High spatial resolution Holocene vegetation and land-use history in West Glen Affric and Kintail, Northern Scotland

Althea Lynn Davies

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Department of Environmental Science
University of Stirling
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Declaration

I hereby certify that the research contained in this thesis is original, has been completed by the author and is not included in any other thesis.

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Althea L. Davies

Abstract

Small peat basins (*c.*10-50 m diameter) were used to obtain fine spatial resolution pollen-stratigraphic records of Holocene vegetation and land-use history in upland West Glen Affric and adjacent lowland Kintail, north-western Scottish Highlands. These data provide evidence for remarkably diverse and dynamic early to mid-Holocene vegetational mosaic and sustained later Holocene upland land-use. While acidophilous *Pinus sylvestris-Betula-Calluna vulgaris* communities on lower hillslopes appear comparable with other areas of the Highlands, data from floodplain and alluvial fan sediments in West Affric indicate a greater woodland diversity. *Betula*-dominated alluvial woods included a species-rich mix of arboreal, fen, tall-herb and ruderal herbaceous taxa, with *Pinus* forming small populations, confined to marginal soils. *Ulmus* was an important component of the lowland *Betula-Alnus* woods. Spatial differences in soil forming processes, particularly nutrient and base status, played a primary role in determining community composition, structure, dynamics, species diversity and stability. Inferred climatic shifts during the mid-Holocene, initially to drier, more continental conditions, followed by increased oceanicity, are suggested to have made woodland communities increasingly vulnerable to low intensity grazing disturbance and anthropogenic interference during the later Neolithic and early Bronze Age. These stresses resulted in widespread woodland decline, including that of *Pinus*, with the spread of blanket peat and heath on poorer hillside soils, and grassland communities on alluvial sediment. Bronze Age agricultural expansion is followed by several phases of expansion and/or intensification, with sustained pastoral and arable activity in the lowlands and on small 'islands' of richer soils in the uplands. There is little evidence for abandonment and the longevity of agricultural activity, particularly cultivation, above 250 m OD clearly indicates that the unqualified assumption of upland marginality is inappropriate. The implications for the interpretation of land-use in the Highlands from conventional palynological and archaeological records are discussed. The level of spatial and temporal detail regarding the palaeoecology of plant communities and adaptive land management evident in the present study is not afforded by conventional pollen analyses. This suggests that fine-spatial resolution palynology has the potential to contribute previously unrecognised information at scales which are directly applicable to ecological and human understanding and which can be more successfully integrated with neoecological and archaeological research, fostering closer collaboration between the disciplines.

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Thoir mo shoraidh le fàilte Chinn t-Sàile nam bò
Say farewell but greet kindly Kintail of the cows

(*Dèan Cadalan Sàmhach*/Sleep Softly; 18th century Gaelic lullaby by emigrant, J. MacRae)

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CHAPTER 1: Introduction, Literature Review and Aims

1.1 Introduction

The history of the peat-covered north of Scotland, including the Highlands, islands and 'Flow Country', has long been the subject of enquiry, as wood-rich layers in the peat indicate that there has been "constant change in the character of the vegetation which has successively covered [these areas]" (Lewis 1911, p.33). Pollen analysis is the primary means of establishing long-term chronologies necessary for elucidating the evolution of such landscapes, and early pollen analytical research by Erdtman (1924, 1928, 1931) and later by Durno (1956, 1958, 1965) confirmed earlier stratigraphic investigations.

These early pollen diagrams, although providing relatively limited information by present standards, emphasised the spatial and temporal variability of past vegetation cover and the stark contrast between past tree growth and the modern predominantly treeless blanket peat-dominated landscape (*e.g.* Durno 1956, 1958). These analyses also raised questions regarding the age and cause of upland blanket peat cover (Durno and Romans 1969), the role of fire (Durno and McVean 1959) and the effects of anthropogenic activity (Knox 1954, Durno 1965).

Since these analyses, a large volume of work has accumulated from the peat-covered Highland zone, particularly since the 1970s, when independent chronologies became available with the application of radiocarbon-dating (see below). However, many of the questions raised by this early research remain insufficiently well resolved at spatial and temporal scales able to address questions posed by ecological and archaeological research. Such data are necessary to enable more secure inferences to be made regarding ecological processes (*cf.* Bradshaw 1988, Bradshaw and Hannon 1992, Birks 1993, 1996a, Huntley 1996), and allow more rigorous testing of hypotheses relating to many aspects of vegetation history, notably the mechanisms of change and differentiation between natural and anthropogenic factors (*cf.* Tipping 1994; see below).

The present study area of Glen Affric and Kintail, in the northern Scottish Highlands (Fig. 1), is an ideal location for the critical investigation of these issues, since this setting encompasses many of the vegetational contrasts evident from previous research. This includes the present contrast between the treeless blanket peat of West Affric, putatively ancient Scots pine and birch woods of East Affric (Steven and Carlisle 1959), and the grass- and heathlands of lowland Kintail (see Section 2.1.5). The abundance of subfossil *Pinus* wood within the peat deposits of West Affric provides evidence for a sharp differentiation between the past and present vegetation of this area, and between West and East Affric.

The study area also straddles the border between two present potential woodland zones which suggest an east-west distinction between mixed boreal and deciduous woodland (McVean and Ratcliffe 1962; see Section 2.1.5). In addition, the study region lies on the boundary between upland *Pinus* and *Pinus/Betula* woodlands and more westerly *Betula/Corylus/Quercus* woods in palynological reconstructions of regional woodland cover at *c.*5000 BP (5730 cal BP) (Bennett 1989, Tipping 1994, Edwards and Whittington 1997). From an archaeological point of view, the strictly limited evidence for past and recent land-use has parallels with much of the Highlands, but again there is an apparent distinction between the upland glens, where only recent historic evidence is recognised, and their inland and coastal lowland counterparts, where some prehistoric remains also survive (Section 2.2).

This suggests that fine spatial and temporal resolution palynological data from Glen Affric and Kintail can provide a valuable contribution towards understanding variations in vegetation mosaics, ecological-scale vegetation dynamics, and both local and regional environmental controls on vegetation development, notably reasons for the loss of woodland in West Affric and Kintail. The study area also has the potential to give a much-needed insight into the timing, extent, nature and intensity of past and recent anthropogenic activities in the uplands relative to adjacent lower altitude valleys.

1.2 The aims and structure of the literature review

Several recent papers synthesise the current palynological database for the Highlands (Huntley *et al.* 1997) and for Scotland (Tipping 1994, Birks 1996b, Edwards and Whittington 1997). This review will focus on the interpretational problems faced by palaeoecologists, to examine how securely Holocene vegetation history and human activity are understood in the Highlands.

The study area in West Glen Affric is today dominated by extensive blanket bog communities which are characteristic of the north-western Highlands (Section 2.1.5). The putatively ancient woodlands of East Affric also suggest links with relict woods in the oceanic north-west, rather than the more extensive continental pinewoods of the Cairngorms. Similarly, recent biogeographical schemes for Scotland suggest that the western Highlands form a coherent, well-defined region, further emphasising the contrasts between the eastern and western Highlands (Brown *et al.* 1993a, b, Carey *et al.* 1995, Usher and Balharry 1996; Section 2.1.6). The review is therefore intended solely to discuss the vegetation history of the north-west Highlands. Sites in the Cairngorms, Skye, Rannoch Moor and the far north are discussed where they highlight interpretational problems and deficiencies in the present database for the north-west. All of the sites included are shown with references in Figure 1 and these references will therefore not be quoted throughout the review. Note that '*eilean*' is Gaelic for 'island', and two diagrams from the Badentarbet area are distinguished by referring to the earlier peat sequence (Johansen in Pennington *et al.* 1972) as Badentarbet, and the later valley mire profile (Bunting and Tipping 1997) as Achiltibuie.

The Holocene is the focus of discussion; the preceding late-glacial period is considered only in relation to its impact on subsequent vegetation development in terms of environmental and edaphic conditions, and the range of plants present at the start of the Holocene, particularly trees and shrubs. It is necessary to recognise that, in this region, some periods of the Holocene have received much attention, particularly the mid-Holocene, while others, notably the last *c.*3000 years, have received comparatively little consideration. This is reflected in the length of discussion relating to different periods of the Holocene. The review is prefaced by a summary of the primary biases which are relevant throughout the review, followed by a chronological discussion of Holocene vegetation history.

1.3 Biases in existing work

1.3.1 Geographical biases

Although the Highland zone encompasses the extensive and mountainous regions of central and north-western Scotland, it also includes many areas of 'lowland' character, such as the western coastal fringe and numerous lower altitude, inland river valleys. However, this is not evenly reflected in the distribution of pollen sites in the region, since most sites in the north-west are located at lower altitudes on the western edge of the uplands, below 200 m OD, rather than in the mountains or high altitude glens. This is one short-coming which may limit our understanding of past environmental gradients and vegetational mosaics.

1.3.2 Spatial and temporal resolution

The size of the sampling site, and thus the pollen source area, determines the spatial resolution of the pollen record (Jacobson and Bradshaw 1981, Sugita 1994, Calcote 1995), while the temporal resolution of a diagram affects the timescale at which changes in vegetation can be detected and interpreted, and is thus dependent on a secure chronology. Recognising the effects of spatial and temporal resolution on the pollen records from different sites is integral to establishing a more secure understanding of the links between environment and vegetation development, reconstructing community composition, detecting small-scale disturbances, and inferring the scale and causes of change, particularly distinguishing, as far as possible, between natural and anthropogenic factors.

Most pollen sites in the Highlands are large lochs (*e.g.* Loch Maree, Loch Sionascaig, Loch Tarff, Loch Clair), which consequently have a large pollen recruitment area, including a composite of many plant communities from a potentially large range of environments in the surrounding landscape. Sediment type also affects the resolution of the record, since taphonomic processes in lake sediments, such as differential focusing, especially of *Pinus* pollen (Pennington 1947, Franks and Pennington 1961, Kerslake 1982; Section 1.7.1), turbation and reworking caused by wind at more exposed sites (Pennington *et al.* 1972), smooth the pollen record, reducing the temporal resolution attainable, and may also introduce dating errors (see below). A comparison of the results from loch and peat sites in the Highlands stresses that smaller peat sites provide a much more detailed and sensitive record of vegetation dynamics and thus of the proximal causes of change. This emerges throughout the following review, and is particularly clear from the work of Kerslake (1982), with parallels in data of O'Sullivan (1973a, b) from the Cairngorms.

1.3.3 Dating issues

The sample size and type of sediment used for dating have a strong influence on our understanding of vegetation development, particularly on rates of change. All of the radiocarbon dates in this review are bulk ^{14}C dates, derived from a sediment thickness of 1-10 cm, but more frequently the broader end of this range. This clearly limits any assessment of the rates of vegetation change, particularly when changes appear to be rapid. As indicated above, numerous taphonomic processes are involved in loch sediment accumulation, with the potential for resuspended and inwashed sediment and allochthonous organic material, although root penetration and erosion in peat basins may also introduce dating errors in peats. This may be particularly important during the early Holocene, when mineral carbon may also cause significant ageing effects (Lowe 1991).

^{14}C and calibrated dates are quoted in this review, indicated by 'BP' and 'cal BP', respectively; dates given in the original papers were calibrated using CALIB 3.0.3 (Stuiver and Reimer 1993).

1.3.4 Aims of researchers

In the Highlands, where peat and lake sediments are relatively abundant, the aims of the researcher dictate the type and size of the selected site, the resolution and chronological focus of the analysis. Thus, the numerous large loch sites in the Highlands were chosen specifically for an abundance of extralocal and regional pollen (*sensu* Janssen 1966), in order to examine regional patterns of environmental and vegetational development, about which relatively little was known at that time (*e.g.* Birks 1972, Pennington *et al.* 1972). In these instances, vegetation development appears to have been complete by the mid-Holocene, since the pollen assemblages following the loss of woodland communities and spread of blanket peat resemble those of the present day. As the aims of the researchers had been fulfilled, little attention was paid to the last *c.*3000 years (Section 1.13).

This bias is thus partly a reflection of the spatial scale of the pollen record, since the pollen source area increases in open environments, thus reducing the spatial resolution and sensitivity of regional-scale pollen records (Sugita *et al.* 1999). This strongly affects spatial and ecological inferences which can be securely made from the pollen data, and the ability to detect small-scale disturbances and anthropogenic activity.

In contrast, most of the small peat sites were selected for their local and extralocal pollen recruitment characteristics in order to obtain pollen records which were sensitive to localised patterns of vegetation development (Kerslake 1982, Smith 1996, 1998). However, Kerslake's (1982) sites were selected for their isolation from human activity, while Smith's (1996, 1998) sites were chosen for their proximity to interdisciplinary archaeological investigations, in order to provide an 'off-site' reconstruction of anthropogenic activity. This again affects our understanding of human activity in this region.

1.4 The Loch Lomond Readvance (*c.*11000-10000 BP; 12920-11180 cal BP)

As a result of its northerly location and mountainous terrain, much of the Highlands have been strongly affected by glaciation. However, the impact of glaciation was not uniform as ice-fields of the Loch Lomond Readvance appear to have been most extensive in the western Highlands, with corrie glaciers to the north, east, and on Skye (Ballantyne and Sutherland 1987, Gordon and Sutherland 1993). This accounts for the uneven distribution of late-glacial sediments, which are absent from the most heavily glaciated regions, such as Western Ross (Birks 1972, Pennington *et al.* 1972, Tate 1995, Anderson 1996), but do occur in the far north-west at Loch Sionascaig and Loch Droma, on Skye, the Morar Peninsula and in the Cairngorms, where glaciers were smaller.

While evidence from the north-western Highlands is therefore limited, data from the far north, Skye and Cairngorms indicate that the Loch Lomond Stadial was a period of unstable soils and solifluction, inferred from the accumulation of minerogenic sediments and high frequencies of *Rumex* and *Artemisia* pollen (Birks 1970, Pennington *et al.* 1972, Birks and Mathewes 1978). Cryoturbation and solifluction may have released sufficient nutrients to support more basiphilous herbs on mineral soils, although diatom evidence from Loch Sionascaig suggests that outside areas of extensive ice cover, weathered soils were eroding, but limited ice cover was insufficient to produce a high mineral content in the loch waters (Pennington *et al.* 1972, *cf.* Sutherland 1980).

Pollen data are not the most secure means of inferring the presence or absence of trees in the open Loch Lomond Stadial landscape due to relatively low pollen concentrations, and the difficulty of distinguishing between long-distance transport under open conditions, especially of *Betula* and *Pinus* (*cf.* Andersen 1973), and sparse local tree growth in sheltered positions. However, macrofossil evidence from the north-west is very limited, due to the absence of macrofossil analyses and Stadial sediments compared with the Cairngorms, where macrofossil data, for the most part, suggest that the vegetation of the Highlands and surrounding regions consisted of treeless tundra (Birks 1970, Birks and Mathewes 1978, *cf.* Pennington *et al.* 1972). There is pollen and macrofossil evidence for *Betula nana* in the Cairngorms and central Grampians (Walker 1975, Huntley 1994), and macrofossil data suggest that occasional *Betula pendula/pubescens* stands may have survived on the southern and eastern margins of the ice sheet (*e.g.* Loch of Park), but there is no indication of trees on Skye (Vasari and Vasari 1968, Fig. 1).

However, sediment reworking is also a problem in the unstable conditions of this period (Lowe 1982, Tipping 1989). This may account for two *Pinus* needles at Loch Kinord in sediments predating 10640 BP (12570 cal BP) (Vasari and Vasari 1968, Vasari 1977). No peat sequences are available to examine local rather than inwashed vegetation composition which may bias macrofossil representation at loch sites.

1.5 The Devensian late-glacial - Holocene transition

Glaciation results in nutrient enrichment through bedrock weathering and the incorporation of solutes into meltwater (Sutherland 1980). However, palaeoenvironmental evidence from within and around the ice-field suggests that this effect was not marked or was relatively short-lived in most areas. *Empetrum*-dominated heath was widespread following deglaciation, suggesting the existence of mineral soils (Williams 1977) as *Empetrum* pollen is poorly dispersed (Moore *et al.* 1986). Within the limits of the Loch Lomond Readvance, low values for basiphilous herbs in loch sequences suggest that glaciation had a limited effect in terms of nutrients in areas of predominantly acidic geology (*e.g.* Loch Maree; Birks 1972). Outside the glaciated area, loch sediment chemistry, pollen and diatom data from Loch Sionascaig suggest progressive base depletion and a change to oligotrophy in the first 1000 years to the Holocene, pre-dating the arrival of trees (Pennington *et al.* 1972).

Empetrum heath was followed by *Juniperus* scrub, in response to ameliorating climatic conditions, with abundant ferns and a mixture of heath and grassland (Birks 1972, Williams 1977, Birks and Mathewes 1978, Kerslake 1982).

1.6 Early Holocene deciduous woodland establishment, *c.*10000-8000 BP (11180-8780 cal BP)

Few sites have sufficient chronological controls to determine the rates of vegetation change during the early post-glacial, due to the small number of radiocarbon dates, which are open to a variety of errors (*e.g.* O'Sullivan 1976, Kerslake 1982; see Section 1.1.3), in addition to a ^{14}C plateau around 10000 BP (11180 cal BP) (Lowe 1991). Where temporal controls are more secure, the succession from *Empetrum* heath to scrub is suggested to have been rapid (Birks and Mathewes 1978).

The regional patterns of colonisation are well-established (Birks 1989). However, during the time-lag between post-glacial climatic amelioration, soil maturation and tree migration, irreversible soil and water changes occurred in areas of base-poor geology, particularly across the far north and the north-west. Diatom, geochemical, palynological and macrofossil data, and blanket peat analyses in the far north suggest soil acidification and local waterlogging, with basin peat inception from around 9000 BP (9980 cal BP) (Birks 1972, Pennington *et al.* 1972, Williams 1977, Kerslake 1982, Robinson 1987, Charman 1992). This is suggested to have affected the composition of woodland communities by limiting the abundance of more nutrient-demanding taxa (Pennington *et al.* 1972, Pennington 1986).

The rate of leaching and trend to podsols may have been slowed by the establishment of *Betula-Corylus* woodland around 9500-9000 BP (9980-10500 cal BP) (Birks 1970, Pennington *et al.* 1972, O'Sullivan 1974a, Williams 1977, Smith 1998), and a reduction in herbs of open and disturbed ground may also reflect the establishment of more stable conditions, with reduced erosion (Pennington *et al.* 1972). However, deposition of eroded sediment is recorded at Loch Maree from *c.*8950-8250 BP (9960-9220 cal BP) (Birks 1972), and at Lochan Doilead from 8440-8060 BP (9440-8980 cal BP) (Williams 1977). This is suggested to reflect open areas or some continued landscape instability, such as fluvial erosion at Loch Maree, but scale and cause are difficult to establish securely in large catchments.

Research at Lairg suggests that fire, possibly reflecting more widespread climatic aridity around *c.*9500-8600 BP (*c.*10500-9600 cal BP) (*cf.* Atkinson *et al.* 1987, Harrison and Digerfeldt 1993), may also have affected the composition of early Holocene woodlands. Fire is suggested to have aided the expansion of *Corylus* here (*cf.* Smith 1970, Huntley 1993), but no such relationship between *C. avellana*-type and charcoal frequencies in evident at more westerly sites, such as Glen Torridon, Glen Carron and Ardheslaig (*cf.* Edwards 1990, Tipping 1994). The absence of quantitative charcoal records from all but the most recently analysed sites (Lairg, Glen Torridon, Glen Carron, Ardheslaig, Achiltibuie) is a major short-coming in the reconstruction of vegetation dynamics in the Highlands.

The abundance of ferns, particularly in the milder, more oceanic western Highlands (Birks 1972), and moderate frequencies of tree and shrub pollen suggest that early Holocene woodlands were rather open. An open or patchy canopy is inferred to have enabled a mosaic of communities to form, including dwarf-shrub heaths, mire and grassland (Williams 1977), but most sites lack sufficient spatial resolution to establish this palynologically and only large-scale variations are visible, such as higher *Corylus* frequencies and the development of valley fen carr on limestone at Strath Oykell, contrasting with more acidophilous vegetation on base-poor soils around Loch Sionascaig. In contrast, the spatial diversity of woodland communities on Skye reflects relatively small-scale geological variations, especially in base status, and climatic gradients, particularly exposure.

Sorbus aucuparia, *Populus tremula* and *Prunus padus* pollen are recorded in many profiles. However, it is difficult to establish the role of these species due to their poor pollen dispersal, the fragility of *Populus* grains (Sangster and Dale 1961), and problems of identification, since many early studies did not identify Rosaceous taxa further than family level. Similarly, low but consistent frequencies of *Ulmus* and *Quercus* at large and small diameter sites from the Morar Peninsula to Inverpolly and Abernethy Forest around 8800-8500 BP (9750-9470 cal BP) are difficult to interpret in terms of presence, absence or abundance. If either genus was local, populations are suggested to have been limited, perhaps restricted by geology to more fertile, better-drained soils (Birks 1970, Williams 1977, Birks and Williams 1983).

Pinus frequencies are also low at this time, perhaps inferring long-distance transport. However, *Pinus* pollen peaks or increased representation in the north-west from *c.*9500-7800 BP (10510-8520 cal BP), preceding the main expansion, are suggested to reflect the establishment of small populations (Bennett 1995), perhaps giving rise to Anderson's (1996) "aborted" expansions. This may result from glacial survival in Ireland, as long-distance sources in northern England and northern Ireland were not extensive at this time (Bennett 1995).

1.7 The role of *Pinus sylvestris* in the north-west Highlands, *c.*8250-6500 BP (9220-7380 cal BP)

1.7.1 Interpretational issues

There is an abundance of palaeoecological literature relating to *Pinus sylvestris*, particularly from the north-western Highlands (Birks 1972, Pennington *et al.* 1972, Huntley *et al.* 1997). However, there are many uncertainties relating to the rate of establishment and abundance of

Pinus and these form the focus in this review. Problems include dating issues discussed above, differences in the interpretation of *Pinus* abundance from palynological data, evidence for the differential flotation and focusing of *Pinus* pollen in loch sediments (Pennington *et al.* 1972, O'Sullivan 1976, Kerslake 1982), and the limited number of small diameter sites where predominantly local pollen production enables variations in local vegetation to be more sensitively recorded (Bradshaw 1988). Despite these constraints, regional vegetational variations are much more apparent from *c.*8250 BP (9220 cal BP) onwards.

1.7.2 *Pinus* establishment and expansion

The earliest *Pinus* populations in Scotland appear to have been established around Loch Maree between 8250 ± 100 BP (9220 cal BP) and 7795 ± 70 BP (8530 cal BP) (Birks 1972, Kerslake 1982, Bennett 1995). An extrapolated date of *c.*8900 BP (9910 cal BP) at Eilean Dubh na Sroine appears questionable in view of the absence of a reliable basal ^{14}C date due to insufficient organic matter, poor pollen preservation and very high errors on two ^{14}C dates above this horizon. No *Pinus* stomata are mentioned.

Despite this cluster of early dates, *Pinus* expansion across the north-west appears to have been temporally and spatially variable, with dates for percentage pollen increases ranging from 8250-2470 BP (9220-2650 cal BP) around Loch Maree (Birks 1972, Kerslake 1982), from at least 7000-6680 BP (7790-7490 cal BP) in Glen Torridon (Pennington *et al.* 1972, Anderson 1998, *contra* Anderson 1996), and from *c.*8900-6800 BP (9910-7580 cal BP) at Lairg. Some variation and uncertainty may result from large standard errors on several of the ^{14}C dates, especially in earlier work, and differential *Pinus* sedimentation in lake sediments, different pollen frequencies used in the definition of 'expansion' (*e.g.* Anderson 1996), and differences in pollen source area. However, the wide range of dates appears to reflect real variations in the spread of earlier small populations (Bennett 1995), at both catchment and regional scales. Possible causes of variation are discussed below.

The rate of *Pinus* expansion within pollen catchments appears variable, but interpretation is again hampered by poor chronological control, difficulties in assessing the temporal resolution of many pollen diagrams, and taphonomic problems relating to the sedimentation of *Pinus* pollen in lake sediments (see Section 1.3.2). Expansion appears to have been most rapid around Loch Maree, where *Pinus* became the dominant pollen producer within 100 ^{14}C years (Birks 1972), and *Pinus* stomata, indicating local growth (*cf.* Bradshaw 1981b, Bennett 1983, Fossitt 1994b), are recorded up to 200 ^{14}C years after pollen frequencies rise on Eilean Subhainn. In contrast, at Lochan Dubh, 800 ^{14}C years elapsed between the rise to relatively low pollen percentages and local growth (7700-6900 BP; 8420-7670 cal BP), with a further

1800 ^{14}C years before maximum Holocene frequencies were attained.

The abundance of *Pinus* in Highland woodlands is even less easily established, due to the high pollen productivity of *Pinus* (Andersen 1973) and taphonomic factors which concentrate *Pinus* pollen in deep lake sediments (Pennington 1947, Franks and Pennington 1961). This is apparent around Loch Sionascaig where *Pinus* frequencies peak at *c.*70% in the main loch core, while values of 25-45% TLP are recorded at three smaller loch sites (Lochs Borralan and Craggie, Lochan Dubh), with *c.*45% *Pinus* in the arboreal pollen sum in four nearby peat profiles. Consequently, the abundance of *Pinus* appears to have been over-estimated at Inverpolly, but it is uncertain how widespread this problem is due to the limited number of small sites.

The impact of *Pinus* expansion on pre-existing woodland taxa is uncertain due to the limited availability of absolute data and the research focus on *Pinus*, at the expense of established taxa. Reductions in *Betula* and *Corylus* frequencies at many sites may be an artefact of percentage data presentation. At Loch Maree, influx data suggest that *Pinus* replaced some *Corylus*, but increased *Betula* pollen influx and macroscopic remains indicate that *Betula* remained an important woodland tree.

Ecological mechanisms of woodland change at this time have been discussed largely from the perspective of *Pinus*, frequently over-looking or relegating the fate of pre-existing woodland taxa (see below), despite evidence that *Pinus* is a poor competitor (Bennett 1986b, Bradshaw 1993), and so was confined in many areas to poorer, acidic soils and mires, where it was able to out-compete established deciduous taxa (Birks 1972, Pennington *et al.* 1972, Smith 1996, 1998). Geochemical evidence for leaching and soil acidification suggests that potentially suitable habitats for *Pinus* establishment may have been widespread, particularly in the north-west (Pennington *et al.* 1972). This is also inferred from the near ubiquitous presence, and frequent expansion, of acidophilous genera such as *Calluna*, *Sphagnum* and *Pteridium aquilinum* with *Pinus* establishment (Birks 1972, Pennington *et al.* 1972, Kerslake 1982, Smith 1996, 1998). These are amongst inferred indicators of early peat communities (Bennett *et al.* 1990, Fossitt 1994b).

There is evidence that *Pinus* colonised mires in the north-west, Cairngorms and Rannoch Moor (Birks 1975, Kerslake 1982, Bridge *et al.* 1990). This could explain why *Pinus* populations may have expanded during an inferred drier or warmer climatic period inferred from humification analyses in Glen Torridon at *c.*6850-6775 BP (7400-7225 cal BP) and, indirectly, from palynological evidence for high tree-lines following *Pinus* colonisation at Beinn Dearg and Gleann Einich around *c.*7250-6600 BP (8030-7470 cal BP) (*cf.* Bridge *et al.* 1990). Increased charcoal is also recorded at Glen Carron, as discussed below. However, evidence for acidic, leached soils and mire development is also evident outside the early range of *Pinus*, for example, on Skye and in the far north (Williams 1977, Robinson 1987, Charman 1992), suggesting that other, unidentified factors also affected *Pinus* establishment.

Small diameter sites indicate mosaics reflecting local conditions, and emphasise the often overlooked role of deciduous species. For example, at Lochan Dubh, low pollen frequencies suggest that *Pinus* probably only existed as scattered individuals within open birchwoods from 7700-5100 BP (8420-5780 cal BP), with species such as *Mercurialis* and *Geranium* on more base-rich soils, perhaps limiting *Pinus* expansion. Similarly, *Betula-Corylus* woodland persisted around Coille na Glas Leitre (Durno and McVean 1959, Kerslake 1982), contrary to Birks' (1972) suggestion that *Pinus* may have replaced *Betula* along the south shore of Loch Maree on the basis of geological variations. Similarly at Lairg, *Pinus* expanded first in the wetter and more sheltered valley, out-competing *Betula* and *Corylus* through lower nutrient and hydrological demands (*cf.* Bennett 1986b), before expanding onto well-drained valley sides (Smith 1996). This emphasises the value of spatially constrained pollen records for reconstructing local conditions and niche competition, and for testing inferences from regional-scale records.

1.7.3 *Pinus* woodland dynamics

Pinus communities were dynamic, fluctuating on both short and long timescales, particularly in Wester Ross, although not all sources are in agreement regarding the nature and timing of change. The inferred cause(s) are important in the light of the later, marked regional decline in *Pinus* (Section 1.12.2). Long-term variations have been related to climatic fluctuations, particularly shifts to wetter conditions. Consequent waterlogging may have created conditions inimical to *Pinus* growth, particularly as is appears to have been established on acid, poorly-drained and peaty substrates, where it would suffer most from paludification (Pennington *et al.* 1972, Birks 1975, Kerslake 1982).

Climatic and edaphic deterioration are suggested as possible causes of declines in *Pinus* from *c.*7000 BP (7790 cal BP) at Loch Maree, and of arboreal pollen reductions around 8000-7500 BP at Lochan Doilead, Lochs Meodal, Ashik and Cleat on Skye. Peat and waterlogged soils are suggested to have spread at Loch Ashik around 7000 BP (7790 cal BP), but vegetational changes at the other sites given little clear indication of cause. However, this inferred climatic deterioration also contrasts with evidence for widespread dryness from *c.*8000 BP (8780 cal BP) (Anderson 1996, Tipping 1996; see Section 1.8). Furthermore, a *Pinus* decline is not evident in the small basins at Loch Maree, with the possible exception of a slight, long-term reduction at Eilean Dubh na Sroine. This stresses the importance of fine spatial resolution analyses for understanding the scale of change and thus of possible causal mechanisms.

Catchments to the south and east record fluctuations in *Pinus*, with the highest coincidence of microfossil, humification and isotopic evidence for wetter conditions and a reduction in *Pinus* pollen frequencies around *c.*6200-5600 BP (7090-6360 cal BP), associated primarily with *Calluna* expansion (Dubois and Ferguson 1985, Bridge *et al.* 1990, Anderson 1996, Smith 1996, 1998, Binney 1997).

1.8 Charcoal data and inferred anthropogenic activity in northern Scotland

On the basis of ecological data and unquantified charcoal observations, primarily in peat profiles (Durno and McVean 1959, Birks 1972, Johansen in Pennington *et al.* 1972, Kerslake 1982), fire has been suggested as an important factor in Highland pinewoods (*cf.* Bennett 1995). However, the limited number of charcoal records suggest that the role of fire may have been varied. This contrasts with the limited number of inferences which can be drawn from Loch Maree, where charcoal is stated to occur from the date of *Pinus* establishment onwards, but was not quantified.

Anderson (1996) correlates higher charcoal frequencies with dry climatic shifts at 6900-6800 BP (7670-7580 cal BP) and 5300-5100 BP (6090-5780 cal BP), suggesting that fire may have favoured *Pinus*, but does not discuss how. At Lairg, a positive correlation between *Pinus* and charcoal frequencies at two sites is suggested to indicate that burning was essential for *Pinus* regeneration (Smith 1996). Intense, natural fires are suggested to have become a more frequent feature of the landscape as *Pinus* migrated and became established. A steady increase in charcoal fragments from *c.*8000 BP (8780 cal BP) is also accompanied by a rise in the abundance and diversity of herbaceous species which are interpreted as indicators of disturbed conditions. These are interpreted as domestic fires associated with small-scale anthropogenic disturbance, chiefly in the valley. However, Smith (1996) accepts the need for more detailed temporal analyses to substantiate this suggestion of natural and anthropogenic burning.

In contrast, Bennett and Hill (1998) suggest that there is slight evidence that fire may have contributed to irreversible soil changes at Ardheslaig, but could find no clear relationship between charcoal, erosion and changes in vegetation. As so few charcoal records are available, the role of fire in pinewood ecosystems and the assertion that fire had been a dominant factor in the development of the local vegetation, and was largely responsible for extreme soil degradation (Durno and McVean 1959) remains to be established.

Contrary to the purely ecological role usually assigned to fire in the Highlands, there is widespread evidence of charcoal at the soil/peat interface in northern Scotland, and elsewhere, which suggests that burning may have been instrumental in peat inception and expansion (Robinson 1987, Tallis 1991, Charman 1992), although the cause of burning is subject to debate (see below). As peat forms a characteristic and widespread feature of the Highland landscape, direct evidence of peat formation derived from peat profiles in the far north is discussed, as very few dated blanket peat profiles with charcoal records are available from the Highlands.

Robinson (1987) and Charman (1992, 1994) suggest that burning may have been involved with blanket mire inception from *c.*8000 BP (8780 cal BP) at Aukhorn and Cross Lochs (Fig. 1). Both authors suggest anthropogenic causes, despite the recognised absence of 'anthropogenic indicators' (*cf.* Behre 1986) at Cross Lochs, but Robinson does not discount the possibility of natural factors, such as lightning strikes.

Charcoal evidence comprises the earliest inferred evidence for human presence at Lairg, Cross Lochs and Aukhorn. However, it is clear that there are problems associated with this inferred link, including a lack of standardisation in charcoal quantification, and an absence of clearly defined palynological indicators from which to infer anthropogenic disturbance, which makes interpretation problematic (Tipping 1994). Alternative explanations need to be carefully analysed. For example, Tipping (1996) presents evidence for a shift to drier conditions across north-west Europe around 8000 BP (8780 cal BP). Combined with evidence for widespread and potentially flammable heathland, and increased charcoal representation across northern Scotland at this time, he suggests a climatic origin for burning.

This stresses the need for quantified charcoal records and small diameter pollen sites to understand the relationship between woodland, peat and burning, since woodland expansion, particularly in the north-west, appears to have been coincident with peat formation (Section 1.6).

1.9 *Alnus glutinosa* expansion, *c.*6500-5000 BP (7380-5730 cal BP)

Alnus appears to have been present at low abundance within the uplands prior to the main expansion, which is characterised by marked temporal and spatial variability, at regional and local scales (*cf.* Chambers and Elliott 1989, Bennett and Birks 1990), with continuous pollen increases from *c.*6080-5520 BP (6900-6300 cal BP) (Kerslake 1982, Anderson 1996, Smith 1996). This variability arises from the localised distribution of suitable ecological conditions and importance of disturbance (Smith 1984, Bennett and Birks 1990), and is reflected in generally low frequencies at a regional scale, with some evidence for localised abundance (*e.g.* Durno and McVean, Kerslake 1982, Smith 1996). *Alnus* expansion is also suggested to have been limited by the abundance of acid soils (McVean 1956a and b, Vasari and Vasari 1968, Williams 1977, Birks 1989), and growth is suggested to have been restricted to lowland valleys, river-side waterlogged alluvial soils, flushed soils within woods, carr woodland (*e.g.* Lochs Borralan and Craggie), and mesotrophic mires (*e.g.* Coire Bog).

Habitat requirements emerge most clearly at smaller sites. *Alnus* abundance on Eilean Subhainn and Eilean Dubh na Sroine may have been limited by the mires, which were important in the local landscape (Kerslake 1982). At Lairg, *Alnus* appears to have colonised the wetter valley at *c.*5900-5700 BP (*c.*6800-6500 cal BP), before expanding onto the more exposed, freer draining valley sides around 5300-5000 BP (6090-5730 cal BP). Expansion is preceded at both sites by increased charcoal, which is suggested to have created disturbed ground necessary for establishment (*cf.* Smith 1984). Burning is attributed to Mesolithic activities, discussed in Section 1.11. Charcoal fragments were also recorded at Coire Bog coincident with local *Alnus* expansion around 6890 BP (7660 cal BP), but no cause was inferred.

Inferring the vegetational effects of *Alnus* expansion is difficult due to the limited availability of absolute data. *Alnus* is suggested to have displaced *Salix* at many sites, replacing *Corylus* (still assumed to be hazel) and occasionally *Betula* (Kerslake 1982, Williams 1977, Birks and Williams 1983). Data from Eilean Mor and sites on the valley floor and side at Lairg, amongst others, suggest that *Alnus* out-competed *Pinus*, perhaps in waterlogged, non-peat soils (Birks 1972, Pennington *et al.* 1972, Kerslake 1982, Bennett 1986b, smith 1996, 1998). However, the reverse occurs at Lochan Dubh around 5100 BP (5780 cal BP), possibly as a result of inferred blanket peat expansion, although no clear mechanism is suggested.

Finer spatial resolution pollen data from Eilean Mor give some idea of the dynamics of *Betula-Alnus* woodland. Cyclical fluctuations in the curves of *Betula*, *Alnus*, *Pinus* and *Calluna* may be indicative of the periodic regeneration of *Betula* and *Alnus* stands around the sampling sites, perhaps with *Alnus* in damper parts of the basin, fringed by *Betula*, with increased *Calluna* pollen deposition, suggested to derive from the extralocal vegetation, when tree pollen frequencies are lower. Fire, windthrow, disease and natural death are suggested as possible causes, but rates of change and charcoal records, essential for understanding vegetational change, are lacking.

Quercus and *Ulmus* may also have been present, as maximum frequencies are recorded around

6500-5500 BP (7380-6300 cal BP). Although it remains difficult to infer the abundance of these genera, periods of higher representation at many sites across the region are suggested to reflect small local populations (O'Sullivan 1976, Williams 1977, Kerslake 1982, Anderson 1996, Smith 1996, 1998, Bunting and Tipping 1997). This is suggested by Williams to reflect warmer climatic conditions, which controlled the northward expansion of *Quercus* on the west coast. However, this contrasts with evidence for peat expansion in the north-west from *c.*6500 BP (7380 cal BP) (Section 1.10), a reduction in woodland density or in the treeline at Beinn Dearg and Gleann Einich from 6500-5700 BP (7380-6480 cal BP) (Binney 1997, *cf.* Dubois and Ferguson 1985).

1.10 Mid-Holocene peat expansion

An abundance of proxy data sources from north-western sites suggest accelerated peat expansion around 5000 BP (5730 cal BP), sealing off mineral soils (Pennington *et al.* 1972, Kerslake 1982), and this is confirmed by blanket peat profiles around Inverpolly, which indicate that topographically unconstrained blanket peat was present by the *Ulmus* decline (Johansen in Pennington *et al.* 1972). Pollen-stratigraphic data from Beinn Dearg and Gleann Einich suggest a regional decline in woodland density or in the altitude of the treeline around 5400 BP (6260 cal BP).

Natural retrogressive succession towards waterlogged soils and climatic changes are suggested as possible causes (Pennington *et al.* 1972, Binney 1997). However, disparities within Glen Torridon indicate that the scale and local mechanisms of change are as yet poorly understood. Anderson (1996, 1998) infers a shift to wetter and/or cooler conditions at *c.*4800-4200 BP (5500-4730 cal BP), which is suggested to have accelerated blanket peat expansion and to have been unfavourable for *Pinus*. Peat expansion is also evident from the upland plateau site at Lairg around 4900 BP (5600 cal BP). This contrasts markedly with palynological data from Loch Clair, which suggests a shift towards *Betula* and a gradual rise in *Calluna* around 5400 BP (6260 cal BP). This is suggested to result from anthropogenic activity, and steeper catchment slopes are suggested to have limited peat formation (see Section 1.11). Similarly, chemical changes in Loch Tarff are suggested to reflect the formation of acid mor soils around 5000 BP (5730 cal BP), and a shift towards dry *Calluna* heath at this time is again attributed to human interference. However, changes are poorly resolved from these large catchments and widespread evidence for soil deterioration, of varying severity, across the north-west, suggests that climatic or edaphic changes should not be dismissed. Anderson focuses on European climatic records and his failure to discuss regional evidence, more pertinent to the reconstruction of palaeoclimatic change across north-west Scotland, is a deficiency in attempts to understand the history of this area.

1.11 Evidence for late Mesolithic and early Neolithic human activity, *c.*5400-5000 BP (6260-5730 cal BP)

Several workers infer anthropogenic vegetation disturbance in the late Mesolithic and early Neolithic, around the regional *Ulmus* decline, *c.*5400-5000 BP (6260-5730 cal BP). However, interpretation remains problematic due to concurrent regional-scale environmental changes, frequently large pollen catchments and poor temporal resolution, which prevent a clear understanding of the species affected, the scale and duration of disturbance. These shortcomings are highlighted by the contrasting results between large and smaller diameter sites.

At larger sites across the Highlands and some adjacent eastern areas, disturbance is inferred from slight, temporary reductions in arboreal pollen frequencies, the appearance or increased representation of herbs frequently associated with human disturbance (*e.g. Plantago lanceolata*) or expansion of heath, occasionally with erosion and, infrequently, with charcoal, as at Loch Clair from *c.*5400 BP (6260 cal BP) and Ardheslaig (*c.*5670-4360 BP, 6450-4870 cal BP). Cereal-type pollen is only recorded at Lairg (see below) and Loch Cleat. There is no evidence for disturbance at the smaller sites of Glen Torridon or Glen Carron, near Loch Clair, perhaps inferring localised disturbances.

Edwards and Ralston (1984) express reservations over the interpretation of some of these events as anthropogenic, preferring natural causes, on the assumption that these sites were isolated and on an absence of archaeological evidence. While the absence of artefactual evidence or cereal-type pollen should not preclude the inference of anthropogenic activity (Tipping 1994, Edwards and Whittington 1997), it is necessary to recognise that woodland did not form a continuous canopy (Edwards and Ralston 1984, Tipping 1994) and herbs often considered to be 'anthropogenic indicators' also occur in naturally open, unstable or disturbed habitats (*e.g. P. lanceolata*; Smith 1970, Fossitt 1990), which may form small parts of the vegetational mosaic. This is especially important when possibly small-scale and short-lived disturbance events are inferred from pollen records of regional 'landform' vegetation cover (Janssen 1981), and these pollen types occur sporadically and at low frequencies during a period of regional change (Section 1.10).

Consequently, small sites can yield more secure evidence of the nature and possible extent of small-scale disturbance and anthropogenic activities. Small diameter sites at Lairg suggest small-scale agriculture in a late Mesolithic or early Neolithic context, with cereal-type pollen at sites on the valley floor (*Avena/Triticum* group) and valley side (*Hordeum* group) from *c.*5400-5200 BP (6260-5940 cal BP). Increased burning near the valley floor from *c.*5700 BP (6480 cal BP) is suggested to have resulted in a fairly open canopy woodland, which could have provided suitable areas for cultivation near the river, perhaps following grazing by wild animals from *c.*7200 BP (7950 cal BP). The finer spatial resolution from small sites allows more critical data analysis and interpretation on a scale applicable to ecological and archaeological understanding.

1.12 Mid-Holocene environmental changes *c.*5000-3000 BP (5730-3190 cal BP)

Evidence for the cause and variety of changes in the north-western Highlands at this time are discussed in some detail to illustrate the complexity of change, which is likely to be relevant to the present study area.

1.12.1 *Pinus* range expansion in the north-west and far north, *c.*4400-4000 BP (4920-4440 cal BP)

In contrast to evidence for widespread peat expansion around *c.*5000 BP, *Pinus* appears to have been able to expand its range northwards only between *c.*4400-4000 BP (4920-4440 cal BP), although scattered trees may have been present before this time (Daniell 1997). *Pinus* was the only species to do this, against a backdrop of regional reduction in other arboreal species (Bennett 1995). Short-lived peaks in *Pinus* pollen are recorded at Loch Ashik, Eilean Mor, Loch Vatachan, Loch Shin, Lochstrathy, Cross Lochs and Badentarbet. This event may been overlooked in earlier research (*e.g.* Loch of Winless; Peglar 1979) due to poor temporal resolution (Gear and Huntley 1991). In contrast, *Pinus* frequencies begin to decline around 4800 BP (5500 cal BP) at Lairg, with slight regeneration at one of the three sites around 4200-4100 BP (4730-4560 cal BP) (Smith 1996, 1998), suggesting that the event was confined to the far north and west.

The apparent duration of *Pinus* growth depends on the threshold value suggested to infer local growth, estimates range between a few centuries (a single generation; Kerslake 1982, Bennett 1995, Daniell 1997) and nearly four centuries (Gear and Huntley 1991, Charman 1994), with a *c.*464 year dendrochronology (Daniell 1997, Huntley *et al.* 1997).

Rapid *Pinus* expansion is thought to be the result of drier climatic conditions, which caused peat surfaces to become dry enough for *Pinus* to colonise and form bog-forests, without competition from other woodland taxa, leaving subfossil pine stumps as testimony to this short-lived expansion (Birks 1975, Bridge *et al.* 1990, Gear and Huntley 1991, Daniell 1997). This may also be reflected by palynological evidence for a return to higher tree-lines or denser pinewood at high altitudes in Beinn Dearg and Gleann Einich at *c.*4300-4000 BP (4860-4440 cal BP), and a short-lived shift to higher humification, inferring drier and/or warmer conditions, in Glen Torridon from *c.*4100-4000 BP (4560-4440 cal BP), which is suggested to have slowed the decline in *Pinus* frequencies there.

Bennett (1995) also proposes that *Pinus* may have been spreading in response to lower competitive pressures in woodland as a consequence of human activity. However, supporting evidence is ambiguous from the regional-scale data available, with very limited evidence for local disturbance (see Section 1.12.2.2).

1.12.2 Woodland decline *c.*4000-3500 BP (4440-3790 cal BP)

The marked woodland contractions and inferred environmental changes which occur in the north-west have been the focus of numerous previous investigations (*e.g.* Birks 1988, 1996b, Bennett 1995, Smith 1996), particularly examining the decline in *Pinus* (Bennett 1995, Bridge *et al.* 1990, Binney 1997, Daniell 1997) and the role of climatic change (Anderson 1996, 1998, Anderson *et al.* 1998, Binney 1997). All of the evidence and arguments presented in the literature will therefore not be repeated here.

Briefly, at a regional scale, the period from *c.*4000 BP (4460 cal BP) is characterised by apparent woodland decline, widespread and accelerated blanket peat and heath expansion. Foremost amongst woodland decline is the contraction in the range of *Pinus*, inferred from percentage and, where available, absolute reductions in pollen frequencies (Birks 1972, Pennington *et al.* 1972, Kerslake 1982, Bunting and Tipping 1997), and from a decline in the frequency of dated *Pinus* stumps, at a time when conditions appear to have been suitable for wood preservation (Birks 1975, Bridge *et al.* 1990, Gear and Huntley 1991, Daniell 1997).

However, patterns of vegetational change were far from uniform or synchronous, even allowing for errors associated with ^{14}C dating. Temporal and spatial variation at catchment and local scales suggests a patchy landscape resulting from catchment-specific response thresholds which cannot be easily or securely reconstructed from large sites. Small diameter and peat sites thus provide essential tests for hypotheses developed primarily from large sites and also provide clearer evidence for proximal causes of change. The clarity and limitations of the present evidence for spatial and temporal variations, and the proximal causes of change are considered in this section, as these aspects are crucial to establishing an ecologically secure understanding of local vegetation development, from which to reconstruct regional patterns.

Six possible causes have been proposed, although they are not mutually exclusive (Bennett 1995):

1. regional climatic deterioration,
2. soil impoverishment,

3. anthropogenic pressure,
4. a change in fire frequency,
5. volcanic eruption,
6. pathogenic attack.

1.12.2.1 Climatic and edaphic deterioration

Vegetational change is frequently attributed to regional climatic and edaphic deterioration. As it is difficult or impossible to separate the influence of climate on soil development, and the impact of both on vegetation, these two subjects are treated together.

Recent palaeoclimatic research reinforces earlier suggestions of a widespread shift to a more oceanic climate, with cooler and/or wetter, and possibly more windy conditions around 4000-3500 BP (4440-3790 cal BP), resulting in rising watertables and peat expansion (Birks 1972, Pennington *et al.* 1972, Dubois and Ferguson 1985, Gear and Huntley 1991, Anderson 1996, 1998, Binney 1997, Anderson *et al.* 1998). This is reflected in an abundance of proxy palynological, humification and geochemical data, although cause and effect are difficult to separate.

For instance, an abrupt decline in inferred *Pinus* bog-forest at Subhainn Bog at 3650 BP (3950 cal BP) coincides with increased representation of *Menyanthes* and Cyperaceae pollen identified by Kerslake as *Rynchospora alba.* This species is associated with wet mire, but this pollen type is not recognised in recent keys (*e.g.* Moore *et al.* 1991, Bennett 1994). At Lochan Dubh, a gradual decline in *Pinus* frequencies and increase in *Myrica* from *c.*3400 BP (3630 cal BP) are followed at 3250 BP (3470 cal BP) by a reduction in *Betula* values, the expansion of mire taxa and marked sedimentary changes. Absolute total land pollen values are halved, suggesting dramatic reductions in *Betula* and *Pinus* (Kerslake 1982).

Dendrochronological data and analyses of blanket peat profiles with *Pinus* stumps provide the clearest evidence of very local changes. At Badentarbet, the top of a *Pinus* stump is associated with high frequencies of Cyperaceae pollen, suggesting inundation of the forest floor (Johansen in Pennington *et al.* 1972), although it is debatable whether this was a "forest" or isolated bog *Pinus* trees, perhaps associated with the *c.*4400 BP (4920 cal BP) event, as wood was dated to *c.*4420 BP (4990 cal BP) and *c.*4220 BP (4740 cal BP). Dendrochronological analyses suggest that root competition between *Pinus* trees was intense, due to the development of shallow plate-like root systems to cope with the limited depth of nutrient-poor peat above the watertable, and this would have made them vulnerable to rising ground waters (Daniell 1997).

Changes in North Atlantic air currents or ocean circulation patterns are considered possible causal factors (Gear and Huntley 1991, Anderson 1996, 1998, Anderson *et al.* 1998), thus affecting the north-west more than the eastern Highlands. It is argued that a northward shift in the Azores high resulted in a northward shift in the jet stream, bringing warmer summers and enabling *Pinus* to expand onto drying blanket peat surfaces in northern Scotland and expand its range northward in Fennoscandia (Gear and Huntley 1991). A subsequent reversal is inferred to have led to the extinction of *Pinus* on blanket mires in Britain, and a southward shift in the *Pinus* treeline in Fennoscandia (Eronen and Hyvärinen 1982, Eronen and Huttunen 1987; see also Barnekow 1999). Similarly, Anderson (1996, 1998, Anderson *et al.* 1998) proposes that reduced thermohaline circulation is implicated in the regional shift to wetter peat-forming conditions. However, Anderson *et al.* (1998) also note that the timing of the transition in northern Scotland is not constrained with high enough precision to examine causal factors in detail.

The complexity of vegetational change and difficulty of inferring causal relationships are highlighted by contrasts between nearby sites, which also suggest interpretational problems. The sequence from Loch Clair suggests a gradual decline in *Pinus* values from *c.*6500-5000 BP (7380-5730 cal BP), followed by continued woodland survival. This contrasts with large and abrupt *Pinus* declines at Glen Torridon and Glen Carron peat sequences at 3940 BP (4410 cal BP) and 3550 BP (3830 cal BP) respectively. The extent to which local woodland survival around Loch Clair affects pollen representation is unclear; Anderson (1996) suggests that this profile may not be representative of the vegetation history of the wider Glen Torridon catchment, while Pennington *et al.* (1972) infer an extralocal pollen source area, suggesting that the steeper slopes around Loch Clair may have prevented extensive blanket peat formation in the loch catchment.

There are no marked trends in lake sediment chemistry to suggest soil deterioration at Loch Clair, while humification records from the Glen Torridon and Glen Carron peat sequences display distinct but asynchronous shifts towards wetter conditions at *c.*4550 BP (5325 cal BP) and 3650 BP (3900 cal BP), respectively. This raises questions regarding the comparability of lake and peat sequences (see Section 1.12.2.5) and palaeoclimatic inference from humification records. Only at Glen Carron does the wet shift coincide with a reduction in *Pinus* values, as *Pinus* frequencies at Glen Torridon fall later, during an inferred dry shift at *c.*4125-3775 BP (4400-4150 cal BP). Binney (1997) suggests that a lack of synchroneity between humification profiles may reflect site-specific humification thresholds which affect the response to wetter conditions. This emphasises the need for multi-proxy analyses to understand local causal mechanisms before establishing regional patterns.

1.12.2.2 Anthropogenic pressure

This period of change occurs during the transition to the Bronze Age (Edwards and Ralston 1997), when many sites show sporadic evidence of disturbance which may be associated with human activity. There is widespread evidence for Bronze Age expansion across Scotland (Tipping 1994) and elsewhere in the British Isles, thus suggesting that this expansion occurred independent of environmental change. However, evidence for anthropogenic pressures in the north-west Highlands remain ambiguous, as it is based on sporadic and low frequencies of herbaceous pollen which suggest disturbance, particularly *P. lanceolata*. Consequently the impact of any anthropogenic or grazing disturbance remains uncertain. Analytical and interpretational problems associated with the detection of human activity, discussed in Sections 1.8 and 1.10, are of continuing importance here, as the slight evidence occurs during a period of landscape-scale vegetational and inferred environmental change.

The ambiguous nature of the evidence is evident at Loch Maree. Birks (1972) suggests that *Pinus* degeneration around Loch Maree at *c.*4200 BP (4730 cal BP) may have been accentuated by adverse climatic change, while selective anthropogenic pressure could explain the uneven distribution of woodland survival. However, the low frequencies of 'weeds' and discontinuous *P. lanceolata* curve suggest that "local activity was very slight" (Birks 1972, p.747). Assigning significance to such slight signs of disturbance is problematic and the finer spatial resolution work of Kerslake (1982) emphasises localised patterns of woodland demise and survival without any associated indication of anthropogenic or grazing disturbance.

Evidence for inferred pastoral activity occurs in peat profiles from Druim Bad a'Ghaill, Strath Oykell and near Loch Sionascaig. A 'landnam' phase involving regular burning at *c.*3250 BP (3470 cal BP) is inferred from the latter peat profile, while earlier small amounts of charcoal with no pollen indicators of human influence are attributed to natural fires (Johansen in Pennington *et al.* 1972). The only evidence of arable activity occurs at Loch Craggie, where a single cereal pollen grain is recorded with herbs associated with pastoral activity. Possible pastoral activity appears to occur after the expansion of open communities and the main woodland decline, although as very few dates are associated with these peat profiles, any assumption of synchroneity cannot be wholly justified, given the extent of temporal variation evident from other sites (*cf.* Kerslake 1982). It is also unclear whether this sporadic evidence represents regional or local agriculture, which complicates any assessment of the impact of these anthropogenic activities on woodland regeneration. These data contrast with the absence of evidence from the Loch Sionascaig sequence.

Finer spatial resolution analyses from Lairg provide clearer, although by no means conclusive, evidence of human activity, but also emphasise the difficulty of distinguishing anthropogenic from environmental change, even where local pollen records are available. There is increasing archaeological evidence of settled farming from *c.*3800 BP (4150 cal BP) (Tipping and McCullagh 1998), with continued evidence for grazing pressure at all three pollen sites (Smith 1996, 1998). A shift to less humified peat on the valley side coincides with apparently synchronous declines in *Pinus* around *c.*3800 BP (4150 cal BP) at small peat basins on the valley floor and valley side, although there is little evidence for accelerated blanket peat growth (Smith 1998, Tipping and McCullagh 1998). Subsequent palynological evidence suggests both secondary woodland succession and the maintenance of open ground, possibly *via* grazing (Tipping and McCullagh *op. cit.*). This interpretation raises the question as to whether pastoralists were creating open areas, or were simply moving into newly available open areas (Smith 1998, Tipping and McCullagh 1998). At present there is insufficient evidence to establish patterns or to test either hypothesis.

These profiles from across the northern Highlands hint at the occurrence of human activity, some possibly local, but also raise many questions. Loch and blanket peat sequences from north-west Scotland suggest the widespread expansion of heathland and mire, but *P. lanceolata* does not grow on these substrates, suggesting grassland communities on soils with a higher nutrient status and better drainage (Sagar and Harper 1964). Temporal and spatial variations between pollen records suggest a mosaic landscape, but, on the basis of the present pollen evidence, the composition of possibly limited areas of grassland cannot be clearly reconstructed. At a wider spatial scale, the appearance of herbs associated with disturbance is diachronous. This may reflect the abundance of *P. lanceolata*, and by association, the age, intensity or extent of disturbance and pastoral activity, but is also likely to be influenced by differences in pollen source area.

The impact of human and grazing activity on woodland and bog communities is difficult to assess; at a time when woodland regeneration was in a delicate balance with peat development, and conditions for tree regeneration appear to have been increasingly marginal, even slight interference by burning, felling or grazing may have led to retrogression (Birks 1972, Pennington *et al.* 1972), shifting the balance in favour of bog communities. Evidence from Lairg suggests that human activity did affect the distribution of *Pinus* and other arboreal taxa, but this area is also thought to have supported a more mixed woodland composition than many Highland sites and deep peat development is limited (Smith 1996, 1998), suggesting that it is not representative of upland areas where blanket peat cover is predominant. This is also indicated by the continued regeneration of mixed woodland communities at Lairg, where anthropogenic activity appears to have controlled subsequent woodland distribution, composition and decline. Consequently, the extent, age, character and vegetational impact of human activity in the uplands is presently uncertain.

1.12.2.3 Changes in fire frequency

Bennett (1995) put forward the hypothesis that *Pinus* woodland in the Highlands may have been affected by a change in fire regimes, following examples presented by Bradshaw (1993), which indicate a strong relationship between burning and *Pinus* populations in Ireland. Bradshaw argues that *Pinus* is a very poor competitor and only survived because early and mid-Holocene fire regimes were sufficient to exclude competitors. He presents examples which suggest that a reduction in fire frequency, possibly aided by human activities, may have contributed to the demise of *Pinus*.

However, this hypothesis receives limited support from the few charcoal records available from the Highlands. Charcoal data from Achiltibuie suggest an increase in fire frequency/intensity around 3890 BP, when *Pinus* values fall. However, as *Pinus* frequencies are relatively low (*c.*10% prior to the decline), it is not clear whether this reflects local or regional populations. Charcoal frequencies at Glen Carron increase at *c.*4100 BP (4560 cal BP), during an inferred dry shift *c.*550 ^{14}C (730 cal) years before the *Pinus* decline, while a rise in charcoal particles around 3700 BP (4030 cal BP) occurs during an inferred wet shift at Glen Torridon, following the *Pinus* decline by *c.*240 ^{14}C (380 cal) years. As this coincides with the appearance of low frequencies of *Plantago lanceolata*, human activity is suggested, but the extent of anthropogenic influence on the bog is unknown (Anderson 1998). Only at Lairg do decreasing *Pinus* values coincide with temporarily lower charcoal frequencies, while changes in charcoal frequencies at Ardheslaig do not coincide with woodland demise.

1.12.2.4 Volcanic eruption and pathogenic attack

Blackford *et al.* (1992) suggested that climatic change or acid pollution caused by the eruption of Hekla 4 in Iceland at *c.*3850 BP (*c.*4270 cal BP; Dugmore *et al.* 1995) may have caused the *Pinus* decline at Altnabreac. However, *Pinus* frequencies are low and it is not possible to establish a clear causal link. Other authors have been highly critical of proposed volcanic impacts (Birks 1994, Buckland *et al.* 1997) and subsequent researchers have found no consistent correlation between the deposition of Hekla 4 tephra, the *Pinus* decline or local bog surface changes (Anderson 1996, Daniell 1997, Anderson *et al.* 1998, Caseldine *et al.* 1998, Tipping and McCullagh 1998). Evidence from recent eruptions suggest that volcanic impact on climate is likely to be slight in the long-term, and is virtually indistinguishable from changes caused by other factors (Mass and Portman 1989). Tipping and McCullagh (1998) suggest that the proposed southerly shift of air currents around 4000 BP (Gear and Huntley

1991) may have determined the direction of Icelandic tephra fallout, resulting in the coincidental occurrence of the Hekla 4 tephra and *Pinus* decline in northern Scotland. There is no evidence to support the theory of pathogenic attack (Bennett 1995, Daniell 1997).

1.12.2.5 Conclusions and questions regarding the demise of *Pinus* and woodlands

Palynological evidence from the north-western Highlands suggests that woodland and bog communities have formed a mosaic since the early Holocene, which became an increasingly delicate balance, particularly after *c.*5000 BP (5730 cal BP), and markedly so around 4000 BP (4440 cal BP). While the *Pinus* decline and expansion of peat and mire can no longer be assumed to represent a synchronous regional shift or the result of a single catastrophe, regional climatic deterioration still appears to have been a major cause. Soil deterioration and anthropogenic pressures may have been contributory factors, which caused a shift in growing conditions beyond the ecological tolerance, or threshold, of many woodland taxa, especially *Pinus*. However, ascertaining the impact of human activities and fire regimes requires further high spatial and temporal resolution research.

Many unanswered questions remain. Foremost is why *Pinus* appears to have been affected more severely than other arboreal species (Bennett 1995). It is usually explained by inferring that *Pinus* was growing on peat which became too wet for successful regeneration, and consequently resulted in the death of these 'pine-bog forests'. The growth and demise of *Pinus* on bogs in response to drier and wetter conditions is demonstrated through the presence of subfossil tree stumps and associated pollen and dendrochronological analyses (Pennington *et al.* 1972, Birks 1975, Bridge *et al.* 1990, Daniell 1997). However, sites suitable for the preservation of pine stumps and pollen are biased towards peat substrates (Bridge *et al.* 1990). Daniell (1997) could find little evidence for the growth of *Pinus* on mineral soils from after 4400 BP (4920 cal BP), although at Lairg, pastoral grassland and secondary woodland are suggested to have formed in gaps left by the death of *Pinus* trees (Smith 1998, Tipping and McCullagh 1998), which implies that these trees are not thought to have grown on peat.

Competitive interactions may also have affected *Pinus*. Daniell (1997) suggests that *Betula* may be more tolerant of oceanic conditions (*cf.* McVean 1953, Atkinson 1992). This assertion may be supported by a shift to *Betula* in surviving woodland in the far north-west (Kerslake 1982), and by the continued regeneration of pinewoods in the more continental Cairngorms (Birks 1970, O'Sullivan 1974a, 1976).

At several sites, the presence of steep, better-drained slopes is suggested to have prevented the formation of extensive peat and enabled *Pinus* and other woodland taxa to persist, including

Loch Clair, Subhainn Lochan, Eilean Dubh na Sroine and Eilean Mor. However, peat sites at Glen Torridon and Subhainn Bog, near to the two lochs, record abrupt *Pinus* declines. Differences between the lake and peat profiles may reflect different catchment histories relating to local conditions; at present mire and blanket peat communities occur around the peat sites, contrasting with slopes supporting pinewood around Loch Clair and Eilean Dubh na Sroine. However, pinewood grew at Coille na Glas Leitre from *c.*2470 BP (2650 cal BP), where the ground is no steeper (Kerslake 1982). In addition, the widespread extralocal decline in *Pinus* would be expected to register in the pollen source area of Loch Clair. This may infer taphonomic problems, thus adding to the uncertainties of comparability between lake and peat sequences.

1.13 Later Holocene landscapes: *c.*3000 BP (3190 cal BP) to present

Relatively little attention has been paid to the vegetation history of the last *c.*3000 (3190 cal BP) years, particularly in the north-west. As indicated in Section 1.3.4, there are two main reasons; firstly, an increase in pollen source area, and thus a further reduction in spatial resolution, results in an appearance of remarkable uniformity in many pollen diagrams, and secondly, because of the aims of many researchers (Section 1.3.4). Consequently, many later sediments have frequently been analysed at low temporal resolutions, and few cores have radiocarbon dates younger than *c.*3000 BP (3190 cal BP) (Tipping 1994). This increases the value of data from small diameter sites, which are more sensitive to local conditions in open environments.

The brevity of discussion of the last *c.*3000 ^{14}C (3190 cal) years is a reflection of the paucity of secure palaeoecological information. There are relatively few records from which to infer vegetation dynamics and mosaics, in relation to natural and cultural disturbance factors. Extrapolation to other areas, with poorly resolved pollen records, may therefore be misleading, and many questions remain to be addressed.

1.13.1 Later Holocene vegetation mosaics and dynamics

Sites with a small pollen source area indicate that, despite the regional abundance of blanket bog, local dynamic mosaics of woodland, bog and heath continued to exist during the mid- and late Holocene. This is illustrated in sequences from Eilean Mor and Lochan Dubh, and also by mor humus profiles from the Cairngorms (O'Sullivan 1973b). Evidence for localised woodland survival at these sites contrasts with uncertainties regarding the interpretation of moderate frequencies of tree pollen which are recorded from large pollen sites. For example, at Loch Sionascaig, *Pinus*, *Betula* and *Alnus* frequencies are of similar magnitude to surface samples from *c.*3000 BP (3190 cal BP), and are considered to reflect the contribution of a few

Pinus trees until *c.*2000 BP (1940 cal BP), when frequencies fall below 10%, and are interpreted as regional pollen contributions (Pennington *et al.* 1972). At Lairg too, the regional upland loch site suggests little vegetation change in the last 3500 years, but smaller sites on the valley floor and side continue to demonstrate variations in vegetation and human activity (Smith 1996, 1998; Section 1.13.2).

On Eilean Mor, following the demise of *Pinus*, *Alnus* became re-established around 3300 BP (3480 cal BP), accompanied by 10-25% *Sorbus aucuparia* pollen. As *Sorbus* is entomophilous, and thus under-represented in the pollen record (Birks 1980), these frequencies suggest substantial quantities growing close to the bog. Kerslake (1982) suggests an edaphically-controlled mosaic, with grasses and *Potentilla*-type in the understorey, as *Alnus* and *Sorbus* have different ecological requirements and no present *Alnus-Sorbus* woodland analogues are known. This illustrates the value of using small pollen collecting sites to determine vegetation composition, and may indicate that *Sorbus* was much more common than low frequencies in loch sequences would suggest.

The profile from Eilean Mor suggests a dynamic relationship between *Betula*, *Pinus* and *Calluna* from 4400-2600 BP (4920-2750 cal BP). Similar evidence emerges over the last *c.*1500 ^{14}C (1350 cal) years from mor humus profiles in the Cairngorms (O'Sullivan 1973b). These results contrast with loch sequences from Inverpolly and the Cairngorms, which suggest an apparently static bog-heath-wood mosaic in the north-west (Pennington *et al.* 1972), and virtually continuous woodland cover in the Cairngorms (O'Sullivan 1974, 1976). Although problems exist in the interpretation of soil profiles, the similarities between these results suggest that the patterns reflected in mor humus profiles are real. This may also have implications for soil status and the long-term stability of mixed *Pinus*, *Betula* and heath communities (O'Sullivan 1977). The cause(s) of changes in the abundance of heath and woodland are not clear from palynological data on Eilean Mor; fire, windthrow, disease and grazing are suggested to have resulted in shifts to *Calluna*. O'Sullivan (1973b) recognises that the dates for heathland formation are poorly constrained, but a possible correlation with Iron Age Pictish clearance is suggested.

The sequence from Lochan Dubh emphasises the need for taxonomic precision and consistency. Contrary to most of Kerslake's other sites, *Myrica* and *Corylus* pollen were not identified separately. Although *Myrica* and *Corylus* pollen cannot be consistently separated (Edwards 1981), *Myrica*-type pollen is recognisable (*cf.* Moore *et al.* 1991) and can provide valuable ecological information. It is thus not possible to determine whether fluctuations in *Betula* and *Corylus*/*Myrica* at Lochan Dubh reflect woodland or wood-mire dynamics, thus limiting the value of the data.

1.13.2 Anthropogenic activity

The extent, intensity and nature of possible human activity are difficult to infer from slight increases in 'anthropogenic indicator' pollen (*cf.* Behre 1981, 1986). This applies to large and small pollen sites. For example, documentary data indicate considerable human activity in the Letterewe oakwoods near Loch Maree during the seventeenth century AD, but this appears inconsistent with the slight increase in 'weed' pollen in the loch profile (Birks 1972). Slight increases in *Plantago lanceolata* and charcoal at smaller kettlehole sites, such as Glen Carron and Glen Torridon, suggest that land-use was never intensive close to the mires (Anderson 1996), but the scale of land-use is also difficult to interpret in a catchment dominated by pollen of heath and bog taxa (*cf.* Edwards 1982).

Ambiguities involved with interpretation remain. For example, on Eilean Mor, small peaks in *Rumex acetosa*, Rosaceae and *Hypericum pulchrum*, and increases in *P. lanceolata* are suggested to be derived from extra-local or regional sources in a sparsely cultivated landscape. However, similar occurrences have elsewhere been interpreted as the result of possible anthropogenic activity (*e.g.* Pennington *et al.* 1972, Birks 1972, Anderson 1996), and Kerslake's (1982, p.86) comparison of pollen influx data from Eilean Mor with an arable landscape with abundant *P. lanceolata* to infer a sparse regional source is perhaps inappropriate.

This contrasts with evidence of local agriculture at Lairg (Smith 1996, 1998) and Achiltibuie (Bunting and Tipping 1997). Marked contrasts in environment and land-use are evident between these two sites and it is difficult to determine whether land-use around these smaller sites in peripheral and coastal areas is comparable with upland activity, which is currently known only from regional pollen records.

The late Holocene history and longevity of woodland communities was temporally and spatially variable. The plateau site at Lairg suggests that blanket peat was a landscape feature from *c.*4200 BP (4730 cal BP), due either to climatic or anthropogenic impacts, but local woodlands persisted in the valley, until *c.*2200 BP (2270 cal BP), when they appear to have been cleared. Periods of regeneration at *c.*1800-1200 BP (1710-1080 cal BP) on the valley side, and over the last 1000 ^{14}C (930 cal) years on the valley floor indicate that the valley was still capable of supporting tree growth, which was largely controlled by anthropogenic and grazing activities (Smith 1998), rather than environmental factors.

Similarly, at Achiltibuie local stands of *Betula* and *Corylus* are thought to have persisted after the general reduction of woodland around 3890 BP (4330 cal BP). Despite a long history of Bronze and Iron Age pastoral activity, these were only lost around 930 BP (830 cal BP), apparently due to an edaphic shift to peat and heathland formation, although with some regeneration between 770-420 BP (670-500 cal BP). The final loss of woodland between *c.*420 and 140 BP (500-140 cal BP) is attributed to human activity, indicated by increased charcoal frequencies, the suppression of regeneration through grazing pressures, or wetter and colder conditions during the Little Ice Age, which may also have made trees more vulnerable to other pressures (Bunting and Tipping 1997).

While pastoral land-use appears to have been common in both areas, the record of cultivation is much more variable in time and space, resuming on the valley floor at Lairg around 3200 BP (3390 cal BP), when pastoral activity commences at Achiltibuie. *Avena/Triticum* grains are recorded on the valley side at Lairg around 1600 BP (1500 cal BP, AD 450), but possible cultivation is not recorded at Achiltibuie until the medieval period, around 770 BP (670 cal BP, AD 1190), when only *Hordeum* group grains are recorded. However, in this coastal location, *Hordeum* group pollen may also have been produced by maritime grasses, although archaeological evidence may also indicate tillage. Despite some uncertainty, this variability is a sharp contrast from the absence of cereal pollen in regional pollen diagrams, with the exception of the undated profile from Loch Tarff, and low frequencies of pastoral indicators.

There is clear evidence for the coexistence of woodland and agricultural activities at Lairg and Achiltibuie and different forms of woodland management have been tentatively suggested, in contrast to simple 'expansion-regeneration' models usually employed (Berglund 1985, *cf.* Tipping 1994). At Lairg, *Quercus* and *Ulmus* pollen representation increased in the valley around 3800-3500 BP (4150-3790 cal BP), while values for other arboreal taxa declined. This is not reflected in the regional pollen rain at this time, and with increased macroscopic *Quercus* charcoal during the Iron Age, is suggested to reflect management for timber (Crone *et al.* 1998, Smith 1998). After subsequent woodland decline at Lairg, the correlation between *Calluna* and charcoal fragments from the pollen site on the valley side may indicate heathland management from the Iron Age, at *c.*2200 BP (2270 cal BP) (Smith 1998).

This forms an interesting comparison with the evidence from Achiltibuie, where woodland regeneration around 770 BP (670 cal BP) is suggested to have resulted from turf stripping, which may have exposed drier soils. Subsequent oscillations in the *Betula* and *Corylus* curves suggest regular disturbance, tentatively suggested to indicate coppicing during a period of increasing pastoral and arable activity (Bunting and Tipping 1997; *cf.* Goransson 1986). These suggestions, although tentative, contrast with the absence of palynological evidence for historically documented timber extraction around Loch Maree (Birks 1972), reflecting again the value of a smaller sampling site, even in more open conditions.

Changes in the uppermost spectra from Achiltibuie clearly demonstrate the impact of nineteenth century changes in land-use. Increased *Calluna*, Ericales and *Potentilla*-type, and a reduction in Poaceae is tentatively suggested to reflect the late nineteenth century failure of sheep farming and conversion of the surrounding land to grouse moor (Bunting and Tipping 1997). A similar correspondence between documented historic land-use changes and palynological data is evident in the Cairngorms, where analysis continued into recent sediments. The pollen data from Loch a'Chnuic correlate well with historical data for the short-lived establishment of farms in the upper forest during the Napoleonic Wars, around AD 1812-1830, followed by clearance in the later nineteenth century (O'Sullivan 1974a). Around Loch Pityoulish, clearance and the expansion of pasture are evident over the last 300 ^{14}C (310 cal) years (O'Sullivan 1976), while at Loch Garten, an increase in arboreal and *Pinus* pollen in the top 4 cm is correlated with replanting in AD 1840 (O'Sullivan 1974a).

The broad range of temporal and spatial contrasts from just two sites in northern Scotland (Achiltibuie and Lairg), with tantalising, but poorly resolved evidence for activity from regional-scale upland sites, suggest the need for further, carefully designed research into human activity in the uplands.

1.14 Aims of the present study

While it is acknowledged that much of the work discussed here was carried out during the 1970s, when regional vegetational and environmental histories were largely unknown, it is clearly inadequate to understand the complex range of vegetational communities, environmental changes and cultural history of the Highland region. This review has sought to highlight these uncertainties. Developments in palynology allow researchers to demand much more of palaeoecological techniques, and conduct much more rigorous tests of hypotheses and questions emerging from earlier work and from related fields (*e.g.* ecology, archaeology) (*cf.* Bryant and Holloway 1983, Berglund 1986, Walker 1990, Birks 1993, 1996a, Bryant and Hall 1993, Huntley 1996). Establishing clear aims or hypotheses is integral to any scientific research programme, as it demonstrates a critical awareness of the relevant previous work, particularly inadequacies and aspects which are in need to further investigation.

In order to meet these challenges, there are two essential prerequisites; firstly a clear understanding of the spatial scale of the pollen record, and secondly, establishing a temporal resolution appropriate to ecological change and human generations. Carefully considered methodological and analytical criteria will enable the generation of pollen records which can be more securely related to vegetation composition and linked to the formative environmental pressures. This provides a more secure basis for palaeoecologists to approach interpretational problems and questions. These prerequisites and the many uncertainties in the present pollen literature for the Highlands are the basis for the development of the aims and palynological research strategy for West Glen Affric and Kintail (see below and Chapter 3).

The objectives of this study are phrased as aims rather than as more specific hypotheses in order to address more of the range and number of questions which presently remain unanswered in this region. Four aims are thus proposed for critical investigation in the present study:

1. **To establish fine spatial and temporal resolution records of Holocene vegetation history.** Many of the present pollen records suggest remarkable homogeneity in Highland vegetation, particularly after the mid-Holocene. However, a smaller number of pollen records and ecological observations suggest that the mosaics and dynamics of past communities may be lacking from many pollen records due to their relatively coarse spatial and temporal resolution, which far exceed the scales associated with ecological processes. In addition, due to taphonomic problems relating to Pinus pollen sedimentation in lochs, the inferred dominance of Scots Pine appears in some areas to be questionable. Careful research design and the analysis of deposits from small basins, including AMS dating to establish a stratigraphically secure chronology, can provide the appropriate spatial and temporal scales from which to approach ecological and anthropogenic questions during the Holocene. This is the overarching methodological aim of the research. As woodland composition and dynamics are the focus of enquiry, high altitude communities are outwith the aims of the present research.
2. **To establish the range of local environmental factors which control vegetation development, composition and stability.** Evidence for spatial and temporal variations in past vegetation and the present uneven survival of woodland in the Highlands, suggest that local environmental contrasts have been influential. However, unlike larger-scale geological and climatic variations on Skye (Williams 1977, Birks and Williams 1983), these environmental gradients appear to be too small to be securely resolved from regional-scale palynological analyses. Consequently, many of the environmental factors controlling vegetation development remain poorly established. These include a wide range of potential disturbance mechanisms, such as autogenic succession processes, hydrological and geomorphological disturbance, burning, animal and anthropogenic intervention. Careful site selection, combined with fine spatial resolution analysis, can help to establish

the impact of local environmental gradients on vegetation development by investigating local processes which may characterise wider landform units to create vegetational mosaics (see Chapter 3).

3. **To establish the impact of these local environmental factors on the spatial and temporal patterns of the mid-Holocene woodland decline.** This period has been a focus of many previous analyses in the north-western Highlands, most notably the demise of *Pinus*. While the temporal and large-scale spatial variability of this horizon is well-established, the reasons for these variations are less securely inferred at many sites; the respective roles of climate, pedogenesis, anthropogenic activity, fire and physical catchment characteristics (*i.e.* drainage, slope) frequently remains ambiguous. This is due to a relatively poor resolution, especially of finer-scale spatial changes within the landscape, which may contribute to our understanding of the nature of environmental changes at this time and the ecological processes which so altered the appearance of the region. Rates of change are difficult to estimate securely due to the use of bulk radiocarbon dates. The methods discussed above can provide the detail necessary for understanding this complex period of change.
4. **To address some of the ambiguities associated with the inference of anthropogenic activity through fine spatial and temporal pollen analyses.** Palaeoecological evidence from Lairg (Smith 1996, McCullagh and Tipping 1998) and Achiltibuie suggest a wide range of temporal and spatial variation in human activity across the Highland region, yet most previous research has failed to securely establish the impact of humans in the Highland region, particularly in the north-west and over the last 3000 years. This is suggested to be due primarily to the difficulty of inferring the nature, scale and intensity of activity from the low and sporadic pollen representation of better dispersed 'anthropogenic indicator' herbs in lochs with a regional catchment or large bogs which are unsuited to the growth of such 'indicator' taxa. This may reflect a real dearth of activity across the region. However, data from Lairg suggest that the regional-scale records could also reflect more intensive but small-scale activity, producing a more elusive pollen signal. Fine spatial and temporal resolution analyses can enable more critical interpretation of disturbance dynamics and small-scale vegetational changes necessary to differentiate between anthropogenic and natural disturbance mechanisms, helping to establish the age, nature and scale of human activities.

In order to fulfil these objectives, the development of a suitable research design is discussed in Chapter 3. The aims specific to each sampling site are presented in the introduction to each of the selected sites (Chapters 5-8).

CHAPTER 2: Glen Affric and Kintail: the physical and cultural landscape

2.0 Introduction

This chapter will introduce the physical and cultural environment of the palynological study area in West Affric and Kintail, to highlight gaps in our present understanding of the evolution of this landscape, and to examine briefly how Affric compares with the surrounding Highland glens. The physical environment is described in terms of its geological and geomorphological background, present edaphic and climatic conditions, and the possible relationship between these environmental factors and modern vegetation. The present vegetation, which includes relict woodlands, is compared with maps of potential woodland in order to examine the contrast between the observed communities and predictions based on ecological and previous palaeoecological data. The study area is then set in a regional context by examining how Glen Affric and Kintail compare and contrast with the surrounding Highlands in recent biogeographical zonation schemes. This is a necessary preface to palaeoecological comparisons of the evolution of the landscape.

This is followed by a discussion of present land-use capability and an overview of the very limited archaeological and documentary records of human activity through the Holocene, emphasising the evidence for land-use, which is re-evaluated in detail in the discussion (Chapter 9).

2.1 Physical Environment

2.1.1 Geographical location

Glen Affric is an east-west trending valley located in the northern Scottish Highlands, stretching from the west coast at Kintail at 5° 23' W to East Affric and Cannich at 4° 45' W, and lying between the latitudes of 57° 12' and 57° 20' N (Figs. 1 and 2). This area encompasses an upland glen, which lies predominantly above 200 m OD, surrounded by mountains, many above 1000 m OD. However, it also includes the lowland coastal Strath Croe valley, at the head of Loch Duich, Kintail, and the inland valley at Cannich, which descends to Strathglass and thence into the Great Glen and the Beauly Firth by Inverness.

Glen Affric and Kintail consequently include many environmental contrasts, encompassing climate, altitude, slope, aspect, and vegetation. The palynological study area includes many of these contrasts, extending from central Affric, near the head of Loch Affric, to the western Kintail lowlands (Fig. 2). A generalised description of the geographical region as the 'Highlands' is thus somewhat artificial, including many valleys of lowland character, as well as the distinctive mountainous zones.

2.1.2 Geology and geomorphology

Glen Affric lies in the Caledonian orogenic belt and is predominantly underlain by the Moine supergroup, which also underlies much of north-western Scotland on the eastern side of the Caledonian Thrust plate, from Morvern, to Kyle of Tongue in the far north of Sutherland, and as far east as Rogart and the head of the Dornoch Firth in south-eastern Sutherland. The Moine supergroup consists of metamorphosed sedimentary rocks, with a few exposures of older Lewisian metamorphic rocks, particularly at Kintail (Harris and Johnson 1991, Mitchell 1997). The Moinian rocks were formed during the Caledonian Orogeny, between 600 and 400 million years ago. A north-south trending fault-line known as the Sgurr Beag Slide runs through West Affric, dividing the western psammite Morar Division at Kintail from the younger, eastern pelite Glenfinnan Division (Harris and Johnson 1991). These rocks consist of mixed assemblages of banded psammite, pelite and semipelite, all of which are acidic and fairly resistant to erosion. The Lewisian outcrops at Kintail are acidic, but more mineral-rich than the Moinian rocks.

Due to the upland, north-westerly location of the glen, the pre-Quaternary and Quaternary land surface has been modified by repeated glaciation throughout the Pleistocene, and most recently by the Loch Lomond Readvance, resulting in the present glacially-eroded trough, which is dominated by the surrounding glacially-sculpted mountain peaks and ridges. The entire glen was covered by the Loch Lomond Readvance ice-field, from the head of Loch Duich eastwards. The end moraine is located near the eastern end of Loch Beinn a'Mheadhoin, where the glacier divided into two lobes (Bennett and Boulton 1993, Tate 1995). As a result of the Loch Lomond Stadial glaciation, late-glacial sediment is absent from Affric (Tate 1995), including Loch Affric (Pennington 1977).

Glacial weathering of the underlying rocks has produced a mantle of hummocky morainic drift on the valley floor and sides. Hummocky moraine is thought to represent ice-marginal landforms deposited by the actively decaying ice sheet (Bennett and Boulton 1993), while exposed bedrock is predominant on the higher hillslopes and peaks.

There is abundant evidence of geomorphic activity in Glen Affric, although none of this has been dated. This includes alluvial fans, debris-flow, gullying and numerous examples of rock slope failure and landslides. Previous research in the Highland region suggests an early Holocene date for rock-slope failure, debris-flow and alluvial fan formation in response to landscape adjustment following deglaciation (Ballantyne 1991). However, this conclusion is frequently based on the relict appearance of the features, with very few radiocarbon dates.

Recent research in the northern Highlands suggests that many 'relict' landforms and land surfaces are in fact mid- or late Holocene in age, including radiocarbon-dated sites in Gleann Lichd, which links Affric and Kintail (Fig. 6), and in Strath Conon to the north (E. Reid pers. comm.). From the synchroneity of response, Reid suggests that the external trigger was climate change, particularly increased precipitation. Enhanced erosion and debris-flow in recent centuries has been attributed to Little Ice age climatic deterioration in nearby glens (Reid pers. comm.), and, in other areas, to burning and overgrazing (Innes 1983, Ballantyne 1991). Further palaeoecological research is thus needed to understand the timing and causes of present landforms, although geomorphological activity is outside the direct scope of this palynological research project.

2.1.3 Soils

The Glen Affric region is dominated by soils of the Arkaig Association. These are mostly peaty and podsolised soils, derived from drift material produced by weathering of the resistant Moinian rocks, and as result are naturally acidic. Leaching is thought to have begun shortly after deglaciation in northern Scotland (Pennington *et al.* 1972, Carter 1998), and the prevailing oceanic climate further predisposes the soils to leaching conditions. On the undulating hills, and hummocky or gullied moraines with steep slopes in Central, West and East Affric, the soils are primarily peaty podsols, peaty gleys and peat. Peaty podsols and peat also occur on the hills and valley sides. Humus iron podsols occur in East Affric and have also been observed in central Affric. Similar peaty and poorly-drained, leached soils occur at higher altitudes, with poorly developed subalpine and alpine soils on the mountains and summits.

Better drained soils have developed on the alluvial deposits which occur on the valley floor and over alluvial fans, which occur quite frequently where streams meet the valley floor. In Glen Affric peaty alluvial soils are of limited extent, occurring in central Affric near the head of Loch Affric, and along a 2.5 km stretch of valley floor in West Affric. Mineral alluvial soils only occur around and downstream of Alltbeithe in West Affric. In contrast, mineral alluvial soils cover most of the low-lying Strath Croe floodplain, where peaty alluvial soils are of limited extent. Saline gleys occur between the alluvial soil and the head of Loch Duich, while brown forest soils and humus-iron podsols are limited to the northern end of Strath Croe.

These data indicate some degree of west-east zonation, with the limited extent of better-drained and less peaty soils most frequent at Kintail. Although the soils of West and East Affric are technically similar, field work indicates that deep peat is much rarer in the east, and suggests that, on average, the depth of peat is greater in West Affric. Although this reflects the outcome of long-term pedogenesis, it is noted that this also coincides with marked climatic and vegetational gradients.

On a broad, regional scale, much of the mountainous Highlands and Islands are characterised by similar peat and organic soils (Coppock 1976), which has marked implications for the present agricultural capability of the land (see Section 2.2.3.2).

