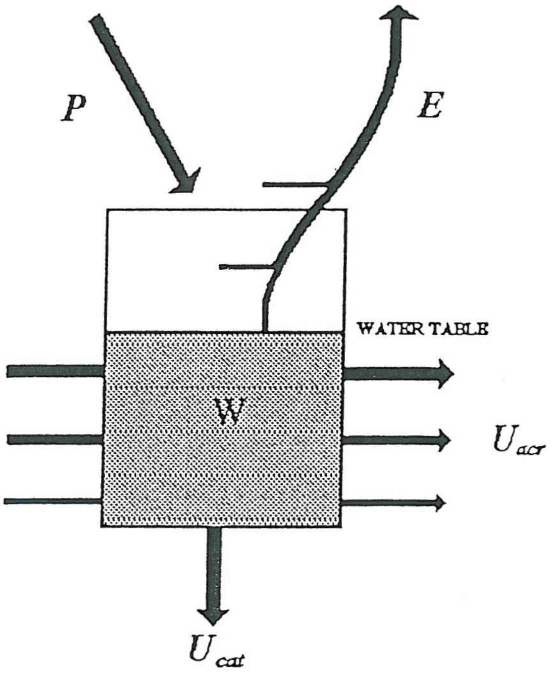
6.5.3.3 Raeburn/Bell's Flow. Site specific differences.

Site specific (autogenic) hydrological variability may explain the markedly different plant macrofossil and testate amoebae diagrams produced from the borehole stratigraphy of Raeburn Flow and Bell's Flow. Hygroscopic *Rhynchospora alba* epidermis and *Sphagnum* section *Cuspidata* leaves are frequently encountered in the stratigraphy of the former site (Figure 5.24), whilst Bell's Flow contains only a single level with pool *Sphagnum* section *Cuspidata* (Figure 5.28). The testate amoebae stratigraphy of Bell's Flow is also markedly dissimilar to that from Raeburn Flow, as the former site contains high abundances of the xeric indicator testate amoebae species, *Hyalosphenia subflava*, whilst it was only recorded from three levels in Raeburn Flow.

The dry, climatically insenstive stratigraphy of the borehole from Bell's Flow may still be explicable in terms of mire hydrology, but rather than hydrological stability, the nature of the acrotelm at this site may be responsible for the relatively xeric nature of the sub-fossil peat macro- and zoofossils. Bragg (1995) describes this soil layer as a 'header tank' or water store, through which water is added through precipitation, and then may either be stored (W), or flow laterally (U_{acr}) or vertically (U_{cat}) to replenish the catotelm (Figure 6.13). High rates of acrotelm and catotelm seepage will reduce storage in the acrotelm and reduce the heights of local water tables. This will in turn be registered by the plant macrofossils and testate amoebae, and may account for the subdued response of this mire to hydroclimatic changes compared to its paired site, Raeburn Flow. This site, by comparison, may display low rates of acrotelm and catotelm seepage.

This is only a hypothetical explanation, as hydrological data from the analyses of dipwells from this site and Raeburn Flow, is lacking. Bell's Flow lies on sloping ground (Scottish Natural Heritage report, unpublished), therefore there is a possibility the mire surface may also be sloping. If this were so, enhanced lateral throughflow of water may occur through the acrotelm, and reduce the height of local water tables, although the absence of EDM levelling data and hydrological measurements again prevents an test of this hypothesis between the two mires.

Figure 6.13 The water balance of the acrotelm (after Bragg, 1995).



Key: **P**=precipitation, **E**=evapotranspiration, **U_{acr}**=acrotelm seepage, **U_{cat}**= catotelm seepage, **W**=storage.

Heathwaite (1995), suggests vertical seepage between the peat and the underlying mineral soil may occur in raised mires. She suggests this component of mire water loss is disregarded, because it is assumed each mire possesses an impermeable base. A permeable base underlying Bell's Flow would prevent the establishment of high local water tables and possibly help to explain the relatively 'dry' plant macrofossil and testate amoebae stratigraphy. This hypothesis can be discounted, however, since the basal stratigraphy of the borehole taken from Bell's Flow contains laminated clay overlying red till at 5.56 m. This material will almost certainly act as an aquiclude.

6.3.4. Summary.

The possible causes for the differential climatic sensitivity of the ombrotrophic mires investigated have been discussed. The variability in the morphology and effective precipitation regimes of the ombrotrophic peat bogs within the study region does not appear to be high, compared to the NW European sites investigated by Haslam (1987). For this reason, hydrological stability based on the water balance equations of Ivanov (1975) and Dupont (1986), may not be responsible for the differential climatic sensitivity of the study sites. The potential operation of this mechanism cannot be ruled out, however, since the inclusion of mean seepage values for mires within Equation 6.1 may be meaningless, given that hydraulic conductivity (K) in peatlands can vary across three orders of magnitude (Chason and Siegel, 1986). Flow paths between pool and hummock networks may also vary over time (Kneale, 1987), which in combination with the variability of K values, suggests the water balance equation adopted here is possibly too simplistic to evaluate the hydrological stability of the study sites. The rôle and importance of methane in determining the height of local water tables is still uncertain (Section 2.2.3.1), and may also have a bearing on the differential registration of climatic change.

The mechanisms which peat bogs can employ to remove high inputs of effective precipitation may explain the relatively dry stratigraphy of the Shaft Hill sites, as with the exception of the LIA event recorded in SHL2, the blanket monoliths appear to be climatically insensitive. This may once again support the severity of the LIA, as throughflow and overland flow processes were not capable of removing the increased effective precipitation away from this area of the blanket bog surface (SHL2). The distribution of rainfall through the year may also account for the greater sensitivity of Coom Rigg/Felecia Moss to respond to climatic change, as the lack of summer water deficits may allow the flora and micro-fauna to respond more rapidly to increases in effective precipitation, since 'periods of water deficiency at the peat surface will be shorter and will occur less frequently', (Casparie and Streefkerk, 1992, p 126).

The analysis of peat humification, testate amoebae and vegetative macrofossils to reconstruct local mire water tables has been significant, since there is a greater chance of detecting changes in effective precipitation using them. The testate amoebae and humification signals from BFML, WLM11, and Bell's Flow in particular (Figure 5.93, 5.95 and 5.99), appear to be more sensitive than the plant macrofossils in recording mire hydro-climatic changes. The ability of *Sphagnum imbricatum* and *Sphagnum* section *Acutifolia* to survive under a range of moisture regimes may explain part of this insensitivity. This is not to devalue the palaeoecological indicator value of the plant macrofossils, since the testate amoebae stratigraphy of Raeburn Flow was less sensitive in recording fluctuations in the acrotelm/catotelm boundary (Figure 5.97).

Chapter 7. Conclusions and Future Research.

7.1 Conclusions.

The mires analysed for this research project unfailingly register wet shifts consistent with the Little Ice Age (LIA), using the *Pinus* pollen/SCP and radiometric chronology, and fulfil an important requirement in that *known* changes in climate can be detected in the peat stratigraphies. This has served as a reference point with which to gauge the severity of more ancient hydro-climatic changes, which clearly do not possess a corroborative instrumental/documentary record.

The LIA is recorded in all of the seven sites investigated. Within the blanket peat stratigraphy of Shaft Hill, the LIA is registered in Monoliths 2, but not in Monolith 1 and 3. Barber *et al.* (in press) claims the LIA 'is the coolest period of the last 2000 years', drawing from his earlier work (Barber *et al.* 1994c, e, 1996 and Barber and Scaife 1995), and that of Chambers *et al.* (in press). The largest inferred hydrological changes recorded from the humification, plant macrofossil and testate amoebae analyses for Bell's Flow and Coom Rigg Moss occur coevally with the LIA and support this claim, although conflicting dates between the radiometric and pollen chronology smear the precise time period over which this climatic deterioration occurred. The date range for Bell's Flow extends from 1420-1800 AD., whilst for Coom Rigg Moss the LIA is registered between 1550-1800 AD. The registration of the LIA in all of the sites sampled, despite their different effective precipitation regimes, also suggests the LIA was a severe climatic deterioration, since with the exception of two blanket peat monoliths from Shaft Hill, the bogs investigated were incapable of removing excess effective precipitation through hydrological negative feedback processes (Section 2.2.3).

Analysis of peat humification, plant macrofossils and testate amoebae is time consuming, but there is a greater chance of detecting changes in mire surface wetness when all three proxies are used. Each technique is likely to be subject to different sources of error, which may explain the unsystematic variation in the amount of wet shifts recorded by each technique.