2.1.4 Climate

Few climatic data are available relating directly to Glen Affric and many of the nearest weather stations, such as the Great Glen, Skye and Inverness, are subject to very different climatic conditions, with very limited upland information in the area. The most comprehensive climatic data are available from 1:625000 maps produced by Birse (Birse and Dry 1970, Birse and Robertson 1970, Birse 1971) using climatic data from early this century, and smaller scale Scottish and national maps from Coppock (1976), Barrow and Hulme (1997), and Roy (1997). Consequently, no accurate estimates of temperature or rainfall are available for the study region.

Although only estimated and extrapolated details of the recent climate of Glen Affric and Kintail are available, they have an important impact on soil development and plant growth, particularly water and nutrient relationships, and thus on agricultural activity. The characteristic climatic features of the area are presented before a more detailed description of climatic gradients within the study region.

The climate of the western Highlands is characterised by oceanic conditions, with strong winds and high effective precipitation due to exposure to the Atlantic Ocean, and prevailing westerly winds. The complex topography of the region results in great climatic diversity, on both local and regional scales (Roy 1997). At the local scale, the effects of altitude, slope, aspect and surrounding topography can result in rapid changes in temperature over short distances, with smaller variations in precipitation. Large-scale variations are related to the proximity of the sea. Shelter plays a very important role in many aspects of the region's climate, due to the vertical and horizontal scale of the mountains. This is particularly true of the north-west, where steep-sided, high mountains are dissected by deep valleys.

The proximity of the Atlantic Ocean has an ameliorating effect on temperature. This influence is felt further inland on the west coast due to prevailing westerly winds and fjord-like sea lochs, compared with a narrower band inland from the east coast (Brown *et al.* 1993b). August is the warmest month, with the coldest temperatures recorded in February. However, the proximity of the west coast to the Atlantic Ocean and westerly systems also means that precipitation and wind speeds are high. Rainfall is highest in autumn and early winter, when westerly systems are most frequent, and lowest from April to June, coinciding with the lowest frequency of westerly winds. Orographic enhancement over mountains and shelter on the leeward side of the peaks play an important role in determining rainfall patterns (Roy 1997).

There is seldom a significant potential water deficit in the west, since the annual rainfall is in excess of 1500 mm (Coppock 1976, Barrow and Hulme 1997), greatly exceeding annual evaporation. For this reason, the region is considered to be one of "climatic bog", where the land is considered to be virtually incapable of cultivation (Green 1964; Section 2.1.5.4).

The north and west Highlands are the windiest parts of the British Isles, since they are most exposed to the Atlantic and lie closest to the deep depressions of the winter months, when the strongest gusts occur. Wind flow over the steep mountain slops is complicated, as the rough terrain can cause a decrease in wind speed, but gusts may still be strong, and funnelling effects can lead to locally intensified airflow (Roy 1997). Windspeed and exposure, more than temperature, set the altitudinal limits of tree growth and make local shelter of great importance (Green 1964, Roy 1997).

The mountainous character of this region leads to a greater frequency of cloudy skies over inland areas than over the sea. Despite long day lengths in the north, cloud cover and topography limit the amount of sunshine (Barrow and Hulme 1997, Roy 1997). Steep-sided mountains may cut off sunshine from narrow valleys for much of the day, particularly to north-facing slopes. This effect is even more pronounced during winter months, when the sun's elevation is low.

At a finer scale, the maps compiled by Birse (Birse and Dry 1970, Birse and Robertson 1970, Birse 1971) suggest that there are clear west-east gradients within the study area. The lowland Kintail valley is characterised by fairly wet, warm conditions, with a long growing season, moderate exposure and fairly mild winters. Exposure and winter severity increase with increasing altitude. These features are characteristic of glens at the head of sea lochs in the western Highlands, while conditions in West Affric are characteristic of upland glens and mountains. The valley floor in West Affric is more exposed and experiences cooler, wetter conditions than Kintail, with a medium length growing season and rather severe winters, increasing to extremely cold and exposed wet mountain regions with very severe winters. Kintail and West Affric fall within the perhumid zone of Birse (1971), in which the summer potential water surplus is greater than 500 mm.

These data suggest a transition around the head of Loch Affric, as conditions become more similar to Kintail, with fairly warm and wet or rather wet lowland and foothill conditions, a long growing season, moderate exposure or sheltered conditions and moderate winters (Birse 1970, 1971, Birse and Robinson 1970). These conditions are characteristic of many inland valleys, including the Great Glen. However, in contrast to the west coast, the area falls in the humid zone, with a summer potential water surplus less than 500 mm, reflecting the greater distance from the Atlantic Ocean. This may be significant in pedogenesis, as discussed above, and in vegetational terms (see below).

2.1.5 Present and recent historic vegetation

At present, there are marked east-west vegetational contrasts in Glen Affric, with putatively ancient Scots pine and birch woodland in East Affric (Steven and Carlisle 1959), large expanses of blanket peat and heathland in central and West Affric, and bracken-infested grassland at Kintail. These variations coincide with present climatic and edaphic gradients, particularly peat development. This poses many questions regarding the evolution of the modern landscape, and may also have implications for the future of the woodlands in East Affric.

At present the only information relating to past woodlands in Glen Affric derives from subfossil *Pinus* wood remains in the peat in West Affric, and from maps dating from the late sixteenth century. This evidence is summarised as it is at present the only source of longer-term information on vegetation and the extent of recent historic changes in the study area. A brief description is then given of the woodlands in East Affric to emphasise the striking contrast between East and West Affric. This is followed by a description of the vegetation cover in West Affric and Kintail. As indicated above, these are then considered in their regional context.

2.1.5.1 Evidence for Holocene vegetational changes in Glen Affric and Kintail

In many areas of West Affric subfossil *Pinus sylvestris* stumps are preserved in the peat, forming virtual 'graveyards' exposed through peat erosion. Although these occur in some abundance, their age is unknown. Research in other areas of Scotland suggests that *Pinus* remains are of variable age, corresponding with wetter climatic periods ('pluvials'), although few post-date 3250 BP (3470 cal BP) (Bridge *et al.* 1990). Wood preservation is thus an artefact of wetter conditions, and not a true reflection of long-term woodland growth (Birks 1975, Bridge *et al.* 1990). Although *Pinus* occurs most frequently in Affric, other species, suggested to be *Betula* or *Alnus* by their silvery bark, have also been observed during field work in Glen Affric.

In contrast to the undated and biased representation of past woodlands provided by subfossil wood in Glen Affric, cartographic evidence provides a generalised indication of the extent of woodland communities in recent centuries. The earliest evidence consists of sketch maps by Timothy Pont, dating from about AD 1585-1596, which were used by Blaeu to produce his atlas of the known world, published in 1654. Eighteenth century maps were produced by Avery (1725-1730) for the York Building Company, in Roy's military survey (*c.*1750) and by Thomson (1830), preceding the first Ordnance Survey map of 1872. Where symbols or notes were made (*e.g.* Avery), they indicate that the woods were composed predominantly of *Pinus* and *Betula*.

These maps suggest that there has been little change in the distribution or, as far as can be discerned, in the composition of the woodland in East Affric between the sixteenth and twentieth centuries. Roy's map depicts scattered trees around Loch Coulavie, near the head of Loch Affric, but it is not clear how accurate Roy's survey was, particularly in more remote locations (Smout 1997). In West Affric and Kintail there are indications of slight changes. The OS maps depict scattered birch trees beside several of the streams and on the intervening hillsides in West Affric, including the area between the pollen site at Carnach Mór and Alltbeithe (Gaelic for 'birch stream'), and above Allt Cam-bàn, near the sampling site at Camban, where several sheepfolds are also marked. These areas are now virtually treeless.

Woodland was known in Kintail during the historic period as notes transcribed in the seventeenth century, thought to be from a lost transcript of Pont's late sixteenth century maps, describe Kintail as 'watered with divers rivers covered with strait glenish woods', *i.e.* narrow woods along watercourses (Smout 1997).

The maps thus give few clues to the former extent of woodland in West Affric and Kintail, highlighting the need for palaeoecological research to fill large lacunae in our present incomplete understanding of this landscape. Similarly, the composition of past woodlands are unknown. Subfossil wood remains reflect only those species which can survive on peat and which were then preserved by a change to wetter conditions. Extrapolating backwards from the present communities is highly fallible, due to their relict nature, which reflects the outcome of selective climatic, edaphic, grazing and anthropogenic pressures operating over much longer timescales than the present data allow us to safely infer (Tipping *et al.* 1999). The contrast between present and potential woodland composition is highlighted by McVean and Ratcliffe's (1962) map of potential woodland distribution (Fig. 4, see Section 2.1.6.2).

2.1.5.2 East Affric

The woodlands of East Affric have been described by Steven and Carlisle (1959) as one of 35 historically important sites in Scotland which are thought to support relicts of formerly more extensive native pinewoods. This is based on the age structure of the present woods, and on the available historical data, which only extends back a few centuries, as discussed above.

The native woods in East Affric consist of varying mixtures of *Pinus sylvestris* and *Betula* (*B. pendula* and *B. pubescens*), ranging from pure *Pinus* stands to *Betula*-dominated woodland, the latter particularly at the eastern end of the glen (Photo 1). *Sorbus aucuparia* is common, particularly in the birchwoods, and there is some *Alnus* and *Salix atrocinerea* along the streams, with *Salix* also growing on some of the bogs. Many of the better stocked *Pinus* stands are growing on knolls with deep, well-drained, sandy and gravelly soils, often covered with a deep layer of litter and raw humus with a clear leached horizon (Steven and Carlisle 1959). The woodland understorey consists of heath species, Poaceae, Cyperaceae and moss communities, which vary in relative abundance with drainage (see Steven and Carlisle 1959).

The woods range in altitude from 180-450 m OD, with a few scattered trees up to 510 m (Steven and Carlisle 1959). There is little difference between *Pinus* and *Betula*, although the latter often forms the upper fringe.

At the time of Steven and Carlisle's study, the woods consisted of even-aged groups, dominated by the 80-140 year age class, which suggests stand-scale seedling establishment and maturation. However, there is little ecological data on the current state of regeneration and long-term trends in woodland structure and recruitment. Recent observations indicate that *Pinus* and *Betula* seedlings are quite numerous in open areas on the southern shore of Loch Affric and on disturbed banks beside the track, particularly where deer fences prevent grazing, but the mortality rate and long-term patterns of regeneration are unknown.

Although palynological investigation cannot work at the scale of the individual, fine spatial resolution analysis can provide data at the scale of woodland stands or communities, and thus provide valuable ecological information on long-term woodland composition and dynamics. East Affric falls outside the scope of this author's research, but recent and ongoing work by other palaeoecologists is furthering our understanding of these woodland communities (see Wolff and Tipping 1999).

Towards the head of Loch Affric, the woods thin, grading to isolated *Pinus* trees on the blanket peat (Photo 2). *Betula* is frequent along stream courses, and regeneration is common in the areas of clear felled conifer plantations on hillslopes on the southern side of the loch. The extent of natural regeneration in these areas, particularly in *Pinus*, may be limited by the increasing depth of an upper peaty soil horizon towards the west. Although climatic records are not available for the immediate area, the gradient around the head of Loch Affric depicted by Birse (1971) suggests that climatic controls may have affected the evolution of the present vegetational transition.

The head of Loch Affric is thus argued to be a key area for understanding the history of the relict woodlands of East Affric, and the contrast with West Affric. Since cartographic evidence indicates that the present pattern was established more than three to four centuries ago, palaeoecological methods are an important source of evidence to resolve when this transition may have come about.

Although East Affric is renowned for its native woodlands, coniferous plantations consisting of *Pinus sylvestris* and exotic conifers are also characteristic of the landscape. Sub-alpine and montane communities are also well-developed (McVean and Ratcliffe 1962).

2.1.5.3 Central and West Affric

In contrast to East Affric, the vegetation of West Affric is dominated by peat, heath and montane vegetation (McVean and Ratcliffe 1962, Land Cover of Scotland 1988). Blanket peat communities mantle the lower hillslopes and valley sides in central and west Affric, covering the bedrock and hummocky moraine (Photo 3). This vegetation is relatively species-poor, dominated by Cyperaceae and *Sphagnum*. *Calluna* assumes greater importance on the higher slopes, where growth is tall, contrasting with more stunted plants on the blanket peat on the lower slopes. However, the frequency of subfossil *Pinus sylvestris* stumps preserved in the peat raises many questions as to the reasons for the present contrast between East and West Affric, and the date of its origin.

Although blanket peat and heath communities are the dominant vegetation types, the coarse scale of resolution on land-cover maps conceals important smaller-scale diversity around numerous streams, flushes and other alluvial sediments. For instance, vegetation cover on the restricted areas of alluvial sediment on the valley floor and fans contains more grass species and a much greater variety of herbs (Photo 4, see Chapters 6 and 7). In addition, the few areas of natural regeneration in West Affric at present occur beside streams. This suggests a marked difference in soil nutrient status, which may have distinguished the Holocene composition and dynamics of alluvial and morainic vegetation. However, the age at which these alluvial features were formed and their vegetational history are unknown. Distribution patterns in the limited archaeological evidence also suggest that the origin and development of alluvium is important for understanding past settlement and land-use (see Section 2.2.3.1).

Limited areas of coarse grassland occur at high altitudes and on steep slopes in West Affric. Further west, in Fionngleann, heather moor and montane vegetation predominate, while extensive blanket bog is absent west of Camban (Fig. 6). Fionngleann appears to form a transitional zone between the extensive peat communities of West Affric and the grass- and heathland of Kintail. As at the head of Loch Affric, there is an association between vegetational, climatic and edaphic gradients in Fionngleann, which may infer causal mechanisms. This suggests that the western end of West Affric is another key area for understanding Holocene landscape development.

2.1.5.4 Kintail

Increasing proportions of coarse and smooth grassland and heather moor, including dry heathland, occur below montane communities from the head of Glen Lichd and west to Strath Croe. The vegetation cover of Kintail is dominated by grassland, with abundant *Pteridium aquilinum*. This may reflect the transition to less peaty, better drained soils (Section 2.1.3). Salt marsh communities occur on saline gleys at the head of Loch Duich. Trees are more frequent towards the west, although they are not abundant; a fringe of *Alnus* occurs along many of the river banks in Glen Lichd and Strath Croe, perhaps a relict of sixteenth or seventeenth century glen woods (see above), with plantations in Strath Croe, Inverinate and Glen Shiel. In contrast to West Affric, vegetation composition in the Kintail region is much more strongly affected by present day and historic anthropogenic activity (see Section 2.2.3.1); grazing is the most extensive land-use, occurring on heathland, on rough hill grassland, on the valley floor, and also on the coastal salt marsh communities.

2.1.6 The regional environmental context of Glen Affric and Kintail

2.1.6.1 Biogeographical zonation of Scotland

It is necessary to understand how the present environment in Glen Affric compares with surrounding regions, since this will give some indication of the major environmental (climatic and edaphic) factors affecting vegetation composition at a regional scale, and thus indicate how wide an area Glen Affric may be characteristic of. This knowledge is important since it places the present landscape in a regional context, and will aid the interpretation of contrasts and gradients in the palaeoecological record.

Plant Communities of the Scottish Highlands by McVean and Ratcliffe (1962) and *The Vegetation of Scotland* by Burnett (1964) remain important sources of information on the environment, distribution, composition and ecology of vegetation in Scotland. More recently, several authors have produced biogeographical zonation schemes for Scotland (Carey *et al.* 1995, Usher and Halharry 1996), and for the Scottish uplands (Brown *et al.* 1993a, 1993b) in an effort to examine regional biogeographic patterns. The variables used included climate, geology, topography, land-use, vegetation and selected animal groups.

In order to delimit regional zones, these models are necessarily simple, but give some indication of generalised patterns and some of the explanatory variables at a landscape scale. The biogeographical zonation schemes differ in detail, but the present study area is consistently included in two zones (Fig. 3). Kintail and Cannich, at the eastern end of East Affric, fall within the Western Mainland zone or Western Highland Fringes, while West and much of East Affric occur in a Central Highland or Western Highlands zone. The former is characterised by high relief and high rainfall (Carey *et al.* 1995, Usher and Balharry 1996), and the latter by high altitude plant communities (McVean 1964, Brown *et al.* 1993a, 1993b, Carey *et al.* 1995), and typically nutrient-poor and acidic soils (Usher and Balharry 1996).

Regional differences in vegetation are determined, on a large scale, by climatic, geomorphological and geological variation (McVean 1964). Multivariate statistical analyses suggest that climatic variables have the strongest explanatory power, while geology was found to have little influence, possibly due to the insulating effect of deep peat, succession or alteration (*e.g.* anthropogenic) from pre-peat communities (Brown *et al.* 1993b).

2.1.6.2 Potential woodland zonation of Scotland

The explanatory variables examined in these studies are largely environmental, although it was recognised that anthropogenic impact has undoubtedly played a major role in shaping the present vegetation of Scotland (*cf.* Brown *et al.* 1993b). However, the extent to which more remote Highland areas have been affected is only poorly determined from the short timescales involved in neoecological research and limited extent of current palaeoecological and archaeological knowledge (see Chapter 1 and Section 2.2.3.1).

Consequently, McVean and Ratcliffe (1962) sought to produce a map of potential woodland zonation for Scotland under present climatic conditions, but in the absence of large-scale human clearance (Fig. 4). This was based on the present distribution of woodland types and tree species, their known ecological requirements, pre-1962 pollen analyses, sub-fossil tree remains in peat and on recorded history. The present distribution of woodland and tree species is largely a relict of human interference and environmental changes, and many more pollen analyses have now been carried out since this was produced. Nevertheless, these have tended to confirm McVean and Ratcliffe's (1962) reconstruction (O'Sullivan 1977, Bennett 1989, Birks 1996b).

This map is an interesting source of comparison and discussion for the work in Glen Affric, due to the sharp present day contrast in vegetation between east and west, and the palaeoecological questions which this raises. Glen Affric falls on the boundary between 'predominantly pine forest with birch and oak' to the east, and 'predominantly oak forest with birch' in the west, with the division running through central Affric (Fig. 4). The smaller scale map (McVean and Ratcliffe 1962, Map B) suggests that *Quercus* assumes a limited role in upland glens such as Glen Affric, being more common in lowland glens such as Kintail, Glen Cannich and Strathglass. This contrasts strongly with the present absence of oak, the limited extent and restricted species composition of the woodland in East Affric, and *Pinus* wood preserved in deep peat in West Affric. Palaeoecological research is the only means of resolving past vegetation composition and change on long timescales, and thus of understanding the evolution of the present landscape.

2.2 Cultural history

2.2.1 Cultural landscapes of the Highlands: deficiencies and potential

On many maps of archaeological monuments and finds of different periods in Scotland, the Highland region is frequently conspicuous for an absence or very sparse distribution of sites. By extension, settlement and land-use in the high altitude glens and mountains have frequently been assumed to be similarly scarce (*e.g.* Edwards and Ralston 1984), particularly in comparison with rich upstanding archaeological records from adjacent areas, such as the Western and Northern Isles, northernmost and north-eastern Scotland. This appears to be largely supported by the palynological evidence, where the archaeological and historical data were touched upon, although there are methodological deficiencies in this assumption (see Chapter 1).

Although prominent monuments may be lacking, the region is not completely barren of known cultural remains, as there is evidence that many river valleys in the Highland massif, with their lowland character, were settled, although the density and duration of occupation, and forms of land-use are largely unknown. In this respect, Glen Affric appears typical of many Highland glens, since, despite archaeological survey, the inferred chronology remains limited to the last few centuries, with a small amount of prehistoric and early historic evidence from adjacent lowland valleys (DES 1987, 1989, 1990, Wordsworth and Harden 1997).

However, there are several reasons why it is difficult to be certain that this is a reflection of the true extent of human activity and occupation:

i) Most obvious is the inaccessibility of many inland Highland glens, except by foot, and this has limited the extent of systematic survey, excavation and possibly also palynological research. The presently harsh and inhospitable landscape and climate have also been extrapolated back through time, to suggest that many areas have been unattractive since earliest times (*e.g.* Edwards and Ralston 1984).

ii) At present, a mantle of blanket peat covers many earlier soils and land surfaces, and thus possibly also archaeological evidence. Palaeoecological records from the north-west Highlands (Chapter 1) demonstrate the presence of extensive peat cover for much of prehistory through to the present and blanket peat has been shown by excavation to conceal subpeat prehistoric archaeological evidence in other areas of Scotland (*e.g.* Scord of Brouster, Whittle *et al.* 1986; Arran, Barber 1997).

iii) The small number of excavations, modern or antiquarian, limits our understanding of the age and extent of upland settlement and the nature of upland land-use. As a consequence, assigning a chronology or function to the limited visible structural remains is problematic and their role in a landscape archaeological-context remains obscure.

iv) The limited extent of ground disturbance arising from historic or present day land-use is a further factor limiting chance discoveries of remains buried by blanket peat; ploughing for forestry is the main cause of disturbance, whereas land-uses such as extensive grazing and leisure pursuits are less likely to expose buried archaeological remains, particularly in areas of deep peat which are unproductive for forestry (*cf.* Henderson and Hudson 1989; see Section 2.2.3.2).

v) Taphonomic factors, such as the use of perishable construction materials and their reuse, which is amply documented for the historic period (Fenton 1976) may further hamper the detection of land-use in the Highlands.

Although these factors may limit the frequency of new discoveries beneath the peat, they suggest that undiscovered remains are perhaps less likely to have been destroyed by subsequent land-use, and thus the potential exists for new discoveries. Field walking and archaeological survey are gradually increasing the number of known sites around Affric, as is evident in *Discovery and Excavation in Scotland* (DES). However, these still leave many gaps in our knowledge of the extent, duration and type of activity which may have occurred in Affric and across the Highlands through prehistory and even into the historic period. This emphasises the potential value of carefully designed palaeoenvironmental research programmes in seeking to discover and understand landscapes buried by blanket peat.

2.2.2 Aims and scope of this section

As indicated above, Glen Affric appears to be characteristic of many Highland glens in terms of an absence of cultural evidence, with the exception of a limited amount of recent, historic land-use (Wordsworth and Harden 1997). In view of the deficiencies noted above, it is uncertain whether similar forms of land-use were practised throughout this large region or whether more localised patterns and periods of agriculture occurred. It may thus be misleading to attempt to trace the cultural history of Glen Affric through the wider evidence.

The purpose of this section is thus to present the archaeological and documentary evidence from Glen Affric, Kintail and some of the surrounding upland glens and intermediate river valleys in order to provide an overview of the extent and limitations of the current archaeological and documentary records of human activity in this area. It is also intended to examine any evidence for spatial or temporal patterns of land-use, as far as can be discerned from the limited data available. Brief descriptions of the archaeological evidence specific to each pollen site are presented in Chapters 5-8, and a detailed discussion of the relationship between archaeological and documentary data, and palynological evidence for land-use is presented in Chapter 9.

In the absence of excavation or dating, all sites discussed are assigned to an archaeological period on the basis of morphology, although this is by no means secure. Unless an alternative source is quoted, references to archaeological remains in and around Glen Affric have been obtained from the National Monuments Record for Scotland (NMRS). This evidence is summarised in Table 1 and archaeological sites mentioned in the text are shown in Figure 2.

2.2.3 Settlement and land-use in Glen Affric, Kintail and the surrounding glens

2.2.3.1 Prehistoric and historic human activity

The surviving archaeological evidence suggests human presence in the lowlands since the Neolithic, when cup-marked standing stones were erected, although nothing is known of land-use or settlement during early prehistory here or in adjacent upland glens. Structural evidence of settlement, agriculture and burial is present from the Bronze Age onwards (Table 1). Evidence for land-use and agriculture are considered to be particularly important as these are the aspects of past subsistence strategies which can be inferred from the palynological record; this discussion thus concentrates on the scant evidence for agriculture and any evidence for spatial and temporal patterns which may relate to environmental constraints on upland activity, or patterns of land-use.

A substantial number of the known sites occur in inland and coastal river valleys, including standing stones, hut circles, round houses, brochs, field systems, farmsteads and shielings in Kintail, Glenelg and Strathglass. These low altitude valleys are linked by upland glens and mountain passes (*e.g.* Kintail to Strathglass *via* Glen Affric, Glen Shiel to Glenelg *via* Bealach Ratagain). In recent times, a path from Morvich in Kintail, through Glen Affric to Strathglass continued in regular use into the twentieth century, as it was the most direct route east (Wordsworth and Harden 1997), particularly as a drove road to markets in the east and south (Haldane 1952). This raises the possibility that, even in the absence of extant or known evidence, the upland glens may have been known as routes between coastal and inland, lower altitude glens since earlier times (Wordsworth and Harden 1997).

The use of valley floors and hillslopes just above the river is another feature common to prehistoric, recent historic and present day land-use in the uplands and surrounding glens. This may be an artefact of preservation or may reflect the real pattern of land-use due to environmental constraints. These areas are presently free from deep blanket peat cover, which may conceal earlier evidence, as indicated above. On the basis of previous palaeoenvironmental evidence (see Chapter 1), blanket peat is likely to have been extensive since the early Bronze Age, and has thus been present for much of the prehistoric period. The recorded sites may thus represent the minimum density or extent of past settlement and land-use, particularly in the western glens such as West Affric, where peat cover is deeper and more extensive (see Section 2.1.3).

Alternatively, if settlement was concentrated on floodplain sediment and on hillsides just above the narrower river valleys, it may be due to freedom from blanket peat and the presence of more fertile alluvial soils (*cf.* Tipping and McCullagh 1998, Welsh 1999). Continuous use or reuse of these parts of the landscape may overlie or have erased earlier evidence. This may also be inferred from the increasing number of known sites through time (Table 1), although this remains to be established through suitably designed palynological research or excavation (see Chapters 9 and 10).

At present, the evidence for agriculture is strictly limited, occurring in the Bronze Age and Iron Age, but is not recognised again until the eighteenth century AD. Prehistoric field systems and cultivation terraces in lowland Strathglass and Strath Croe (DES 1987, 1989, 1990, Wordsworth and Harden 1997) suggest cultivation and/or enclosures around the hut circles and round houses. The only artefactual evidence for prehistoric cereal processing originates from the Glenelg brochs, where quernstones were found (MacSween and Sharp 1989). The extent of Bronze and Iron Age land-use beyond the recorded settlement and field systems is unknown, and this lack of knowledge extends through to recent centuries, again emphasising the fragmentary nature of the record of past cultural activities.

Numerous putative shielings and farmsteads in West Affric have been interpreted as evidence of historic grazing dating from the seventeenth century onwards (Wordsworth 1995, Wordsworth and Harden 1997). However, the date at which this form of upland land-use originated has not been securely established. Transhumant pastoralism is suggested to have originated in Scotland during the Dark Ages (Bil 1990), although the data to support this are limited. Inferred and documented examples can be cited from other upland parts of Britain and Europe from the Neolithic until recent times (Kvamme 1988, Moe *et al.* 1988, Bradley and Edmonds 1993). This form of land-use infers possibly large-scale spatial and/or temporal organisation of the agricultural landscape (Fenton 1976, Bil 1989, 1990; see Chapter 9).

There is little evidence to fill the gap between the Iron Age and historic periods, and no data on agriculture. Nothing is known of Pictish, early medieval or medieval settlement in Affric. The remains of St. Dubhthach's church at Kintail have a tenth century date, and the name of Loch Duich is said to be associated with the saint, born in Tain, near the Dornoch Firth around AD 1000 (Mould 1950, Close-Brooks 1995). In the neighbouring glens, Urquhart Castle dates from the thirteenth century, and Eilean Donan castle has a fourteenth century date, although vitrified stone on the shore may indicate an Iron Age or Pictish fort (Close-Brooks 1995).

The first documentary mention of land-use in Glen Affric dates from the seventeenth century, when land was let to farmers from Kintail for cattle grazings (MacDonald 1985), a practise still recorded in the late nineteenth century, when Glen Affric passed out of the hands of the Chisholm clan. However, the limited number of documentary sources for Kintail and for Glen Affric in particular, suggest that little can be securely inferred regarding the history of this landscape. For example, it is impossible to determine whether earlier land-use was restricted to the more accessible, lower altitude glens, with permanent settlement not occurring until the end of the seventeenth century, as suggested for the neighbouring Glen Strathfarrar (Mather 1969), or whether agriculture extended away from the major river valleys, such as Strathglass and Kintail, and further into the upland glens, in prehistory or in recent centuries.

Roy's military map of 1755 suggests that there were many cultivation plots or fields at Kintail and Glen Shiel. Although no settlement or agriculture is marked in Affric, it is unclear how extensive research into upland glens was, away from the proposed military roads (*cf.* Smout 1997). The earliest documented permanent settlement in West Affric occurred in the first half of the nineteenth century, and included families at Camban, Alltbeithe, Athnamullach and

Coulavie (see Fig. 6). However, the nature of upland land-use is uncertain; the residents are described as agricultural labourers, but it is unclear whether or not they had arable land (Wordsworth 1995). On the basis of this limited evidence, it is impossible to determine when permanent occupation was established and what the basis of agricultural settlement was following settlement.

Drastic changes to settlement and land-use occurred in the Kintail region between AD 1792 and 1836, with the introduction or sheep, and consequent enforced abandonment of upland farmsteads and shielings, although some shepherds and later deer watchers were still resident in the glen (Wordsworth and Harden 1997). However, sheep farming did not prove successful and Glen Affric was converted to Deer Forest by 1886. In 1848, following the Highland Clearances and potato famine, Robert Somers made a tour of the Highlands, where he described the misery of Kintail's inhabitants due to the poverty of the land. In contrast, he commented on the rich and extensive plain in cultivation at Beauly, declaring it to be unusual in the Highlands, while Glenelg was famed for the richness of its pastures, although cultivation had by then ceased in favour of sheep farming. This emphasises contrasts within coastal and lowland, inland river valleys during recent centuries.

This is also reflected at a regional scale, as data from AD 1870-1970 indicate that the cultivation of cereal and roots crops in the northern and central Highlands was very limited, consisting predominantly of the hardiest corps, such as oats and potatoes (Coppock 1976).

The detail and coverage of known archaeological and documentary sources are severely limited. This emphasises that fine spatial scale palaeoecological research is one of very few resources which can begin to answer questions regarding the origins of the more marked contrast between upland and low altitude Highland glens, the age at which land-use commenced and the forms of agriculture practised in prehistoric times through to recent centuries.

2.2.3.2 Present day land-use

At present, land use in West Affric consists predominantly of leisure pursuits such as hill walking, and some stalking, although sheep from Kintail also wander into the glen. In contrast, forestry is an important form of land-use in East Affric, combined with leisure activities, while croft-based pastoralism predominates in Kintail, although at relatively low densities, again with some areas of forestry plantation. Land-use is thus mainly non-destructive and of low intensity throughout the study area.

Much of this is a reflection of the capability of the land, as Glen Affric and Kintail, in common with much of the western Highlands, are considered to be of use only as rough grazing, and much of this is of low grazing value (Coppock 1976, Soil Survey of Scotland 1982).

Land classification in terms of capability for forestry (Henderson and Hudson 1989) provides a telling indication of the harshness of the environment. The valley floor and sides in West Affric and Kintail are considered to possess only very limited flexibility, due to limitations from adverse climate and poor soil conditions. Areas with limited flexibility for the growth and management of tree crops occur in East Affric, and are those which are predominantly wooded, including plantations and the native woodland communities discussed above. By far the largest part of the land surface in West Affric and Kintail, including the lower and upper hillsides, are considered to be unsuitable for producing tree crops due to extremes of climate, wetness, rockiness and extreme slopes.

2.2.4 Conclusions: biases and potential for understanding the cultural history of Glen Affric and Kintail

On the basis of such scant structural and documentary knowledge, it is difficult and potentially misleading to attempt to construct a chronology or map the extent and nature of past land-use in this region. This highlights the extent of our ignorance of the cultural history of much of the Highlands, not only of upland glens such as Glen Affric, but also of adjacent lowland regions such as Kintail and Strathglass. It also suggests that palaeoecological methods form a valuable, but hitherto under-used, tool for the detection and reconstruction of past activity (*cf.* Whittington and Edwards 1994), particularly in peat-covered landscapes, with all the attendant problems of locating archaeological evidence, and where documentary records are scarce. The previous chapter emphasises the imbalance of spatial scales between previous regional-scale palynological research and the limited archaeological evidence for anthropogenic activity and occupation. Carefully designed research strategies are therefore needed to test hypotheses regarding the age, extent and nature of past human activity in the Highlands, as discussed in Chapter 3.

CHAPTER 3: Research Design

3.0 Introduction

Palynology is a powerful tool for investigating past vegetation at various scales across the landscape, as the foregoing literature review indicates (see Chapter 1). However, it is clear that there are many short-comings in palynological data from conventional, regional-scale sites, such as large lochs. These data provide limited evidence from which to reconstruct spatial and temporal mosaics, or indicate the environmental constraints and pressures that shaped past landscapes. The refinements offered by small hollows and lochans enable past communities to be reconstructed at scales that are relevant to ecological processes and to archaeological understanding.

Secure ecological interpretation of palynological data requires a thorough knowledge of recruitment processes, particularly the effects of transport processes, distance of travel and the productivity and dispersal of individual pollen types on the spatial resolution of the pollen data. Recognising how these factors change with site type and size is essential to ensure that the choice of study area, basin size and sampling strategy are appropriate to the research problem (Jacobson and Bradshaw 1981, Bradshaw 1988).

This chapter will discuss briefly the development and value of pollen source area models, since these are essential for the interpretation of palynological data, then consider the implications for site selection and hypothesis testing, and finally detail the development of a sampling strategy for palaeoecological research in Glen Affric. Discussion of pollen source area models is important in the context of fine spatial resolution palynological research design in Glen Affric.

3.1 Pollen source area: the relationship between sampling basin and pollen representation

Pollen source area may be defined as the area from which a fixed proportion of the pollen sampled at a site is derived (Jacobson and Bradshaw 1981), although it is usually regarded as the finest scale (area or radius) at which vegetation can be reconstructed from the pollen record (*cf.* Sugita *et al.* 1999). Empirical and modelling studies have shown that the source area of pollen is correlated with the size of the sampling site (*e.g.* Bradshaw and Webb 1985, Prentice 1985, Sugita 1994, Calcote 1995). Sites can therefore be selected to gain the desired level of spatial resolution in palaeoecological studies (Jacobson and Bradshaw 1981), since palaeoecologists need to understand the spatial and temporal resolution of the pollen data in order to formulate a research design that will answer specific hypotheses (Sugita 1998).

3.1.1 Model development and estimates of source area

Although subsequent work has quantitatively refined our understanding of pollen source area, the paper by Jacobson and Bradshaw (1981) remains an important model defining the generalised relationship between the size of a sampling site and relative proportions of pollen deriving from different areas around the site. This model incorporates earlier concepts on modes of pollen transport developed by Tauber (1965) and distance-dispersal relationships defined by Janssen (1966, 1973). However, a paper by Webb *et al.* (1978) is also important in recognising the influence of basin size on pollen representation, implicit in Jacobson and Bradshaw's model.

Tauber (1965, 1977) defined a model for pollen dispersal in forests, which recognised different modes of pollen transport and considered the area of vegetation represented in pollen diagrams as a consequence of these different forms of transport (Table 2). The model incorporates transport above the canopy (C_c), through the trunk-space (C_t), by rainfall (C_r) and surface run-off (C_w). Tauber considered that the trunk space component was the dominant source of arboreal pollen deposited in small lakes in wooded areas.

Research by Janssen (1966, 1973) focused on the relationship between the distance of the pollen source from the sampling sites and the magnitude of pollen deposition, emphasising the concept of distance decay (Table 2). Four kinds of pollen deposition were defined from transects of surface samples:

1. *Local* pollen is derived from the collection site, and shows highly exponential distance decay, which enables local plant communities to be recognised. Herb pollen in particular shows very local pollen distribution.
2. *Extralocal* pollen shows transitional values between local and regional pollen, as values do not change over short distances, like local pollen, but is distinctly higher than regional values.
3. *Regional* pollen has a constant rate of deposition, regardless of distance from source, such that only large vegetation types, or landform-vegetation units (Lichti-Federovich and Ritchie 1968), are recognisable.
4. *Extraregional* pollen derives from greater areas, outside the formation studied.

Although the paper by Webb *et al.* (1978) focused on the calibration of pollen data to vegetation composition at broad scales, the authors recognised how the size of a study area and the sedimentary environment sampled affects the spatial scale of the pollen record. Moss or soil samples from within forests were recognised as sensors of variation within plots or stands, due to high local pollen influx (Turner 1965, Janssen 1966), while moderate-sized lake basins collect mainly regional pollen inputs by smoothing out the detailed spatial patterns of vegetation within the landscape. Webb *et al.* recognised a need to sample small lakes or bogs (<1 ha), or litter samples from small openings in forests to record variation at the extralocal scale.

Jacobson and Bradshaw (1981) combined these models by introducing a gravity component (C_g) to include the vertical deposition of local pollen from plants fringing or overhanging the sampling basin. This model emphasises distance decay in pollen transport from the source and changes in the proportion of each form of pollen transport as basin size increases (Fig. 5). The model proposes the following definitions:

1. *Local* pollen originates from plants growing within 20 m of the edge of the sampling basin.
2. *Extralocal* pollen derives from plants growing between 20 and several hundred metres of the basin, and
3. *Regional* pollen is derived from plants at greater distances.

Following work by Andersen (1970) and Bradshaw (1981a), Jacobson and Bradshaw (1981) further suggested that most of the pollen in small forest hollows and mor humus profiles within closed forests derives from the surrounding 20-30 m (see Table 2). An increase in pollen source area with basin size was subsequently confirmed by other workers (*e.g.* Bradshaw and Webb 1985, Prentice 1985). The effect of basin size is strongest at small sizes (Jackson 1994), as there is a major increase in source area between small hollow and small basin sites (Prentice 1985).

In order to understand the relationship between site size, surrounding vegetation composition and the pollen signal, more recent empirical research has focused on small basins within forested landscapes. This has several advantages, since pollen production by trees is frequently high (Andersen 1973), producing a readily quantifiable local pollen signal which is dominant over the pollen rain from extralocal to extraregional sources (*sensu* Janssen 1966), and can therefore be more readily related to the surrounding vegetation cover, particularly 'basal area' measurements of canopy composition (*e.g.* Bradshaw and Webb 1985, Jackson and Wong 1994, Calcote 1995, Jackson and Kearsley 1998).

Recent simulations and empirical research on small diameter sites (*c.*5 m in diameter) indicate that the correlation between vegetation and pollen representation improves if the vegetation survey radius is increased from 20 m to 100 or 120 m (Sugita 1994, Calcote 1995, Jackson and Kearsley 1998). This indicates that most pollen derives from greater distances away from the sampling site than was estimated by Jacobson and Bradshaw (1981). Sugita (1994) defined a 'relevant source area', beyond which there is no improvement in the correlation between pollen and vegetation, suggesting that 30-40% of the pollen derives from <10-100 m. This simulation has been confirmed by empirical data, indicating that perhaps 40-50% of the pollen in forest hollows (*c.*5-6 m diameter) is from trees growing within 50-100 m (Calcote 1995). These results confirm some of the estimates by earlier researchers (see Table 2).

As vegetation patches at the stand scale are generally larger than the finest spatial resolution depicted by small forest hollows (*c.*50-100 m source radius), it is possible even in patchy or mosaic landscapes to resolve such variations in vegetation cover through the pollen record (Sugita 1994, Calcote 1995, Jackson and Kearsley 1998).

3.1.2 Source area in forested and open environments

The majority of the models and studies presented involve small basins within forested landscapes, where the high pollen production of the canopy contributes the dominant pollen signal and acts as a filter against greater regional inputs. Consequently, the representation of non-arboreal pollen (NAP) has been frequently excluded from study (*e.g.* Calcote 1998). However, as the canopy cover opens, this relationship breaks down, allowing more extralocal and regional pollen inputs. This is due to a decrease in the proximity and thus relative abundance of local arboreal (C_g) pollen deposition. The relative magnitude of various source components is thus the key difference between closed- and open-canopy assemblages (Jackson and Wong 1994); the local pollen signal becomes 'diluted' by pollen carried from greater distances above the canopy.

At present, the absence of data for open landscapes is a major short-coming; current research into this area is only in preliminary stages and only a few estimates of source area are available from lakes in a small area of Scandinavia (Broström *et al.* 1998, see Gaillard *et al.* 1998, Sugita *et al.* 1999). Although much of the discussion in this section is based on recent palynological simulations, which necessarily simplify the scenario, the results appear to be supported by the limited amount of empirical data currently available and are considered useful for suggesting the potential and limitations of pollen records for quantitative reconstruction of landscape openness.

The over-representation of tree pollen in open landscapes is well documented (Andersen 1973, Bradshaw 1981a), but less is known about NAP pollen dispersal and representation. For instance, Tauber (1965) concluded that NAP deposited in lakes reflects only ecological conditions at the forest edge and in the littoral zone due to poor dispersal from low-growing taxa beneath the canopy. Recent research suggests that NAP percentages are insufficient to quantify the extent of open land in open and partially open landscapes as the relationship between NAP and open land is not straightforward (Broström *et al.* 1998, Sugita *et al.* 1999). Herb representation is affected by the vegetation structure of the surrounding landscape and the relative degree of landscape openness, *e.g.* mainly treeless or intensively farmed (Broström *et al.* 1998, Sugita *et al.* 1999). High regional background AP contributions play an important role and may result in low NAP values even near or within open areas (Sugita *et al. op. cit.*).

At present, research on quantifying open areas from simulated palynological data suggests that the finest spatial scale of pollen reconstruction in open landscapes (60-80% cultivated or pastoral) is a radius of *c.*800 m, and *c.*1000 m in partially open landscapes (50-60% forested). The relevant pollen source area in the simulated landscapes is virtually the same for both small hollows (*c.*5 m radius) and small lakes (*c.*100 m, 3.14 ha), regardless of vegetation composition and patchiness. This compares closely with palynological results suggesting a source radius of *c.*1000 m for lakes in similar environments (Broström *et al.* 1998, see Table 2). Comparison with simulated and empirical data from forested environments suggests that the closed canopy pollen source area is around one-tenth of the predicted radius in open landscapes (Sugita *et al.* 1999).

3.1.3 Modifying factors

Palaeoecological reconstruction requires an awareness of other factors, both biological and environmental, which modify the representation of individual taxa and affect pollen assemblage formation. These subjects are presented in summary here (see Moore *et al.* 1991) and, where appropriate, are discussed in the chapters dealing with vegetation reconstruction and in the discussion (Chapters 5-9).

3.1.3.1 Biological factors

The source area for each pollen taxon will vary according to the relative pollen productivity, dispersal mechanisms, the size and weight of the pollen grains (Tauber 1965, Anderson 1973, Jacobson and Bradshaw 1981, Janssen 1981). Reasons for poor representation include low pollen production and limited dispersal, due to insect, animal or self-pollination mechanisms, and/or the production of large or heavy pollen grains. In this respect, the over-representation of many arboreal taxa and under-representation of herbaceous taxa due to differences in pollen productivity and dispersal are well-documented (Tauber 1965, Janssen 1966, Andersen 1973). The height at which pollen is released (source elevation) also influences pollen dispersal, particularly that of low-growing herbs, although less information is available on this subject relative to AP dispersal (Sugita *et al.* 1999, see Randall *et al.* 1986). Bradshaw and Webb

(1985) stress the importance of different dispersal properties in various pollen types in determining how best to reconstruct vegetation composition from pollen data.

Pollen representational differences have led some researchers to define pollen representation or correction (R-) factors in order to 'calibrate' pollen data to the vegetation through regression analysis (Davis 1963, Andersen 1973, Bradshaw 1981a). Although such factors are useful for understanding relative differences in pollen production and dispersal between taxa, they are strongly influenced by local conditions and results differ between studies, although the rank may be similar (*e.g.* Bradshaw 1981a), reflecting relative differences in pollen production and dispersal.

Source area/pollen assemblage relationships are also modified by structure of the surrounding vegetation. The density, structure and stand height of a woodland canopy strongly affects pollen dispersal and representation. High canopy pollen production may filter out pollen transported above the canopy and reduce the dispersal of low-growing understorey taxa (Tauber 1965), thus swamping NAP contributions. The dispersal of pollen from herbs in the understorey or in clearings is markedly influenced by canopy density; pollen dispersal in a very open forest is much better than closed woodland (Hicks 1998). The nature of the understorey strongly influences pollen frequencies, since insect-pollinated Ericaceae may be under-represented (Dambach 1998). Seasonal differences in the timing of canopy formation, leaf-fall and flowering also affect transport in forested environments, particularly between boreal and deciduous forests.

In open landscapes, high AP contributions continue to play a very important role, as indicated above. Consequently, regional pollen production and transport need to be understood. The degree of landscape openness, the spatial patterning of vegetation patches and the species composition of individual patches of vegetation around the sampling site all affect the relationship between pollen representation and open land (Broström *et al.* 1998, Sugita *et al.* 1999).

3.1.3.2 Environmental factors

Environmental factors can also play an important role in pollen production and dispersal, especially in upland areas, where climatic conditions are more severe. Exposure, particularly wind strength and direction, can markedly influence pollen dispersal (Randall *et al.* 1986, Gearey and Gilberston 1997). Where the sampling site is upwind of the area in question, strong winds can have a marked impact on the palynological detection of vegetation types with a restricted distribution or of land-use. Microclimate differences, particularly in wind speed, within and above the canopy and over woodland openings further affect the dispersal patterns of pollen grains, since wind speeds are much lower within the canopy and air currents above the canopy may be sufficient to carry pollen over small openings (Tauber 1965).

Environmental conditions (climate, soil status) exert a clear influence on vegetation productivity, but the impact on pollen production is poorly understood. For example, in Finland, Sarvas (1962, cited in Ledig 1998) recorded almost a four-fold difference in annual *Pinus sylvestris* pollen production between poor and fertile sites. This may be of particular importance in the blanket peat-dominated Highland zone, where conditions for tree growth are frequently marginal (see Section 9.4.3.3).

Site characteristics, such as topography and morphology, particularly the presence of streams, further modify pollen representation by affecting the modes of pollen transport and catchment area of the sampling basin. Stream-borne pollen is an important source of pollen in lake sediment (Peck 1973, Bonny 1976, 1978, Tauber 1977), and will increase the catchment area of the pollen site to include vegetation along inflowing water courses (Pennington 1979). In areas of high relief, with steep slopes, and high precipitation, run-off and rain-out components are likely to be important (Bonny 1978).

These factors, environmental and biological, all need to be considered in formulating an initial sampling strategy and in subsequent interpretation of the pollen assemblages. However, it is important to recognise that estimated source area figures (Table 2) are relevant for the vegetation structure and taxa considered in simulations and empirical investigations, and are not necessarily directly applicable to other situations (Broström *et al.* 1998).

3.1.4 Peat *versus* lake sites

Most of the empirical and simulation results discussed above are limited to small forest hollows or lakes; there is an absence of work and also of discussion relating to basin size/pollen source area relationships on peat deposits. The abundance of pollen producers growing on peat sites can lead to local over-representation due to the dominance of the C_g component in pollen deposition, thus imposing difficulties in estimating the size of the pollen source area (Jacobson and Bradshaw 1981). Large bogs have been used as sensors of regional vegetation (Bradshaw 1988) and pollen production by peat vegetation is recognised as a source of local variability in peat profiles (Webb *et al.* 1978), and indeed has been used to demonstrate the ability of palynology to detect fine spatial-scale vegetational variation (Waller 1998). Sedimentological issues in lakes, such as bioturbation, reworking, sediment focusing and smoothing of the pollen record exert a marked impact on the stratigraphic integrity and resolving power of pollen records from lakes (*cf.* Cushing 1964, Lowe 1982, Hirons 1988), but may be less important, although not absent, on bogs (*cf.* Clymo and McKay 1987, Moore *et al.* 1991, Tipping 1995a).

However, no systematic research on pollen source areas has been carried out on small peat basins, where local pollen deposition from dryland vegetation surrounding and overhanging the site may approach the depositional environment of forest hollows. At present it is not possible to assess how estimates of pollen source area based on lakes and small hollows will vary when applied to small peat deposits, or the magnitude of differences between paired lake and peat sites, although the available palynological data suggests that peat basins may be more sensitive to local vegetation change than equivalent-sized lakes, and of considerable ecological and archaeological value.

Some of these sites have already been discussed in Chapter 1, particularly the vegetation dynamics evident in the work of Kerslake (1982). One other example is given here, that of Callanish, on Lewis in the Western Isles, as radiocarbon-dated sites are available which illustrate the contrast in spatial resolution and palynological sensitivity between small loch and peat sites. Fossitt (1990, 1996) investigated the history of Loch Buailaval Beag, a small loch (*c.*1.0 ha, radius *c.*50 m) on Western Lewis, while Bohncke (1988) examined three short peat cores from an unnamed blanket peat-covered peninsula, *c.*200 m wide by *c.*500 m long, around 9.0 km to the south (Fig. 1). Peat boring suggested that the central part of the peninsula forms a reasonably distinct basin (Bohncke 1988), although no dimensions are given. The blanket peat site is thus suggested to be at least equal in size to the loch, if not larger. Both sites are situated in an archaeologically rich landscape, which includes the Callanish stone circle, situated < 8.0 km south of Loch Buailaval Beag and *c.*1.0 km north of the peat site.

Both loch and peat profiles suggest rapid woodland decline around 7900 BP, associated with the spread of blanket peat (Fossitt 1996), heather moor and grassland (Bohncke 1988). While Fossitt attributes woodland decline to climatic deterioration, discounting fire and anthropogenic activity, charcoal is present in the peat profiles and Bohncke suggests Mesolithic involvement. *Plantago lanceolata* is recorded from 7800 BP at Loch Buailaval Beag, where it is suggested to have been a component of natural maritime grassland communities.

Subsequently, Fossitt infers that small pockets of woodland or scrub remained, on the basis of the tree and shrub pollen frequencies. In contrast, the peat profiles indicate several *Betula* regeneration phases between 4800 and 4000 BP, in dynamic communities with grasses, heaths and herbs, in which human activity, burning and grazing are suggested to have been involved. Although higher tree and shrub frequencies at the peat site can be explained in terms of local exaggerated pollen representation from plants growing on or near the site (Fossitt 1996), an inference supported by the presence of birch wood in the peat (Bohncke 1988), this illustrates the value of peat sequences for reconstructing patchy landscapes, as a direct result of the proximity of plant growth and anthropogenic activity, both of which appear to be lacking even from a small loch site.

The loch sequence provides little evidence of vegetation disturbance at any time during the Holocene, despite the present of archaeological evidence and abundant runrig around the loch, while the peat sequences suggest continued agricultural activity, including cultivation, from the Neolithic to the present. This again suggests that small peat sites are more sensitive to local vegetation dynamics and anthropogenic activity, possibly as a result of more localised pollen recruitment characteristics than small lakes can provide.

3.1.5 Value of source area concepts in palaeoecological research

The discussion above is primarily concerned with source area as a methodological approach for site selection, and factors which affect pollen source area/vegetation relationships and thus need to be considered in palaeoecological reconstruction. However, there are difficulties and compromises necessary in the transfer of modern studies to subfossil pollen data.

Most modern empirical studies have made use of small diameter forest hollows. However, there are several problems associated with the use of mor humus accumulations of similar diameter (*c.*5-6 m), which affect temporal and stratigraphic security. Dating can be problematic as sediment accumulation is slow and the sites may dry out due to their small size, resulting in poor pollen preservation and hiatuses in sediment accumulation, which may be difficult or impossible to detect (Bradshaw 1988).

In this respect, small basins (*c.*5-50 m diameter) have the advantage in that, although the area of vegetation represented in the pollen record is larger (Prentice 1985, see Table 2), sediment accumulation appears to be more regular, and the sequences can thus be dated by radiometric techniques and more securely interpreted as a record of the changes in surrounding woodland communities. Although suitable peat basins and lakes are therefore available, and several of the studies mentioned are based on small lakes (*e.g.* Sugita 1994, Broström *et al.* 1998), the discussion above (Section 3.1.4) suggests that small peat basins may be more sensitive to local vegetational changes than lakes of equivalent size.

A compromise is thus necessary, between the very restricted pollen source area of short-term, potentially biased forest hollow mor humus records, and either small peat or lake basins, with a larger source area but more secure sedimentary history. Studies which explicitly apply the principles of pollen source area are termed fine spatial-resolution pollen analyses. These illustrate the value of small sites and restricted source areas for resolving pollen data at scales which are relevant to ecological and archaeological research.

Fine-spatial resolution pollen analysis enables vegetation composition and dynamics to be examined at the scale of woodland stands or communities (*e.g.* Bradshaw and Hannon 1992, Bjorkman 1997). This method can help to establish a more complete record of vegetation composition, since the close proximity between vegetation and sampling site allows taxa with low pollen production or dispersal to be better represented (*e.g.* Kerslake 1982, Mitchell 1988, 1990). Spatially-constrained pollen analysis can also provide a more sensitive record of local vegetation dynamics due to high pollen contributions form local stands and communities. This may allow the cause and impact of disturbance to be more securely inferred. This applies to local, small-scale disturbances, such as burning or flooding, and to regional-scale events, such as climate change, particularly where several sites are available for comparison (Bradshaw and Zackrisson 1990, Bradshaw and Hannon 1992). It should be noted that most of these study sites were small peat basins or forest hollows, not lakes. In this context, the value of research by Kerslake (1982) in the Scottish Highlands has already been highlighted (Chapter 1).

With secure chronological controls and sufficiently detailed temporal resolution (Turner and Peglar 1988), fine spatial-resolution pollen analysis can enable closer links with ecological data. This includes more secure palynological vegetation reconstruction using the abundance of neoecological literature, and long-term palynological contributions to understanding vegetation history and landscape evolution (Birks 1993, 1996a, Huntley 1996).

The use of small hollow/basin sites in cultural contexts is limited, but has considerable potential to elucidate finer-scale patterns of vegetation disturbance and manipulation, and land management. For example, Smith (1996, 1998) inferred spatial patterns in small-scale cultivation through the comparison of two small peat sites at Lairg (see Chapter 1). Tipping (1997) was able to suggest coppice management, hedging and other undocumented farming practices from fine-spatial resolution work on a ditch fill from the archaeological site of Over Rig in the Scottish southern uplands. Wood remains from the site also provided some evidence for woodland management (Boyd 1988b).

In both of these studies, the spatial scale of the palaeoecological work was such that it was able to contribute directly to nearby archaeological research, allowing closer integration between disciplines. Such interdisciplinary research can achieve greater insights into the relationship between humans and vegetation, and land management (*e.g.* Whittle *et al.* 1986, Barber 1997, McCullagh and Tipping 1998).

This technique can generate hypotheses to stimulate thought and future research by palynologists, archaeologists and environmental archaeologists in other fields, such as archaeobotany, dendrochronology and soil micromorphology. For example, palynological analysis of small sites may help to elucidate changing spatial patterns of land-use through time, in contrast with the palimpsest of fragmentary archaeological records of human activities within the landscape. A combination of dendrochronolocial and palynological research, such as that at Lairg and Over Rig cited above, may help to achieve a fuller understanding of past woodland management. The potential of fine spatial resolution palynology combined with documentary sources for understanding land-use in the more recent past (*e.g.* Tipping 1998) is largely untapped.

Over much of the Highlands, where upstanding archaeological evidence and excavation are limited or absent (see Chapter 2), and previous regional-scale palynological work is unable to resolve questions about human activity in any detail, the value of this technique has yet to be assessed, but the potential appears great (*cf.* Whittington and Edwards 1994).

3.2 Research design and site selection in Glen Affric

3.2.1 Site selection criteria

In order to design a sampling strategy to address the aims of palynological research in Glen Affric (Section 1.14), it is necessary to understand and apply the principles of pollen source area-basin diameter relationships. However, in order to investigate some of the controlling ecological and environmental factors on local vegetation development and human activity, it is also necessary to develop site selection criteria that incorporate different environmental pressures and gradients present within the landscape. Consequently, three site selection criteria were established, each incorporating environmental gradients of different magnitudes.

3.2.1.1 Basin diameter

Small, clearly delimited peat basins were the preferred sampling sites in order to maximise the magnitude of local pollen deposition, thus providing pollen records that are sensitive to local vegetation change. As discussed above, the palaeoecologist must achieve a balance between a small source area, and sufficient temporal coverage and stratigraphic integrity. Sites considered in Glen Affric therefore included basins up to *c.*50 m in diameter, rather than very small forest hollows. Although small, closed loch basins are not available in West Affric, with the exception of a few high altitude lochans, peat basins were considered to be a more desirable site type in light of the evidence presented in Section 3.1.4 and in Chapter 1, which suggests that small peat basins provide more sensitive records of vegetational change than lochs of equivalent-size. This was considered of prime importance for obtaining palynological records at temporal and spatial scales appropriate to ecology and archaeology.

3.2.1.2 Landform units

Each site was located within a distinct 'landform' unit, in order to obtain pollen records which characterise patches of vegetation which developed in response to different environmental and anthropogenic pressures. This strategy maximises the pollen contribution from patches of vegetation which appear to have been subject to similar environmental processes, within a landscape mosaic of contrasting environmental conditions and vegetational types.

A landform unit is defined as a part of the landscape with distinct topographic, edaphic, geomorphological and/or hydrological characteristics, which are at present reflected in vegetational differences. Four landform units were delimited in Glen Affric (Fig. 6) using the following sources: 1:50000 Ordnance Survey solid and drift geology maps, 1:50000 Soil Survey of Scotland provisional soil maps, 1:25000 Land Cover of Scotland (1988) maps and field observations.

1. *Upper montane slopes and corries* characterised by steep bedrock slopes, limited soil development and montane vegetation. The upper slopes may experience more frequent, extensive and/or intensive geomorphological activity due to instability caused by steep gradients, greater extremes of climate. This landform unit lies outside the scope and aims of the research in Glen Affric (see Chapter 1).

2. *Lower hill- and valley-side slopes* with hummocky morainic topography, bedrock knolls and blanket peat cover are subject to little geomorphological disturbance, with the exception of some peat gullying, and geomorphic activity from the steep slopes above. The main source of runoff is from immediately surrounding basin slopes. This landform unit can be divided into two on the basis of present vegetational and climatic differences (see Chapter 2):

   a) In the uplands, these areas are characterised by acidic, relatively species-poor heather moor and blanket bog communities, and experience high orographic precipitation and wind speeds characteristic of the western Highlands.

    b) Grassland and heather moor are characteristic of more westerly and lowland hillslopes. Temperatures are ameliorated by the proximity of the Atlantic Ocean, but annual rainfall is high and winds frequent.

3. *Major alluvial fan complexes*, which receive sediment and water in sheetwash down the hillsides. The flushed vegetation of alluvial fans has a distinctly lusher appearance than the surrounding heath and peat.
4. *Holocene valley floors* can be subdivided into two subunits on the basis of ontogeny:
    a) *Alluvial valley floor* - these areas are subject to flooding and consequent mineral sediment deposition, and are characterised by a more species rich flushed vegetation, in which grassland taxa play a much more important role than in the peatlands.
    b) *High level marine surface* - this comprises estuarine and intertidal sediment at lowland loch shores, and marine sediment overlain by later alluvium above the main Holocene marine transgression. The marine sediment is characterised by salt marsh communities, while areas of overlying alluvium are the focus of agricultural activity.

3.2.1.3 Transect of sites

The third criterion was to select sites along a latitudinal transect through Glen Affric, from central Affric, through West Affric to the coast at Kintail. This introduces the present day, larger scale environmental gradients of climate and altitude, between the more severe upland settings and oceanic lowland conditions, and a west-east gradient of oceanicity within the uplands (Chapter 2). This allows a range of environmental factors influencing vegetation development to be investigated, and their effects on species composition, woodland structure, peat expansion and human activity to be explored. Previous literature provides some evidence for vegetational gradients in response to variations in geology and exposure (Williams 1977, Birks and Williams 1983), but most sites lack the necessary spatial resolution to establish secure links between the local environment and vegetation composition (Chapter 1).

3.2.2 Sites selected

Four pollen sampling sites were selected on the basis of these three criteria. The location of the sites is illustrated in Figure 7. Comparative differences in present day environmental gradients, landform characteristics, site morphology and estimated source area are presented briefly here (see Table 3) as the sites are described fully in Chapters 5-8, where the effects of landform type on source area are evaluated.

Estimates of source area are based primarily on the lake surface simulations of Sugita (1994, Sugita *et al.* 1999), as few papers provide quantitative estimates of source area for more than a single basin diameter and, with the exception of research on small hollows, none relate to terrestrial sediments. The estimates of Sugita (1994, Sugita *et al.* 1999) are supported by empirical surface sample studies (Calcote 1995, Broström *et al.* 1998, Gaillard *et al.* 1998). Source area estimates are of radius beneath a closed canopy, since little information is available for open landscapes, as discussed in Section 3.1.2.

3.2.2.1 Torran Beithe

Torran Beithe (TOR) is located in Central Affric, at 265 m OD, *c.*1500 m west of Loch Affric. The pollen site is an enclosed bedrock basin located in the lower hillslopes to the north of the River Affric (landform unit 2a), with a present surface radius of *c.*28 m (Fig. 10, Photo 3). The site receives runoff predominantly from the immediately adjacent hills and is sheltered from wind by surrounding hillslopes. At the present diameter and beneath a canopy, the site has an estimated pollen source radius of *c.*100-300 m (Fig. 12). However, the basin measured *c.*4 m in radius in the early Holocene, when the source area radius is estimated at *c.*50-100 m (Chapter 5).

3.2.2.2 Carnach Mór

Carnach Mór (CAR) is located in West Affric, at 250 m OD. The pollen site is a relict, infilled river channel located at the junction between the hillslopes (unit 2b) and valley floor alluvium (unit 4a) (Fig. 24, Photo 7). The site is therefore exposed to water and sediment influx through flooding and hillslope runoff. The projecting hillside adjacent to the channel may provide some shelter from prevailing westerly winds. The channel is about 10 m wide (Fig. 25), suggesting a closed canopy source area of *c.*100-200 m in radius, as this site lies between the site radii simulations of Sugita (1994) (see Tables 2 and 3). However, hydrological inputs are likely to increase the source area by introducing water-borne pollen derived from hillslope runoff and erosion along stream and river courses. This is termed the 'effective source area'. Stratigraphic and pollen preservation evidence of inwashed and redeposited pollen during the Holocene is discussed in Chapter 6.

3.2.2.3 Camban

Camban (CAM) is located in Fionngleann, which connects West Affric with Kintail (Fig. 7). This is the highest and most westerly of the three upland pollen sites analysed, lying at *c.*307 m OD. Consequently, Camban is likely to experience more oceanic and possibly harsher climatic conditions, since the site is exposed to prevailing westerly winds and lies on the lea side of steep and high mountains, which may result in orographic enhancement of rainfall (Roy 1997, see Chapters 2 and 7).

The sampling site is a basin within the peat which has formed over an alluvial fan (unit 3) (Fig. 36). The small basin has a surface area of *c.*20 x 40 m (*i.e.* 10-20 m radius; Fig. 37, Photo 9), suggesting a pollen source area of 50-200 m radius (Sugita 1994). The basin is located in the centre of the alluvial fan which is *c.* 170 m across x 200 m long and alluvial vegetation will thus dominate the extralocal pollen signal. As at Carnach Mór, sheetwash is likely to have increased the pollen source area by incorporating pollen from the upper hillslope (see Chapter 7).

3.2.2.4 Morvich

Morvich (MOR) is located at the southern edge of the Strath Croe floodplain in lowland, coastal Kintail. Lying at 23 m OD, this site is likely to experience milder conditions associated with coastal regions of the western Atlantic seaboard, contrasting with the upland sites in Glen Affric, although still with high precipitation and frequent, strong winds. The pollen site is a small, enclosed bedrock basin in rocky ground at the junction between the floodplain (unit 4a) and hillslopes (unit 2b) (Fig. 48, Photos 11 and 12). With a radius of just 2.5 m, the estimated pollen source area for the site is 50-100 m (Fig. 49). Although there is with some water movement across the site at present, there is no evidence for alluvial sediment deposition during the Holocene which could have increased the effective source area (see Chapter 8). Vegetation on the high level marine surface at the head of the river (unit 4b) is likely to be represented in the extralocal pollen signal (Fig. 6b).

In conclusion, it is evident from this summary data that none of the sites have directly comparable pollen source areas, but each does characterise a selected landform unit. Consequently, each site is interpreted at the estimated spatial resolution appropriate to that site (see Chapters 5-8) and site-specific differences in source area, both in space and time, are considered in the discussion (Chapter 9).

CHAPTER 4: Materials and methods

4.0 Introduction

Details of the field and laboratory sampling and processing methods, recording and analytical techniques are detailed in this chapter. Many of the techniques used in pollen analysis, such as sediment sampling, pollen processing and identification, are standardised, and are thus presented in schematic form. Justification is given where the methods adopted deviate from standard practice. However, quantification techniques for some aspects of palaeoecological investigation are less uniform, particularly charcoal analysis, or are less frequently used, such as pollen preservation and humification analyses. Consequently, the merits and potential problems associated with the chosen techniques are presented briefly in order to justify their use.

4.1 Field techniques

4.1.1 Site selection and evaluation

Site selection criteria in Glen Affric have been discussed above, Section 3.2, with a brief assessment of the potential sources of sediment and pollen. Further details of site morphology and palaeoecological evaluation are presented in Chapters 5-8.

4.1.2 Site surveying

Each site was surveyed by establishing a regular grid across each sampling site, at each point recording the depth of sediment using a 2.5 cm diameter Eijelkamp gouge, and then surveying the points to an arbitrary datum using a theodolite or electronic distance metre (EDM). The size of the grid and scale of mapping varied in relation to the size of the site, from 1.0-4.0 m intervals at the smallest sites, Morvich and Carnach Mór, to 8.0 m intervals at Torran Beithe and 25.0-50.0 m intervals at Camban (see Chapters 5-8). Maps of bedrock, surface and peat contours were produced for the basins at Torran Beithe and Morvich. The morphology of the channel at Carnach Mór is depicted in a transect of sediment stratigraphy, while a combination of peat contour mapping and transects of surface, peat and bedrock profiles were produced for the basin in the sloping alluvial fan at Camban. These are illustrated in Figures 10, 25, 37 and 50.

4.1.3 Sediment sampling

Surveying and depth-probing was used to locate the deepest sediment accumulation at each site in order to obtain the longest possible chronology and maximise the temporal resolution of the pollen stratigraphic record. A series of overlapping cores was sampled using a 1.0 m long Russian corer with a cylinder diameter of 6.0 cm (Jowsey 1966). Overlapping 1.0 m cores were sampled from within *c.*50 cm of one another. A modified golf-hole corer (A. Tyler, unpubl.) with a sampling chamber measuring 15.0 cm wide x 50.0 cm long was used to sample the top sediment at the four sampling sites. This consists of a central stabilising unit and two semicircular blades which are hammered down to sample the surface peat sediment. The large volume of sediment extracted enables the core to be halved length-wise in order to use the newly exposed, uncontaminated and stratigraphically secure cut face for analysis. Some sediment compaction may occur during sampling, as the sampling blades are hammered down, but the top core can be stratigraphically correlated with the Russian cores.

All cores were placed in labelled guttering and sealed in 'layflat' plastic wrap in the field and stored at 4 ° C in the laboratory.

4.1.4 Surface samples

In order to characterise the present surface pollen rain, two homogenous samples of unhumified surface mosses were taken from within 1.0 m of three of the coring sites (Torran Beithe, Camban, Morvich). The moss samples consisted predominantly of *Sphagnum*, with *Polytrichum* at Camban and Morvich. Two samples were taken in order to provide sufficient fresh, unhumified moss for pollen extraction and in order to homogenise chance variations in pollen composition. Due to winter flooding, the river could not be forded to surface sample Carnach Mór, and surface *Sphagnum* moss from the golf-hole core was thus used *in lieu* of other surface sediment. Moss samples were placed in seal-top plastic bags and stored at 4 ° C in the laboratory.

4.1.5 Vegetation description

A record was made of the relative abundance of taxa on the sampled landform unit and, where present, adjacent landform units. At Carnach Mór this comprised the sampling channel, hillside and alluvium, while at Camban species on the fan and surrounding blanket peat were recorded, with local mire and adjacent grassland recorded at Morvich. Vegetation description at the four main sites was undertaken during late May 1999, supplemented by records of herbaceous taxa during earlier visits to select and sample the sites, thus covering several seasons. This affects the Poaceae most strongly, as they were not yet in flower during recording, in contrast to Cyperaceae and the more easily identifiable vegetative and floral parts of herbaceous taxa. Plant nomenclature follows Stace (1997).

4.2 Laboratory techniques

4.2.1 Sediment-stratigraphic techniques

The cores were cleaned in the laboratory and the stratigraphy for each set of cores was described using a modified Troels-Smith recording system (1955, Aaby and Berglund 1986) (Tables 7, 14, 21 and 31). *Pinus* bark was identified by its distinctive plate-like structure, but other wood remains were not identified.

Loss-on-ignition (LOI) was used to determine sediment organic content. Contiguous 4.0 cm long x 1.0 cm thick samples were dried for at least 12 hours at 105 °C and then ignited for 3-4 hours at 550 °C. Organic content is expressed as weight loss as a percentage of dry weight using the following formula:

$$\text{Loss-on-ignition} = \frac{\text{dry weight-ashed weight}}{\text{dry weight}} \times 100$$

Magnetic susceptibility could not be used to characterise mineral matter because the bedrock is poor in iron minerals and was non-responsive (E. Tisdall, pers. comm.).

The cores from each site were correlated by careful measurement during field sampling, which was confirmed by brief notes made in the field from the freshly exposed, unoxidised face, stratigraphic description and LOI analyses in the laboratory.

The peat cores from Torran Beithe were analysed by X-radiography to assess the usefulness of this technique for describing and correlating cores, and as a possible means of locating eroded material (Dorfler 1992) and tephra layers (Dugmore and Newton 1992). X-ray analysis was carried out using the ScanRay AC 120L X-radiography machine at the British Geological Society in Edinburgh. However, the technique was not considered to provide data which could not already be gained from stratigraphic and LOI records, and consequently none of the other cores were X-rayed.

4.2.2 Pollen processing

Pollen analysis was carried out at depth-intervals of 2.0, 4.0 or 8.0 cm. Samples of 0.5 cm vertical thickness and 0.5 cm^3 were extracted by volumetric displacement. The samples were processed using standard techniques (Moore *et al.* 1991), shown schematically in Figure 8. The function of each chemical reagent is summarised in Table 4. *Lycopodium clavatum* spores were added as an exotic to enable the calculation of 'absolute' (concentration and accumulation) pollen frequencies (Stockmarr 1971). One *Lycopodium* tablet was added to each sample, except at Morvich, where high pollen concentrations required the addition of two tablets to each subsample. Hydrofluoric acid (HF) treatment was only used where sufficient mineral material was present to make slide preparation and counting difficult; no HF was required at Torran Beithe or Morvich, but was necessary for most samples from Carnach Mór and Camban.

The two surface samples from each site were combined and homogenised during processing. Slight variations were necessary for the processing of surface samples, and these are depicted in Figure 9. Due to the lack of control of the thickness of uncompacted surface samples and thus uncertain age-span, compared with fossil subsamples, no *Lycopodium* tablets were added.

4.2.3 Humification analysis

Humification is a measure of the amount of humic acid produced during peat decomposition, and is thus used as a proxy for peat wetness and effective precipitation (precipitation minus evaporation), since peat decays more under dry conditions, resulting in more humic acid being produced, and the opposite applies under dry conditions.

A replicate core from Torran Beithe was sampled for humification analysis. This was carried out by Eleanor Charman, an undergraduate student, using 9.0 cm contiguous samples, following the method of Blackford and Chambers (1993). The humic acid extract is measured using light transmission, and the results are expressed as percentage transmission, where higher transmission indicates less humic acid and wetter conditions.

4.3 Data collection and presentation

4.3.1 Pollen analysis

Pollen counts were made using a Leica DMLS microscope at x400 magnification, and at x800 and x1000 under oil immersion for critical examination of pollen sculpture and measurement of cereal-type pollen grains. A minimum pollen sum of 500 land pollen grains, excluding spores and aquatics, was employed, with the following exceptions, where pollen concentrations in the uppermost uncompacted sediment were very low; the TLP sum is indicated in brackets: Torran Beithe 20.5 cm (Σ446), Carnach Mór 16 cm (Σ410), Morvich 4 cm (Σ417).

4.3.1.1 Pollen identification and taxonomy

Pollen grains were identified mainly using the key of Moore *et al.* (1991) and the pollen reference collection at the University of Stirling, with reference to Faegri and Iversen (1989) and Andrew (1984). The descriptions and photographs of Punt *et al.* (1980-1995) were used where further clarification was required. The designation '*cf.*' indicates that this was the closest identification possible but not an exact match, or that type material was not available to confirm the identification. Pollen and spore identification was made to the lowest taxonomic level possible using the available references and following the nomenclature of Bennett (1994) and Bennett *et al.* (1994), with the following exceptions:

1. *Sorbus*-type pollen was identified to several species and genera. *Sorbus aucuparia* is present within Glen Affric and it was thus considered necessary to identify as far as possible the individual genera grouped under *Sorbus*-type by Bennett (1994) to understand woodland composition and history. *Sorbus aucuparia, Prunus padus* and *Crataegus* pollen were identified. Although there are some contradictions in criteria used by different authors (*e.g.* compare Andrew (1984) with Boyd and Dickson (1987)), research by Boyd and Dickson (1987) and examination of the reference material at the University of Stirling, suggests that it is possible to identify some genera and species within the pollen group *Sorbus*-type (*sensu* Bennett 1994). Relative to *Crataegus*, striations were very fine and grain size for *S. aucuparia* appeared relatively small, although no measurements were made in the present study. Like *Crataegus*, the pores are ragged-edged, but are smaller and frequently rather indistinct. *P. padus* pollen was distinguished by coarse, wide striae (Moore *et al.* 1991). The class *cf. Sorbus* was employed for Rosaceae grains which resembled this pollen type, as the grains were thought to compare more closely with *Sorbus* than unidentified *Sorbus*-type grains (*sensu* Bennett 1994).
2. Separate *Corylus avellana* and *Myrica gale* pollen types were identified. Grains possessing intermediate characteristics were assigned to the class *Corylus/Myrica*. While it is accepted that *Corylus* and *Myrica* pollen cannot be separated consistently (Edwards 1981), the present scheme was employed in recognition of the occurrence of clear *Myrica*-type grains (Moore *et al.* 1991) and importance of the different ecological conditions implied by these two species. Differentiation was based on the absence or dissolution of the nexine around the porus, where the sexine is thickened (Moore *et al.* 1991), resulting in a more diffuse wall within each porus, compared with the clearly defined inner pore wall of *Corylus* (see Plate 17e in Moore *et al.* 1991). On many grains, the mouth of each porus was asymmetrical, such that one side protruded more than another in polar view.
3. The key of Moore *et al.* (1991), following Oldfield (1959), was used in the identification of Ericales pollen as far as possible. *Calluna vulgaris* and *Empetrum nigrum* pollen was easily distinguished, but distinction between *Vaccinium* and *Erica* grains was frequently uncertain due to distortion or faint resolution of surface sculpture and aperture morphology which prevented the necessary identification criteria from being sufficiently well resolved (*cf.* Oldfield 1959). Consequently, *Vaccinium*-type grains reflect those tetrads which were identified as definite *Vaccinium* grains and those grains where the necessary features were not distinct enough to enable secure identification as either *Vaccinium* or *Erica*. *Erica* grains were identified on the basis of aperture morphology, particularly uniform thickening along the colpus, and the flattened poles of each tetrad.

4. Cereal pollen identification follows the groups defined by Andersen (1979), with reference to Dickson (1988). *Hordeum* group and *Avena/Triticum* group were identified on the basis of size, as sculptural differences were not always distinct. No *Secale cereale* pollen was identified. Wild-type grass pollen is designated Poaceae anl-D (annulus diameter) <8 μm. Poaceae with an annulus diameter >8 μm, but mean grain dimensions (M+ + M-/2) <32 μm necessary to be classed as cereal-type pollen, are recorded as Poaceae anl-D> 8 μm. Larger Poaceae pollen, with annulus diameters less than 8 μm, but a mean grain size of greater than 37 μm, are recorded as Poaceae >37 μm. Size criteria for cereal-type pollen identification are shown in Table 5.
5. On the basis of the available reference material and Punt and Blackmore (1991), a few pollen grains were identified separately from *Ranunculus acris*-type. This was particularly the case at Morvich, where the frequency of grains resembling aquatic *Ranunculus* pollen types prompted the inclusion of a separate group, *R. trichophyllus*-type, after Birks (1973). These were distinguished from *R. acris*-type grains primarily on the basis of their fine, evenly distributed columellae and obtuse-ended colpi. Several grains designated *cf. Anemone* were also identified.
6. *Plantago media* and *P. major* were not identified separately, as it was considered that the necessary clarity of surface sculpture was lacking on subfossil pollen grains. Pollen referable to either of these species was thus identified as *P.media/major.*
7. Fossil *Lycopodium clavatum* spores were identified by differences in staining and preservation, which allowed them to be distinguished from the exotic marker spores. Fossil grains were lighter in colour, having only undergone a single acetolysis, compared with double acetolysis of the exotic markers. Inferred fossil grains were frequently less crumpled than the more darkly stained exotics. The frequency of fossil *Lycopodium* spore was low in all samples, suggesting that misclassed fossil grains are unlikely to bias the exotic count.

4.3.1.2 Presentation of pollen data

The programmes TILIA and TILIA • GRAPH (Grimm 1991) were used to construct spreadsheets and pollen diagrams. The pollen sum consists of total land pollen grains (TLP), excluding aquatics and spores. The percentage values for taxa outside the TLP sum were calculated as TLP + taxon or group. Non-pollen sums (charcoal, stomata and spherules) were calculated as a percentage of TLP in order to quantify the counts relative to pollen data. All diagrams are plotted against uncalibrated radiocarbon years BP (see Section 4.3.5).

Pollen concentration and accumulation (influx) values were also calculated using TILIA. These measures of 'absolute' pollen frequencies have several disadvantages, since each increases the number of errors included in the calculated value. Sources of error in pollen concentrations include inaccuracies involved with volumetric displacement of sediment samples, the loss of exotic marker grains during processing, the error range on the number of exotics per tablet, and the need to count a sufficient number of marker grains to overcome biasing caused by the non-random distribution of grains on the slide (Maher 1981). The calculation of pollen accumulation rates is affected by these errors and also relies on the availability and number of radiocarbon dates, with their associated error ranges, in order to determine the rate of sediment deposition. In addition concentration and accumulation data are not dependent solely on the surrounding vegetation, but are also affected by sedimentary processes (Birks and Birks 1980).

Despite these sources of error, both accumulation and concentration data allow each pollen, spore or microfossil type to be evaluated independently, thus overcoming some of the problems inherent in percentage representation (Faegri and Iversen 1989).

4.3.1.3 Zonation of the pollen diagrams

Dividing each pollen diagram into smaller units, or pollen zones, aids the description, discussion and comparison of the pollen sequences. Birks (1973, p.273) defined pollen zones as "a body of sediment with a consistent and homogeneous fossil pollen and spore content that is distinguished from adjacent sediment bodies by differences in the kind and frequencies of its contained fossil pollen grains and spores."

Local pollen assemblage zones and sub-zones (West 1970) specific to each site were defined. Regional pollen assemblage zones encompassing all of the sites would be inappropriate as each sampling site has predominantly local pollen recruitment characteristics, reflecting contrasting local environmental conditions (Section 3.2). Local pollen assemblage zones (LPAZ) were delimited with the aid of CONISS (Grimm 1987), using all pollen taxa with a frequency of greater than 2%. CONISS performs a stratigraphically-constrained cluster analysis of pollen data by the method of incremental sum of squares. The technique thus assesses the relative dissimilarity between pollen samples, splitting the stratigraphic sequence into groups of samples (depths), which are of broadly similar composition that differs from the adjacent samples.

Zones were defined primarily on the basis of percentage pollen data. The cut-off point after which further zones were not delimited is determined by the point at which all consistent pollen changes had been recognised, thus delimiting homogeneous assemblages (*sensu* Birks *op. cit.*). The same zones were imposed on concentration, influx, preservation and charcoal diagrams in order to assess how the palynological curves are affected by changes in sediment composition, absolute pollen and charcoal values.

4.3.2 Pollen preservation data

The differential preservation of pollen and spore types and evidence of pollen deterioration are potentially serious sources of error which can affect interpretation of the data and reconstruction of vegetation history (*e.g.* Sangster and Dale 1961, Havinga 1964, 1984). Preservation data are a useful tool for assessing the reliability of the pollen spectra and for understanding the sedimentological history of the sampling basin and the taphonomy of pollen grains, thus helping to establish more securely the relationship between the sampling basin, pollen assemblage and past vegetation.

Determinable and indeterminable pollen grains were recorded in five preservation states. Determinable pollen grains were recorded in the following five categories. Definitions follow Birks' (1970) modification of the classification proposed by Cushing (1964, 1967):

1. *Well-preserved* grains exhibit no distinct damage to the structure or sculpture of the grain wall.
2. *Broken* grains are those with distinctly ruptured exines, or which are broken so badly that part of the grain is missing (Lowe 1982).
3. *Crumpled* grains are badly folded, twisted or collapsed. There is some subjectivity involved with the recognition of this class, since grains which exhibit a slight depression, as opposed to clear folding, are classed as well-preserved.
4. *Corroded* grains have pitted or etched exines. The corroded areas appear to be randomly distributed over the surface of the grain (Cushing 1967, Birks 1970), or may occur over the entire grain surface (Lowe 1982). Typically only the outer layer of the spore or pollen wall (the ektexine) is affected.
5. *Degraded* grains are those whose structural and sculptural elements cannot be resolved. This process usually affects the entire exine and suggests some rearrangement of the pollen wall substance, where structural wall elements appear partially fused, such that the wall becomes essentially amorphous, the term preferred by Lowe (1982). Also included in this class are those grains where the entire surface of the grain was thinned, so that only a 'shadow' of the former wall structure remained. Although this could have been recorded as severe corrosion, the severity of the deterioration was felt to warrant classification as degraded, since this class represents the most severe pollen deterioration, where it becomes

difficult to distinguish degraded pollen and spores from other organic particles and recognition becomes highly subjective (Cushing 1964).

Breakage in *Pinus* grains can be the result of processing rather than transport or sediment formation processes (Cushing 1967). Thus to prevent over-representation of broken *Pinus* grains in the pollen counts, tallies of half grains were made, two records representing one grain. A single air sac was considered to constitute a half grain, since these were easily recognisable. Broken Ericaceae were similarly recorded, two grains representing a half tetrad.

No hierarchy was applied during counting, the dominant preservation state being recorded (*cf.* Tipping *et al.* 1993) to remove any additional subjectivity involved with assigning relative importance to different forms of deterioration. The preservation data are presented in two forms:

1. Summary preservation data - cumulative curves for each preservation class, as a percentage of TLP grains, *i.e.* classes cumulatively adding up to 100%.
2. Individual species preservation curves - where the changes in summary curves are considered important for the interpretation of pollen spectra, preservation data for selected (major) taxa are presented; these are calculated as a percentage of each individual pollen type, *e.g.* corroded *Betula* grains expressed as a percentage of well-preserved + broken + crumpled + corroded + degraded *Betula* pollen, thus totalling 100% for each pollen type. This sum provides independently-calculated taxon curves, which can be used to assess changes in preservation within and between pollen types.

Indeterminate grains are recorded as concealed, broken, crumpled, corroded or degraded, following the same definitions. Concealed grains are those where essential features are obscured in some way, although the grains may be well-preserved, preventing the grains from being assigned with confidence to any pollen type, known or unknown (Cushing 1964). Unknown grains were those which could not be identified to any known pollen or spore type. Percentages of indeterminate and unknown grains were calculated on the basis of TLP + indeterminate, or TLP + unknown grains, respectively.

4.3.2.1 Causes of pollen deterioration

The primary processes which are believed to be responsible for different types of pollen and spore deterioration are summarised in Table 6. This is based on experimentally-controlled investigations, primarily those of Havinga (1964, 1984), and inferences made from numerous fossil pollen assemblages. From this, it is evident that several possible causes exist for all deterioration states, but many uncertainties remain; most experimental work has focused on corrosion and oxidative effects (Havinga 1964, 1984), but relatively little is known of other inferred mechanisms, including the effects of taphonomic processes such as the mode, time and distance of transport, and microfaunal ingestion (Lowe 1982).

4.3.2.2 Pollen deterioration and assemblage formation

There are three stages during which pollen deterioration may occur, none of which are mutually exclusive:

1. *Syn-depositional* or *penecontemporaneous* processes cover the period between pollen production and its deposition within the sediment basin. This includes all forms of pollen transport (Tauber 1965, Peck 1973), and incorporates contemporaneous (cpr^1) or near-contemporaneous pollen, and older, reworked (cpr^2) pollen (West 1973, Pennington 1979), derived from erosion of soils or other sediments.
2. *Post-depositional* or *diagenetic* deterioration includes burial and compression of the sediment, resulting in physical damage to pollen grains. Also included are changes in water-tables and consequent drying or erosion, which can produce further deterioration of the *in situ* assemblage, including all forms of deterioration. Establishing a firm distinction between syn- and post-depositional processes is difficult, since Lowe (1982) regards enhanced corrosion and physical damage through the lowering of water-tables as diagenetic, but classes basin-edge collapse and pollen redeposition as non-contemporaneous, while Tipping (1984) considers any post-burial change as diagenetic. This latter definition is adopted here.
3. *Sample processing* can introduce further deterioration into the assemblage, notably the breakage of *Pinus* grains (Cushing 1967). To minimise the biasing caused by these processes in this study, preparation techniques remained consistent, with the exception of selective HF treatment and surface sample processing. Samples were stirred for the minimum length of time necessary to disaggregate the pellet.

4.3.2.3 Interpretation of pollen preservation data

Regardless of terminological distinctions, distinguishing between these components in the pollen record is difficult, due to the composite nature of the pollen record, the multiplicity of pathways which result in deterioration between pollen production, and sample counting and data interpretation (*e.g.* Lowe 1982). This subject is therefore discussed fully in the pollen site chapters (Chapters 5-8), since the importance of different deterioration processes varies between sites, influenced by differences in setting and local environmental conditions.