Analysis of fossil testate amoebae assemblages from British peatlands remains a relatively underexploited field, although the quantitative palaeo-hydrological reconstructions of Charman and Warner (1992), Tolonen *et al.* (1992), Warner and Charman (1994) and Woodland (1996), have demonstrated the primary importance of local water tables on the micro-distribution of these protists. Drawing from this research, the analysis of thecamoebae has served to significantly improve the interpretation of palaeo-mire hydrological conditions where *Sphagnum* section *Acutifolia*, *Sphagnum imbricatum* or *Eriophorum vaginatum* macrofossils are abundant in the peat stratigraphy, and is a welcome tool to improve the accuracy of mire water level reconstructions.

Ombrotrophic mires which do not experience a potential summer water deficit appear to be the most sensitive in recording palaeoclimatic changes. The specific reasons for this are difficult to determine, although it is possible that growth conditions for *Sphagnum* are supra-optimal in these sites (Coom Rigg and Felecia Moss). This is supported by the research of Backéus (1988), since multiple regression between climatic variables and the growth of *Scirpus cespitosus* in a Swedish mire, suggests the distribution of precipitation through the year, particularly between June and August, and the August of the preceding year, has the highest statistical correlation with the length of growth of bog *Sphagna*.

Compared to the raised peat bogs investigated, the blanket peat monoliths examined from Shaft Hill, within the Moor House Reserve, are insensitive in recording changes in climate with the exception of the LIA. The operation of potential hydrological mechanisms in the form of throughflow and overland flow as a response to the extreme precipitation this site receives, may explain the relatively dry stratigraphy of these monoliths. The existence of a hiatus, however, is more likely to be responsible, given the ability to detect climate signals in Welsh blanket bogs which receive an equal amount of precipitation (Blackford, 1990).

The extinction of *Sphagnum imbricatum* in the six lowland raised mires studied occurred between 1030-1470 AD. The demise of this moss appears to have been climatically induced, as increases in mire surface wetness are associated with its extinction. The evidence for increases in local water tables between 1030-1470 AD. is strong, since all three proxy-climate records suggest increases in effective precipitation occurred during this time period. The presence of *Sphagnum magellanicum and S. papillosum* following the extinction of *S. imbricatum,* suggests the replacement of the latter species may have also occurred through competitive interactions.

Time series analysis of the humification and DCA axis 1 scores from two raised peat bogs (Walton Moss and Bolton Fell Moss), has revealed a replicable response, in terms of the significant wavelengths identified. Wavelengths of a period ranging from 261-282 years are common to both sites using both colorimetric and DCA based water level reconstructions. Spectral analysis of climate-proxy data generated from the stratigraphies of ombrotrophic bogs in Scotland is ongoing (Langdon, in prep.), and may complement the periods identified here.

7.2 Future research.

7.2.1 Chronology.

Conventional radiocarbon dating of bulk peat samples spanning 8 cm. of the peat stratigraphy has reduced the precision of the palaeoclimatic reconstructions attempted here. The radiocarbon determinations were also imprecise, in that the quoted standard deviations of the dated samples extended up to ± 55 years. This analytical uncertainty arising from laboratory preparation and processing errors is extended further when calibration is undertaken, because of the nature of the calibration curve (Section 3.9). AMS dating of fruits, seeds or *Sphagnum* leaves would have circumvented the need to sample large slices of the peat stratigraphy, which in combination with a "wiggle-match" (Van Geel and Mook, 1989), may have improved precision. Peat accumulation rates can be rapid, for example Stoneman (1993) and Barber *et al.* (1994d), report average peat accumulation rates of 10-15 yrs. cm.$^{-1}$. The ability to date small homogeneous units of organic material from a single cm. slice of peat using AMS dating would, in conjunction with a wiggle match, provide a higher temporal resolution to palaeoclimatic reconstructions from ombrogenous peat stratigraphy. AMS dating needs to be used with caution, however, since 'the smaller the sample the greater the effect of any contaminant present' (Shore *et al.,* 1995), although Harkness (pers. com.), believes an AMS dated sample is every bit as good as a conventionally dated sample, provided it is sampled well.