4.3.3 Charcoal data

As discussed in Chapter 1, the number of studies providing quantitative charcoal counts in the Highland region is limited. Charcoal analysis is one aspect of palaeoecological investigation for which there is little standardisation. A brief justification for the methods adopted in Glen Affric is therefore necessary.

4.3.3.1 The use of microscopic charcoal

The choice of analysing microscopic, rather than macroscopic, charcoal was made partly to make the most efficient use of the time available, since charcoal particles could thus be quantified during pollen counting. This technique has received criticism as theoretical models and empirical data from lake sediments have suggested that pollen-slide size charcoal fragments reflect only regional or background fires, and tend to be under-represented near the burn site due to preferential export (Clark 1988), while macroscopic and thin section size charcoal particles are inferred to be representative of local fires (MacDonald *et al.* 1991, Clark and Royall 1995).

However, Swain (1973, 1978) found that microscopic charcoal peaks provide a reasonable proxy for past fire events in large lakes. In addition, results from recent experimental burns suggest that fuel type and stature affect the intensity of the fire, the height to which charcoal fragments are lofted on hot air currents, and thus the distance of transport (Dark 1998). Data from controlled experimental burns further suggest that charcoal particle sizes, micro- and macroscopic, are rather conservative, and that there is no distinct dichotomy between small/background and large/local fire signals (Clark and Patterson 1997, Sugita *et al.* 1997, Clark *et al.* 1998), as has been inferred previously. Microscopic charcoal data are thus inferred to provide a reasonable proxy for fire history.

4.3.3.2 Charcoal quantification through length and size classes

There is little standardisation of charcoal quantification techniques, microscopic or macroscopic (Tolonen, 1986, Patterson *et al.* 1987), and different laboratories have frequently developed different methods (Bradshaw *et al.* 1997). The most frequently used methods involve some form of quantification of either length or area, the latter frequently using the point count method of Clark (1982). Length and area measurements appear to yield comparable results (Patterson *et al.* 1987), but charcoal length also enables inferences to be made regarding local and distant/background charcoal signals through patterns in the distribution of size classes.

Previous research into the use of size classes suggests a positive correlation between different charcoal size classes (Mehringer *et al.* 1977, Tolonen, 1986, MacDonald *et al.* 1991, Tipping *et al.* 1993), and that the distribution of larger charcoal particles does not necessarily provide clear evidence of fires near to the sampling site (Sarmaja-Korjonen 1991). However, Clark and Patterson (1997) suggest that although clear local/background signals do not occur, particle size distribution remains sensitive to the source of the fire, as transport mechanisms may emphasise large charcoal fragments from local burns in sediment profiles. This is also evident from recent research on Scottish heathland (Stevenson *et al.* 1996), which suggests that recording charcoal size classes may aid the reconstruction of fire histories (see Section 4.4.2).

Length measurements may be biased by differences in the cellular structure of different fuel types, and by distortion due to fragmentation during processing. Little work has been done on the character of charcoal produced by burning different vegetation types (Patterson *et al.* 1987). Preliminary observations by Dark (1998) suggest that the fuel type influences the quantity, size and fragility of charcoal fragments, although this is based only on the contrast between reeds, which produce more robust charcoal particles, and rushes, which produce mainly fine, fragile charcoal particles.

Clark (1984) examined the effects of pollen preparation procedures on charcoal abundance, concluding that standard chemical treatments all progressively reduce the area or number of particles, although HF and acetolysis do not reduce the number of fragments. However, effects on the distribution pattern of charcoal size classes are unknown (*cf.* Patterson *et al.* 1987). Although it is not possible to determine the extent of charcoal fragmentation and changes in size class distribution patterns, a standard preparation technique was applied to all samples from Glen Affric (Section 4.2.2) in order to maximise comparability between sites.

4.3.3.3 Charcoal quantification in Glen Affric

Microscopic charcoal counts were made on pollen slides. Charcoal fragments were identified as black, opaque and angular (Patterson *et al.* 1987). To avoid confusion with oxidised organic matter in the cores, any fragments which appeared partially blackened, with some brown coloration, were excluded. Charcoal fragments were measured and recorded in four size classes: 10-25 μm, 26-50μm and 51-75 μm, and fragments larger than 75 μm, which were measured individually (*cf.* Tipping *et al.* 1993). Charcoal data are expressed as a percentage of TLP.

4.3.3.4 Presentation of charcoal data

Charcoal data are expressed as percentages of total land pollen, concentrations and as a ratio of charcoal to total land pollen concentrations. Five percentage curves are presented for each site, one for each of the four size classes, and a fifth curve for the sum of charcoal fragments. Concentration and accumulation rate curves are presented for the charcoal sum only. Charcoal-to-pollen ratios are were calculated to overcome the problem of changes in charcoal caused by variations in TLP concentration.

4.3.4 Other micromorphological data

4.3.4.1 Stomata

Stomatal guard cells were recorded during pollen counts. These have been found in several studies to be a valuable indication of the local growth of conifers (Dunwiddie 1987), particularly of *Pinus sylvestris* (Bradshaw 1981b, Kerslake 1982, Bennett 1983). Stomatal records have proven especially useful where the trees are infrequent and associated with low pollen frequencies which are inconclusive evidence for the presence of trees (Fossitt 1994b). *Pinus sylvestris* stomata were identified using the photographs and key of Trautmann (1953), aided by the diagrams of Hansen (1995). Other non-coniferous, stomatal guard cells were very occasionally observed, and their presence was also recorded, although their identity is unknown.

4.3.4.2 Spheroidal carbonaceous particles

Spheroidal carbonaceous particles (SCPs) are the product of incomplete fossil fuel combustion (Rose *et al.* 1995). Fossil fuel use is mirrored by SCP concentrations in loch sediment across Britain and Scandinavia (Wik and Natkanski 1990, Rose *et al.* 1995); the record of SCPs thus provides an independent dating tool for the upper part of a sequence. SCP production began around AD 1900, increased after the Second World War and then declined in near-surface sediments. SCPs were identified following the descriptions of Wik and Natkanski (1990), who describe them as more than 5-10 µm in diameter, black, porous and spheroidal. Counts are expressed as a percentage of TLP. Counts were too low to justify the presentation of meaningful accumulation rate curves.

4.3.4.3 Sulphide spherules

A second form of spherule was also identified: sulphide spherules are formed by microbial activity under anaerobic conditions, which results in the production of metallic sulphides. They are identifiable as black, opaque non-aggregated spherical particles, typically 3-30 µm in diameter (Wiltshire *et al* 1994). These were observed only in the sediment from Morvich, but due to initial uncertainty as to their identification, counts were not made throughout the core and thus a complete record of their presence or absence is not available.

4.3.5 Radiocarbon analyses

A precise correlation between the pollen data and dating horizons is essential for establishing secure temporal correlations between sites. Where radiocarbon samples are taken from the same core used for pollen analysis, the small sediment mass required for Accelerator Mass Spectrometry (AMS) dating can provide the required close correlation between pollen and dating horizons.

Dating horizons were selected on the basis of changes in relative and absolute pollen frequencies, charcoal curves, and on sediment stratigraphic changes, which were deemed significant firstly in a local context and frequently also in a regional context. Locally important stratigraphic horizons were dated to construct an independent chronology for each local pollen recruitment site (Section 3.2), although several were also of regional significance. This enabled the synchroneity or otherwise of regional events occurring in the study area to be established. Additional pollen stratigraphic changes which were inferred to have extralocal or regional significance were also selected for AMS dating in order to further establish regional patterns of vegetation development and land-use.

Material for dating was sampled from the same cores used for pollen and other microfossil analyses. The radiocarbon samples were of 0.5 cm vertical thickness, identical to the subsamples extracted for pollen analysis. The only exception was the basal dating horizon at Carnach Mór, where the sediment was highly minerogenic, and a sample of 1.0 cm thickness was used to ensure that sufficient carbon was present for radiocarbon dating.

At the NERC radiocarbon facility at East Kilbride, raw samples were pre-treated to extract and assess the humin fraction. The division between humic and humic fractions is arbitrary, the product of laboratory extraction procedures, and in reality there is a continuum. The humin fraction consists of acid-insoluble organic matter, while the acid- and alkali-soluble humic fraction is potentially more mobile. Differences between that dates returned by the different components can be significant (*e.g.* Harkness and Walker 1991), as the more mobile humic component can have a 'younging' effect, thought to be due to downward movement in sediments. This can have significant effects on the interpretation of pollen data (*e.g.* Bartley and Chambers 1992). The use of the humin fraction may be particularly important in peats where there may have been movement of water through the peat (Bartley and Chambers 1992). For radiocarbon-dating the peats from Glen Affric, the less mobile humin component was therefore selected on the basis that potentially lower mobility may provide a better estimate of the date of peat deposition, particularly where water movement had occurred.

Samples were digested in 2M HCl and KOH to discard the mineral and humic acid components, isolating the alkali- and acid-insoluble humin fraction. Dried, homogenised samples were combusted to CO_2 in sealed quartz tubes. CO_2 was purified by cryogenic separation from other combustion products. A subsample of CO_2 was used to measure stable carbon isotope ratios, relative to the Pee-Dee Belemnite carbonate standard. A further CO_2 subsample was converted to a graphite/iron mixture by iron/zinc reduction (Slota *et al.* 1987) and sent to the NSF-AMS Facility at the University of Arizona, Tuscon, for ^{14}C analysis, with the exception of an additional sample from Camban, which was sent to the Lawrence Livermore National Laboratory, University of California. Here a particle accelerator was used to count the number of ^{14}C atoms, as opposed to their decay products in conventional radiocarbon dating (Donahue 1990).

Uncalibrated ^{14}C and calibrated dates are quoted in years BP (before AD 1950) throughout this thesis. ^{14}C dates were calibrated using the CALIB 3.0.3 programme (Stuiver and Reimer 1993). All dates are rounded to the nearest 10 years. Uncalibrated dates are indicated by the suffix 'BP', while calibrated dates are quoted as 'cal BP', using the middle intercept on the calibration curve, where there is more than one (Stuiver and Reimer 1993). All diagrams are plotted against uncalibrated ^{14}C years BP.

Radiocarbon dates BP are quoted in order to enable comparison with older literature as well as much recent research where calibrated dates are not used, and in case of future improvements to the calibration curve. Calibrated dates are included to enable the temporal scale of vegetation dynamics to be reconstructed on a calendrical timescale which has ecological relevance. Where documentary and historical sources are considered, calibrated dates in years AD are also given. The need for critical interpretation of dates and caution when comparing data sources is borne in mind (*cf.* Pilcher 1991).

The radiocarbon dates are presented in tabular form (Tables 8, 15, 22 and 32) and are used to construct a time-depth curve for each site (Figs. 13, 26, 38 and 50). Within a core, changes in accumulation rate with time result in variations in the temporal resolution of the pollen diagram. In order to interpret the pollen data in ecological terms, considering the time-scale of vegetation development, succession and disturbance, the time-depth curves are used to determine the temporal resolution of the sampling intervals used in pollen analysis (Tables 9, 16, 23 and 33). It is acknowledged that this is constrained by the number of radiocarbon dates, since changes in accumulation rate between dating horizons may not be detectable.

4.4 Data analysis

4.4.1 Pollen analytical techniques

In order to assist interpretation and comparison of the pollen diagrams, several further analytical techniques were applied to the data.

4.4.1.1 Ordination

Ordination techniques attempt to represent the trends in multivariate datasets in a reduced number of dimensions, displaying the major gradients or directions of variation within the data. One of the primary advantages of such methods is that they make use of the whole assemblage, in contrast with more subjective groups, such as so-called 'anthropogenic indicator' taxa (Behre 1981, 1986).

Correspondence analysis techniques assume that taxa exhibit a unimodal response curve to the underlying gradients, which carries some ecological plausibility and is both a convenient and robust approximation (ter Braak 1987, Birks 1995). This method was preferred over principal components analysis (PCA), which assumes a linear response curve and is strongly influenced by differences in relative pollen representation. An unfavourable consequence of this is that the PCA is relatively insensitive to rare species, emphasising species-poor sites which are dominated by a few species, while species-rich sites appear to be more similar (ter Braak 1983, Birks *et al.* 1988).

Detrended correspondence analysis (DCA) (Hill 1979) was considered to be the most appropriate technique for the present data as it is a relatively robust method which avoids several of the major faults associated with conventional correspondence analysis (Hill and Gauch 1980, ter Braak 1987). The main limitation of DCA is its inability to cope with extreme outliers and discontinuities (Hill and Gauch 1980) and this is borne in mind in the interpretation of the DCA results.

DCA was implemented on all TLP taxa with a value of ≥2% in at least one sample using CANOCO Version 4.0 (ter Braak and Šmilauer 1998). The taxa used were recalculated to a sum of 100% and transformed from TILIA to Cornell condensed format using the programme TRAN Version 1.8 (Juggins 1997). The data were detrended by segments and square root transformed during the analysis, as this is appropriate for percentage data. The taxon and sample scores for the first two axes are presented on separate plots for each site. Biplots were considered impractical as differences in scale between the taxon and sample scores resulted in the large number of sample scores for each site being clustered at the centre of the biplot, rendering viewing and interpretation difficult. The results are presented in Figures 18, 32, 46 and 60. As indicated in Chapters 5-8, the DCA axes, particularly the first two axes, represent a high proportion of the cumulative variance in the taxa data and are thus a good approximation of the main directions of variation within each dataset.

4.4.1.2 Rarefaction analysis (palynological richness)

Reconstructing vegetation diversity is critically important in modern ecological interpretation, as it represents the influence of local- and regional-scale processes on vegetation communities. Rarefaction analysis was developed by Birks and Line (1992) as a method of estimating palynological richness in pollen-analytical data. This is done by standardising pollen counts to a fixed number of grains, usually the smallest total count in the samples to be compared, after which the total number of taxa present in a sample is a robust measure of palynological diversity. The variance or 95% confidence intervals of the rarefaction values are presented as horizontal bars.

Rarefaction estimates can be influenced by a number of factors, including site morphology, vegetation structure, which affects pollen dispersal, and vegetation composition, floristic, vegetational and landscape diversity within the pollen catchment (Birks and Line 1992). The changing mosaic structure of the landscape and changes in floristic richness of constituent vegetation types within the pollen source area are important factors affecting rarefaction (Birks and Line *op. cit.*). Rarefaction can also highlight the role of disturbance in influencing taxonomic richness.

However, several assumptions are also made, including a similar depositional environment and pollen source area through time (Birks and Line 1992, Odgaard 1994, cited in Seppä 1998). The same also applies in the comparison of values between sites.

Rarefaction was implemented using psimpoll 3.0 (Bennett 1998), using a standardised count of 400 grains, due to the small number of levels where low pollen concentrations prevented a count of 500 grains from being attained (Section 3.6.1). This was applied to all of the sites in order to enable greater inter-site comparability, mindful of the caveats discussed above. The results are presented in Figures 17, 30, 42 and 55.

4.4.1.3 Rates of palynological change

The analysis of rates of vegetational change from pollen records is a useful technique for assessing the temporal stability of communities and their response to environmental change, including natural and anthropogenic mechanisms. Rate of change measurements use a quantitative, but arbitrary, measure of difference or 'dissimilarity coefficient' (DC) between samples (Bennett and Humphry 1995). Many possible measures of dissimilarity coefficient can be used, each of which has both advantages and disadvantages in obtaining a balance between 'noise' and 'signal' (see Bennett and Humphry 1995).

There are also many possible methods of calculation, including data smoothing and interpolation to constant time intervals (Bennett and Humphry 1995). This is because rates of change are not only dependent on dissimilarity, but also on the time difference between samples (Seppä 1998) and comparisons calculated over non-equal time intervals must be interpreted with caution (Bennett and Humphry 1995). In addition, noise is more apparent in rate of change for diverse samples, as counts for more important taxa are smaller, resulting in higher relative random sampling errors associated with smaller counts (Maher 1972, Bennett and Humphry 1995). Bennett and Humphry (1995) found that smoothing the data had little effect in reducing noise, and the use of calibrated ages also had little effect.

Although no single DC is best for all data and Bennett (1997) recommends trying them all, signal-noise DCs are most widely recommended and chord distance is commonly used (Bennett and Humphry 1995). This DC was implemented in rate of change analysis of the Affric data. Rates of change were determined using psimpoll 3.0 (Bennett 1998). The data were not smoothed or interpolated to constant time intervals prior to rate of change analysis. The results are presented in Figures 17, 30, 43 and 56.

4.4.2 Charcoal analysis

Regression analyses on charcoal size classes was performed in order to assess whether a correlation exists between the frequency of different size classes. Rhodes (in Stevenson *et al.* 1996) suggests that the relationship between macroscopic charcoal size class distribution and fire proximity is reflected by subtle changes in the proportion of different size classes (charcoal "size-class signatures"), with higher proportions of medium-sized charcoal fragments and lower numbers of smaller fragments. Changes in the ratio of largest (>75 μm) to smaller (10-25 μm, 26-50 μm, 51-75 μm) charcoal particles were therefore examined in order to infer possible changes in the proximity of fires to the sampling site.

CHAPTER 5: Torran Beithe

5.1 Site selection

Low, undulating hills covered by blanket peat with subfossil *Pinus sylvestris* stumps exposed through erosion are dominant features of the upland landscape of Glen Affric (see Chapter 3, Fig. 6a) and are common throughout much of the mountainous Highland region, as are the limited areas of putatively ancient *Pinus sylvestris* woodland which survive in East Affric (Steven and Carlisle 1959; Section 2.1.5.2). The pollen site at Torran Beithe was selected to typify the Holocene evolution of this widespread blanket peat-covered landscape.

The present landscape around Torran Beithe contrasts sharply with the woodlands of East Affric, which reach their western limit around the head of Loch Affric, *c.* 1.25 km east of the sampling site (Fig. 7), and with the abundance of *Pinus* subfossil macro-remains at this site and elsewhere in West Affric. This suggests that the wood remains buried within the peat may give some indication of past woodland composition (Section 2.1.5). However, this may represent only a biased indication of prior communities due to preferential preservation (*e.g.* Bridge *et al.* 1990).

The relatively species-poor, acidophilous taxa forming the extensive blanket peat around Torran Beithe also contrast with species-rich vegetation on alluvial sediments (Section 2.1.5.3). Long-term differentiation between these landform units may have restricted the abundance of more nutrient-demanding taxa, including *Corylus avellana*-type, *Quercus* and *Ulmus*. Woodlands on poorer moraine-derived soils may have been comparatively fragile ecosystems, sensitive to environmental pressures, including pedogenic processes on nutrient-poor substrates, regional climatic change and more localised grazing or anthropogenic activity. The spread of blanket peat from basins onto intervening land surfaces, however triggered, could have resulted in the demise of fragile woodland communities.

These edaphic implications and the near absence of archaeological evidence for settlement and land-use on hillsides in upland glens (Section 2.2.3) suggest that nutrient-poor, acidic and wet soils may have imposed restrictions on human activity, perhaps limiting land-use to comparatively low intensities and less demanding forms of agriculture, such as pastoralism.

5.2 Site description

The valley floor in central Glen Affric is flanked to the north and south by hillslopes, frequently rising to peaks above 1000 m (Fig. 10, Photo 3). The floodplain west of the head of Loch Affric forms a large, shallow basin, which contrasts with the steep, wooded slopes on either side of Lochs Affric and Beinn a'Mheadhoin, and the narrower expanse of flat alluvial sediment towards West Affric (Fig. 10, Photo 4).

Torran Beithe is one of the relatively low, treeless hills on the northern side of the floodplain, rising to 302 m OD. The lower slopes on the northern hillsides are undulating and blanket peat covered, and include the sampling basin. Rising steeply to the north is Carn Eighe, at 1183 m OD. Torran Beithe lies around 500 m north-west of Athnamulloch, formerly a hill sheep farm, and *c.*600 m from the ruins of Coulavie, on the northern bank of the River Affric (Fig. 10). These farmsteads are recorded in the First Census of AD 1841 (Wordsworth 1995, Wordsworth and Harden 1997).

A transect was surveyed across this area, from National Grid Reference NH 131209, north-west to NH 128211 (Fig. 10). The results of depth probing at intervals of 10-40 m with an Eijelkamp gouge were used to produce a map of peat depth and to locate the deepest peat basin for sediment sampling (Fig. 11). This was then surveyed and depth-probed with an 8.0 m grid interval to locate the deepest point and define the basin more closely. The sampling site is situated on the northern side of the hill after which it is named, NGR NH130210, at an altitude of 260 m OD. The site receives some degree of shelter from prevailing westerly winds by the surrounding hillslopes. The enclosed, infilled bedrock basin is defined by peat-covered ridges with bedrock exposures (Fig. 12a). The results of surveying and coring are presented below (Fig. 12a-c). Subfossil *Pinus* stumps are exposed in an erosion channel on the north side of the basin.

The relatively sparse and species-poor vegetation on and around the basin consists of *Trichophorum cespitosum*, *Eriophorum angustifolium* and *E. vaginatum*, *Calluna vulgaris* and Poaceae. *Sphagnum* is abundant and *Myrica gale* is common, whilst *Erica tetralix* and small, stunted *Salix* bushes occur as rarer shrubs. *Potentilla erecta* is common, with less frequent *Polygala serpyllifolia*, *Pinguicula vulgaris* and *Drosera intermedia*. The nearest trees are sparse *Alnus glutinosa*, *Sorbus aucuparia* and *Betula* which survive beside the River Affric, Allt Dubh (*allt* is Gaelic for stream or burn) and Loch na Camaig, *c.*500-750 m away; *Betula* is also regenerating amongst felled plantation *Picea* on the southern side of the valley floor overlooking Athnamulloch, around 750 m to the south (Fig. 10).

5.3 Results

5.3.1 Basin morphology and source area

The morphology of the Torran Beithe basin is important in limiting the pollen recruitment area and providing a sensitive pollen record of the stand or community-scale vegetation mosaics and dynamics which characterise this landform type. Basin contour maps indicate a present diameter of 56 m (Fig. 12a) and the enclosing bedrock ridges may result in most runoff being derived from the immediately surrounding slopes. This suggests a pollen source area of approximately 100-300 m under a closed woodland canopy (Sugita 1994, Chapter 3). It should be noted that this is estimated as an intermediate value between Sugita's figures for a small forest hollow of 2 m radius (50-100 m relevant source area), and a small lake with a radius of 50 m (300-400 m source area). In addition, this estimate is based on the present surface diameter; the enclosed bedrock basin underlying the peat has a diameter of less than 8 m, which has been gradually increasing as the depth of peat increased (Fig. 12). This would suggest an initial source area of slightly in excess of 50-100 m under a canopy, again based on Sugita's (1994) model of source area (Chapter 3, Table 3).

5.3.2 Sediment description

A sediment core 4.62 m in length was obtained from the deepest deposit in the basin in December 1996 by the method described in Section 4.1.3 (Fig. 12b, c). The sediment stratigraphic description is presented in Table 7, which indicates that the cores consist of highly organic peat with basal mud, confirmed by loss-on-ignition analysis (Fig. 14).

5.3.3 Radiocarbon dates

Ten peat samples were submitted for AMS radiocarbon-dating. With the exception of the uppermost sample, these depict a conformable sequence (Table 8). The radiocarbon sample at 20 cm returned a modern date which is thought to be the result of modern root penetration in the upper, poorly humified peat. This horizon is therefore dated by interpolation between the date below and the surface, which is assumed to represent the present. The interpolated date of 150 BP (140 cal BP) yields a calibrated date of AD 1684-1954, which may thus be consistent with estimated dates for the rise in pollen from plantation conifers at 12-16 cm, documented for the Affric region during the twentieth century, and spheroidal carbonaceous particles from 12 cm, which commence at around AD 1900 (Wik and Natkanski 1990, Rose *et al.* 1995).

The time-depth curve generated by linear-interpolation is presented in Figure 13. The temporal resolution of the pollen sampling intervals is presented in Table 9, which indicates that time intervals between subsamples range from 4-347 ^{14}C years (4-287 cal years), with a mean of 90 ^{14}C years (100 cal years).

5.3.4 Pollen and microfossil analysis

Percentage pollen data are presented in Figure 14, with concentration and accumulation data in Figures 15 and 16, respectively. From this it can be seen that concentration and accumulation rates have been very similar throughout the Holocene. The results of rarefaction and rate-of-change analyses are shown in Figure 17. All diagrams are plotted against uncalibrated ^{14}C years BP. The results of detrended correspondence analysis for the first two axes are presented in Figure 18a-b. 61.3% of the cumulative variance of the taxa data is captured in the first four DCA axes, with 51.9% represented by the first two axes.

Seven local pollen assemblage zones and subzones were defined; the site designation 'TOR' precedes each zone or subzone division. These are summarised in Table 10. The dimensions of cereal-type pollen grains and large Poaceae are given in Table 11 (see Section 4.3.1.1 for identification criteria).

5.3.5 Pollen preservation data analysis

Summary pollen preservation data are depicted in Figure 19. Pollen is predominantly well-preserved throughout the sequence (38-92% TLP, mean 66%). Increased breakage around 30 BP (9 cm, modern calibrated date) may reflect the increase in *Pinus* frequencies (Cushing 1967). Frequencies of crumpled pollen mirror the curve for well-preserved pollen. Increased crumpling occurs during periods of higher *Calluna* and Cyperaceae frequencies, in part reflecting the balloon-like structure of Cyperaceae, but not confined to these taxa. Crumpling may result from sediment compression.

Values for corroded pollen are generally very low; peaks at 8710 BP (9780 cal BP), 7140-6790 BP (7920-7580 cal BP) and 6390 BP (7260 cal BP) coincide with increased mineral content, and may result from compression and abrasion in mineral sediment (Cushing 1964, Birks 1970) or soil erosion (Lowe 1982, Tipping 1995). The palynological evidence for either process is discussed in Section 5.5. Single spectra corrosion peaks from 6180-5130 BP (5910 cal BP) and 690-230 BP (660-290 cal BP) may reflect short-term variations in surface wetness. The low frequencies of determinate corroded pollen during these periods (max. 23% TLP) indicates that differential deterioration has not skewed the assemblage. Indeterminate pollen frequencies remain low (max. Σ6%) throughout the Holocene, suggesting that differential pollen preservation has not biased the assemblage.

5.3.6 Charcoal analysis

Charcoal data are presented in Figure 20, in percentage, concentration, accumulation and charcoal-to-pollen concentration form. A summary of the age and spread of the charcoal peaks is presented in Table 12.

Regression analyses of charcoal size class data (Table 13) indicate that that the smallest and larger size classes are fairly well correlated ($r^2 = 0.65\text{-}0.91$). However the larger size classes are poorly correlated with one another ($r^2 = 0.15$) and scatter is high. This may in part be due to chance variations in charcoal counts arising from relatively low charcoal frequencies during the early to mid-Holocene (Maher 1972).

The ratios of charcoal size classes provides more information on the relative abundance of different size classes through time (Fig. 21). The erratic curve during the early to mid-Holocene emphasises chance variations due to low charcoal counts, compared with consistently higher frequencies after *c.*4100 BP (4560 cal BP). Around 2980 BP (3200 cal BP), a slight increase in ratios of fragments >75 µm:10-25 µm may infer that fires occurred in closer proximity to the site (Patterson *et al.* 1987, Stevenson *et al.* 1996). This is discussed in relation to the palynological and sedimentological data in Section 5.5.

5.3.7 Humification analysis

Previous work has established the use of humification records as a measure of climatic wetness, notably in relation to the pine decline (*e.g.* Anderson 1998, Anderson *et al.* 1998). Water-shedding sites have been preferred for humification analyses in order to isolate a climatic signal, although valley mires have also been used to generate humification data (Anderson 1996, 1998, Smith 1996).

Humification data from Torran Beithe are presented in Figure 22. The relationship between the humification record and wetness from a small, water-collecting basin is uncertain, as the curve will reflect not only climatic wetness, but also local hydrology, including runoff from the enclosing slopes, which will have varied through time due to changes in vegetation cover and in topography as peat expanded from basins onto the intervening ground, both with associated effects on water interception and runoff. The humification curve is therefore interpreted as a measure of local site wetness, rather than as a proxy for climatic wetness.

5.4 Description

5.4.1 Zone TOR1a: *Betula-Corylus avellana*-type (462-436 cm; 8800-7890 BP, 9740-8590 cal BP)

The sediment consists of amorphous gyttja and minerogenic lake mud. Organic content rises from 45% in the basal sediment to *c.*90%. The zone is characterised by high frequencies for *Betula* and declining values for *Juniperus*, with increasing pollen frequencies for *Corylus avellana*-type and *Sphagnum*. *Salix* pollen is consistently present at frequencies of just less than 5%. Sporadic *Sorbus aucuparia* and *Populus* grains are recorded. *Calluna vulgaris* and *Empetrum nigrum* pollen maintain frequencies of *c.*5%, while Poaceae values decline from a basal peak of 18%. *Filipendula* and *Potentilla*-type are the most frequent herbaceous pollen types. Pteropsida (monolete) indet. spores are present at around 5%. Several aquatic pollen types occur, of which *Menyanthes trifoliata* is the most consistently represented.

Total land pollen concentration reaches peak values just above the base, before falling to low and moderate values. The same pattern is reflected in accumulation rates, although the initial peak is less pronounced. Following a basal peak in corroded pollen, the zone is dominated by well-preserved pollen. Palynological richness rises gradually from the base of the core. Rates of change are low. Charcoal frequencies and the charcoal-to-pollen ratio decrease from low to very low values.

5.4.2 Zone TOR1b: *Betula-Pinus sylvestris-Calluna vulgaris-Corylus avellana*-type (436-402 cm; 7890-6720 BP, 8590-7540 cal BP)

The sediment consists of highly organic mud, with a minerogenic horizon above 7140 BP, reducing the LOI to 23%. This zone is characterised by decreasing *Betula* pollen frequencies, and a step-wise increase in *Pinus sylvestris* frequencies, rising from less than 1% to 15% and then to a second peak of 20% before decreasing in the upper horizons of the zone. Rising frequencies for *Ulmus* and *Quercus* pollen are also recorded. Frequencies for *Salix*, *Sorbus* and *Populus* are lower. *Empetrum* and *Calluna* pollen frequencies increase gradually to around 20%, with an increase in *Sphagnum* values from 9% to 52%. *Potentilla*-type remains the most characteristic herbaceous pollen taxon, with *Filipendula*.

TLP concentrations and accumulation rates increase through the minerogenic horizon at the top of the zone. Values for crumpled and corroded pollen increase at the end of the zone. Indeterminate pollen frequencies remain low. Palynological richness increases markedly across the upper minerogenic horizon, when rates of change increase slightly. The first *Pinus sylvestris* stomate is recorded near the top of the zone. Charcoal frequencies and charcoal-to-pollen ratios increase slightly, remaining relatively low.

5.4.3 Zone TOR2a: *Pinus-Betula*-Cyperaceae (402-377.5 cm; 6720-6360 BP, 7540-7230 cal BP)

The transition from amorphous organic mud to peat occurs around 6590 BP (7400 cal BP, 395 cm); *Pinus* bark is present within the peat. Organic matter comprises 84-93% of the sediment, decreasing to 77% at the end of the zone. The pollen assemblage is characterised by rising frequencies of *Pinus*, Cyperaceae and *Sphagnum*, and reduced frequencies of *Betula*, *Sorbus*, *Populus*, *Calluna*, *Empetrum* and Pteropsida (monolete) indet. Near the end of the zone *Pinus*, Cyperaceae and *Sphagnum* frequencies decrease, as values for *Calluna* increase and a peak in *Betula* pollen is recorded. Aquatic pollen types are absent.

TLP concentration and accumulation rate data are more erratic, with a mid-zone increase followed by a second high peak at the transition to zone TOR2b. Concentration and accumulation curves for individual pollen types show similar patterns to percentage curves, with a marked rise in *Pinus* concentrations and accumulation rates. Frequencies of well-preserved pollen increase slightly, then decrease at the transition to zone TOR2b. Frequencies of broken and crumpled grains are *c.* 10%, with an increase in crumpled and corroded pollen at the end of the zone. Palynological richness is slightly lower, peaking at the end of the zone, as do rates-of-change. *Pinus* stomata are more frequently recorded. Charcoal frequencies are low. The peat is slightly more humified.

5.4.4 Zone TOR2b: *Pinus-Betula-Calluna* (377.5-186 cm; 6360-3600 BP, 7230-3890 cal BP)

The sediment consists of peat with *Pinus* bark near the base, followed by peat with frequent Cyperaceae remains. Organic content remains high, with the exception of a decrease to 61% at 4500 BP (5120 cal BP). *Pinus* pollen frequencies increase and *Calluna* pollen values rise further. *Betula* values remain consistently around 20%. Frequencies of *Alnus* increase, reaching a maximum of 18%. *Quercus* and *Ulmus* frequencies rise from the start of the zone, peaking at 8% and 6% respectively. Frequencies for *Pinus* and *Calluna* fluctuate throughout the zone, with a sustained reduction in *Pinus* frequencies from 5680 BP (6460 cal BP) and an increase in *Calluna* frequencies. A reduction in *Quercus* pollen frequencies is followed by a permanent reduction in *Ulmus* frequencies at 5240 BP (5970 cal BP). *Pinus* frequencies increase from 4390 BP (4930 cal BP), with an increase in *Quercus* around 4280 BP (4840 cal BP). *Potentilla*-type remains the most frequent herbaceous pollen type. *Sphagnum* frequencies fluctuate markedly between 5% and 58%.

TLP concentration and accumulation rates remain low throughout the zone. Concentration and accumulation curves for individual pollen types follow similar patterns to percentage trends. Well-preserved pollen values are high at the start and end of the zone. From *c.*5960-4280 BP (6840-4840 cal BP) frequencies of crumpled pollen increase, and corroded pollen is more frequent from 6390-5130 BP (7260-5910 cal BP). Frequencies of crumpled and broken indeterminate pollen are slightly higher in this zone, but do not exceed 2.6% and 0.5% respectively. Palynological richness values fluctuate, but are lower than the previous zone, increasing towards the end of the zone before dropping at the transition to zone TOR3a. Rates-of-change are moderate to low, rising slightly at the end of the zone. *Pinus* stomata occur frequently. Charcoal frequencies and charcoal-to-pollen ratios are low but peak sharply from 5240-4960 BP (5970-5690 cal BP), with further peaks at 4280 BP (4840 cal BP) and 3940-3880 BP (4410-4340 cal BP). Humification values are higher in the first half of the zone, low between 5430 and 5030 BP (6230-5840 cal BP), and increase slightly to the end of the zone.

5.4.5 Zone TOR3a: *Calluna*-Cyperaceae (186-82 cm; 3600-1290 BP, 3890-1200 cal BP)

The sediment comprises herbaceous peat and the organic content is consistently high. The transition to zone TOR3a is marked by a permanent drop in *Pinus* frequencies, from 37% to 18%. This coincides with a temporary rise in *Alnus*, increasing frequencies for Cyperaceae and a peak in *Quercus*, before frequencies decline. *Betula* and *Corylus avellana*-type frequencies rise, then decrease slightly and gradually through the zone. Subsequent *Pinus* percentages fluctuate from 5-23%. *Calluna* frequencies return to the levels of the previous zone. *Sphagnum* frequencies increase through the zone. Poaceae frequencies rise gradually, but remain low. *Potentilla*-type and *Plantago lanceolata* pollen are more frequently recorded. Low frequencies of *Myrica gale* pollen occur from mid-way through the zone.

TLP concentrations and accumulation rates are low, rising to moderate at *c.*2030 BP (1970 cal BP). This is reflected in the concentration and accumulation rate curves for Cyperaceae, Poaceae and *Calluna*. Values for arboreal taxa are more erratic, but between peaks, accumulation rates are lower than the previous zone. Frequencies of crumpled pollen increase to 38%, and well-preserved pollen values fall to around 50%. The palynological richness curve is more stable and slightly higher than the previous zone. Rates of change are low. *Pinus* stomata are present until 2540 BP (2720 cal BP). Frequent high peaks in charcoal are recorded. The humification curve begins a gradual, sustained increase from 1980 BP (1910 cal BP).

5.4.6 Zone TOR3b: *Calluna*-Cyperaceae-*Sphagnum* (82-28 cm; 1290-190 BP, 1200-150 cal BP)

The peat is increasingly less well-humified with increasing proportions of *Sphagnum*. Organic content remains high. The pollen assemblage is characterised by high frequencies of *Calluna*, Cyperaceae and *Sphagnum*, and consistently low frequencies for all arboreal pollen types. Herbaceous pollen is more frequent, including *Plantago lanceolata*, *Potentilla*-type, *Ranunculus acris*-type and *Rumex* species.

TLP concentrations and accumulation rates remain moderate to low, increasing markedly at the end of the zone to very high values, which are reflected in all pollen types. Crumpled pollen frequencies increase further, with an increase in corroded pollen in the second half of the zone, with peaks of 23% and 21% at 290 BP (310 cal BP) and 230 BP (290 cal BP), respectively. Palynological richness and rates-of-change remain as in the previous zone, before increasing from *c.*410 BP (490 cal BP). Charcoal-to-pollen values are lower, with an increase in charcoal-to-pollen ratios at the transition to zone TOR 3c. Percentage transmission values from humification analysis increase more steeply from 940 BP (840 cal BP).

5.4.7 Zone TOR3c: Cyperaceae-Poaceae-*Calluna-Pinus* (28-0 cm; 190-0 BP, 150-0 cal BP)

The sediment consists of organic *Sphagnum* peat. The pollen assemblage is characterised by rising frequencies for Poaceae and Cyperaceae, decreasing *Calluna* values and a large increase in *Pinus* frequencies, rising from 10% at 90 BP (*c.*50 cal BP), to 36% in the surface sample. Single *Hordeum* group pollen grains are recorded at 12 cm and at 0 cm (surface sample). *Potentilla*-type and *Plantago lanceolata* remain the most frequent herbaceous pollen types, the former increasing to 5% at the surface.

TLP concentration and accumulation rates are low. Palynological richness is high, decreasing in the two uppermost samples. Rates of change remain high, attaining a very marked peak at 150 BP (*c.*140 cal BP). Following two peaks in corroded pollen at the start of the zone, well-preserved pollen dominates, with a reduction in crumpled pollen and a rise in broken grains. Charcoal-to-pollen ratios are high at the start of the zone, decreasing to the surface.

5.5 Inferred vegetation history

5.5.1 Zone TOR1a: *Betula-Corylus avellana*-type (462-436 cm; 8800-7890 BP, 9740-8590 cal BP)

Early Holocene sediment consists of basal gyttja and overlying limnic mud, and the sampling basin contained sufficient depth of water to support aquatic taxa. The bedrock contour map indicates that the basin had a diameter of *c.*8 m at this time (Fig. 12c). *Isoetes* was replaced by *Menyanthes* as the water became shallower, with *Potamogeton* and *Myriophyllum* species. This suggests a progression from minerogenic sediments in water that may have been moderately shallow to several metres deep, to shallower more organic mud or peat, as indicated by the LOI data, since *Isoetes* and *Myriophyllum* grow in minerogenic soils, while *Menyanthes* is found on organic sediments, anaerobic mud or peat (Haslam *et al.* 1975). The basin may have been fringed by Cyperaceae, perhaps with *Caltha palustris*-type and *Equisetum*. Although *Sphagnum* sporulation is known to be erratic (Conway 1954), consistently high frequencies at Torran Beithe suggest that this genus may have been established in wet or acidic conditions within the basin (Conway 1954, Tipping 1995b). *Isoetes* is also characteristic of low alkaline environments (Haslam *et al.* 1975).

The sediment stratigraphic description and LOI curve for the early Holocene sediments indicate that the deposits were more minerogenic than in later periods. Increasing organic content may reflect the development of a filtering fen around the edge of the basin, indicated by rising Cyperaceae values, rather than soil stabilisation on the slopes surrounding the basin by woodland development as a sum of 78-86% tree and shrub pollen in zone TOR1a suggests that woodland communities were already established when sediment accumulation began. A basal peak in corroded (21%) and degraded (1.8%) pollen consists primarily of *Betula*. This may reflect dry conditions and more aerobic minerogenic soils during the early Holocene (Cushing 1964, Lowe 1982, Tipping 1995a).

Open, grassy *Betula-Juniperus* scrub and *Empetrum* heath appear to have formed the earliest communities recorded at Torran Beithe and form a distinctive group in the DCA plots (Fig. 18). A date of 8775 ± 80 BP (9740 cal BP) from the basal mineral-organic sediment suggests early Holocene woodland development. However, the presence of *Empetrum* and basal peaks in *Juniperus* and Poaceae may imply a compressed early post-glacial sequence, arising from slow sediment accumulation, suggesting that the basal date is too young. This could also be inferred form the apparently late expansion of *Corylus avellana*-type (at this time assumed to represent hazel rather than *Myrica gale*; Godwin 1975), from *c.*8710-8300 BP (9780-9310 cal BP) (*cf.* Birks 1989). The basal samples are thus suggested to reflect the development of early Holocene woodlands, which shaded out *Juniperus* and Poaceae. Frequencies for *Sorbus aucuparia* and *Populus tremula* are low, but since *Sorbus* pollen is poorly dispersed (Birks 1980) and *Populus* pollen is poorly preserved (Sangster and Dale 1961, Havinga 1984), these pioneer species may have been important in early Holocene woods, perhaps contributing to the decrease in *Juniperus*.

Glaciation causes nutrient enrichment through bedrock weathering and the incorporation of solutes into meltwater, increasing soil and water pH during the early Holocene (Pennington *et al.* 1972, Sutherland 1980). However, the abundance of heaths (below) suggests that soils around Torran Beithe were acidic when sediment accumulation commenced. High frequencies of *Sphagnum* spores could also infer acidic conditions, although *Sphagnum* may have grown in the sampling basin. This may reflect the outcome of the *c.*1200 ^{14}C (1400 cal) year gap between deglaciation and sediment accumulation, although if, as suggested above, the basal date is too young, glaciation may have had only a limited effect on soil nutrient status around Torran Beithe.

C. avellana-type frequencies are low, attaining a maximum of 20% at 8300 BP (9310 cal BP), followed be a decline to *c.*10%. The relatively open canopy cover, with a maximum of 68% tree pollen during zone TOR1, suggests that the flowering of *Corylus* is unlikely to have been restricted by low light conditions in the understorey (Huntley and Birks 1983), since it flowers early in the season, before the canopy is fully established. Edaphic conditions are thus suggested to have controlled the abundance of *C. avellana*-type. Competition from taxa which are more tolerant of poorer edaphic conditions, such as *Betula* and *Erica*les, may have prevented *Corylus* from becoming established in any abundance around the sampling site. The decline in *C. avellana*-type values above 8300 BP (9310 cal BP) suggests that local soils conditions became more acidic or wetter, perhaps enabling more acid-tolerant woodland and understorey taxa to replace it.

The pollen of *Empetrum* is poorly produced and dispersed (Birks 1975, Evans and Moore 1985), suggesting that frequencies of 3-6% reflect growth around the sampling site. *Empetrum* colonised open mineral soils in the early Holocene (Tipping 1989), but at present also grows in some open *Pinus* and *Betula* woods (Bell and Tallis 1973). The persistence of *Empetrum* into the period of *Betula* woodland around Torran Beithe may indicate that suitably well-drained and relatively dry mineral or acid soils were common around the basin (*cf.* Tallis 1997).

Comparison with surface sample studies (Tinsley and Smith 1974, Evans and Moore 1985), suggests that *Calluna* may have been present locally, again suggesting relatively acidic, nutrient-deficient soils. *Vaccinium*-type pollen is very poorly represented in surface samples, even where it grows in abundance (Tinsley and Smith 1974, Lloyd 1998), suggesting that *Vaccinium* and/or *Erica* may also have formed the ground cover beneath the *Betula* canopy. The low frequencies of Poaceae and herbs further suggest that the field layer consisted predominantly of *Calluna* and *Empetrum*. The most frequent herbaceous pollen taxa is

Potentilla-type, with occasional pollen from *Melampyrum*, which is very poorly dispersed (Birks 1975), and is thus likely to have been present in the heath and woodland mosaic on the lower hill slopes around Torran Beithe. Both of these pollen types include species which are favoured by acidic conditions (*cf. P. erecta* and *M. pratense*).

Frequencies for *Salix* remain consistent despite changes in dryland arboreal taxa. This may indicate that *Salix* formed separate communities, perhaps on wetter soils with ferns, *Filipendula* and Apiaceae in tall-herb vegetation. Sporadic *Viburnum opulus* may have grown on damp soils in *Salix* and tall-herb communities. Both shrub taxa are likely to be under-represented in the pollen record, since they are insect-pollinated. *Salix* scrub may have formed on the banks of the nearby Allt Dubh or around damp flushes.

5.5.2 Zone TOR1b: *Betula-Pinus sylvestris-Calluna vulgaris-Corylus avellana*-type (436-402 cm; 7890-6720 BP, 8590-7540 cal BP)

There is a transition in woodland communities around 7890 BP (8590 cal BP), at the zone TOR1a/b boundary, as frequencies of *Pinus sylvestris*, *Quercus* and *Ulmus* increase. This is reflected in the DCA results (Fig. 18). The first *Pinus* stomate, indicative of local *Pinus* growth, is recorded at 7205 ± 65 BP (7950 cal BP), with 20% *Pinus* pollen. This concurs with previous suggestions that a value of at least 20% is necessary to represent local *Pinus* growth (Bennett 1984). The contrast with more recent research (Fossitt 1994b, Lageard *et al.* 1999) is discussed in Section 5.5.5. A period of *c.*550 ^{14}C years (*c.*510 cal years) elapses between the start of the percentage rise at 7750 BP (8460 cal BP), possibly reflecting regional or extralocal population expansion, and subsequent local establishment. Earlier lower frequencies may reflect regional population or range expansion (*cf.* Bennett 1984).

The decline in *Betula* percentages appears to coincide with the start of rising *Pinus* frequencies, but this may be an artefact of percentage data calculation. Absolute (concentration and accumulation) pollen data suggest that *Betula* frequencies are reduced relative to TLP production from around 6720 BP (7540 cal BP), when absolute *Pinus* values increase rapidly. *Corylus* does not appear to have been affected after the earlier decline at 8300 BP (9310 cal BP), suggesting that this shrub may have grown in areas which were not affected by the expansion of *Pinus*. This may be a reflection of the different ecological requirements to the two species, since *Pinus* is adapted to poorer, more marginal soils (Scholes and Nowicki 1998). This may infer that *Pinus* gradually became established around the basin but was not able to out-compete *Betula*, *Sorbus* and *Populus* for *c.*480 ^{14}C (410 cal) years, before disturbance and further edaphic deterioration appear to have enabled *Pinus* to become dominant (below).

Percentage values for *Quercus* and *Ulmus* increase above the 2% threshold which is thought to represent local growth (Huntley and Birks 1983) at 8020 BP (8950 cal BP) and 7750 BP (8460 cal BP), respectively. However, there is no increase in accumulation rates until 6720 BP (7540 cal BP) for *Quercus*, and 6600 BP (7470 cal BP) for *Ulmus*. The earlier increase in percentages may thus reflect long-distance transport derived from mixed deciduous woodland which was developed more fully further south (Bennett 1989, Tipping 1994, Edwards and Whittington 1997).

The palynological and sediment stratigraphic data suggest that disturbance was an important factor controlling the local establishment and abundance of *Pinus*. This is considered to be important in view of the later decline and eventual demise of *Pinus*. Local *Pinus* establishment at 7205 BP (7950 cal BP) coincides with a 25% fall in *Betula* frequencies, increases in *Calluna* and *Empetrum*, a peak in Poaceae frequencies, a reduction in LOI (92-76%) and rising deteriorated pollen values. This suggests that local *Pinus* establishment may have occurred in response to disturbance, which may have created an opening in the canopy and bare soils needed for *Pinus* seedling establishment (Carlisle and Brown 1968). A slight increase in charcoal-to-pollen ratios coincides with the increase in *Pinus* pollen, although the impact of burning is uncertain as charcoal values are low and the frequency of larger fragments increases only slightly, suggesting a small, low intensity or distant fire (Fig. 21).

The subsequent reduction in *Pinus* frequencies over 70 ^{14}C (60 cal) years coincides with a further rise in deteriorated pollen and mineral deposition in the limnic sediment, suggesting increasing soil erosion and some reworking of pollen bearing sediment (below). Consequently, it is difficult to interpret vegetational changes during the *c.*480 ^{14}C (410 cal) year interval between local *Pinus* establishment and a rise to percentage dominance. Possible causes are discussed below.

Stratigraphic, LOI and X-ray (Table 7, Figures 14 and 23) analyses suggest a prolonged phase of erosion between 416 and 400 cm, since there is a gradual increase in inwashed sediment prior to the deposition of a layer of sand and silt at 408-403 cm, rather than sharp upper and lower boundaries which would be expected from a single event. This may be supported by the radiocarbon framework, as dates from the upper and lower boundaries are statistically distinguishable and suggest, at the 2σ level, a duration of *c.*320-800 ^{14}C (220-700 cal) years for inwashing, although the estimated dates for the main inwash band are statistically inseparable (6930-6790 BP; 7690-7580 cal BP).

The increase in total pollen concentration and in crumpled, corroded and broken pollen (Σ19-31% TLP) is consistent with the interpretation of soil erosion or the inwashing of pollen-bearing sediments into the basin, if both contemporaneous and secondary pollen are present. Residual soil pollen frequencies may be relatively high in acidic soils (Pennington 1979). This makes interpretation of the pollen data problematic. An increase in frequencies of *Betula*, *Corylus*, *Empetrum* and fern spores may indicate the reworking of older sediments, as all were more frequent during the early Holocene. *Huperzia selago*, *Empetrum*, *Rumex acetosa* and *Thalictrum* pollen may indicate that early Holocene sediments form part of a secondary pollen component. Alternatively, open rocky outcrops or heath around the basin may have enabled *Huperzia* to persist, while *R. acetosa* and *Thalictrum* pollen may reflect contemporaneous plant growth in response to the disturbance and the availability of fresh mineral nutrients, as *Thalictrum* is indicative of a higher pH. The increase in *Calluna* and *Empetrum* also may indicate the inwash of surface sediment, concentrating local soil pollen and resulting in crumpling and breakage.

An increase in palynological richness is recorded across the mineral horizon. In view of the evidence for secondary pollen incorporation, this may also be a response to the addition of reworked pollen taxa, rather than increased diversity resulting from numerous species colonising an opening in the canopy. The slight fall in rates of change may be a reflection of the increased time interval between samples across the mineral horizon (*cf.* Seppä 1998).

There is little evidence preceding the erosional phase from which to infer a causal mechanism, although this may in part reflect the relatively poor temporal resolution of the analyses (Table 9). Prolonged soil erosion suggests a relatively fragile ecosystem, in which the response may not be proportionate to the original cause(s). Nevertheless, animal disturbance is not considered a plausible explanation over the estimated timeframe. Prolonged soil instability may have been caused by climatic dryness or anthropogenic disturbance. Charcoal frequencies remain elevated across the mineral band, but this may reflect sediment reworking, as there is also evidence for secondary pollen deposition (above). Low values for the ratio of large (>75 m) to small (10-25 m) charcoal fragments may result from an increase in breakage due to reworking, or reflect distant fires. If contemporaneous, climatic dryness and/or anthropogenic causes may be inferred. Although the uncertain quantity of secondary pollen complicates ecological interpretation, there is no clear motive for deliberate anthropogenic manipulation; there is little herbaceous pollen evidence for the creation of more open, lush vegetation or grazing disturbance, which may be associated with anthropogenic vegetation manipulation. Thus it is tentatively suggested that the prolonged instability reflects the impact of drier conditions on a relatively fragile ecosystem around 7400-6540 BP (8140-7390 cal BP). Regional evidence for environmental, vegetational and climatic changes at this time is discussed in Chapter 9.

5.5.3 Zone TOR2a: *Pinus-Betula*-Cyperaceae (402-377.5 cm; 6720-6360 BP, 7540-7230 cal BP)

Zone TOR2a marks a transition in the sediment and surface vegetation of the sampling basin. Around 7300 BP (8040 cal BP), aquatic species disappear as Cyperaceae with *Sphagnum* and

Equisetum colonise the basin as the sediment changed from limnic mud to fen peat. This may reflect a fall in the water table or gradual terrestrialisation.

Pinus appears to have become established as the major canopy tree around the sampling site, rising from 12% at 6790 BP (7580 cal BP) to 46% at 6550 BP (7390 cal BP), with a decease of 30% in *Betula* over the same period. Local establishment around or on the peaty basin soils is inferred from the presence of *Pinus* stomata and bark. A shift to drier conditions may have favoured the expansion of *Pinus* by causing a reduction in the watertable. However, the preservation of *Pinus* bark may also imply wetter conditions (*cf.* Birks 1975, Bridge *et al.* 1990). Consistently higher values for broken pollen appears to reflect the increased frequencies of *Pinus*, grains which are known to break during processing and slide preparation (Cushing 1967).

Pinus appears to have out-competed *Populus* (*cf.* Steven and Carlisle 1959) and *Sorbus* may have become less abundant. In the understorey, *Dryopteris filix-mas*-type may have been replaced by *Pteridium aquilinum*, perhaps inferring increasing soil acidity.

5.5.4 Zone TOR2b: *Pinus-Betula-Calluna* (377.5-186 cm; 6360-3600 BP, 7230-3890 cal BP)

A reduction in relative and absolute Cyperaceae values may infer that *Calluna* became established on the basin surface, suggesting that the basin became drier, perhaps as sediment accumulation raised the deposits further above the watertable. This process may also be reflected in the transition from sedge peat to herbaceous peat with *Pinus* bark at *c.*6430 BP (7320 cal BP) (383 cm). However, the humification data suggest a shift to wetter conditions from 6650-6280 BP (7500-7200 cal BP), which may have led to the preservation of *Pinus* bark (*cf.* Bridge *et al.* 1990).

Although *Pinus* was the dominant pollen producer around the sampling site, a decrease in *Pinus* with concomitant peaks in *Betula*, *Salix* and *Calluna* pollen at 6340 BP (7220 cal BP), suggests that *Betula* was still present locally. Erosion and peaks in crumpled and corroded pollen suggest local disturbance. This may result from stand-scale death through autogenic processes, as *Pinus* stands are characteristically even-aged due to group regeneration patterns following disturbance (McVean 1964, McVean and Ratcliffe 1962). This may have enabled more prolific flowering or growth in *Betula* and *Calluna* as both are intolerant of shading; *Betula* and *Salix* are rapid colonisers of bare soils (Grime *et al.* 1988, Atkinson 1992). Increased pollen production is recorded over *c.*50 ^{14}C (*c.*40 cal) years, within a generation for *Betula*, and may have resulted in a peak in rates of change at this horizon.

Disturbance could have created suitably open and unstable sediments for the growth of *Ranunculus acris*-type, *Rumex acetosa*, Rosaceae and Chenopodiaceae, which may have survived within the woodland due to continued autogenic death and regeneration, and disturbance. Alternatively, or in addition, a reduction in *Pinus* may have allowed pollen from more distant communities to penetrate the canopy. Either source may have contributed to the peak in palynological richness.

The return to previous *Pinus* frequencies over *c.*170 ^{14}C (160 cal) years, suggests that within a generation, the woodland had reverted to previous cover, as longer-lived *Pinus* over-shadowed and replaced *Betula* (*cf.* Bennett 1984). This successional process and time-scale suggest an autogenic cause, rather than purposeful anthropogenic disturbance or the maintenance of an opening by grazing (*cf.* Buckland and Edwards 1984). Subsequent short-lived, less pronounced fluctuations in *Pinus*, *Betula* and *Calluna* suggest similar small-scale natural mosaic shifts around the sampling basin.

Alnus glutinosa frequencies increase from the zone TOR2a/b boundary, at 6360 BP (7230 cal BP), following slight percentage and absolute increases in the previous zone. *Alnus* is an abundant pollen producer (Andersen 1973) and values of more than 10% are thought to reflect *Alnus*-dominated vegetation within the site catchment (Huntley and Birks 1983). A maximum of 18% at 5630 BP (6410 cal BP) therefore suggests that the species was not abundant near the sampling site. A shift to wetter conditions (above) may have enabled the formation of local stands (Bennett and Birks 1990, Chambers and Elliott 1989). In the extralocal area, *Alnus* may have formed small stands on damp and unstable soils, such as the banks of Allt Dubh, the shores of Loch Coulavie, floodplain alluvium and other flushed soils, as well as peats (*cf.* McVean 1953). It is possible that the abundance of *Alnus* may have been checked by altitudinal constraints, since, at present, seed production ceases at *c.*275-305 m OD (McVean 1956a, b).

The relatively low frequencies suggest that *Alnus* may have been able to compete with *Pinus* and *Betula* only to a limited extent, although it appears to have displaced *Salix*. The difference in magnitudes between the *Alnus* and *Salix* curves may result from the higher pollen production and dispersal of anemophilous *Alnus* compared with entomophilous *Salix*. The decline in *Filipendula*, which is thought to have grown in damp tall-herb communities with *Salix* suggests that a denser canopy may also have formed, shading tall-herb communities.

Other deciduous trees may have had a limited distribution within the woodlands around Torran Beithe. Percentage and absolute values for *Ulmus* and *Quercus* also increase at 6360 BP (7230 cal BP). Frequencies are consistently near or above the 2% value considered to reflect local growth (Huntley and Birks 1983) from 6340 BP (7220 cal BP) and 6240 BP (7100 cal BP), respectively. *Ulmus* attains a maximum of 6% at 5240 BP (5970 cal BP), immediately preceding its decline, with a peak of 8% in *Quercus* at 5410 BP (6250 cal BP). The pollen record for *Fraxinus* is low, but more frequent after 5520 BP (6300 cal BP). *Fraxinus* pollen is poorly dispersed (Andersen 1973, Birks 1980), suggesting that the maximum of 0.7% may derive from sparse local or extralocal growth (Huntley and Birks 1983). The presence of *Fraxinus* would infer that the woodland canopy was open, as ash is relatively shade-intolerant.

Quercus, *Ulmus* and *Fraxinus* require richer and/or better drained soils (Grime *et al.* 1988). As local edaphic conditions are inferred to have been acidic and nutrient-poor, more suitable substrates may have existed on alluvial soils, which can be enriched by sediment deposition during flooding, such as better-drained ground beside the nearby Allt Dubh, the River Affric and Loch Coulavie. These taxa may have had a restricted local distribution or have formed part of the extralocal pollen component. Lower absolute frequencies for *Betula* and *Pinus* may reflect competition from *Alnus*, *Quercus* and, to a lesser extent, *Ulmus* on different soils within the pollen local and extralocal source area. The decline in *Ulmus* at 5240 BP (5970 cal BP) may have enabled several other tree species to fill the gaps created, as no one tree or shrub appears to respond.

Betula and *Corylus* percentages show little long-term variation, remaining at around 20% and 10%, respectively. The status of *Corylus* is unclear; it may have been able to maintain a subsidiary role on more nutrient-rich soils such as alluvium, where *Pinus* was out-competed. Widespread, although perhaps scattered, *Betula* populations may account for the small size of percentage fluctuations and low absolute values. Pollen derived from a larger source area will tend to display smoother curves which represent the sum of a more regional pollen signal, thus dampening any localised smaller-scale population changes. In contrast, the more abrupt changes in pollen spectra for *Pinus*, *Calluna* and Cyperaceae suggest variations in local communities.

The longevity of the *Pinus-Calluna* mosaic, and minor role of more nutrient-demanding arboreal or herbaceous taxa has several implications for pedogenesis and soil fertility. In the local source area, the relatively low abundance of taxa requiring richer soils suggests that soil nutrient status may always have been low, as could perhaps be expected from the underlying nutrient-poor Moinian schists (Section 2.1.2). This may have allowed *Pinus* to compete successfully, as its association with nutrient-poor soils is well-documented (*e.g.* Miles 1985, Keeley and Zedler 1988, Scholes and Nowicki 1998). In addition, *Pinus* has a podsolizing effect on soils and causes changes in nutrient cycling as increased surface pH reduces rates of litter decomposition, reinforcing the podsolization process (Miles 1985, Scholes and Nowicki 1998). Pronounced podsolization can appear within 200 years (Miles 1985). Similarly, *Calluna* is a strong acidifier and can result in soil changes within a decade (Miles 1985). *Sphagnum* growth is favoured by low pH values, and in turn promotes further acidification, decreases microfaunal and microbial activity and thus reduces nutrient cycling (Moore 1988, 1993).

The vegetation around Torran Beithe may thus have caused gradual retrogressive pedogenesis. This has implications for competition interactions and the ability of less acid-tolerant arboreal and herbaceous species to invade the woodland once established. Over the long-term, soil retrogression may have helped to perpetuate the *Pinus-Calluna* mosaic and may have conferred stability, inferred from the low rates of change, although the gradual increase in basin size and thus in source area through time will have dampened the pollen record's sensitivity to change.

Within the woodland, long-term population shifts may be evident. There are troughs in *Pinus* frequencies from 5570-4960 BP (6360-5690 cal BP) and 4620-4390 BP (5310-4930 cal BP), when *Calluna* values are higher. Maximum mid-Holocene *Pinus* values occur between 4390 and 3765 BP (4930-4110 cal BP), with a peak of 35%. Long-term shifts are also recorded in other trees; higher *Quercus* frequencies are recorded from 6240-5960 BP (7100-6840 cal BP), 5520-4960 BP (6300-5690 cal BP) and 4280-3540 BP (4840-3830 cal BP), and there are slight variations in *Alnus* frequencies, with higher values around 4620-4330 BP (5310-4860 cal BP) and from 3710-3320 BP (4030-3510 cal BP). There is no evidence for human or grazing interference. The different ecological niches occupied by *Pinus*, *Calluna*, *Quercus* and *Alnus* may indicate long-term climatic variations which shifted the balance of competitions interactions, hence the concentration of sample scores between these taxa in the DCA data. The humification curve suggests that the period between 5430 and 5030 BP (3660-5840 cal BP) was one of relative local dryness, which could have favoured *Quercus* over *Pinus*. This is considered important in relation to vegetation changes around 3765 BP (4110 cal BP). The evidence from Affric for controls on long-term vegetation composition and dynamics is discussed in Chapter 9.

There is abundant ecological data relating to the importance of fire in pinewood and heathland ecosystems (*e.g.* Hobbs and Gimingham 1987, Agee 1998). However, charcoal frequencies at Torran Beithe remain low for much of zone TOR2b, when *Pinus* and *Calluna* are abundant. Charcoal peaks at 5240 BP and 5070 BP (5970 and 5820 cal BP) do not coincide with changes in *Pinus* or *Calluna* curves and there are no changes in stratigraphy which may indicate local soil disturbance. Although *Pinus* frequencies during this period are low, at *c.*13-21%, stomata are recorded. There is thus no evidence that fires affected the local dynamics of *Pinus* and *Calluna*, although these are the only charcoal peaks where large fragments (>75 μm) are much more abundant than the smallest size particles (10-25 μm) (Fig. 21).

The map of bedrock contours for the sampling basin indicates that midway through zone TOR2b, at around 300 cm (*c.*5300 BP, 6090 cal BP), the diameter of the sampling site appears to have increased more rapidly (Fig. 12). Assuming peat growth to be simple and depth-controlled, local peat formation may have spread from the confines of the hollow onto the flatter slopes surrounding the basin. The increase in basin diameter will have increased the pollen catchment area of the sampling site (*cf.* Jacobson and Bradshaw 1981). However, this point is not marked by any obvious changes in pollen spectra, in percentage or absolute data, or large shifts in the DCA plot, suggesting that the earlier record of a mosaic of relatively open *Pinus* woodland, *Calluna*, some *Betula* and mire, is representative of the larger area.

Potentilla-type, *Sphagnum*, *Calluna* and Cyperaceae appear to have formed the vegetation cover on the spreading basin peat, perhaps with *Narthecium ossifragum* and *Drosera* species. However, these four pollen types are also associated with blanket peat (Fossitt 1994b) and a peat basin is thus not an ideal site from which to infer more widespread peat expansion at this time. In addition, *Potentilla*-type includes several species, which cover a wide ecological range, from grassland, heath and bog to mountains, suggesting that this pollen type should not be regarded solely as an indicator of blanket peat (*cf.* Fossitt 1994b). Nevertheless, the presence of numerous other bog taxa suggests that mire communities had by now begun to form a natural part of the open pinewood mosaic. These taxa may also infer that damp *Calluna* heath communities formed the understorey of the woodland, as there are few herbs of dry heath, with only a single grain of *Rumex acetosella*, and sporadic *Pteridium aquilinum* spores. Consistent *Empetrum* pollen, with *Vaccinium*-type and *Erica*, suggest a range of heath, bog and understorey communities with *Potentilla*-type.

There is limited evidence for grassland development near Torran Beithe. This may be in part the result of filtering and high pollen production by trees and *Calluna* (O'Sullivan 1973a, Tinsley and Smith 1974). Little of the Poaceae pollen recorded appears to be derived from heathland taxa such as *Molinia caerulea* or *Deschampsia flexuosa* as the low Poaceae curve shows no correlation with fluctuations in *Calluna* or Cyperaceae. Pollen from herbs associated with dry grassland, particularly where there is disturbance, occurs sporadically. Soil conditions around the sampling site appear to have been acidic, unsuitable for the establishment of herbs such as *P. lanceolata* or *Artemisia*-type, which may therefore be derived from less acid pockets, such as flushes or streams. It is possible that these herbs may have been sustained by natural disturbance on such alluvial soils, or as a result of the activity of wild herbivores. Grassland communities are discussed is more detail in Chapters 6-9 as the results from Carnach Mór and Camban are important for establishing the composition and spatial distribution of grassland communities and of disturbance mechanisms.

At around 4390 BP (4930 cal BP) there appears to have been a change in dwarf shrub composition, with a shift from *Empetrum* to *Vaccinium* and *Erica*. The difficulty of identifying the pollen to genus or species level, poor pollen production and dispersal (Tinsley and Smith 1974, Evans and Moore 1985, Lloyd 1998) and over-lapping ecological ranges of *Vaccinium*, *Erica* and *Empetrum* pose problems for securely establishing the ecological conditions and abundance of these taxa. In addition, these three genera co-occur in many heath and bog communities. The transition from *Empetrum* to *Vaccinium*-type pollen does, however coincide with the start of increased charcoal representation. *Empetrum* is sensitive to severe fires (Bell and Tallis 1973), while *Vaccinium* and *Erica* sprout following fire (Ritchie 1955, 1956, Bannister 1965, 1966). Although charcoal frequencies are low, the change in species composition may indicate a response to burning.

Numerous vegetational changes occur after 3765 BP (4110 cal BP), particularly during the period until *c.*3000 BP (3190 cal BP), and these have strong environmental and ecological implications. The changes are summarised in Figure 24 and are analysed first in terms of changes in vegetation composition and ecological relationships, and then in relation to the possible mechanisms of change, where the importance of the charcoal data are assessed. The vegetation changes are discussed chronologically, examining the arboreal changes in zone TOR2b which precede shifts in herbaceous vegetation in zone TOR3a.

An abrupt fall in *Pinus* percentages is recorded from 3765 ± 45 BP (4110 cal BP) (192 cm). As *Pinus* percentages fall, temporary increases are recorded in *Quercus*, *Alnus*, *Corylus avellana*-type and *Betula* between approximately 3765 and 3600 BP (4110-3890 cal BP), with higher *Alnus* frequencies until 3320 BP (3510 cal BP). *Pinus* frequencies fall from 37-18% over a single sampling interval, an estimated period of 56 ^{14}C years (68 cal years) (192-190 cm), during which other arboreal taxa increase. A marked decline is also recorded in *Pinus* concentrations and accumulation rates, commencing at 3990 BP (4420 cal BP). The normal lifespan of indigenous *Pinus* in Scotland appears to be somewhere below 200 years (Carlisle and Brown 1968), although on bog surfaces, *Pinus* may have had difficulties surviving to ages of more than 125 years (Bridge *et al.* 1990). This suggests a very rapid decline in pollen production, which may reflect the death of *Pinus* trees, or vegetative survival, with greatly reduced pollen and seed production in order to cope with stressful conditions (*cf.* Sarvas 1962, cited in Ledig 1998). This may also indicate that the *Pinus* ecosystem was relatively fragile.

Before these data can be interpreted in terms of vegetation composition and dynamics, or causal factors inferred, the sources of the different components of the pollen assemblage must first be considered. It appears that arboreal taxa were able to take advantage of a reduction in *Pinus* in the woodland around Torran Beithe. Two opposing hypotheses can be proposed to account for this pattern: (1) that the arboreal pollen signal derives from an extralocal or regional source, in response to a reduction in *Pinus* pollen production and canopy cover, or (2) that the increase in tree pollen reflects the real expansion of other woodland taxa as *Pinus* populations declined and niches became available.

The data are argued to support the second hypothesis, that of a real shift in woodland composition. Local understorey taxa, such as *Calluna* and Cyperaceae, do not respond to the large reduction in pollen production by the dominant canopy tree around Torran Beithe. This may infer that the shading *Pinus* canopy remained, simply producing less pollen and thus providing no light stimulus to increase flowering in the understorey. However, the relative and absolute expansion of several AP taxa suggests that trees which had previously been minor woodland components rapidly replaced *Pinus* as the sum of tree and shrub pollen remains at 73% in the level immediately following the *Pinus* decline (3710 BP, 4030 cal BP), before declining to 57% at 3650 BP (3950 cal BP).

The rapid change in woodland composition around 3765 BP (4110 cal BP) contrasts with the preceding period of approximately 2760 ^{14}C (*c.*3340 cal) years during which *Pinus* was the dominant tree in a *Pinus-Calluna* mosaic. Although there were long-term fluctuations in the relative abundance of these dominant species, *Pinus* was able to maintain its position in the canopy, while *Quercus* and *Alnus* were minor taxa. Subsequent changes therefore suggest a change in competition relationships between these taxa. The rapidity of the AP response around 3770 BP (4110 BP), over 60 ^{14}C (70 cal) years infers that these species were present in the local woodland. This can also be inferred from the ecology of both genera; the dominance of acidophilous *Calluna* in the understorey suggests base-poor and infertile soils around Torran Beithe, but *Quercus* is able to persist in relatively infertile soils and *Alnus* can tolerate some acidity (Grime *et al.* 1988).

Quercus frequencies increase from *c.*4280 BP (4840 cal BP), suggesting that it was able to expand its niche within the woodland, and a change in the balance of woodland composition around 3765 BP (4110 cal BP) suggests an abrupt change in growing conditions, which enabled other trees to compete more effectively with *Pinus* on a range of soils (see Section 5.5.5). Increased palynological richness may reflect an increase in the mosaic structure of the vegetation at this time (*cf.* Seppä 1998). The canopy position of *Pinus* may have been taken over by *Quercus* (increasing to 9%), which shows the largest absolute rise, and, to a lesser extent, by *Alnus* (at 10-14%) and perhaps *Betula* (rising from 17-24%) and *C. avellana*-type (increasing from 6-12%). At this time, there is no evidence that *Corylus* pollen is derived from *Myrica gale* (Fig. 14). *Quercus* may have out-competed *Pinus* and possibly *Betula* on drier acidic soils, perhaps on better-drained hillslopes, and/or on damp, more base- and nutrient-rich alluvial soils (Jones 1959, Grime *et al.* 1988), and was possibly doing so from *c.*4280 BP (4840 cal BP). *Quercus* may have been able to respond rapidly to increased light or space arising from the death of *Pinus*, by producing epicormic shoots (Jones 1959). Increased waterlogging, particularly on flushed soils, may have enabled *Alnus* to compete more effectively with *Pinus* and *Betula* on damp soils (*cf.* Bennett 1984), perhaps in gaps created by the death of *Pinus*, as *Alnus* is very sensitive to shading (McVean 1953). *Alnus* may also have replaced *Pinus* on moister river banks and wet alluvial soils (Steven and Carlisle 1959).

The very slight response in *Betula* is notable in view of its wide climatic and edaphic tolerance, and competitive ability on poorer soils (Atkinson 1992), which, from the abundance of *Pinus*, *Calluna* and *Sphagnum*, are inferred to have occurred around Torran Beithe. *Betula* establishment is most effective on bare soils and is poor in even the lowest vegetation (Atkinson *op. cit.*). However, an increase in the diversity of herbs at this time, discussed below, suggests that some open areas or woodland-edge niches were present. *Betula* establishment may have been prevented by a dense *Calluna* field layer in which few *Betula* seedlings survive (Atkinson 1992), although *Calluna* pollen frequencies decline as *Pinus* frequencies fall. The environmental changes which affected *Pinus* are thus suggested to have had a similar, although less marked impact on *Betula*, which may also have been in competition from *Quercus* and *Alnus*. The internal evidence for mechanisms of change are discussed below.

An increased diversity of herbs prior to and during the main *Pinus* decline, and a small increase in Poaceae suggests the occurrence of new niches in woodland edge habitats or in limited areas of open ground on a variety of soil types. The peak in *Potentilla*-type as *Pinus* frequencies fall may result from increased light beneath the canopy. Herbs of woodland edges, open ground or disturbance include *Ranunculus acris*-type, *Rumex acetosa*, *Hypericum perforatum*-type and several Lamiaceae pollen types. Pollen of *Plantago lanceolata*, *Achillea*-type and the recurrence of *Filipendula* suggest that both dry and damper soils were present within the pollen catchment. Increased *Pteridium* representation between 3940 and 2760 BP (4410-2850 cal BP), with a peak at *c.*3710 BP (4030 cal BP) may also be indicative of more open woodland on well-drained areas, although the extent and location of more open areas are unclear from the data due to the low frequencies. Herbaceous pollen changed during this period of woodland transition are quantitatively small, but they may be ecologically significant in determining the cause of vegetation change around 3770 BP (4110 cal BP), as discussed below.

5.5.5 Zone TOR3a: *Calluna*-Cyperaceae (186-82 cm; 3600-1290 BP, 3890-1200 cal BP)

Although marked changes in woodland composition are recorded near the end of zone TOR2b, NAP changes are limited. This contrasts with the evidence from *c.*3600 BP (3890 cal BP), where the NAP evidence suggests the spread of blanket peat (*cf.* Fossitt 1994b), associated with woodland reduction. An increase in Cyperaceae pollen at 3600 BP (3890 cal BP) coincides with a further, but more gradual, decline in *Pinus* percentages. *Quercus* frequencies fall and there is a step-wise reduction in *Alnus* and *Corylus avellana*-type. From 3430 BP (3660 cal BP) *Calluna* frequencies increase to become the dominant pollen producer by 3200 BP (3390 cal BP). *Sphagnum* spores show sustained abundance and *Potentilla*-type values are continuous. The DCA also reflects the magnitude of these changes, as the sample scores shift towards the origin, where acidophilous taxa are concentrated (Fig. 18).

Increasing peat depth or area will have sealed off mineral or shallow peaty soils around the basin. Blanket peat expansion does not appear to have been the initial cause of reduced *Pinus* representation, and would not have favoured *Quercus* or *C. avellana*-type expansion, but the increase in peat depth will have had severe implications for continued tree regeneration around the basin. The lag between the reduction in AP and mire expansion may imply that tree growth, especially that of *Pinus*, was sensitive to changes in water levels, while peat expansion required more prolonged waterlogging or higher watertables to trigger formation (*cf.* Moore 1988, 1993; below). *Pinus*, however, persisted near the basin, as indicated by a later increase in pollen frequencies with stomata.

Ecologically, the data thus suggest a two-fold process in the loss of *Pinus* woodland, first a reduction in *Pinus* and a short-lived arboreal expansion, inferring a change in competition relationships, followed by blanket peat expansion and more widespread woodland reduction. Only the internal evidence for mechanisms of change are considered in this chapter; wider spatial- and temporal-scale patterns and inferred causal mechanisms are discussed in Chapter 9.

Moore (1988, 1993) proposed a model of factors leading to peat accumulation following the removal of trees. This demonstrates pathways by which numerous interacting factors which can result in blanket peat growth. However, woodland decline at Torran Beithe is also complex. The data from Torran Beithe allow five possible processes which lead to woodland decline and peat expansion, as discussed by Moore (1988), to be investigated, although none are mutually exclusive:

1. Humification data may provide some evidence for climate change.
2. The ecological requirements and affinities of the taxa concerned may allow inferences to be made regarding possible changes in edaphic conditions.
3. The charcoal record allows the role of burning to be investigated.
4. The palynological data enable questions of anthropogenic impact to be considered.
5. Grazing can also be examined through the pollen record.

Evidence for a species-specific mechanism, such as disease, which may account for the marked reduction specific to *Pinus* (Bennett 1995), cannot be directly investigated from this pollen data, but may be proposed in coincidence with other causal mechanisms which may have damaged or lowered the competitive ability of *Pinus*, as has been suggested for the *Ulmus* decline (Peglar 1993).

Factors affecting the interpretation of the humification record in terms of wetness have been discussed above in Section 5.3.7, and are important caveats here. There is no sustained shift in the humification curve at this time which may infer local or climatic shifts to wetter or drier conditions. Woodland loss is thought to increase run-off and raise water tables (Moore 1988, 1993), but this is dependent on woodland density, which around Torran Beithe did not perhaps form a closed canopy. Nevertheless, the humification data do not provide evidence for increased wetness which could have effected a decline in *Pinus* or blanket peat expansion.

There is a danger of circularity in arguments concerning soil change from pollen data as edaphic conditions are inferred from palynological changes. It is possible that natural retrogressive pedogenesis caused by long-term *Pinus* and *Calluna* dominance could have crossed a tolerance threshold for *Pinus*, after which the community could no longer survive. Increased runoff and water input to basin mires as woodland failed to regenerate may have led to paludification and enabled basin peats such as Torran Beithe to spread, thus further reducing regeneration (*cf.* Moore 1993). However, the palynological evidence for mire expansion only occurs after the *Pinus* decline, suggesting that peat expansion was not the immediate cause of *Pinus* reduction. Similarly, a rise in water-tables would also not account for the expansion in *Quercus* or *C. avellana*-type, which do not persist in waterlogged soils.

A shift to more frequent and/or intense burning at *c.*3880 BP (4340 cal BP), following a smaller charcoal peak at 4280 BP (4840 cal BP), precedes the decline in *Pinus* frequencies (see Table 12). Increased charcoal representation is therefore not the result of a reduction in *Pinus* canopy, which was never completely closed. The main reduction in *Pinus* coincides with rising charcoal-to-pollen ratios, but charcoal values do not peak until 3540 BP (3830 cal BP). The temporal resolution of the diagram at this time is *c.*60 ^{14}C (70 cal) years between samples immediately above the *Pinus* decline horizon, and each pollen subsample covers 10 ^{14}C (20 cal) years. At this resolution, charcoal values appear to increase over *c.*220 ^{14}C (260 cal) years, in contrast to the much more rapid reduction in *Pinus* and increases in *Quercus*, *Alnus* and *C. avellana*-type.

Burning does not appear to have caused the initial decline in *Pinus*, but it may have aided the expansion of *Alnus* and blanket peat, and could also have been responsible for a further reduction in *Pinus* populations. Increasing charcoal frequencies coincide with the expansion of *Alnus*, which has been suggested to respond to fire disturbance (McVean 1956b, Smith 1970). It is possible that fires may have caused sufficient disturbance to enable a short-lived *Alnus* expansion (Smith 1984a), which was perhaps limited in the longer-term by climatic stress (*cf.* McVean 1955).

The initial increase in Cyperaceae pollen and further decline in *Pinus* at 3600 BP (3890 cal BP) coincides with a peak in charcoal frequencies. Burning has been associated with peat initiation, by impeding drainage and resulting in waterlogging and peat formation (Mallik *et al.* 1984, Moore 1988, 1993). It is thus possible that fire may have contributed directly or indirectly to further loss of *Pinus* through peat expansion. The evidence for increased burning through climatic change and anthropogenic activity is discussed below. The increase in crumpled pollen is due predominantly to the expansion of balloon-like Cyperaceae grains, and is not considered to reflect sedimentary disturbance or pollen redeposition (*cf.* Lowe 1982).

The pollen data provide little unambiguous evidence for local anthropogenic vegetation manipulation or of grazing pressures. The complexity of woodland transition and decline does not suggest a response to felling and the pollen record for dryland herbs favoured by disturbance or grazing is sporadic. The environment around Torran Beithe appears to have been damp, acidic and nutrient-deficient, and may thus have had low agricultural potential. However, this may also pose a problem for the detection of anthropogenic or grazing activity through conventional interpretation using 'agricultural indicator' herbs (Behre 1981) as few niches for such herbs may have been present in woodland with a field layer of heath and mire. Furthermore, it is difficult to distinguish grazed heathland in the pollen record as the response of *Calluna* is very strongly dependent on its age, the species composition of the heathland and the intensity of grazing (Grant *et al.* 1985, Miles 1988). The charcoal data may thus provide the clearest evidence for anthropogenic activity, as a sustained rise in burning at a time when vegetational changes suggest increasing climatic wetness, may reflect human-set fires, independent of climatic change, although this is one of several possible explanations, discussed below.

Plantago lanceolata pollen becomes more frequent only after the reduction in *Pinus* frequencies and cessation of the stomatal curve at 2540 BP (2720 cal BP), thus providing no evidence for grazing contemporary with the *Pinus* decline at Torran Beithe. However, under conditions of environmental stress, woodland regeneration may have been sensitive even to limited grazing, by wild or domesticated herbivores, which is not evident in the pollen record through conventional interpretational techniques. Similarly, limited anthropogenic vegetation disturbance, such as burning, may have triggered blanket peat expansion (Moore 1988, 1993).

The palynological, charcoal and humification data thus suggest apparently conflicting environmental changes: increased burning suggests a drier climate, seasonally dry conditions, increased storminess with more lightning, anthropogenic activity, or a shift to more flammable vegetation, while the expansion of blanket peat and failure of arboreal regeneration suggest wetter conditions, due to woodland loss, natural retrogressive pedogenesis, climatic change or anthropogenic interference.

Increased seasonality or short-term fluctuations, particularly in wetness, appear necessary to account for the selective reduction in *Pinus*, short-lived arboreal expansion and subsequent decline, before blanket peat expansion. The root system in *Pinus* is frequently shallow and plate-like (Carlisle and Brown 1968), which may have made trees vulnerable to both rising and falling water-tables. *Quercus* does not persist in strongly waterlogged soils and appears to be relatively intolerant of flooding (Longman and Coutts 1974, Grime *et al.* 1988), but may have been favoured by short-lived, perhaps seasonal, waterlogging (Jones 1959). *Alnus* is able to grow in habitats with a fluctuating water-table (McVean 1953). Drier, flushed steam edges could have supported *C. avellana*-type, in increased numbers or through higher pollen production or dispersal under a lighter canopy. At present, *Quercus* replaces *Betula* under more continental conditions in the Highlands (Atkinson 1992), which may have limited *Betula* expansion.

Pinus and *Calluna* are both fire-responsive taxa (Hobbs and Gimingham 1987, Agee 1998). Increased continentality or storminess may account for increased burning, while earlier more oceanic conditions may have been too wet to allow frequent fires, although this does not rule out the possibility that sustained increases in charcoal result from human-set fires. Although increased charcoal representation predates the rise in flammable *Calluna*, which only expanded around 3430 BP (3660 cal BP), an increase in the proportion of *Calluna* on blanket peats, may have contributed to continued burning. The causes of burning are discussed further in Chapter 9, where temporal and spatial patterns of charcoal representation within the uplands is examined.

Increased wetness, perhaps aided by natural or human-set fires, may have led to subsequent peat expansion. Fluctuating water tables associated with climatic change may have resulted in a lag in peat expansion by slowing many of the retrogressive soil changes associated with waterlogging, such as the reduction in microbial activity and acidification promoted by *Sphagnum* growth (see Moore 1988, 1993). Once blanket peat expansion commenced, the system may have been self-perpetuating (Moore 1993) and the step-wise reduction in arboreal taxa after *c.*3320 BP (3510 cal BP) may represent the point at which thresholds for continued arboreal regeneration were crossed.

In summary, climatic change, particularly increased wetness, initially with seasonal fluctuations in wetness, are seen as the most likely cause of woodland change, blanket peat expansion and continued woodland decline at Torran Beithe. Differences between species-specific tolerance thresholds and time-lags between the processes leading to peat expansion could have resulted in a protracted period of change (Moore 1988, 1993). Under climatic stress, limited herbivory or anthropogenic pressures may have been sufficient to prevent tree regeneration and aid the spread of blanket peat, although the extent of this activity, if any, is uncertain.

Following this period of major vegetation change, palynological richness and rates of change decline. This may suggest a more uniform, stable landscape, with a less variable mosaic structure.

Despite the rapid decline in *Pinus* frequencies, there is evidence for continued local growth as pollen values increase from 8% to between 17 and 23%, and stomata are present between 2980 and 2540 BP (3200-2720 cal BP). A fall in *Betula* frequencies may indicate competition from *Pinus*, perhaps due to the limited availability of soils free from deep peat. High values for *Calluna*, Cyperaceae and *Sphagnum*, and the occurrence of *Narthecium* pollen suggests that *Pinus* growth around Torran Beithe was occurring either on or within blanket peat communities, perhaps as scattered stands or individuals on the rocky slopes around the sampling basin or shallower blanket peat. The dwindling *Pinus* frequencies as blanket peat taxa increase suggest that *Pinus* was gradually ousted from the local environs, possibly regenerating or surviving when and where conditions allowed. This may also be inferred from the DCA data as sample scores alternate between acidophilous taxa near the origin and positions with a higher score on Axis 2, where the taxon scores for *Pinus* and other AP taxa are located. The presence of *Pinus* stomata with low pollen frequencies illustrates the value of *Pinus* stomatal records (*cf.* Dunwiddie 1987) since these percentages centre on the 20% value which has been used as a threshold for inferring local growth (Bennett 1984).

A reduction in *Pinus*, *Betula*, *Alnus* and *Corylus avellana*-type pollen frequencies from 2030 BP (1970 cal BP) (124 cm) coincide with increased Cyperaceae, *Calluna* and then Poaceae, with a small peak in *Potentilla*-type. A peak in concentration and accumulation rate curves for all taxa may indicate a change in accumulation rate not detected from the time-depth curve, rather than a pulse in pollen production caused by disturbance (*cf.* Aaby 1988). The percentage curves suggest that blanket peat expansion or increasing peat depth gradually reduced the areas suitable for tree regeneration. This does not appear to have been a steady process, but may have occurred in pulses, as thresholds for tree regeneration were crossed in different areas around the sampling basin, due to possibly subtle or small-scale variations in local environmental gradients.