Tephrochronology offers a relatively new technique (Dugmore, 1989) to date discrete layers in British peat stratigraphy, since volcanic glass shards can be geochemically linked to historical and radiocarbon dated volcanic events in Iceland (Blackford *et al*., 1992; Pilcher and Hall, 1993; Hall and Pilcher, 1993 and Pilcher *et al*, 1995). Where they can be found in multiple sites, tephra particles represent synchronous horizons that allow these sites to be very closely correlated in time. A search for tephra layers in future research will provide an extension to the radiocarbon chronology, and a means to test the importance of autogenic versus allogenic forcing factors. Sufficient material to undertake tephra analysis is available from the study site monoliths and core samples, therefore this option is clearly open for future research. The furnace technique of Pilcher and Hall (1992) allows a rapid search for tephra particles to be made, and was adopted here to identify possible tephra shards from Bolton Fell Moss - Core L. Preliminary results suggest there is a tephra layer between 445-450 cm. depth. The eruption of Hekla 4 has been wiggle match dated to 2310 ± 20 BC. by Pilcher *et al.* (1995), whilst the peat matrices sampled between 400-408 cm. have a 2 σ calibrated date of 2290-1980 BC. (SRR-4936). There is a clear possibility these shards originate from the Hekla-4 eruption, which can be confirmed by future electron microprobe analysis.

The analysis of SCP's has served to highlight the existence of a possible hiatus in the Shaft Hill blanket peat stratigraphy. It is a cheap, straightforward technique, and the correspondence between the SCP and Pine pollen dates identified in this research project, suggests it is a useful dating technique to employ with recent peat samples.

More detailed pollen analysis may refine the chronology obtained from each peat borehole, as pollen diagrams can be related to known historical vegetation changes. Within the study region, declines in hemp (*Cannabis sativa*) and mugwort (*Artemisia*) pollen, can be used to assign a late eighteenth/early nineteenth century date to peat stratigraphy (Oldfield, 1963, 1969; Barber, 1981). This feature of the regional pollen rain is related to the cessation of hemp cultivation between 1750-1800 AD. (Houseman, 1800) and the introduction of deep ploughing in 1810 AD. (Farrer and Brownbill, 1911). Pollen analysis is a useful technique to back up ^{14}C dates, particularly where these are likely to be in error. This has been shown by the pollen analytical work of Hall (1994) and Hall and Pilcher (1995), since a chronology derived from changes in pollen spectra was used to date recent peat samples, due to the contamination of five radiocarbon assays with "bomb carbon" (Barber *et al*., in press). Tallis (1995) used the rise in *Plantago* pollen to date multiple blanket peat profiles. The analysis of *Empetrum* and *Vaccinium* grains by the same author, was also useful, in that phases of drier mire conditions could also be identified. Future research on ombrotrophic peat would therefore clearly benefit from a detailed pollen analysis.

The magnetic susceptibility (χ) or saturated isothermal remanent magnetization (IRM) of recent peat matrices can be non-destructively measured to determine the onset of the Industrial Revolution. This technique has been successfully applied to peat bogs by Oldfield *et al.* (1978), using pollen stratigraphic analyses as an independent check. This technique could also be used to date the remaining peat samples from each site, to corroborate the pollen and ^{14}C dates.

7.2.2 Quantitative water level reconstructions using Testate Amoebae.

Due to the failure of DCA to consistently ordinate the testate amoebae in relation to their hydrological preferences, a weighted averaging procedure was used to create a water level index for the study sites, based on the ecology of each species in terms of their niche preference with respect to local water tables (Section 5.5.2). A more objective approach to quantitatively reconstruct mire water table *depths* has been developed by Woodland (1996), using data from British ombrotrophic peatlands. The derivation of transfer functions using Canonical Correspondence Analysis (CCA) from modern Testate Amoebae communities has great implications for reconstructing palaeo-mire water tables, as these values derived from a training set of British peatlands can be applied to fossil rhizopod thanatocoenoses. The refinement of these transfer functions is ongoing (pers. com., Dr. Dan Charman), which may explain some of the differences noted in Section 5.6.2 between the DCA plant macrofossil and CCA testate amoebae derived hydrological curves. Once this process is complete, however, future quantitative water level reconstructions based on testate amoebae species assemblages may be more accurate, and justifies a closer sampling interval of these organisms in forthcoming research. A closer sampling interval will also serve to give a better indication of the correspondence between these two climate proxies, as there are indications from the trial CCA based hydrological reconstructions, that testate amoebae are more sensitive in responding to climatic deteriorations.

Plant macrofossil and humification analysis can currently only be used to reconstruct the relative degree of mire surface wetness. The ability to reconstruct actual water table depths using testate amoebae is to be welcomed, and offers an exciting advance in this area of research. If better models can be devised to improve water-level reconstructions from testate amoebae, future quantitative palaeo-hydrological research may serve to confirm or refute the semi-quantitative mire surface wetness reconstructions derived from the humification, plant macrofossil and testate amoebae data.