Pinus stomata with a blackened or charred appearance are recorded around 2030 BP (1970 cal BP) and at 1750-1600 BP (1660-1510 cal BP), with pollen frequencies of 5-15%. These do not coincide with peaks in charcoal. Blackened and normal stomata occur together during the early Holocene, at 6440 BP (7330 cal BP) (384 cm), again with no increase in charcoal. This suggests that the blackened stomata may be reworked by inwashing or erosion from surrounding peat deposits (*cf.* Fossitt 1994b), for which there is no sedimentological evidence, or that the darkened appearance is not the result of charring. Mineral erosion or inwashing may have been prevented by blanket peat cover overlying mineral sediment, but there is no increase in crumpled or corroded pollen which could suggest redeposited grains or pollen that had been exposed to aerobic deterioration following peat combustion. In the absence of comparable material this identification remains tentative.

There is a large ecological literature on the effects of burning on *Calluna* heath (Hobbs and Gimingham 1987). Although both charcoal and *Calluna* frequencies increase during the mid-Holocene, there is little correspondence between the two curves at Torran Beithe; this applies to large and smaller charcoal particles, which are closely correlated, as discussed in Section 5.3.6. In this zone, only two peaks in charcoal and charcoal-to-pollen ratios coincide with increases in *Calluna* pollen, at 2980 BP (3200 cal BP) and 2170 BP (2140 cal BP). This suggests that, over a long timescale, burning did not maintain *Calluna* heath at Torran Beithe. It is possible that the blanket peat was too wet to burn, except perhaps in very dry periods when the upper peat layers remained above the ground water table long enough to become dry. The humification record does not suggest significantly drier periods during this zone, however the temporal resolution of the analyses may be too coarse to detect short-term shifts to drier conditions.

There is little evidence for the cause(s) of burning. From *c.*3100 BP (3280 cal BP), levels of 'background' charcoal between peaks are higher, which may infer that burning was more frequent, with perhaps small-scale or low intensity fires. The wide dispersal distance for charcoal particles (*cf.* Clark 1988), particularly in an open landscape, may account for the lack of local pollen evidence for the effects or cause of fires. Landscape-scale charcoal patterns and inferred causal mechanisms are discussed in Chapter 9.

From *c.*2760 BP (2850 cal BP) the Poaceae curve begins a gradual rise. Grassland taxa recorded include species which are often associated with pasture and disturbance, such as *Plantago lanceolata*, *Artemisia*-type and *Rumex acetosa*, as well as herbs which also occur in damp grassland, such as *Filipendula*. The curve for P. *lanceolata* becomes nearly continuous from *c.*2320 BP (2340 cal BP), suggesting the establishment or expansion of pasture (Behre 1981, Gaillard *et al.* 1992).

However, the structure, extent and dynamics of grassland communities is uncertain due to the low frequencies and sporadic occurrence of grassland herbs and high frequencies of blanket peat taxa. The low frequencies of Poaceae and herb pollen may derive from extralocal vegetation, such as alluvial sediment on the valley floor, or around Loch Coulavie. The herb pollen types represented (*Plantago lanceolata*, *Rumex acetosa*, *Ranunculus acris*-type) are those with well-dispersed pollen (*cf.* Randall *et al.* 1986); taxa with poorly dispersed pollen may thus be absent from the pollen record, thus presenting a partial reflection of grassland communities and possible associated human activity, particularly grazing.

At 2320 BP (2340 cal BP) pollen of *Myrica gale* becomes more frequent. *Myrica* pollen is poorly dispersed (Birks cited in Kerslake 1982, Lloyd 1998), suggesting that the pollen record reflects a local source. *Myrica* occurs on wet mire or blanket bog with some water movement and nutrient-enrichment (McVean and Ratcliffe 1962). The rising humification curve suggests a more marked trend towards wetter conditions only from *c.*1980 BP (1910 cal BP). This coincides with an increase to higher Cyperaceae frequencies, which may indicate wetter blanket peat conditions. A subsequent increase in *Calluna* from 1460-1320 BP (1930-1270 cal BP) may result from a shift to drier conditions, which enabled *Calluna* to expand at the expense of Cyperaceae, although in this instance there is no corroborative evidence from the humification curve.

5.5.6 Zone TOR3b: *Calluna*-Cyperaceae-*Sphagnum* (82-28 cm; 1290-190 BP, 1200-150 cal BP)

A final, single *Pinus* stomate recorded at 410 BP (490 cal BP) may indicate peat erosion or local *Pinus* growth. Erosion is not suggested by pollen preservation data, as there is no increase in damaged pollen, and there is no increase in total pollen concentrations which could suggest erosional pollen deposition. The presence of low *Pinus* pollen frequencies (13%) does not rule out the growth of a few or single tree adjacent to the site, where better drainage or thinner peat cover may have enabled establishment.

The transition to zone TOR3b coincides with a return to Cyperaceae-dominated blanket peat, possibly on the basin surface, as the pollen-stratigraphic change coincides with a reduction in lignified, possibly Ericaceous, roots (Table 7). The DCA sample scores are more strongly associated with acidophilous taxa near the origin.

The reduction in *Calluna*, from 47% to 27% between 1320-1250 BP (1270-1170 cal BP), may reflect a return to wetter conditions, which could have caused *Sphagnum* sporulation. The fall in *Calluna* frequencies also coincides with a large charcoal peak at 1250 BP (1170 cal BP). There is no stratigraphic evidence for a local fire in the form of mineral deposition, but this could indicate extensive, deep blanket peat cover which prevented fires from exposing underlying mineral soils, as suggested above. Pollen preservation data do not suggest sediment disturbance and reworking.

Two further associations between *Calluna*, Cyperaceae and charcoal occur in zones TOR3b and TOR3a, suggesting a possible ecological interpretation. A peak in charcoal-to-pollen ratios at 410 BP (490 cal BP) coincides with the rapid transition from *Calluna*→Cyperaceae→*Calluna* in samples either side of the charcoal peak, from *c.*550-380 BP (540-470 cal BP). At *c.*180 BP (150 cal BP), very high charcoal values coincide with a permanent reduction in *Calluna*, with increased Poaceae and Cyperaceae. Peaks in corroded pollen at *c.*290 BP (310 cal BP) and *c.*230 BP (290 cal BP) (40 and 32 cm) may result from drier, aerobic conditions but these do not coincide with charcoal peaks and thus appear not to indicate drier surface conditions which could have lead to burning, or surface dryness arising from peat combustion.

Under many conditions, *Calluna* is known to respond positively to burning (Hobbs and Giminghan 1987), as it appears to do at *c.*410 BP (490 cal BP). However, the charcoal peak at 1250 BP (1170 cal BP) coincides with a reduction in *Calluna* and increased Cyperaceae, while at 180 BP (150 cal BP) (zone TOR3b), *Calluna* is replaced permanently by Cyperaceae, Poaceae and *Potentilla*-type. The apparent difference in vegetation response may then reflect different consequences of burning; on wet heath frequent burning (*c.*10 years) can shift the balance from *Calluna* to *Eriophorum* or *Molinia* dominance (Hobbs 1984, Hobbs and Gimingham 1987), and on mineral soils very frequent burning (*c.*3-6 years) or intense fires can shift dominance from *Calluna* to Poaceae (Miles 1988). At Torran Beithe the temporal resolution of the pollen analyses are thus insufficient to record fires with a return interval of less than *c.*30 ^{14}C (*c.*40 cal) years (Table 9), but the abundance of charcoal during this period could reflect frequent or intense burning, perhaps sufficient to result in the inferred changes in vegetation composition.

There is increased palynological evidence for agriculture in zones TOR3a-b, which suggests that the fire regime was controlled or modified by humans. *Plantago lanceolata* pollen is consistently present at low frequencies, with higher values from 550-350 BP (540-470 cal BP, cal AD 1410-1490) and 260-90 BP (300-50 cal BP, cal AD *c.*1650-1920). Several other taxa of pastoral or disturbed grassland and nutrient-enrichment occur, including *Rumex acetosa*, *R. acetosella*, *Cichorium intybus*-type, *Solidago virgaurea*-type, *Artemisia*-type, *Urtica*, Chenopodiaceae and Caryophyllaceae. *R. acetosella* may indicate the presence of dry heath. A single *Hordeum* group pollen grain is recorded at *c.*410 BP (490 cal BP), which, in the absence of other aquatic or wetland taxa, is suggested to derive from *Hordeum*, rather than *Glyceria*. It is possible that *Calluna* communities were burnt to encourage more nutritious, fresh growth for grazing animals, perhaps on the slightly better-drained slopes with shallower peat cover.

The edaphic requirements of the herb taxa suggest that pastoral grassland and cultivation may have occurred on the floodplain, rather than around Torran Beithe. As a result of the open landscape, the source area of the sampling basin at this time is likely to have been wider than the estimated 100-300 m radius (*cf.* Sugita 1994), and may thus include agricultural activity on the valley floor and around Loch Coulavie, *c.*350-450 m away. Although the extent and species composition of grassland is unclear from this pollen site, the burning of heath and mire may have implications for interpretation of the size of human and stock populations, and the extent or quality of the pasture required to support them.

The first cereal-type grain is recorded at 410 BP, which at 2 sigma calibrates to AD 1430-1630, with a mid-point of cal AD 1460. This suggests that cultivation was occurring just before or during a period of climatic deterioration known as the Little Ice Age, which is thought to have reached a zenith between the mid-sixteenth and mid-nineteenth centuries (Grove 1988).

However, secure interpretation of the scale and character of land-use and the possible agricultural impact of climatic deterioration at this site are difficult, as cereal pollen dispersal is low, only single grains of *Hordeum* group pollen are recorded, and alluvial soils, better suited to cultivation, may occur on the periphery of the pollen source area for this site. The context and possible extent of upland agriculture in Glen Affric is discussed in Chapter 9.

Rarefaction analysis suggests that from *c.*410-70 BP (490-modern cal BP) species diversity was much higher than the remainder of the Holocene, only equalled by the period of transition from *Betula-* to *Pinus*-dominated woodland at around 7140-6790 BP (7920-7580 cal BP). Rates of change during between 410 BP (490 cal BP) and the present are also much more rapid, and are again only equalled around 6290 BP (7200 cal BP), where woodland and basin-surface vegetation successions occur. This may reflect greater vegetational disturbance and instability, or result from the method of rate of change calculation. Greater vegetational instability, relating to human disturbance, could have resulted in more marked and rapid community changes (*cf. Homo sapiens* phase, Birks 1986), although this conflicts with the relatively small extent of local vegetation disturbance and low frequencies of herbs which suggest extralocal agricultural vegetation disturbance.

As stated in the methodology (Section 4.4.1.2), the calculation of rates of change is dependent not only on dissimilarity between samples, but also on the time difference between samples; unreliable results may arise when sample time intervals vary within the dataset (Bennett and Humphry 1995, Seppä 1998). Seppä (1998) found that rates of change between sites became divergent due to high sedimentation rates and short time intervals between samples. At Torran Beithe, very rapid accumulation rates between 380-180 BP (470-150 cal BP), with a sample interval of *c.*30 ^{14}C years (*c.*35 cal BP), may influence the rate of change calculations. This is clear from the single very high peak in rates of change from 20-20.5 cm, arising from the sampling overlap to correlate between the uppermost core segments, where the interpolated time interval is only *c.*4 ^{14}C and cal years. High accumulation rates may be the result of surface wetness or the uncompacted nature of the acrotelm. The relationship between rates of change, vegetation dynamics and anthropogenic activity are discussed in Chapter 9.

A steeper increase in the humification curve from *c.*940 BP (840 cal BP, cal AD 1120) (71 cm) suggests wetter conditions. There is no palynological evidence for wetter surface conditions, as Cyperaceae, *Calluna* and *Sphagnum* show continued local dominance, with no change in relative or absolute frequencies. This lack of correlation may be indicative of the wide ecological tolerance of the taxa concerned, or the complexity of the factors leading to humification changes.

5.5.7 Zone TOR3c: Cyperaceae-Poaceae-*Calluna-Pinus* (28-0 cm; 190-0 BP, 150-0 cal BP, cal AD *c.*1800-0)

There is evidence for continued pastoral grassland and cultivation in zone TOR3b. The low frequencies suggest extralocal and/or small-scale activity. A second *Hordeum* group pollen grain is recorded at *c.*90 BP (12 cm; 50 cal BP, cal. AD 1891-1907/1954-1955). Single grains of Chenopodiaceae and *Urtica* may derive from weed communities of arable fields or farmyards. Pollen of Brassicaceae, another possible weed or crop, is present from *c.*70-0 BP (modern cal BP, 9-0 cm). Despite the presence of these sporadic cereal- and weed-type pollen grains, the extent and age of cultivation near Torran Beithe is not securely established; a *Hordeum* group grain occurs in the surface sample and must have a regional source. The present blanket peat vegetation on the sampling site is sparse and may thus contribute a relatively small amount of pollen, which could allow increased percentage representation for extralocal and regional taxa, such as *Pinus*, discussed below.

Although the extent of land-use around the site is not clearly resolved from these data, the permanent shift from *Calluna* to Poaceae and Cyperaceae at 180 BP (150 cal BP, cal AD 1676-1954) could result from a burning regime which was too intense or frequent for successful *Calluna* regeneration, particularly when combined with grazing pressure (Hobbs and Gimingham 1987). A shift away from *Calluna* is also evidence in the DCA scores. The decline in charcoal from *c.*120 BP (130 cal BP, cal AD 1700-1955) may reflect a change in management, possibly occasioned by the loss of *Calluna*. If the increasing frequency of *Potentilla*-type pollen derives from *P. erecta*, which is unpalatable to stock (Grime *et al.* 1988), it may be further evidence of vegetation shifts due to grazing pressure or over-burning, which could also be inferred from the reduction in palynological diversity. *P. erecta* occurs on a range of acidic soils, including grassland, heath and mire. It is the most common herb in Glen Affric at present and peaks at 4.8% in the surface sample.

During this zone, frequencies of tree and shrub pollen remain relatively low, generally less than 30%, which are difficult to interpret in terms of woodland abundance (Goddard 1971, Tinsley and Smith 1974; see Chapter 9). Comparable frequencies have occurred since *c.*1460 BP (1330 cal BP, cal AD 620), and from 2030-1890 BP (1970-1830 cal BP, 80 cal BC-cal AD 120), suggesting that the pollen source area has been virtually treeless since this time. General Roy's map of around AD 1750 depicts some scattered tree cover in the sampling area and around Loch Coulavie, although Avery's map of AD 1725-1730 and other later maps do not suggest any tree cover west of Loch Affric; the accuracy of these maps, particularly in more remote, inland glens, is uncertain (Smout 1997; Section 2.1.5). The palynological data suggest that trees were largely absent during the period represented by the maps.

Pinus pollen frequencies increase from *c.*70 BP (modern cal BP) to a peak of 36% at the surface, with sporadic *Picea* and/or *Abies* grains. This date is close to the limits of ^{14}C dating and gives a modern calibrated age. However it does correlate very well with Forestry Enterprise records, which indicate that the earliest plantations including *Pinus* or *Picea* were established to the south-east from 1938. The occurrence of spheroidal carbonaceous particles above 90 BP (50 cal BP, cal AD 1891-1907/1954-1955) is also consistent with the age estimates derived from radiocarbon-dating and plantation taxa.

5.6 Conclusions from Torran Beithe

The results of pollen analysis at Torran Beithe indicate that this landform unit has been characterised by nutrient-poor and acidic soils since the early Holocene, which may reflect natural pedogenesis from poor parental materials. These have exerted a strong influence on vegetation composition. The abundance of subfossil *Pinus* stumps is a fair representation of Holocene woodland composition, although the chronology of these macro-remains has yet to be established, and need not reflect the temporal pattern of *Pinus* at the site. However, the palynological evidence suggests that the blanket peat matrix in which they occur was not widespread until *c.*3430 BP (3660 cal BP). This may infer that the preserved remains represent the last phases of growth (*cf.* Bridge *et al.* 1990), or earlier *Pinus* growth on drier parts of basin mires which were present from *c.*5300 BP (6090 cal BP). Although widespread treeless blanket peat cover may reflect the ultimate outcome of mid-Holocene climatic deterioration, this belies the complexity of mid-Holocene vegetational changes. The initial demise of *Pinus* does not appear to have been a direct result of blanket peat expansion, although subsequent woodland loss may have been caused by an increase in the depth and/or extent of peat cover.

It is difficult to infer the extent and impact of mid-Holocene human and grazing activity, since the acidic nature of the environment restricts the occurrence of conventional 'anthropogenic indicator herbs'. The charcoal record may be the most secure evidence of human presence, although comparison with other sites may allow more secure interpretation of the cause of burning at this time. An increase in ruderals from *c.*2760 BP (2850 cal BP) may thus infer more extensive or intensive activity within the pollen source area, when the charcoal record may be more securely related to anthropogenic activity. Evidence of cultivation is sparse, and may reflect limited pollen transport from an extralocal source, or environmental limitations on more nutrient-demanding forms of agriculture.

CHAPTER 6: Carnach Mór

6.1 Site selection

Alluvial sediment is of limited extent in Glen Affric (Chapter 2), and takes the form of a flat strath, which allows lateral migration of the riverbed and sediment deposition through flooding. Alluvial soils, including relict fluvial terraces and active river floodplain soils, are characterised by relatively basiphilous, species-rich grassland, which contrasts markedly with the extensive heath and blanket peat-covered moraine sediment elsewhere on the valley floor and on the surrounding hillsides (Fig. 6a, Photos 4 and 5). This raises the question as to when these environments and plant communities first became differentiated. At present, better drainage and sediment deposition during flooding appear to maintain a relatively high soil nutrient and base status on the valley floor. This may have enabled more nutrient-demanding species to colonise and thrive on the valley floodplain, relative to morainic soils, which may thus have supported taxa which are adapted to marginal conditions (*e.g. Pinus*, *Betula*).

Hydrological and geomorphological activity in the active fluvial environment, including flooding, and the erosion and reworking of unstable banks and gravel bars, may have also helped to maintain high species diversity, promoting the formation of communities which were adapted to disturbance. It is also possible that the maintenance of a higher soil nutrient status may have delayed the loss of woodland cover during the mid-Holocene, compared with blanket peat-covered areas of the glen.

However, many of the known archaeological sites in West Affric, and adjacent glens, are located near the valley floor (Section 2.2). The limited extent of alluvial soils may have made them attractive and valuable to humans, although the age at which the floodplain formed will also have determined when this resource first became available. More favourable edaphic conditions may also have enabled more extensive or intensive, and more prolonged activity on alluvium than on morainic soils, perhaps making them the focus for land-use and settlement.

6.2 Site description

The pollen site of Carnach Mór is located at the edge of the flat valley floor, on one of the few extensive areas of relatively wide alluvial sediment in the glen, covering *c.*2.5 km east-west, and approximately 200-250 m wide (Photo 4). In the absence of a named topographic feature immediately adjacent to the channel, the sampling site is named after the peak which overlooks the site from across the valley (Fig. 25). There is currently considerable geomorphic activity on the adjacent floodplain caused by lateral movement of the coarse stone and gravel bed of the River Affric across alluvial sediment. This results in the erosion of alluvium, undercutting and bank collapse, and in the formation of unstable gravel bars (Photo 6). The flanking hills and mountains rise steeply to a mountainous ridge to the north. The southern slopes rise more gently and project out onto the valley floor to the west, which may increase the amount of sunlight reaching this area of the valley floor, whilst perhaps affording some shelter from prevailing westerly winds.

The coring site is an infilled channel at the ecotone between the southern hillside and strath, on the highest of three alluvial terraces (National Grid Reference NH 097 206), at an altitude of 251 m OD (Fig. 25, Photo 7). To the north, wet blanket peat and damp grassland overlie the alluvial terraces, while to the south, blanket peat-covered hillslopes rise gradually to Mullach Fraoch Choire (Gaelic for 'top of heather corrie'), at 1102 m OD. On the southern hillslopes immediately adjacent to the sampling site is an unnamed, stone-built ruin (Photo 8). There are two more, much less distinct and therefore perhaps older ruins on the northern side of the valley floor and another two on the hill slopes to the north-west, which are marked on the OS 1:10000 OS map (Fig. 25). These have been interpreted as farms or shielings dating from last century (Wordsworth 1995, Wordsworth and Harden 1997).

Sphagnum is the dominant vegetation component and forms unconsolidated, floating mats within the channel, with *Menyanthes trifoliata* in open water. *Eriophorum angustifolium*, *E. vaginatum* and *Scirpus cespitosa* are abundant, with *Luzula* and *Juncus*. Poaceae are also common, including *Holcus lanatus*. *Narthecium ossifragum*, *Potentilla erecta*, *Polygala serpyllifolia* and occasional *Myrica gale* were also recorded. Peat communities on the hillslopes to the south are dominated by *Calluna vulgaris*, Cyperaceae and *Sphagnum*. North of the channel, wet mire merges gradually into drier alluvial sediment, and the vegetation grades from mire through *Juncus*-Poaceae communities to meadow with numerous herbs. *Ranunculus* sp., *Succisa pratensis* and *Anemone nemorosa* are most common in long grass, while *Galium saxatile*, *Euphrasia nemorosa*, *Thymus*, *Lotus corniculatus*, *Trifolium pratense*, *Rumex acetosa*, *Potentilla erecta* and *Leontodon* are common in shorter grass and unstable gravel bars beside the River Affric. Occasional individuals of *Stellaria/Cerastium*, *Achillea millefolium*, *Plantago maritima*, *Pedicularis palustris*, *Alchemilla* and *Epilobium palustre* were also observed.

6.3 Results

6.3.1 Site morphology and source area

The sediment stratigraphy and width of the channel were recorded using a north-south transect, with sample points generally at 1.0-4.0 m intervals (Fig. 26). The basal stratigraphic units could be correlated, indicating that the channel was formed though meander migration, rather than avulsion. The transect indicates that the channel is *c.* 10 m wide. On the basis of recent research, this suggests a pollen source area of approximately 50-200 m radius under a closed woodland canopy (Sugita 1994; Section 3.2.2.2, Table 3). However, water-borne particles can form a potentially major source of pollen in lake and alluvial sediment (Peck 1973, Bonny 1976, 1978, Pennington 1979, Scaife and Burrin 1992, Schirmer 1991). The fluctuating loss-on-ignition values indicate that sediment has been introduced, probably through flooding or runoff from the adjacent slope, as inferred from the location of the site at the edge of a slope and floodplain, and transect stratigraphic results (Figs. 25 and 26). This is likely to have increased the effective source area of the sampling channel, including a larger, but unquantified, hydrological catchment. A radius of 50-200 m for the relevant source area is therefore likely to be a minimum estimate. The evidence for inwashed pollen is discussed further in Sections 6.3.5 and 6.5.

6.3.2 Sediment description

A sediment core 4.62 m in length was obtained from the deepest point in the channel (Fig. 26), using the methods described in Section 4.1.3. The sediment description is shown in Table 14, from which it can be seen that the stratigraphy consisted of peat with varying mineral content, which was quantified through loss-on-ignition (Fig. 28). LOI data confirms the correlations made between the cores in the field, as results from the overlapping sections of the cores were closely comparable (not presented).

6.3.3 Radiocarbon dates

Nine peat samples were submitted for AMS radiocarbon dating (Table 15). These returned a conformable sequence at the 2σ range, as indicated in the time-depth curve (Fig. 27). Although the palynological and microfossil evidence suggests that the radiocarbon dates may be around 90-190 ^{14}C (70-240 cal) years too early in comparison with plantation indicators and spheroidal carbonaceous particles (SCPs), this is probably within the 2σ error range associated with radiocarbon dating.

Changes in the temporal resolution and rates of sediment accumulation of the diagrams are presented in Table 16, which indicates that time intervals between subsamples range from 8-228 ^{14}C (10-208 cal) years, with a mean of 88 ^{14}C years (94 cal years)/sampling interval.

6.3.4 Pollen and microfossil analyses

The results of the pollen analyses are presented as percentage diagrams in Figure 28, with selected concentration and accumulation curves in Figures 29 and 30, respectively. The results of rarefaction and rate-of-change analyses are shown in Figure 31. The results of detrended correspondence analysis for the first two axes are presented in Figure 32a-b. 52.6% of the cumulative variance in the taxa data is captured in the first four DCA axes, with 43.1% represented by the first two axes.

Seven local pollen assemblage zones and subzones (lpaz) were defined; the site designation 'CAR' precedes each zone or subzone division (Table 17). The measurements used for the identification of large and cereal-type Poaceae grains are presented in Table 18 (see Section 4.3.1.1 for identification criteria).

6.3.5 Pollen preservation data analysis

Summary pollen preservation data are presented in Figure 33 and preservation class data for selected individual pollen types are shown in Figure 34 (see Section 4.3.2 for calculation sum). These indicate that the profile is dominated by well-preserved grains.

With a mean of 20%, crumpling is the most frequent form of pollen deterioration. There are two main points in the profile at which the crumpling curve changes. Crumpled pollen increases in frequency in zone CAR1b, around 7800 BP (8520 cal BP), and in zone CAR2c at *c.*3730 BP (4020 cal BP). However, these shifts do not mirror sustained changes in the LOI curve, suggesting that crumpling is not primarily the result of compression in mineral sediment (Cushing 1964, Birks 1970, *cf.* Lowe 1982), or of the redeposition and/or inwashing of soil or sediment (Lowe 1982, Tipping 1995a). Neither does increased crumpling reflect changes in peat stratigraphy (Fig. 33, Table 14), indicating that the preservation curves do not reflect changes specific to the accumulating peat deposits, but may also reflect changes in environmental and ecological factors in the surrounding vegetation, which are discussed in Section 6.5.

The clearest association is between the frequencies of corroded pollen, Pteropsida (monolete) indet. spores and mineral content (Fig.33). This cannot be statistically demonstrated, yielding low regression coefficients, as the frequencies of corroded pollen and of spores are not directly proportional to the percentage of mineral sediment. Although corroded pollen may be introduced or formed through numerous mechanisms (Section 4.3.2), the association noted above is suggested to reflect the inwashing of contemporaneous or secondary pollen and resistant fern spores (*cf.* Peck 1973, Pennington 1979), as spore frequencies are not correlated with woodland or tall-herb pollen, with which ferns may be expected to have an ecological association.

However, well-preserved pollen remains dominant throughout the profile (range: 47-87%, mean: 67%), compared with a mean of 5% corroded and 8% broken. In addition, frequencies of indeterminate pollen are low, with an average of 3%, and a range of 0.3-8.0%, and frequencies of degraded (determinate and indeterminate) pollen are consistently very low (Fig. 33). This suggests that the pollen assemblages are not significantly biased by the inclusion of large frequencies of non-contemporaneous, reworked pollen corroded through residence or transport in aerobic environments. Increased breakage during zone CAR2a-c, with a slight rise mid-way through zone CAR1b, may reflect the increase in *Pinus* frequencies (Figs. 33 and 34), possibly broken during pollen processing (Cushing 1964).

6.3.6 Charcoal analysis

Percentage and absolute charcoal data are presented in Figure 35. Table 19 presents a summary of temporal patterns of charcoal representation.

The correlation between different size classes indicates that adjacent range size classes are more highly correlated than small and larger size classes (Table 20), perhaps reflecting changes in the proximity, size and intensity of the fire, and the fuel source. The ratios of charcoal size classes (charcoal "size class signature") provide more information on the temporal patterns of charcoal size distribution (Fig. 36), indicating that from *c.*4100-4030 BP (4560-4480 cal BP), and from *c.*2730-0 BP (2790-0 cal BP), large fragments (>75 μm) are more abundant relative to smaller size classes. This may infer that fires burnt closer to the sampling site (Patterson *et al.* 1987, Stevenson *et al.* 1996) and is discussed in comparison with palynological evidence in Section 6.5.

Comparison of charcoal, LOI and pollen preservation data shows no consistent relationship between charcoal frequencies and either organic content or pollen preservation state, particularly crumpling and corrosion, which may result from the incorporation of secondary soil or sediment pollen (Lowe 1982, Tipping 1995a). This suggests that, although in some instances charcoal may have been deposited through runoff and water transport, this is not generally the case. Individual periods, such as *c.*7050-6140 BP (7860-7010 cal BP), when charcoal and LOI or deterioration curves may infer reworking are discussed in relation to sedimentary and palynological data in Section 6.5.

6.4 Description

6.4.1 Zone CAR1a: *Betula-Sorbus aucuparia*-Cyperaceae (462-444 cm; 9470-9160 BP, 10470-10040 cal BP)

The sediment consists of well-humified peat with a decreasing minerogenic component, as organic content rises from a basal minimum of 18% to 48% at the top of the zone. The lpaz is characterised by maximum frequencies of *Sorbus aucuparia* pollen, rising to 27%. *Betula* and Cyperaceae are the other dominant pollen taxa. Low frequencies of *Corylus avellana*-type and *Salix* are recorded. Other prominent taxa include Pteropsida (monolete) indeterminate, *Filipendula*, Apiaceae, *Caltha palustris*-type and *Equisetum*, with two grains of *Plantago lanceolata*.

Total land pollen (TLP) concentration and accumulation rates increase slightly from the base of the core, maintaining moderate values. Well-preserved pollen is predominant. Relative to the whole profile, palynological richness is consistently high and rates of change are moderate. The charcoal-to-pollen ratios and frequencies of charcoal fragments are high, with a peak in the basal sediments.

6.4.2 Zone CAR1b: *Betula-Salix-Corylus avellana*-type (444-290 cm; 9160-5950 BP, 10040-6780 cal BP)

The sediment consists of well-humified peat with frequent wood and some small lignified twigs. Organic content is variable, with a range of 23-80%. The zone is characterised by high but variable frequencies of *Betula* pollen, with a maximum of 83% and falling to 29% as *Salix* pollen values rise from 10 to 45% between 6990 and 6760 BP (7770-7550 cal BP). *C. avellana*-type frequencies attain maximum Holocene levels (18%), while Cyperaceae pollen values gradually decline. *Viburnum opulus* pollen is frequent. Values for *Ulmus* and *Quercus* pollen are low but the curves are continuous and rise gradually to the end of the zone. The curve for *Pinus sylvestris* becomes continuous, rising to 10% at 7280 BP (8040 cal BP). *Alnus* pollen frequencies also increase at the end of the zone. A wide range of herb pollen types are recorded of which *Filipendula*, *Rumex acetosa*, *Potentilla*-type, *Ranunculus acris*-type, Apiaceae and *Melampyrum* are most common. Pteropsida (monolete) indet. values range between 5 and 45%. Pollen of several aquatic taxa are recorded in this zone.

TLP concentrations and accumulation rates increase from the previous zone and fluctuate between high and moderate values. Well-preserved pollen frequencies are high, decreasing from 82% at 8070 BP (8980 cal BP), where values for crumpled pollen increase to between 11 and 27%, with a slight increase in broken pollen. Corroded pollen frequencies rise to 13% between 6820-6590 BP (7620-7400 cal BP), and there are peaks in degraded pollen of 2.4-4.4% at 7730 BP (8480 cal BP) and 6820-6590 BP (7620-7400 cal BP). Palynological richness remains high, decreasing over two spectra from 8000-7870 BP (8780-8570 cal BP). Rates of change are moderate, with a peak at 7590-7530 BP (8370-8330 cal BP). Charcoal-to-pollen ratios remain high, rising to a peak at 6360 BP (7230 cal BP), before a decline to low values at the transition to zone CAR2a.

6.4.3 Zone CAR2a: *Betula-Pinus sylvestris-Alnus glutinosa* (290-250 cm; 5950-4190 BP, 6780-4720 cal BP)

The sediment consists of amorphous peat with wood fragments and small twigs below 5520 BP (6300 cal BP, 281 cm). A high mineral content is recorded from 4630-4460 BP (5320-5040 cal BP, 260-256 cm), with a low of 12% organic matter, before LOI values rise again.

The tree pollen record is dominated by *Betula*, still with very variable frequencies. *Pinus* values peak at 29% at 5880 BP (6720 cal BP), while *Alnus* pollen frequencies continue to increase, reaching a Holocene maximum of 32% at 4460 BP (5040 cal BP). *Salix* and *Filipendula* pollen frequencies fall and henceforth remain consistently low. *Ulmus* pollen attains a maximum frequency of 3% at 5610 BP (6410 cal BP) before declining from 4900 BP (5630 cal BP). There is a temporary increase in several heath pollen taxa, primarily *Calluna* *vulgaris*, from 5170-4630 BP (5920-5320 cal BP), and Poaceae values rise between 4990 and 4460 BP (5730-5040 cal BP).

TLP concentrations and accumulation rates are initially low, increasing to maximum concentrations for the profile between 5170-4460 BP (5920-5040 cal BP), before decreasing to moderate values. A less pronounced rise occurs in TLP accumulation rates. Well-preserved pollen frequencies decrease from an initial high of 82% as frequencies of crumpled pollen increase. Well-preserved pollen frequencies decrease further between 4990-4460 BP (5730-5040 cal BP), where values for broken, corroded and degraded pollen increase to between 11 and 24%. Frequencies of indeterminate pollen remain low (<4%), of which crumpled and corroded grains are most frequent. Palynological richness is slightly reduced and rates of change are consistently low. Percentage charcoal frequencies are low, but fragment concentrations and charcoal-to-pollen ratios increase from 5170 BP (5920 cal BP, 272 cm), before declining near the end of the zone.

6.4.4 Zone CAR2b: Cyperaceae-*Betula-Alnus-Pinus* (250-214 cm; 4190-3870 BP, 4720-4280 cal BP)

There is a change in sediment from amorphous peat below 4080 BP (4540 cal BP, 245 cm) to a coarse root mat between 4030 and 3960 BP (4470-4410 cal BP, 236-224 cm) with small twigs. Organic content is high (>77%), except for a fall to 48% at 4050 BP (4460 cal BP). The zone is characterised by high and fluctuating Cyperaceae pollen values, an increase in *Potentilla*-type and more frequent *P. lanceolata* pollen. *Quercus* reaches maximum pollen frequencies of 4% before values decline after 3910 BP (4370 cal BP). *Betula* pollen frequencies remain below 31%, while the *Pinus* and *Alnus* pollen curves follow similar patterns, with values ranging between 5 and 20%. Frequencies for *Potentilla*-type pollen are consistently higher, at 3-24%, while frequencies for *Filipendula* are reduced. *Plantago lanceolata* pollen commences consistent, low frequencies in this zone.

Moderate TLP concentrations in the first half of the zone coincide with very high total accumulation rates. Concentration and accumulation rates then decrease to low and moderate values, respectively. Crumpled pollen frequencies are slightly lower and there is a single peak in corroded pollen grains at 4050 BP (4460 cal BP) before a return to predominantly well-preserved pollen. Palynological richness and rates of change peak in the first half of the zone, where rates of change attain maximum values for the profile. *Pinus* stomata are present throughout the zone. Charcoal values remain very low; reflected in moderate to low charcoal-to-pollen ratios, with a single peak at 4050 BP (4460 cal BP).

6.4.5 Zone CAR2c: *Calluna vulgaris*-Cyperaceae-*Betula* (214-178 cm; 3870-2920 BP, 4280-3060 cal BP)

The peat consists of organic, herbaceous detritus. Tree and shrub pollen frequencies are reduced, falling further above 3180 BP (3380 cal BP, 188 cm). *Calluna* pollen values increase abruptly and Cyperaceae pollen frequencies return to high values. *Melampyrum* pollen becomes less common. *Potentilla*-type pollen remains the most common pollen type, although values are reduced form the previous zone. Of the other herbaceous pollen taxa, *Filipendula*, Apiaceae and *Rumex acetosa* are the most common, with frequent *Plantago lanceolata* and *Ranunculus acris*-type.

TLP concentrations and total pollen accumulation rates are moderate. Well-preserved pollen grains are less frequent, at 79-50%, and frequencies of crumpled pollen are higher, rising to 35% at the end of the zone. Palynological richness and rates of change remain moderate, with a peak in rate of change at the transition to zone CAR3a. *Pinus* stomata are absent. Charcoal frequencies increase sharply; this is reflected in all size classes, and is evident in percentage and charcoal-to-pollen ratios.

6.4.6 Zone CAR 3a: Poaceae-*Myrica gale*-*Calluna* (178-122 cm; 2920-1880 BP, 3060-1820 cal BP)

The herbaceous peat is less humified between 2620 and 2100 BP (2750-2050 cal BP, 162-134 cm), with a gradual shift to more humified material above and below. Loss-on-ignition values exhibit a gradual decline from the start of the zone, followed by an increase to high values above 2290 BP (2330 cal BP, 144 cm).

Frequencies of tree and shrub pollen decline further as *Myrica gale* pollen values rise abruptly from 5 to 39% across the zone CAR2/3 boundary. *Calluna* pollen frequencies are reduced before rising to a maximum of 39% at 3510 BP (3760 cal BP). Poaceae pollen is abundant and Cyperaceae pollen is well represented. Pollen of *P. lanceolata* and *Succisa pratensis* is more frequent. A single *Hordeum* group grain is recorded at 2600 BP (2760 cal BP).

TLP concentrations and accumulation rates are high. Well-preserved pollen dominates the assemblage, with 13-36% crumpled pollen. Palynological richness is high to moderate and rates of change are higher than the previous zone. Charcoal percentage and charcoal-to-pollen ratios remain high.

6.4.7 Zone CAR 3b: Poaceae-*Calluna*-Cyperaceae (122-50 cm; 1880-410 BP, 1820-490 cal BP)

Herbaceous roots are abundant in the peat, with a change to *Sphagnum* peat at the upper zone boundary. Organic content is markedly lower, ranging between 20-60%. The lpaz is characterised by the dominance of Poaceae, *Calluna* and Cyperaceae pollen, and much lower levels of *Myrica*. With the exception of higher *Betula* values (rising to 43%) from 1840-1760 BP (1740-1650 cal BP), tree and shrub pollen frequencies are low. The main herbaceous pollen taxa are *P. lanceolata*, *Cichorium intybus*-type, *R. acris*-type, Rubiaceae and *Succisa*. *Papaver rhoeas*-type, *Rumex acetosella*, *Hordeum* group, Poaceae with an annulus diameter >8 µm (anl-D>8 µm) and one possible *Avena/Triticum* group pollen grain are recorded.

TLP concentrations and accumulation rates are moderate, decreasing to low from 1480-1380 BP (1350-1290 cal BP) and around 470 BP (510 cal BP). Frequencies of crumpled pollen grains are slightly higher than the previous zone and corroded pollen is more frequent, with a slight fall in well-preserved pollen values. Palynological richness increases. Rates of change increase to high at *c.*870 BP (760 cal BP, 80 cm). After initially high values, charcoal frequencies are lower. Charcoal-to-pollen ratios are slightly decreased from the previous zone but high peaks are still recorded.

6.4.8 Zone CAR3c: Cyperaceae-*Calluna* (50-0 cm; 410-0 BP, 490-0 cal BP)

Sphagnum increases in abundance towards the surface, with a corresponding decline in humification. Fine and coarser non-lignified roots are present. Organic content shows a gradual rise to sustained high values. The zone is characterised by higher levels of Cyperaceae pollen and lower Poaceae frequencies. The main herb pollen taxa remain as in the previous subzone, but many decrease or are absent after *Hordeum* group ceases to be recorded. This coincides with a slight increase in *Pinus* pollen values and the start of *Picea* and spheroidal carbonaceous particle representation.

TLP concentrations and accumulation rates are very low to moderate. Well-preserved pollen becomes more frequent as crumpled and corroded pollen values decrease. Values for palynological richness are initially high, decreasing gradually to a profile minimum in the surface sediment. Rates of change remain high and fluctuating. Charcoal values are moderate and decline towards the top of the profile.

6.5 Inferred vegetation history

6.5.1 Zone CAR1a: *Betula-Sorbus aucuparia*-Cyperaceae (462-444 cm; 9470-9160 BP, 10470-10040 cal BP)

During the early Holocene, the channel may have had sparse aquatic vegetation, suggested by occasional grains of *Myriophyllum* and *Potamogeton* in zones CAR1a-b, perhaps with Cyperaceae and *Caltha palustris*-type in the shallow water margins. This suggests that some Poaceae pollen may derive from aquatic taxa, such as *Phragmites*. Although the aquatic taxa suggest relatively slow or still water within the channel, high frequencies of mineral matter in the core during zone CAR1a may reflect the proximity of the river and/or be indicative of more inorganic and skeletal soils, with consequently high sediment loads in water. A high energy fluvial system, particularly during the first *c.*500 years of the Holocene and preceding channel formation, may have contributed to the formation of the strath, inferred from the stratigraphic (Fig. 26) and palynological data (below).

Woodland cover was established around the channel prior to sediment accumulation. *Betula* was the dominant pollen producer, with increasing frequencies of *Sorbus aucuparia*, and some *Corylus avellana*-type and *Salix*, both represented by frequencies of less than 10%. *Sorbus* is insect-pollinated (Grime *et al.* 1988) and surface sample studies indicate that even where *Sorbus* comprises around 40% of the woodland vegetation, pollen frequencies of only a few percent are recorded, suggesting poor pollen production and dispersal (Birks 1980). At Carnach Mór, the increase from 8 to 28% between 9440 and 9300 BP (10410-10240 cal BP) therefore suggests that *Sorbus* may have been dominant or co-dominant with *Betula* for a around single generation, as *Sorbus* presently lives to a maximum of 150 years (Grime *et al.* 1988). Several grains of *Prunus padus* may suggest the growth of the species as a minor woodland tree, as this species is also entomophilous (Birks 1973).

Sorbus is a pioneer species of acidic and well-drained soils, occurring in woodland or skeletal habitats (Grime *et al.* 1988). If, as suggested above, high mineral content infers the presence of inorganic soils, early Holocene conditions on the lower hillslopes and valley floor may have been more favourable for *Sorbus* growth prior to the accumulation of organic soils.

The woodland understorey consisted of fern-rich tall-herb communities with *Filipendula* and Apiaceae. *Rumex acetosa* is infrequent in woodlands (Grime *et al.* 1988), and the near continuous curve suggests that it may have been present in tall-herb vegetation or in less stable habitats on river banks and on alluvial gravel bars, where conditions might have been suitably open and disturbed for *Plantago lanceolata*, of which two grains were recorded in consecutive levels at 9370-9300 BP (10360-10240 cal BP).

6.5.2 Zone CAR1b: *Betula-Salix-Corylus avellana*-type (444-290 cm; 9160-5950 BP, 10040-6780 cal BP)

The channel continued to support a sparse aquatic vegetation , consisting of *Myriophyllum*, *Potamogeton* and *Menyanthes*. This suggests that the *Hordeum* group and Poaceae pollen with annulus diameters greater than 8 µm (Poaceae anl-D>8 µm) grains recorded at 8890-8820 (9910-9870 cal BP) and 8690 BP (9600 cal BP) derive from aquatic grasses such as *Glyceria*, which commonly occur in slow-moving water and mud in ditches and marshes (Grime *et al.* 1988). These taxa suggest still or slow-moving water with a mineral substrate and a possible depth range of 0.5 to 2.0 m (Haslam *et al.* 1975). *Caltha palustris*-type and *Equisetum* may have grown on the margins, possibly with tall-herb or marsh communities including *Filipendula* and *Valeriana officinalis*. *Menyanthes* is the only species requiring organic sediment.

From 7830 BP (8550 cal BP) there is a shift to increased pollen crumpling, which is reflected in most pollen types (Figs. 33 and 34). Crumpling may result from changes in the conditions under which sediment was accumulating within the channel. A higher mineral content suggests an increase in erosion or inwashing. A slight increase in frequencies for Pteropsida (monolete) indet. may also derive from water-borne pollen grains (Peck 1973). This may arise from geomorphological changes around the channel, such as the closer proximity of the river, depositing more sediment.

The decline in *Sorbus* frequencies to values of around 1-2% from 9090 BP (10030 cal BP) may indicate the continued presence of *Sorbus* as a common tree within the open woodland, with stand-scale replacement by *Betula* in a shifting mosaic. The development of more organic soils may have enabled *Betula* to out-compete *Sorbus*, inferred from the increasing organic content of the channel sediment. Woodland cover gradually became more extensive in zone CAR1b, reaching maximum early Holocene tree and shrub frequencies of 91% at 7590 BP (8370 cal BP). However, the abundance of herbaceous taxa suggests that the canopy was not dense or continuous.

Betula may have formed a mosaic with *Corylus avellana*-type and *Salix*, perhaps on drier and damper soils, respectively. The relatively low frequencies for *C. avellana*-type, with a maximum of 19% at 8340 BP (9370 cal BP), suggest that *Corylus* was a minor woodland constituent. The diverse ground flora includes species more common is open environments, such as *Ranunculus acris*-type, *Rumex acetosa*, Rubiaceae, and *Cichorium intybus*-type with *Dryopteris filix-mas*-type, indicating that poor light intensity is unlikely to have prevented *C. avellana* from flowering (*cf.* Birks 1970). Open conditions are also suggested by occasional *Hedera helix* pollen.

Fluctuations in sediment organic content and in the frequencies of the main pollen taxa, with the consistent presence of pollen from open ground herbs, suggest that disturbance may have been a characteristic feature of the environment around the sampling site. In zone CAR1b, the temporal resolution is *c.*8-19 (*c.*10-20 cal) years/pollen sample, with 68-228 ^{14}C (77-208 cal) years between samples. The pollen spectra can thus resolve relatively short-lived fluctuations resulting from disturbance events as well as woodland processes such as shifting mosaics at the scale of single tree generations, since the intervals are generally equal to or less than the generation time of *Betula* and *Sorbus*. Disturbance may have helped to maintain relatively a high palynological richness throughout zone CAR1 by creating a mosaic of species and age classes (*cf.* Seppä 1998).

Several fluctuations in pollen frequencies coincide with reductions in the LOI curve, suggesting minerogenic influx due to flooding, runoff or soil erosion. Neither *Sorbus* nor *Corylus* frequencies appear to respond to sedimentological or palynological evidence of disturbance in other taxa. Both occur on drier soils and *Sorbus* does not occur in wetland habitats (Grime *et al.* 1988), suggesting that disturbance may have been more frequent on the floodplain, rather than the rocky and perhaps better drained hillslopes on the southern side of the channel. This is also suggested by the rapid response of fen taxa and shrubs of damp soils to disturbances in the *Betula*-dominated canopy.

Flooding and runoff may have resulted in soil enrichment through the deposition of fresh nutrients, suggested by the fluctuations in LOI. Fresh nutrients, deposited through flooding, may have replenished or maintained the soil nutrient and base-status, resulting in the abundance of tall-herb species and taxa which occur in damp or periodically flooded environments. This includes *Filipendula*, Apiaceae, *Valeriana officinalis*, *Potentilla*-type, *Succisa pratensis*, Rubiaceae, Cyperaceae, *Caltha palustris*-type, *Epilobium*-type and *Mentha*-type. In addition, *Betula* is regarded as a 'soil improver' (Miles 1985, Atkinson 1992), and the dominance of *Betula* within the woodlands around Carnach Mór may also have helped to maintain the soil quality. However, the consistent presence of *Sorbus* and *Pteridium aquilinum* suggest that acidic soils were also present, perhaps forming relatively open woods on better-drained soils or rock outcrops at the edge of the valley floor.

These species appear to have formed a tall-herb fen *Betula*-dominated woodland, with *Salix* and *Viburnum opulus* on damp floodplain soils. *Salix* is commonly associated with fen carr or grows in the understorey of woods on damp soils (Huntley and Birks 1983). Both *Salix* and *Viburnum* are entomophilous and may therefore have been more abundant than the percentage values suggest (*cf.* Janssen 1966, Caseldine 1981). *Melampyrum pratense* has been found to grow abundantly in *Sphagnum*-rich fen-wood (Birks 1975). The stratigraphy consists of wood peat with fluctuating mineral content, suggesting fen woodland communities with periodic sediment influx, perhaps though flooding or runoff from the hillside. The sample scores for zones CAR1a-b are associated with these tall-herb fen wood taxa.

Intermittent, possibly frequent, small-scale disturbance appears to have resulted in a dynamic woodland mosaic, in which fen and shrub taxa were able to flourish in openings in the canopy. This is evident at 7530 BP (8300 cal BP), when a short-lived drop in percentage and absolute *Betula* curves coincides with a peak in Cyperaceae and *Potentilla*-type pollen, perhaps *P. palustris*, before *Betula* returns to dominance over a 70 (80 cal) year period. This coincides with increased rates of palynological change. Between 6990 and 6760 BP (7770-7550 cal BP), *Salix* frequencies increase to 45% at the expense of *Betula*, suggesting local species replacement. This is again associated with a slight fall in organic content. Peaks in Poaceae and *Filipendula*, then in *Rumex acetosa* and *Ranunculus acris*-type, suggest a more open canopy beneath *Salix*, perhaps with further disturbance. *Salix* persisted for 110 ^{14}C (100 cal) years, with a gradual rise in *Betula* frequencies over the subsequent 460 ^{14}C (420 cal) years, perhaps due to more disturbance events, which are not resolved in the pollen diagram. Reductions in *Betula* may have arisen due to gaps created by windthrow, flooding or the death of canopy trees (Peterken 1996), as *Betula* may form shallow and horizontal rooting systems on waterlogged soils and rarely regenerates in birchwood, even when the canopy is open (Atkinson 1992).

Pteropsida (monolete) spores are common throughout the Holocene, particularly in zone CAR1. While some spores may reflect the growth of ferns under the woodland canopy and in tall-herb communities, the absence of a consistent correlation between Pteropsida and tree cover or tall-herb species suggests that a high proportion of spores may represent a water-borne component (*cf.* Peck 1973). This is supported by the frequent association of low organic content with high Pteropsida frequencies. Similarly high percentages of fern spores have been recorded at a floodplain site in the English Midlands (Brown 1988).

In acid, organic soils the residual soil pollen component may be high (Pennington 1979) and the pollen preservation data from Carnach Mór suggest that some reworking may have occurred, particularly after 7870 BP (8570 cal BP), where the frequencies for crumpled and corroded pollen, and Pteropsida spores increase, mirroring the LOI curve (Fig. 35). This may reflect the deposition of soil pollen which has been aerobically corroded and crumpled through compression in minerogenic sediment (Cushing 1964, Birks 1973, Lowe 1982, Tipping 1995a). However summary and species preservation data indicate that most pollen is well-preserved (55-87%) and thus possibly contemporaneous (Figs. 33 and 34), suggesting that inwashed and reworked pollen does not significantly distort the pollen spectra. At present, many of the ferns in Affric grow in beside water channels and streams, where flushed conditions may be less acidic and sporulation could inject spores directly into the water, rather than deriving only from reworking and erosion.

Unstable, skeletal habitats on river banks and gravel bars within the river may have supported ruderal species, often regarded as indicators of anthropogenic disturbance, including *Plantago lanceolata*, Chenopodiaceae, *Artemisia*-type, *Urtica dioica* and *Cichorium intybus*-type (*cf.* Behre 1981). *Rumex acetosa* pollen is consistently present and may have been sustained by the frequency of disturbance. *P. lanceolata* is not recorded again until *c.*4280 BP (4840 cal BP). Although the species is able to grown on alluvial soils (Sagar and Harper 1964), the pollen evidence suggests that it was not common in such environments near Carnach Mór.

Charcoal is recorded throughout the early-mid Holocene and charcoal-to-pollen frequencies and absolute are moderate to high. The charcoal curve does not correlate with fluctuations in LOI, suggesting that water-borne transport does not account for the frequency and consistent high charcoal values. The dominance of smaller charcoal fragments may indicate frequent distant fires (Clark 1988), although this is argued against by the high charcoal frequencies (5-79% TLP). This may infer the occurrence of high frequency, low intensity and/or distant fires, which cannot be distinguished between at the temporal resolution of the data.

The longevity of moderate-high charcoal frequencies at Carnach Mór is unexpected, as the vegetation around the channel appears to have been dominated by damp fen carr woods of *Betula*, *Salix* and tall-herbs. Wet temperate forest does not appear to burn readily, even during very dry summers (Rackham 1980, Peterken 1996). However, there is evidence for fire disturbance at Carnach Mór. A trough in the *Betula* curve from 7830-7660 BP (8550-8410 cal BP) coincides with a peak in charcoal and increased herb pollen, particularly Poaceae, Cyperaceae and *Filipendula*, perhaps reflecting increased herb pollen dispersal or flowering within an opening in the canopy created by fire. The slight rise in corroded pollen may indicate soil disturbance and erosion, which allowed aerobic pollen oxidation (Havinga 1964, 1984, Cushing 1964, 1967). At 6140 BP (7010 cal BP), a peak in *Sorbus* coincides with a fall in Poaceae, perhaps indicating post-fire succession on drier soils. There is no evidence at Carnach Mór that *Melampyrum* responded to burning (*contra* Moore *et al.* 1986, Innes and Simmons 1988, Caseldine and Hatton 1993); it is suggested to have formed part of the damp, possibly acidic, woodland understorey.

The clearest pollen-charcoal correlation is between Poaceae and charcoal values from 9470 BP (10470 cal BP) until around 4460 BP (5040 cal BP). Burning may have maintained open areas of grassland, perhaps in the seasonally or periodically inundated littoral zone with *Phragmites* (*cf.* Mellars and Dark 1998), and on vegetated gravel bars and river banks, where more freely-draining alluvial and gravel sediment could have allowed the soils and vegetation to become dry enough to ignite more readily. Macroscopic charcoal recorded at the mineral/wood peat interface in an alluvial profile adjacent to the channel (Fig. 26) indicates that fires did occur on the alluvial sediment. The correlation between charcoal frequencies, corroded pollen and increased mineral content from *c.*7050-6140 BP (7860-7010 cal BP) may infer inwashing of charcoal, crumpled and corroded pollen (particularly *Betula* and Poaceae) following burning.

The small literature on the quantity and size characteristics of charcoal produced by burning different vegetation types suggests that charcoal characteristics (dimensions, fragility) are dependant on fuel type and fire intensity (Dark 1998, Umbanhowar and McGrath 1998, Pitkänen *et al.* 1999). It is possible that the Poaceae species involved produce small and fragile charcoal, which is more easily broken, thus contributing to high frequencies of small charcoal fragments.

This long-lasting fire regime is not associated with a decline in woodland cover or in grazing-sensitive tall-herb communities. The continuous presence of herbs which are adapted to disturbance may have been maintained by frequent, low intensity disturbance and unstable niches. This suggests that grazing pressure, if present, was of low intensity, and perhaps that human interference, such as burning to maintain nutritious, open grassland to attract herbivores (*cf.* Bennett *et al.* 1992, Simmons and Innes 1996b, Mellars and Dark 1998), was not involved. The dominance of relatively short-lived trees, contributing fuel, on well-drained alluvial sediments, may have been easily flammable in dry seasons and lightening storms. The palaeoecological data from Glen Affric are compared with palaeoclimatic evidence from the Highlands in Chapter 9, and possible reasons for the cessation of the charcoal-Poaceae correlation at 4630 BP (5320 cal BP) are discussed in Section 6.5.3.

The initial small increase in absolute and percentage *Pinus* values at *c.*8340 BP (9370 cal BP) coincides with a reduction in absolute and relative *C. avellana*-type and *Filipendula* frequencies and a slight increase in *Calluna vulgaris* and *Potentilla*-type values. This may indicate soil deterioration, which allowed *Betula* to expand onto formerly more nutrient-rich soils formerly occupied by *C. avellana*-type. If this is representative of more widespread change, this may also have aided the regional spread of *Pinus sylvestris.*

A further rise in *Pinus* percentage and concentration values above 7420 BP (8160 cal BP) suggests that *Pinus* became established in the extralocal source area. Increased *Pinus* representation may be the cause of a slight increase in broken pollen (*cf.* Cushing 1964). There is no stomatal evidence for local *Pinus* growth; extralocal establishment may have caused the marked fall in absolute *Betula* frequencies with a slight percentage decline, a reduction in *Sorbus* and *Prunus padus* representation. *Sorbus* and *Prunus* pollen is poorly dispersed, suggesting that *Pinus* may have become established in quite close proximity to the channel, perhaps on better-drained, acidic soils on the surrounding hillslopes which may have been suitable for *Sorbus.*

At this time, *Pinus* does not appear to have been able to invade the local woodland adjacent to the sampling channel, since *Pinus* values remain constant at *c.*10% through inferred local fluctuations in *Betula* and *Salix* between 6990 and 6760 BP (5730-7550 cal BP). Competitive exclusion may have prevented *Pinus* from taking advantage of local soil disturbance as *Pinus* gives way to *Betula* on better soils, only predominating under less favourable and more continental climatic conditions (Steven and Carlisle 1959). This may be inferred at Carnach Mór from the continued presence of more nutrient-demanding tall-herb taxa, and stratigraphic evidence for sediment deposition. The palynological evidence for environmental factors affecting the balance between *Betula* and *Pinus* in the uplands of Glen Affric are discussed further in Chapter 9.

A shift from tall-herbs to Cyperaceae around 6140 BP (7010 cal BP) is followed, at 5880 BP (6720 cal BP), by the onset of highly organic sediment accumulation and a sudden increase in absolute and percentage values for *Sphagnum*. The shift in channel vegetation may be a response to more acidic conditions, resulting in the replacement of more basiphilous tall-herbs by Cyperaceae and *Sphagnum*. This may be reflected in the slight fall in palynological richness around 6140 BP (7010 cal BP). As some of the water flowing into the channel will have been derived from runoff and flooding from the adjacent hills and valley floor, this may reflect a wider change in soil and growing conditions, which could have enabled *Pinus* to compete with *Betula* and thus become established locally (*cf.* Carlisle and Brown 1968, Richardson 1998). There is a further decline in *Betula* percentages as *Pinus* values rise slightly at 6250 BP (7170 cal BP), with a more pronounced *Betula* reduction as *Pinus* frequencies increase from 6020 BP (6870 cal BP). Wetter conditions may have resulted in a reduction in charcoal frequencies at 6140 BP (7010 cal BP). Evidence for regional climatic changes is discussed in Chapter 9.

6.5.3 Zone CAR2a: *Betula-Pinus sylvestris-Alnus glutinosa* (290-250 cm; 5950-4190 BP, 6780-4720 cal BP)

Evidence for changes in woodland and understorey vegetation during this zone suggests changes in soil nutrient pH which may have climatic implications, with limited palynological evidence for anthropogenic or grazing disturbance. These are summarised in Figure 37 and are reflected in the DCA results by a shift away from earlier fen wood taxa. As the composition and structure of herbaceous and woodland communities appear to be closely inter-related, arboreal and herbaceous data are integrated, before examining the possible causes of change.

High TLP concentrations and accumulation rates are recorded from 5170-4460 BP (5920-5040 cal BP) (Figs. 29 and 30). Relatively slow accumulation, not detected with the available dating controls, could have inflated absolute pollen values, as all taxa are affected, particularly *Pinus*, *Alnus* and *Calluna*, initially *Betula* and *C. avellana*-type and latterly Poaceae, Pteropsida.

Changes in woodland composition and structure during zone CAR2a suggest increasing differentiation between communities within the woodland mosaic. Changing edaphic and possibly over-riding climatic conditions, are inferred, with slightly later evidence for grazing and thus possibly human activity. Maximum Holocene *Pinus* frequencies of 29% are recorded at 5880 BP (6720 cal BP), although there is only a single *Pinus* stomate in zone CAR2a, at 5340 BP (6140 cal BP). This coincides with NAP evidence for a shift to more acidic conditions which may have allowed *Pinus* to encroach on birchwood growing on the floodplain or on the hillslopes. Although it is difficult to infer mire expansion from a peat accumulation with possible *in situ* growth of peat species, increased acidity is inferred from a peak in Cyperaceae at 5700 BP (6480 cal BP) and sustained high *Sphagnum* frequencies. A further reduction in tall-herb taxa may also reflect increased acidification and wetness, which enabled mires to expand. However, subsequent shading and grazing pressure are also suggested to have tall-herb communities (below).

Mire expansion may have constrained woodland growth, whilst perhaps shifting the balance in favour of *Pinus* at the expense of *Betula*, as *Pinus* is generally associated with leached soils of low base status (Carlisle and Brown 1968, Richardson 1998). The increase in *Calluna vulgaris*, *Vaccinium*-type and *Erica* frequencies from 5170-4630 BP (5920-5320 cal BP), and rising Poaceae values from 4990-4460 BP (5730-5040 cal BP) provide further evidence for the development of a more acidophilous, nutrient-deficient ground cover. The range of *Calluna* values from surface sample studies in open and wooded environments suggests that *Calluna* frequencies of 14% at Carnach Mór may reflect limited local growth or derive from extralocal and regional pollen deposition beneath a more open or patchy canopy (Tinsley and Smith 1974, Caseldine 1981, Evans and Moore 1985, Gearey and Gilbertson 1997). No pollen clumps were recorded to suggest local growth, but the frequencies of *Vaccinium*-type and *Erica* suggest the local presence of heath species, since these taxa can be absent in surface sample studies, even when they are present in abundance in the vegetation (Tinsley and Smith 1974, Lloyd 1998). Increased *Calluna* and maximum *Sphagnum* frequencies may indicate local peat growth, which could reflect acidification as organic sediment accumulated and drainage became impeded (Conway 1954, Tipping 1995b).

The relatively high nutrient status of alluvial or flushed soils, and perhaps better drainage, may have continued to prevent *Pinus* from assuming dominance. Frequent, low intensity disturbance may have helped to perpetuate vegetation dominated by ruderal and pioneer taxa, by favouring species with a high reproductive capacity, such as *Betula* (Atkinson 1992), although this is not clearly resolved at the lower temporal resolution of 180 ^{14}C (220 cal) years/interval.

The composition of the woodland within the source area of Carnach Mór changed further with the gradual expansion of *Alnus glutinosa*. Absolute and percentage values rise around 6080 BP (6940 cal BP). *Alnus* does not show high values that might be consistent with local over-representation (Janssen 1959, Andersen 1973), suggesting that the species was not abundant. Only around 5170 BP (5920 cal BP) do *Alnus* values rise above the 10% level thought to indicate *Alnus*-dominated vegetation within the catchment (Huntley and Birks 1983). The stepped rise in *Alnus* culminates in a Holocene maximum of 32% at 4460 BP (5040 cal BP), which is late in the Holocene, even allowing for localised factors leading to expansion (Bennett and Birks 1990). *Alnus* expansion is associated with a further decline in *Betula* frequencies, suggesting that the extent of *Betula* woodland was reduced due to competition from *Pinus* and *Alnus*. *Alnus* may have replaced or reduced the flowering of damp tall-herb and shrub communities on seasonally flooded ground on the floodplain, reducing the percentage and absolute values of *Salix*, *Viburnum*, *Filipendula*, *Valeriana officinalis* and Apiaceae from 5950 BP (6780 cal BP).

The relatively low abundance of *Alnus* does not seem to be due to an absence of suitable habitats, since flushed soils and floodplain habitats are inferred around the channel (*cf.* McVean 1953, Huntley and Birks 1983). *Alnus* expansion may have been restricted by altitudinal constraints on reproduction (*cf.* McVean 1955, 1956a, b; see Section 9.1.4). It is also possible that, within the shifting woodland mosaic, locally suitable conditions for *Alnus* establishment did not occur until 4460 BP (5040 cal BP). Expansion may have been aided by disturbance (Chambers and Elliott 1989), indicated by an influx of mineral sediment, which could have exposed bare soil suitable for seedling establishment (Bennett and Birks 1990) and shaded out *Calluna* and Poaceae. However, the *Alnus* peak is confined to a single pollen subsample, suggesting that *Alnus* may have been more abundant for only a single or few generations, before *Betula* expanded *c.*180 ^{14}C (*c.*220 cal) years later. The role of *Alnus* in the uplands of Affric is discussed further in Chapter 9.

The decrease in Poaceae and *Calluna* at 4460 BP (5040 cal BP) coincides with the expansion of *Alnus* and the end of the correlation between the Poaceae and charcoal curves, as discussed above (Section 6.5.2). Subsequently, charcoal values are temporarily reduced, and Poaceae values only increase markedly again around 2730 BP (2790 cal BP). Wetter climatic conditions may have reduced burning, or the development of denser woodland with larger and longer-lived trees such as *Pinus*, *Quercus* and *Ulmus* may have reduced the cover of previously flammable herbaceous vegetation and tied up more fuel in growing tissues.

Changing environmental conditions may have enabled *Quercus* and *Ulmus* to become established, contributing to increased arboreal diversity in zone CAR2a and causing a shift in the DCA sample scores. *Quercus* attains 2% values around 6140 BP (7010 cal BP) and maintains higher percentages until *c.*4720 BP (5350 cal BP). *Ulmus* frequencies rise above 2% at *c.*5610 BP (6400 cal BP), before declining at *c.*4900 BP (5630 cal BP). This suggests sparse local growth (Huntley and Birks 1983), as the dates are late for regional expansion, particularly that of *Ulmus* (Birks 1989). The establishment of even limited numbers of longer-lived and taller *Quercus* and *Ulmus* trees within the woodland canopy may have reduced the flowering or growth of *Betula*. *Ulmus* may have grown on more base-rich flushed soils, perhaps with *C. avellana*-type. *Quercus* is tolerant of more acidic soils and may thus have grown with *Betula*, *Sorbus* or *Alnus*, perhaps with *Pinus* on wetter acidic soils. This may indicate edaphically-controlled patterning in the woodland mosaic.

Although the number of arboreal species appears to have increased, palynological richness is lower in zone CAR2a, perhaps reflecting a reduction in understorey pollen productivity beneath a denser canopy cover, as cumulative frequencies of tree pollen are slightly higher (Fig. 28). The slight reduction in rates of change may result from the reduction in temporal resolution during this zone (*cf.* Seppä 1998) and consequently, an apparently gradual rate of change.

The reappearance of *Plantago lanceolata* at 4280 BP (4840 cal BP) coincides with increased *Rumex acetosa*, more frequent *Cichorium intybus*-type, the absolute and relative expansion of *Betula* and reductions in *Pinus* and *Alnus*. As indicated above, *P. lanceolata* does not appear to have been common in naturally unstable alluvial habitats. This may infer a change in the cause of disturbance, such as the onset of grazing disturbance. Browsing is also suggested to have been one of several factors affecting arboreal regeneration.

Although the poor temporal resolution (180 ^{14}C/220 cal years/sampling interval) limits interpretation of the rapidity and possible causes of change, increasing oceanicity may have enabled *Betula* to out-compete *Pinus* and *Alnus* (McVean 1953, Carlisle and Brown 1968, Atkinson 1992), as the evidence for deliberate clearance and scrub regrowth is limited; only *Betula* responds and there is no rise in non-arboreal pollen as would be expected from the creation of open ground. Peat formation is not evident until 4190 BP (below) but it is possible that there was a lag between climatic change and peat expansion. The decline in *Filipendula* on the zone CAR2a/b boundary may be indicative of a lower pH due to leaching, and/or the effects of grazing (Bennett *et al.* 1992).

Despite the evidence for acidification and peat formation, there is evidence that more nutrient-rich soils were still present. *Corylus avellana*-type values do not change as *Pinus* frequencies increase and the presence of herbs such as *P. lanceolata*, *Filipendula*, *Ranunculus acris*-type, *Potentilla*-type, *Melampyrum* and *Succisa pratensis*, does not suggest replacement by a uniformly species-poor heathland or peat flora. Neither do the DCA results suggest a large shift towards acidophilous taxa. The reduction in *Sorbus* may infer that *Pinus* spread onto more acidic soils. Patches of more nutrient-rich soils with *C. avellana*-type and species-rich grassland are suggested to have occurred on well-drained, more rocky slopes or alluvial river terraces which received groundwater and perhaps slight flushing from the river or streams. There is no evidence that *C. avellana*-type represents *Myrica gale* at this time, contrasting with the clear later Holocene separation of these pollen types. Evidence for edaphic controls in community distribution on the floodplain and hillside are discussed further in Chapter 9.

The relatively short-lived changes in arboreal frequencies between *c.*4630 and 4280 BP (5320-4840 cal BP) suggest that fluctuations in growing conditions temporarily allowed *Pinus* and *Alnus* to expand but then enabled *Betula* to once more out-compete *Alnus*. Changes in woodland cover continue through zones CAR2b and CAR2c, where additional evidence for possible causal mechanisms is discussed.

6.5.4 Zone CAR2b: Cyperaceae-*Betula-Alnus-Pinus* (250-214 cm; 4190-3880 BP, 4720-4280 cal BP)

A complex and rapid series of changes occur in zones CAR2b and CAR2c (Fig. 37). These suggest a number of environmental changes which had contrasting effects related to soils, hydrology and geomorphology. Renewed mire expansion suggests wetter and more acidic conditions, which appear to have curtailed woodland regeneration, culminating in woodland decline and the transition to an open landscape. This contrasts with the expansion of more nutrient-demanding, dryland herb and arboreal taxa, and increased charcoal frequencies, which strongly suggest anthropogenic and grazing pressures on woodland communities which were already growing under climate-induced stress. Woodland reduction coincides with the only period during which *Pinus* stomata suggest local growth. The DCA evidence also implies a transition from woodland to acid and open communities.

Rapid peat accumulation (Fig. 27) is suggested to have resulted in a rapid shift to very high rates of change and finer temporal resolution (Table 16). The vegetation shifts and the inferred causes are described in this and the following zone, discussing in chronological order the non-arboreal and arboreal pollen evidence of change.

The most marked changes in zone CAR2b are recorded in herbaceous taxa, as the range of herbs suggests the expansion of mire and dry grassland communities from around 4190 BP (4720 cal BP), indicating environmental changes which created ecologically contrasting open communities, one favoured by wet, low pH conditions and the other by drier, more nutrient- and base-rich conditions, which may have been affected by grazing. Evidence for mire expansion is discussed first as these data may relate, at least in part, to changes within the sampling channel.

Increases in Cyperaceae, *Potentilla*-type and *Sphagnum*, with a smaller rise in Poaceae and *Calluna* pollen infer mire or peat formation at 4190 BP (4720 cal BP) (*cf.* Fossitt 1994b). Changes in channel vegetation are indicated by the stratigraphic change from wood to herbaceous peat around 5520 BP (6300 cal BP) at 280cm, and a fibrous root mat between 4030 and 3960 BP (4470-4410 cal BP), from 235-225 cm.

The scale of mire expansion is difficult to infer from the site. Lower frequencies for *Filipendula*, Apiaceae, *Valeriana officinalis* and Rubiaceae may indicate that mire or blanket peat replaced tall-herbs. This suggests a reduction in soil nutrient status, with at least a local change to wetter and more acidic conditions which may have been less favourable for tree regeneration, as discussed below. However, from *c.*4080 BP (4540 cal BP), absolute arboreal pollen values are reduced relative to Cyperaceae and *Potentilla*-type, indicating that the percentage reduction in tree and shrub pollen is not an artefact of the method of calculation, and suggesting a reduction in the extent of woodland, coincident with the expansion of mire taxa.

Pollen from herbs of drier, neutral or more base-rich soils and open ground or woodland edges are also recorded more frequently in zone CAR2b. This includes *Plantago lanceolata*, *Solidago virgaurea*-type, *Stellaria holostea*, *Artemisia*-type and spores of *Selaginella selaginoides*, and suggests that woodland loss was not confined to wet soils such as the sampling channel, but was also occurring on dryland, possibly alluvial, soils. The increased frequency of *P. lanceolata* in particular suggests a distinct ecological change, inferring that grazing disturbance may have placed further stress on tree regeneration. This is discussed below in zone CAR2c, where continued and more marked changes are recorded.

A sharp peak in charcoal-to-pollen ratios at 4050 BP (4460 cal BP) coincides with peaks in *Betula*, *Sorbus* (to 3.5%), *Calluna*, *Vaccinium*-type, *Rumex acetosa*, *Filipendula*, Apiaceae, *Polypodium* and Pteropsida spores, with a grain of *Fraxinus*. This may indicate that scrubby woodland, pioneer herbs and heaths colonised the burnt ground. Charcoal size class data for this period show an increase in the abundance of large (>75 μm) relative to smaller fragments (10-25 μm, 26-50 μm and 51-75 μm) (Fig. 36). This suggests a fire closer to the sampling site, rather than a secondary charcoal source, where breakage during transport may increase the number of smaller fragments. A slight rise in corroded pollen grains suggests a small amount of inwashed or reworked pollen, but most pollen remains well-preserved (62%), suggesting that the pollen spectra can still be considered a reliable indication of vegetation changes at this time. The abrupt decline in sediment organic content is therefore interpreted as a consequence of burning, rather than the cause of charcoal deposition and pollen fluctuations. High temporal resolution during this zone suggests that post-fire succession occurred over a short time period, with a maximum duration of *c.*20 ^{14}C (30 cal) years between this horizon and adjacent samples, above and below, perhaps indicating a natural fire rather than deliberate vegetation manipulation.

Frequencies of *Betula*, *Pinus*, *Quercus*, *Alnus* and *C. avellana*-type decline from *c.*4190-4000 BP (4560-4440 cal BP). Percentage reductions are non-synchronous, possibly reflecting differences in ecological tolerance to mire expansion and grazing pressure. Subsequently however, *Pinus*, *Alnus* and *Quercus* frequencies increase between 3980 and 3840 BP (4420-4230 cal BP), with a slight increase in *Corylus avellana*-type. A reduction in grazing pressure or low intensity grazing, possibly combined with short-term climatic fluctuations may have enabled regeneration or increased flowering. *Quercus*, *Alnus* and *Pinus* are able to tolerate wetness and acidity, which may have enabled regeneration on peaty soils when drier conditions allowed. *Alnus* may have fringed the river, as values of 7-20% suggest some *Alnus* growth around the channel or within the wider source area. *Quercus* values of 1.2-3.9% suggest that *Quercus* was not abundant, but may have been present in the local or extralocal source area (Huntley and Birks 1983), growing on acidic and damp, not waterlogged, soils (Jones 1959, Grime *et al.* 1988).

Pinus stomata are recorded from 4100-3840 BP (4560-4230 cal BP) with pollen values of between 5.5 and 16.6%. Pollen preservation data do not suggest the erosion of peat containing *Pinus* pollen and stomata, which may be expected to contribute peaks in both with damaged *Pinus* grains due to reworking. Previously, 20% has been regarded as a minimum to indicate local pine growth (Bennett 1984), but stomata have been found in lake sediments with comparable percentages to Carnach Mór, and at values of less than 5% *Pinus* pollen (Fossitt 1994a and b). Such low pollen percentages with stomata may imply that *Pinus* growing locally in low numbers, or in larger proportions but with flowering suppressed by sub-optimal conditions, perhaps on peat, as low pollen percentages have been recorded from peat adjacent to subfossil pine stumps (Bridge *et al.* 1990).

Local *Pinus* growth may therefore only have occurred for a short period, under climatically and/or edaphically adverse conditions. *Pinus* may also have faced competition from *Quercus* and *Alnus* on drier and wetter soils, respectively. The normal lifespan for *Pinus* appears to be less than 200 years, and may be no more than 125 years on bogs (Steven and Carlisle 1959, Carlisle and Brown 1968, Bridge *et al.* 1990). The duration of the stomatal curve (260 ^{14}C/310 cal years) suggests only around two generations may be represented at Carnach Mór. Many subfossil *Pinus* stumps are eroding out of the peat on the low hill to the west of the site and indicate one possible source of *Pinus* pollen in the immediate vicinity and infer wetter conditions for preservation (Birks 1975, Bridge *et al.* 1990), although these are undated.

Single spectral peaks in *Betula* at 4280 BP (4840 cal BP) and 3840 BP (4230 cal BP) may indicate intermittent growth near the channel, resulting in short-lived bursts of pollen production above the extralocal or regional background signal. The preservation data do not suggest that the peaks are the result of reworking as well-preserved pollen remains dominant through zone CAR2b. The temporal resolution (see Table 16) suggests only two to three generations growth, as *Betula* trees live only 60-70 years (Grime *et al.* 1988) and each sampling interval represents *c.*180-110 ^{14}C (220-150 cal) years between samples. This may be the result of edaphic deterioration and/or grazing pressure, which prevented even *Betula*, which is tolerant of marginal conditions (Atkinson 1992), from successfully regenerating.

The changes in arboreal and herbaceous pollen taxa in zone CAR2 infer marked environmental changes around the sampling site, with increasing wetness and acidity, possibly caused by climatic deterioration, contrasting with evidence for grazing disturbance as woodlands declined, replaced by mire and grassland. Although a reduction in pollen interception by the canopy cover could have made pre-existing grass- or heathland communities more visible in the pollen record during zone CAR2b, absolute pollen changes and the stratigraphic change from wood to herbaceous peat support the argument that increases in Poaceae, open ground herbs and *Calluna* frequencies reflect the contemporaneous expansion of open communities. Variations in mid-Holocene arboreal pollen responses are discussed in more detail in Chapter 9.

6.5.5 Zone CAR2c: *Calluna vulgaris*-Cyperaceae-*Betula* (214-178 cm; 3870-2920 BP, 4280-3060 cal BP)

There is continued evidence for local mire and blanket peat expansion in zone CAR2c, with an increase in *Calluna* frequencies at 3870 BP (4280 cal BP), higher Poaceae and rising Cyperaceae values. Frequent *Vaccinium*-type, *Erica* and *Empetrum* pollen suggests that these poorly represented taxa were present locally. A single *Rumex acetosella* grain may infer dry heathland or acidic grassland. Absolute reductions in arboreal pollen, and lower and more sporadic records for *Plantago lanceolata*, *Ranunculus acris*-type, *Potentilla*-type, *Filipendula*, *Succisa pratensis* and Asteraceae suggest that heath and mire expansion was not confined to the sampling channel alone. Heath and mire expansion suggests a further reduction in soil nutrient status, which may have been detrimental to tree regeneration, reflected in the stepped reduction in *Betula*, *Pinus*, *Quercus*, *Alnus* and *C. avellana*-type at 3870 BP (4280 cal BP) and 3180 BP (3380 cal BP), particularly if grazing was sustained.

Coincident with the expansion of *Calluna* at 3870 BP (4280 cal BP), the charcoal record shows a sharp increase in all fragment size classes. A slight increase in the ratio of fragments >75 µm:10-25 µm may indicate that the fires were in closer proximity to the channel (see Fig. 36). The sudden rise in charcoal fragments cannot be explained by the disappearance of a woodland canopy, as woodland decline was a more gradual process. In addition, high levels of charcoal occur during the earlier Holocene under woodland cover. LOI values are high and do not suggest reworking. A sustained increase in crumpled pollen at this horizon is most apparent in easily collapsed grains, such as Poaceae and Cyperaceae, and also in *Betula*, perhaps indicating an increase in the distance between *Betula* populations and the sampling site.

It is difficult to ascertain whether the expansion of *Calluna* is the cause or result of increased burning, and thus whether burning aided blanket peat expansion, as both curves rise simultaneously at the temporal resolution of 67 ^{14}C years (86 cal years) between samples and *c.*8 ^{14}C years (*c.*11 cal years) per subsample. *Calluna* responds to burning (Hobbs and Gimingham 1987). Heathland may have been more easily flammable than earlier woodland communities, due to the build up of surface litter beneath *Calluna*, compared with the more rapid breakdown and recycling of litter in woodlands (Hobbs and Gimingham 1987, Peterken 1996). However, the palynological evidence strongly supports an anthropogenic interpretation. The evidence for climatic and anthropogenic controls are discussed below.

The curve for *Melampyrum* ends around 3510 BP (3760 cal BP) and may result from the loss of suitable woodland habitats and changing environmental conditions, again suggesting that it is not a fire-responsive taxon. There is a more pronounced increase in the absolute values of heaths and herbs relative to trees and shrubs from 3180 BP (3380 cal BP), suggesting a transition to a more open landscape around Carnach Mór. A single grain of *Frangula Alnus* pollen was recorded at 3180 BP (3380 cal BP). This entomophilous shrub occurs on peaty, often base-poor soils in open woods or on bogs, and may thus have been a minor, palynologically silent component of open woods or mire vegetation on damp floodplain soils (*cf.* Chambers and Elliott 1989).

The wide number and ecological ranges of the species involved suggest a non-specific mechanism, such as climatic change or sustained grazing. Climatic deterioration, with increased precipitation, leaching, rising watertables and paludification, may have promoted mire expansion at the expense of woodland regeneration. Mires may have become self-perpetuating, reinforcing woodland decline, as the canopy became sparser (*cf.* Moore 1988, 1993). However, climatic deterioration would not be expected to increase *Quercus* frequencies. At present, *Quercus* is dominant over *Betula* in Highland birch- and oakwoods in the more continental climate of eastern Scotland, with *Betula* attaining dominance in the north and west (Atkinson 1992). Increased seasonality or periods of summer dryness may have enabled small *Quercus* populations persisting on damp acidic soils to expand slightly, particularly between 3980 and 3910 BP (4420-4370 cal BP), although the genus remained subordinate to *Betula*, *Pinus* and *Alnus*.

The evidence for mire expansion and short-lived arboreal expansion in zone CAR2b may also infer that periods of dryness shifted the balance between blanket peat expansion and tree regeneration, perhaps also causing changes in peat accumulation and fluctuations in absolute pollen values (Fig. 27, 29-30). Although drier summers may also have increased burning, the increase in charcoal frequencies occurs later, at 3870 BP (4280 cal BP) and an anthropogenic explanation is preferred, as discussed below.

Grazing is difficult to conclusively identify in the pollen record from Carnach Mór, as some 'pastoral indicators' occur earlier in the Holocene in response to natural disturbance and unstable, flushed alluvial soils around the sampling site. However, the contrast between wet, acidic mire expansion and the rising number of species associated with disturbed and relatively base-rich grassland, with higher charcoal frequencies from zone CAR2c, strongly suggest increasing anthropogenic activity and grazing pressure from stock rather than wild herbivores. This may have suppressed woodland regeneration and contributed to mire expansion. Under adverse climatic conditions, even low intensity grazing may have prevented tree regeneration in the long term.

As indicated above, the timing of the abrupt and sustained expansion in *Calluna* and charcoal frequencies at 3870 BP (4280 cal BP), coinciding with increasing evidence for grazing disturbance, is argued to reflect early Bronze Age land management rather than a seasonally dry climate. Heathland management could have been used to supplement possibly limited upland grassland pastures. Two Poaceae grains with annulus diameters greater than 8 µm were recorded at 4080 BP (4540 cal BP) and 3180 BP (3380 cal BP), in zones CAR2b and CAR2c. This pollen type exhibits a strong correlation with *Hordeum* group pollen during the early and later Holocene, but it is unclear whether these two grains represent small cereal grains, aquatic grasses or other wild grasses. The grain size measurements of the first was below the normal range for *Hordeum* group and the second was too poorly preserved to measure (Table 5).

6.5.6 Zone CAR3a: Poaceae-*Myrica gale*-*Calluna* (178-122 cm; 2910-1880 BP, 3060-1820 cal BP)

There is increasing evidence for grassland, meadow and mire diversification, and for agricultural land-use during the late Bronze Age. Increasing palynological richness from 2890-2440 BP (*c.*2980-2380 cal BP) is taken to indicate an increase in vegetational diversity as a result of the creation of new niches by anthropogenic disturbance and settlement.

Zone CAR2c terminates with the expansion of *Myrica gale* pollen to 39% over an interval of *c.*74 ^{14}C (90 cal) years, and a corresponding fall in Cyperaceae values. More frequent *Corylus*/*Myrica* pollen is also recorded, while *C. avellana*-type pollen frequencies remain below 10%. Although the separation of *Corylus avellana* and *M. gale* pollen is problematic (Edwards 1981; Section 4.3.1.1), surface sample studies indicate that *Myrica* pollen is poorly dispersed, producing a local pollen signal (Birks cited in Kerslake 1982, Lloyd 1998). *Myrica* pollen at Carnach Mór may thus derive from mire communities within the sampling channel, dominated by *Myrica*, Cyperaceae and *Calluna*, perhaps with *Drosera intermedia*.

Increased Poaceae and *Potentilla*-type frequencies at 2730 BP (2790 cal BP) may derive from either grassland or mire habitats. A fall in *Myrica* pollen frequencies at *c.*2510 BP (2570 cal BP) suggests that some of the Poaceae pollen was derived from bog species such as *Molinia caerulea*, rather than dryland taxa. *Molinia*-*Myrica* mires occur on periodically flooded ground alongside water courses, producing peat which is well humified with a large amount of alluvial sediment (McVean and Ratcliffe 1962), and may have occurred in the sampling channel at

Carnach Mór with *Calluna* and Cyperaceae, as lower organic content is recorded from 2920 - 2320 BP (3070-2340 cal BP, 178-146 cm). This is evidence in the DCA from the association of sample scores with Poaceae, *Potentilla*-type, *Calluna* and *Myrica*.

Although it is difficult to distinguish between grassland types in the pollen record (*cf.* Greig 1984, 1988), many herbaceous species in zone CAR3a suggest the spread of species-rich meadow and grassland. This includes *P. lanceolata*, the increased occurrence of *Ranunculus acris*-type, *Succisa pratensis*, *Cichorium intybus*-type and *Solidago virgaurea*-type, *Thalictrum*, *Urtica* and *Trifolium*-type pollen, and continued *Filipendula*, Apiaceae and *Rumex acetosa*. Marshy grassland and flood meadows are dependent on the deposition of mineral-rich silt when rivers over-top their banks, and may thus have been maintained near the channel by a seasonal flooding regime. This rich source of upland grazing could have attracted farmers to the area, perhaps also providing winter fodder through mowing (Gaillard *et al.* 1992). At present, *P. lanceolata* is absent from acidic upland soils, where it is restricted to tracks and sheep-walks (Sagar and Harper 1964); the continuous curve for *P. lanceolata* therefore suggests grazed grassland or mown meadow (Sagar and Harper 1964, Gaillard *et al.* 1992). It has also been interpreted as a species of fallow ground (Groenman-van Waateringe 1986), although modern surveys suggest that it is less common in arable than grassland communities (Sagar and Harper 1964).

A single *Hordeum* group pollen grain at *c.*2660 BP (2760 cal BP), with occasional *Artemisia*-type and Chenopodiaceae pollen, infer late Bronze Age cultivation and arable weeds. With the possible exception of *Filipendula*, there are no marsh or aquatic taxa suggesting wetland habitats suitable for *Glyceria* (*cf.* Grime *et al.* 1988). The increased frequency of herbs which prefer drier, better-drained and more base- or nutrient-rich soils suggests that ground suitable for barley cultivation may have been present locally on alluvial sediment, rather than originate from distant habitats and activity (*cf.* Vuorela 1973).

Continuing high charcoal values may indicate associated heathland management as well as domestic burning. An increase in charcoal size class ratios from *c.*2730 BP (2790 cal BP) suggests that fires may have burned in closer proximity to the site. This further suggests that human activity was occurring near the sampling site. Higher rates of vegetation change from 2510 BP (2570 cal BP) and increased palynological richness may result from soil disturbance caused by animal trampling, soil enrichment due to dung and other vegetation manipulation caused by farmers and their livestock.

6.5.7 Zone CAR 3b: Poaceae-*Calluna*-Cyperaceae (122-50 cm; 1880-410 BP, 1820-490 cal BP)

During zone CAR3b, the peat is consistently highly minerogenic (19-56% organic content). This coincides with higher frequencies of crumpled and corroded pollen (in all major taxa), and Pteropsida spores. This suggests inwashing or erosion. However, as well-preserved pollen still dominates the assemblage, and indeterminate pollen frequencies are low, the assemblage is not suggested to have been significantly distorted.

Several possible causes of erosion can be suggested: anthropogenic activity, such as bare soils exposed by cultivation, trampling and soil disturbance by humans and grazing animals, increased natural flushing and runoff from the adjacent hillsides, or the closer proximity of the river. The evidence does not suggest a single source of eroding sediment, although agricultural land-use and settlement may have increased natural rates of erosion, such as more intensive or extensive agriculture from *c.*780 BP (680 cal BP, cal AD 1280). The increase in LOI in zone CAR3c, when evidence for agriculture declines and ceases, may in part be associated with a reduction in soil disturbance due to the decline and abandonment of agricultural settlement.

The decline in *Myrica* at 1840 BP (1740 cal BP) is as rapid as its expansion, occurring over an interval of 70 ^{14}C (90 cal) years. The decline coincides with an increase in Poaceae and *Betula*. Higher *Betula* values are sustained over two sampling intervals, from *c.*1840-1760 BP (1740-1650 cal BP), an estimated period of 80 ^{14}C years (90 cal years), approximately one to two generations. A rise in damaged, mainly corroded, pollen at this time may arise from erosion or flooding, indicated by increased LOI. However, the preservation data for *Betula* do not suggest that the sustained increase is the result of reworked pollen. The opportunist strategy of *Betula* may have enabled chance establishment beside the sampling channel.

Betula colonisation may have occurred as the sampling site and surrounding ground became drier, allowing increased frequencies of Poaceae and grassland herbs, slight increases in *Vaccinium*-type and *Empetrum*, and reducing the local abundance of *Myrica*. The subsequent decline in *Betula* from 1760 BP (1650 cal BP) indicates that conditions were not conducive to regeneration over the longer term. This may have been due to human or grazing activity, as the palynological evidence for pastoral and arable activity is more abundant in zone CAR3b, and increased palynological richness from 1760 BP (1650 cal BP, cal AD 300) is associated with cultivation and a more diverse grassland flora.

Increased herb frequencies in zone CAR3b, especially of *P. lanceolata*, suggest intensified or more extensive pastoral land-use during the Iron Age. This is reflected by a shift in DCA sample scores towards taxa of open and agricultural environments which persists to the top of the sequence. Pastoral resources may have included dry grassland and wet meadow. Possible meadow species include Poaceae, Cyperaceae, *R. acris*-type, *P. lanceolata*, Fabaceae, Asteraceae, *Filipendula* and Apiaceae, with less frequent *Caltha palustris*-type, *Thalictrum* and *Succisa* (Greig 1984, 1988, Rodwell 1992). A number of possible habitats may be inferred from the increase in Rubiaceae pollen, several of which may also be suggested from other herbaceous taxa recorded, including acid heath or grassland (*cf. Galium saxatile*), mown meadow or drier fens (*cf. G. palustre*), fen or waste ground (*cf. G. aparine*).

Three Poaceae with large annulus diameters, including one *Hordeum* group, were recorded with *Papaver rhoeas*-type between 1760 and 1590 BP (1650-1500 cal BP, cal AD 300-450), suggesting some cultivation during the later Iron Age or Pictish period. The close correspondence between *Hordeum* group pollen and Poaceae anl-D>8 µm in both early and later Holocene suggests that many of the latter may be small or damaged *Hordeum* group grains (Fig. 28). Wagenitz (1955, cited in O'Connell 1986) demonstrated that cereal pollen size is affected by soil fertility and water availability, although the range of variation is not stated. The generally nutrient-poor status of soils in Affric may have affected cereal pollen size, thus resulting in the close correspondence between Poaceae anl-D>8 µm and *Hordeum* group pollen frequencies.

The *P. rhoeas*-type curve is continuous from 1280 BP (1210 cal BP, cal AD 740), and a further increase in the range of herbs occurs at 1170 BP (1070 cal BP, cal AD 890), when the records of *Hordeum* group and Poaceae with an annulus diameter greater than 8 µm (Poaceae anl-D>8 µm) become consistent. A single possible *Avena/Triticum* group grain occurs at 640 BP (590 cal BP) (see Table 18), suggesting that oats may also have been grown, as climatic and edaphic conditions do not appear conducive to the cultivation of wheat (*cf.* Coppock 1976). Higher values for *P. lanceolata*, *R. acris*-type, *Rumex acetosella*, Fabaceae and *Cichorium intybus*-type may infer more intensive or extensive pastoral land-use. Sustained *P. lanceolata* values pre-date the evidence for more frequent or abundant cultivation, suggesting that this herb may have occurred predominantly in grassland, rather than as a field edge species, or a ruderal of arable or fallow ground (*cf.* Groenman-van Waateringe 1986, Molloy and O'Connell 1991). *R. acetosella* may reflect the presence of dry, acidic grassland or heath.

Neutral or more base-rich conditions and higher nutrient levels are inferred from the frequent occurrence of *Selaginella* spores and many of the herbs in zone CAR3, including *Plantago lanceolata*, *P. media/major*, *Thalictrum*, *Lychnis flosi-cuculi*, *Artemisia*-type, *Urtica* and *Centaurea nigra*. As indicated above, natural flushing with mineral-rich soils may have contributed to their presence, and consequent wet meadow formation. Alternatively, nutrient-enrichment from dung, whether purposeful or incidental to grazing, may have been created suitable edaphic conditions, as taxa such as *Artemisia*-type and *Centaurea nigra* occur on dry soils rather than as meadow species. There is archaeological and ethnographic evidence for the importance of manuring for cultivation from prehistoric until recent times in the Highlands and Islands (Fenton 1976, Simpson *et al.* 1998; see Section 9.6.2.5). Unfortunately it is difficult to separate natural and anthropogenic elements of the pollen record and thus distinguish the sources of nutrient enrichment, particularly where natural disturbance occurs on river banks and unstable alluvial gravel bars. Recording fungal spores might have helped to establish whether manure was present locally (*cf.* Van Geel 1978, Van Geel *et al.* 1981, Long *et al.* 1998).

More frequent *Cryptogramma crispa* spores during zones CAR3b and CAR3c, between *c.*1170-240 BP (1050-290 cal BP, cal AD 300-1660) suggests that better-drained peaty soils became available or more abundant. Although this covers a long period, it is possible that the farmers may have attempted to drain areas of peat to increase the quality of heathland grazing, thus creating suitable habitats for *C. crispa*, which disappeared following abandonment of the site.

In addition to grassland, the abundance of *Calluna*, *Sphagnum* and Cyperaceae pollen, with Ericaceae, *Narthecium ossifragum* and *Myrica*, suggests that heathland and blanket peat were present around Carnach Mór, probably within the channel and perhaps on the hillsides. These acidic, nutrient-poor communities could have provided another grazing resource, particularly valuable over the winter months if occupation was permanent. It is not possible to distinguish grazed heathland in the pollen record, as the response of *Calluna* is very strongly dependent of the age of stands, the species composition of the heathland and the intensity of grazing (Grant *et al.* 1985, Miles 1988).

Moderate to high levels of charcoal are present throughout zones CAR2c and CAR3a-b, when *Calluna* pollen is most abundant. Although few peaks in *Calluna* pollen and charcoal frequencies coincide (*e.g.* 750-725 BP, 670-660 cal BP, cal AD *c.*1280-1290), it is possible that pollen fluctuations relate predominantly to the local channel surface vegetation, while charcoal fragments derive from the wider source area, including the surrounding hills, thus producing disturbance events that are not resolved in the pollen record (*cf.* Brayshay and Edwards 1996, Sugita *et al.* 1997).

There is, however, some evidence for pasture and heathland management through burning. The abrupt reduction in *Calluna* frequencies at 810 BP (710 cal BP, cal AD 1250) coincides with a peak in charcoal fragments and a rapid rise in Poaceae. The high temporal resolution of the diagram at this point indicates that the change occurred over as little as 28 ^{14}C (16 cal) years between samples, with each subsample representing just *c.*7 ^{14}C (*c.*8 cal) years peat accumulation. A reduction in *Potentilla*-type, large increase in *P. lanceolata* pollen, small peak in *Rumex acetosella*, increasing *R. acris*-type and *R. acetosa* frequencies, suggest that dry *Calluna* heath may have been burnt, transforming it to pastoral grassland, perhaps aided by the fertilising effect of the ash. *Vaccinium*-type and *Empetrum* may have been able to increase in abundance with the removal of the *Calluna* canopy (Hobbs and Gimingham 1987). Continued frequent burning and grazing may have helped to prevent *Calluna* from returning to dominance (*cf.* Hobbs and Gimingham 1987).

The gradual rise in Cyperaceae frequencies from 750 BP (670 cal BP, cal AD 1280) results in a reduction in percentage and absolute Poaceae values, suggesting a gradual increase in wetness. However, this shift is not immediately reflected in the *P. lanceolata* curve, inferring that wetter ground did not encroach on dry grassland (*cf.* O'Connell *et al.* 1988); the expansion of Cyperaceae may therefore reflect changes within the channel and perhaps on the adjacent hillsides. A Holocene maximum in palynological richness at 700 BP (660 cal BP, cal AD 1290), with high values until *c.*620 BP (600 cal BP, cal AD 1350), also suggests that human activity continued to promote species richness through disturbance, nutrient enrichment and burning, all of which maintained niches which did not occur around the site naturally.

6.5.8 Zone CAR3c: Cyperaceae-*Calluna* (50-0 cm; 410-0 BP, 490-0 cal BP)

A single *Pinus* stomate is recorded at 400 BP (480 cal BP, cal AD 1470). This is not associated with an increase in *Pinus* pollen frequencies or mineral sediment which could suggest local growth or reworking. However, there is a small increase in deteriorated pollen frequencies which may result from peat erosion, perhaps on the hill to the south of the channel where *Pinus* stumps occur. This may have been caused by natural peat gullying, trampling by animals, or peat cutting for fuel and animal bedding.

Maximum values for *Hordeum* group and Poaceae anl-D>8 μm grains are recorded at *c.*400 BP (480 cal BP, cal AD 1470), with higher *Hordeum* group values in adjacent levels, between 440 and 390 BP (510-470 cal BP, cal AD 1450-1480). This may infer more extensive or closer crop growth on alluvium near the channel. Upland arable intensification appears to occur near the beginning of the Little Ice Age (Grove 1988); the significance of this is discussed in Chapter 9.

Cyperaceae values continue to increase through this zone. The decrease in *Hordeum* group, Poaceae anl-D>8 μm, *P. lanceolata* and the loss of Brassicaceae, *Cirsium*-type, Fabaceae, *P. major/media* and other ruderals between *c.*410-200 BP (490-150 cal BP, cal AD 1460-1800) suggests a gradual decline in agriculture, both arable and pastoral, prior to abandonment. This pattern is paralleled by the palynological richness curve, which remains high during the first part of the zone, but declines from *c.*240 BP (290 cal BP, cal AD 1660). A reduction in charcoal frequencies around 160 BP (140 cal BP, cal AD 1800) suggests that much of the charcoal during zones CAR2b-c, and possibly from zone CAR3c, may represent the use of fire as a management tool or from domestic use.

The penultimate *Hordeum* group grain coincides with the start of the *Picea* curve and a rise in *Pinus*, suggested to reflect the extralocal and regional establishment of conifer plantations. This suggests that cultivation and thus occupation may have continued until the late nineteenth century or early twentieth century AD, as the radiocarbon chronology appears to be *c.*90-190 ^{14}C (70-240 cal) years older than plantation and SCP indicators would suggest (Section 6.3.3). The archaeological and documentary evidence for historical land-use is discussed in Chapter 9.

It is possible that residual seed from cereals, weeds of cultivation and some pastoral herbs was able to germinate and flower for an unknown number of years following abandonment. This is clearest for *Papaver rhoeas*-type and *Urtica*. These taxa may have survived until nutrients returned to pre-settlement levels and a reduction in disturbance resulted in the survival of only those species with wider ranges of tolerance, such as *R. acris*-type and *R. acetosa*. Following abandonment, it is possible that extensive, low intensity grazing by sheep and cattle, and by wild herbivores, predominantly red deer, may have allowed herbs such as *P. lanceolata* to survive, rather than inferring long-distance transport (see Chapter 9). However, a single *Hordeum* group pollen grain was recorded in the surface sample, thus suggesting that, within the present open landscape, long-distance pollen transport of 'anthropogenic indicator' types may also be involved.

The surface sample assemblage contains 19% tree and shrub pollen, which must represent long-distance transport in the present open environment around Carnach Mór. Comparison with earlier spectra suggests that the pollen source area may have been treeless, or predominantly so, since around 3000 BP (3190 cal BP), at the zone CAR2c/3a boundary. This is discussed further in Chapter 9, where the data are compared with other sites in this study.

6.6 Conclusions from Carnach Mór

The palynological evidence from Carnach Mór suggests an early Holocene age for the formation of the floodplain and thus long-term differentiation between vegetation of the valley floor and morainic sediments. The species-rich deciduous woodland and tall-herb vegetation which developed on the floodplain and adjacent hillslopes were very different form the relatively short-lived deciduous woodland and mixed boreal-deciduous woods at Torran Beithe, on morainic sediment. A relatively high base status was maintained, possibly through sediment deposition during floods, and also perhaps by the abundance of *Betula*, which is known to reduce soil pH (Miles 1985, Atkinson 1992). Disturbance, particularly through flooding, may have played an important role in the maintenance of high species diversity, although the role of fire is less clear (see Chapter 9).

There is no evidence that a higher soil nutrient or base status delayed mid-Holocene woodland loss. However, it is possible that grazing pressure, in addition to perhaps more marked environmental changes above 250 m OD, caused the demise of woodland communities, since species-rich grassland, rather than mire alone, appears to have replaced woodlands on the alluvial floodplain soils. In an upland context, the longevity of agricultural activity, including cultivation, is remarkable, and suggests that site selection, for natural grazing resources and soil fertility, may have played an important role in Highland farming since the early Bronze Age, enabling sustained, localised and small-scale barley cultivation.

CHAPTER 7: Camban

7.1 Site selection

In West Affric, alluvial fans form limited areas of flushed vegetation, which is easily distinguished from the surrounding blanket peat (Section 2.1). The third pollen site at Camban is set within this landform unit and was chosen to investigate further the impact of nutrient status on vegetation composition and dynamics, and on the potential for anthropogenic activity (see Chapter 6).

Current natural tree regeneration occurs on flushed soils beside streams where seedlings and trees are protected from herbivores by rocky, inaccessible slopes or a growth habit which leans out over the water. This suggests that water movement and the deposition of suspended sediment on alluvial soils may have maintained more nutrient-rich soils during earlier periods and consequently enabled the establishment of more nutrient-demanding taxa, perhaps at the expense of species such as *Pinus sylvestris*, which compete more successfully on poorer soils. Water and sediment movement also resulted in the development of vegetation which was adapted to frequent low intensity disturbance. This soil replenishment may have delayed the decline of woodland communities during the mid-Holocene by maintaining a higher soil nutrient status than on the surrounding moraine sediment during climatic deterioration, perhaps to a greater extent than on the floodplain, where relict terraces may become isolated from fluvial deposition. Flushed alluvial soils may therefore have formed important areas suitable for scrub survival and regeneration during the mid-later Holocene.

The abundance of recent historical archaeological evidence for settlement and land-use at Camban (below) suggests that occupation may have been more intensive and perhaps have a longer history on alluvial soils than on the surrounding moraine-derived soils. Edaphic conditions may also have attracted farmers to the limited areas of flushed soils, and may also have enabled longer duration settlement and more nutrient-demanding forms of agriculture, such as cultivation.

However, as the highest pollen site in upland West Affric, vegetation development and agricultural land-use at Camban may also have been more sensitive to climatic changes or the pressures of prolonged land-use. At present it is unclear whether the hypothesised buffering effects of sediment deposition will have been sufficient to confer stability or resilience to these processes.

7.2 Site description and sampling

Camban is located in Fionngleann, the south-western branch of the main Glen Affric valley (Fig. 7). This narrow valley is bounded to the north and south by steep, rocky slopes, rising to more than 962 m OD (Photo 9). In contrast to the flat floodplain of the River Affric and Strath Croe, the Allt Cam-bàn flows through an incised channel at the base of the hillslopes. Limited areas of flat alluvial sediment occur *c.*1.0-0.5 km west of the sampling site. Lying at over 300 m OD, Camban is the highest pollen site in Glen Affric and may receive orographically enhanced rainfall due to its westerly location in the lea of steep mountain slopes. The altitude and narrow width of the glen may also increase site exposure, due to funnelling of the prevailing westerly winds (Section 2.1.4).

Camban has a documentary history dating from the mid-nineteenth century, and there are many stone-built structures, including houses, enclosures and dykes, including the building which has been restored and is in current use as a bothy. These are focused on and around the alluvial fan descending from Beinn Fhada to Allt Cam-bàn (Fig. 38). Other dry-stone structures in Fionngleann have been interpreted as shielings (Wordsworth and Harden 1997). Two stone-built enclosures at Camban have deepened topsoils and more species-rich herbaceous vegetation than the surrounding blanket peat (see Photo 10). In addition to the stone structures, there are also drainage channels and peat cuttings. These features suggest that much hard work went into farming this apparently unpromising location. This contrasts with a complete absence of human activity at Torran Beithe and few structures near Carnach Mór, with no evidence of land-use.

The pollen sampling site is a small bedrock basin located in the centre of the sloping, minerogenic peat, which has formed on the alluvial fan (Fig. 38, Photo 9). The coring site is situated at an altitude of 307 m OD, at National Grid Reference NH 054182. At this point, the fan is approximately 150-200 m across and 220 m long, with streams at the eastern and western edges. The western stream appears to have been modified to form a drainage ditch. A moraine bar separates the fan from the river at the base of the slope. The surrounding ground consists of uneven and rocky moraine debris, mantled by eroding, acidic blanket peat, which is generally less than 1 m deep.

The present fan vegetation is dominated by *Polytrichum*, several species of Poaceae and Cyperaceae, including *Anthoxanthum*, *Scirpus cespitosa*, *Eriophorum angustifolium* and *E. vaginatum*, with *Luzula*, *Sphagnum* and some *Hylocomium*. *Eriophorum* and *Myrica gale* become more frequent in areas of poorer drainage, such as the junction of alluvial and moraine sediment at the base of the fan. *Juncus* is more common on sloping alluvial sediment and beside the streams. The most frequent herbs are *Potentilla erecta* and *Succisa pratensis*, with some *Pedicularis palustris*, *Polygala serpyllifolia* and *Galium saxatile*. *Cardamine pratensis*, *Ranunculus ficaria* and *Orchis mascula* occur near the streams, while *Pinguicula vulgaris* is found where vegetation cover is sparser or lower. Small *Vaccinium myrtillus* and *Salix* shrubs occur infrequently on the fan. *Ranunculus cf. repens*, *Rumex acetosa*, *R. acetosella*, *R. obtusifolius*, *Lotus corniculatus* and *Digitalis purpurea* occur near the buildings, where the ground slopes more steeply and peat cover is shallow or absent, and in former enclosures (Photo 10).

7.3 Results

7.3.1 Site morphology and source area

Contour and section maps produced from surveying and depth-probing indicate that the sampling site occurs in a basin measuring *c.*20 x 40 m, which is a present concealed by the convex surface of the fan peat. The basin may have acted as a water collecting site, which resulted in peat initiation, as peat depth shallows rapidly around the central coring site (Fig. 39a-c), although no basal dates are available from the surrounding peat to test this hypothesis. The basin dimensions suggest a pollen source radius of *c.*50-200 m (Sugita 1994; Section 3.2.2.3) at the centre of a well-defined landform unit, which is likely to have been the dominant source of pollen through out the Holocene, independent of changes in woodland canopy cover.

As discussed in Chapter 3, however, water movement across the fan is likely to increase the effective source area to include some pollen from vegetation beside the inflowing burns and runoff from the adjacent hillsides. Streams may receive drainage from a potentially large surface area and consequently, stream-borne sediment can be an important source of pollen (Peck 1973, Bonny 1976, 1978, Pennington 1979). The evidence for redeposited pollen from this source at Camban is discussed in Section 7.3.5.

7.3.2 Sediment description

A peat core 3.44 m in length was obtained from the deepest point in the centre of the fan peat using the methods described in Section 4.1.3 (Fig. 39). The sediment stratigraphic description is shown in Table 21, from which can be seen that the stratigraphy consisted of detrital peat with varying mineral content, which was quantified through loss-on-ignition. LOI and stratigraphic data confirm the correlations made between the cores in the field, as results from the overlapping sections of the cores are closely comparable, with the exception of the basal metre, which had a more variable minerogenic content (not presented).

7.3.3 Radiocarbon dates

Initially, seven AMS samples from the Camban sequence were submitted for AMS dating (Table 22). However, the ^{14}C date at 114 cm (AA-32262) appears anomalous, representing a reversal; the date of 1790 ± 45 ^{14}C BP (1706 cal BP) contrasts with the interpolated date of 710 ^{14}C BP (660 cal BP). An additional date was obtained from 108 cm, with an interpolated date of *c.*700 BP (660 cal BP), as the anomalous date derives from an important horizon in terms of human activity, reflecting permanent clearance. This horizon was considered to be more stratigraphically secure on the basis of a higher percentage of well-preserved pollen grains (Fig. 47). This was proven by the additional sample, which returned a date of 640 ± 40 BP (590 cal BP) (CAMS-57201) (Table 22; Fig. 40).

Comparison of radiocarbon dates with marker horizons provided by plantation conifer pollen and SCPs, suggests that the radiocarbon chronology is *c.*110 ^{14}C (90 cal) years too old in the top part of the sequence, as conifer pollen, increased *Pinus* and SCPs are recorded around 140-160 BP (*c.*140 cal BP, cal AD *c.*1810). However, with a range of cal AD 1681-1954 and with 1σ errors of 40-50 ^{14}C years , the radiocarbon age estimates fall within the expected age range.

Changes in the temporal resolution and rates of pollen accumulation in the diagrams are presented in Table 23, which indicates that time intervals between subsamples range from 7-148 ^{14}C (4-161 cal) years, with a mean of 48 ^{14}C (55 cal) years/sampling interval.

7.3.4 Pollen and microfossil analyses

The results of the pollen analyses are presented as percentage diagrams in Figure 41, with selected concentration and accumulation curves in Figures 42 and 43, respectively. The results of rarefaction and rate-of-change analyses are shown in Figures 44 and 45. All diagrams are plotted against uncalibrated radiocarbon years BP. The results of detrended correspondence analysis for the first two axes are presented in Figure 46a-b. 56.4% of the cumulative variance in the taxa data is captured in the first four DCA axes, with 46.3% represented by the first two axes.

Twelve local pollen assemblage zones and subzones were defined; the site designation 'CAM' precedes each zone or subzone division. These are summarised in Table 24. Measurements used for the identification of large and cereal-type Poaceae grains are presented in Table 25 (see Section 4.3.1.1 for identification criteria).

7.3.5 Pollen preservation data

Summary pollen preservation data are presented in Figure 47, while preservation class data for selected individual pollen types are shown in Figure 48 (see Section 4.3.2 for calculation sum). Pollen preservation data from Camban and the landform characteristics of the site suggest that water-borne sediment, and thus possibly reworked pollen, may have been incorporated during sediment accumulation. This section will discuss the possible causes of pollen deterioration at Camban and assess the possible extent of biasing which may affect that stratigraphic integrity of the assemblage; changes in the source and cause of deterioration in each local pollen assemblage zone are summarised in Table 26 and are discussed in the relevant sections of the interpretation (Section 7.5).

The assemblage is dominated by well-preserved pollen followed by crumpled grains (Fig. 47). However, the most striking pattern in the preservation data is an association between corroded determinate pollen, crumpled and corroded indeterminate pollen, Pteropsida spores and mineral content (Fig. 47; Table 26). Although this is not statistically demonstrable through regression analysis, as the relationship is not directly proportional (Table 27), the association suggests that the influx of water-borne or eroded sediment is associated with pollen and spore corrosion, and with inflated spore frequencies.

The extent of corrosion indicates the need to assess the severity of possible biasing in the pollen assemblage. The level of deterioration does not suggest that severe deterioration and differential preservation has resulted in the high number of spores; resistant palynomorphs such as *Cichorium intybus*-type are not more frequent than less robust pollen types and many of the levels with a high mineral content in zone CAM4 were species rich (Fig. 41), which would support their interpretation as disturbance-related communities, rather than as inwashed pollen assemblages. Frequencies of determinate degraded and indeterminate pollen are also low (0-2% determinate degraded, 0.1-13% indeterminate), again indicating that biasing is not severe. These two factors also argue against the inclusion of large amounts of secondary soil pollen.

However, the anomalous radiocarbon date from zone MOR3c, marked fluctuations in preservation and LOI coincide with palynological changes which are inferred to represent the incorporation of reworked pollen and organic sediment. The correspondence between zone boundaries at zone CAM3b/c and CAM3c/4, and changes in preservation may indicate that the data have been significantly skewed (*cf.* Tipping 1995b); this is discussed further in Section 7.5. Similarly, in zone CAM4, the increase in mineral content and corroded tree pollen, particularly *Betula* and *Pinus*, may represent secondary pollen derived from soil erosion, as research in Affric and throughout much of the Highland region, suggests that *Betula* and *Pinus* are likely to have been the main tree species during the early and mid Holocene (Bennett 1989, Tipping 1994; Chapter 1), particularly on the hillslopes (Chapter 5). The reservoir of pollen is likely to be relatively high in acidic peat or mor soils (Pennington 1979, Havinga 1984). The decline in arboreal and Ericaceous pollen, Pteropsida spores and charcoal frequencies at the zone CAM4/5 boundary, *c.*370 BP (460 cal BP) may reflect a reduction in secondary pollen.

The close correspondence between the individual taxa corrosion curves suggests that similar processes of decay affected all taxa, regardless of their frequency in the pollen record (Fig. 48). This is interpreted as evidence that all taxa affected by corrosion were introduced simultaneously by inwashing from areas of similar vegetation upslope from the sampling site, thus causing minimal changes to the pollen stratigraphy, with the exception of the periods discussed above.

However, Pteropsida frequencies show no correlation with woodland or tall-herb cover, which would be expected if the ferns were predominantly growing in the understorey (Fig. 41). This suggests that the spores are associated with mineral influx, and are either reworked or contemporary with the pollen assemblage. Pteridophyte spores are resistant to deterioration and high proportions have been noted in soil pollen assemblages (*e.g.* Tipping *et al.* 1994) and in stream-borne pollen (Pennington 1964, Peck 1973, Havinga 1984, Brown 1988). However, discussion above suggests that evidence for soil erosion and secondary pollen is limited. Ferns may alternatively have been growing contemporaneously with the fan vegetation, perhaps beside streams which feed the fan, thus depositing spores directly into the water. Under the present predominantly acidic conditions in Glen Affric, ferns are most frequent beside the numerous rocky burns and in drainage channels through the peat and down to the bedrock, which may account for high spore representation at Camban, as stream-gullies are numerous on the hillsides. The analysis of surface pollen samples from these environments may resolve this question, but was not undertaken in the present study.

In order to assess these conclusions more objectively, rigorous tests developed for assessing pollen samples from unusual contexts (Tipping *et al.* 1994, Tipping and Carter 1998, Bunting and Tipping, submitted) were applied. These are designed to provide some quantitative, although subjectively selected measures of spore enrichment, and the severity of post-depositional pollen deterioration. The results are presented in Table 28. These indicate that all the pollen samples passed the tests, with the obvious exception of test 7 (spore enrichment) and the possible exception of the sample at 3770 BP (4110 cal BP, 272 cm), which has the highest spore enrichment. This supports the conclusions based on preservation data, which suggest that the assemblage is not strongly biased by reworked pollen and post-depositional corrosion. Similar conclusions have been reached in previous research of (floodplain) alluvial through comparison with conventional peat sequences (Scaife and Burrin 1992).

Crumpling and breakage are usually associated with minerogenic sediment (Cushing 1964, Birks 1970, Lowe and Walker 1977, Tipping 1984) and stream-borne pollen (Peck in Birks 1970, 1973). However, at Camban the proportion of determinate broken pollen remains relatively constant, despite fluctuating mineral content, suggesting that breakage may be the result of processing techniques rather than sedimentary processes, particularly in the case of *Pinus* (Cushing 1964, Fig. 47). Frequencies of crumpled pollen are most closely linked with changes in the frequencies of Poaceae and, to a lesser degree, Cyperaceae pollen, both of which show the highest frequencies of crumpling (Fig. 48). The slight reduction in crumpled determinate pollen grains at the top of the profile, when Poaceae frequencies rise, suggests that sediment compression has a limited effect on pollen distortion. Crumpling is therefore argued to be predominantly a reflection of changes in the composition of the pollen assemblage, rather than changes in sediment composition.

7.3.6 Charcoal analysis

Percentage and absolute charcoal data are presented in Figure 49. Table 29 presents a summary of temporal patterns of charcoal representation. As a result of the frequency of pollen deterioration, the extent of reworking through inwashing or erosion was examined by comparison with LOI and pollen preservation data, which can provide evidence for these processes (see above). In order to look for patterns in the charcoal data, particularly in relation to size class data, size class regression analyses (Table 30) and size class ratios (Fig. 50) were analysed.

Regression of charcoal-to-pollen ratios against organic content (as an inverse measure of erosion), corroded pollen and Pteropsida frequencies (as possible measures of reworking), all showed very low regression coefficient (not presented). This suggests that, for the profile as a whole, charcoal is not consistently the result of reworking, contrary to the palynological data discussed above, although evidence for periods when charcoal may have been reworked are discussed in Section 7.5 and are summarised in Table 29. The high regression coefficients between charcoal size classes also suggests that the charcoal size class data is not skewed towards smaller fragments by breakage which could be associated with reworking. Changes in the size class ratios (Fig. 50), particularly in relation to sedimentary and pollen preservational changes, indicate that the recognition of subtle changes may be necessary to evaluate the proximity and possible influence of burning (*cf.* Stevenson *et al.* 1996).

7.4 Description

7.4.1 Zone CAM1a: *Betula*-*Salix*-Poaceae (342-314 cm, 4980-4470 BP, 5730-5200 cal BP)

The sediment consists of amorphous wood peat with a high organic content. The lpaz is characterised by initially high, but decreasing, frequencies of *Betula* pollen as *Salix* pollen frequencies rise. The other characteristic taxa are Poaceae and *Alnus*. Low pollen frequencies of *Corylus avellana*-type, *Pinus sylvestris*, *Sorbus aucuparia*, *Quercus* and *Ulmus* are recorded. The main herbaceous pollen types are *Potentilla*-type, *Succisa pratensis*, *Melampyrum* and *Filipendula*. Frequencies of indeterminate Pteropsida (monolete) and *Sphagnum* are low, rising slightly near the end of the zone.

Concentrations and accumulation rates are moderate and dominated by tree pollen. Well-preserved pollen dominates the zone, with the exception of an increase in corroded determinate pollen from 4980-4800 BP (5720-5500 cal BP), attaining 56% at 4870 BP (5600 cal BP). *Betula* and *Alnus* are the main corroded taxa. Palynological richness values and rates of change remain moderate, with a slight fall in rarefaction mid-zone. Charcoal frequencies are very low.

7.4.2 Zone CAM1b: *Betula*-*Alnus glutinosa*-Poaceae-*Calluna* (314-271 cm, 4470-3700 BP, 5200-4030 cal BP)

The sediment consists of amorphous peat with wood and an increasing mineral component, rising abruptly to 73% (26% organic matter) at 3770 BP (4110 cal BP). The zone is characterised by fluctuating *Betula* pollen frequencies with higher values for *Alnus*, Poaceae, *Calluna vulgaris* and Cyperaceae pollen. *Pinus* and *Quercus* pollen values are slightly higher while *Salix* pollen frequencies are reduced. Several *Pinus* stomata are recorded. *Sorbus* and *Fraxinus* pollen is consistently present. *Vaccinium*-type and *Erica* pollen values rise to 3 and 5% respectively at 4250 BP (4830 cal BP). Herb pollen frequencies are higher. *Potentilla*-type, *Filipendula* and *Melampyrum* remain the most frequent herbaceous pollen types, with *Ranunculus acris*-type, *Rumex acetosa* and frequent *Silene dioica*-type. Several grains of *Plantago lanceolata* and grains of Chenopodiaceae, *Papaver rhoeas*-type and Poaceae with an annulus diameter greater than 8 μm (anl-D>8 μm) are recorded. Pteropsida (monolete) indet. spores are more frequent, with peaks at 4390 BP (4930 cal BP) (22% TLP + spores) and 3770 BP (4110 cal BP) (80% TLP + spores). *Sphagnum* spores are more frequent mid-zone. *Polypodium* and *Pteridium aquilinum* spores are consistently present at low frequencies throughout the Holocene.

Total land pollen (TLP) concentrations and accumulation rates rise at 4050 BP, and this is most apparent in absolute herb values. Well-preserved determinate pollen remains dominant, with a peak in corroded pollen at 3840-3770 BP (4230-4110 cal BP). This is reflected in all major pollen taxa. Frequencies for crumpled and broken pollen remain more consistent, at 5-19% and 5-10% respectively. Frequencies of indeterminate pollen increase, consisting mainly of corroded and crumpled grains, coinciding with a peak in corroded determinate grains. Rarefaction values are higher and gradually increasing. Rates of change are higher, with peaks at 4260-4150 BP (4840-4640 cal BP) and 3770-3740 BP (4110-4020 cal BP). Charcoal frequencies are low to moderate, with higher relative and absolute values at 4460-4390 BP (5040-4930 cal BP) and 3840-3730 BP (4230-4020 cal BP).

7.4.3 Zone CAM1c: *Alnus*-Poaceae-*Betula* (271-259 cm, 3700-3510 BP, 4030-3760 cal BP)

The sediment consists of amorphous peat with wood and a return to high organic content. Frequencies of *Betula* pollen are lower, with successive peaks in *Alnus*, Poaceae and *Salix*. *Pinus* values fall and are low for the remainder of the Holocene. *Filipendula*, *Rumex acetosa* and Apiaceae are the most frequent herbaceous pollen types, with lower values for *Potentilla*-type and *Melampyrum*. Pollen from *P. lanceolata*, *P. rhoeas*-type, *Hordeum* group and Brassicaceae are recorded. Pteropsida (monolete) indet. values are lower.

TLP concentrations and accumulation rates are slightly higher. Frequencies of well-preserved pollen are high with a peak in crumpled pollen (mainly Poaceae) at 3600-3570 BP (3890-3840 cal BP). Indeterminate pollen is less frequent. Palynological richness remains high, while rates of change are high and variable. Charcoal values are reduced.

7.4.4 Zone CAM1d: *Salix*-*Betula*-Poaceae-*Calluna vulgaris* (259-247 cm, 3510-3320 BP, 3760-3510 cal BP)

The sediment consists of highly organic, amorphous peat with wood. The pollen data are characterised by an initial peak in *Salix* pollen, rising *Calluna* values and consistent *Betula* values. *Melampyrum*, *Filipendula* and *Potentilla*-type are the most characteristic herbaceous pollen taxa. A single *Hordeum* group grain is recorded with at 3370 BP (3620 cal BP) with a grains of Poaceae anl-D>8 μm. Pteropsida (monolete) indet. frequencies are lower.

TLP concentration and accumulation rates decrease slightly. Determinate pollen is predominantly well-preserved, with 14-24% crumpled pollen grains. Crumpled pollen is the most frequent form of indeterminate pollen deterioration. Palynological richness and rates of change rise through the zone, while charcoal frequencies remain low.

7.4.5 Zone CAM2a: Poaceae-*Betula*-Cyperaceae-*Filipendula* (247-194 cm, 3320-2470 BP, 3510-2650 cal BP)

The organic content of the woody, detrital peat is highly variable, with high mineral content at 3240-3100 BP (3460-3280 cal BP), 2900-2840 BP (2990-2940 cal BP) and 2650-2640 BP (2760-2750 cal BP). An initial peak in Poaceae pollen is followed by higher *Calluna* pollen frequencies between 3270 and 3240 BP (3470-3460 cal BP). *Betula* and Cyperaceae pollen values fluctuate, while Poaceae frequencies gradually increase. Values for *Filipendula*, *Potentilla*-type, *R. acris*-type and *Rumex acetosa* are higher. The curves for *P. rhoeas*-type and *P. lanceolata* are continuous for most of the zone. *Hordeum* group and Poaceae anl-D>8 µm grains are recorded. The record of *Melampyrum* pollen is discontinuous. Pteropsida percentages rise sharply with *Calluna* pollen values, before declining at 2640 BP (2750 cal BP).

Arboreal pollen concentrations and accumulation rates are lower during this zone, while absolute values of herb pollen are higher. The assemblage is characterised by more variable preservation curves, with higher frequencies of determinate and indeterminate corroded and crumpled pollen, rising to 33% and 35%, respectively. Determinate and indeterminate degraded pollen is more frequent, but remains at less than 1% TLP/TLP + indet. Rarefaction and rates of change are high, with a slight fall in palynological richness through the zone. Charcoal values are higher in the first half of the zone, before decreasing.

7.4.6 Zone CAM2b: *Calluna*-Poaceae-*Betula*-Cyperaceae-*Potentilla*-type (194 -165 cm, 2470-1490 BP, 2650-1350 cal BP)

The sediment consists of amorphous, sticky peat with some decomposed wood and consistently high organic content. The pollen assemblage is characterised by higher frequencies of *Calluna* pollen from *c.*2410 BP (2360 cal BP), declining Cyperaceae values, lower Poaceae frequencies and a continuous curve for *Myrica gale*. *Alnus*, *Sorbus aucuparia* and *Corylus avellana*-type frequencies are reduced. *Betula* values increase mid-zone with a peak in *Salix* percentages at 1590 BP (1500 cal BP) with more frequent *Melampyrum* pollen. With the exception of *Potentilla*-type, herb pollen frequencies are lower. *P. lanceolata* and *P. rhoeas*-type pollen are still recorded, while *Hordeum* group pollen is absent from 2410-1590 BP (2360-1500 cal BP). Pteropsida (monolete) indet. values remain low, with the exception of a peak at the end of the zone, and *Sphagnum* spores are more frequent. Absolute TLP values are reduced and well-preserved pollen dominates the zone. Rates of change are low and rarefaction values are slightly reduced. Charcoal values increase between 2180 and 1740 BP (2150-1670 cal BP).

7.4.7 Zone CAM3a: *Salix*-Poaceae-*Betula* (165-159 cm, 1490-1330 BP, 1350-1270 cal BP)

The sediment consists of increasingly minerogenic, fine fibrous peat. The pollen assemblage is characterised by high *Salix* pollen frequencies and lower values for *Betula*, *Calluna*, Poaceae, Cyperaceae and *Potentilla*-type pollen. The *P. lanceolata* pollen curve is continuous from 1350 BP (1280 cal BP). Pteropsida spores are more frequent. Absolute pollen values are higher. The fall in organic content is mirrored by a decrease in well-preserved pollen and increasing frequencies of corroded and crumpled pollen. Palynological richness rises slightly and rates of change peak in mid-zone. Charcoal frequencies are low.

7.4.8 Zone CAM3b: *Betula*-Poaceae-*Salix*-Cyperaceae (159-133 cm, 1330-780 BP, 1270-680 cal BP)

The sediment is composed of amorphous, fibrous peat with some decomposed wood and an increasing organic content through the zone. The zone is characterised by higher *Betula* pollen frequencies, rising Poaceae and Cyperaceae pollen curves, and falling *Salix* pollen frequencies. Pollen frequencies for *Filipendula*, Apiaceae, *Rumex acetosa* and *Succisa* are higher. *Hordeum* group and Poaceae anl-D>8 μm are recorded at 820 BP (720 cal BP). Pteropsida (monolete) spore frequencies are variable.

Absolute TLP values decline from the zone CAM3a peak to moderate values. Pollen preservation is variable, with lower values for well-preserved pollen and more frequent corrosion. Rarefaction falls before increasing at the end of the zone. Rates of change increase to very high values at the end of the zone. Charcoal frequencies rise slightly.

7.4.9 Zone CAM3c: *Betula*-Poaceae-*Salix*-*Calluna*-*Myrica gale* (133-115 cm, 780-680 BP, 680-650 cal BP)

The sediment consists of amorphous woody peat, changing to minerogenic peat between 750-710 BP (*c.*670-660 cal BP, 128-120 cm), with fibrous, amorphous peat above. The zone is characterised by very high pollen frequencies for *Myrica gale* from 780-760 BP (680-670 cal BP), followed by increased *Betula*, *Salix*, *Calluna* and Poaceae pollen values. *Filipendula*, *Potentilla*-type, *Ranunculus acris*-type, Apiaceae, *P. lanceolata* and *Succisa* are the most frequent herbaceous pollen types. Pollen of *Hordeum* group and Poaceae anl-D>8 μm are recorded. Frequencies of Pteropsida spores are high mid-zone and spores of subfossil *Lycopodium clavatum*, *Selaginella selaginoides* and *Equisetum* are recorded.

TLP concentrations are moderate, while pollen accumulation rates are very high and variable. The curves for deteriorated pollen mirror the organic content and Pteropsida (monolete) spore curves, with higher frequencies of crumpled and corroded pollen mid-zone and peaks of well-preserved pollen on the zone boundaries. Palynological richness values fall from the previous zone, before increasing to higher values. Rates of change are high, particularly at the zone boundaries. Charcoal frequencies follow a similar pattern to LOI, organic content and Pteropsida spores rising in mid-zone, with low frequencies on the zone boundaries.

7.4.10 Zone CAM4: Poaceae-Cyperaceae-*Calluna-Betula* (115-21 cm, 680-370 BP, 650-460 cal BP)

The sediment consists of amorphous peat with fine fibrous roots, with coarse mineral bands, including small stones. Organic content fluctuates between *c.*90 and 9%. High pollen frequencies for Poaceae and Cyperaceae characterise the zone, with continuous, low percentages of *Betula* and *Calluna* pollen. Herbaceous pollen dominates the pollen assemblage, with the highest frequencies contributed by *R. acris*-type, *P. lanceolata*, *Potentilla*-type, *Filipendula* and *Cichorium intybus*-type. *R. acetosa*, *P. rhoeas*-type and *Succisa* pollen are present at lower frequencies. *Hordeum* group and Poaceae anl-D>8 µm pollen are present throughout the zone, and *Avena/Triticum* group grains were recorded at 660, 470 and 400 BP (650, 510, 480 cal BP). Frequencies of Pteropsida (monolete) spores are very high from 630-420 BP (600-500 cal BP).

TLP concentration values are moderate, while pollen accumulation rates are very high and variable. Frequencies of well-preserved pollen fluctuate around 50%, with equal frequencies of crumpled and corroded pollen, the latter decreasing at the beginning and end of the zone, when organic content is higher, as do values of indeterminate crumpled and corroded pollen. This is reflected in all main pollen types, with crumpling predominating in Poaceae. Rarefaction values are high and quite variable, and rates of change are high, with a peak at the start of the zone. Charcoal fragments are present in high numbers.

7.4.11 Zone CAM5a: Poaceae-Cyperaceae (21-6 cm, 370-110 BP, 460-60 cal BP)

The sediment consists of fine fibrous peat, with poorly humified non-lignified root peat above *c.*250 BP (290 cal BP, 14 cm). Organic content is rising. Pollen frequencies for Poaceae and Cyperaceae are high. Very low pollen values are recorded for arboreal and heath taxa. Characteristic herb pollen types include *R. acris*-type, *P. lanceolata*, *C. intybus*-type, *P. rhoeas*-type and Fabaceae, which decrease around 160 BP (140 cal BP) as *Potentilla*-type pollen values increase. Curves for *Hordeum* group and Poaceae anl-D>8 µm are continuous from 410-210 BP (490-160 cal BP) and 390-160 BP (470-140 cal BP), respectively. Single grains of *Picea* and *Pinus* subspecies Haploxylon, and several spheroidal carbonaceous particles (SCPs) are recorded above 160 BP (140 cal BP), followed by a rise in *Pinus* pollen values. Pteropsida spore frequencies remain very low.

TLP concentrations and pollen accumulation rates peak at 350 BP (360 cal BP), declining to the top of the zone. Frequencies of well-preserved pollen are higher, with very low frequencies of pollen corrosion, a slight increase in broken grains, and 23-42% crumpled pollen, reflected predominantly in Poaceae pollen. Rarefaction values are high at the beginning of the zone, before falling. Rates of change are lower, with a peak at 160 BP (140 cal BP). All measures of charcoal abundance exhibit very high levels at the start of the zone, with a peak at 350 BP (360 cal BP).

7.4.12 Zone CAM5b: Poaceae-Cyperaceae-*Potentilla*-type (6-0 cm, 110-0 BP, 60-0 cal BP)

The peat is characterised by poorly-humified non-lignified roots with high organic content. High pollen frequencies are recorded for Poaceae and *Potentilla*-type, with decreasing Cyperaceae pollen values and increasing *Pinus* pollen frequencies. Pollen frequencies for other herbs are reduced. *Hordeum* group, Poaceae anl-D>8 µm and a single *Avena/Triticum* group grain are recorded. Pteropsida spore frequencies remain low.

TLP concentration and pollen accumulation rates are very low. Well-preserved pollen dominates the preservation data, with falling values for crumpled pollen. Values for palynological richness are lower, falling to a Holocene low in the surface sample. Rates of change peak at *c.*40 BP (modern), before falling sharply. Charcoal frequencies are very low.

7.5 Inferred vegetation history

7.5.1 Zone CAM1a: *Betula-Salix*-Poaceae (342-314 cm, 4980-4470 BP, 5730-5200 cal BP)

The pollen is predominantly well-preserved, with the exception of a peak in corroded determinate pollen from 4980-4800 BP (5720-5500 cal BP). During this period all major taxa are corroded, but frequencies of indeterminate pollen and Pteropsida spores remain low, and sediment organic content is high, suggesting that the peat deposit may have dried out, resulting in post-depositional corrosion. The increase in crumpling from *c.*4670 BP (5410 cal BP) reflects the increase in balloon-like Poaceae pollen.

Relatively open woodland or scrub was established on the alluvial fan at Camban when peat accumulation began around 4980 BP (5720 cal BP). The peat core is underlain by at least 30 cm of sand and gravel, and as this is the deepest peat deposit on the fan, trees may have been growing on mineral soils around the small peat deposit or on the shallow peat surface, suggested by the presence of wood in the core.

Betula was the dominant pollen producer, with *Salix*, *Alnus glutinosa* and *Sorbus aucuparia*. The low frequencies for *Salix* and *Sorbus* may infer relatively abundant local growth, as both are strongly under-represented in the pollen record (Janssen 1966, Birks 1980). *Sorbus* pollen suggests that drier soils were present as it is not a wetland species (Grime *et al.* 1988). The predominance of relatively short-lived pioneer taxa and increasing abundance of non-arboreal pollen may infer rather scrubby or open woodland. A single grain of *Lonicera periclymenum* may derive from local shrub growth.

The role and abundance of *Alnus*, *Corylus avellana*-type and *Pinus sylvestris* in the woodland around the fan is less clear. *Alnus* is an abundant pollen producer and thus may only have been sparsely present around the fan. The site is at the present altitudinal limit for successful *Alnus* seed set (McVean 1955, 1956a, b) and may thus have been restricted by climatic constraints. *C. avellana*-type may have been present as a subsidiary woodland shrub as the canopy does not appear to have been dense enough to prevent *Corylus* from flowering and there is no evidence that *C. avellana*-type pollen derives from *Myrica gale* at this time. *Pinus* frequencies are low and there is no stomatal evidence for local *Pinus* growth in this zone, perhaps inferring very limited extralocal growth.

Higher *Salix* frequencies from 4740-4390 BP (5550-4930 cal BP) coincide with a reduction in *Betula* values. As there is no stratigraphic evidence for sediment disturbance, this may reflect local succession patterns; an expansion of *Salix* flowering and growth may have occurred as gaps were left by the demise of *Betula*, which does not regenerate beneath its own canopy (Atkinson 1992). The presence of Poaceae, Pteropsida (monolete) indet. spores, *Potentilla*-type, *Melampyrum*, *Succisa pratensis* and *Filipendula* may infer a damp grassy understorey vegetation with ferns and perhaps some *Sphagnum*. The DCA results also suggest a combination of wood and fen taxa. Several grains of *Pedicularis* may derive from peat-forming vegetation or from a wet meadow understorey.

Betula frequencies show only a limited recovery as *Salix* values fall from 4670 BP (5410 cal BP). The accompanying rise in Poaceae, Cyperaceae and numerous herbaceous taxa suggests that the woodland or scrub canopy became more open towards the end of the zone. *Betula* frequencies continue to decline after 4600 BP (5310 cal BP), while *Alnus*, Poaceae and Cyperaceae frequencies rise. This is also reflected in absolute pollen data. Increased light or open ground may have increased pollen dispersal and allowed the local expansion of *Potentilla*-type, *Rumex acetosa*, *Melampyrum*, *Filipendula* and Apiaceae. This suggests damp, moderately fertile soils, supporting tall-herb communities and mildly acidic soils with meadow-like grassland including *R. acetosa* and *Melampyrum*. The expansion of herb communities is reflected in rising rarefaction values. The possible cause of a reduction in canopy cover is discussed in the next zone, where there is a continued reduction in AP frequencies.

7.5.2 Zone CAM1b: *Betula-Alnus glutinosa*-Poaceae-*Calluna vulgaris* (314-271 cm, 4470-3700 BP, 5200-4030 cal BP)

The slight increase in broken pollen between 4530 and 3980 BP (5150-4420 cal BP) is reflected in several taxa, particularly *Betula*, *Pinus* and *Calluna*. This is associated with a slight reduction in organic content and an increase in Pteropsida spores, perhaps inferring limited inwashing of contemporaneous or secondary pollen. High frequencies of corroded pollen from 3840-3730 BP (4230-4020 cal BP) coincide with peaks in mineral content, Pteropsida spores and charcoal fragments (Table 29). Corrosion occurs in all major pollen taxa, including Pteropsida, suggesting inwashing of the corroded assemblage from upstream (Section 7.3.5). There are no marked changes in the pollen spectra coincident with the corrosion, suggesting that secondary pollen does not bias the assemblage. The charcoal consists predominantly of smaller fragments, which may reflect redeposition or a distant fire and chance association with local inwashing.

Although percentage and absolute values for tree and shrub pollen decline in this zone, there is evidence for increased arboreal diversity, which is suggested to have contributed to lower *Betula* frequencies through competition. The concomitant expansion of tall-herb and meadow suggest that the changing canopy was more open. The evidence for woodland composition and herbaceous communities is presented before the possible causes of change are discussed. Inferred mid-Holocene vegetational and environmental changes at Camban are summarised in Figure 51.

Salix pollen frequencies of 3.8-0.3% suggest that *Salix* remained an important shrub, perhaps in scrubby *Salix*-tall-herb communities. *Alnus* values of 16% may suggest limited growth within the local pollen source area, and *Alnus* may have replaced *Betula* on flushed or seasonally wet soils and in areas where drainage was impeded, forming a *Betula-Alnus-Salix* mosaic (McVean 1953, Atkinson 1992). There is little change in *Sorbus* frequencies, suggesting that woodland or scrub cover on drier soils persisted unchanged. Higher relative and absolute *Quercus* frequencies between 4530 and 3770 BP (5150-4110 cal BP), with a peak of 5.3%, may infer sparse local growth (*cf.* Huntley and Birks 1983), perhaps shading-out some *Betula*. Increased *Fraxinus* representation suggests its growth within relatively open woodland on fertile, moist soils, perhaps flushed but well-drained alluvial soils (Grime *et al.* 1988), as *Fraxinus* in under-represented in the pollen record (Birks 1980).

The presence of small numbers of *Pinus* stomata between 4390 and 4110 BP (4930-4600 cal BP) may infer very limited local growth, reflected in the pollen record by frequencies of 1.7-10.2%. This is closely comparable with surface sample research, in which sparse local *Pinus* growth in a virtually treeless landscape is represented by stomata and low pollen percentages, including values less than 5.5% (Fossitt 1994b). At Camban, the stomata do not coincide with pollen-preservation evidence for reworking, suggesting that the stomata are not derived from the reworking of early Holocene sediment from upstream, pre-dating peat growth in the basin. The range of herbaceous pollen types and low frequencies for more acidophilous dwarf shrubs may infer that more nutrient-rich conditions prevented *Pinus* from out-competing *Betula* (*cf.* Steven and Carlisle 1959). Other interpretations relating to the abundance of *Pinus* and a possible west-east gradient are discussed in Chapter 9.

Quercus frequencies rise above 2% at *c.*4320 BP (4860 cal BP), which may indicate sparse local growth (*cf.* Huntley and Birks 1983). This late expansion (*cf.* Birks 1989) is suggested to result from a change in climatic controls, which are discussed further below in relation to the late and short-lived local expansion of *Alnus* (see also synthesis in Chapter 9).

Although arboreal diversity appears to have increased, a mosaic of communities spread as the woodland structure became more open, including tall-herbs, meadow and heath. *Potentilla*-type shows a marked increase, possibly due to more open conditions, and may derive from *P. erecta*, which has a wide ecological tolerance, and/or *P. palustre*, present in tall-herb communities with *Filipendula* and Apiaceae. Increased *R. acetosa* and *Ranunculus acris*-type may reflect the expansion of meadow communities, in which *Plantago lanceolata* may have occurred from *c.*4460 BP (5410 cal BP).

P. lanceolata is commonly associated with grassland, pasture and mown meadows, particularly grazed grassland habitats (Behre 1981), and does not become established in woodland communities (Sagar and Harper 1964). However, the palynological evidence does not provide unambiguous evidence of the cause of *P. lanceolata* growth at this time. It is possible that, under more open conditions, alluvial soils with low intensity disturbance from flushing may have provided niches for *P. lanceolata*, rather than invoking grazing disturbance (*cf.* Behre 1981). The reduction in *Valeriana officinalis*, which is vulnerable to grazing (Grime *et al.* 1988), may infer some grazing disturbance, although *Filipendula* is also sensitive to grazing (Grime *et al. op. cit.*) but was able to expand during zone CAM1b. This may indicate that grazing was not necessarily the cause of change (*cf.* Bennett *et al.* 1992), although the relative sensitivity of *Filipendula* and *Valeriana* to grazing is unknown.

Communities on more acidic substrates are also evident. Heath and possibly mire expansion are suggested by increased frequencies of *Calluna*, Cyperaceae, *Sphagnum* and *Pteridium aquilinum*. In part, this may reflect pollen from vegetation around the fan as a result of the decline in filtering tree cover, perhaps inferring a difference in soil status between the fan, supporting tall-herbs, and surrounding morainic sediment (see Chapters 5 and 9). However, pollen frequencies of around 5% for *Vaccinium*-type and *Erica* suggest that a heath component was present in local, open woodland, as pollen of these taxa are very poorly represented in modern pollen samples (Tinsley and Smith 1974), even where *Vaccinium* forms a dense understorey in *Betula* woodland (Lloyd 1998). The DCA also suggests that *Vaccinium*-type and *Erica* are associated with a more diverse woodland (Fig. 46). The slight rise in *Pinus* frequencies as dwarf shrub frequencies increase may be indicative of soil acidification, which allowed *Pinus* to compete a little more effectively with deciduous woodland taxa such as *Betula*, although not apparently sufficiently to become established with any frequency.

Around 3910 BP (4370 cal BP), frequencies of heath taxa decline as *Filipendula*, Apiaceae, *R. acris*-type, *Silene dioica*-type and *Succisa* values increase, evident also in rising palynological richness. This coincides with a reduction in LOI and a steeply rising curve for Pteropsida spores which is interpreted as evidence for the introduction of nutrient-rich mineral sediment with large numbers of fern spores, which enabled tall-herb and meadow vegetation to flourish, creating conditions unsuitable for Ericaceae.

Higher charcoal-pollen ratios from 3840-3730 BP (4230-4020 cal BP) are associated with mineral deposition. A slight rise in charcoal size class ratios (Fig. 50) indicates a small increase in larger charcoal fragments and may infer burning closer to the sampling site, rather than redeposition. The combination of sporadic *P. lanceolata* grains, erosion, charcoal, two Poaceae grains with an annulus diameter greater than 8 µm (anl-D>8 µm) and *Papaver rhoeas*-type pollen suggests an anthropogenic cause.

7.5.3 Zone CAM1c: *Alnus*-Poaceae-*Betula* (271-259 cm, 3700-3510 BP, 4030-3760 cal BP)

At 3730 BP sediment deposition due to erosion or inwashing may have caused the short-lived expansion of Poaceae, Cyperaceae, tall-herbs and other herbaceous communities, lasting *c.*35 ^{14}C (41 cal) years. This is followed by the expansion of *Alnus* over *c.*69 ^{14}C (86 cal) years to maximum frequencies of 42% between 3700 and 3630 BP (4030-3920 cal BP). This may reflect only a single generation's growth, as *Alnus* trees may live for *c.*120 years (McVean 1953). Localised *Alnus* establishment expansion may have been aided by disturbance (*cf.* Chambers and Elliott 1989), particularly nutrient flushing and a reduction in shading tall-herb vegetation. This may reflect a chance colonisation event, as suitable conditions for *Alnus* establishment are patchy in time and space (Bennett and Birks 1990). However, this is a very late expansion date (Birks 1989) and both climatic and anthropogenic factors are suggested to have affected *Alnus* growth (Smith 1984).

In the absence of a full Holocene record, it is possible that *Alnus* may have been abundant before sedimentation commenced at Camban. However, as discussed above, persistently low frequencies from the base of the profile at *c.*4980 BP (5720 cal BP) are suggested to reflect climatic constraints on growth above *c.*305 m OD. The combination of declining *Betula* values, increased *Pinus*, *Quercus* and *Alnus* frequencies are suggested to reflect climatic changes, which may have temporarily removed the climatic constraints on *Alnus* around 3700 BP (4030 cal BP).

Betula has a very wide climatic and edaphic tolerance (Atkinson 1992), but values at Camban decline from 4800 BP (5500 cal BP). As this predates evidence for grazing or anthropogenic activity, this may reflect a gradual climatic deterioration, as there is very limited evidence for soil retrogression only beginning after the decline in *Betula* commences (above). As indicated above, the late date for *Quercus* expansion, if local or extralocal, may also infer a change in earlier climatic and competition restrictions (*cf.* Birks 1977), such as a shift to drier, more continental conditions under which *Quercus* is able to compete more successfully with *Betula* (Atkinson 1992). The significance of the stratigraphic association of the *Alnus* decline with percentage and absolute reductions in *Pinus* is discussed in relation to the Glen Affric and regional evidence for environmental change in Chapter 9.

While changes in *Betula*, *Pinus* and *Quercus* appear to predate evidence of anthropogenic or grazing disturbance, the reduction in *Alnus* frequencies coincides with a rise in Poaceae to 51% TLP, with higher *Rumex acetosa* and *Succisa* frequencies. There is no sediment-stratigraphic evidence for disturbance, but single pollen grains of *Hordeum* group, Poaceae anl-D>8 µm, *P. rhoeas*-type and Brassicaceae suggest that the reduction in *Alnus* may be influenced by agricultural activity. The reduction in tall-herb taxa may be a reflection of grazing pressure (Bennett *et al.* 1992), which could have enabled the spread of *R. acetosa* and *R. acris*-type in meadow or pasture. Tall-herb vegetation may have been preferentially grazed, as grassland species such as *Stellaria holostea* and *Succisa* are intolerant of heavy grazing pressure, yet become more frequent in the pollen record.

The continued presence of wood in the peat suggests that local scrub or open woodland persisted, perhaps with *S. holostea* and *Stachys*-type in the grassy field layer. A more open canopy structure may have allowed *Lonicera periclymenum* to flower and increased the pollen dispersal of this entomophilous species. *Rosa* and, in the next zone, *Rubus*, may also have been present. A 2% peak in *Sorbus* at 3570 BP (3840 cal BP) suggests that anthropogenic woodland interference did not significantly affect woodland on drier or rocky soils.

7.5.4 Zone CAM1d: *Salix-Betula*-Poaceae-*Calluna* (259-247 cm, 3510-3320 BP, 3760-3510 cal BP)

The transition to zone CAM1d is marked by the expansion of *Salix* frequencies from *c.*3580 BP (3860 cal BP). Continued grazing may subsequently have reduced *Salix* growth, whilst higher frequencies for *Vaccinium*-type and *Erica* again suggest local growth, possibly with *Calluna* within *Betula* scrub. It is possible that the absence of flushing and nutrient deposition, possibly combined with cultivation and grazing, may have resulted in acidification of the naturally acidic and nutrient-poor Moinian bedrock, thus enabling heath taxa to spread. *Potentilla*-type and *Melampyrum* include more acid-tolerant species which may have occurred in this scrub-grass-heath mosaic. The percentage decline in *Alnus* from the previous zone, with permanent concentration and accumulation rate reductions, may infer that *Alnus* was lost from the local pollen source area.

7.5.5 Zone CAM2a: Poaceae-*Betula*-Cyperaceae-*Filipendula* (247-194 cm, 3320-2470 BP, 3510-2650 cal BP)

Preservation changes in this zone appear to be closely associated with several changes in pollen representation and are thus discussed in chronological order.

The zone CAM1/2 boundary is marked by a second, higher expansion of Poaceae pollen, increasing to 60% over *c.*30 ^{14}C (40 cal) years. The reduction in *Betula*, *Calluna*, *Vaccinium*-type and *Erica* suggests that grassland replaced part of the scrub-heath mosaic. Peaks in *Rumex acetosa*, *Potentilla*-type, *Succisa*, *Pteridium* and the start of a continuous curve for *P. lanceolata*, and rising Cyperaceae infer more sustained grazing pressure. Absolute values for arboreal pollen taxa also decline at this horizon, suggesting a permanent woodland reduction. An increase in charcoal values from *c.*3300 BP (3470 cal BP) post-dates the vegetational shifts, indicting that they were not the result of burning. *Hordeum* group grains at 3300-3270 BP (*c.*3470 cal BP) indicate continued cultivation. An increase in crumpled pollen grains from 3300-3240 BP (3470-3460 cal BP) is reflected mainly in easily distorted Poaceae grains.

Poaceae remained abundant for *c.*100 ^{14}C years (110 cal years), until 3250 BP (3470 cal BP), when *Calluna* values increase rapidly to 41% over a *c.*30 ^{14}C (40 cal) year period, before a gradual decline over the subsequent *c.*130 ^{14}C (140 cal) years. The increase in *Calluna* coincides with a stratigraphic change from amorphous woody peat to fine fibrous peat, still with wood, increased representation of charcoal, corroded pollen and fern spores, and a fall in organic content (91-79%). Charcoal-to-pollen ratios increase from *c.*3300-3270 BP (*c.*3470 cal BP). Burning is known to favour *Calluna* (Hobbs and Gimingham 1987) and may have, purposefully or inadvertently, achieved this at Camban. An increase in charcoal size class ratios during this period suggests burning closer to the coring site (Fig. 50), and the stratigraphic change may reflect a local change from Poaceae to *Calluna*, perhaps occurring as a result of local fires.

The abundance of Pteropsida spores and corroded pollen from 3250 BP (3470 cal BP) suggests inwashing. However, the main reduction in organic content (79-34%) between 3240 and 3170 BP (3460-3370 cal BP) post-dates the transition from Poaceae to *Calluna* at *c.*3250 BP (3470 cal BP), and the duration of the shift to increased *Calluna* does not coincide with the non-specific increase in corrosion, suggesting that this sudden palynological change is not the result of reworking.

Melampyrum pollen appears to be associated with woodland taxa, suggesting that it was part of the understorey flora, as frequencies decline around 3240 BP (3460 cal BP), as absolute and relative arboreal frequencies fall. Since this occurs as charcoal frequencies increase, *Melampyrum* does not appear to be a fire-responsive taxon (*contra* Moore *et al.* 1986, Innes and Simmons 1988). This pattern also suggests that distortion caused by reworked pollen, particularly secondary pollen (cpr^2), is not sufficient to prevent local vegetation changes from being recorded and interpreted at Camban (*cf.* Hirons 1988). Similarly, the peak in *Betula* pollen at 2840 BP (2940 cal BP) consists of well-preserved pollen, and the second peak at 2500 BP (2580 cal BP) coincides with increased corrosion in all taxa, which is not more pronounced in *Betula*, suggesting that neither peak is the result of reworked pollen. In addition, frequencies of degraded pollen are low, suggesting that residual soil pollen, which has been subject to long-term deterioration (Lowe 1982, Tipping 1995a) does not form a large proportion of the assemblage.

Charcoal-to-pollen ratios remain elevated until *c.*2860 BP (2950 cal BP), before falling to lower values. Evidence for agriculture during periods of high and lower charcoal frequencies may indicate the use of fire as a management tool from *c.*3300-2860 BP (3470-2950 cal BP), which was then abandoned. Size class ratios indicate the continued abundance of larger charcoal particles after 2860 BP (2950 cal BP), inferring a local, perhaps domestic, source of charcoal, rather than regional transport of smaller charcoal particles. Fire may have been used to remove some vegetation cover, perhaps encouraging Poaceae and Cyperaceae to replace *Betula*, for pasture or cultivation, thus making use of fertilising ash.

Throughout zone CAM2b, *Hordeum* group pollen, frequent *P. rhoeas*-type, several Brassicaceae and *Artemisia*-type grains suggest barley cultivation with associated weeds, while increases in *R. acris*-type, *R. acetosa*, *P. lanceolata* and *Succisa*, with Fabaceae, *Cichorium intybus*-type and *Solidago virgaurea*-type, suggest meadow and pastoral grassland. The abundance of tall-herb species and increased frequencies of taxa which are sensitive to grazing may infer low grazing pressures, landscape division (*e.g.* enclosure) or careful herd management. A vegetation mosaic is implied by *Rumex acetosella*, which prefers more acidic, dry and well-drained grass- or heathland, contrasting with damp conditions inferred from tall-herb and some meadow taxa. Burning and agriculture may have maintained higher rarefaction values during zone CAM2a.

The *Betula* curve becomes more erratic above 2900 BP (2990 cal BP), as charcoal values fall. *Betula* peaks are recorded at 2900-2770 BP (2990-2860 cal BP) and at 2500 BP (2580 cal BP). At a temporal resolution of *c.*70 ^{14}C (80 cal) years/interval (Table 23), this suggests a possible range of between one and three generations for each peak, as *Betula* trees normally live for *c.*60-70 years (Grime *et al.* 1988).

It is not possible from a single core to determine whether the fluctuations reflect (1) spatial patterning, with sporadic, chance regeneration near the sampling site, perhaps reflecting relatively low grazing pressures, or (2) whether *Betula* peaks and increased *Salix* frequencies reflect periodic regeneration within a single area, which may have been protected from grazing. In relation to the first interpretation, the presence of a scrubby canopy, rather than restricted patches of woodland and grassland, may account for the relatively low frequency of herbs often associated with pasture, in comparison with zone CAM4 (below). Relatively open *Betula-Salix* scrub with a species-rich tall-herb and meadow understorey including Cyperaceae, Poaceae, *Filipendula*, *Potentilla*-type, *Rumex acetosa* and *Melampyrum* could have provided pasture and leaf fodder for browsing animals.

Alternatively, conservation is also possible as *Betula* and *Salix* frequencies do not decline through the phase of Bronze Age and earliest Iron Age activity between *c.*3600 and 2470 BP (3890-2650 cal BP). This may indicate that the valuable wood resource was actively managed, since *Betula* seedlings and trees are vulnerable to damage by domestic and wild herbivores (Atkinson 1992), and *Salix* is highly preferred by most herbivores (Hester 1997). With an interval of *c.*270 ^{14}C (280 cal) years between the *Betula* peaks, and *c.*66 ^{14}C (83 cal) years/sampling interval, the periodic peaks are not, however, suggested to reflect coppice management.

The record of agricultural land-use provides evidence for small-scale, low intensity agriculture or active woodland conservation. A reduction in *P. rhoeas*-type at 2900 BP (2990 cal BP) may infer more intensive crop management, rather than shading or filtering by scrub regeneration, as the continuous curve for *Hordeum* group from 2770 BP (2860 cal BP) and increased Poaceae at 2700 BP (2780 cal BP) suggest the expansion of arable and pastoral activity. More intensive or extensive land-use may have resulted in a decrease in *Filipendula* and Apiaceae from 2640 BP (2750 cal BP). Pollen from *Silene vulgaris*-type, Fabaceae, *Vicia sylvatica*-type and *Thalictrum* continue to suggest species-rich grassland and meadow communities and the presence of more base-rich soils.

Organic content increases around 2570 BP (2740 cal BP) and, at the end of the zone, Cyperaceae and *Sphagnum* frequencies rise, while *Betula* and Poaceae values show sustained reductions. The increase in more acidophilous taxa may infer soil acidification and local mire expansion arising from a reduction in flushing and sediment deposition, with further evidence for nutrient-depletion in zone CAM2b. This illustrates the impact of soil development on vegetation composition at Camban. Natural and anthropogenic causes can be suggested, including a natural change in geomorphological or hydrological patterns, deliberate damming of the streams, or from soil exhaustion due to cropping and higher grazing pressures, if nutrient removal was more rapid than replenishment, particularly on soils developed from acidic, nutrient-poor geology.

7.5.6 Zone CAM2b: *Calluna*-Poaceae-*Betula*-Cyperaceae-*Potentilla*-type (194-165 cm, 2470-1490 BP, 2650-1350 cal BP)

A peak in Cyperaceae and *Sphagnum* spores at 2440 BP is followed by rising *Calluna* frequencies, which attain 43% at 2030 BP (1970 cal BP). Highly organic peat accumulation continues in zone CAM2b and, combined with the reduction in grassland herbs and increase in acidophilous taxa, may infer further soil deterioration and consequent shifts in vegetation. Once established, *Calluna* and *Sphagnum* can promote podsolization and acidification (Miles 1981, 1985). The reduction in *Rumex acetosa* also suggests a contraction of former mildly acidic grassland and pasture. The palynological evidence for wet or drier heath is equivocal; infrequent *R. acetosella* infers dry soils, while fewer *Pteridium* spores and low frequencies of *Myrica gale* pollen and a reduction in *Sorbus* frequencies may indicate wetter conditions. *Erica* pollen may infer either wet (*E. cf. tetralix*) or drier heath (*E. cf. cinerea*).

Calluna pollen is over-represented in the pollen record and may have a swamping effect on taxa with lower pollen production (Tinsley and Smith 1974, Evans and Moore 1985). Although the spatial scale of change cannot be determined from a single core, fluctuations in

Poaceae, *Betula* and *Salix* suggest that vegetation within the pollen source area consisted of a mosaic of heath, grassland and scrub. Wood is absent from the core between 2540 and 2000 BP (2720-1940 al BP), implying a shift to dwarf shrub and herb communities immediately around the coring site.

The inferred decrease in soil nutrient status may have necessitated a change in land-use, as the area available for agriculture, particularly higher quality grassland and cultivation, is inferred to be restricted to flushed alluvial soils on the fan, contrasting with the surrounding acidic, nutrient-poor soils developed on Moinian bedrock and moraine sediment (see Chapter 9). *P. lanceolata* continues to be represented continuously until 1890 BP (1830 cal BP), but *Hordeum* group pollen is absent between 2330 and 1520 BP (2340-1400 cal BP) and *P. rhoeas*-type is less frequent. Lower palynological richness from 2410 BP (2360 cal BP) is suggested to reflect a reduction in the frequency of many grassland and ruderal herbs. Sporadic pollen from possible weeds of cultivation and pasture may reflect continued, although spatially restricted, agricultural activity and/or the survival of herbs such as *Artemisia*-type, Chenopodiaceae, *P. lanceolata*, *Cichorium intybus*-type, Fabaceae and *P. rhoeas*-type in natural flushed communities further from the sampling site. These palynological changes suggest a reduction in arable activity and the extent of pastoral grassland, which is not due to shading and high pollen production by local scrub cover, as cumulative tree and shrub frequencies are between 17 and 52%.

Increased charcoal frequencies from *c.*2330 BP (2340 cal BP) may indicate moor burning, perhaps signalling a change in management and land-use in response to the depleted nutrient status of local fan soils and the consequent shift in plant communities. Cultivation may have been maintained until crop failure forced a change in land-use (*cf.* Halstead and O'Shea 1989). Heathland burning may have been adopted as a means of maintaining more nutritious grazing in the poorer quality pasture now available. *Betula* and *Salix* regeneration may have been checked by grazing under less favourable conditions for regeneration. This suggests that the early Iron Age farmers were highly capable of adapting to change in the upland environment. This subject is important for understanding Highland land-use, in terms of both spatial and temporal patterns of agriculture, which is discussed in more detail in Chapter 9.

Betula frequencies increase after 2030 BP (1970 cal BP), rising to 34% at 1740 BP (1670 cal BP). The corresponding reduction in *Calluna*, *Myrica*, *Potentilla*-type, *P. rhoeas*-type, *Succisa*, *P. lanceolata* and *R. acetosa* frequencies may reflect an increase in shading and/or filtering. Although absolute *Calluna* values decline, the increase in *Betula* accumulation rates is slight. *Salix* values rise from 1890 BP (1830 cal BP), with a peak at 1590 BP (1500 cal BP).

The stratigraphic presence of wood from 1990 BP (1930 cal BP) suggests that the percentage rise could reflect limited local *Betula* establishment, which may have reduced herbaceous pollen dispersal. The return of *Melampyrum* pollen, with a peak at 1590 BP (1500 cal BP), infers the re-establishment of previous damp, lightly-shaded understorey communities, perhaps with *Filipendula* and Apiaceae, which are more frequent from 1890 BP (1830 cal BP), while Poaceae values decrease from *c.*1740 BP (1670 cal BP). *Equisetum* (*cf. arvense*) may have been present in damp grassland.

The cause(s) of scrub regeneration are not clear. A change in land-use or land management, and in soil conditions are suggested. Sustained higher *Betula* frequencies from 1960 BP (1880 cal BP) contrast with short-lived regeneration in zone CAM2a. As *Betula* is tolerant of a wide range of soils, a reduction in grazing pressure or abandonment are argued to have enabled regeneration, and perhaps also that of *Salix* scrub with tall-herbs. Alternatively, a return to wetter, flushed conditions may have contributed to the expansion of *Salix* and tall-herbs. There is no stratigraphic evidence for sediment inwashing and inferred nutrient flushing until 1410 BP (1300 cal BP), but a return to more nutrient-demanding vegetation and rise in Pteropsida at 1520 BP (1400 cal BP) may indicate water movement and sediment deposition around the sampling site (below), rather than reworking, as determinate TLP remains predominantly well-preserved. Higher palynological richness from 1520 BP (1400 cal BP) may reflect a return to more diverse herbaceous vegetation. The relationship between edaphic conditions and vegetation is discussed further in zone CAM3a. It is possible that a combination of natural sediment disturbance and enrichment from flushing and agricultural disturbance resulted in frequent shifts between open, tall-herb and woodland communities in the DCA for much of the sequence (Fig. 46).

Charcoal frequencies decline from 1740 BP (1670 cal BP). A reduction in burning, particularly if earlier fires were frequent, may have resulted in the decrease in Poaceae, as frequent fires can maintain Poaceae within heathland, in addition to keeping *Calluna* in young, more nutritious growth stages (Hobbs and Gimingham 1987). However, at a temporal resolution of 150 ^{14}C (160 cal) years/interval during high charcoal frequencies, it is not possible to determine the frequency of burning. If, as argued, burning reflects grazing management, a decrease in charcoal also infers a change in land-use or management practices, perhaps following a reduction in stocking levels which enabled local *Betula* regeneration.

A reduction in agricultural activity or abandonment are also inferred from the limited amount evidence for anthropogenic activity. Possibly sporadic cultivation is suggested by a single grain of *Hordeum* group at 1520 BP (1400 cal BP), preceded by single *P. rhoeas*-type and

Chenopodiaceae grains at 1590 BP (1500 cal BP). Subsequently *Hordeum* group pollen is absent until 820 BP (720 cal BP) and pollen from inferred arable weeds occurs only occasionally, perhaps, as suggested above, surviving as ruderals in natural communities. There is little evidence for disturbance by grazing animals. The palynological evidence does not provide a clear reason for the apparent decline in land-use during the Pictish period, as the change in vegetation suggests a return to better soil conditions; regional evidence for changes in land-use are discussed in Chapter 9.

This interpretation contrasts with higher rarefaction values for a short period between 1520 and 1140 BP (1400-1060 cal BP). It is possible that very low intensity anthropogenic or grazing activity and a return to less acidic flushed soils around the sampling site may have resulted in low intensity disturbance which maintained a greater natural diversity.

7.5.7 Zone CAM3a: *Salix*-Poaceae-*Betula* (165-159 cm, 1490-1330 BP, 1350-1270 cal BP)

Abundant local *Salix* growth (*cf.* Janssen 1966) may have replaced or filtered out pollen from *Calluna*, Poaceae, *Betula* and *Potentilla*-type from *c.*1490 BP (1350 cal BP). While no wood fragments were noted in the stratigraphy, this is suggested to reflect localised events, around which grassland and tall-herb continued to diversify, resulting in a continued rise in palynological richness. The DCA also suggests a temporary shift to more wooded conditions (Fig. 46). As suggested above, wetter conditions or a decline in grazing pressure may have allowed *Salix* to expand (Hester 1997). *Salix* species tolerate a wide range of nutrient levels (Huntley and Birks 1983). Although the palynological evidence precedes local sediment deposition, which is recorded from *c.*1410 BP (1300 cal BP), an increase in flushed soils around the sampling site may have enabled less acidophilous taxa, such as *Filipendula*, *P. lanceolata*, *Succisa*, and perhaps *C. intybus*-type and *Equisetum* (*cf. arvense*), to expand (Grime *et al.* 1988). *Caltha palustris*-type pollen also suggests that mineral soils were available.

The increase in mineral content from 1410 BP (1300 cal BP) coincides with higher frequencies for Poaceae, Cyperaceae, *Filipendula*, Apiaceae, *R. acris*-type and *Succisa*, suggesting tall-herb and damp grassland expansion in response to flushed soils. This is accompanied by an increase in pollen corrosion and crumpling, and continued high Pteropsida frequencies. As discussed in Section 7.3.5, crumpling is suggested to reflect the increase in balloon-like Poaceae and Cyperaceae, while corrosion affecting all major pollen types may result from increased biological activity in less acidic flushed soils. The frequency of near-contemporaneous or reworked pollen is thought to be limited, as the spectrum is dominated by entomophilous *Salix* pollen.

7.5.8 Zone CAM3b: *Betula*-Poaceae-*Salix*-Cyperaceae (159-133 cm, 1330-780 BP, 1270-680 cal BP)

Again, the summary and all selected species curves for TLP corrosion and Pterospida spores mirror the frequencies for organic content. It is thus possible that the slight percentage increase in *Alnus* between 1350 and 1140 BP (1280-1060 cal BP) reflects a small local presence, rather than the result of reworking, which would be expected to result in a relative increase in deteriorated *Alnus* pollen.

Around 1330 BP (1270 cal BP) *Salix* was replaced by *Betula*, possibly through natural succession. Values of *c.*10-16% *Salix* pollen suggest a mixture of open damp *Betula-Salix* scrub with Poaceae and Cyperaceae in the understorey and open areas. Wood is present in the core from 1190 BP (1070 cal BP). *Calluna* does not recover and frequencies for tall-herb taxa rise. The reversion to fluctuating organic content may have raised the pH and nutrient content sufficiently to exclude *Calluna*, favouring tall-herb taxa such as *Filipendula* and Apiaceae. This reversal of the patterns evident in zone CAM2c indicates that the soil changes were not permanent. This has implications for the stability and sustainability of woodland and nutrient-demanding species, and appears to have prevented a succession to acidic peat communities (Walker 1970).

The combination of tall-herbs, *P. lanceolata*, *P. rhoeas*-type, *Cerastium*-type, *Stellaria holostea*, *Succisa* and *Rumex acetosa*, with *R. acetosella* and *Melampyrum* suggests a mosaic of damp, flushed soils, drier, neutral grassland and more acidic substrates. Several of the herb pollen types infer disturbance which may be due in part to natural geomorphological and hydrological processes on the fan. Increased representation of *R. acetosa*, *P. lanceolata* and *Papaver rhoeas*-type around 1030 BP (940 cal BP) post-dates the increase in sediment mineral content, and may thus infer a return to pastoral disturbance, although this appears to conflict with a reduction in palynological richness and rates of change between 1250 and 930 BP (1170-830 cal BP). Secure evidence for a resumption in agricultural activity occurs at 820 BP (720 cal BP), when *Hordeum* group and Poaceae anl-D>8 µm are recorded, accompanied by a rise in the rarefaction and rate of change curves.

A shift to a more rapid sedimentation rate from 815 ± 40 BP (710 cal BP) coincides with the transition to a consistently higher proportion of mineral sediment, suggesting increased rates of erosion. A reduction in concentration and accumulation rates may reflect 'dilution' of the pollen signal due to more rapid sedimentation. Absolute reductions are most marked in arboreal pollen, suggesting a decline in the abundance of trees and shrubs. Finer temporal resolution may have resulted in high rates of palynological change, although it is argued that this is also related to more frequent or intensive disturbance. Increased palynological richness reflects the increase in the diversity of arable and pastoral herbs.

7.5.9 Zone CAM3c: *Betula*-Poaceae-*Salix*-*Calluna*-*Myrica gale* (133-115 cm, 780-680 BP, 680-650 cal BP)

This short zone is characterised by a sudden peak in *Myrica gale* type pollen from *c.*780-760 BP (680-670 cal BP). This consists of about 12% corroded pollen, but organic content remains high, falling from 760 BP (670 cal BP), suggesting local pollen production. *Myrica* pollen is poorly dispersed (Birks cited in Kerslake 1982, Lloyd 1998), but there is no information on the comparative magnitude of pollen production, probably due in part to identification problems (Edwards 1981). High frequencies (38-66%) suggest a short-lived local proliferation on the sampled peat surface, perhaps favoured by the movement of water across the site (Ratcliffe 1959). The DCA suggests that this represents a marked change, although this may in part be due to the inability of the technique to deal with outliers (*cf.* Hill and Gauch 1980; see Fig. 46: Axis 2 score = 0). *Betula*, Poaceae and Cyperaceae are the main taxa affected by *Myrica* expansion, suggesting an open scrubby fen consisting of *Betula* and *Salix* with *Myrica*, *Filipendula* and Apiaceae in the understorey (Rodwell 1991).

The palynological data suggest an expansion or intensification of agriculture in this zone, as *Hordeum* group and Poaceae anl-D>8 µm are recorded more frequently, with an increase in the representation of the possible arable weeds *P. rhoeas*-type, Brassicaceae and possibly *cf. Anagallis arvensis*-type. The rise in *P. lanceolata* and *R. acris*-type curves, and the more frequent occurrence of *Cichorium intybus*-type, Fabaceae, *S. holostea* and *Cerastium*-type, suggest pastoral grassland or meadow. Increased *R. acetosella* also infers acidic grassland or heath. Rubiaceae pollen may derive from acidic grassland, scrub or heath (*cf. Galium saxatile*, which is common at present). However, an increase in the abundance of *Filipendula* and *Succisa* pollen suggests at least some areas of relatively low grazing pressure on the fan, as both species are intolerant of grazing disturbance and *Stellaria holostea* is not frequent in highly disturbed grassland (Grime *et al.* 1988). Agricultural expansion or intensification is reflected in an increase in palynological richness from *c.*750 BP (670 cal BP).

The data are argued to reflect agricultural intensification, as relatively high nutrient and base status soils are suggested to have been restricted to flushed soils. The diversity of communities inferred from the pollen record, all of which are suggested to require more nutrient-rich alluvial soils, suggest careful landscape management and partitioning, in order to maintain this diversity and successfully integrate arable and pastoral agriculture. The evidence for spatial patterns of upland land-use are developed further in Chapter 9, through the integration of upland datasets.

Peaks in crumpled and corroded determinate and indeterminate pollen grains, Pteropsida spores and charcoal fragments coincide with the rise in mineral content between 760 and 670 BP (670-650 cal BP); all major pollen types are affected (Fig. 48). Some of the changes in the pollen assemblage are suggested to reflect soil or peat erosion, including small rises in *Pinus*, *Alnus*, *Quercus* and *Corylus avellana*-type, and a *Pinus* stomate at 730 BP (660 cal BP). The origin of *Calluna* pollen is less clear; the influx of minerals can, in ecological terms and from the earlier palynological evidence at Camban, be argued to favour tall-herb and ruderal expansion, rather than acidophilous taxa, perhaps indicating a secondary origin for *Calluna* pollen.

Percentages of tree and shrub pollen in zones CAM3b and CAM3c range between 84-42%, with a mean of 57%. This suggests that trees remained an important contributor within the pollen source area, which is estimated at a radius of *c.*50-200 m (Chapter 3, Section 7.3). The increasing abundance of herbs which are intolerant of shading and do not occur in woodland may infer that the woodland or scrub had a restricted distribution, perhaps in small copses with open grassland, meadow and perhaps small fields, rather than scattered in a more even, shading scrub/herb mosaic. The question of spatial distribution is discussed further in Chapter 9, where the evidence from different environmental settings within the uplands is integrated.