7.2.3 Non-pollen microfossils and Oribatid mites.

Fungal spores and hyphae, algal spores and animal remains were frequently encountered on the slides used for testate amoebae identification. A great deal of these non-pollen microfossils, particularly fungal spores, have been assigned to "types" which are related to the peat-forming vegetation and to the degree of peat humification

(Van Geel, 1972; 1978; Blackford, 1990). Their identification in future research may serve to complement the techniques used in this research project.

Oribatid mites were frequently encountered in the testate amoebae and plant macrofossil sub-samples. Their identification to species level may also serve to improve water level reconstructions, as species inhabiting *Sphagnum* mires are also sensitive to changes in the depth of the acrotelm (Markkula, 1986).

7.3 Final Remarks.

Contrary to the remarks of Heathwaite *et al.* (1993), it has been possible to identify climatic influences on peat stratigraphy, as the LIA was detected, whilst the identification of common periods of change in the direction of mire surface wetness, both between paired sites and the other sites investigated in the study region, is highly likely to represent palaeoclimatic changes. A review of the palaeoclimatological literature in Chapter 6, supports the date ranges for possible allogenic forcing identified in this research project. The timing of these palaeoclimatic changes are subject to the limitations of radiometric dating, but future research which incorporates some of the suggestions in Section 7.2.1 may help to resolve this imprecision.

This research project has served to reinforce the existence of a palaeoclimatic archive in ombrotrophic peatlands, and has extended modern research into these fascinating ecosystems. There is clearly potential to improve peat based climate reconstructions, therefore the remaining 4% of intact raised peat bogs (Lindsay and Ross, 1994) must continue to be protected, to ensure baseline climatic change data generated from these ecosystems is of the highest quality.

Appendix 1.

Experimental method for colorimetric determination of peat humification, after Blackford and Chambers (1993).

Samples of peat were dried under an infra-red lamp. Where fibrous sedge peat was present it was cut with scissors, since it can form a felty mass. Once dry, peat samples were ground with a pestle and mortar. 100 mg. of powdered peat was then placed into a 150 ml. beaker and 100 ml. of freshly mixed 5% NaOH added. The beaker was then heated on a hot plate in a fume cupboard until the solution boiled. Samples were then simmered for one hour at a lower temperature setting to reduce evaporation of the solution. Upon cooling, solutions were transferred into a 200 ml. flask, topped up with distilled water to the mark, shaken, and filtered through 'Whatman Qualitative 1' paper. 50 ml. of the filtrate was then diluted 1:1 with distilled water in a 100 ml. flask, and shaken well. The time of this final mixing was then recorded, and the percentage transmission of each sample at a wavelength of 540 nm. was recorded three hours later on a WPA HC 6000 Hydrocheck photometer. The mean transmission of three samples was recorded, after first zeroing the colorimeter with distilled water.

Appendix 2.

Experimental method for SCP Analysis (Rhodes, 1996).

0.2 g of air dried sediment was placed into a 250 ml. conical flask, 20 ml. of distilled water added, then the flask was covered and left for 24 hours (this allows the sediment to rehydrate).
20 ml. of 6% hydrogen peroxide was then added, the flask was recovered and left in an oven at 50 °C. for 48 hours. This stage of the experimental procedure is designed to bleach organic material to allow easier identification of black charcoal particles.
The sample was filtered on Whatman No. 1 filter paper (pore size ~11 μm.), to separate organic material from the dark organic leachate. Centrifugation was not adopted to separate the two fractions, since this may cause particle fragmentation (Clark, 1984).
The filtrate was washed into a 9 cm. diameter plastic petri-dish using distilled water. The petri-dish was then transferred to a oven and the excess water evaporated away, using a setting of 50°C., until the sample was barely covered in liquid. 20 ml. of 6% hydrogen peroxide was added again, the petri-dish recovered and left in the oven at 50 °C. for 48 hours. This second digest serves to bleach any remaining dark organic material.
The excess liquid was evaporated off until the sample was dry, by placing the petri-dish into an oven set at 50°C. The sample was then ready for SCP counting. Quantification of SCP's (> c. 10 μm.) was performed under a stereo-microscope at x40 magnification.

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