7.5.10 Zone CAM4: Poaceae-Cyperaceae-*Calluna-Betula* (115-21 cm, 680-370 BP, 650-460 cal BP)

The radiocarbon age reversal at 114 cm, with an interpolated date of 670 BP (650 cal BP), indicates that old organic sediment was being eroded onto the fan, suggesting the possible presence of secondary pollen. High frequencies of crumpled and corroded pollen and spores coincide with low organic content. Much of the crumpling is attributed to increased Poaceae and Cyperaceae frequencies. Increased corrosion occurs in *Betula*, *Alnus*, *Calluna*, Poaceae and herb pollen, and in Pteropsida spores. As *Betula* and *Calluna* pollen was more frequent earlier in the Holocene, it is possible that some of this pollen is reworked with resistant fern spores.

The transition to zone CAM4 at 680 BP (650 cal BP, cal AD 1290) is marked by a reduction in relative and absolute values for *Betula* and *Salix* over a period of *c.*30 ^{14}C (*c.*16 cal) years and *c.*7 ^{14}C (4 cal) years, respectively. This suggests rapid clearance. Wood is also absent from the core after 730 BP (660 cal BP). Charcoal frequencies do not increase until 630 BP (600 cal BP), suggesting that fire was not used to remove the trees.

The removal of woodland or scrub infers a change in land management, perhaps agricultural intensification. Increased frequencies of Poaceae, Cyperaceae, pastoral herbs, arable weeds and cereal grains, including *Avena/Triticum* group, may indicate more intensive use of the limited area of nutrient-enriched ground on the fan. *P. lanceolata* and *R. acris*-type maintain frequencies of between 2 and 5%. This would suggest that the plants grew on the minerogenic fan peat and thus that grazing occurred on this area, which dominates the pollen recruitment area. Other grassland herbs are also more frequent, including *Cichorium intybus*-type, Rubiaceae, *Succisa* and *Stachys*-type. *Potentilla*-type remains common. *R. obtusifolius*-type pollen is also indicative of meadow and grassland on neutral soils and may indicate high grazing pressures as *R. obtusifolius* is avoided by cattle, sheep and horses (Grime *et al.* 1988). *R. acetosella* pollen infers acidic, well-drained grass- and/or heathland. Maximum rarefaction values for the profile are recorded at *c.*570 BP (550 cal BP).

It is possible that a regime of periodic flooding, which introduced fresh nutrients, promoted naturally tall, meadow-like grassland. Such vegetation would have been an attractive and valuable source of fodder, particularly during winter (Fenton 1976, Greig 1988, Hughes and Huntley 1988, Mitchell 1997; see Chapter 9). Medieval clearance may have been aimed at increasing this resource in order to expand, or make more intensive use of, good grazing and/or fodder, either using natural flushing or through deliberate management of water and sediment deposition.

Possible weeds of arable ground which increase in frequency include *P. rhoeas*-type, Brassicaceae, Chenopodiaceae, *cf. Anagallis arvensis*-type and perhaps *Solidago virgaurea*-type. In addition to *Hordeum* group, three grains of *Avena/Triticum* group pollen were recorded, at *c.*660 BP (650 cal BP), and 400-390 BP (480-470 cal BP), the latter preceded by maximum *Hordeum* group and Poaceae anl-D>8 µm values, both at 0.7%, around 410 BP (490 cal BP). *Avena/Triticum* group pollen probably derives from *Avena* cultivation as, at present, *Triticum* requires warmer, drier conditions and grows less successfully in poorer soils, preferring drier sandy soils (Coppock 1976, Boyd 1988a). *Avena* pollen is better dispersed that *Hordeum* (Vuorela 1973), suggesting that *Avena* may have been an infrequent or minor crop. This may be a response to the environmental conditions, since *Hordeum* withstands poorer soils (Zohary and Hopf 1994), and gives higher yields than *Avena* where ground is limited (Fenton 1976).

The increase in charcoal-to-pollen ratios at 630 BP (600 cal BP) is reflected in all size classes, but the relatively slight rise in size class ratios indicates that larger fragments are not much more frequent. This could infer frequent small fires, with limited heat convection and thus charcoal dispersal (Bennett *et al.* 1990), an increase in more distant fires (Clark 1988), or reworking, which resulted in higher frequencies of smaller fragments due to breakage during transport.

Pollen preservation data suggest that the latter interpretation is possible, as some arboreal and *Calluna* pollen may be secondary (above), but sustained and relatively high charcoal frequencies suggest that some charcoal is also the result of local fires. This contrasts with zone CAM2a, where local fires are inferred and are associated with higher size class ratios. The influence of fuel type on size classes is unknown (Patterson *et al.* 1987) and it is possible that the loss of the woodland resource may have led to a change in fuel types, which may have produced a different charcoal 'signature' (*cf.* Dark 1998).

Relatively intensive land-use suggests that charcoal derived from small, continuously burning domestic fires or more distant land-use contexts, such as muirburn, are also possible, but cannot be securely distinguished from reworked charcoal on the basis of the available evidence. Systematic stratigraphic surveying and the analysis of additional cores from on and around the fan at Camban could reveal the extent of mineral deposition and establish spatial patterns of charcoal and vegetation distribution which might help resolve the problems of disentangling secondary and contemporaneous local pollen production. A secondary origin cannot be attributed to the dominant pollen taxa during this zone, Poaceae, Cyperaceae, *P. lanceolata* and *R. acris*-type, as well as the cereal-type pollen.

LOI values are also lower in zone CAM2a, when cultivation and grazing are inferred, perhaps indicating destabilisation due to anthropogenic activity in both periods (*cf.* Edwards *et al.* 1991). Several possible mechanisms of erosion can be suggested: animals, humans or natural peat gullying may have caused the erosion of peat and alluvium on the slopes above Camban, contributing organic and mineral sediment. Large numbers of fern spores may reflect a residual soil component or stream-side growth. Management practices such as the application of turf or peat ash from hearths to manure fields could perhaps have contributed to large numbers of small charcoal fragments. The spatial scale of mineral deposition is unknown, although LOI curves for individual cores taken from within *c.*50 cm of one another are well-correlated (data not presented).

The pollen source area of the sampling site is suggested to be dominated by the fan (Section 3.2) and the vegetation surrounding the fan is hard to establish clearly. *Betula* pollen may be derived from regional or reworked pollen, local and extra-local trees growing dispersed around the fan. Low frequencies of *Alnus* and *Salix* may derive from a narrow fringe of trees surviving beside the river at the base of the slope and stream-courses, from the regional pollen rain or from reworking. Cyperaceae, *Calluna*, *Potentilla*-type and *Sphagnum* suggest blanket peat cover (Fossitt 1994a), perhaps on surrounding moraine-derived soils, contrasting with the inferred evidence for pasture on the fan.

A gradual decrease in *Filipendula* from *c.*540-500 BP (540-520 cal BP) suggests the loss of tall-herb communities. The decline in *R. acetosa* may also be linked with the disappearance of tall-herb vegetation, despite its frequent association with pastoral activity (*cf.* Behre 1981). *S. dioica*-type may also have been a component of tall-herb vegetation. Fluctuating LOI values and frequent *Selaginella* spores suggest that base-rich conditions still existed and the decline may thus have been occasioned by increased grazing pressure, leading to the expansion of pasture or meadow, or by an increase in cultivation, indicated by more frequent *Hordeum* group and *P. rhoeas*-type pollen.

7.5.11 Zone CAM5a: Poaceae-Cyperaceae (21-6 cm, 370-110 BP, 460-60 cal BP)

Several changes occur at the start of zone CAM5; this includes a reduction in Pteropsida spores, arboreal, Ericaceous and *Myrica* pollen, a decrease in determinate corroded pollen, indeterminate pollen and *Selaginella* spores. This coincides with a large peak in charcoal frequencies and in TLP concentrations. Organic content remains at moderate to low levels. Although minerogenic sedimentation does not automatically result in an increase in deteriorated pollen (Lowe 1982), this may reflect a change in the patterns, and perhaps the source, of water and mineral input, resulting in a reduction in reworked pollen or extralocal contemporaneous pollen such as *Calluna* from the slopes above the sampling site.

Charcoal frequencies are very high between 400 and 210 BP (480-160 cal BP), with a final peak at 350 BP (360 cal BP), although the small rise in charcoal size class ratios does not suggest that burning occurred closer to the sampling site as larger fragments are not abundant. Numerous cores and close stratigraphic correlation would be required to test whether frequent extralocal burning reduced *Calluna* growth (*cf.* Hobbs and Gimingham 1987) and removed the remaining trees from around the fan. Alternatively, charcoal and pollen frequencies may have been inflated by a period of drier conditions.

These changes may signal another shift in land management, as the composition of the herb flora also changes, as indicated by a strong association between DCA sample scores and taxa of open, disturbed agricultural ground which have low and negative scores on Axis 1. Tall-herb species are lost, while *Potentilla*-type, Rubiaceae, *Succisa* and *Sphagnum* frequencies decline. Fabaceae frequencies are higher from 350 BP (360 cal BP). *P. lanceolata*, *R. acris*-type and *C. intybus*-type are still well-represented. Grassland interpretation from pollen data is difficult (*cf.* Greig 1984, 1988), and the nature of this change is not clear. Purposeful management for meadow may have contributed to the loss of some shorter herbs and tall-herbs, in addition to filtering out more of the extralocal and regional pollen rain. Identification of the Fabaceae pollen to a lower taxonomic level might have suggested more clearly what this change was, but this was not possible with the available reference material.

A change in drainage or changes in stock types during the historic period can also be suggested as possible reasons for the shifts. A spatial or temporal change in drainage patterns may have shifted the composition of the grassland, as well as affecting pollen recruitment, as discussed above. The age at which the stream channel on the western side of the fan and nearby drainage ditches were constructed is unknown.

Alternatively, changes in grazing preferences due to a change in livestock may have affected grassland composition, and may have resulted in a gradual decline in diversity from *c.*310 BP (310 cal BP, cal AD 1640). A change in stock type is more securely inferred at *c.*160 BP (140 cal BP, cal AD 1800, but possibly after AD 1900; see Section 7.3.3), when a reduction in *P. lanceolata*, C. intybus-type, Fabaceae, *P. rhoeas*-type, many other grassland and ruderal herbs coincides with the expansion of *Potentilla*-type pollen and a continuing reduction in rarefaction. This may reflect the conversion to intensive sheep farming around the establishment of coniferous plantations. *Hordeum* group, Poaceae anl-D>8 µm, *P. rhoeas*-type and Brassicaceae are still recorded, suggesting that Camban continued to be occupied into the nineteenth century. The palynological evidence for historic, and earlier, land-use in Glen Affric is compared with documentary data in Chapter 9.

7.5.12 Zone CAM5b: Poaceae-Cyperaceae-*Potentilla*-type (6-0 cm, 110-0 BP, 60-0 cal BP)

The top spectra are dominated by Poaceae, *Potentilla*-type and Cyperaceae, reflecting the present vegetation cover on the fan. However, arable weed and cereal-type grains are also recorded, including a possible *Avena/Triticum* grain in the surface sample. The meaning of this is not clear, as the temporal scale reflected by the sample of uncompacted surface mosses is unknown, but must suggest very recent cereal-type production. It is possible that the drainage ditches, which are visible at present, may have provided a niche for *Glyceria*, although the source of seed would be questionable and no other aquatic taxa are recorded throughout the profile. The botanical survey was carried out too early in the season to identify Poaceae to genera or species. Documentary evidence for land-use at Camban is discussed in Chapter 9.

Frequencies of 15% tree and shrub pollen in the surface sample are higher than values of 2.5-6.4% recorded in zone CAM5a, prior to the increase in plantation taxa. This suggests that the long-distance component is limited and comparison with earlier Holocene frequencies suggests that tree cover has been sparse or limited since *c.*640 BP (590 cal BP) and may have been similarly low from 2470-1960 BP (2650-1880 cal BP). Low frequencies of mire species recorded on the surrounding blanket peat (*Myrica*, *Calluna* and *Sphagnum*) indicate that the pollen recruitment area is dominated by fan vegetation (*contra* Sugita *et al.* 1999), and, even in the present treeless landscape, suggests that the pollen source area of the site is predominantly local, although in the past more vigorous or frequent flushing is suggested to have incorporated higher frequencies of extralocal pollen.

7.6 Conclusions from Camban

The palynological data illustrate the impact of localised environmental processes on vegetation development, and the importance of being able to relate palynological data to its local environmental context. Frequent low intensity disturbance on flushed soils with a higher nutrient and base status appear to have been especially important in maintaining a more nutrient-demanding and species-rich flora and sustaining woodland regeneration for much of the later Holocene. The local and extralocal abundance of species such as *Pinus sylvestris*, which compete more effectively on poorer soils, appears to have been limited. Although this may result in part from edaphic conditions on the fan, there may also have been an east-west gradient in *Pinus* abundance (see Chapter 9). Edaphic conditions are also considered to have strongly influenced the longevity of local land-use and also enabled sustained upland cereal growth, including the more demanding *Avena/Triticum* group at more than 300 m OD.

CHAPTER 8: Morvich

8.1 Site selection

At present there are many contrasts between the lowland Strath Croe valley in Kintail and adjacent upland Glen Affric, including those of climate, land-use and vegetation, particularly the absence of extensive blanket peat (Chapter 2). A pollen site was selected in Kintail in order to investigate woodland development and decline, and the duration and possible intensity of land-use in order to determine when these upland-lowland contrasts originated.

Present climatic conditions in the coastal Kintail valley are less severe than in Glen Affric due to the lower altitude and ameliorating influence of the Atlantic Ocean (Section 2.1.4). As a result, woodland composition may have differed markedly from the uplands, perhaps allowing the establishment of more thermophilous taxa at the expense of *Pinus*, which competes better under marginal conditions. In addition, palaeoecological woodland zonation maps for the mid-Holocene (*e.g.* Tipping 1994, Edwards and Whittington 1997), and present potential woodland distribution maps (McVean and Ratcliffe 1962) infer that *Quercus* assumed a more important role in the coastal lowlands. However, the closest pollen sites are on Skye and, as the northern limits of *Quercus* are suggested to lie in this region, woodland composition is uncertain (Williams 1977, Birks and Williams 1983; see Chapter 1).

The response of vegetation to changing climatic conditions is expected to differ between a relatively sheltered lowland site at the head of a sea loch, and the harsher climatic conditions and rougher terrain of upland sites. This may have affected the sensitivity of vegetation to climatic change and also to anthropogenic or grazing pressures. Sea-level change is a further environmental factor which will have influenced vegetation development on the western seaboard, since eustatic sea-level rise outstripped isostatic uplift following deglaciation. Consequently, sea levels rose, resulting in marine transgression which will have affected the composition and distribution of vegetational communities in low-lying areas such as Strath Croe. The results of recent sea-level research from Loch nan Corr enable the relationship between vegetation history and sea levels to be evaluated (see Sections 8.2 and 8.6; Fig. 6b).

There is abundant evidence for the use of western lowland and coastal locations from the Mesolithic period onwards (Finlayson and Edwards 1997), and the archaeological and historical record for Kintail provides evidence of human presence and land-use since the Neolithic through to the present day, in contrast to more limited records for upland land-use (Section 2.2). The record of habitation may therefore extend back further than the archaeological record suggests, although sea level changes will have affected the distribution and availability of coastal and terrestrial resources. Climatic and edaphic contrasts between Kintail and upland West Affric may also have resulted in more substantial occupation in the lowlands, and, if lowland ecosystems were buffered against change, as suggested above, land-use and settlement may have been of longer duration. A more favourable lowland environment may have enabled more extensive, intensive or longer duration cultivation than that in the uplands, perhaps including more edaphically demanding crops, such as wheat (Coppock 1976).

The analysis of a small site in a lowland location, comparable to those in upland Glen Affric, is therefore necessary to understand the wider context for upland activity, particularly the history of an area whose farmers have used Glen Affric as a source of grazing and as a route to the east since at least the seventeenth century AD (Wordsworth and Harden 1997).

8.2 Site description

The lowland, coastal Strath Croe valley in Kintail is approximately 800 m across at its widest point, by 2000 m long, narrowing at the inland eastern end and grading into salt marsh at the head of Loch Duich to the west (Fig. 6b). The valley is bounded by mountain peaks and ridges, with heights of 703-891 m OD, including the Five Sisters of Kintail to the south (Photo 11). Strath Croe and West Affric are connected by two upland passes; the pass between Glean Lichd and Fionngleann lies at 361 m OD, while the Bealach an Sgairne pass rises above 600 m OD, before dropping to Gleann Gniomhaidh and West Affric (Fig. 6b).

The vegetation history of the Strath Croe floodplain, and thus extralocal pollen influx to the present sampling site, will have been affected by sea-level change. As this subject is not applicable to any of the other pollen sites in this study, the evidence for sea-level change at Loch nan Corr (Shennan *et al.* in press) is briefly summarised here and discussed in Section 8.5. Maximum sea-levels were attained around 7330-7100 BP (8100-7900 cal BP), although the early Holocene sea-level is poorly defined from the sequence and the height of the Holocene marine transgression is poorly constrained. Subsequently, the basin became gradually isolated, with the lower boundary of the freshwater assemblage dated to *c.*820-570 BP (725-550 cal BP).

Morvich is a small township located at the southern edge of Strath Croe, just above the river (Fig.

52). The few small farms belong to crofters, with extensive grazing for sheep in the uplands and on the salt marsh, and a small herd of Highland cattle. This area has the longest known archaeological and documentary record of the sampling sites in this study (Section 2.2). Morvich is one of several locations in Strath Croe and the neighbouring Glen Shiel which is named and marked as farmsteads with cultivation plots on Roy's military map of AD *c.*1755, and it is also listed in the census records of AD 1841 and 1861. In addition, traces of Iron Age settlement and agriculture above Inchnacroe (Wordsworth and Harden 1997) lie *c.*600 m east of Morvich.

The sampling site is located in rough grazing, between the flat valley floor and rising, rocky slopes, at an altitude of 25 m OD; National Grid Reference NG 965209; the local vegetation and pollen source area thus include several of the characteristic vegetation types of this region (Section 2.1.5.4, Figs. 6b and 52). The coring site is a very small rock basin (Fig. 53), currently supporting aquatic and mire vegetation. Immediately north of the basin is a small stream with a gravel bed. The River Croe lies 150 m to the north, and Morvich is screened from the extensive strath on the northern shore by a fringe of *Alnus glutinosa* beside the river (Photo 12). Immediately to the south is a rocky gully, with walls around 3 m high, which rises towards the hills (Photo 13). This rock mass also projects out to the west of the basin, providing some shelter from prevailing westerly winds. At present the site is grazed by both sheep and cattle.

The basin vegetation is dominated by *Myrica gale* and mats of *Sphagnum*, with abundant *Potamogeton* and aquatic *Ranunculus* sp. in the water. *Juncus* is common, with *Eriophorum vaginatum* and *E. angustifolium*, *Scirpus cespitosa* and Poaceae, which were not yet in flower at the time of recording. *Calluna vulgaris*, *Myrica gale*, *Pteridium aquilinum*, *Potentilla erecta*, *Galium palustre*, *Narthecium ossifragum* and *Pinguicula vulgaris* occur on peaty and rocky ground around the basin, with occasional *Erica tetralix* and *Vaccinium myrtillus*. *Lotus uliginosus* and *Ranunculus* sp. are abundant near the stream. A few individuals of *Crataegus monogyna*, single *Sorbus aucuparia* and *Rosa* shrubs, and *Hyacinthoides non-scriptus* were recorded further up the gully.

8.3 Results

8.3.1 Basin morphology and source area

Contour maps for the sampling site at Morvich (Fig 53) indicate that the rock basin has a present area of *c.*13.0 x 9.0 m, although the deepest deposits are confined to a basin with a diameter of 5.0 m, which measured *c.*1.5 x 0.5 m near the base. On this basis, the pollen source area is estimated at a radius of *c.*50-100 m under a woodland canopy (Sugita 1994, Calcote 1995), increasing to around 800-1000 m in an open landscape (Sugita *et al.* 1999). This suggests that the pollen source area will reflect primarily local vegetation composition and dynamics (Bradshaw 1988, 1991). No contour map is presented for the mire surface, which was virtually flat. The gravel bed stream on the northern side of the basin is a recent formation, as adjacent peat deposits are deep, and suggest that a second basin may lie to the north, running beneath the present stream (see Fig. 55). In addition, there is no mineral material in the core that would indicate the stream had switched nearer to the sampling basin (Section 8.3.2, Fig. 55).

8.3.2 Sediment description

A peat core 502 cm in length was extracted from the deepest point in the basin (Fig. 53a) using the techniques described in Section 4.1.3. The sediment stratigraphic description is presented in Table 31, with a simplified description in the stratigraphic column on the pollen diagrams (Figs. 55-57). This indicates that, above the basal mineral sediment and overlying charcoal, the cores consist of highly organic peat, confirmed by loss-on-ignition analysis (Fig. 55).

8.3.3 Radiocarbon dates

Ten peat samples were submitted for AMS radiocarbon-dating. The dates depict a conformable sequence (Table 32), with the exception of the uppermost sample at 50 cm, which returned a modern date. A time-depth curve generated by linear-interpolation is presented in Figure 54. The modern date at 50 cm is excluded from the chronology used to plot the pollen and microfossil diagrams, and the estimated age of the sediment above 70 cm (1365 ± 45 BP) is based on interpolation to the surface. On this basis, the modern date at 50 cm is interpolated to c.980 BP (920 cal BP).

However, comparison with recent historic marker horizons provided by the rise in plantation conifers and SCPs suggests that this estimated chronology is too old. *Picea* pollen is present from 40 cm, apparently *c.*780 BP (*c.*680 cal BP, AD *c.*1280), and thus seemingly nearly 700 cal years too "early". Pinus values rise from 44 cm, at *c.*860 BP (*c.*740 cal BP, AD *c.*1220), although the main rise occurs at 12 cm, *c.*230 BP (290 cal BP, AD 1660), nearly 300 cal years earlier than documented plantations records. The first SCP is recorded at 20 cm, estimated at 390 BP (470 cal BP, AD 1480), which is *c.*420 cal years before expected. The discrepancy remains, even allowing for 2σ radiocarbon errors of ± 90-100 years.

This suggests a shift to rapid peat accumulation in the upper, poorly humified sediment, which is not resolved by the extrapolated radiocarbon chronology, and may indicate that the modern date at 50 cm is correct, as a "modern" radiocarbon date can be *c.* 100-150 years old. The age of events younger than 1365 BP (70 cm) is therefore uncertain, as indicated in the interpretation (Section 8.5, zones MOR3b-4b). While all radiocarbon dates should be regarded as *circa*, dates above 1370 BP (1290 cal BP) are prefaced with '*c.*' as a reminder of the added uncertainties in this section of the profile.

The temporal resolution of the pollen sampling intervals is presented in Table 33, which indicates that time intervals between subsamples range from 11-375 ^{14}C (13-439 cal) years, with a mean of 80 ^{14}C (90 cal) years/interval.

8.3.4 Pollen and microfossil analysis

Percentage pollen data are presented in Figure 55, with concentration and accumulation data in Figures 56 and 57 respectively. The results of rarefaction and rate-of-change analyses are shown in Figures 58 and 59. The results of detrended correspondence analysis for the first two axes are presented in Figure 60a-b. 65.3% of the cumulative variance in the taxa data is captured in the first four DCA axes, with 56.8% represented by the first two axes.

Eight local pollen assemblage zones and subzones were defined (Table 34); the site designation 'MOR' precedes each zone or subzone division. The dimensions of cereal-type pollen grains and large Poaceae are given in Table 35 (see Section 4.3.1.1 for identification criteria).

8.3.5 Pollen preservation data analysis

Summary pollen preservation data are presented in Figure 61 and preservation class data for selected individual pollen types is shown in Figure 62 (see Section 4.3.2 for calculation sum).

The summary preservation data indicate that well-preserved and corroded pollen are the predominant preservation categories, followed by crumpling. Frequencies of broken pollen remain relatively constant, suggesting that the damage may be primarily the result of processing techniques (*cf.* Cushing 1967). However, the temporal variability of corrosion suggests a more complex origin for this form of deterioration.

Corroded pollen comprises 1.2-69.7% of the TLP assemblage, with a mean of 30.6%. Degraded pollen is more frequent during periods of higher corrosion, although frequencies remain low. The individual taxon preservation curves (Fig. 61) indicate that corrosion affects all major taxa similarly. This implies either a post-depositional, diagenetic origin, or that the corroded pollen represents an inwashed assemblage. Consistently high sediment organic content (Fig. 62) indicates that inwashed and secondary pollen, derived from soil or sediment redeposition (*cf.* Lowe 1982, Tipping 1995), can be excluded. Although peat erosion cannot be discounted, the limited palynological and present day soil and vegetation evidence for blanket peat formation around the site (Section 2.1) indicates that this is perhaps unlikely to cause high frequencies of corroded pollen.

Corroded pollen is thus argued to have occurred as a result of post-depositional deterioration. Anaerobic conditions could be caused by the sampling basin drying out; this has been recorded as a potential problem in dealing with small pollen sites (Bradshaw 1988) due to their restricted surface area and often shallow depths of water. Higher and more consistent frequencies of aquatic pollen coincide with low (early zone MOR1, zones MOR3b, MOR4) or slightly lower frequencies (zone MOR 2b) of corroded pollen, thus providing some support for this interpretation, as aquatics may have flourished under more consistently wet conditions.

It is thus necessary to assess the severity of inferred post-depositional corrosion in order to determine to what extent, if any, the assemblage may have been biased. In soil pollen assemblages, high frequencies of Pteropsida, degraded and robust pollen taxa are considered to indicate severe biasing (*e.g.* Tipping *et al.* 1994, Tipping and Carter 1998). At Morvich, Pteropsida frequencies remain relatively low and are well-correlated with periods of more open woodland, suggesting an ecological association. There is no correlation between the frequency of resistant Pteropsida spores and TLP corrosion (Fig. 61). As indicated above, degraded and indeterminate corroded pollen form a very minor part of the assemblage. While robust pollen taxa, such as Asteraceae, Caryophyllaceae, Chenopodiaceae and *Plantago*, occur quite frequently, they occur in ecologically interpretable pollen suites and are more frequent during the mid-later Holocene, when frequencies of corroded pollen are generally lower. Thus, although corroded pollen forms a significant part of the assemblage, deterioration is not considered to be severe and is not thought to have biased the data.

'Mild' corrosion of the entire assemblage may have occurred if the basin dried out periodically, even for brief periods, leading to 'secondary decomposition', although a probable hiatus between zones MOR1 and 2 (see Section 8.5) suggests that during the early Holocene, when the basin diameter was very small, longer periods of dryness may also have occurred.

This interpretation appears to be at odds with the presence of sulphide spherules, which form as a result of microbial activity under conditions of low redox potential, and are thought to indicate deep or shallow standing water and/or inwashing (Wiltshire *et al.* 1994; Section 4.3.4.3). Sulphide spherules were not consistently recorded owing to initial uncertainty in their identification, but some tentative inferences are possible, as sample depths during counting occurred throughout the profile, not in stratigraphic blocks.

As there is no evidence for inwashing in the profile from Morvich, the presence of spherules may infer ion-rich water, including ferric (Fe^{+3}) and sulphate compounds and organic matter necessary for spherule formation. It is not clear from the literature how long is required for spherule formation; short-lived fluctuations in wetness may have been sufficient to allow spherule formation and cause mild corrosion during wet and dry periods respectively, as inferred above. However, the admittedly incomplete record for sulphide spherules appears to coincide with periods when aquatic taxa are absent, suggesting that spherules formed mainly when the water was too shallow or intermittent to support aquatic vegetation, or when the water was too stagnant to support aquatic taxa due to the presence of reducing conditions necessary for spherule formation.

Unfortunately the relationship between corrosion, sulphide spherules and aquatic taxa is incomplete and suggested complexities, which do not emerge from the present small literature on sulphide spherules in stratigraphic sequences, cannot be securely explored. Ecological and hydrological inferences are thus limited as secondary decomposition may have distorted pre-existing evidence for drier conditions in the basin.

As the pollen preservation data are percentage-based, variability in crumpling may be determined more by changes in corrosion, than by independent factors. Peaks in crumpling do not appear to correlate with variations in absolute pollen frequencies, which could suggest inwashing. Therefore, crumpling, like corrosion does not appear to be the result of redeposition or inwashing. Inferred fluctuations in watertables may indicate that changes in the effective overburden weight could have resulted in crumpling due to compaction (*cf.* Smith 1984b). A slight increase in crumpling from zone MOR2c, with a further increase in zones MOR3b and 4 reflect higher frequencies of crumpled balloon-like Poaceae and Cyperaceae pollen.

8.3.6 Charcoal analysis

Charcoal data are presented in Figure 63, in percentage, concentration, accumulation and charcoal-to-pollen concentration form. Table 36 provides a summary of the age and spread of the charcoal peaks.

Regression analyses of charcoal size class data (Table 37) indicate that there is a high correlation between charcoal size classes ($r^2 = 0.64-0.91$). This suggests that charcoal size classes are rather conservative, and do not exhibit marked variations. However, very high charcoal frequencies in a single spectrum at 8230 BP (9210 cal BP) form an outlier, which reduces the effects of scatter at lower frequencies. Variability in the data is evident in the charcoal size class ratios (Fig. 64). This may reflect chance variations associated with low charcoal counts, particularly from *c.*6510-2690 BP (7390-2770 cal BP), when charcoal frequencies are very low and charcoal size class ratios are highest and most erratic (*cf.* Maher 1972). However, real variations in fire size, intensity and fuel source may also affect the charcoal size class signature. These complexities indicate that inferences regarding the proximity of fires to the sampling site, derived from the charcoal size class signature (*cf.* Rhodes in Stevenson *et al.* 1996) need to be made cautiously. The possible significance of temporal changes in charcoal size class ratios are discussed in the relevant zones in Section 8.5.

8.4 Description

8.4.1 Zone MOR1: *Betula-Salix-Corylus avellana*-type (500-471 cm, 9730-7100 BP, 10960-7910 cal BP)

The basal sediment (502-497.5 cm, 9920-9490 BP, 11010-10520 cal BP) consists of coarse, silty sand with charcoal flecks at the transition to woody peat, where organic content rises from 5.5-82.5%. The zone is characterised by high basal pollen frequencies for *Betula*, which fall as *Salix* pollen values rise to a Holocene maximum of 77% at 7110 BP (7910 cal BP). *Juniperus* pollen is recorded in the basal sample. The curve for *Corylus avellana*-type pollen peaks at 34% around 8980 BP (9970 cal BP) before a gradual decline. Consistent low pollen frequencies are recorded for *Pinus sylvestris*, *Sorbus aucuparia*, *Ulmus*, Poaceae and *Calluna*. *Filipendula*, Rosaceae, *Potentilla*-type and Apiaceae are the most frequent herb pollen types. Amongst the less common herb pollen taxa are *Lysimachia vulgaris*-type, *Caltha palustris*-type, *Ranunculus* acris-type, *Rumex acetosa* and *Succisa pratensis*. Single grains of *Avena/Triticum* group and *Hordeum* group are recorded. *Myriophyllum* pollen is present from 9920-9350 BP (11010-10310 cal BP). *Polypodium* and Pteropsida (monolete) indet. spores are present throughout the zone, with a peak in Pteropsida at 9350 BP (10310 cal BP). Low frequencies of *Pteridium aquilinum* and *Sphagnum* are recorded.

Total land pollen concentrations are variable, following a basal peak. Concentration curves for the major pollen taxa display similar patterns to the percentage data. Pollen accumulation rates are low. The pollen preservation data are dominated by well-preserved and corroded pollen, with lower frequencies for crumpled pollen and consistently low values for broken grains. This pattern is reflected in all major taxa. Palynological richness is high, falling at the end of the zone. Rates of change are very low. Charcoal values are high throughout the zone and a peak at 8230 BP (9210 cal BP) is reflected in all measures of charcoal abundance.

8.4.2 Zone MOR2a: *Betula-C. avellana*-type-*Alnus-Ulmus* (471-446 cm, 7100-6730 BP, 7910-7540 cal BP)

The sediment consists of woody peat of high organic content. The pollen assemblage is characterised by abrupt changes in all of the major taxa; increased *Betula*, *Alnus*, *Ulmus*, *Pinus* and *C. avellana*-type pollen frequencies correspond with a decrease in *Salix* pollen values from 77-12%. *Pinus* pollen attains a maximum of 15% at 6760 BP (7550 cal BP) as *Ulmus* and *Alnus* pollen values increase and *Betula* and *C. avellana*-type frequencies fall. Consistently low values are recorded for *Quercus* pollen. *Filipendula* and Rosaceae pollen values are reduced, while *Potentilla*-type, Apiaceae and Rubiaceae pollen is more frequent. *Potamogeton* pollen is present and there is a rise in Pteropsida (monolete) indet. values.

TLP concentrations are reduced, before increasing gradually through the zone. Total pollen accumulation rates increase. Absolute pollen changes are again similar to the percentage pollen curves. Pollen preservation values are similar to the previous zone. Rarefaction values are variable and slightly reduced from the previous zone. A peak in chord distance at 7130-7090 BP (7920-7850 cal BP) is associated with a change to higher rates of palynological change. Charcoal frequencies are slightly lower but remain variable.

8.4.3 Zone MOR2b: *Alnus-Betula-Ulmus-C. avellana*-type (446-378 cm, 6730-5690 BP, 7540-6470 cal BP)

The peat consists of amorphous woody peat with high organic content. *Alnus* is the dominant pollen producer and *Ulmus* pollen values are higher. Pollen frequencies for *Betula, Pinus, C. avellana*-type and *Salix* are reduced. All curves are very variable. *Lonicera periclymenum* and *Hedera helix* pollen are recorded frequently. The most common herbaceous pollen types include *Ranunculus acris*-type, *Filipendula*, Rosaceae, Apiaceae, Rubiaceae and *Lysimachia vulgaris*-type. The curve for *Potamogeton* pollen is continuous from 6210-5720 BP (7090-6490 cal BP), with a peak at 5780 BP (6590 cal BP). Pteropsida (monolete) indet. spores are present at *c.*5-15%.

Absolute pollen values are variable, but higher than zone MOR2a. Well-preserved and corroded pollen dominate the assemblage, with lower frequencies of crumpled pollen. Rarefaction values decline gradually to 5840 BP (6670 cal BP), before increasing. Rates of change increase from 6700 BP (7530 cal BP), rising to higher but more erratic values at 5930 BP (6750 cal BP). Charcoal frequencies are low, particularly after 6570 BP (7400 cal BP).

8.4.4 Zone MOR2c: *Alnus-Betula* (378-269 cm, 5690-4200 BP, 6470-4730 cal BP)

The sediment consists of woody peat with fine roots and monocot leaves. Sediment organic content remains high. *Alnus* pollen frequencies are slightly lower, while *Betula* pollen values rise. *Salix* pollen is recorded less frequently. The *Ulmus* pollen curve shows stepped reductions at 5410 BP (6250 cal BP) and 5060 BP (5830 cal BP). *Pinus* pollen values fall gradually and *C. avellana*-type pollen frequencies are lower after 4290 BP (4850 cal BP). Poaceae values rise from 5690 BP (6470 cal BP). The most frequent herbaceous pollen types remain as in the previous zone, with the exception of less frequent *L. vulgaris*-type and Rubiaceae pollen. *Polypodium* spores are more abundant and the curve for Pteropsida (monolete) indet. spores falls at 5080 BP (5810 cal BP). Aquatic pollen is absent.

Absolute TLP values remain high and variable. *Ulmus* pollen concentrations are lower from 5250 BP (5960 cal BP) and absolute *Pinus* pollen values are reduced from 4320 BP (4860 cal BP). Well-preserved and corroded pollen dominate the zone, with a slight rise in crumpled pollen, which is reflected in all taxa, particularly Poaceae. Frequencies of well-preserved pollen increase from 4890 BP (5610 cal BP) as corroded pollen values decline. Decreased deterioration occurs in all major pollen types. There is a continuing overall reduction in palynological richness. Rates of change remain high until 5330 BP (6140 cal BP), when values fall. Charcoal frequencies remain very low and are nearly absent from 4570 BP (5290 cal BP).

8.4.5 Zone MOR3a: *Betula*-Poaceae-*Alnus* (269-146 cm, 4200-3480 BP, 4730-3710 cal BP)

Sediment organic content remains uniformly high, but sediment composition is more variable, including twigs, small roots, monocot leaves and wood. The pollen assemblage is characterised by a permanent reduction in *Alnus* pollen and higher pollen frequencies for *Betula* and Poaceae. *Sorbus* pollen frequencies are higher between 4070 and 3720 BP (4530-4020 cal BP), with peaks of 10.0 and 10.4%. *Pinus* and *Ulmus* pollen frequencies are consistently low, with a slight increase in *Quercus* pollen around 3750 BP (4090 cal BP). *Salix* pollen frequencies increase at the end of the zone. *Calluna* pollen values show a small increase from 3720 BP (4020 cal BP). Cyperaceae pollen frequencies rise slightly and *Hordeum* group pollen is more frequent. The herb assemblage is characterised by *Potentilla*-type, *Plantago lanceolata*, *R. acris*-type, Rosaceae, *Filipendula*, *R. acetosa* and *Succisa*. *Papaver rhoeas*-type and *Urtica* pollen are also present.

Pteridium spores are more frequent, with peaks at 3940-3910 BP (4410-4370 cal BP) (3.0-3.1%), 3750-3720 BP (4090-4020 cal BP) (22.4-33.2%) and 3640 BP (3960 cal BP) (7.5%). *Polypodium* spores are present at lower frequencies. Higher frequencies of *Sphagnum* and Pteropsida (monolete) indet. spores are recorded from 3790 BP (4150 cal BP) and 3680 BP (3980 cal BP), respectively.

TLP concentrations decrease gradually through the zone, but concentration values for *Potentilla*-type and *P. lanceolata* rise. Pollen accumulation rates are initially very high, falling from 4090 BP (4560 cal BP). Well-preserved pollen is dominant, with slightly lower values for corroded pollen; frequencies of crumpled and broken pollen remain consistent. Rarefaction values rise gradually through the zone and rates of change are very high between 4240 and 3580 BP (4830-3860 cal BP). Charcoal frequencies remain very low.

8.4.6 Zone MOR3b: *Betula*-Poaceae-*Alnus*-*C. avellana*-type (146-46 cm, 3480-*c.*900 BP, 3710-*c.*790 cal BP)

Sediment composition remains variable, including wood, fine roots and twigs, with *Phragmites* leaf sheaths between 1870 and 1550 BP (1820-1410 cal BP). Organic content is very slightly lower above 2690 BP (2770 cal BP). *Betula* pollen frequencies remain high, with the exception of a trough at 3510-3060 BP (3760-3300 cal BP), when pollen values for *Salix* are higher and the

Poaceae curve peaks at 60.1%. Subsequently, *Betula* pollen values decline from *c.*1090 BP (*c.*970 cal BP). *Alnus* pollen values are less variable, falling from *c.*1250 BP (*c.*1170 cal BP). *C. avellana*-type pollen frequencies are higher in mid-zone and maximum *Quercus* pollen values of 5.4-5.2% are recorded at 1520-1420 BP (1400-1300 cal BP). Poaceae pollen values are lower than the previous zone, while *Calluna* and Cyperaceae pollen frequencies are higher. The pollen curve for *Myrica gale* rises from 1840 BP (1740 cal BP). *Erica* and *Vaccinium*-type pollen are more frequent.

Hordeum group and *Avena/Triticum* group pollen grains are recorded. The herbaceous pollen assemblage is characterised by *Potentilla*-type and *P. lanceolata*, with *R. acris*-type, *Succisa*, *R. acetosa*, *Filipendula* and Rosaceae. *Ranunculus trichophyllus*-type, *Plantago media/major* and *P. rhoeas*-type pollen are more frequent. *Pteridium* spores remain frequent and Pteropsida and *Sphagnum* spores show slightly increased values. *Potamogeton* and *Equisetum* spores are also recorded.

TLP concentrations range between moderate to high and absolute pollen curves display similar patterns to percentage data. Pollen accumulation rates remain at moderate levels, with higher values for NAP taxa than AP types. Well-preserved pollen dominates the assemblage, while crumpled pollen is more frequent from 2580 BP (2740 cal BP) as corroded pollen values decline in all major taxa. Rarefaction values are high, with a single spectral drop at 3320 BP (3510 cal BP) and a slight troughs at *c.*1100-940 BP (*c.*980-830 cal BP). Rates of palynological change fall from the previous zone to 3070 BP (3300 cal BP), remaining low until a small rise around 1420 BP (1300 cal BP). Charcoal frequencies rise to moderate values between 2370-1950 BP (2350-1880 cal BP).

8.4.7 Zone MOR4a: *Betula*-Poaceae-Cyperaceae (46-6 cm, *c.*900-120 BP, *c.*790-110 cal BP)

The highly organic peat becomes more humified with an increasing proportion of *Sphagnum* as depth decreases. This zone is characterised by lower arboreal pollen frequencies and higher pollen values for *Myrica*, *Calluna*, Poaceae, Cyperaceae and *Sphagnum*, although *Betula* pollen frequencies rise between 1170 and 1090 BP (*c.*1060-970 cal BP). *Pinus* pollen frequencies rise at the end of the zone and *Picea* pollen is recorded. *Fraxinus* pollen is more frequent.

The curve for *Hordeum* group pollen is continuous and maximum frequencies of 4.6% are recorded at *c.*230 BP (*c.*290 cal BP). *R. trichophyllus*-type, *Potentilla*-type and *P. lanceolata* are the more common herb pollen taxa, with *Succisa*, *Cichorium intybus*-type, *Pedicularis*, *R. acris*-type, *P. rhoeas*-type, *R. acetosa* and *Filipendula*. *Narthecium ossifragum* pollen is more frequent. *Potamogeton* pollen is still present and the curve for *Pteridium* spores remains constant. Pteropsida (monolete) indet. frequencies are lower.

Absolute TLP values are lower, decreasing near the end of the zone. Well-preserved pollen dominates the zone, with rising values for crumpled and corroded pollen. Rarefaction values are high throughout the zone. Rates of change maintain similar values to zone MOR3b, before rising from *c.*120 BP (*c.*110 cal BP). Charcoal frequencies remain at moderate levels. Single spheroidal carbonaceous particles are recorded at *c.*390 BP (*c.*470 cal BP) and *c.*230 BP (*c.*290 cal BP).

8.4.8 Zone MOR4b: Poaceae-Cyperaceae (6-0 cm, *c.*120-0 BP, *c.*110-0 cal BP)

The highly organic sediment consists of poorly humified *Sphagnum* peat with *Myrica* leaves and monocot stems. The zone is characterised by slight increases in *Pinus* and *Alnus* pollen, as *Betula* frequencies decline. Poaceae and Cyperaceae are the dominant pollen producers, with *Myrica* and *Calluna*. The characteristic herbaceous pollen types are *P. lanceolata*, *Potentilla*-type, *Pedicularis* and *cf.* Liliaceae.

Absolute pollen frequencies are low and the pollen assemblage is dominated by well-preserved pollen. Rarefaction values remain high. Rates of change continue to rise, falling in the surface sample. Charcoal frequencies are low. A single SCP is recorded at *c.*40 BP (modern cal BP).

8.5 Inferred vegetation history

8.5.1 Zone MOR1: *Betula-Salix-Corylus avellana*-type (500-471 cm, 9730-7100 BP, 10960-7910 cal BP)

The age of the basal sand deposit is difficult to assess as only one pollen sample was analysed from the upper section of this mineral unit. The presence of high frequencies of *Betula* with *Juniperus*, *Rumex acetosa* and *Cryptogramma crispa* may indicate an early Holocene age, possibly with limited earliest Holocene elements. This is as expected, since the site lies within the limits of the Loch Lomond Readvance (Bennett and Boulton 1993; Section 2.1.2). The extrapolated date for the basal sediments may thus be slightly too young, or infer that an open flora was maintained, perhaps due to exposure and proximity to the coast.

The presence of macroscopic charcoal fragments at the mineral-organic interface may indicate that peat initiation was the result of a local fire, which caused paludification by blocking the pores in the sand (Mallik *et al.* 1984). This is suggested to have contributed to the relatively high charcoal frequencies in the basal pollen sample. However, there is no correlation between micro- and macroscopic charcoal records. Very high microscopic charcoal frequencies are recorded throughout zone MOR1, particularly later in the zone, while macroscopic charcoal particles were only recorded at the base of the sequence. In addition, the microscopic charcoal size class signature does not suggest higher frequencies of large fragments, which would be expected from a local fire (*cf.* Stevenson *et al.* 1996).

There is no clear explanation for this apparent conflict, particularly with the poor temporal resolution of analyses available, which does not allow any assessment of whether this reflects a protracted period of frequent/intense fires or more sporadic burning. It is possible that the source of charcoal produced very fragile charred particles, but this cannot be investigated without identifying the fuel source and data from experimental burning (*cf.* Dark 1998).

During the early Holocene, the basin at Morvich supported *Myriophyllum alterniflorum*, which may have flourished in the highly minerogenic sediments (*cf.* Haslam *et al.* 1975). A decrease in water depth or succession to fen carr may have eliminated *Myriophyllum* around 8600 BP (9520 cal BP). An increase in corroded pollen may reflect terrestrialisation of the basin, as small hollows are prone to dry out, causing aerobic pollen deterioration (Bradshaw 1988), as discussed below.

Single grains of *Hordeum* and *Avena/Triticum* group pollen are suggested to derive from aquatic grasses, such as *Glyceria*, although maritime grasses may also have been present in the extralocal area. *Caltha palustris*-type may have grown on the margins of the small pond, fringed by tall-herb and marsh vegetation, including *Filipendula*, *Potentilla*-type (*cf. P. palustris*), *Epilobium*-type, Apiaceae, *Lysimachia vulgaris*-type and perhaps *Succisa pratensis*. These taxa may also have formed the woodland understorey.

Shrubby woodland was established around the basin, dominated by *Betula* and *Salix*. As indicated above, *Juniperus* pollen in the basal minerogenic sediment may have been a relict of open scrub of the early Holocene. Although temporal resolution is poor in this zone (Table 33), *Salix* and *C. avellana*-type appear to have replaced *Betula*. This may reflect terrestrialisation of the basin surface, as inferred above, and successional changes in the surrounding woodland.

Terrestrialisation or a fall in water levels may have enabled *Salix* carr to invade the basin from 8600 BP (9520 cal BP). The high *Salix* frequencies suggest possible local over-representation (Janssen 1966) or a dense thicket, which suppressed *Betula* and *Juniperus* representation.

Around the basin, the increase in *Corylus avellana*-type pollen from 5.7% at 9350 BP (10310 cal BP) to 34.3% at 8980 BP (9970 cal BP) suggests that hazel became a relatively abundant shrub in the local woodland. *Betula* does not regenerate successfully beneath its own canopy (Atkinson 1992), and this may have enabled *C. avellana*-type to become established closer to the site, in woodland previously dominated by *Betula*. A continuous curve for *Sorbus aucuparia*, with a peak of 2.3% at 9350 BP (10310 cal BP), suggests that *Sorbus* may have been a common woodland tree (*cf.* Birks 1980).

Charcoal frequencies rise to a peak at 8230 BP (9210 cal BP) as *Salix* values increase further. It is possible the fires created openings which enabled *Salix* or *C. avellana*-type to become established. However, the coarse temporal resolution limits secure ecological inference about the relationship between charcoal and vegetation composition and dynamics. The cause of burning is not clear; consistently high AP sums may argue against inferences of deliberate anthropogenic vegetation manipulation, although high charcoal representation may reflect local domestic or camp fires (Bennett *et al.* 1990), with limited impact on the vegetation. Palaeoclimatic research elsewhere provides evidence for early Holocene aridity, as discussed in Chapter 9.

Numerous entomophilous shrubs and climbers also appear to have been present, including *Prunus padus*, *Viburnum opulus*, *Lonicera periclymenum* and *Hedera helix*. Consistently low frequencies for *Pinus sylvestris*, *Ulmus* and *Quercus* pollen are suggested to derive from long-distance transport from trees which were becoming established further south, although *Ulmus* may have established populations in the extralocal source area by the end of the zone, at *c.*8500 BP (9470 cal BP) (Huntley and Birks 1983, Birks 1989).

Uniform, low frequencies of *Calluna* may derive from within the canopy or perhaps from more exposed, higher altitude communities on the surrounding hillsides. However, the poor modern pollen representation of *Empetrum* and *Vaccinium*-type suggests that low pollen frequencies from these genera may be indicative of heath taxa within the shrubby woodland (Tinsley and Smith 1974, Lloyd 1998). Ferns appear to have been relatively abundant in the understorey, including epiphytic *Polypodium*. *Botrychium lunaria* may have grown on rocky ground around the basin.

Pteridium aquilinum spores and heath pollen suggest that more acidic soils were present, although, the relative abundance of *C. avellana*-type and monolete Pteropsida spores imply that the soil was not highly acidic.

8.5.2 Zone MOR2a: *Betula-C. avellana*-type-*Alnus-Ulmus* (471-446 cm, 7100-6730 BP, 7910-7540 cal BP)

Abrupt changes are registered in many pollen curves, particularly arboreal taxa, over the 20 ^{14}C (26 cal) year interval across the zone MOR1/2a boundary. The rapidity of change and the stratigraphic proximity of increased *Ulmus* and *Alnus* values may indicate an hiatus in sediment accumulation, although there is no sedimentological evidence for an hiatus and concentration data do not change significantly at this boundary. Two closely-spaced radiocarbon dates were obtained in an effort to detect the suspected hiatus. These 0.5 cm thick samples were carefully selected to date the successive rises in *Ulmus* and in *Alnus* pollen. The rationale is illustrated in Figure 65: *Ulmus* frequencies rise above 2% at 471 cm and *Alnus* values exceed 2% at 468 cm. However, samples from 472 cm (AA-33332) and 468 cm (AA-33333) returned statistically inseparable dates (Table 32). It is therefore suggested that an hiatus occurred around 470 cm, but was too brief to be recognised in the ^{14}C sequence. The transition to lower sample scores on DCA Axis 2 reflect the expansion of *Alnus* and *Ulmus*, and a reduction in the importance of *Salix* (Fig. 60).

This may be associated with the continuing process of terrestrialisation which is inferred during zone MOR1, as *Salix* appears to have been replaced by *Betula, C. avellana*-type, *Alnus* and ferns. Drier conditions may also be inferred from the sharp rise in corrosion (Fig. 61).

Subsequent to the inferred brief hiatus, a rise in water levels may have reinforced the decline in *Salix*, allowing increased extralocal pollen representation and colonisation by *Potamogeton* at 6940 BP (7710 cal BP), with *Hordeum* group (*cf. Glyceria*). Little can be inferred of water depth or quality due to the wide ecological range represented by the number of species included in *P. natans*-type. The high organic content of the cores suggests that there was little water movement to deposit mineral sediment, inferring a small confined pond. Increased corrosion and the presence of sulphide spherules suggests that the basin may have dried out frequently, perhaps on a seasonal basis. There is no evidence that secondary pollen was incorporated through inwashing or the collapse of basin margins, since these processes might be expected to incorporate mineral sediment. Tall-herb and marsh communities with *Filipendula, Potentilla*-type, Apiaceae, Rubiaceae, *L. vulgaris*-type and higher frequencies of ferns, including *Polypodium, Dryopteris* *filix-mas*-type and *cf. D. filix-mas*-type, may have been present in openings around damp hollows in and around the sampling basin (see Fig. 53).

Locally, the mixed deciduous woodland consisted of *Betula*, *Alnus*, *Sorbus*, *C. avellana*-type and *Salix*, possibly with *Lonicera*, *Hedera* and *Viburnum*. The rational age limit of *Alnus* is uncertain due to the probable hiatus, but local or extralocal establishment is securely dated to 7065 ± 65 BP (7856 ± 65 cal BP) (AA-33333). *Ulmus* may have been present on moist soils beside the River Croe, in unshaded rocky niches around the sampling basin and on the less acidic outcrops of Lewisian rock which occur in Kintail (Section 2.1.2). A slight rise in *Quercus* frequencies may indicate rare local or extralocal growth. Possible reasons for low *Quercus* frequencies, relative to *Ulmus*, are discussed in Chapter 9.

Pinus pollen frequencies are higher in zone MOR2a, rising to a Holocene maximum of 15.5% at 6760 BP (7550 cal BP). Although the values recorded at Morvich are comparable with estimates suggested to indicate local presence (Fossitt 1994b), there is no stomatal evidence for local *Pinus* growth. *Pinus* is thus suggested to have become established in the extralocal pollen source area, perhaps in woodland on the surrounding hillsides, although the composition of these communities cannot be resolved from the spatially-restricted Morvich pollen profile.

Fluctuations in the curves for *Betula*, *Alnus*, *C. avellana*-type and *Salix* may reflect shifts in local stand composition, since both *Betula* and *Alnus* seedlings establish less successfully beneath their own canopy (McVean 1953, Atkinson 1992). Woodland composition may also have been affected by variations in soil moisture and burning, with wetter conditions favouring *Alnus* and *Salix*, and drier conditions aiding *Betula* and *C. avellana*-type. Disturbance and canopy opening caused by fire may have encouraged sprouting and increased flowering in *Alnus* and *Salix* at 6940 BP (7710 cal BP), and in *C. avellana*-type at 6820-6760 BP (7620-7550 cal BP). Although there is no evidence of any associated soil disturbance, the unevenness of the underlying bedrock, as suggested by basin surveying (Fig. 53), may have limited lateral soil movement. Fluctuations in the rarefaction curve may result from variations in the flowering and dispersal of pollen of understorey herbs and shrubs due to changes in local canopy density.

8.5.3 Zone MOR2b: *Alnus-Betula-Ulmus-C. avellana*-type (446-378 cm, 6730-5690 BP, 7540-6470 cal BP)

The sampling basin continued to support *Potamogeton*, possibly with *Hordeum* group (*cf. Glyceria*). Rising pollen frequencies for *Potamogeton* from *c.*6210 BP (7090 cal BP) coincide with a reduction in corroded pollen, and suggests a shift to more permanently waterlogged conditions. The pond may have been fringed by tall-herb and fen vegetation including *Filipendula*, *L. vulgaris*-type, *Caltha palustris*-type, Rubiaceae, *Valeriana officinalis*, possibly with *Urtica* and *Silene dioica*-type. However, around 5690 BP (6470 cal BP), the basin appears to have become too shallow to support aquatic taxa, perhaps allowing grasses to colonise the surface, as there is a peak in Poaceae pollen production around 5650-5600 BP (6420-6380 cal BP), across the zone MOR2b/c boundary. Cyperaceae frequencies remain very low, suggesting that sedges may not have been common in the local vegetation. The early appearance of *Myrica gale* pollen at 6760 BP (7550 cal BP), followed by *C. palustris*-type, may reflect wetter conditions.

Periodically or more permanently waterlogged and highly organic soils around the basin in zone MOR2b may have enabled *Alnus* to compete more successfully with *Betula*, *Salix* and *C. avellana*-type around 6730 BP (7540 cal BP), as *Alnus* is able to grow in habitats with a fluctuating watertable (McVean 1953, 1956a). *Alnus* maintained local pollen dominance until *c.*5900 BP (6730 cal BP), although single spectral fluctuations in *Alnus*, *Betula* and *C. avellana*-type suggest that the other species continued to grow locally, perhaps around a thicket of *Alnus*. The dense canopy may have eliminated *Viburnum* from the site, although moist, shaded conditions may have favoured *Hedera* (Grime *et al.* 1988). The dispersal of *C. avellana*-type pollen to the site may have been reduced by the formation of a fringe of *Alnus* around the basin.

High local *Alnus* representation may also have affected the flowering and pollen dispersal of understorey and extralocal vegetation, perhaps including *Calluna*. Frequencies of heaths and herbs remain low (1.2-7.1% TLP), including the tall-herb taxa which are inferred to have fringed the basin. This suggests that a relatively dense *Alnus*-dominated canopy cover formed and was maintained over and around the basin. This may have contributed to a reduction in rarefaction values.

Earlier frequencies of *Sorbus* are maintained, indicating that woodland composition on drier, acidic soils, perhaps including the rocky ground around the sampling basin, remained unaffected by *Alnus* expansion. Climbing shrubs such as *Lonicera*, *Hedera* and *Rosa* may have been frequent components of the surrounding woodland. Percentage *Pinus* frequencies decline in a step-wise fashion from 6730 BP (7540 cal BP); this may be the result of the formation of a filtering *Alnus* thicket around the sampling basin, as absolute values do not decline, suggesting the continued presence of *Pinus* in the extralocal source area.

There is a marked reduction in charcoal representation from *c*.6570 BP (7400 cal BP). This appears to coincide with evidence for increased local waterlogging (above), perhaps inferring a more widespread rise in watertable, affecting terrestrial soils. However, charcoal frequencies remain relatively low until 2580 BP (2740 cal BP), despite evidence for intervening dryness in zones MOR2c and MOR3a (below). The data provide no clear explanation for this shift. Evidence for regional controls are discussed in Chapter 9.

From *c*.5840 BP (6670 cal BP) the balance of woodland composition altered. The *C. avellana*-type curve peaks at 59% at 5840 BP (6670 cal BP), falling to 26% at 5780 BP (6590 cal BP). Disturbance or changes in soil moisture could have enabled *C. avellana*-type to rapidly expand into the *Alnus*-dominated stand, perhaps flowering more profusely as a result of an opening in the canopy. Increased *Sorbus* representation at 5780-5720 BP (6590-6490 cal BP), a peak in *Pteridium* at 5720 BP (6490 cal BP) and single grains of *Urtica* and *P. lanceolata* at 5840 BP (6670 cal BP) and 5660 BP (6420 cal BP), respectively suggest soil enrichment and/or disturbance, with a reduction in filtering and local over-representation of *Alnus* pollen. A peak in *Potamogeton* pollen at 5780 BP (6590 cal BP) may also reflect nutrient enrichment of the basin.

There is no evidence for fire disturbance, as charcoal frequencies remain low. Grazing disturbance may have caused small-scale woodland disturbance and soil enrichment. However, this was relatively short-lived, as *C. avellana*-type was replaced by *Salix* and *Alnus* within *c*.60-120 ^{14}C (80-180 cal) years, suggesting a natural succession on damp soils. This was followed by a single spectral shift to increased *Betula* at 5660 BP (6420 cal BP), across the zone MOR2b/c boundary, which marks a trend towards increased *Betula* representation.

The appearance of *Plantago maritima*, with *Artemisia*-type, *Rumex acetosa* and possibly *P. lanceolata*, *P. media/major* (*cf.* Smith 1970, Fossitt 1990) and *Silene dioica*-type, suggests the formation or expansion of salt marsh and coastal communities. This may have been a response to a fall in sea-level (Shennan *et al.* in press; Section 8.2). Alternatively or in addition, wild herbivores may have been attracted to open coastal grazing (*cf.* Evans 1975), thus creating the disturbed conditions necessary to support these species of *Plantago*.

8.5.4 Zone MOR2c: *Alnus-Betula* (378-269 cm, 5690-4200 BP, 6470-4730 cal BP)

Changes in arboreal, herbaceous and aquatic pollen representation during this zone suggest a shift to drier conditions on and around the basin. Stagnant or shallow water in the basin may have enabled sulphide spherule formation, while drier conditions around the site may have resulted in continued high corrosion.

The disappearance of aquatic taxa suggests drier local conditions, as a result of which the surface of the sampling basin appears to have been colonised by damp grass, fern and tall-herb vegetation with *Filipendula* and possibly *C. palustris*-type, *V. officinalis*, *Mentha*-type and *Equisetum*. Ferns may also have colonised the damp soils, particularly after 5550 BP (6310 cal BP). The slight increase in NAP (Fig. 55), a gradual increase in the surface area of the basin (Fig. 53) and a reduction in the abundance of wood in the core (Table 31) suggests that the fringe of trees may have retreated from the central sampling point, or that drier conditions (see below) may have been less suitable for the preservation of wood.

Drier conditions are suggested to have resulted in an increase in the abundance of *Betula* from *c.*5490 BP (6290 cal BP) and a reduction in *Alnus*, *Salix* and possibly *Lysimachia* and *Viburnum*. The surrounding vegetation appears to have been composed of more open *Betula-Alnus* woodland, with damp soils continuing to support tall-herbs, ferns and an increased abundance of Poaceae in the understorey.

Although charcoal frequencies remain low, more erratic charcoal representation, especially in accumulation data, and the palynological evidence suggest small-scale, short-lived woodland disturbances associated with burning from 5380 BP (6460 cal BP). This may also have maintained higher Poaceae frequencies (see below). Peaks in charcoal and *Pteridium aquilinum* at 5380 BP (6460 cal BP) coincide with a reduction in tree cover and increased palynological richness, suggesting sporulation or the spread of *Pteridium* following a woodland fire (*cf.* Rymer 1976). The sum of tree and shrub pollen falls from 94-68% over a *c.*60 ^{14}C (60 cal) year period, involving *Betula*, *Ulmus* and *C. avellana*-type. A peak of 28.3% *Filipendula* pollen may be associated with a more open canopy or result from on-site vegetation, as may the small rise in Apiaceae pollen. A slight rise in *Sorbus* and single grain of *Fraxinus* pollen may infer that pioneer species also invaded bare ground created by burning or increased pollen dispersal under more open conditions. Arboreal cover recovered over a similar period, with no detectable deflection of succession or delay in regeneration as a result of grazing disturbance (*cf.* Buckland and Edwards 1984).

There is little evidence of woodland disturbance associated with the larger peaks in charcoal and *Pteridium* at 5110 BP (5900 cal BP), although the 41% peak in Pteropsida (monolete) undiff. may result from increased sporulation as a result of light penetration to the woodland floor, or could again reflect vegetation changes restricted to the basin surface. Higher palynological richness at 5110-5060 BP (5900-5830 cal BP) may also reflect small-scale disturbance associated with burning. Smaller peaks in charcoal, *Pteridium* and *C. avellana*-type are recorded at 4890 BP (5610 cal BP), with a slight fall in *Alnus*.

Charcoal frequencies are relatively low and, with the exception of the phase at 4950 BP (5660 cal BP), small charcoal fragments remain most abundant (Fig. 64), thus providing no evidence for fires in close proximity to the site. The repeated association between *Pteridium* and charcoal peaks, variable sporulation (Conway 1957) and poor dispersal of *Pteridium* spores (Tinsley and Smith 1974) may infer that small, low intensity fires burnt in the local source area, producing only small amounts of charcoal with limited dispersal due to low heat convection and filtering by a dense canopy (*cf.* Bennett *et al.* 1990, Pitkänen *et al.* 1999).

The repeated pattern of small-scale burning, at 110-270 ^{14}C (110-560 cal) year intervals may infer a natural cause, such as lightening fires (*cf.* Miles and Kinnaird 1979) as a result of the build up of fuel in woodland dominated by relatively short-lived trees. The change in fire regime may indicate drier climatic conditions (see Chapter 9). Alternatively, small fires may have been caused by humans, perhaps for camp fires or to encourage wild herbivores to graze in selected, known clearings (*cf.* Mellars 1976). In this context, it is noted that peaks in Poaceae appear to coincide with troughs in charcoal. This is tentatively interpreted as evidence that grazing pressure maintained a more open canopy between fires, although the temporal resolution is insufficient to establish this more securely, at *c.*50 ^{14}C (60 cal) years between sampling intervals (Table 33). Deliberate woodland clearings may have provided necessary cover for hunting, unlike open maritime grassland.

The sum of tree and shrub pollen remains high following an initial fall in *Ulmus* pollen at 5410 BP (6250 cal BP), and after the second, permanent reduction at 5080 BP (5810 cal BP). This suggests no diminution of woodland cover. The position of *Ulmus* appears to have been taken over by *Betula* and, after 4890 BP (5610 cal BP), by *C. avellana*-type. This may infer a natural, rather than anthropogenic cause for the *Ulmus* decline (see Chapter 9).

Hordeum group pollen grains are present with increasing frequency around 4350 BP (4870 cal BP). However, inferring the source of this pollen at this site is difficult as there are three possible origins: aquatic, maritime or arable communities. *Glyceria* could have grown locally in mud or water too shallow to support aquatic vegetation, perhaps with some Poaceae pollen from aquatic grasses such as *Phragmites*, although no leaf sheaths were noted. Maritime grasses may have been present with *Armeria maritima*, Chenopodiaceae, *P. maritima* and *Silene vulgaris*-type in the extralocal area.

Possible reasons for the decline in *C. avellana*-type, *Polypodium* and monolete Pteropsida frequencies around 4270 BP (4860 cal BP) are discussed below, in zone MOR3a, as this heralds the start of more marked changes in the composition and structure of the local woodland, with increasing evidence for an anthropogenic presence as well as for climatic change. This is evident in the DCA from a shift to lower sample scores on Axis 1, from mixed deciduous woodland towards NAP scores.

Apparently rapid changes in pollen representation and similarly abrupt increases in corroded pollen and in pollen accumulation rates across the zone MOR2/3 boundary are interpreted as evidence of a second possible hiatus just before 4240 BP (4830 cal BP). The age of events between *c*.4240 and 3940 BP (4830-4410 cal BP) is thus slightly uncertain. An hiatus is suggested to reflect drier conditions, with possible regional significance (see Chapter 9). The apparent sensitivity of the basin to hydrological change is discussed below.

8.5.5 Zone MOR3a: *Betula*-Poaceae-*Alnus* (269-146 cm, 4200-3480 BP, 4730-3710 cal BP)

During zone MOR3a, marked vegetation changes occur both on and around the basin, which suggests that the causes were not restricted to the local source area; these are summarised in Figure 66. Vegetational changes are suggested to result from soil acidification, increased wetness and anthropogenic activity. The palynological changes are described and interpreted in terms of vegetation composition in and around the basin before the possible causes of change are discussed.

The reasons for a rapid change in sediment accumulation rates at the zone MOR2/3 boundary are discussed after vegetation changes are described, as sedimentation patterns are argued to be closely linked with the causes of vegetational change.

The appearance of *Ranunculus trichophyllum*-type with single grains of *Potamogeton* and *Equisetum* may indicate a slight increase in water levels in the basin, fringed by tall-herbs and *Lysimachia*, which reappears in this zone. However, several pollen taxa also suggest a shift to mire formation, possibly indicative of increased waterlogging. This includes a small increase in Cyperaceae from 4240 BP (4830 cal BP), increased *Potentilla*-type pollen, particularly around 3770 BP, higher *Sphagnum* frequencies from 3790 BP (4150 cal BP), and a rise in *Calluna* representation around 3720 BP (4020 cal BP). Single grains of *Narthecium ossifragum* and *Drosera intermedia* are also indicative of peat communities. These changes are quantitatively small, suggesting that more acidic, nutrient-poor communities were not widespread. In addition, these taxa are unlikely to reflect blanket peat formation (*sensu* Fossitt 1994b), as pollen frequencies are low and blanket peat is at present largely absent from the sampling region (Section 2.1.5.3). A reduction in the abundance of fern spores around 4270 BP (4860 cal BP) may also have resulted from a rise in the watertable.

These shifts in basin vegetation coincide with abrupt changes in woodland composition, as *Alnus* gives way to *Betula* from *c*.4240 BP (4830 cal BP). This suggests that the changes were not restricted to the basin surface. The sharp reduction in *Alnus*, from 62 to 18%, is estimated to have occurred over a period of *c*.140 ^{14}C (100 cal) years, with a similarly large increase in *Betula*, from 18-56% over the same period. However, evidence for a possible hiatus (above) necessitates caution in inferring the timescale of events during this period.

Increased acidification, associated with the local change from more base-rich fen and soils to mire and acidic organic matter in better drained areas could have been more favourable to *Betula* (Rodwell 1991, Atkinson 1992). Acidification may also have reduced the abundance of *C. avellana*-type *c*.60 ^{14}C (60 cal) years earlier.

It is difficult to determine the scale of change. A fall in the AP sum from a mean of 90% tree and shrub pollen in zone MOR2c to 75% in zone MOR3a, suggests a reduction in canopy density. Increasing evidence for open grassland, with shade-intolerant herbs, through the zone may infer a mosaic of woodland, which persisted locally, and grassland, perhaps on the valley floor and/or surrounding hillsides.

As indicated above, there is an increase in the diversity and frequency of many herbs which are associated with agricultural disturbance in this zone. Uncertainties relating to the interpretation of anthropogenic activity in a coastal and aquatic environment were alluded to above and assume greater importance here in seeking to assess the role of anthropogenic activity in vegetation change.

Palynological evidence for agriculture increases through this zone, commencing very close to the date at which vegetation change begins at the end of zone MOR2c. It is therefore difficult to infer whether human activity was becoming more visible as the woodland became less dense, or whether agriculture was expanded or intensified, as it appears to have been around *c.*3980 BP (4420 cal BP). *Hordeum* group pollen becomes more frequent around 4350 BP (4870 cal BP), although this cannot be regarded as a simple signal of agricultural activity, as indicated above and discussed further below. *Plantago lanceolata* and *Ranunculus acris*-type pollen become more frequent from *c.*4210 BP (4740 cal BP), post-dating the change in woodland cover by *c.*30 ^{14}C (90 cal) years. More extensive or intensive late Neolithic or early Bronze Age pastoral activity is therefore suggested to have occurred only after woodland cover was reduced, although the woodland was subsequently modified by anthropogenic activities, as discussed below.

Inferring the cause of these changes is complicated by the association between major palynological transitions and rapid changes in sediment accumulation at radiocarbon horizons (see Fig. 57), which raises ecological and taphonomic questions about the relationship between vegetation and sediment accumulation. The small size of the basin and catchment may render it sensitive to changes in water-table, either drier conditions (*e.g. c.*7100 BP, *c.*4240 BP), or increased wetness, as discussed below. However, the association between marked palynological change and increased sedimentation in this zone may infer that only major hydrological events, resulting in vegetational change, are detected, since these are more likely to have been selected for radiocarbon-dating biostratigraphic horizons.

A shift to very rapid sediment accumulation at *c.*4240-4210 BP (4830-4740 cal BP), from 14 ^{14}C (16 cal) years/cm to 6 ^{14}C (7 cal) years/cm suggests increased wetness. The slight reduction in AP frequencies may have resulted in increased runoff and a rise in local watertables (Moore 1988, 1993). A shift to very high rates of change coincides with the change in sediment accumulation rates, and should thus be interpreted primarily as a result of this change in temporal resolution (Seppä, 1998, Section 4.4.1.2), rather than a clear indicator of more rapid vegetational change.

Frequencies of corroded pollen remain relatively high, which may infer that waterlogging was not severe in the surface layers, leading to post-depositional corrosion of all pollen types. If this is representative of drainage on woodland soils, it is possible that increased climatic wetness could have contributed to a rise in ground watertables, leaching and limited acidification, which enabled *Betula* to flourish on relatively well-drained soils, whilst contributing to small-scale mire formation in areas where drainage was impeded and waterlogging occurred. It is noted that an absolute decline in *Pinus* frequencies occurs around 3910 BP (4270 cal BP) (see Chapter 9).

Relatively high frequencies of tree and shrub pollen with continued wood in the sampling core indicate that woodland communities were still present locally. Rapid fluctuations in *Betula*; *Alnus* and Poaceae, by around 1-28% over *c.*10-40 ^{14}C (10-50 cal) year intervals from 4200-3480 BP (4730-3710 cal BP) are suggested to reflect fine temporal resolution local woodland dynamics. The rapidity of change, occurring within the life-time of the arboreal taxa concerned, are tentatively suggested to be associated with woodland management, such as coppicing (*cf.* Tipping 1997), since coppice rotations of 4-28 years are known from archaeological and documentary sources from the Neolithic until recent centuries (Rackham 1977, 1980).

Light trampling and grazing pressure, and/or disturbance and small clearings created by people harvesting the woodland resource, may have aided *Betula* regeneration (Atkinson 1992) as there is herbaceous pollen evidence for grazing (below). Coppice management and wood pasture both result in the formation of a more grassy woodland (Goransson 1982, 1986, Buckley 1992, Lindbladh and Bradshaw 1995), as observed at Morvich. However, the sustained increase in *Sorbus* frequencies from 3980-3270 BP (4420-3470 cal BP) and more frequent *Fraxinus* representation suggests that grazing pressures were not intense as both species are sensitive to grazing pressure and are able to establish and regenerate successfully in shaded environments; *Sorbus*, in particular, is very palatable to domestic and wild herbivores (McVean and Ratcliffe 1962, McVean 1964, Miles and Kinnaird 1979, Grime *et al.* 1988). The palynological evidence may thus infer controlled grazing or enclosure, which is also essential for the regeneration of coppice stools (Rackham 1986, Dingwall 1997).

In addition to inferred woodland pasture, the pollen data suggest that other pastoral resources present around Morvich included grassland, perhaps on valley floor alluvium and/or the surrounding hillsides, as well as salt marsh (*cf.* Evans 1975). Grassland communities are inferred from *R. acris*-type, Fabaceae, *Succisa*, *Stachys*-type, *Cichorium intybus*-type, *Thalictrum* and possibly *Veronica*, while increased frequencies of *P. lanceolata* and *Rumex acetosa*, with *P. media/major* and *Rumex obtusifolius*-type suggest grazing disturbance. Two grains of *Primula scotica* suggest damp pasture and are noteworthy as the species is presently endemic to western Sutherland, Caithness and Orkney. Increasing woodland and grassland diversity may be inferred from rising rarefaction values.

Pteridium may have benefited from more open conditions (Rymer 1976), as higher frequencies are recorded, particularly at 3940-3910 BP (4410-4370 cal BP) and 3700-3630 BP (4030-3920 cal BP), reaching 22-33% between 3750 and 3720 BP (4090-4020 cal BP). The use of the woodland as a source of pasture and browse may also have favoured *Pteridium*, as it is invasive and heavily defended against herbivores (Grime *et al.* 1988). The inferred use of woodland pasture and continued woodland regeneration suggests either light grazing pressures or, as indicated above, a need for stock management.

Hordeum group pollen is recorded more frequently from 4350 BP (4870 cal BP), with a continuous curve from 3720 BP (4020 cal BP). The range of herb pollen types suggests aquatic habitats together with increasing evidence for disturbed communities associated with agricultural activity. The occurrence of an *Avena/Triticum* group pollen grain at 3640 BP (3960 cal BP), *Papaver rhoeas*-type, *Urtica* and single grains of Chenopodiaceae and Brassicaceae suggest arable activity. However, an *Avena/Triticum* group grain was recorded in the early Holocene, where it must be interpreted as a wild grass (O'Connell 1987), suggesting that the palynological distinction between wild and cultivated grasses may be less clear than is desirable. In addition, *Urtica* may derive from fen habitats and Chenopodiaceae and Brassicaceae pollen may reflect extralocal maritime communities, with *Plantago maritima* and *Armeria maritima*. In the DCA, *Hordeum* group is also located between 'agricultural indicators' and aquatic taxa.

Despite these uncertainties, the evidence for pastoral grassland and woodland pasture strongly suggest an increase in anthropogenic activity during this zone, which may allow the *Avena/Triticum* group and some of the *Hordeum* group pollen to be more securely inferred to be of anthropogenic origin, particularly when local basin and woodland changes suggest some reduction in nutrient status, and thus conditions less favourable for more basiphilous fen species such as *Glyceria* and *Urtica* (Grime *et al.* 1988). However, it is not possible to conclusively exclude *Glyceria* or *Elymus* from the interpretation. Macrofossil evidence from Scotland suggests that *Avena* was not cultivated as a crop until the Iron Age (Boyd 1988). Although *Triticum* has been cultivated in Scotland since the Neolithic, it is more demanding in terms of soils and climate (Godwin 1975, Coppock 1976, Boyd 1988a). This *Avena/Triticum* group record could derive from oats growing as a weed in a barley crop (*cf.* Godwin 1975, Dickson 1988).

The agricultural landscape is difficult to reconstruct, since the extent of woodland and open ground outside the immediate vicinity of the wooded basin are difficult to infer. Coppice management can reduce pollen production from young, dense stands of *Betula* (Bradshaw 1981a), which could have facilitated pollen dispersal from arable fields and open grassland outside the local woodland, perhaps on the valley floor in the extralocal pollen source area. However, the occurrence of a suite of cereal-type pollen and inferred arable weeds may indicate relatively proximate cultivation, as the pollen dispersal properties of these taxa are very different (Vuorela 1973, Hall 1989). The occurrence of cereal-type pollen with more open woodland may infer coppice woodland with small-scale cultivation (*cf.* Goransson 1986) in the local and possibly extralocal source area.

The early Bronze Age landscape around Morvich appears to have provided a mosaic of grassland, woodland, riverine and marine resources. Estimates of palynological richness increase through the zone, particularly after 3720 BP (4020 cal BP), perhaps suggesting a gradual diversification of the surrounding landscape.

8.5.6 Zone MOR3b: *Betula*-Poaceae-*Alnus*-*C. avellana*-type (146-46 cm, 3480-*c.*900 BP, 3710-*c.*790 cal BP)

From 2820 BP (2920 cal BP), the basin once more supported *Potamogeton*, possibly with *R. trichophyllus*-type and *Equisetum*. A gradual rise in *Calluna* and Cyperaceae, and more frequent *Myrica gale* pollen from 2820 BP (2920 cal BP), suggests that mire and heath communities may have expanded, perhaps at the expense of tall-herb and fen taxa. Further increases are recorded between *c.*1330 and *c.*1250 BP (*c.*1270-1170 cal BP), and from *c.*940-860 BP (*c.*830-740 cal BP), across the zone MOR3b/c boundary. These dates fall within the estimated chronology, as discussed in Section 8.3.3. In view of the present limited extent of blanket peat (Section 2.1.5.3), this is suggested to reflect limited local peat growth.

Two possible causes are inferred. An increase in well-preserved pollen and a reduction in corroded grains from 2580 BP (2740 cal BP) may result from a local shift to more waterlogged, anaerobic conditions, which could have favoured aquatic and mire taxa. The increase in crumpling reflects a rise in the frequency of fragile Poaceae and Cyperaceae grains (Fig. 62). Increased charcoal values are recorded at 2580 BP (2740 cal BP) and *c.*1010 BP (*c.*930 cal BP), with an intervening decline in both charcoal and mire pollen representation. Although burning did not cause mire formation, heath communities may have been favoured by burning in the later expansion phase.

However, the charcoal size class signature suggests that fires may have occurred in the extralocal source area, as frequencies for larger fragments remain low, while the stratigraphic shift from woody to herbaceous peat and local pollen representation of *Myrica* (Birks in Kerslake 1982, Lloyd 1998) suggests that mire communities occurred locally. A change in fuel source, perhaps from woody to herbaceous vegetation, may have changed the charcoal signature (*cf.* Dark 1998), although there are little data on this subject (Patterson *et al.* 1987). Although the repeated association of mire and charcoal is noted, the relationship between mire or heath and charcoal at this time remains uncertain.

Around the basin, the transition to zone MOR3b is marked by a shift to more open woodland, with an increased shrub component. *Betula* frequencies decline from 3580 BP (3860 cal BP), as *Alnus* and *Salix* values begin to rise. *Betula* values then fall sharply from 3510 BP (3760 cal BP), with a slight rise in Poaceae, followed by peaks in *Alnus* and *Salix* at 3440 BP (3690 cal BP). Although interpretation is constrained by a reduction in sediment accumulation rates and consequent loss of temporal resolution (Table 33), these changes may reflect disturbance, associated with a shift to damper soil conditions, also inferred from aquatic and mire pollen data. Peaks in Poaceae and *Urtica*, with *Stachys*-type, *P. media/major*, *Rumex acetosella*, Fabaceae and continuous *Succisa* representation before *Alnus* and *Salix* values peak suggest pastoral disturbance. Increased wetness could have facilitated the expansion of sub-dominant *Salix*, with a shorter-lived increase in *Alnus*.

Subsequently, Poaceae frequencies increase to 60% at 3310 BP (3510 cal BP) as *Betula*, *Alnus* and *Salix* pollen values fall over a sampling interval of *c.*120 ^{14}C (180 cal) years. Although no sediment disturbance is recorded, this suggests more extensive incursions into the local woodland and is reflected by a closer association between DCA sample scores and taxa of open communities. Pastoral activity is inferred from 6% *P. lanceolata* pollen. Increased pollen representation for *P.*

lanceolata, *Potentilla*-type, *Succisa*, *R. acris*-type and *R. acetosa*, with an increase in grassland herb diversity, suggests the expansion of grazed grassland communities near or within the woods around the site.

Betula frequencies recover by 3070 BP (3300 cal BP), while *Alnus* maintains lower frequencies of *c.*15-20% and *Salix* pollen remains frequent until *c.*2580 BP (2740 cal BP). *Sorbus* may have remained a common tree on drier soils around the site, perhaps with *Pteridium*, which shows continuous representation. Several grains of *Crataegus* pollen suggest that hawthorn formed part of a scrubby woodland component, with *Lonicera*, *Hedera* and *Rosa*.

C. avellana-type appears to have recolonised or expanded its role in the local woods, increasing to 18% around 2370 BP (2350 cal BP). Although *Myrica gale* and *Corylus/Myrica* pollen also become more frequent around this time, the *C. avellana*-type curve is argued to reflect hazel expansion since the *Myrica* and *Corylus/Myrica* curves are very similar and do not correlate with changes in *C. avellana*-type representation (Fig. 55). *C. avellana* prefers richer soils, in contrast to poorer conditions tolerated by *Betula* and inferred from the expansion of mire taxa (Rodwell 1991). Deliberate human intervention, such as coppice management, selective felling of *Betula* or fencing, is therefore suggested to have been necessary to encourage increased growth and pollen production in *C. avellana*-type.

A reduction in *C. avellana*-type frequencies from 2260-1950 BP (2320-1880 cal BP) coincides with lower AP, *Betula*, *Polypodium* and Pteropsida values, with more frequent *P. lanceolata*, *Pteridium*, *Potentilla*-type, *Filipendula*, *Ranunculus trichophyllus*-type and *Hordeum* group, and a slight increase in Poaceae. More open conditions due to pastoral incursions could have enabled increased representation of local basin plants and possibly arable taxa.

The increase in *Quercus* from 1840 BP (1740 cal BP, AD 220) is also argued to reflect woodland management. *Quercus* values rise above 5% between 1520 and 1420 BP (1390-1300 cal BP, AD 560-650), after which the curve declines to previous low levels. This is not associated with a fall in AP frequencies. The data are therefore suggested to reflect the formation and/or expansion of local *Quercus* populations, rather than an increase in regional or extralocal *Quercus* representation which could result from a more open canopy locally. The later Holocene *Quercus* curve contrasts with consistently low values (mostly <1%) throughout the Holocene, which are inferred to reflect very sparse local or extralocal growth, and regional pollen rain. This expansion is very late (Birks

1989) and is short-lived relative to a potential *Quercus* lifespan of >500 years (Jones 1959). These factors suggest that *Quercus* expansion may have occurred as a result of deliberate woodland management, perhaps by manipulating populations of an initially infrequent genus, rather than as an autogenic process in woodlands which were growing in intimate proximity to late Iron Age and Pictish agricultural settlement.

Quercus pollen frequencies do not suggest that oak contributed significantly to the vegetation (Huntley and Birks 1983) and *Quercus* expansion does not appear to have depressed representation of other arboreal taxa, inferring limited *Quercus* growth in open woodland. Lower frequencies for Poaceae and *Potentilla*-type between 1840 and 1420 BP (1740-1300 cal BP), and a reduction in percentage and absolute *P. lanceolata* and *Hordeum* group values from 1730-*c.*1010 BP (1670-*c.*930 cal BP) may be an artefact of canopy filtration, rather than a real reflection of reduced pastoral grassland. Rarefaction values remain high, suggesting that landscape diversity was maintained. A limited area of *Quercus* woodland may thus have been grown and managed for timber production before being felled after *c.*100 ^{14}C (90 cal) years. Evidence for regional parallels and possible reasons are discussed in Chapter 9.

Although woodland remained a significant part of the local and possibly extralocal landscape during the Bronze and Iron Ages, pastoral grassland and cereal crops were also maintained. The range of open ground taxa suggests a diverse grassland flora, some of which may also have occurred in woodland edge habitats, including *Stachys*-type, *Stellaria holostea, S. dioica*-type. Disturbed ground is inferred from *P. lanceolata, Rumex acetosa, R. acetosella, R. obtusifolius*-type, *P. media/major, Cichorium intybus*-type, *Solidago virgaurea*-type and *Polygonum.* Other grassland taxa include *Ranunculus* acris-type, *Succisa,* Rubiaceae, Fabaceae, *Vicia sylvatica*-type, *Veronica* and *Polygala.*

Hordeum group pollen is recorded nearly continuously in zone MOR3b and higher frequencies from 2260-1840 BP (2320-1740 cal BP) coincide with the start of more frequent *Avena/Triticum* group and *Papaver rhoeas*-type pollen. This provides more secure evidence for cereal cultivation, as opposed to aquatic or maritime grasses. *Avena/Triticum* group may derive from oats, which appears to have been introduced as a crop during the Iron Age (Boyd 1988), rather than the more edaphically and climatically demanding wheat (Coppock 1976). Brassicaceae may have grown in maritime communities, as an arable weed or as a cultivar.

Occasional *Armeria maritima* and *Plantago coronopus* pollen grains continue to suggest extralocal salt marsh and coastal communities. Again, several species of disturbed ground may have occurred in these as well as anthropogenic habitats, including Chenopodiaceae and *Silene vulgaris*-type.

Following the period of inferred Iron Age and Pictish woodland management, a permanent and possibly widespread woodland decline is recorded between 1420 and *c.*1090 BP (1300-*c.*970 cal BP), first in *Quercus* and last in *Betula*. This is recorded in both relative and absolute data. A reduction in woodland habitats is also reflected in the loss of climbing shrubs, such as *Lonicera* and *Hedera*. The timescale of woodland decline suggests relatively rapid clearance, first of *Quercus*, *Alnus* and *C. avellana*-type over *c.*92 ^{14}C (*c.*30 cal) years between 1420 and *c.*1330 BP (1300-*c.*1270 cal BP), with a second fall in *C. avellana*-type over an interval of *c.*78 ^{14}C (*c.*90 cal) years from *c.*1170 BP (*c.*1060 cal BP). The decline in *Betula* is more gradual, lasting over *c.*300 ^{14}C years (*c.*330 cal years), between *c.*1090 and *c.*780 BP (*c.*970-680 cal BP, cal AD *c.*980-1280). This may reflect the selective felling of *Quercus* and *Alnus* for timber and *C. avellana*-type for coppice products. Alternatively, *Betula* may have been utilised, but pollen production and abundant growth may have been maintained as seedlings rapidly colonised bare and disturbed soils (Atkinson 1992). *C. avellana*-type may have exhibited a similar enhanced growth response, resulting in a stepped decline in pollen representation.

Woodland appears to have been replaced by grassland and mire, although the latter is argued to reflect predominantly local communities, as discussed above. Mire taxa expand only after the AP reduction, indicating that woodland decline is not an artefact of vegetation changes on the basin. Grazing disturbance is still inferred from the range of grassland species recorded. Increased palynological richness may reflect increased diversity in grassland and peat communities, rather than just the expansion of established taxa, particularly in grassland habitats. Consistently low sample scores on DCA Axis 1 reflect the dominance of open ground taxa.

This change in land management occurs in the Pictish period. The events may fall within the time of Norse influence along the west coast and islands, which commenced during the late eighth and early ninth centuries AD (Crawford 1987, Ritchie 1993), although in view of the chronological uncertainties, the existence of any possible association cannot, unfortunately, be assessed.

8.5.7 Zone MOR4a: *Betula*-Poaceae-Cyperaceae (46-6 cm, *c.*900-120 BP, *c.*790-110 cal BP)

Mire communities consisting of *Myrica gale*, *Calluna*, Cyperaceae, *Potentilla*-type, *Sphagnum* and possibly Poaceae expanded on and around the sampling basin, which supported *Potamogeton*, a greater abundance of *Ranunculus trichophyllus*-type, and possibly *Menyanthes trifoliata* and *Equisetum*. This is also inferred from the accumulation of herbaceous and *Sphagnum* peat (Table 31). *Pteridium*, *Narthecium*, *Pedicularis*, *Vaccinium*-type, *Erica*, *Filipendula*, Apiaceae and *Mentha*-type may have fringed the water and grown on rocky ground around the basin. Although no mineral influx is recorded, *Myrica* is more frequent on flushed peat, perhaps inferring water movement from the southern hillsides to the mouth of the gully, where the sampling site is located.

Charcoal frequencies increase, although small fragments remain most abundant, suggesting that burning may not have occurred in the local pollen source area. The increase in charcoal in zone MOR3b coincides with rising *Calluna* values, as noted above, but charcoal fluctuations are not reflected in the *Calluna* curve, inferring that burning did not affect *Calluna* pollen production.

Limited regeneration appears to have occurred from *c.*470 BP (*c.*510 cal BP), as *Betula* values rise to 37% TLP and 1.2% *Sorbus* pollen is recorded at *c.*310 BP (*c.*320 cal BP), although the presence of higher *Pinus* values, *Picea* and *Abies* pollen and SCPs suggest that events in this zone may have occurred during recent centuries (see Section 8.3.3). This is suggested to reflect local regeneration. *Betula* may have colonised recently burnt ground near the basin (*cf.* Atkinson 1992), as the pollen increase coincides with a peak in charcoal. Rocky ground around the site may have favoured chance establishment of *Sorbus* in positions which are protected from grazing, as recorded at present (see Section 8.2). It is also possible that limited areas of scrub also remained, since consistent frequencies of *c.*6% *Alnus* and *c.*5% *C. avellana*-type are recorded. *Fraxinus* may also have been present.

Continued pastoral and arable agriculture are recorded, with similar grassland composition to the previous zone, dominated by *P. lanceolata*, several species of *Rumex*, *Ranunculus* acris-type, *Succisa*, Asteraceae, *Heracleum* and *Thalictrum*. It is again difficult to assess whether higher frequencies of *Hordeum* group, rising to 4.6% at *c.*230 BP (*c.*290 cal BP, AD *c.*1660), reflect cereals or local *Glyceria* growth, as arable weeds and aquatic taxa are present, although the latter are recorded at lower frequencies at this time. Several grains of *Avena*/*Triticum* group coincident with maximum *Hordeum* group values could indicate more extensive or closer cereal production, but conclusive distinction is not possible.

Higher rarefaction values may infer greater diversity in agricultural habitats and in local mire vegetation, although an increase in extralocal and regional pollen is also likely following an increase in pollen source area resulting from the loss of woodland cover in zone MOR3b. Higher rates of palynological change may arise from frequent disturbance as a result of agricultural activity or as an artefact of increased vegetational diversity and consequently increased likelihood of random variations (Maher 1972, Bennett and Humphry 1995, see Section 4.4.1.2).

8.5.8 Zone MOR4b: Poaceae-Cyperaceae (6-0 cm, *c.*120-0 BP, *c.*110 cal BP-present)

This zone is distinguished from zone MOR4a by local changes and a reduction in most AP taxa, with the exception of *Pinus* and *Alnus*. Locally, Cyperaceae, Poaceae, *Pedicularis* and *Potentilla*-type appear to have expanded. *Caltha palustris*-type and *Mentha*-type may also have grown locally. Comparison with the surface sample suggests that the local vegetation may have been much the same over the last *c.*900 ^{14}C (*c.*790 cal) years, with *Myrica*, *Sphagnum*, Cyperaceae, Poaceae, *Potamogeton*, *R. trichophyllus*-type and *Potentilla*-type in the basin, and *Calluna*, other heaths, *Narthecium* and *Pteridium* growing on the rocky ground of the gully. *Cf.* Liliaceae pollen in the surface sample may reflect growth near the basin or perhaps in the nearby crofters garden, although no possible source was recorded during vegetation surveying and the garden flora was not examined. The palynologically invisible *Juncus* may also have grown locally.

A decline in charcoal and *Calluna* frequencies is registered in this zone, but, again, a causal connection is difficult to determine. A reduction in burning may also relate to changes in land-use, inferred from the reduction in cereal-type pollen, although this interpretation is also problematic, as discussed below. The relationship between charcoal and *Calluna* in Glen Affric during the Holocene is discussed in Chapter 9.

The recent expansion of pastoral grassland is inferred from a rise to 7% *P. lanceolata* pollen in the surface sample, with continuing high palynological diversity. Due to the time of vegetation surveying, it was unfortunately not possible to determine whether *Glyceria* is present. *Hordeum* group pollen is recorded at relatively high frequencies in recent sediments, with a single grain in the surface sample. This may reflect a recent decline in cultivation, *Glyceria* or maritime grasses. Documentary evidence and the cultural and social context of crofting agriculture are discussed in Chapter 9.

A continued decline in *Betula* at the end of zone MOR4a coincides with rising curves for *Alnus* and *Pinus*. This may reflect the local extinction of *Betula*, which could have increased pollen representation from the present fringe of *Alnus* by the River Croe, *c.*100 m to the north. This may also account for the increase in *Pinus* from extralocal and regional plantations. A sum of 27% tree and shrub pollen in the surface sample suggests that, with the exception of a single subsample at 3310 BP (3510 cal BP) (Σ28% AP), the pollen catchment was not as open as the present until *c.*780 BP (*c.*680 cal BP, AD *c.*1280).

8.6 Conclusions from Morvich

The palynological data from Morvich indicate that lowland climatic conditions, possibly combined with geological differences, had a clear effect on vegetation composition, resulting in the development of relatively dense mixed deciduous woodland in which boreal, heath and mire elements have always played only a very limited role. Vegetational response to environmental change, particularly in the mid-Holocene, suggests that the lowland, Atlantic position location may have buffered the vegetation against climatic change, but also exposed the vegetation to other causal agencies, such as sea-level change. A fall in sea-level after *c.*7100 BP (7900 cal BP) is suggested to have aided the spread of *Alnus* by providing suitable local habitats (*cf.* Bennett and Birks 1990).

Detecting the earliest agricultural land-use, particularly cultivation, is complicated by factors specific to the basin site and by the proximity to unstable coastal habitats. Consequently pre- and post-*Ulmus* decline cereal-type pollen grains cannot be securely identified as crops. Although archaeological finds and palynological research elsewhere along the western seaboard suggests that these areas have been favoured for occupation since the early Holocene, the evidence from Morvich indicates that the area does not appear to have been heavily populated, since woodland survived into the late Pictish period, possibly aided by long-term woodland management.

There is some evidence for late Mesolithic activity, with evidence of pastoral land-use commencing during the late Neolithic or early Bronze Age, during a period of inferred climatic change, with secure evidence for cultivation commencing around 3700-3600 BP (4030-3890 cal BP). Different forms of woodland management are suggested to have occurred from the Bronze Age to the Pictish period, perhaps reflecting the limited and localised availability of this resource. The lowland evidence thus provides an essential source of data necessary to understand upland vegetational developments and the landscape context of land-use.

CHAPTER 9: Discussion

9.1 Woodland composition

9.1.1 Early Holocene deciduous woodlands

The three near complete Holocene sequences from West Affric and Kintail suggest that sediment accumulation post-dates woodland establishment (Table 38). Extrapolated basal dates suggest accumulation from *c.*9920-8775 BP (11010-9780 cal BP), although, as discussed in Section 5.5.1, the youngest date, from Torran Beithe, appears too young in comparison with pollen-stratigraphic evidence. These dates for basin peat inception fall within the rather variable range of early Holocene dates derived from other sequences located within the limits of the Loch Lomond Readvance in the north-western Highlands (Bennett and Boulton 1993; Section 2.1.2), ranging from *c.*9210-8570 BP (10270-9490 cal BP) (Birks 1972, Anderson 1996).

However, on pollen stratigraphic grounds, accumulation at the present sites appears somewhat later, since other sequences contain *Empetrum*, *Juniperus* and open ground assemblages pre-dating the arrival of *Betula* and *Corylus avellana*-type (*e.g.* Loch Clair, Glen Carron, Glen Torridon, Loch Maree islands; Pennington *et al.* 1972, Kerslake 1982, Anderson 1996, 1998, see also Walker and Lowe 1977, 1979, 1981). This suite is also evident at three undated profiles from East Affric, on either side of the proposed Loch Lomond Readvance limits (Tate 1995; see Fig. 1).

While the lag between deglaciation and the formation of the floodplain at Carnach Mór may account for the absence of a comparable early Holocene pollen sequence there, as at Camban, the absence or poor representation of open *Empetrum* and *Juniperus* assemblages at all three full Holocene records suggests that there may have been a more substantial lag preceding soil stabilisation and accumulation of organic waterlogged deposits (*cf.* Matthews 1992). Tate (1995) also suggests that recovery from glacial conditions was more prolonged than that inferred from other areas, but as her pollen analyses are undated, further work is needed to establish whether this is a localised or more widespread feature.

Betula emerges at the main early Holocene woodland tree in Affric, possibly replacing *Juniperus* scrub at Torran Beithe and Morvich. However, the pollen profiles indicate that vegetation on the upland hillslopes, high and low altitude valleys has been differentiated since the early Holocene. Associated arboreal and herbaceous species clearly reflect a mosaic of woodland communities which developed in response to local environmental conditions, including moisture, sediment type and nutrient status. This is reflected by differences between the pollen taxa associated with basal samples in the detrended correspondence analyses. Thus *Empetrum*, *Populus* and *Sorbus aucuparia* pollen at Torran Beithe infer rather poor mineral soils (Bell and Tallis 1973, Grime *et al.* 1988), suggesting that nutrient enrichment during glaciation had a very limited or short-lived impact on the underlying moinian rocks, at least on the hillsides (*cf.* Pennington *et al.* 1972, Sutherland 1980, Pennington 1986).

Although high *Sorbus* pollen values at Carnach Mór imply slightly acidic soils, perhaps on the hillside, the diversity and wide ecological range represented by fen carr, tall-herb, marsh and ruderal taxa, suggest a local patchwork of well-drained, minerogenic, unstable and damper soils, reflecting the diversity of floodplain niches (*cf.* Peterken 1996). The palynological and radiocarbon evidence clearly indicate that the floodplain formed during the earliest Holocene, creating a contrast between morainic and alluvial soils.

The densest woodland appears to have been established around Morvich, with the lowest tree and shrub pollen sums at Torran Beithe. This is not reflected in influx data, suggesting that upland exposure did not significantly reduce pollen productivity, but may reflect the relative soil fertility of the lowlands (see Section 2.1.3). This evidence for vegetational mosaics relating to environmental gradients is comparable with results from Skye (Williams 1977, Birks and Williams 1983), but has few parallels within the Highlands.

Sorbus has previously been considered a minor component of Highland woods (Birks 1977). However, the results from Carnach Mór, and later Holocene records from comparable small-diameter sites at Morvich, on Eilean Mór (Kerslake 1982) and at Ceide Fields, Western Ireland (Molloy and O'Connell 1995), suggest that the importance of *Sorbus* may have been overlooked in profiles from larger sites. The fine spatial resolution pollen data may be comparable with modern examples in which *Sorbus* is common, even attaining co-dominance or dominance in Highland birchwoods (McVean 1958, Miles and Kinnaird 1979).

Although *Corylus avellana* is tolerant of a range of soil conditions (Rodwell 1991), relatively low frequencies in West Affric suggest that *C. avellana*-type was not abundant in the uplands, attaining higher frequencies in the lowlands around Morvich. The low values recorded in West Affric are comparable with evidence from previous research at a range of altitudes in the north-west, reinforcing suggestions that *C. avellana*-type growth was localised, restricted to more basic soils (Birks 1996b). Competition from *Betula* may have limited the growth of *C. avellana*-type on acidic upland soils, as *C. avellana*-type abundance does not appear to be strongly limited by exposure in the open woods of the far north and west of Scotland (Bennett 1989, Tipping 1994, Bennett and Hill 1998). Higher *Corylus avellana*-type frequencies at Morvich are suggested to reflect the competitive advantage conferred by a slightly more mineral-rich Lewisian outcrops (Section 2.1.3), as is evident on a larger scale on limestone at Strath Oykell (Pennington *et al.* 1972).

Fire appears to have been important in the woods around Morvich and Carnach Mór from the earliest Holocene until *c.*6570 BP (7400 cal BP) and *c.*6080 BP (6900 cal BP) respectively, in contrast to low charcoal frequencies at Torran Beithe (Fig. 67). Burning may have been involved with peat inception at Morvich and on the floodplain near to Carnach Mór, as macroscopic charcoal fragments occur at the interface between mineral and organic sediment (Table 31, Fig. 26). Charcoal particles may have reduced soil porosity, thus impeding drainage and leading to peat inception (*cf.* Mallik *et al.* 1984, Robinson 1987, Tallis 1991, Charman 1992).

Relatively frequent burning may have aided the establishment and regeneration of *Betula* (Miles and Kinnaird 1979, Atkinson 1992), and is also suggested to have helped to maintain Poaceae around Carnach Mór (Section 6.5.2). There is no clear evidence that *C. avellana*-type was favoured by burning (*cf.* Huntley 1993); the highest charcoal and *C. avellana*-type frequencies occur at Morvich and although interpretation is complicated by poor temporal resolution, there does not appear to be any correlation between C. *avellana*-type and charcoal frequencies. In the uplands, *C. avellana*-type appears to have been more abundant at Torran Beithe, where charcoal values are low.

The cause(s) of burning are difficult to infer. Broadly similar temporal patterns from two sites may infer regional climatic controls, although inter-site differences indicate the need to consider local factors (below). There is no clear temporal correlation between the charcoal data from Morvich or Carnach Mór, and periods of dryness inferred from palaeoclimatic research in north-western Europe. Palaeoclimatic reconstructions suggest arid conditions from *c.*9500-8690 BP (10500-9600 cal BP) (Atkinson *et al.* 1987, Harrison and Digerfeldt 1993), with further dryness from *c.*8000 BP (8780 cal BP) (Anderson 1996, Tipping 1996).

Spatial differences in charcoal representation within Glen Affric suggest local controls, such as vegetation composition, flammability and fuel loads, or anthropogenic interference. There is no evidence that fires were fuelled by heathland, particularly at Torran Beithe, where consistently low charcoal frequencies are associated with an inferred dry heath-birchwood mosaic (Section 5.5.4). It is possible that short-term, perhaps seasonal, dryness, fuelled by an abundance of dead and moribund trees in woodlands dominated by relatively short-lived arboreal taxa growing on relatively well-drained alluvial soils, such as at Carnach Mór, may have been sufficient to cause repeated burning, although this cannot be tested using palynological data and does not account for low charcoal frequencies at Torran Beithe.

Previous researchers have also postulated a climate controlled fire regime (*e.g.* Anderson 1996, 1998). This hypothesis appears to be supported by data from the far north after 8000 BP (8780 cal BP) (Tipping 1996), but the relatively small number of charcoal records from the Highlands suggest that fire regimes were, spatially and temporally, highly variable (*e.g.* Anderson 1996, 1998, Smith 1996, 1998, Bennett and Hill 1998). This may be suggested to support anthropogenic involvement (*cf.* Robinson 1987, Charman 1992, Smith 1996, 1998). However, there are strong environmental contrasts between these sites and there is as yet inadequate high spatial resolution evidence from which to infer the relationship between environment, vegetation and fire. Repeated use of certain locations by hunter-gatherers has been inferred (Smith and Cloutman 1988, Simmons and Innes 1996a, Mellars and Dark 1998), but the longevity of high charcoal values is suggested to argue against a solely anthropogenic interpretation in West Affric. The role of fire in pinewood ecosystems and possible reasons for the change in fire regime during the mid to late seventh millennium BP are discussed below (Section 9.1.2).

9.1.2 The role of *Pinus sylvestris* in Glen Affric and Kintail

Prior to *c.*7500 BP (8220 cal BP), low *Pinus* frequencies suggest regional pollen sources, but a subsequent increase in percentage and absolute values in the uplands, and the appearance of *Pinus* stomata at Torran Beithe around 7205 BP (7950 cal BP), infer regional and local population expansion (Table 39). This relatively early date may support a suggested glacial refuge off the north-west of Scotland, rather than expansion for the south (Bennett 1995). .The palynological data and present day environmental gradients in Affric suggest that the spread and abundance of *Pinus* may have been controlled by competition interactions, local edaphic and regional climatic factors.

Prolonged erosion and perhaps a slight increase in burning between *c.*7400 and 6540 BP (8140-7390 cal BP) appear to have been important for local establishment at Torran Beithe, perhaps creating suitably open or bare soils for *Pinus* establishment (*cf.* Miles and Kinnaird 1979). An inferred short-lived hiatus at Morvich around 7100 BP (7910 cal BP) may also reflect climatic dryness. The evidence from the present study correlates well with regional evidence for drier conditions from *c.*7300-6600 BP (8040-7470 cal BP), frequently associated with *Pinus* expansion, as discussed in Section 1.7.2 (Dubois and Ferguson 1985, Bridge *et al.* 1990, Anderson 1996, Binney 1997). This may be correlated with evidence for a widespread, short-lived cool, dry or windy shift around 7700-7200 BP (8400-8000 cal BP) (Alley *et al.* 1997).

There is abundant ecological and regional palaeoecological evidence for an association between poor soils and *Pinus*, which is suggested to result from the competitive exclusion of *Pinus* on richer soils (Steven and Carlisle 1959, Bennett 1986b, Richardson 1998; see Sections 1.7.2 and 6.5). This is clear from a comparison of the results from Torran Beithe and Carnach Mór, as *Pinus* appears to have out-competed *Betula*, *Sorbus* and *Populus* on acid, nutrient-poor hillsides around Torran Beithe, which supported a dwarf shrub understorey. In contrast, at Carnach Mór, *Betula* maintained dominance in mixed deciduous woodland with a field layer of tall-herb, fen and ruderal species, possibly due to frequent nutrient replenishment through flooding on alluvial soils (Sections 6.3.1 and 6.5). Consistently low *Pinus* frequencies preceding a rise to 29% at 5880 BP (6730 cal BP), are suggested to derive from *Pinus* populations on the hillside above the floodplain.

In addition to the inferred edaphic controls, there is also evidence for an east-west gradient in *Pinus* abundance within Glen Affric. Although information from more westerly uplands is limited due to the absence of an early Holocene sequence from Camban, relatively low frequencies at Morvich and Carnach Mór preceding *c.*4000 BP (4440 cal BP) suggest that *Pinus* may have reached its western limits in central Affric. Data from Skye, particularly Loch Ashik and Loch Meodal, also indicate that *Pinus*' range did not extend across the Sound of Sleat, at least in the early Holocene (Williams 1977, Birks and Williams 1983). It is argued that increasing oceanicity towards the west, and competition in the lowlands on slightly more nutrient-rich soils may have favoured *Betula*, restricting *Pinus* to the poorer moraine-derived soils on the hillsides and relatively less oceanic central and East Affric, where pinewoods have been a feature for much of the Holocene (C. Froyd, pers. comm.).

These data reinforce previous evidence from the far north-west which suggests that *Pinus* was less abundant than has been inferred from regional-scale loch sequences due to distortion caused by the differential flotation of *Pinus* pollen (Kerslake 1982, Section 1.7.2). The evidence for small-scale edaphic controls on the expansion and abundance of *Pinus* in Glen Affric are comparable with data from Lairg, which indicate that *Pinus* expanded first on the upland plateau, gaining only a short-lived foothold within the sheltered valley (Smith 1996, 1998). However, it is not at present possible to establish whether the westward decline in *Pinus* in Glen Affric is a local or regional characteristic. The interpretation of percentage *Pinus* values in terms of vegetation presence and abundance is discussed in Section 9.4.3.3.

Ecological references suggest that coniferous woodlands are more flammable than broad-leaved woods, due to the accumulation of larger fuel loads and presence of resins (Rackham 1986, Peterken 1996, Agee 1998). Similar inferences have been made relating to Holocene pinewoods in the Highlands (Durno and McVean 1959), although on the basis of very limited data (Bennett 1995; Section 1.5.3.3). This hypothesis is not supported by the data from Affric, since charcoal frequencies at Torran Beithe are consistently low and sporadic peaks do not coincide with changes in *Pinus* or *Calluna* frequencies (Fig. 15; Section 5.5), with the exception of *c.*5600-4900 BP (6380-5630 cal BP) (below). At Carnach Mór, an increase in *Pinus* values from *c.*6020 BP (6870 cal BP) follows a reduction in fire frequency/intensity at *c.*6080 BP (6900 cal BP), but is suggested to be a response to a shift to more acidic soils, which may have enabled *Pinus* to compete more effectively with *Betula* (Carlisle and Brown 1968; Section 6.5), rather than the result of a change in the fire regime. Similar non-pyrogenic *Pinus* woodland may have occurred around Ardheslaig Loch (Bennett and Hill 1998).

9.1.3 *Quercus* and *Ulmus*

Consistently low frequencies for *Quercus* and *Ulmus* across the Highlands have been suggested to reflect small populations or regional pollen influx (Birks 1996b). However, the data from Affric suggest two distinct distribution patterns. In the uplands, there appears to be an east-west gradient of decreasing *Quercus* and *Ulmus* frequencies, as the highest values are recorded at Torran Beithe, where both species, but particularly *Quercus*, are suggested to have been present in small numbers. Lower frequencies occur at Carnach Mór and, as far as can be discerned after *c.*4980 BP (5730 cal BP), at Camban. In contrast, the lowest *Quercus* frequencies are recorded in the lowlands at Morvich, where *Ulmus* was a component of mixed deciduous lowland woods. Very low *Quercus* frequencies at Morvich suggest that, if *Quercus* was approaching its northern limit on the west coast around southern Skye (Birks 1977, Williams 1977), its range did not extend as far as Kintail. The present data thus contrast with the western coastal distribution of *Quercus* inferred from palaeoecological woodland reconstruction maps (Bennett 1989, Tipping 1994, Edwards and Whittington 1997) and by the present potential woodland distribution map of McVean and Ratcliffe (1962) (Section 2.1.6.2).

Quercus and *Ulmus* may have been restricted to richer soils in more sheltered valleys, such as Loch Tarff (Pennington *et al.* 1972) and perhaps Lairg in the east (Smith 1996, 1998). It is not clear why *Ulmus* was able to become established at Morvich while *Quercus* could not. It is important to note that both *Quercus* and *Pinus* appear to have reached their western limits in upland central Affric. This is considered important in view of evidence of mid-Holocene interactions between *Pinus* and *Quercus* at Torran Beithe, and a temporary increase in *Quercus* representation across the study region during the mid-Holocene woodland decline (Sections 5.5 and 9.4).

There is no evidence from Morvich or Torran Beithe, where the highest *Ulmus* frequencies are recorded, for any other than natural causes associated with the *Ulmus* decline of c.5080 BP (5810 cal BP) and 5240 BP (5970 cal BP) respectively. *Ulmus* appears to have been replaced by other arboreal taxa, with no evidence for disturbance. This contrasts with slight and ambiguous evidence for anthropogenic disturbance at several Highland pollen sites at this time (Section 1.11).

9.1.4 *Alnus glutinosa* expansion

The earliest date for *Alnus* expansion in the study area occurs at Morvich (Table 40), where *Alnus* expansion at *c.*7065 BP (7860 cal BP) may have occurred in response to sea-level reduction and floodplain development after *c.*7300-7100 BP (8100-7900 cal BP) (Shennan *et al.*

in press), thus providing some support for the suggestion that floodplain development may have influenced *Alnus* expansion (Birks and Bennett 1990). However, *Alnus* expansion in the uplands is clearly not related to floodplain formation, since the evidence from Carnach Mór suggests that the floodplain formed in the earlier Holocene (Section 6.5.1), although *Alnus* expansion at Torran Beithe coincides with a shift to wetter local conditions (Section 5.5.3).

Relatively low *Alnus* frequencies recorded at Torran Beithe, Carnach Mór and Camban suggest that low values recorded in many regional sequences from the Highlands reflect relatively small populations. It has been suggested that *Alnus* was restricted to favourable habitats, limited by altitudinal constraints and by an abundance of acidic soils (McVean 1956b, Birks 1970, Pennington *et al.* 1972). However, *Alnus* does not appear to have been abundant even in apparently favourable habitats, such as waterlogged alluvium, flushed soils and carr woodland reflected at Carnach Mór and Camban. Comparison with the data from Morvich, where *Alnus* was abundant, suggests that altitudinal constraints may have restricted *Alnus* expansion in the uplands. The sites in West Affric lie at *c.*250-307 m OD, but at present seedlings are only recorded up to 240 m OD, and seed formation does not occur above 275-305 m OD (McVean 1956b, Grime *et al.* 1988). Climatic controls may account for the continued abundance of *Salix* and tall-herb taxa at Camban, the highest site, in contrast to Torran Beithe and Carnach Mór, where *Alnus* appears to have displaced *Salix* and shaded out tall-herb communities. Further evidence for climatic controls on *Alnus* abundance are discussed below.

9.2 Woodland dynamics

9.2.1 Short-term fluctuations

Woodland communities are characterised by a range of autogenic and cyclic successional and disturbance processes (Peterken 1996), particularly in woods which are dominated by pioneer and successional taxa such as *Betula* (*cf.* McVean and Ratcliffe 1962, McVean 1964). Autogenic succession and disturbance occur at a wide range of spatial and temporal scales, controlling community structure and helping to maintain diversity and long-term stability by aiding regeneration. The detection of these processes in the palynological record depends on the scale and proximity of the event, temporal and spatial resolution of the pollen record (Bradshaw 1988, Sugita *et al.* 1997).

The data from Morvich and Torran Beithe provide evidence for generation-scale fluctuations and long-term shifts in vegetation composition which can be related to such ecological processes. At Morvich, fine temporal resolution data are argued to reflect a shifting mosaic of *Betula* and *Alnus* around the sampling site due to natural autogenic succession, which may have conferred long-term woodland stability, as neither species regenerates freely beneath its own canopy (McVean 1953, Atkinson 1992). Similar *Betula-Alnus* wood dynamics are evident from the small-diameter basin on Eilean Mór (Kerslake 1982), although the data are presented with a three-point smoothing average, thus limiting interpretation.

At Torran Beithe, inferred interactions between *Pinus*, *Betula* and *Calluna*, particularly in zones TOR2a and TOR2b, are similar to data from Eilean Mór (Kerslake 1982), the Cairngorms (O'Sullivan 1973b), and possibly Beinn Eighe (Durno and McVean 1959). Fluctuations are suggested to indicate that a dynamic relationship between woodland and heath has been a feature of Highland woodlands throughout the Holocene. This is comparable to ecological data from relict Highlands woodlands (*e.g.* McVean and Ratcliffe 1962, McVean 1964), although fine resolution palaeoecological records are essential for assessing the dynamics, composition and long-term stability of woodland communities, since present relict woodlands may consist of only the most hardy surviving remnants (Tipping *et al.* 1999).

This is highlighted by the evidence for distinctive, species-rich, mixed deciduous woodlands at Carnach Mór, Camban and Morvich, since there are few, if any, Holocene or present day analogues for such communities in the Highlands. In addition to providing evidence for disturbance regimes, succession and shifting mosaics, these records stress the importance of understanding links between environment and vegetation. Flooding and hillwash at Carnach Mór and Camban are suggested to have caused frequent, small-scale and low intensity disturbance, thus maintaining consistently high herbaceous and woodland diversity. These inferences are again supported by ecological data, which emphasise the distinctive disturbance regime associated with floodplains, in which the dynamic interaction of fluvial and terrestrial processes creates numerous diverse habitats, contributing to patchworks of plant communities (Peterken 1996, Petts 1998).

9.2.2 Long-term changes

There are dangers associated with climatic inference from pollen data due to the complex array of regional and local factors affecting plant distribution, abundance and dynamics. Taxa such as *Pinus*, *Quercus* and *Alnus*, which were growing near the edge of their ranges may have been more sensitive to environmental changes (*cf.* Binney 1997). Synchronous long-term palynological trends inferring changes in moisture and warmth are suggested to indicate climatic shifts, which resulted in changes in competition interactions and fire regimes. Evidence from Affric and selected Highland sites is summarised in Table 41.

Warmer and/or drier conditions at *c.*5600-4900 BP (6380-5630 cal BP) are suggested to have resulted in more intense and/or frequent burning at Torran Beithe, Morvich, Glen Torridon, Glen Carron and Lairg (Anderson 1996, 1998, Smith 1996, 1998). At *Pinus*-dominated sites, such as Torran Beithe, Glen Torridon, Glen Carron and Lairg, this species may have been favoured by increased burning, fuelled by understorey heaths or by *Pinus* itself, both of which could have been more easily combustible under drier conditions (*cf.* McVean and Ratcliffe 1962, Carlisle and Brown 1968, Miles and Kinnaird 1979, Bradshaw 1993, Agee 1998). Although mixed deciduous woodlands are thought to be largely fire-resistant, even during dry seasons (Rackham 1980), the data from Carnach Mór and Morvich suggest that deciduous woodlands are flammable, perhaps due to the presence of a lush understorey (*cf.* Peterken 1996). Natural factors may thus have been sufficient to ignite dead wood and understorey vegetation. However, drier conditions may also have encouraged the use of fire as a management tool by Mesolithic and Neolithic peoples, resulting in the pattern of intermittent, repeated burning at Morvich, as discussed in Section 8.5.4.

In the absence of fire, climatic variability is suggested to have enabled the long-term regeneration of pinewoods in northern Sweden by controlling *Pinus* seed production and understorey composition, which influenced the success of *Pinus* regeneration on the forest floor (Zackrisson *et al.* 1995). Similar mechanisms may have operated around Torran Beithe.

The evidence from Glen Affric suggests that climatic shifts may have most strongly affected the competitive ability of taxa growing near the edges of their range or tolerance, especially *Pinus*, but also *Alnus* and *Quercus*. This is especially evident from *c.*4400-3500 BP (4920-3790 cal BP), when the high incidence of similar inferences from the present sequences strongly suggest regional environmental change (Table 38). Regional environmental changes between 4800 and 3500 BP (5500-3790 cal BP) are discussed in Section 9.4.

9.3 Early to mid-Holocene peat formation and mire distribution

The four sampling sites present contrasting evidence for the development and importance of mire communities in different landform units. However, as local factors, such as topography, may play an important role in peat inception and expansion (Tallis 1991, Charman 1992), it is dangerous to extrapolate across the landscape from the present limited data (*cf.* Tipping 1994). In addition, inferring peat expansion from the present sites may be problematic due to the possible growth of peat species on the surfaces of the sampling sites.

The earliest fen vegetation at Torran Beithe, forming at *c.*7300 BP (8040 cal BP), is suggested to be acidic, while at Carnach Mór, a transition from tall-herbs to similar Cyperaceae- and *Sphagnum*-dominated mire did not occur until 6140 BP (7010 cal BP). Mire communities appear to have spread onto flatter ground around the sampling basin at Torran Beithe at *c.*5300 BP (6090 cal BP), forming a natural part of the woodland mosaic on the lower hillsides. Peat accumulation appears to have begun at Camban around 4980 BP (5730 cal BP). This suggests a reduction in fan activity. It is possible that a regional shift to wetter conditions may have resulted in the more rapid accumulation of organic matter, coincident with continued sedimentological evidence for inwashing. However, there is no evidence for the acidification of fen carr communities at Camban or Morvich until *c.*4480 BP (5190 cal BP) and 4240 BP (4830 cal BP) respectively, when limited expansion of acidic mire and blanket peat is inferred (see Section 9.4).

The evidence from Torran Beithe may be comparable with undated blanket peat profiles from around Loch Sionascaig and the upland loch site at Lairg, which indicate that, in areas dominated by acidic *Betula* and *Pinus* woods with an understorey dominated by heath taxa, unconfined blanket peat communities had formed by around 5000-4800 BP (5730-5500 cal BP) (Pennington *et al.* 1972, Smith 1996, 1998). Pennington *et al.* (1972) suggest a natural retrogressive shift towards blanket peat expansion. However, peat expansion at Torran Beithe, the gradual decline in relative and absolute AP values from 4740 BP (5550 cal BP) at Camban, and evidence for palaeohydrological evidence for wetter and/or cooler conditions in Wester Ross from *c.*4900-4200 BP (5630-4730 cal BP) (Anderson 1996, 1998), may indicate that conditions for woodland regeneration were becoming increasingly stressful and marginal on acid morainic sediments and more fertile alluvial and lowland soils, even for *Betula* (see Table 41).

9.4 Mid-Holocene environmental change

A comparison of local pollen assemblage zones from the four study sites (Table 38) indicates that the most widespread and marked vegetational changes occurred from *c.*4400-3600 BP (4920-3890 cal BP). This is reflected in the four DCAs by shifts in sample scores from woodland to open and acidophilous taxa scores. This is comparable with previous evidence for vegetational shifts across the north-western Highlands (Section 1.10). However, changes in woodland composition, fragmentary woodland survival, and localised changes in burning with grazing and agricultural activity, suggest far greater complexity than has been previously recognised at many sites, where the role of human intervention and fire is frequently ambiguous (Section 1.12). Local environmental controls are suggested to have played a key role in mid-Holocene vegetational changes in West Affric and Kintail, mitigating or exacerbating the effects of external pressures on woodlands and affecting the composition of the open communities which replaced them over much of the upland landscape. The evidence for regional climatic controls are presented before these local factors are discussed. As has been recognised previously (Bennett 1995), these factors are closely inter-related.

9.4.1 Climatic change and edaphic deterioration

There is evidence for *Pinus* growth or expansion at all three upland sites in West Affric from *c.*4390-3770 BP (4930-4110 cal BP). This correlates well with regional evidence for *Pinus* expansion at the edges of its established range between *c.*4400 and 4000 BP (4920-4440 cal BP), which is suggested to reflect a regional climatic shift to warmer conditions controlled by Atlantic air or ocean currents (Gear and Huntley 1991; Section 1.12.1). This may have caused a short-lived hiatus at Morvich around 4250 BP (4830 cal BP). However, evidence for the spread of blanket peat and changes in the structure and composition of woodlands at Camban and Morvich from *c.*4740-4270 BP (5550-4860 cal BP) suggest that *Pinus* expansion could have occurred at a time when arboreal regeneration was becoming increasingly difficult due to edaphic deterioration (below).

There is also clear evidence for a subsequent local and regional decline in *Pinus* populations between *c.*3910 and 3770 BP (4370-4110 cal BP) at all four sites, which is comparable with regional evidence (Section 1.12.2). However, changes in woodland composition in West Affric suggest that inferred mid-Holocene climatic shifts may also have been characterised by increased seasonality, which appears to have removed earlier climatic and competitive constraints on *Quercus* and *Alnus* at the three upland sites between *c.*4530 and 3600 BP (5150-3890 cal BP), as discussed in Chapters 5-7.

Initially, warmer, more continental conditions are suggested to have enabled *Pinus*, *Quercus* and *Alnus* to compete more effectively with *Betula* in West Affric (*cf.* Jones 1959, Steven and Carlisle 1959, Bennett 1984, Barnekow 1999). At Carnach Mór, increased seasonality may also have contributed to fluctuations between mire and woodland communities from *c.*4190-3870 BP (4720-4280 cal BP). Further increases in *Quercus* and *Alnus* frequencies as *Pinus* values decline suggest that competition from these deciduous taxa may have contributed locally to the decline in *Pinus* and *Betula.*

Increased *Quercus* representation is also recorded following the *Pinus* decline at Lairg and Rogart (Smith 1996, 1998, Tipping pers. comm.). Although this is interpreted as the result of anthropogenic manipulation at Lairg, the present evidence may indicate more widespread *Quercus* expansion, with natural causal factors. On White Moss, in Cheshire, *Quercus* appears to have expanded as *Pinus* was struggling to regenerate, and this is interpreted as evidence for fluctuating surface wetness on the mire (Lageard *et al.* 1999). Similarly, on Dartmoor, increased *Alnus* and *Quercus* frequencies are suggested to reflect increased local wetness with *Quercus*/*Alnus* woodland in valley bottoms prior to local blanket peat development (Caseldine and Hatton 1993).

Rising watertables after *c.*4000 BP (4440 cal BP), caused by a shift to more oceanic conditions, have been suggested as the proximal cause of woodland decline and blanket peat expansion over much of the north-west (Birks 1972, Pennington *et al.* 1972, Kerslake 1982, Gear and Huntley 1991, Anderson 1996, 1998). This may have acted in a degenerative spiral once the threshold for change was crossed (*cf.* Moore 1988, 1993, Smith 1996; Section 1.10.2.1). These inferences are supported by the present evidence for woodland decline and peat expansion on the hillsides at Torran Beithe and, to a lesser extent, at Carnach Mór. Naturally acidic, nutrient poor soils at Torran Beithe, combined with a long history of acidifying *Pinus-Calluna* vegetation (Miles 1985), may have predisposed the area to blanket peat expansion through progressive soil deterioration, although burning may have been the proximal trigger for peat expansion (see below). However, the data from Camban and Morvich emphasise the contrasts caused by localised environmental differences, and may help to explain temporal variations.

Climatically less severe conditions and better soil quality at Morvich are suggested to have limited the extent of vegetational changes in the mid-Holocene. However, proximity to the Atlantic Ocean may have resulted in comparatively early woodland changes, commencing around 4270-4240 BP (4840-4830 cal BP) since changes in Atlantic Ocean or air currents are suggested to have been mechanisms of climatic change (Gear and Huntley 1991, Anderson *et al.* 1998). Relatively sheltered conditions at the head of Loch Duich may have enabled woodland survival and limited heath and mire expansion, as at Lochan Doilead (Williams 1977), since woodland cover was reduced at more exposed coastal sites such as Achiltibuie and Ardheslaig (Bunting and Tipping 1997, Bennett and Hill 1998).

The spread of peat may have resulted in woodland decline on the hillside at Carnach Mór. This contrasts with the inference that alluvial soils at Carnach Mór and Camban were earlier rejuvenated by sediment deposition. Mid-Holocene differences between these two sites are suggested to result from the progressive marginalisation of trees growing on floodplain soils due to rising watertables, exacerbated by grazing pressure and burning (below), which resulted in the replacement of trees by shallow-rooting herbs and heaths. At Camban more frequent sediment deposition, evident through loss-on-ignition data, and the gradient of the slope may have aided drainage sufficiently to enable continued woodland survival, albeit with a more open structure with meadow and tall-herb vegetation, despite grazing pressure.

The survival of more open woodland may be comparable with evidence from two sites in the valley at Lairg, where wetter conditions and woodland openings are inferred from humification and pollen records, respectively, without evidence for the spread of blanket peat (Smith 1996, 1998, Tipping and McCullagh 1998). Woodland survival is also evident at other sites, including Eilean Mór (Kerslake 1982), but the relationship between environment and vegetation is less clearly established there.

9.4.2 Local factors

9.4.2.1 Grazing and anthropogenic activity

While both regional climatic change and site-specific environmental conditions appear to have determined the severity of mid-Holocene vegetational changes (Section 9.4.1), burning, grazing and agriculture are suggested to have created additional stresses which affected the trajectory of change and composition of open communities. However, as discussed in Chapter 1, there are also problems associated with the identification of anthropogenic activity and interpretation of charcoal data. Several additional ecological factors are evident from the present data:

1. It may be difficult to infer anthropogenic interference in woodlands dominated by relatively short-lived, pioneer taxa, which may be more likely to produce pollen fluctuations as a result of natural dynamics, due to generation-scale autogenic changes and frequent small-scale disturbance on alluvial soils.

2. The data emphasise the need for critical interpretation of 'anthropogenic indicator' herbs. Grazing disturbance is usually inferred from the sporadic presence of *Plantago lanceolata* pollen (*e.g.* Birks 1972, Pennington *et al.* 1972, Anderson 1996, 1998). However, at a finer spatial scale, disturbance appears to have been common throughout the Holocene, particularly in alluvial and coastal environments (*cf.* Brown 1997). At Carnach Mór, Camban and Morvich, natural disturbance is suggested to have enabled the growth of ruderal species such as *Rumex*, Chenopodiaceae and sporadic *P. lanceolata* since the early Holocene (*cf.* Sagar and Harper 1964; but see below). Proximity to the coast may also account for frequent *P. lanceolata* at Ardheslaig Loch throughout the Holocene (Bennett and Hill 1998, *cf.* Smith 1973, Fossitt 1990).

3. The need for critical interpretation may be extended to the occurrence of *Hordeum* group pollen in coastal or aquatic environments. This is evident at Carnach Mór and, more problematically, at Morvich, where *Hordeum* group grains are recorded since the early Holocene, increasing in frequency around 4350 BP (4870 cal BP). Early records of cereal-type grains are also recorded at Achiltibuie (Bunting and Tipping 1997). While early Holocene grains at all three sites may derive from aquatic or maritime grasses (*cf.* O'Connell 1987), there is herbaceous evidence suggesting aquatic, maritime and arable environments around Morvich from the mid-Holocene (Section 8.5).

4. The fourth issue, evident at Torran Beithe, suggests that conventional 'anthropogenic indicators' may be absent or scarce in environments which are dominated by damp, acidic and nutrient-poor vegetation, due to an absence of suitable ecological niches. Furthermore, detecting grazing disturbance in heathland and bog is difficult, as discussed in Section 5.5.5.

These issues increase the difficulties of identifying and separating anthropogenic disturbance from increasingly adverse climatic conditions. Inferences are more secure when several lines of evidence occur simultaneously, and this is used as the basis for interpretation here. Deteriorating climatic and edaphic conditions may have made vegetation increasingly sensitive to even slight grazing or anthropogenic pressures. The palynological evidence from West

Affric and Kintail suggests that these two pressures are closely associated. *P. lanceolata* is one of the main herbs recorded in increasing frequencies during the mid-Holocene. This contrasts with sparse pollen of this species recorded since the early Holocene, and suggests that increased frequencies may be indicative of changes in the nature of disturbance, such as increased grazing pressure from domesticates rather than wild herbivores, which would have been present throughout the preceding period. As discussed above, this indicates the necessity of establishing the relationship between environment and vegetation at a local scale to enable more secure interpretation.

A combination of climatic and anthropogenic stresses, particularly grazing pressure, are suggested to have resulted in a gradual decline in woodland regeneration, both prior to and following the main reduction in woodland canopy. Preceding the main woodland decline, tentative evidence for grazing pressure at Carnach Mór, Camban and Morvich between 4480 and 4190 BP (5190-4720 cal BP) is suggested to have made use of and/or created a more open woodland canopy and increased representation of herbs which are characteristic of grassland and meadows. There is increasing evidence for agricultural activity and burning coinciding with the main reduction in woodland cover at Camban, while increased anthropogenic and pastoral disturbance is recorded slightly after this horizon at Carnach Mór and Morvich. These data suggest that grazing pressures on alluvial soils may have reduced arboreal regeneration and affected the composition of grasslands that expanded around 4240 BP (4830 cal BP) and 3630 BP (3920 cal BP) at Carnach Mór and Camban respectively. Woodland composition at Morvich is also suggested to have been altered by grazing following the shift to possibly more oceanic birchwoods at *c.*4240 BP (4830 cal BP).

The relative impact of climatic, edaphic, anthropogenic and grazing pressures remains difficult to infer. The stepped decline in arboreal taxa at Carnach Mór and Torran Beithe may reflect the failure of arboreal regeneration as blanket peat expanded and species-specific thresholds for successful regeneration were crossed, and/or the death of parent trees and failure of seedling establishment under sustained grazing pressure. In contrast to the asynchronous decline in woodland cover, the dates at which cereal-type pollen and inferred arable weeds are recorded at Camban and Morvich are statistically inseparable (*c.*3600 BP (3890 cal BP) and 3640 BP (3960 cal BP) respectively). This may suggest that more extensive or intensive lowland activity and expansion into upland West Affric occurred at a similar time (Section 9.5.1). There is little unambiguous evidence for anthropogenic activity until the later Holocene at Torran Beithe, as at many Highland pollen sites (Section 1.12), suggesting a greater role for climatic and edaphic changes, although the charcoal data may suggest otherwise (see below).

9.4.2.2 Changes in fire regimes

The interpolated dates for a shift to more frequent or intense burning during the mid-Holocene at Torran Beithe, Carnach Mór and Camban are statistically inseparable, ranging from *c.*3880-3840 BP (4340-4230 cal BP). This may infer a similar mechanism at all three sites. Increased mid-Holocene charcoal representation is also recorded at Achiltibuie (*c.*3980 BP, 4420 cal BP), Ardheslaig (4950-3900 BP, 5670-4360 cal BP), Glen Carron (*c.*4100 BP, 4560 cal BP) and Glen Torridon (*c.*3700 BP, 4030 cal BP) (Anderson 1996, 1998, Bunting and Tipping 1997, Bennett and Hill 1998), although this does not occur at Lairg, further east (Smith 1996, 1998).

A change in fire regime has been suggested as a possible contributory factor in the *Pinus* decline (Bradshaw 1993, Bennett 1995). There is no evidence to support this hypothesis in West Affric, in agreement with previous results from the north-western Highlands (Section 1.12.2.3). Following the main decline in relative and absolute AP curves, burning is, however, suggested to have contributed to the long-term failure of woodland regeneration at the local scale around Torran Beithe and Carnach Mór by triggering the expansion of blanket peat and *Calluna* respectively. At Camban, increased burning may have aided the short-lived expansion of *Alnus* and the spread of grassland.

Anthropogenic interference, climatic or vegetational change may have resulted in increased burning, although inferring cause and effect is difficult (Section 1.8). Increased seasonality or storminess could have acted at a regional scale to increase the frequency or intensity of burning, even, perhaps, under wetter conditions, where flammable vegetation or human intervention occurred. However, the temporal and spatial variability of vegetational changes in West Affric at this time (Section 9.4.1) suggests that climatic change or a shift to more flammable vegetation alone cannot account for the near synchronous change in upland fire regimes.

The frequent association between higher frequencies of charcoal particles and evidence for disturbed communities suggests that the fire regime may have been anthropogenically-controlled. The evidence is clearest at Camban, where higher charcoal frequencies coincide with grassland and *Alnus* expansion, pastoral and possible arable activity. Although causal mechanisms are less easily established at Carnach Mór, evidence for grazing disturbance preceding the apparently simultaneous expansion of *Calluna* and charcoal may imply anthropogenic involvement, either in the expansion or maintenance of *Calluna* heath. In the light of evidence from the other sites in West Affric, the charcoal record from Torran Beithe may be the clearest evidence for anthropogenic presence (*cf.* Robinson 1987, Charman 1992), although palynological data from the immediately adjacent valley floor (*e.g.* Athnamulloch; see Fig. 10), where most activity in West Affric appears to have been focused (see Section 9.6.2.1), would provide a more rigorous test for this hypothesis.

Anthropogenic burning in a domestic or management context is also inferred at Achiltibuie, Ardheslaig, Glen Carron and Glen Torridon (Anderson 1996, 1998, Bunting and Tipping 1997, Bennett and Hill 1998). A similar interpretation is made at Lairg, although this involved the abandonment of burning as a management regime, which is suggested to have contributed to the elimination of *Pinus* (Smith 1996, 1998). Low frequencies of *P. lanceolata* pollen recorded in mire-dominated sites such as Glen Carron and Glen Torridon are, however, far from secure evidence to support this interpretation. Data from smaller sites, such as those in West Affric and at Lairg provide more secure information regarding vegetation-fire interactions which are necessary to aid interpretation of the relative impacts of climatic and anthropogenic pressures (*cf.* Bennett and Hill 1998).

9.4.3 Conclusions regarding mid-Holocene vegetational and environmental changes

9.4.3.1 Causal factors

The relative impact of climatic, edaphic, pastoral and anthropogenic pressures remains difficult to separate. The earliest changes in the composition or structure of woodland communities, around 4400 BP (4920 cal BP), are suggested to reflect a shift to more a more seasonal continental climate, which initially favoured *Pinus*, but also enabled *Quercus* and *Alnus* to compete more successfully with *Pinus* and *Betula*. Subsequently, widespread changes in the composition and density of woodlands coincide with evidence for spatially variable intensities and forms of land-use. This is interpreted as evidence that climatic deterioration, particularly a rise in watertables, resulted in an increasingly fragile balance between woodland and herbaceous communities, especially on poorer soils such as the moraine-covered hillsides around Torran Beithe and Carnach Mór. This made arboreal regeneration increasingly vulnerable to additional stresses, such as agriculture, grazing and burning. However, the impact of both climatic change and anthropogenic pressure was mediated or exacerbated by local environmental conditions, including soil status, altitude and exposure. This enabled continued woodland or scrub regeneration at Camban, despite arable and pastoral agriculture, while regeneration gradually failed at Carnach Mór and Torran Beithe in response to less intensive anthropogenic pressures (see below). The contrasts between West Affric and lowland Kintail suggest that upland ecosystems were relatively fragile and susceptible to even slight environmental stresses, particularly on morainic soils.

9.4.3.2 The *Pinus* decline

The data from West Affric suggest that *Pinus* may have been most strikingly affected by mid-Holocene environmental changes due to a combination of (a) competition from *Quercus* and *Alnus*, which also appear to have displaced *Betula* in some areas, (b) competitive exclusion from richer alluvial soils, and (c) rising watertables on damp and peaty substrates. *Pinus* is thus inferred to have been restricted to marginal peaty soils, which may have been more susceptible to edaphic deterioration in response to climatic stress, increased burning and grazing pressure.

It is possible that *Pinus* faced similar competition from *Betula* in the far north-west, where a shift from *Pinus* to *Betula* woodland is interpreted as a response to increased oceanicity (Kerslake 1982, Daniell 1997), although *Betula* too was unable to survive in Affric.

9.4.3.3 Percentage limits for establishing local *Pinus* growth

The palynological and stomatal data from West Affric suggest that the use of a 20% limit to infer local *Pinus* growth (Bennett 1984) needs to be applied cautiously, particularly in the Highlands where *Pinus* appears to have been limited to more marginal substrates. Between 4390-3765 BP (4930-4110 cal BP), low pollen frequencies with *Pinus* stomata are recorded at Carnach Mór and Camban, with higher values at Torran Beithe (Table 39). This could be interpreted as evidence for suppressed pollen production as a result of marginal growth conditions (*cf.* Sarvas 1962, cited in Ledig 1998), since low *Pinus* pollen frequencies have been recorded in previous palynological and dendrochronological analyses (*e.g.* 3-9% *Pinus* pollen on White Moss; Lageard *et al.* 1999). However, in Glen Affric, low pollen frequencies with stomata are suggested to indicate small *Pinus* populations within the vegetation (*cf.* Fossitt 1994a, b), restricted by competition from arboreal taxa on richer alluvial soils prior to *c.*3840-3630 BP, and by later blanket peat expansion around Torran Beithe (Section 5.5.5).

9.5 Mid-Holocene transitions

9.5.1 Bronze Age upland agricultural expansion

As indicated above, the early Bronze Age appears to have been a period of upland expansion. This occurred after more extensive or intensive pastoral activity, with initially ambiguous evidence for cultivation, during the later Neolithic and earliest Bronze Age at Morvich, around 4350-3640 BP (4870-3960 cal BP) (Sections 8.8.5.4-8.5.5). Growing lowland farming communities may have been attracted to the uplands by the expansion of open pastures as woodland regeneration began to fail, but may also have helped to create or expand them (Section 9.4.2) (*cf.* Tipping and McCullagh 1998). Evidence for cultivation at Camban from *c.*3600 BP (3890 cal BP) suggests that settlement may have been permanent, since the palynological record resembles evidence from lowland sites, albeit probably on a smaller spatial scale due to the limited availability of suitable soils (see Section 9.6.2). In contrast, the predominance of pastoral indicators at Carnach Mór could be interpreted as transhumant use of better quality upland grazings on alluvial soils, on a seasonal or daily basis (*cf.* Fenton 1976).

Bronze Age expansion could also be inferred from an increase in archaeological visibility in coastal and inland glens around Glen Affric (Section 2.2). However, the palynological data form a striking contrast with local archaeological data, which suggest limited, if any, prehistoric activity in upland Affric and suggest that permanent settlement may not have been established until the end of the seventeenth century (Section 2.2.3).

Early Bronze Age expansion is a feature of many upland landscapes, evident in palynological and archaeological records, not only in Scotland (Fleming 1988, Mercer and Tipping 1994, Leighton 1997), although this was by no means a synchronous event (Tipping 1994, Cowie and Shepherd 1997). The causes are very poorly understood; increasing population pressure and territoriality have been suggested (Cowie and Shepherd 1997), although the latter theory is based primarily on evidence for a change from open, unenclosed settlements to enclosed farmsteads and settlements in much less harsh upland landscapes outside the Highland zone. While the data from Morvich provide only a very localised vegetation history, there is no evidence of population pressure or large herds, since woodland, albeit perhaps managed to ensure survival (below), coexisted with pastoral and possibly arable agriculture until *c.*1420 BP (1300 cal BP).

This suggests that other, perhaps social motives, need to be considered, although this is likely to pose untestable hypotheses, as there may be little, if any, material evidence. Possible reasons include changes in land tenure and thus in the organisation of the agricultural landscape, perhaps with increasing territoriality, as has been previously inferred elsewhere in Scotland (above), in which individuals or groups controlled larger tracts of land. Alternatively, a shift to reliance on livestock and a consequent need for extensive pastures, may have necessitated the use of the uplands, although, as indicated above, the present evidence does not suggest that grazing pressures were high in the uplands or adjacent lowlands.

9.5.2 Fragmentary woodland survival

Despite the marked expansion of herbaceous pollen taxa during the mid-Holocene, comparison of surface sample and fossil pollen data from the four sites indicates that trees remained part of the landscape (Table 42). On the hillsides and valley floor around Torran Beithe and Carnach Mór, this may have consisted of small stands, which became progressively isolated by peat expansion and grazing. Trees appear to have disappeared earliest around Carnach Mór, around 3000 BP (3190 cal BP), despite palynological evidence for poorer soils around Torran Beithe. At Torran Beithe, palynological and stomatal evidence suggest the local survival of *Pinus* until *c.*2540 BP (2720 cal BP), with extralocal stands or trees until *c.*2030-1890 BP (1970-1830 cal BP), or perhaps as late at 1460 BP (1330 cal BP). This may indicate that sustained grazing pressure was concentrated on the valley floor, which would have provided more nutritious pastoral grassland. These two sites contrast with the survival of *Betula*-dominated woodland on the alluvial fan at Camban, and around the basin at Morvich until the later Holocene, as discussed below.

There is thus growing evidence for the localised survival of woodland stands from small diameter pollen sites across the north-west Highlands after the mid-Holocene (Kerslake 1982; Sections 1.12.2.5 and 1.13.1). This contrasts with ambiguities associated with the interpretation of moderate arboreal pollen frequencies in earlier work from large sites with poor controls on spatial resolution (*e.g.* Birks 1972, Pennington *et al.* 1972). Woodland survival has previously been attributed to topography, particularly the presence of rocky and steep slopes (Pennington *et al.* 1972, Kerslake 1982). Although these may have been contributory factors, local soil properties, drainage and both upland/lowland and east/west climatic gradients are suggested to have been important. In East Affric, better drainage on the steeper, rocky lower hillslopes and an east-west climatic gradient which may have existed throughout the Holocene (Sections 2.1.4 and 9.1.2), could have contributed to the continued survival of pinewoods. The results of analyses from East Affric, particularly the nature and extent of mid-Holocene change, are required to test this hypothesis.

While there is little or only very recent evidence for human interference in mid- to later Holocene woodlands in the north-west (Birks 1972, Kerslake 1982; Section 1.13), data from the alluvial upland sites in Affric and at Morvich have more in common with sites at Achiltibuie, Lairg and Lochan Doilead (Williams 1977, Smith 1996, 1998, Bunting and Tipping 1997), where woodland composition and regeneration appear to have been closely linked with anthropogenic activities, as discussed below.

9.6 Mid- to later Holocene cultural landscapes

As much of the palynological evidence from Glen Affric and Kintail suggests that agricultural activity played an increasingly important role in the landscape, this forms the focus for the discussion of later Holocene vegetation history. This subject is discussed in three main sections: firstly, a discussion of the broad-scale temporal and spatial patterns of land-use, regional parallels and contrasts. This is followed by a discussion of the evidence for management techniques which formed the basis for agricultural subsistence, and finally, an examination of the concept of marginality which has been so frequently applied to upland landscapes, particularly in the Highlands.

9.6.1 Temporal and spatial patterns in West Affric and Kintail

As the archaeological and documentary records for land-use around Glen Affric and across the Highlands are sparse (Section 2.2), wider regional parallels are included in the following discussion, although conclusions for the Highlands are necessarily limited at present.

9.6.1.1 The later Bronze Age and early Iron Age

Following late Neolithic and early Bronze Age expansion into the uplands, and the expansion or intensification of lowland agriculture (Section 9.5.1), there is evidence for a further increase in agriculture during the late Bronze Age and early Iron Age, commencing around 3310 BP (3510 cal BP) at Morvich, and from *c.*2910-2700 BP (3060-2780 cal BP) in the uplands. At Morvich, this involved pastoral expansion and more marked local woodland incursions, while in the uplands, an increase in arable and pastoral indicators is recorded at Camban, with grassland expansion at Torran Beithe and Carnach Mór.

This may indicate a need for more extensive pastures, although woodlands at Morvich and Camban survived, possibly reflecting woodland or stock management, through enclosure or careful shepherding (see Section 9.6.1.2). A single *Hordeum* group grain recorded at Carnach Mór at *c.*2660 BP (2760 cal BP) may indicate occasional cultivation, probably on more fertile alluvial soils, perhaps encouraged by manuring incidental to long-lived grazing (see Section 9.6.1.2). The increase in grassland herbs at Torran Beithe is suggested to derive from extralocal activity, probably also on the valley floor. This emphasises how poorly the prehistoric archaeological record reflects the scale and nature of upland activity, as it provides only limited evidence for Bronze and Iron Age agriculture in the adjacent lowlands (Section 2.2.3).

There is some evidence for pastoral and arable expansion in the uplands and foothills of the Highlands during this period, including Achiltibuie, Loch Clair, Rogart, Braeroddach Loch and, more briefly, at Carn Dubh around 3250-2900 BP (3470-2990 cal BP) (Pennington *et al.* 1972, Edwards 1978, Edwards and Rowntree 1980, Tipping 1995a, Bunting and Tipping 1997, Tipping pers. comm.).

In contrast, archaeological data from Lairg suggest abandonment around 2900 BP (2990 cal BP), although pastoral activity appears to have been sustained (Smith 1996, 1998, Tipping and McCullagh 1998). Evidence from Arran also suggests a contraction in upland activity around 2750-1850 BP (2830-1780 cal BP) (Robinson and Dickson 1988, Barber 1997). Late Bronze Age upland abandonment was once considered to be a widespread feature, attributed variously to climatic deterioration, volcanic eruption, peat expansion and soil exhaustion (Burgess 1980, 1985, Baillie 1995, Anderson 1996, 1998, Barber 1997, Tipping and McCullagh 1998). However, this phenomenon is not evident at many upland and exposed sites, including West Affric, at the sites indicated in the paragraph above, in the Cheviots (Tipping 1994) or in northern England (Young and Simmonds 1995). This suggests that farmers in many areas which are frequently considered to be 'marginal' were highly capable and well-adapted to their environment and stresses the need for more regional palaeoclimatic records (see Section 9.6.3).

9.6.1.2 Iron Age diversification

A shift to more extensive or intensive pastoral and arable land-use around Morvich around 2260-1950 BP (2320-1880 cal BP) appears to have been confined to the lowland valley, since the upland evidence suggests a continuation of predominantly pastoral land-use. A decline in activity and palynological richness at Camban from *c.*2330 BP (2340 cal BP) is attributed to local geomorphological and edaphic changes, which emphasise the dependence of soil status and tree regeneration on continued alluvial sediment deposition (Sections 7.5.5-7.5.6). The apparent cessation of cultivation and rise in charcoal frequencies at this time are suggested to reflect a change in management in response to vegetational changes, again stressing the adaptability of upland farmers (Section 9.6.3).

There is palynological, archaeological and pedological evidence for renewed activity in the valley at Lairg from *c.*2450 BP (2500 cal BP), including possible heathland management by burning from *c.*2050 BP (2000 cal BP), although there is little evidence for upland land-use after the late Bronze Age, possibly following the loss of agricultural productivity during the Neolithic (Smith 1996, Tipping and McCullagh 1998). The data from Affric and Lairg thus indicate spatial differences in patterning both at a landscape and more localised scale.

9.6.1.3 Later Iron Age and Pictish expansion

Further expansion and/or intensification occur at Kintail and in West Affric from *c.*1760-1520 BP (1650-1400 cal BP), although this was spatially and temporally variable. In the lowlands, there appears to have been a change in management, since local woodlands underwent a gradual decline between 1420 BP and *c.*780 BP (1300-680 cal BP), following a period of inferred management of *Quercus* for timber at 1520-1420 BP (1400-1300 cal BP) (see Section 9.6.2.3). This may imply a change in attitudes towards the land, perhaps with greater value placed on land as a source of pasture, at the expense of the woodland cover. This period thus contrasts with the inferred long-term conservation management of the Bronze and Iron Ages (Sections 8.5.5-8.5.6 and 9.6.3).

Although upland activity appears to have remained predominantly pastoral, intermittent or limited cultivation may have commenced at Carnach Mór at *c.*1760 BP (1650 cal BP), possibly with settlement around 1170 BP (1060 cal BP), inferred from consistent *Hordeum* group and Poaceae anl-D>8 µm representation. Cereal-type pollen is again recorded at Camban around 1520 BP (1400 cal BP), but cultivation appears to have remained sporadic until *c.*820 BP (710 cal BP, AD 1240). Increased charcoal representation from *c.*1250 BP (1170 cal BP) at Torran Beithe may indicate that agricultural expansion included this area, but this remains difficult to infer.

At a wider geographical scale, numerous sites provide evidence for late Iron Age and Pictish expansion, including the Spey valley around 1500-1000 BP (1350-930 cal BP), possibly with sporadic cultivation near Loch Pityoulish from *c.*1850 BP (1780 cal BP) (O'Sullivan 1973b, 1974a, b, 1976). Further clearance is recorded at Lochan Doilead from 1580 BP (1460 cal BP), with cereal pollen before *c.*660 BP (650 cal BP) (Williams 1977), and there was renewed agricultural activity at Rogart from an estimated date of 1250 BP (*c.*1170 cal BP) (Tipping pers. comm.). However, at Lairg, a shift to increased pastoral activity around 1110 BP (1000 cal BP) coincides with a reduction in cultivation (Smith 1996, 1998).

9.6.1.4 Medieval maximum

More widespread agricultural expansion may have occurred across the Highland region during the thirteenth to fifteenth centuries AD. Although interpretation at Morvich is hampered by chronological uncertainties (Section 8.3.3), the data suggest that the catchment was as open as the present by *c.*780 BP (680 cal BP). In West Affric, renewed activity at Camban from 820 BP (720 cal BP) involved more extensive or intensive grazing and cultivation, and clearance of the surviving scrub around 730 BP (660 cal BP). Mixed agricultural activity continued at Carnach Mór, while a rise in *P. lanceolata* suggests increased grazing activity from *c.*550 BP (540 cal BP) around Torran Beithe, although again probably in the extralocal pollen source area.

Maximum cereal pollen frequencies are recorded at all three upland sites at 410-390 BP (490-470 cal BP), suggesting a real arable intensification or expansion, rather than simply activity closer to each sampling site. These dates calibrate to AD 1430-1640, thus around the onset of the Little Ice Age, which attained maximum intensity between the mid-sixteenth and mid-nineteenth centuries (Grove 1988). However, continued evidence of agriculture until recent centuries again suggests that upland farms and, more particularly, cultivation, were by no means abandoned during this period of supposed climatic deterioration (*cf.* Tipping 1998, *contra* Parry 1981, Parry and Carter 1985; Section 9.6.3). Furthermore, climatic deterioration in the Highlands is poorly supported by the present limited data, as the timing of the proposed 'Little Ice Age' in Wester Ross occurs at *c.*1000-850 BP (940-760 cal BP), thus predating the historical evidence (Anderson 1996, 1998).

The present palynological data are broadly comparable with evidence from Achiltibuie, which suggests an expansion of pastoral and possibly arable activity from 770 BP (670 cal BP), with increased *Hordeum* group pollen recorded from 320 BP (410 cal BP), thus at a very similar age to maximum representation in West Affric, although maritime grasses cannot be excluded at Achiltibuie (Bunting and Tipping 1997). There is also some evidence for regional expansion in the north-west Highlands at this time, since cultivation on Skye coincides with the widespread destruction of remnant *Betula-Corylus* scrub during the last 700 ^{14}C (660 cal) years, with similar activity around Lochan Doilead from 660 BP (650 cal BP) (Williams 1977, Birks and Williams 1983).

9.6.1.5 Historical changes and the development of the modern landscape

Comparison of palynological and documentary data from West Affric and Kintail suggests that changes in settlement and land-use are incompletely understood from the written and cartographic records in this area. The earliest documentary references refer to the letting of land in Affric as shielings to men from Kintail during the seventeenth and eighteenth centuries (Wordsworth 1995), although no placenames in West Affric occur in cartographic sources of this period. This contrasts markedly with the palynological evidence, which suggests that agricultural settlement had been long-established by this period, having attaining maximum levels during the fifteenth century. Although the palynological data from Morvich can be correlated with cultivation plots recorded on Roy's map of AD *c.*1755 (Sections 2.2.3.1 and 8.2), the absence of cartographic evidence from upland glens is by no means a certain indication of an absence of settlement in more remote areas and urges caution in the interpretation of cartographic evidence (*cf.* Smout 1997). Due to chronological uncertainties at Morvich (Section 8.3.3) it is unfortunately difficult to compare and correlate the lowland pollen data with lowland documentary sources and upland palynological evidence for changes in land-use.

The First Census (AD 1841) records families resident at farmsteads including Camban and Athnamullach, on the valley floor near Torran Beithe (*e.g.* Fig. 10), although this source does not indicate whether they cultivated crops (Section 2.2.3.1). The palynological evidence suggests that the residents of these two farms, and the unnamed one at Carnach Mór, at least, were certainly growing crops in addition to grazing their animals. The conversion to sheep farming by AD 1851 is thought to have resulted in the enforced abandonment of upland farmsteads and shielings, although the eight households listed in Glen Affric included shepherds at Camban and Athnamulloch (Wordsworth and Harden 1997). While stock may have formed the main livelihood following the Highland Clearances, the palynological data suggest that small-scale cultivation continued.

The palynological evidence suggests that farming ceased in the nineteenth century AD near Torran Beithe and Carnach Mór, just before plantations were established. It is possible that, with the expulsion of sheep in the late to mid-nineteenth century, Athnamullach and perhaps Carnach Mór, were no longer occupied by farmers. However, this interpretation cannot be applied to Camban, where cultivation appears to have continued until the late nineteenth and even into the present century. Cattle and sheep were re-introduced, possibly during the First World War, concentrated in the fine grazings of West Affric (Wordsworth and Harding 1997). While sheep were removed around 10 years ago, a small herd of cattle was taken up for summer grazing until the sale of the estate to the National Trust for Scotland in 1993. A photograph from *c.*1915 records hay being mown at Camban, again agreeing well with palynological inference (below).

Extensive grazing by larger herds and expanding deer populations in the uplands may have contributed to the recent historic expansion of *Potentilla*-type and Poaceae at Torran Beithe, Camban and Morvich. The abandonment of previous careful husbandry techniques and consequent soil deterioration in the transition to extensive grazing may have occasioned the demise of *Calluna* at Torran Beithe and a decline in *P. lanceolata* at Camban. This may be compared with evidence for the widespread loss of heathland evident at many upland pollen sites in the British Isles, due to higher grazing pressures during the last 2-300 years (Stevenson and Thompson 1993, Tipping in press). In contrast, at Morvich better quality soils and the husbandry techniques of crofters may have resulted in continued high palynological diversity and the recent expansion of *P. lanceolata*, resulting in DCA sample scores which are more closely associated with open ground taxa than at the other three sites (Fig. 60).

The upland evidence compares well with nineteenth century changes recorded at Achiltibuie and Lochan Doilead in response to the failure of sheep farming and crofting, respectively (Williams 1977, Bunting and Tipping 1997; see Section 1.11.2).

The data thus suggest that, while population growth may have resulted in increased agricultural activity, particularly cultivation, during the thirteenth to fifteenth centuries AD, changes in land management during more recent centuries appear to have had a far more deleterious impact on the landscape. This evidence contrasts with the sixteenth to eighteenth century date for population growth and land pressure inferred by Dodgshon (1988) from documentary data sources. Dodgshon (1988, 1998) suggests that clan system control in the Highlands created ties between society and the land which led to an acceptance of the high costs on marginal lands, by making use of the abundance of labour in order to sustain arable productivity. It is possible that the paucity or, in many cases, the absence of earlier documentary data may bias our understanding of long-term changes in land-use based on this source alone.

9.6.2 Highland land management

Discussion in this section is focused on upland activity, since the data from West Affric provide evidence for an unexpected range of activities which appear to have been sustained for four millennia. In addition, the results from Morvich provide only limited information regarding agricultural activities at any distance from the sampling site due to the small size of the basin. In the absence of palynological comparanda, discussion in this section draws on ethnographic and historical parallels, and limited archaeological evidence.

9.6.2.1 Site selection for land-use

Comparison of the palynological data and landform unit classifications (Section 3.2.3) suggests that relatively acidic, nutrient-poor vegetation on moraine-derived soils may have dominated the landscape of West Affric. Soils of higher nutrient and base status have always been relatively limited in extent, maintained by fluvial and slope sediment deposition. The palynological data suggest that these latter areas have been the focus of human activity and this careful site selection by farmers is suggested to have allowed sustained agricultural land-use in the uplands.

There are archaeological and historical parallels for the selective use of 'islands' of more fertile and better-drained ground. Excavations on Arran indicate that settlement was highly fragmented, being concentrated on discrete pockets of better soils (Barber 1997). Similarly, at Lairg, settlement and tilled ground were focused on the fairly restricted areas of better drainage and slightly elevated pieces of drier ground within the generally hummocky and damp terrain (McCullagh and Tipping 1998). The same pattern is repeated during the prehistoric period in the uplands of South Wales (Leighton 1997), and at later shielings on Skye (MacSween and Gailey 1961).

Documentary sources from the seventeenth century onwards mention the use of broader straths and alluvial fans within the Highland massif, not only for pasture and shieling grounds, but also for cultivation. For example, in eighteenth and nineteenth century Perthshire, cereal cultivation often occurred on a surprisingly intensive scale in better favoured straths (Bil 1990). Archaeological survey in Glen Achall, near Ullapool also indicates that alluvial fans and debris cones were the focus of settlement (Welsh 1999). This suggests that spatial patterns in the archaeological evidence from around Glen Affric (Section 2.2) are a real, although incomplete, reflection of the location of past activity.

The use of these fertile pockets of ground reflects a response to the fragmented opportunities for cultivation, despite the considerable risks of flooding and crop failure (Dodgshon 1988, Bil 1990) and indicates that in prehistory, as in the more recent past, farming systems were adapted to the fragmented opportunities for farming, particularly cultivation.

The evidence for different aspects of the agricultural economy are examined before discussion of inferred evidence for their integration and organisation.

9.6.2.2 Pastoral resources

The most abundant agricultural resource in the uplands of Affric is suggested to have been pastoral, albeit consisting predominantly of extensive and, in nutritional terms, poor quality heath and bog. The charcoal data from Camban, Carnach Mór and possibly Torran Beithe suggest that even this may have been managed using fire, as inferred at Lairg (Smith 1996, 1998).

Although grassland ecology is difficult to infer from the pollen record, meadow-like grasslands are suggested to have formed on alluvial soils due to damp conditions and sediment deposition. In the last few centuries, wet meadows have been utilised as a rich source of grazing and have been valuable to farmers as a source of hay for winter feed as well as an 'early bite' for over-wintered stock, particularly in the uplands (Greig 1988, Hughes and Huntley 1988, Mitchell 1997). In England, there is documentary evidence for meadows since the Saxon period, with some archaeobotanical data suggesting grassland management since the Roman period and perhaps earlier (Greig 1988). A system of grassland management, utilising upland or low-lying floodplain grassland as summer pasture and preserving other areas for winter grazing, has been documented for the Early Christian period in Northern Ireland, and may have operated since the Iron Age (Weir 1994). Although hay-making was not widely practised in Scotland, bog- and meadow-hay were cut from patches where stock were excluded during the nineteenth century in the Highlands (Fenton 1976). Photographic evidence demonstrates that hay was cut at Camban in the early twentieth century. Similar activities may have occurred from a much earlier period and mowing may have favoured *P. lanceolata* (Groenman-van Waateringe 1986, Gaillard *et al.* 1992).

9.6.2.3 Woodland management?

Palynological evidence for grazing disturbance, cultivation and the continued regeneration of woodland and scrub at Morvich and Camban since the Bronze Age suggests that woodlands may have been integrated into land management systems by enclosure or controlled grazing (*i.e.* wood pasture; *cf.* Dingwall 1997, Fleming 1997).

Macroscopic wood evidence indicates that prehistoric people were skilled wood workers, including evidence for woodland management (Rackham 1977, Coles and Coles 1986, Taylor in Mellars *et al.* 1998). However, this is difficult to detect in the pollen record, due to the need for fine spatial and temporal resolution, and, more problematically, an absence of comparable palynological data from managed and natural woodlands (*cf.* Stevenson and Harrison 1992). Although coppice management has been tentatively inferred at Morvich, Achiltibuie and Rogart on the basis of regular pollen fluctuations (Bunting and Tipping 1997, Tipping pers. comm.), the cyclic, sub-generational pollen changes at Morvich are remarkably similar to earlier, lower temporal resolution variations which are interpreted as natural woodland dynamics. More fine temporal and spatial resolution research is thus required to examine this issue by establishing a correlation between fluctuations in the pollen and known or historically attested natural and managed woodland dynamics.

As discussed in Section 8.5.6, the comparatively late (*cf.* Birks 1989) and relatively short-lived expansion of *Quercus* from 1520-1420 BP (1400-1300 cal BP, AD 560-650) is suggested to reflect possible timber management at Morvich. However, the reason for an inferred need for larger timbers is uncertain; there is no known local or regional archaeological or documentary evidence to provide a wider context for this change in values, and/or construction needs. Timber may have been used for the construction of buildings or ships. For example, early monastic communities on Iona are known to have imported oak timbers (Crone 1998). As yet, however, our understanding of woodland management is poor. There is some evidence for the preferential management of *Quercus* for timber at Lairg during the Iron Age, when other AP frequencies are lower and *Quercus* formed 45% of the charcoal assemblage (Crone *et al.* 1998, Tipping and McCullagh 1998).

9.6.2.4 Cultivation

The pollen records from Camban and Carnach Mór indicate that long-term cultivation was possible in the uplands, despite the inferred environmental hardships. As indicated above, this is suggested to have been possible due to the careful selection of naturally more fertile soils which were maintained by natural sediment deposition and possibly also by manuring (see below).

Differences in cereal type between the sites is Glen Affric and Kintail are suggested to provide further evidence of adaptation to the upland environment. *Hordeum* group pollen suggests that barley was cultivated most frequently. This represents a response to the environmental conditions, since barley withstands poorer soils (Zohary and Hopf 1994). In the Highland and Islands bere barley was preferred where arable ground was limited, as it gave better yields than oats (Fenton 1976). *Hordeum vulgare* (6-row barley) is the predominant cereal in macrofossil assemblages since the Neolithic (Boyd 1988a). A single *Avena/Triticum* group grain at Carnach Mór, several grains at Camban and a more frequent *Avena/Triticum* group record at Morvich probably reflect the more frequent cultivation of oats in less severe and more fertile environments. The growth of wheat is considered unlikely as it is edaphically and climatically more demanding (Godwin 1975, Coppock 1976, Boyd 1988a). The close correlation between *Hordeum* group and Poaceae anl-D>8 µm may indicate that pollen sizes, and thus perhaps yields, were affected by relatively poor growing conditions (*cf.* Wagenitz 1955, cited in O'Connell 1986). It is not possible to establish whether the absence of *Avena/Triticum* group pollen from Torran Beithe is real or an artefact of poor pollen dispersal from the inferred site of cultivation of the valley floor.

Pollen data cannot indicate whether barley was grown for human or animal consumption. Historical data from the Central Highlands indicates that inferior quality cereals were highly prized as fodder, helping to ensure the survival of cattle through the winter (Bil 1990). This emphasises the interdependence of livestock and crop husbandry (below).

Other crops are very difficult to recognise in the pollen and macrofossil records (*cf.* Tipping and McCullagh 1998). Brassicaceae pollen appears frequently in association with cereal pollen at each of the study sites, and may indicate its growth as a weed or crop.

9.6.2.5 Organisation of the agricultural landscape

These alluvial 'islands' of better soil appear to have supported a rich variety of vegetational communities and agricultural activities, since many of the taxa recorded at Carnach Mór and Camban could not have survived on acidic, peaty soils, especially cereals (*cf.* McNaughton and Harper 1964, Sagar and Harper 1964, Grime *et al.* 1988). The evidence for cultivation, pasture and possibly scrub on alluvial soils suggest that each can only have taken place on a small-scale. This implies that the spatial organisation of activities and the husbandry techniques employed were well-adapted and highly integrated systems, able to sustain agricultural productivity on the small and valuable areas of better soil.

The sophisticated organisation of infield-outfield farming over the last 2-3 centuries involved practises that separated the livestock from arable fields (Fenton 1976). This included transhumance, folding and boundary dykes. As indicated above (Section 9.5.1), straths such as Carnach Mór may have functioned as areas of extensive, transhumant grazing during the growing season, prior to the inferred establishment of permanent settlement during the Pictish period. Enclosure and/or careful herding are suggested to have occurred at Camban and possibly at Morvich in order to enable cultivation and the regeneration of trees and grazing-sensitive tall-herbs (Sections 7.5.5 and 8.5.5). Even recent historic boundaries may not have survived due to the use of perishable materials such as hurdles or turf (MacSween 1959, Haggarty 1991, Dodgshon 1993), or as a result of the reworking of fluvial sediment. Alternatively, animals may have been hobbled or tathed, thus manuring selected pieces of land (*cf.* Fenton 1976; see below).

The limited area and fragmented distribution of soils capable of sustaining crops, meadows and grassland pastures suggests that traditional infield-outfield systems are unlikely to have operated in the uplands, except perhaps on a different scale, in which the moor and bog or distant alluvial soils formed extensive grazing, equivalent to the outfield. At a landscape scale, these patches of land may have formed elements of a 'multiple estate' (Fleming 1998), in which different areas had recognised uses, perhaps forming small dependencies within a larger, integrated system of land-use. The methods by which this may have been achieved are discussed below.

Historical and ethnographic sources emphasise the likelihood of recurring risks and difficulties associated with crop growth in the Highlands due to acidic and infertile soils, rough terrain, wet climate and the relatively short growing season, in addition to the risk of flooding on low-lying ground (MacSween 1959, Fenton 1976, Bil 1990, Dodgshon 1998, Entwistle *et al.* 1998). Although the evidence from West Affric suggests that farmers were well-adapted to their environment, under such circumstances, subsistence based on livestock and supplemented by small-scale cultivation may have enabled farmers to risk a failed harvest (*cf.* Halstead and O'Shea 1989). Farming systems concentrating on livestock husbandry with a limited amount of cultivation are recorded from many marginal areas of Europe, including Highland Perthshire during the last two or three centuries (Bil 1990), southern Sweden since at least the sixteenth century (Olsson 1988), and Norway during the Viking and Medieval periods (Martens 1992).

Historical systems also emphasise the strong links between arable and livestock elements of farming, since manure was essential for maintaining arable and pastoral productivity, while crops provided the fodder which was essential for over-wintering stock, particularly cattle (Fenton 1976, 1981, Dodgshon 1994). Although the palynological data can only be used to infer potential sources of grazing and pastoral activity, livestock also produce dung. Soil micromorphological and ethnographic data provide many examples of the use of dung, turf and other household wastes to fertilise arable ground, dating from the Iron Age until recent centuries (Fenton 1976, Simpson 1997, Carter 1998a, Simpson *et al.* 1998a, b, 1999). This implies considerable organisation within agricultural systems since prehistory.

Manure enabled grazing fertility to be maintained and was of primary importance in extending the limits of cultivation in marginal and more remote upland areas (MacSween 1959, Simpson *et al.* 1998a, b). Repeated use of shieling sites and the consequent manuring on better drained sites produces a green sward (MacSween and Gailey 1961), which is still evident is several areas of Affric (Photo 14). Systematic folding or tathing of animals resulted in intensive manuring of sites which are known to have eventually became choice land for small-scale cultivation (Bil 1989). This may have resulted in the settlement of Carnach Mór during the Pictish period. As discussed in Section 6.5.7, dung is one possible source of nutrient enrichment which may have influenced the grassland flora around Carnach Mór.

From the limited areas of ground available for cultivation and possible risk buffering through reliance on livestock, it is argued that the small fields may have been more akin to garden plots. Historical records indicate that, where ground for cultivation was limited or difficult, labour-intensive garden-like techniques were used (Fenton 1976, Dodgshon 1988). Similar small-scale, intensive cultivation has been inferred for the Bronze and Iron Ages in Orkney (Simpson *et al.* 1998a). There is archaeological evidence from the Scottish Borders, Suisgill (Sutherland) and North Mains (Strathallan) (Fig. 1) for the use of hand tools, such as the spade and hoe, either alone or with the ard or plough, on inferred cultivation plots between the late Neolithic and Iron Age (Barclay 1985, 1989, Halliday 1993). These techniques continued in use in the Highlands until the fourteenth century (Carter 1994). Hand-tillage may have left few surface traces, especially if alluvial soil did not require techniques such as lazy-bedding to help drainage (*cf.* Fenton 1976, Romans and Robertson 1983).

9.6.3 Marginality: adaptation or extinction?

Upland regions such as the Highlands have long been viewed as marginal areas, largely incapable of supporting viable agriculture except for extensive grazing and transhumance systems, very much on the periphery of inferred core settlement areas (*cf.* Halliday 1993, Cowley 1998). The constraints posed by geographical isolation, uneven topography, inherently poor soils, wet climate and short growing season (MacSween 1959, Fenton 1976, Bil 1990, Entwistle *et al*, 1998) have all been seen as factors enforcing environmental, economical and social marginality (*cf.* Mills and Coles 1998, Young and Simmonds 1999). This led Parry (1985) to define much of the Highlands, including the study area, as recurrently 'marginal' and 'sub-marginal' for agriculture. These views suggest that occupation in marginal areas was always discontinuous, typified by a cycle of expansion through necessity (*e.g.* population growth, social pressures) and contraction or abandonment during times of environmental stress (*cf.* Bailey 1989, Cowley 1998).

However, recent research is challenging this long-held view (*e.g.* Tipping 1998, Young and Simmonds 1995, 1999). This is highlighted by Bronze Age upland expansion in West Affric, during a period of climatic deterioration (Sections 9.4.2.2 and 9.5.1), when there is no evidence for population or land pressure in the adjacent lowlands. Indeed, as far as can be discerned from the palynological data, at Morvich there is no indication for a shortage of land which is assumed, from the established model, to be typical of a lowland 'core' settlement area. The identification of expansion/intensification phases in the lowland valley and uplands during the Bronze Age and the early Iron Age (above) may be indicative of some diffusion from lowland to upland glens, but does not provide evidence of expansion/contraction cycles inferred from core-periphery models (*e.g.* Cowley 1998).

This suggests either that Morvich was not the core area for expansion into the uplands, and thus that recent historic use of West Affric by farmers from Kintail is a more recent development (see Section 2.2), or that the core-periphery/expansion-contraction models are not applicable to this area (*cf.* Young and Simmonds 1995), where mass population movement is not evident. This indicates the need for a less negative and rigid, environmentally deterministic model, in which more flexible landscape-scale land-use networks can be recognised (Section 9.6.2.5 and below).

Long-term prehistoric and historic pastoral and arable practice at favourable sites such as Camban and Carnach Mór, which are near to the maximum altitude usually deemed viable for cultivation, contrast with the fragmentary archaeological record and documentary references to the occasional cultivation of shieling grounds (Bil 1990). This suggests that the risk or actuality of crop failure was not sufficient to prevent continued occupation and cropping. This is argued to be the result of careful site selection and husbandry techniques, enabling sustained farming during the prehistoric and historic periods. It is also essential to recognise that human response to long-term climatic change depends on the rate of environmental change relative to human generations (*cf.* Whyte 1981, Halstead and O'Shea 1989), and in most cases the palaeoclimatic data are too poorly resolved to establish this (*cf.* Anderson *et al.* 1998).

The only evidence for contraction is recorded at Camban from *c.*2330-1590 BP (2340-1500 cal

BP), suggested to result from local environmental changes which rendered the site less fertile. However, pastoral use appears to have been maintained, similar perhaps to apparent late Bronze Age abandonment at Lairg (Tipping and McCullagh 1998). The increase in charcoal at Camban may imply adaptation (*cf.* Berglund 1986), in the form of a shift to heathland management for grazing (Section 7.5.6). This is argued to reflect the resilience of the Iron Age upland farmers. Historical evidence indicates that subsistence strategies in the Highlands evolved to suit their environment and we should not assume that past farmers were any less capable of selecting the appropriate husbandry techniques to ensure continued viability (*cf.* Fenton 1976). Archaeological evidence for adaptation is evident from changes in cultivation techniques during the Iron Age at Lairg, and in fuel sources in the Northern Isles during the Iron Age and Norse period (Carter 1998a, b, Tipping and McCullagh 1998).

Long-term upland agriculture and possible adaptation to environmental change provides evidence for resilience and flexibility in dynamic communities, emphasising the dangers of environmental determinism and subjective judgements regarding marginality (*cf.* Bailey 1989, Young and Simmonds 1995, 1999, Barber 1997). Although there may have been less room for experimentation and change than on lowland farms (Hughes and Huntley 1988), the present data suggest the need to question the blanket interpretation of many upland regions, particularly the Scottish Highlands, as inherently and overwhelmingly 'marginal'. The data also emphasise the need to establish close links between palaeoenvironmental and archaeological evidence, where the latter exist (*cf.* McCullagh and Tipping 1998). There is also a clear need for more palaeoenvironmental data to see how widespread or comparable periods of expansion and contraction were, before making social, environmental or economic judgements regarding marginality, developing and testing new models for Highland settlement and land-use.

9.6.4 Implications for detecting and understanding the scale of land-use in the Highlands

The present research suggests that several factors have contributed to the lack of palynological and archaeological visibility of land-use in the Highlands, in addition to those already discussed in Sections 1.3 and 2.2.

1. The long-term use of restricted areas of more fertile soils suggests an archaeological palimpsest, which may have resulted in the selective survival of only more recent evidence (*cf.* Halliday 1993), as has been suggested by recent research on Ben Lawers (Atkinson *et al.* 1997), with evidence dating from the Mesolithic to the recent historic period.
2. Hand-tillage, the use of perishable materials and recycling of waste products (*e.g.* turf, thatching, ash, dung, bedding) to maintain fertility may have left little surface trace (Smith 1994, Simpson 1997, Simpson *et al.* 1998a, b, 1999), especially if alluvial soil did not require techniques such as lazy-bedding to help drainage (*cf.* Fenton 1976).

3. An additional factor is the dynamic floodplain environment, where fluvial processes are constantly reworking sediment. Research in Gleann Lichd indicates that river meander in a narrow section of the valley floor probably accounts for the fact that the earliest extant floodplain peats only date from 1100 BP (980 cal BP) (E. Reid, pers. comm.) (Fig. 6). Alluvial sediment deposition may both destroy and conceal earlier evidence (*cf.* Barclay 1985). These factors impose severe restrictions on the record gained from archaeological surveys.

This invisibility emphasises the value of fine spatial resolution palynological research design for the detection of small-scale activity, which is heightened by the contrast between the present and previous palynological research in the Highlands. The evidence for careful site selection since prehistory suggests that the present palynological data could be used to develop a successful predictive site location strategy for future palaeoecological and archaeological research in the Highlands.

CHAPTER 10: Conclusions and future research

10.1 Fulfilment of aims

1. To establish fine spatial and temporal resolution records of Holocene vegetation history.

Although it is difficult to assess pollen source areas in the fossil record, clear differentiation between the present pollen sequences and the relatively small spatial extent of many of the landform units sampled suggest that the diverse range of communities inferred from the palynological data reflect the vegetational mosaics which existed in the study region. The radiocarbon chronologies from the four study sites suggest that many of the palynological fluctuations from the small basins reflect generation-scale or shorter term vegetation dynamics within their respective landform units. These factors strengthen the ecological inferences made from the data, particularly those relating to spatial patterning across the landscape, competition interactions and mechanisms of change, as indicated below. This stresses the value of this methodological approach for furthering our understanding of past communities in this region and elsewhere (see below).

The present data indicate that *Pinus*, which has hitherto formed the focus of much previous research, was far less abundant in West Affric than may be inferred from past evidence and this has implications for the reconstruction of Highland vegetation. The present data are comparable with earlier evidence from small basin sites analysed by Kerslake (1982), but contrast markedly with the results from regional sequences which reflect a composite of many plant communities, and where inferences relating to spatial patterning and community composition are frequently problematical, particularly in the case of *Pinus* and after the mid-Holocene reduction in woodland due to a further increase in pollen source areas.

2. To establish the range of local environmental factors which control vegetation development, composition and stability.

The range of contrasts between the present pollen sites in terms of diversity, composition and stability can be closely related to local environmental mosaics arising from differences in hydrology, geomorphology, pedogenesis, exposure and altitude, grazing and anthropogenic disturbance. The most marked contrast is probably that between the acidophilous *Pinus*-heath communities on moraine-derived soils, which appear to have been relatively fragile, affected most markedly by inferred climatic shifts, and the mixed deciduous woodland and herbaceous vegetation established on alluvial sediments, which appear to have been adapted to frequent, low intensity disturbance. Flushing sustained a higher soil nutrient and base-status which, with the disturbance regime, maintained high diversity and possibly greater stability. The upland-lowland contrast is most marked in terms of exposure and pedogenic processes, which appear to have conferred greater stability in the lowlands. Such environmental controls are rarely evident in previous research, as the many of the environmental factors appear from the present evidence to have operated at localised scales and thus cannot be discerned in regional-scale diagrams which reflect predominantly communities such as those around Torran Beithe.

3. **To establish the impact of these local environmental factors on the spatial and temporal patterns of the mid-Holocene woodland decline.**

Although it is now recognised that mid-Holocene vegetational changes across the western Highlands were by no means synchronous, the present data suggest that the nature of environmental change and the spatial and temporal response of plant communities was far more complex than has been previously recognised. The results from upland West Affric in particular suggest that several climatic fluctuations occurred between *c.*4400 and 3600 BP (4920-3890 cal BP), and that the nature and severity of change was exacerbated or mitigated by local environmental conditions, particularly soil status, but also grazing pressure, burning and other anthropogenic interference. However, the relative impact and distribution of each of these factors appears to have varied at a local scale, and this period thus requires further spatially constrained pollen analytical research.

The demise of *Pinus* and expansion of blanket peat evident in previous research are by no means characteristic of the region as a whole. While the marginal soils to which *Pinus* appears to have been confined may have rendered boreal woodlands vulnerable to climatic deterioration and additional stresses caused by grazing or burning, regeneration in upland deciduous woods was also affected by these factors. Indeed the higher nutrient and base-status of the soils on which deciduous woodlands were located appear to have made them the focus of anthropogenic and grazing activities from the late Neolithic and early Bronze Age onwards, as indicated below.

4. **To address some of the ambiguities associated with the inference of anthropogenic activity through fine spatial and temporal pollen analyses.**

The great contrast between favourable upland sites in Glen Affric and published pollen diagrams from the Highland region suggests that human activity, particularly the extent of cultivation, is very poorly resolved and may be under-represented across the whole upland region. More detailed analyses covering the last 3000 years are clearly needed (*cf.* Sections 1.3.4 and 1.13). The data from Camban and Carnach Mór suggest that penetration into the Highland massif may have occurred more frequently and at an earlier date than has been thought. Sites in the Highland region are unsuited to the detection of small-scale activity, particularly where the extent of better land in the uplands is limited. This has probably resulted in the apparent similarity between the Affric data and lowland or foothill sites around the Highland uplands, where pollen data reflect activity on more extensive tracts of better quality ground, with consequent records of long-term and larger-scale activity. However, the absence of suitable niches for traditional 'anthropogenic indicator' herbs needs to be recognised as a complicating factor in the inference of grazing or anthropogenic activity on wet heaths and bogs. In this respect charcoal records and additional palynological data from more favourable sites nearby attain greater importance.

These factors urge against making sweeping statements about anthropogenic activity in upland regions on the basis of a database clearly unsuited to such inferences, as indicated by the results from Torran Beithe. The present results also emphasise the need for critical assessment of the criteria used to infer human activity, particularly of 'anthropogenic indicator' herbs, since the role of natural disturbance, which is clear from the ecological literature, is frequently overlooked in palynological research.

Critical interpretation is especially necessary to establish the relative intensity of land-use, particularly during periods of environmental stress, such as the mid-Holocene, when it appears that even slight grazing or anthropogenic pressure may have been sufficient to upset the fragile balance between woodland regeneration and herbaceous cover. As indicated above, this period of the Holocene would benefit from further fine spatial resolution pollen analyses, with the more consistent quantification of charcoal.

Assumptions of marginality and environmental determinism relating to human activity in upland glens are clearly unjustified and highly misleading in our attempts to understand past human communities. The capability of upland farmers from prehistory through to the recent historic period and their understanding of the Highland environment has clearly been overlooked, perhaps reflecting our own subjective judgements and distance from food production and subsistence strategies. However, the present results suggest that, with careful research design, palynology can be successfully developed into a predictive tool for the elucidation of distant and more recent activities in the uplands (*cf.* Whittington and Edwards 1994).

10.2 Assessment of the methodology and future work

The present research design, using small peat basins to obtain fine spatial resolution records which are sensitive indicators of vegetation composition and dynamics, has the potential to meet many of the challenges faced by palynologists, not only in the Highland region. This includes fostering successful collaboration and greater understanding between palaeoecologists, archaeologists and ecologists, since the fine spatial and temporal resolution attainable from the present research methodology enables data to be generated at scales which are directly applicable to ecological evidence and human understanding, in contrast with regional-scale composite records from larger pollen sites.

Sites such as Morvich, whilst perhaps being too small to provide sufficient information on vegetation history and land-use in the extralocal pollen source area, have the potential to contribute to ecology by generating sensitive long-term records of vegetation composition, competition interactions, dynamics and environmental controls (*cf.* Bradshaw 1988, Bradshaw and Hannon 1992). This type of site is also necessary to establish the palynological signal for natural and potentially managed woodland dynamics.

However, more regional, rather than national or more distant palaeoclimatic records are also needed to understand the impact of wider climatic gradients on vegetation development, particularly during periods of complex change, such as the mid-Holocene. Fine spatial resolution pollen records and palaeoclimatic data are also necessary to resolve the complex interplay between regional climatic, local anthropogenic and environmental factors during this period.

Fine spatial resolution pollen records can also foster closer links between palynologists and archaeologists, particularly in the Highland region where the upstanding archaeological record is poor. The present evidence for careful site selection by upland farmers throughout the later Holocene may enable sites of past occupation to be located, and human responses to the environment to be productively examined. The use of multiple coring techniques or three-dimensional palynological reconstruction (*cf.* Turner 1975, Whittington *et al.* 1991) may also prove to be a valuable means of reconstructing past land-use on and around the small 'islands' of fertile upland soil, particularly where archaeological evidence is absent.

The technique thus provides a large amount of new data regarding vegetation history and land-use in the Highlands, identifying many uncertainties in the established database for the region. This methodological approach has the potential to contribute greatly to our understanding of palaeoecology, neoecology and human activity on a much wider geographical scale.

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Table 1. Summary of the evidence for settlement and land-use in and around Glen Affric and Kintail. See Figure 2 for locations; symbols in brackets refer to map: closed = settlement/land-use, open = burial/ ritual monuments.

Inferred period	**Evidence**	**Topographic location**
Neolithic (●/○)	Cup-marked standing stones, Strath Croe & Guisachan (DES 1987)	Edge of the floodplain strath
	Hengiform enclosure, Glen Shiel	Head of glen & L. Duich
	Chambered cairn, Gleann Beag	Above river
Bronze Age (■/□)	Settlement:	
	Hut circles in East Affric, Culligran, Strathglass and Glenstrathfarrar (DES 1990); with field system (clearance cairns and field dyke) in E. Affric (DES 1987)	Gravel terrace above floodplain, hillside above river
	Burial monuments:	
	1. Corrimony passage grave, cup-marked cap-stone (Piggott 1956) & burial mound 30 m to NE (DES 1989)	Floodplain of R. Enrick
	2. Cist enclosed by cairn & (1882) by standing stones (Jolly 1882), Knockfin, East Affric	Floodplain
Iron Age (▲/△)	Settlement:	
	Round houses at Inchnacroe (Kintail), Culligran (Strathglass & Strathfarrar), Eskdale Forest; some with field systems (dykes, clearance cairns, cultivation terraces, field boundaries (DES 1989, Wordsworth & Harden 1997)	Edge of valley floor, river terrace, hillsides above valley, uplands
	Brochs, duns and forts:	
	1. Brochs in Glenelg, Strathglass	On or above river/loch
	2. Duns in Strath Croe, Strathglass, Strathfarrar	Above river/floodplain
	3. Forts in East Affric, possibly Guisachan, Glen Shiel, on R. Enrick	Above river
	Other:	
	Site of souterrain, Glen Shiel, possible crannog, Glen Shiel	Above river, high altitude lochan (*c.*720 m OD)
Pictish and Medieval (▼/▽)	1. St. Dudhthach's church (remains), 10th century	Head of L. Duich,
	2. ?Mony's Stone & Char's Stone, nr Corrimony, E of Strathglass	Edge of floodplain, gentle hill above river
	3. Placename evidence for Norse influence along the west coast (Crawford 1987, Ritchie 1993)	Coastal fringe
Post-Medieval & historic (♦/◊)	1. Numerous ruins and structures interpreted as shielings, farmsteads and sheepfolds in Affric, Guisachan, Strathglass, Strath Croe, including turf-built structures in W. Affric (see Wordsworth 1995, Wordsworth & Harden 1997).	On valley floor & lower hillslopes
	2. Many plots of rig/fields marked in Strath Croe and Glen Shiel on Roy's Military Map (1855)	Valley floors
	3. Corn-drying kiln, Strath Croe	
	4. Lazy-beds, Strathglass (DES 1989)	Hillside above river
	5. Route & drove road from W to Inverness passed through Affric before the Glen Shiel military road (Haldane 1952, Wordsworth & Harden 1997)	Linking upland and inland glens with coastal lowlands

Table 2. Estimates of pollen source area in the literature.

Reference (data source)	**Relative pollen source/site size**	**Source area estimate (radius)**
Tauber (1965) (estimated)	Under canopy:	
	50%	250 m
	75%	≤ 5 km
	5%	5-10 km
	Edge effect:	
	At 500 m 50% from	>7 km
	At 1 km 50% from	>10 km
	At 5 km 50% from	>30 km
Janssen (1966, 1973) (empirical)	Local	<10 - 100 m
	Extralocal	100 m - 1 km
	Regional	1 - 1000 km
	Extraregional	10^3 - 10^7 km
Tauber (1977) (empirical)	Trunk space component	<200 m (60% pollen)
	Above canopy component	Within *c.*1000 m (*c.*35%)
	Lake surface deposition	200-400 m (includes *c.*5% 'rainout' pollen)
	Waterborne component	Too distorted (*c.*50%)
Jacobson and Bradshaw (1981) (estimated)	Local	<20 m of basin edge
	Extralocal	20-several hundred m
	Regional	Greater distances
Prentice (1985) (simulated)	Local	Within-forest sites (moss polsters)
	Major increase in source area	Within-forest sites to small basins
	Extralocal & regional	Medium-sized basins
Fossitt (1990) (estimated)	Local (small lochs 1.0-1.5 ha, *i.e.* radius *c.*50-60 m)	Within catchment, max. radius = 500 m from shore
	Regional	Outside local catchment, but within island
	Long-distance	Off-island
Jackson (1990, 1994) (empirical)	lakes (0.1-0.5 ha, *i.e.* radius *c.*20-40 m)	minimum c.1000 m for assemblages dominated by *Pinus*, *Betula* and *Quercus*
Sugita (1994, 1998) 'relevant' source area (supplies 30-45% total pollen) (simulated)	forest hollows (radius = 2 m)	50-100 m
	small lakes (r = 50 m)	300-400 m
	medium lakes (r = 250 m)	600-800 m
	large lakes (r = 750 m)	little variation (*i.e.* regional)
Jackson and Wong (1994) (empirical)	30 moss polsters beneath closed forest canopy compared with vegetation within 20 m radius	25-90% tree pollen derives from >20 m radius.
Jackson and Kearsley (1998) (empirical)	60 moss polsters beneath closed forest canopy, compared with vegetation within 120 m radius	Improved model fit with vegetation sampling radius increased from 20 m (above) to 120 m
Calcote (1995) 'relevant source area' (supplies 40-50% total pollen) (empirical)	small forest hollows (radius *c.*2.5 m)	*c.*50-100 m
Broström *et al.* (1998) (empirical)	22 lakes with radii of 5-250 m (average *c.*100 m)	*c.*1000 m NB Includes open, semi-open and forested landscapes
Sugita *et al.* (1999) 'relevant source area' (simulated)	Both *c.*5 m small hollows & *c.*100 m radius lakes	*c.*800 m (open landscapes, 60-80% cultivated/pastoral) *c.*1000 m (semi-open landscapes, 50-60% forested)

Table 3. Basin characteristics, landscape setting and estimated pollen source area of sampling sites in Glen Affric. NB source area estimates are based on pollen representation beneath a closed canopy.

Site	Basin diameter and morphology	Landform unit/landscape topography/altitude	Hydrological influence	Estimated source area (radius under a canopy)
Torran Beithe (TOR)	• enclosed bedrock basin • surface diameter 56 m (r = 28 m) • basal diameter 8 m (r = 4 m)	• landform unit 2a • undulating lower hillslopes • 265 m OD	No - minimal	100-300 m[1], nearer 50-100 m at the base
Carnach Mór (CAR)	• infilled river channel • *c.*10 m (r = 5 m)	• landform unit 4a • junction between flat valley floor and base of undulating hillslopes • 250 m OD	Yes - flooding, runoff	50-200 m[2], but increased by hydrological input
Camban (CAM)	• bedrock basin in peat over alluvial fan • *c.*20 x 40 m (r = *c.*15 m)	• landform unit 3 • flushed hillslope • narrow, steep-sided valley • 307 m OD	Yes - runoff	50-200 m[2], but increased by hydrological inputs
Morvich (MOR)	• bedrock basin • 5 m (r = 2.5 m)	• landform unit 2b • mouth of rocky gully • junction between wide, flat valley floor and rising, rocky hillslopes • 23 m OD	No - minimal	50-100 m

[1] Estimated between small hollow (radius = 2 m, source area = 50-100 m) and small lake (radius = 50 m, source area = 300-400 m) (Sugita 1994).

[2] Estimated as slightly greater than small hollow (radius = 2 m), but less than a small lake (radius = 50 m) (Sugita 1994).

Table 4. Function of chemical reagents used during pollen processing (from Faegri and Iversen 1989, Moore *et al.* 1991).

Chemical reagent	**Function**
10% Hydrochloric acid (HCl)	1. Remove calcium carbonate. Necessary before HF treatment. Here, used mainly to ensure dissolution of Lycopodium tablets, as sediment was not calcareous. 2. Remove silicofluorides produced during HF treatment.
10% Potassium hydroxide (KOH)	1. Break up peat matrix 2. Dissolve humic materials, producing dark brown solution. 3. Neutralise any residual acid from acetolysis.
10% Hydrofluoric acid (HF)	Remove silica.
Glacial acetic acid	Dehydrate organic material prior to addition of acidic reagent.
Acetolysis mixture (9 parts acetic anhydride:1 part concentrated sulphuric acid)	Remove cellulose, leaving slightly darkened sporopollenin shell of pollen and spores.
Safranin	Stain palynomorph exine.
Tertiary-butyl alcohol (TBA) or 2-methylpropan-2-ol tert-butanol	Dehydrate sample for permanent mounting
Silicone oil	Fluid mounting medium. Preferable to glycerine as it allows grains to be turned under cover slip and does not swell grains.

Table 5. Criteria for cereal-type pollen identification. Following Anderson (1979) and Dickson (1988).

Group	**Annulus diameter (µm)**	**Mean pollen size (µm)**
Wild grass group (Poaceae anl-D<8 µm)	<8 µm	<37 µm
Hordeum group	8-10 µm	32-45 µm
Avena/Triticum group	>10 µm	>40 µm
Poaceae anl-D > 8 µm	>8 µm	<37 µm
Poaceae >37 µm	<8 µm	>37 µm

Table 6. Pollen deterioration classes and inferred causal mechanisms.

Deterioration	**Cause(s)**
Mechanical damage (breakage and crumpling)	• breakage - pollen preparation techniques (Cushing 1964) • physical abrasion or compression in minerogenic sediment (Cushing 1964, Birks 1970), but the presence of minerogenic sediment does not always result on deterioration (Lowe 1982) • redeposition/inwashing of soil/sediment (Lowe 1982, Tipping 1995a)
Corrosion	• biochemical (microbial) oxidation, under aerobic conditions (Havinga 1964, 1984, Cushing 1964, 1967) • chemical oxidation, causing secondary pitting (Brooks & Elsik 1974, cited in Berglund & Ralska-Jasiewiczowa 1986)
Degradation (amorphous grains)	• aeration and chemical oxidation (Lowe 1982, Berglund & Ralska-Jasiewiczowa 1986) • physical abrasion or compression, especially in minerogenic sediment (Cushing 1964); but also see above (Lowe 1982) • long-term deterioration; thus possible contrast between Holocene and late-glacial minerogenic sediments (Lowe 1982) • residual soil pollen (Tipping 1995a, Tipping *et al.* 1994)

Table 7. Sediment stratigraphy of the Torran Beithe sequence.

Depth (cm)	Description
0-4	Unhumified, elastic *Sphagnum* peat; Tb4 Th+
4-13	Slightly darker and more humified *Sphagnum* peat with fine and coarser roots; Tb2 Th2
13-40	Yellow-brown, poorly humified peat, with gradually decreasing *Sphagnum* and increasing roots and amorphous component; Dh+ Tb3/0 Th1/3 Sh+/1
40-87	Dark brown, moderately humified homogeneous peat becoming slightly lighter and less humified from 43 cm; Th1 Sh3
87-180	Dark brown, well humified herbaceous peat; Dg1 Tb+ Th1 Sh2
180-234	Dark brown, well humified herbaceous peat; Dg2 Tb+ Th+ Sh2
234-263	Black, well humified herbaceous peat with roots, especially at 242-244 cm; Dg2 Tb+ Th1 Sh1
263-271	Black, moderately humified fibrous sedge peat with lignified root fragments; Dl+ Dg+ Tb1 Th3
271-282	Black, moderately humified homogeneous herbaceous peat; Dg1 Tb1 Th1 Sh1
282-286	Black, well humified moss peat; Dg1 Tb2 Th+ Sh1
286-291	Black, well humified herbaceous peat with root mat; Dg+ Tb1 Th3
291-304	Black, well humified homogeneous moss peat; Tb2 Th+ Sh2
304-315	Black, moderately humified, fibrous sedge peat; Dg+ Tb+ Th3 Sh1
315-326	Black, moderately humified peat; Dh1 Tb1 Th1 Sh1
326-347	Black, poorly humified sedge leaf peat; Dg2 Th2 Sh+
347-383	Black, moderately humified herbaceous peat with *Pinus* bark; Dl+ Dh1 Dg+ Tb+ Th2 Sh1
383-390	Black, moderately humified, coarser Cyperaceae peat; Dh2 Dg+ Tb+ Th2 Sh1
390-395	Black, well humified herbaceous peat with *Pinus* bark fragments; Dh2 Dg1 Th1
395-398	Black, well humified stiff, homogeneous silty mud/fen peat with mica flecks; Ag1 Dl+ Dh1 Sh2
398-403	Black, stiff silty amorphous mud with mica flecks; Ag1 Sh3
403	Thin inwash band 2-4 mm thick of silt and fine sand, present in 1 overlapping core only; Ag2 Ga2
403-406	Black, well humified amorphous mud/peat; Ag1 Ga1 Sh2
406-408	Main inwash, slanting; Ag2 Ga2
408-419	Black, well humified stiff, sandy amorphous mud; Ga1 Ld3 Dl+ Tb+
419-434	Black, amorphous organic mud with sedge leaves, fine roots, sand and mica flecks; Ga+ Ld2 Dh1 Th1
434-462	Black, silty stiff amorphous gyttja and lake mud with mica flecks and some roots from 434-442 cm; Ag1 Ld3 Dl+ Th+

Table 8. Radiocarbon assays from Torran Beithe.

Lab. Code	Depth (cm)	Age (^{14}C BP)	Age (cal BP)	Age (cal BC/AD)	δ^{13}C (± 0.1 ‰)
AA-28203	462	8775 ± 80	1σ - 9892-9595 2σ - 9963-9500	1σ - cal BC 7942-7645 2σ - cal BC 8013-7550	7.0
AA-28204	416	7205 ± 65	1σ - 8063-7921 2σ - 8123-7840	1σ - 6113-5971 2σ - 6173-5890	49.0
AA-28205	400	6650 ± 55	1σ - 7536-7428 2σ - 7553-7391	1σ - 5586-5478 2σ - 5603-5441	50.0
AA-28206	372	6290 ± 65	1σ - 7227-7095 2σ - 7320-7017	1σ - 5277-5145 2σ - 5370-5067	53.3
AA-28207	300	5295 ± 50	1σ - 6175-5953 2σ - 6197-5931	1σ - 4226-4004 2σ - 4248-3982	44.7
AA-28208	192	3765 ± 45	1σ - 4222-3997 2σ - 4263-3981	1σ - 2273-2048 2σ - 2184-2032	19.3
AA-28209	140	2315 ± 45	1σ - 2348-2321 2σ - 2357-2157	1σ - 399-372 2σ - 408-208	43.4
AA-28210	80	1250 ± 45	1σ - 1255-1083 2σ - 1280-1061	1σ - 695-867 2σ - 670-889	25.8
AA-28211	56	410 ± 40	1σ - 507-339 2σ - 518-319	1σ - cal AD 1443-1611 2σ - cal AD 1432-1631	41.0
AA-28212	20	modern	-	-	48.0

Table 9. Temporal resolution of data from Torran Beithe. ^{14}C and calibrated ages rounded to nearest one; temporal resolution and accumulation rates rounded to one decimal place.

Depth (cm)	Sampling interval (cm)	Age range (^{14}C BP)	Age range (cal BP)	Resolution (^{14}C years/ sampling interval)	Resolution (cal years/ sampling interval)	Sediment accumulation rate (^{14}C years/cm)	Sediment accumulation rate (cal years/cm)
0-5	5	0-37	0-44	36.6	43.6	7.3	8.7
5-9	4	37-66	44-78	29.3	34.9	7.3	8.7
9-12	3	66-88	78-105	22.0	26.1	7.3	8.7
12-20	4	88-146	105-174	29.3	34.9	7.3	8.7
20-20.5	0.5	146-150	174-179	3.7	4.4	7.3	8.7
20.5-24.5	4	150-179	179-214	29.3	34.9	7.3	8.7
24.5-32	7	179-234	214-279	54.9	65.4	7.3	8.7
32-56	4	234-410	279-488	29.3	34.9	7.3	8.7
56-80	4	410-1250	488-1171	140.0	113.8	35.0	28.5
80-92	4	1250-1463	1171-1405	71.0	77.9	17.8	19.5
92-140	8	1463-2315	1405-2339	142.0	155.7	17.8	19.5
140-164	8	2315-2984	2339-3157	223.1	272.8	27.9	34.1
164-188	4	2984-3654	3157-3976	111.5	136.4	27.9	34.1
188-192	2	3654-3765	3976-4112	55.8	68.2	27.9	34.1
192-196	2	3765-3822	4112-4185	28.3	36.3	14.2	18.1
196-220	4	3822-4162	4185-4620	56.7	72.6	14.2	18.1
220-284	8	4162-5068	4620-5782	113.3	145.2	14.2	18.1
284-300	4	5068-5295	5782-6072	56.7	72.6	14.2	18.1
300-372	4	5295-6290	6072-7202	55.3	62.8	13.8	15.7
372-400	4	6290-6650	7202-7495	51.4	41.9	12.9	10.5
400-404	4	6650-6789	7495-7610	138.8	114.8	34.7	28.7
404-414	10	6789-7136	7610-7897	346.9	286.9	34.7	28.7
414-416	2	7136-7205	7897-7954	69.4	57.4	34.7	28.7
416-432	4	7205-7751	7954-8575	136.5	155.1	34.1	38.8
432-448	8	7751-8297	8575-9195	273.0	310.3	34.1	38.8
448-460	4	8297-8707	9195-9660	136.5	155.1	34.1	38.8
460-462	2	8707-8775	9660-9740	68.0	80.0	34.0	40.0

Table 10. Summary of local pollen assemblage zones and sub-zones for Torran Beithe.

Local pollen assemblage zones		**Depth (cm)**	**Sub-zone**		**Depth (cm)**	**Age (^{14}C BP)**	**Age (cal BP)**
TOR3	*Calluna vulgaris*-Cyperaceae	0-186	TOR3c	Cyperaceae-Poaceae-*Calluna*	0-28	0-195	0-150
			TOR3b	*Calluna*-Cyperaceae	28-82	195-1285	150-1200
			TOR3a	*Calluna*-Cyperaceae-*Pinus*	82-186	1285-3600	1200-3890
TOR2	*Pinus sylvestris*-*Betula*	402-186	TOR2b	*Pinus*-*Calluna*-*Betula*	186-377.5	3600-6360	3890-7230
			TOR2a	*Pinus*-*Betula*-Cyperaceae	402-377.5	6360-6720	7230-7540
TOR1	*Betula*-*Corylus avellana*-type	462-402	TOR1b	*Betula*-*Pinus*-*Calluna*-*Corylus*	436-402	6720-7890	7540-8590
			TOR1a	*Betula*-*Corylus*	462-436	7890-8775	8590-9740

Table 11. Dimensions of cereal-type and large Poaceae pollen grains from Torran Beithe. Italics denote minimum size estimates from damaged or partially concealed grains.

Depth (cm)	**Age BP (cal BP)**	**Annulus diameter (µm)**	**Grain length x width (µm)**	**Average diameter (µm)**	**Identification**
0	present	10.0	41.25 x 31.25	36.25	*Hordeum* group
12	90 (105)	9.375	*35.0* x 30.o	*32.5*	*Hordeum* group
		8.75	30.0 x 27.5	28.75	Poaceae anl-D > 8 µm
56	410 (490)	10.0	*37.5 x 37.5*	*39.375*	*Hordeum* group
190	3710 (4040)	8.75	31.25 x *32.5*	*31.875*	Poaceae anl-D > 8 µm

Table 12. Summary of charcoal data from Torran Beithe.

Age of charcoal peaks	**Relative magnitude**
7610-6790 BP (8370-7580 cal BP)	low, spread
5240 BP (5970 cal BP)	Moderate
5070 BP (5820 cal BP)	Moderate/high
4280 BP (4840 cal BP)	Moderate
3940-3880 BP (4410-4340 cal BP)	High
3710-3430 BP (4030-3660 cal BP)	high, spread
2980-2170 BP (3200-2140 cal BP)	Moderate continuous 'background', very high peak at 2170 BP (2140 cal BP)
1890-1750 BP (1830-1660 cal BP)	very high, broad peak
1250 BP (1170 cal BP)	very high
1250-230 BP (1170-290 cal BP)	low, continuous 'background'
230-120 BP (290-130 cal BP)	very high, single spectra peaks

Table 13. Results of charcoal size class regression analyses at Torran Beithe.

Charcoal size classes	**R^2**	**Charcoal size classes**	**R^2**
10-25 µm *vs.* 26-50 µm	0.91	26-50 µm *vs.* 51-75 µm	0.82
10-25 µm *vs.* 51-75 µm	0.80	26-50 µm *vs.* >75 µm	0.15
10-25 µm *vs.* >75 µm	0.65	51-75 µm *vs.* >75 µm	0.15

Table 14. Sediment stratigraphy of the Carnach Mór sequence.

Depth (cm)	Description
0-6	Fresh *Sphagnum* with Poaceae and *Juncus*/Cyperaceae stems, Th1 Tb3
6-15.5	Poorly humified peat with coarse rhizomes and *Sphagnum*, Dh+ Tb2 Th2
15.5-20	Less *Sphagnum*, finer roots, Tb1 Th3
20-26.5	Becoming more humified with finer roots, Dh+ Th4 Sh+
26.5-31.5	Higher proportion of humified material, Dh+ Th3 Sh1
31.5-42.5	Coarser peat with tough roots, Dh1 Tb1 Th2
42.5-46.5	Coarse peat with roots and some *Sphagnum*, Tb1 Th3 Sh+
46.5-50	As above, with less *Sphagnum* and increased humification, Tb+ Th3 Sh1
50-93.5	Roots abundant, mica frequent, Ga+ Dh1 Th3
93.5-95.5	Inwash band in peat, mica abundant, Ga3 Th1 Sh+
95.5-134	Becoming more humified, mica common, Ga+ Dh1 Th2 Sh1
134-150	Drier peat, mica rare with 5 mm band at 135 cm, Ga+ Dh+ Th1 Sh3
150-162	Drier and less humified peat, mica common, Ga+ Dh+ Th3 Sh1
162-179	Gradual change to more humified peat with mica common, Ga+ Dh+ Th2 Sh2
179-224	Mica infrequent, twig *c.*1 cm diameter at 221-224 cm, Ga+ Dl+ Dh+ Th1 Sh3
224-236	Coarse root mat, mica infrequent, small twig *c.*1 cm long by 3 mm diameter, Ga+ Dl+ Th3 Sh1
236-245	Peat of roots and humified material, mica occasional, Ga+ Dh+ Th2 Sh2
245-255	Highly humified, homogeneous peat, mica rare, Ga+ Sh4
255-263	Inwash band, mica abundant, Ga2 Sh2
263-281	Highly humified, amorphous, plastic peat, sticky, mica rare, Ga+ Dh+ Th+ Sh4
281-295	Highly humified, sticky peat with wood fragments and small twigs (2-3 mm diameter), mica rare, Dl1 Sh3
295-304	Coarser, slightly less well humified peat, wood fragments and twigs, mica occasional, Ga+ Dl1 Th1 Sh2
304-306	Woody inwash band, mica frequent, Ga1 Dl1 Th+ Sh2
306-310.5	Coarse, woody peat with wood flakes and 1.5 cm diameter twigs, Ga+ Dl2 Th1 Sh1
310.5-317	Inwash band with organic sediment, mica abundant, twigs present, Ga1 Dl+ Th2 Sh1
317-334	Well humified, amorphous peat with wood flakes and *c.*1 cm diameter twigs, mica rare, Ga+ Dl1 Th2 Sh1
334-341.5	Amorphous, plastic peat with wood, slightly sticky, 2-3 mm diameter twig, mica occasional, Ga+ Dl1 Th1 Sh2
341.5-343	Inwash in highly humified, sticky peat, Ga1, Th+ Sh3.
343-348	Slightly sticky, amorphous peat, mica occasional, Ga+ Th1 Sh3
348-377.5	Highly amorphous peat with occasional twigs and mica, Ga+ Dl+ Th+ Sh4
377.5-381.5	Fibrous mat in amorphous peat, mica rare, Ga+ Dh+ Th2 Sh2
381.5-387	Amorphous peat with infrequent mica, Ga+ Dl+ Th1 Sh3
387-434	Amorphous peat with frequent wood, mica rare, Dl+ Th1 Sh3
434-443	Quite dry, plastic peat with *Sphagnum*, twigs and coarse roots as 224-230 cm, with monocotyledon leaf sheath (?*Phragmites*), mica rare, Dl+ Dh+ Tb1 Th1 Sh2
443-454	Increased mica in quite dry, well-humified, plastic peat, Ga+ Dh+ Th1 Sh3
454-462	Less well-humified peat, quite dry, mica frequent, Ga1 Th1 Sh2

Table 15. Radiocarbon assays from Carnach Mór.

Lab. Code	**Depth (cm)**	**Age (^{14}C BP)**	**Age (cal BP)**	**Age (cal BC/AD)**	**$\delta^{13}C_{PDB}$ (± 0.1 ‰)**
AA-32248	462	9470 ± 75	1σ - 10796-10365 2σ - 10902-10227	1σ - 8846-8415 cal BC 2σ - 8952-8277 cal BC	-27.8
AA-32249	340	7390 ± 100	1σ - 8310-8007 2σ - 8367-7945	1σ - 6360-6058 cal BC 2σ - 6417-5995 cal BC	-27.4
AA-32250	290	5965 ± 70	1σ - 6882-6730 2σ - 6988-6663	1σ - 4932-4780 cal BC 2σ - 5038-4713 cal BC	-28.0
AA-32251	248	4100 ± 55	1σ - 4811-4456 2σ - 4826-4420	1σ - 2861-2506 cal BC 2σ - 2876-2470 cal BC	-26.7
AA-32252	214	3895 ± 70	1σ - 4415-4158 2σ - 4516-4091	1σ - 2465-2208 cal BC 2σ - 2566-2141 cal BC	-27.4
AA-32253	180	2955 ± 45	1σ - 3206-3010 2σ - 3254-2955	1σ - 1257-1061 cal BC 2σ - 1305-1006 cal BC	-27.5
AA-32254	112	1690 ± 45	1σ - 1685-1532 2σ - 1702-1509	1σ - cal AD 265-418 2σ - cal AD 248-441	-26.1
AA-32255	78	810 ± 60	1σ - 759-668 2σ - 899-654	1σ - cal AD 1191-1282 2σ - cal AD 1051-1296	-27.6
AA-32256	49	400 ± 45	1σ - 506-331 2σ - 518-312	1σ - cal AD 1444-1619 2σ - cal AD 1432-1638	-27.8

Table 16. Temporal resolution of data from Carnach Mór. ^{14}C and calibrated ages rounded to nearest one; temporal resolution and accumulation rates rounded to one decimal place.

Depth (cm)	**Sampling interval (cm)**	**Age range (^{14}C BP)**	**Age range (cal BP)**	**Resolution (^{14}C years/ sampling interval)**	**Resolution (cal years/ sampling interval)**	**Sediment accumulation rate (^{14}C years/cm)**	**Sediment accumulation rate (cal years/cm)**
0-4	4	0-33	modern	32.7	38.9	8.2	9.7
4-8	2	33-65	modern	16.3	19.5	8.2	9.7
8-24	4	65-196	modern-154	32.7	38.9	8.2	9.7
24-48	2	196-392	154-473	16.3	19.5	8.2	9.7
48-49	1	392-400	473-477	8.2	9.7	8.2	9.7
49-52	3	400-442	477 504	42.4	23.6	14.1	7.9
52-78	2	442-810	504-705	28.3	15.7	14.1	7.9
78-96	2	810-1276	705-1214	51.8	50.4	25.9	25.2
96-112	4	1276-1690	1214-1561	103.5	100.7	25.9	25.2
112-180	4	1690-2955	1561-3096	74.4	90.3	18.6	22.6
180-212	4	2955-3840	3096-4234	110.6	144.6	27.6	36.1
212-216	4	3840-3931	4234-4406	67.4	86.4	16.8	21.6
216-248	4	3931-4100	4406-4564	24.1	28.1	6.0	7.0
248-288	4	4100-5876	4564-6722	177.6	216.3	44.4	54.1
288-292	4	5876-6136	6722-7007	145.8	160.1	36.5	40.0
292-304	4	6136-6364	7007-7230	114.0	103.9	28.5	26.0
304-312	8	6364-6706	7230-7530	228.0	207.8	28.5	26.0
312-328	4	6706-7048	7530-7861	114.0	103.9	28.5	26.0
328-336	8	7048-7390	7861-8134	228.0	207.8	28.5	26.0
336-340	4	7390-7458	8134-8239	114.0	103.9	28.5	26.0
340-368	4	7458-7867	8239-8571	68.2	76.7	17.0	19.2
368-376	8	7867-8072	8671-8983	136.4	153.3	17.0	19.2
376-384	4	8072-8140	8983-8994	68.2	76.7	17.0	19.2
384-392	8	8140-8345	8994-9374	136.4	153.3	17.0	19.2
392-400	4	8345-8413	9374-9402	68.2	76.7	17.0	19.2
400-408	8	8413-8618	9402-9526	136.4	153.3	17.0	19.2
408-440	4	8618-9095	9526-10032	68.2	76.7	17.0	19.2
440-448	8	9095-9231	10032-10195	136.4	153.3	17.0	19.2
448-460	4	9231-9436	10195-10400	68.2	76.7	17.0	19.2
460-462	2	9436-9470	10400-10472	34.1	38.3	17.0	19.2

Table 17. Summary of local pollen assemblage zones and sub-zones from Carnach Mór.

Local pollen assemblage zone		Depth (cm)	Subzone		Depth (cm)	Age (^{14}C BP)	Age (cal BP)
CAR3	Poaceae-Cyperaceae -*Calluna*	0-178	CAR3c	Cyperaceae -*Calluna*	0-50	0-415	0-490
			CAR3b	Poaceae-*Calluna*-Cyperaceae	50-122	415-1875	490-1820
			CAR3a	Poaceae-*Myrica*-*Calluna*	122-178	1875-2920	1820-3060
CAR2	*Betula*-Cyperaceae -*Pinus sylvestris*-*Alnus glutinosa*	178-290	CAR2c	*Calluna*-Cyperaceae -*Betula*	178-214	2920-3875	3060-4280
			CAR2b	Cyperaceae -*Betula*-*Alnus*-*Pinus*	214-250	3875-4190	4280-4725
			CAR2a	*Betula*-*Pinus*-*Alnus*-Cyperaceae	250-290	4190-5950	4725-6780
CAR1	*Betula*-*Corylus avellana*-type-*Salix*	290-462	CAR1b	*Betula*-*Salix*-*Corylus*	290-444	5950-9165	6780-10045
			CAR1a	*Betula*-*Sorbus*-Cyperaceae	444-462	9165-9470	10125-10472

Table 18. Dimensions of cereal-type and large Poaceae pollen grains from Carnach Mór. Italics denote minimum size estimates from damaged or partially concealed grains.

Depth (cm)	Age BP (cal BP)	Annulus diameter (μm)	Grain length x width (μm)	Mean diameter (μm)	Identification
0	present	11.25	36.875 x 36.25	36.5625	*Hordeum* group
24	200 (150)	10.0	33.75 x 32.5	33.125	*Hordeum* group
26	210 (160)	11.25	35.0 x 33.75	34.375	*Hordeum* group
28	230 (290)	11.25	38.75 x 36.25	37.5	*Hordeum* group
30	240 (290)	11.25	31.25 x 32.5	31.875	*Hordeum* group
		8.75	*? x 28.75*	?	Poaceae anl-D>8 μm
34	280 (300)	12.5	36.25 x 35.0	35.125	*Hordeum* group
		12.5	? x 31.25	?	Poaceae anl-D>8 μm
		11.25	35.0 x 33.75	34.375	*Hordeum* group
		11.25	35.0 x 33.75	34.375	*Hordeum* group
		11.25	33.75 x 31.25	32.5	*Hordeum* group
		10.0	33.75x 31.25	32.5	*Hordeum* group
		8.75	31.25 x 30.0	30.625	Poaceae anl-D>8 μm
		8.75	*? x 32.5*	?	Poaceae.anl-D>8 μm
36	290 (310)	11.25	35.0 x 35.0	35.0	*Hordeum* group
		11.25	31.25 x 31.25	31.25	Poaceae anl-D>8 μm
		10.0	35 x *31.25*	*33.125*	*Hordeum* group
		10.0	32.5 x 31.25	31.875	Poaceae anl-D>8 μm
38	310 (310)	11.25	35.0 x 35.0	35.0	*Hordeum* group
		11.25	33.75 x *33.75*	*33.75*	*Hordeum* group
		11.25	32.5 x *30.0*	*31.25*	Poaceae anl-D>8 μm
		10.625	37.5 x 35.0	36.25	*Hordeum* group
40	330 (390)	10.0	37.5 x 36.25	36.875	*Hordeum* group
42	340 (380)	11.25	31.25 x 31.25	31.25	Poaceae anl-D>8 μm
		10.625	31.25 x 32.5	31.875	Poaceae anl-D>8 μm
		10.0	*33.75 x 38.75*	*36.25*	*Hordeum* group
		10.0	37.5 x 32.5	35.0	*Hordeum* group
		10.0	*32.5* x 32.5	*32.5*	*Hordeum* group
		10.0	35.0 x 28.75	31.875	Poaceae anl-D>8 μm
		8.75	37.5 x 33.75	35.625	*Hordeum* group
		8.75	35.0 x 32.5	33.75	*Hordeum* group
		8.75	*31.25 x 32.5*	*31.875*	Poaceae anl-D>8 μm
		8.75	? x 32.5	?	Poaceae anl-D>8 μm
		8.125	*35.0 x 31.25*	*33.125*	*Hordeum* group
44	360 (350)	11.25	*36.25* x 31.25	*33.75*	*Hordeum* group
		11.25	33.75 x ?	?	Poaceae anl-D>8 μm
		11.25	33.75 x 31.25	32.5	*Hordeum* group
		11.25	30.0 x ?	30.0	Poaceae anl-D>8 μm
		11.25	32.5 x 32.5	32.5	*Hordeum* group
		10.0	37.5 x 35.0	36.25	*Hordeum* group
		10.0	*35.0 x 35.0*	*35.0*	*Hordeum* group
		10.0	35.0 x 32.5	33.75	*Hordeum* group

Table 18. Continued.

Depth (cm)	**Age BP (cal BP)**	**Annulus diameter (μm)**	**Grain length x width (μm)**	**Average diameter (μm)**	**Identification**
46	380 (470)	12.5	*41.25 x 36.25*	*38.75*	*Hordeum* group
		12.5	36.25 x 32.5	34.375	*Hordeum* group
		11.25	36.25 x 36.25	36.25	Poaceae anl-D>8 μm
		11.25	35.0 x 32.5	33.75	Poaceae anl-D>8 μm
		11.25	*29.75 x 28.5*	*29.125*	*Hordeum* group
		11.25	? (broken)	?	*Hordeum* group
		10.625	36.25 x 35.0	35.625	*Hordeum* group
		10.625	31.25 x 30.0	30.625	Poaceae anl-D>8 μm
		10.0	*36.25 x 29.75*	*33.75*	*Hordeum* group
		10.0	35.0 x 35.0	35.0	*Hordeum* group
		10.0	32.5 x 33.75	33.125	*Hordeum* group
		10.0	32.5 x 31.25	31.875	Poaceae anl-D>8 μm
		10.0	*31.25 x 31.25*	*31.25*	Poaceae anl-D>8 μm
		8.75	42.5 x 30.0	36.25	*Hordeum* group
		8.75	36.25 x 31.25	33.125	*Hordeum* group
		8.75	32.5 x 32.5	32.5	*Hordeum* group
48	390 (470)	11.25	38.75 x 35.0	36.875	*Hordeum* group
		11.25	36.25 x 23.75	30.0	Poaceae anl-D>8 μm
		11.25	35.0 x 32.5	33.75	*Hordeum* group
		11.25	33.75 x 32.5	33.125	*Hordeum* group
		11.25	32.5 x 32.5	32.5	*Hordeum* group
		10.0	37.5 x 36.25	36.875	*Hordeum* group
		10.0	33.75 x 32.5	33.125	*Hordeum* group
		10.0	33.75 x ?	?	Poaceae anl-D>8 μm
		10.0	32.5 x 33.75	33.125	*Hordeum* group
		10.0	32.5 x 31.25	31.875	Poaceae anl-D>8 μm
		10.0	31.25 x 27.5	29.375	Poaceae anl-D>8 μm
49	400 (480)	12.5	32.5 x 33.75	33.125	*Hordeum* group
		12.5	? x *37.5*	?	Poaceae anl-D>8 μm
		11.25	37.5 x 37.5	37.5	*Hordeum* group
		11.25	35 x 33.75	34.375	*Hordeum* group
		11.25	33.75 x 32.5	33.125	*Hordeum* group
		11.25	31.25 x 33.75	32.5	*Hordeum* group
		11.25	30.0 x 31.75	30.875	Poaceae anl-D>8 μm
		11.25	? x 32.5	?	Poaceae anl-D>8 μm
		11.25	? (broken)	?	Poaceae anl-D>8 μm
		10.625	30.0 x 38.75	34.375	*Hordeum* group
		10.0	36.25 x *35.0*	*35.625*	*Hordeum* group
		10.0	36.25 x 32.5	34.375	*Hordeum* group
		10.0	35.0 x 32.5	33.75	*Hordeum* group
		10.0	33.75 x 36.25	35.0	*Hordeum* group
		10.0	*33.75 x 30.0*	*31.875*	Poaceae anl-D>8 μm
		10.0	30.0 x 30.0	30.0	Poaceae anl-D>8 μm
		10.0	? x 30.0	? (broken)	Poaceae anl-D>8 μm
		10.0	? x 36.25	?	*Hordeum* group
		9.375	33.75 x 33.75	33.75	*Hordeum* group
		8.75	43.75 x 32.5	38.125	*Hordeum* group
		8.75	36.25 x 32.5	34.375	Poaceae anl-D>8 μm
		8.75	31.25 x 32.5	31.875	Poaceae anl-D>8 μm
		8.75	*30.0 x 30.0*	*30.0*	Poaceae anl-D>8 μm
		8.75	26.25 x 31.25	28.75	

Table 18. Continued.

Depth (cm)	**Age BP (cal BP)**	**Annulus diameter (μm)**	**Grain length x width (μm)**	**Average diameter (μm)**	**Identification**
52	440 (510)	12.5	? x 31.25	?	Poaceae anl-D>8 μm
		11.25	37.5 x 36.25	36.875	*Hordeum* group
		11.25	35.0 x 31.25	33.125	*Hordeum* group
		11.25	? (broken)	?	Poaceae anl-D>8 μm
		10.625	32.5 x 33.75	33.125	*Hordeum* group
		10.0	32.5 x 33.75	33.125	*Hordeum* group
		10.0	31.25 x 33.75	32.5	*Hordeum* group
		10.0	*31.25* x 33.75	*32.5*	*Hordeum* group
		10.0	? (broken)	?	Poaceae anl-D>8 μm
54	470(510)	10.625	37.5 x *31.25*	*34.375*	*Hordeum* group
58	530 (540)	11.25	32.5 x 31.25	31.875	Poaceae anl-D>8 μm
		10.0	30.0 x 35.0	32.5	*Hordeum* group
		8.75	31.25 x 31.25	31.25	Poaceae anl-D>8 μm
		8.125	35.0 x 32.5	33.75	*Hordeum* group
60	560 (540)	12.5	*41.25* x 33.75	*37.5*	*Hordeum* group
		12.5	*33.75 x 33.75*	*33.75*	*Hordeum* group
		10.0	38.75 x 33.75	36.25	*Hordeum* group
		10.0	? x 35.0	? (concealed)	Poaceae anl-D>8 μm
		9.375	35.0 x 31.25	33.125	*Hordeum* group
		9.375	33.75 x 33.75	33.75	*Hordeum* group
		8.125	36.25 x *28.75*	*32.5*	*Hordeum* group
62	580 (590)	10.0	40.0 x *36.25*	*38.125*	*Hordeum* group
		10.0	? (crumpled)	?	Poaceae anl-D>8 μm
		8.125	38.75 x *28.75*	*32.75*	*Hordeum* group
64	610 (610)	10.0	35.0 x 35.0	35.0	*Hordeum* group
		10.0	40.0 x 30.0	35.0	*Hordeum* group
66	640 (590)	12.5	42.5 x 37.5	40.0	?*Avena/Triticum* group
		10.0	38.75 x *31.25*	*35.0*	*Hordeum* group
		8.75	32.5 x *30.0*	*31.25*	Poaceae anl-D>8 μm
68	670 (650)	11.25	35.0 x 32.5	33.75	*Hordeum* group
		11.25	32.5 x 33.75	33.125	*Hordeum* group
		10.0	40.0 x 32.5	36.25	*Hordeum* group
		10.0	38.75 x *26.25*	*32.5*	*Hordeum* group
70	700 (660)	10.0	35.0 x *31.25*	*33.125*	*Hordeum* group
		8.75	*32.5 x 40.0*	*36.25*	*Hordeum* group
		8.75	*31.25 x 30.0*	*30.625*	Poaceae anl-D>8 μm
72	730 (660)	10.0	45.0 x 32.5	38.75	*Hordeum* group
74	750 (670)	10.0	36.25 x *28.75*	*32.5*	*Hordeum* group
		8.75	33.75 x *27.5*	*30.625*	Poaceae anl-D>8 μm
76	780 (680)	11.25	41.25 x 33.75	37.5	*Hordeum* group
		11.25	33.75 x *26.25*	*30.0*	Poaceae anl-D>8 μm
		11.25	31.25 x 31.25	31.25	Poaceae anl-D>8 μm
		10.0	33.75 x 33.75	33.75	*Hordeum* group
		10.0	32.5 x 31.25	31.875	Poaceae anl-D>8 μm
		10.0	*32.5 x 30.0*	*31.25*	Poaceae anl-D>8 μm
		10.0	31.25 x 31.25	31.25	Poaceae anl-D>8 μm
		10.0	31.25 x 28.75	30.0	Poaceae anl-D>8 μm
		10.0	*31.25* x ?	? (crumpled)	Poaceae anl-D>8 μm
		10.0	30.0 x 28.75	29.375	Poaceae anl-D>8 μm

Table 18. Continued.

Depth (cm)	Age BP (cal BP)	Annulus diameter (µm)	Grain length x width (µm)	Average diameter (µm)	Identification
76	780 (680)	9.375	36.25 x 32.5	34.375	*Hordeum* group
		8.75	33.75 x 28.75	31.25	Poaceae anl-D>8 µm
		8.75	33.75 x *27.5*	*30.625*	Poaceae anl-D>8 µm
		8.75	32.5 x 30.0	31.25	Poaceae anl-D>8 µm
		8.75	31.25 x 27.5	29.375	Poaceae anl-D>8 µm
		8.75	30.0 x 28.75	29.375	Poaceae anl-D>8 µm
		8.75	28.75 x 27.5	28.125	Poaceae anl-D>8 µm
		8.75	*27.5 x 23.75*	*25.625*	
82	910 (790)	8.75	36.25 x 33.75	35.0	*Hordeum* group
		8.75	33.75 x *30.0*	*31.875*	Poaceae anl-D>8 µm
86	1020 (930)	10.625	35.0 x 32.5	33.75	*Hordeum* group
		8.125	? (broken)	?	Poaceae anl-D>8 µm
88	1070 (960)	10.0	35.0 x 35.0	35.0	*Hordeum* group
90	1120 (1040)	10.0	36.25 x 32.5	34.375	*Hordeum* group
		8.75	*32.5 x 37.5*	*35.0*	*Hordeum* group
		8.75	28.75 x 26.25	27.5	Poaceae anl-D>8 µm
92	1170 (1070)	10.0	35.0 x *31.25*	*33.125*	*Hordeum* group
		10.0	32.5 x 32.5	32.5	*Hordeum* group
96	1280 (1210)	11.25	*37.5 x 40.0*	*38.75*	*Hordeum* group
108	1590 (1510)	10.0	35.0 x *24.25*	*30.625*	Poaceae anl-D>8 µm
112	1690 (1560)	10.0	32.5 x 32.5	32.5	*Hordeum* group
116	1760 (1650)	8.75	30.0 x 21.25	25.625	Poaceae anl-D>8 µm
148	2360 (2350)	10.0	? (broken)	?	Poaceae anl-D>8 µm
164	2660 (2760)	11.25	*37.5* x 38.75	*38.125*	*Hordeum* group
188	3180 (3380)	8.75	? (broken)	?	Poaceae anl-D>8 µm
244	4080 (4540)	8.75	*23.75* x 26.25	*25.0*	Poaceae anl-D>8 µm
416	8690 (9600)	10.625	43.75 x *31.25*	*37.5*	*Hordeum* group
424	8820 (9870)	10.0	*36.25* x ?	?	Poaceae anl-D>8 µm
		10.0	35.0 x 28.75	31.875	Poaceae anl-D>8 µm
		10.0	? (broken)	?	Poaceae anl-D>8 µm
		8.75	35.0 x 30.0	32.5	*Hordeum* group
		8.75	32.5 x 31.25	31.875	Poaceae anl-D>8 µm
		8.75	*35.0* x ?	? (crumpled)	Poaceae anl-D>8 µm
428	8890 (9910)	10.0	*30.0 x 30.0*	*30.0*	Poaceae anl-D>8 µm
		8.75	35.0 x 35.0	35.0	*Hordeum* group
		8.75	33.75 x *30.0*	*31.875*	Poaceae anl-D>8 µm
		8.75	*31.25 x 26.25*	28.75	Poaceae anl-D>8 µm
		8.75	? (crumpled)	?	Poaceae anl-D>8 µm
		8.125	36.25 x 28.75	32.5	*Hordeum* group
		8.125	*35.0 x 31.25*	*33.125*	*Hordeum* group

Table 19. Summary of charcoal data from Carnach Mór.

Age of charcoal peaks	Relative magnitude
9440 BP (10430 cal BP)	High peak
9440-7700 BP (10430-8420 cal BP)	Consistently high 'background' levels, with peaks at 7800-7730 BP (8520-8480 cal BP), 8410 BP (9400 cal BP) and 8140 BP (8990 cal BP).
7700-7160 BP (8420-7930 cal BP)	Moderate levels
7160-6080 BP (7930-6900 cal BP)	High levels, with an early-mid-Holocene maximum at 6360 BP (7230 cal BP)
6080-3870 BP (6900-4280 cal BP)	Low-moderate, with peaks at 4460 BP (5040 cal BP) and 4050 BP (4460 cal BP)
3870-1430 BP (4280-1310 cal BP)	Frequent very high peaks with consistently high 'background' levels
1430-510 BP (1310-520 cal BP)	Fewer very high peaks and slightly lower 'background' levels
510-0 BP (520-0 cal BP)	Consistently moderate-high levels, slightly lower after 200 BP (150 cal BP)

Table 20. Results of charcoal size class regression analyses for Carnach Mór data.

Charcoal size classes	R^2	Charcoal size classes	R^2
10-25 µm *vs.* 26-50 µm	0.74	26-50 µm *vs.* 51-75 µm	0.75
10-25 µm *vs.* 51-75 µm	0.53	26-50 µm *vs.* >75 µm	0.58
10-25 µm *vs.* >75 µm	0.30	51-75 µm *vs.* >75 µm	0.77

Table 21. Sediment stratigraphy of the Camban sequence.

Depth (cm)	Description
0-14	Poorly humified peat with black roots and a mixture of thinner and more fleshy roots; Th4 Sh+
14-21	More humified, fine fibrous peat with occasional mica flexks; Ga+ Th1/2 Sh2/3
21-39.5	Well-defined boundary to peat with thicker roots, occasional monocot leaves increased mica and occasional small stones to c.5 mm diameter; Ga1 Gs+ Dh+ Th2 Sh2
39.5-41	Increased coarse sand; Ga1 Gs1 Dh+ Th1 Sh1
41-52	Increased inorganic component with occasional to frequent stones up to 15 mm in diameter; Ga1 Gs1 Gg+ Dh+ Th1 Sh1
52-64	Decreased inorganic component, fine fibrous peat; Ga+ Th2 Sh2
64-85	More humified, slightly sticky peat; Ga+ Dh+ Th1 Sh3
85-92	Increased inorganic component, increase in elasticity with depth; Ga1 Gs+ Dh+ Th1 Sh2
92-122	More fibrous, amorphous peat; Ga+ Dh+ Th2 Sh2
122-124	Minerogenic, amorphous peat; Ga1 Gs+ Th1 Sh2
124-132.5	Wood peat with large pieces gradually changing to decomposed wood flakes; Ga+ Dl £ Th1 Sh+
132.5-135.5	Fibrous peat with wood flakes and occasional coarse sand; Ga+ Gs+ Dl2 Dh+ Th2 Sh1
135.5-150.5	Fibrous, amorphous peat with occasional wood flakes; Ga+ Dl1 Th1 Sh2
150.5-153.5	Fibrous, amorphous peat with a band of wood fragments *c*.30-60 mm long: Ga+ Dl1 Th1 Sh2
153.5-168	Finely fibrous peat; Ga+ Th1 Sh3
168-179	Amorphous, slightly sticky peat with wood flakes; Ga+ Dl1 Dh+ Th+ Sh3
179-198	More amorphous, sticky peat; Dh+ Th1 Sh3
198-200	Decomposed woody peat with large wood fragment at *c*.191-200 cm: Ga+ Dl1 Dh+ Th1 Sh2
200-221.5	Inorganic band in sticky, amorphous peat; Ga1 Dh+ Th1 Sh2
221.5-233	Detrital peat; Dh1 Th1 Sh2
233-235	Inorganic band with coarse mineral component; Ga1 Gs2 Th+ Sh1
235-241	Fine fibrous peat with wood; Ga+ Gs+ Dl+ Dh+ Th+ Sh3
241-271	Highly amorphous black peat, wood common; Ga+ Gs+ Dl+ Dh+ Th+ Sh4
271-274.5	Increased inorganic component; Ga1 Gs+ Th+ Sh3
274.5-298	Finely fibrous, amorphous peat with occasional to common wood flakes; Ga+ Dl+ Th1 Sh3
298-318	Amorphous peat with frequent wood; Ga+ Dl2 Th+ Sh2
318-323	Very soft amorphous black peat with small wood fragments occasional to common; Ga+ Dl+ Th+ Sh4
323-339	Black, amorphous peat with fine roots and wood flakes and fragments, gradually becoming firmer; Ga+ Dl2 Th+ Sh2
339-344	Amorphous, woody peat, becoming firmer towards the base; Ga+ Dl1 Th+ Sh3

Table 22. Radiocarbon assays from Camban.

Lab. Code	**Depth (cm)**	**Age (^{14}C BP)**	**Age (cal BP)**	**Age (cal BC/AD)**	**$\delta^{13}C_{PDB}$ (± 0.1 ‰)**
AA-32257	338	4925 ± 150	1σ - 5886-5487 2σ - 5982-5315	1σ - 3936-3537 cal BC 2σ - 4032-3365 cal BC	-28.4
AA-32258	271	3700 ± 45	1σ - 4088-3931 2σ - 4146-3890	1σ - 2139-1982 cal BC 2σ - 2197-1941 cal BC	-29.5
AA-32259	190	2405 ± 45	1σ - 2468-2348 2σ -2709-2339	1σ - 519-399 cal BC 2σ - 760-390 cal BC	-29.2
AA-32260	166	1515 ± 40	1σ - 1411-1342 2σ - 1511-1310	1σ - cal AD 539-608 2σ - cal AD 439-640	-27.9
AA-32261	140	815 ± 40	1σ - 735-672 2σ - 784-664	1σ - cal AD 1215-1278 2σ - cal AD 1166-1286	-28.5
AA-32262	114	1790 ± 45	1σ - 1733-1623 2σ - 1822-1566	1σ - cal AD 217-327 2σ - cal AD 128-384	-28.3
AA-32263	22	390 ± 50	1σ - 504-323 2σ - 518-306	1σ - cal AD 1446-1627 2σ - cal AD 1432-1644	-27.9
CAMS-57201	108	640 ± 40	1σ - 653-554 2σ - 663-544	1σ - cal AD 1297-1396 2σ - cal AD 1287-1406	-29.0

Table 23. Temporal resolution of data from Camban. ^{14}C and calibrated ages rounded to nearest one; temporal resolution and accumulation rates rounded to decimal place.

Depth (cm)	**Sampling interval (cm)**	**Age range (^{14}C BP)**	**Age range (cal BP)**	**Resolution (^{14}C years/ sampling interval)**	**Resolution (cal years/ Sampling interval)**	**Sediment accumulation rate (^{14}C years/cm)**	**Sediment accumulation rate (cal years/cm)**
0-4	2.0	0-71	modern	35.5	42.9	17.7	21.5
4-8	4.0	71-142	modern-140	70.9	85.8	17.7	21.5
8-9	1.0	142-160	138-143	17.7	21.5	17.7	21.5
9-12	3.0	160-213	143-158	53.2	64.4	17.7	21.5
12-16	4.0	213-284	158-304	70.9	85.8	17.7	21.5
16-22	2.0	284-390	304-472	35.5	42.9	17.7	21.5
22-24	2.0	390-396	472-476	5.8	4.0	2.9	2.0
24-112	4.0	396-662	476-648	11.6	7.8	2.9	2.0
112-116	2.0	662-684	648-653	10.9	2.5	5.5	1.3
116-128	4.0	684-749	653-670	21.9	5.7	5.5	1.4
128-136	2.0	749-793	668-691	10.9	5.8	5.5	2.9
136-140	4.0	793-815	691-714	21.9	23.0	5.5	5.8
140-156	4.0	815-1246	714-1170	107.7	104.3	26.9	26.1
156-160	2.0	1246-1354	1170-1283	53.8	52.2	26.9	26.1
160-164	4.0	1354-1461	1283-1332	107.7	104.3	26.9	26.1
164-166	2.0	1461-1515	1332-1392	53.8	52.2	26.9	26.1
166-168	2.0	1515-1589	1392-1504	74.2	80.4	37.1	40.2
168-188	4.0	1589-2331	1504-2342	148.3	160.8	37.1	40.2
188-190	2.0	2331-2405	2342-2357	74.2	80.4	37.1	40.2
190-192	2.0	2405-2438	2357-2387	33.2	41.4	16.6	20.7
192-236	4.0	2438-3169	2387-3373	66.4	82.8	16.6	20.7
236-248	2.0	3169-3368	3373-3622	33.2	41.4	16.6	20.7
248-256	4.0	3368-3501	3622-3792	66.4	82.8	16.6	20.7
256-264	2.0	3501-3634	3792-3923	33.2	41.4	16.6	20.7
264-268	4.0	3634-3700	3923-4030	66.4	82.8	16.6	20.7
268-272	2.0	3700-3769	4030-4110	34.5	41.4	17.3	20.7
272 276	2.0	3769-3838	4110-4233	34.5	44.5	17.3	22.2
276-292	4.0	3838-4114	4233-4601	69.0	95.1	17.3	23.8
292-300	2.0	4114-4252	4601-4833	34.5	47.5	17.3	23.8
300-340	4.0	4252-4942	4833-5655	69.0	95.1	17.3	23.8
340-342	2.0	4942-4977	5655-5730	34.5	47.5	17.3	23.8

Table 24. Summary of local pollen assemblage zones and sub-zones for Camban.

Local pollen assemblage zones		**Depth (cm)**	**Sub-zone**		**Depth (cm)**	**Age (^{14}C BP)**	**Age (cal BP)**
CAM5	Poaceae-Cyperaceae	0-115	CAM5b	Poaceae-Cyperaceae-*Potentilla*-type	0-6	0-110	0-60
			CAM5a	Poaceae-Cyperaceae	6-21	110-370	60-460
CAM4	Poaceae-Cyperaceae-*Calluna*-*Betula*	21-115	-	-	-	370-680	460-650
CAM3	*Betula*-*Salix*-Poaceae-Cyperaceae	115-165	CAM3c	*Betula*-Poaceae-*Salix*-*Calluna*-*Myrica*	115-133	680-780	650-680
			CAM3b	*Betula*-Poaceae-*Salix*-Cyperaceae	133-159	780-1330	680-1270
			CAM3a	*Salix*-Poaceae-*Betula*	159-165	1330-1490	1270-1350
CAM2	Poaceae-*Betula*-Cyperaceae-*Calluna*	165-247	CAM2b	*Calluna*-Poaceae-*Betula*-Cyperaceae-*Potentilla*-type	165-194	1490-2470	1350-2650
			CAM2a	Poaceae-*Betula*-Cyperaceae-*Filipendula*	194-247	2470-3320	2650-3510
CAM1	*Betula*-Poaceae-*Alnus*-*Salix*	247-342	CAM1d	*Salix*-*Betula*-Poaceae-*Calluna*	247-259	3320-3510	3510-3760
			CAM1c	*Alnus*-Poaceae-*Betula*	259-271	3510-3700	3760-4030
			CAM1b	*Betula*-*Alnus*-Poaceae-*Calluna*	271-314	3700-4470	4030-5200
			CAM1a	*Betula*-*Salix*-Poaceae	314-342	4470-4980	5200-5730

Table 25. Dimensions of cereal-type and large Poaceae pollen grains from Camban. Italics denote minimum size estimates from damaged or partially concealed grains.

Depth (cm)	Age BP (cal BP)	Annulus diameter (μm)	Grain length x width (μm)	Mean diameter (μm)	Identification
0	present	11.875	40.0 x 40.0	40.0	?*Avena/Triticum* group
		11.25	36.25 x 35.0	35.625	*Hordeum* group
		11.25	36.25 x 35.0	35.625	*Hordeum* group
		10.0	*30.0* x 40.0	*35.0*	*Hordeum* group
		8.75	28.75 x 31.25	30.0	Poaceae anl-D>8 μm
4	modern	8.75	36.25 x 30.0	33.125	*Hordeum* group
		8.75	35.0 x *27.5*	*31.25*	Poaceae anl-D>8 μm
8	140 (140)	8.75	33.75 x 32.5	33.125	*Hordeum* group
9	160 (140)	8.75	32.5 x *25.0*	*28.75*	Poaceae anl-D>8 μm
12	210 (160)	10.0	*32.5* x 36.25	*34.375*	*Hordeum* group
		10.0	31.25 x 36.25	33.75	*Hordeum* group
		10.0	30.0 x 28.75	29.375	Poaceae anl-D>8 μm
		8.75	32.5 x *22.5*	*27.5*	Poaceae anl-D>8 μm
		8.75	30.0 x 40.0	35.0	*Hordeum* group
		8.75	*31.25* x 28.75	*30.0*	Poaceae anl-D>8 μm
16	280 (300)	8.75	33.75 x *31.25*	*32.5*	*Hordeum* group
		8.75	31.25 x 31.25	31.25	Poaceae anl-D>8 μm
18	320 (410)	10.0	37.5 x 35.0	36.25	*Hordeum* group
		10.0	30.0 x 32.5	31.25	Poaceae anl-D>8 μm
		8.75	36.25 x 27.5	31.875	Poaceae anl-D>8 μm
		8.75	35.0 x 32.5	33.75	*Hordeum* group
		8.75	35.0 x 31.25	33.125	*Hordeum* group
20	350 (360)	8.75	37.5 x 32.5	35.0	*Hordeum* group
		8.75	*33.75* x 35.0	34.375	*Hordeum* group
		8.75	32.5 x 31.25	31.875	Poaceae anl-D>8 μm
		8.125	33.75 x 32.5	33.125	*Hordeum* group
22	390 (470)	11.875	46.25 x 42.5	44.375	*Avena/Triticum* group
		10.0	38.75 x 32.5	35.625	*Hordeum* group
		9.375	36.25 x *23.75*	30.0	Poaceae anl-D>8 μm
		8.125	36.25 x 31.25	33.75	*Hordeum* group
24	400 (480)	11.25	41.25 x 40.0	40.75	*Avena/Triticum* group
		10.0	35.0 x 31.25	33.125	*Hordeum* group
		8.75	35.0 x *32.5*	*33.75*	*Hordeum* group
		8.75	33.75 x 31.25	32.5	*Hordeum* group
		8.75	*32.5 x 36.25*	*34.375*	*Hordeum* group
28	410 (490)	10.0	32.5 x 28.75	30.625	Poaceae anl-D>8 μm
		10.0	30.0 x 26.25	28.125	Poaceae anl-D>8 μm
		8.75	36.25 x 30.625	33.4375	*Hordeum* group
		8.75	35.0 x 40.0	37.5	*Hordeum* group
		8.75	*32.5 x 40.0*	36.25	*Hordeum* group
		8.75	*32.5 x 23.75*	28.125	Poaceae anl-D>8 μm
		8.75	27.5 x 32.5	30.0	Poaceae anl-D>8 μm
		8.125	36.25 x 30.0	33.125	*Hordeum* group
32	420 (500)	10.0	*41.25 x 28.75*	*35.0*	*Hordeum* group
		8.75	36.25 x 31.25	33.75	*Hordeum* group
		8.75	33.75 x 32.5	33.125	*Hordeum* group
		8.75	*30.0 x 26.25*	28.125	Poaceae anl-D>8 μm
		8.75	32.5 x *26.25*	*29.375*	Poaceae anl-D>8 μm
		8.125	35.0 x 32.5	33.125	*Hordeum* group

Table 25. Continued.

Depth (cm)	**Age BP (cal BP)**	**Annulus diameter (μm)**	**Grain length x width (μm)**	**Mean diameter (μm)**	**Identification**
36	430 (500)	8.125	35.0 x 33.75	34.375	*Hordeum* group
40	440 (500)	8.75	35.0 x 32.5	33.75	*Hordeum* group
44	450 (510)	10.0	*35.0 x 33.75*	*35.375*	*Hordeum* group
		10.0	35.0 x 32.5	33.75	*Hordeum* group
48	470 (510)	8.78	33.75 x *26.25*	30.0	Poaceae anl-D>8 μm
		8.75	? (crumpled)	?	Poaceae anl-D>8 μm
52	480 (510)	8.75	37.5 x *27.5*	*32.5*	*Hordeum* group
56	490 (520)	9.375	33.75 x *31.25*	*32.5*	*Hordeum* group
60	500 (520)	11.25	*27.5* x 37.5	*32.5*	*Hordeum* group
		8.125	38.75 x 31.25	35.0	*Hordeum* group
		8.125	36.25 x 30.0	33.125	*Hordeum* group
64	510 (520)	10.0	40.0 x *30.0*	*35.0*	*Hordeum* group
		8.75	33.75 x 31.25	32.5	*Hordeum* group
68	520 (530)	10.0	33.75 x 35.0	34.375	*Hordeum* group
		10.0	33.75 x 31.25	32.5	*Hordeum* group
76	550 (540)	8.75	33.75 x 30.0	31.875	Poaceae anl-D>8 μm
80	560 (550)	10.0	36.25 x 35.0	35.625	*Hordeum* group
		8.75	32.5 x 27.5	30.0	Poaceae anl-D>8 μm
		8.75	30.0 x 30.0	30.0	Poaceae anl-D>8 μm
84	570 (550)	8.75	? (crumpled)	?	Poaceae anl-D>8 μm
88	580 (550)	10.0	33.75 x 32.5	33.125	*Hordeum* group
		8.75	? x *28.75*	?	Poaceae anl-D>8 μm
		8.75	? x *28.75*	?	Poaceae anl-D>8 μm
		8.125	37.5 x 33.75	35.625	*Hordeum* group
92	590 (550)	11.25	41.25 x 37.5	39.375	*Hordeum* group
		8.125	41.25 x 35.0	38.125	*Hordeum* group
96	610 (610)	11.25	*32.5* x 33.75	*33.125*	*Hordeum* group
		10.625	*30.0* x 33.75	*31.875*	Poaceae anl-D>8 μm
		8.75	33.75 x 32.5	33.125	*Hordeum* group
		8.125	37.5 x 33.75	35.625	*Hordeum* group
100	620 (600)	8.75	35.0 x *22.5*	*28.75*	Poaceae anl-D>8 μm
104	630 (600)	8.75	*26.25* x 33.75	*30.0*	Poaceae anl-D>8 μm
108	640 (590)	10.0	41.25 x 33.75	37.5	*Hordeum* group
		10.0	32.5 x 30.0	31.25	Poaceae anl-D>8 μm
		8.75	36.25 x 31.25	33.75	*Hordeum* group
112	660 (650)	11.25	45.0 x 36.25	40.625	*Avena/Triticum* group
		10.0	33.75 x 33.75	33.75	*Hordeum* group
		8.75	31.25 x 28.75	30.0	Poaceae anl-D>8 μm
		8.125	*33.75 x 37.5*	*35.625*	*Hordeum* group
114	670 (650)	10.0	42.5 x 35.0	38.75	*Hordeum* group
		8.75	35.0 x 30.0	32.5	*Hordeum* group
116	680 (650)	10.0	33.75 x 31.25	32.5	*Hordeum* group
120	710 (660)	8.75	? x *38.75*	? (crumpled)	Poaceae anl-D>8 μm
124	730 (660)	10.0	? (crumpled)	?	Poaceae anl-D>8 μm
		8.75	? (crumpled)	?	Poaceae anl-D>8 μm
128	750 (670)	8.75	*42.5 x 28.75*	35.125	*Hordeum* group
		8.125	*32.5* x 30.0	*31.25*	Poaceae anl-D>8 μm
130	760 (670)	8.75	27.5 x 30.0	28.75	Poaceae anl-D>8 μm

Table 25. Continued.

Depth (cm)	**Age BP (cal BP)**	**Annulus diameter (µm)**	**Grain length x width (µm)**	**Mean diameter (µm)**	**Identification**
132	770 (670)	8.75	36.25 x 32.5	34.375	*Hordeum* group
134	780 (680)	13.75	36.25 x 35.0	35.625	?*Hordeum* group
		8.75	37.5 x 32.5	35.0	*Hordeum* group
140	820 (720)	10.0	? (broken)	?	Poaceae anl-D>8 µm
		8.75	35.0 x *27.5*	*31.25*	Poaceae anl-D>8 µm
		8.75	25.0 x 26.25	25.625	Poaceae anl-D>8 µm
		8.125	*31.25 x 36.25*	*33.75*	*Hordeum* group
160	1350 (1280)	8.75	32.5 x *28.75*	*30.625*	Poaceae anl-D>8 µm
166	1520 (1390)	11.25	35.0 x 33.75	34.375	*Hordeum* group
188	2330 (2340)	10.0	36.25 x *28.75*	*32.5*	*Hordeum* group
		8.75	40.0 x 31.25	35.625	*Hordeum* group
		8.125	32.5 x 32.5	32.5	*Hordeum* group
190	2410 (2360)	8.75	37.5 x 32.5	35.0	*Hordeum* group
192	2440 (2390)	11.25	*32.5 x 26.25*	*29.375*	Poaceae anl-D>8 µm
		8.75	37.5 x *32.5*	*35.0*	*Hordeum* group
		8.75	35.0 x *30.0*	*32.5*	*Hordeum* group
		8.75	33.75 x *28.75*	*31.25*	Poaceae anl-D>8 µm
		8.125	37.5 x *30.0*	*33.75*	*Hordeum* group
196	2500 (2580)	11.25	31.25 x 35.0	33.125	*Hordeum* group
		10.0	37.5 x 35.0	36.25	*Hordeum* group
		8.75	33.75 x *30.0*	*31.875*	Poaceae anl-D>8 µm
		8.75	31.25 x 30.0	30.625	Poaceae anl-D>8 µm
		8.75	*30.0* x 27.5	*28.75*	Poaceae anl-D>8 µm
		8.75	27.5 x *23.75*	*25.625*	Poaceae anl-D>8 µm
200	2570 (2740)	10.0	27.5 x 27.5	27.5	Poaceae anl-D>8 µm
		8.75	41.25 x *33.75*	*37.5*	*Hordeum* group
		8.125	35.0 x 31.25	33.125	*Hordeum* group
204	2640 (2450)	11.25	*32.5 x 36.25*	34.375	*Hordeum* group
		10.0	36.25 x 36.25	36.25	*Hordeum* group
		10.0	33.75 x *40.0*	36.875	*Hordeum* group
		10.0	33.75 x 38.75	36.25	*Hordeum* group
		10.0	*31.25* x 38.75	35.0	*Hordeum* group
		9.375	37.5 x 32.5	35.0	*Hordeum* group
		9.375	31.25 x 33.75	32.5	*Hordeum* group
		8.75	38.75 x *31.25*	35.0	*Hordeum* group
208	2700 (2780)	11.25	36.25 x 31.25	33.75	*Hordeum* group
		8.75	32.5 x *32.5*	*32.5*	*Hordeum* group
		8.125	30.0 x *28.75*	*29.375*	Poaceae anl-D>8 µm
212	2770 (2860)	11.25	37.5 x *40.0*	*38.75*	*Hordeum* group
		11.25	*33.75 x 40.0*	*36.875*	*Hordeum* group
		10.0	36.25 x 25.0	30.625	Poaceae anl-D>8 µm
		8.75	35.0 x *25.0*	*30.0*	Poaceae anl-D>8 µm
		8.75	26.25 x 28.75	27.5	Poaceae anl-D>8 µm
216	2840 (2940)	10.0	? x *35.0*	?	Poaceae anl-D>8 µm
220	2900 (2990)	8.75	30.0 x 31.25	30.625	Poaceae anl-D>8 µm
224	2970 (3110)	10.0	37.5 x 35.0	36.25	*Hordeum* group
228	3040 (3230)	8.75	*31.25 x 36.25*	*33.75*	*Hordeum* group
242	3270 (3470)	*8.75* (broken)	41.25 x *31.25*	*36.25*	*Hordeum* group

Table 25. Continued.

Depth (cm)	**Age BP (cal BP)**	**Annulus diameter (μm)**	**Grain length x width (μm)**	**Mean diameter (μm)**	**Identification**
244	3300 (3470)	11.25	33.75 x 35.0	34.375	*Hordeum* group
248	3370 (3620)	10.0 8.75	28.75 x 27.5 38.75 x 32.5	28.125 35.625	*Hordeum* group Poaceae anl-D>8 μm
260	3570 (3840)	8.125	*31.25 x 28.75*	*30.0*	Poaceae anl-D>8 μm
262	3600 (3890)	12.5 10.0	35.0 x 41.25 ? x *35.0*	38.125 ?	?*Hordeum* group Poaceae anl-D>8 μm
276	3840 (4230)	8.75	31.25 x *30.0*	*30.625*	Poaceae anl-D>8 μm
280	3910 (4370)	8.75	? (crumpled)	?	Poaceae anl-D>8 μm

Table 26. Summary of trends in pollen preservation at Camban.

Zone or sub-zone	**Preservation and sedimentary changes**
CAM1a	Peak in corrosion at 4980-4800 BP (5720-5500 cal BP) evident in most curves, especially *Betula*, which is the dominant taxon. Organic content is high, with low frequency of Pteropsida (monolete) indet.
CAM1b	Slight increase in corrosion and crumpling, and peak in Pteropsida spores with reduction in LOI at 4460-4390 BP (5040-4930 cal BP). Also slight increase in charcoal frequencies. Peak in corrosion at 3840-3730 BP (4230-4020 cal BP) with slight, gradual rise in crumpled and lower breakage coinciding with fall in LOI and rise in Pteropsida (monolete) spores and charcoal fragments.
CAM1c	Rising LOI curve mirrored by well-preserved pollen frequencies, as corrosion, Pteropsida and charcoal values fall. Peak in crumpled pollen at the end of the zone is mainly reflected in the Poaceae curve, which shows a similar percentage increase.
CAM1d	Predominantly well-preserved pollen and high organic content, with slight mid-zone rise in crumpling coinciding with increased Poaceae.
CAM2a	Very variable preservation and LOI curves. Poaceae and Cyperaceae show a high frequency of crumpling which remains a relatively constant proportion of both pollen curves. Corrosion, Pteropsida and mineral content follow similar patterns, with higher charcoal frequencies in the first half of the zone. This corrosion pattern is evident in most major pollen types. Indeterminate crumpled and corroded pollen curves show a similar pattern to determinate corroded pollen.
CAM2b	Predominantly well-preserved pollen with constant low breakage frequencies and decreasing crumpled pollen; corroded pollen values are low, with slight increases at 2330 BP (2340 cal BP), 1740 BP (1670 cal BP) and to the end of the zone at 1490 BP (1350 cal BP), paralleled by increases in Pteropsida spores. Organic content remains high throughout and charcoal frequencies are high.
CAM3a	Falling well-preserved pollen values and organic content contrast with rising corrosion, crumpling and Pteropsida spores. There is a slight rise in charcoal frequencies. Increased deterioration is not restricted to any particular pollen taxon.
CAM3b	As CAM2a: parallels in corrosion, Pteropsida and mineral content; only slight changes in charcoal frequencies.
CAM3c	As CAM2a: corrosion, crumpling, Pteropsida and charcoal mirror sediment mineral content.
CAM4a	Consistently high mineral content, corrosion, crumpling, Pteropsida spores and higher charcoal values. Frequencies of indeterminate corroded and crumpled pollen are higher. Corrosion is higher in most major pollen types, with increased crumpling most evidence in Poaceae, which shows percentage increases in this zone. Reductions in corrosion and Pteropsida at the end of the zone mirror increasing organic content.
CAM4b	Frequencies of well-preserved pollen decrease as crumpling and breakage increase. This is reflected in Poaceae, Cyperaceae and herbs, as well as the minor pollen types, such as *Betula*. Very high charcoal frequencies at 350 BP (360 cal BP) coincide with lower organic content at the start of the zone. Well-preserved pollen values increase at the end of the zone as LOI rises above 80%.
CAM4c	Well-preserved pollen is the dominant preservation type, with decreasing values for corroded pollen. Organic content unknown. A small rise in corroded pollen at c.40 BP (modern, 2 cm) coincides with slight increases in Pteropsida spores and charcoal frequencies.

Table 27. Results of regression analysis on pollen preservation data from Camban.

Regression analysis	R^2 value (slope of linear regression line)
Organic content *vs.* corroded determinate pollen	0.23 (negative)
Organic content *vs.* undifferentiated Pteropsida (monolete) spores	0.56 (negative)
Corroded determinate pollen *vs.* undifferentiated Pteropsida (monolete) spores	0.49 (positive)

Table 28. Assessment of post-depositional biasing at Camban (following Tipping *et al.* 1994, Tipping and Carter 1998, Bunting and Tipping, submitted).

Test	Failure threshold	Number of samples failing
TLP sum	<300	0
Total pollen concentration	<3000 grains cm^{-3}	0
Number of main sum taxa	<10	0
Percentage of severely deteriorated grains	>35%	0
Percentage indeterminable	>30%	0
Percentage 'resistant' taxa	>6%	0
Percentage Pteropsida (monolete) indet.	>40%	38/105 (36% of samples fail)
Spore:pollen concentration ratio	>0.66	0 (0.6 at 3770 BP (4110 cal BP), coinciding with highest Pteropsida value of 80.5%)
Spore:pollen taxa ratio	>0.66	0

Table 29. Summary of charcoal data at Camban in relation to evidence for reworking (see text for discussion).

Date	Relative magnitude	Possible reworking
4980-4490 BP (5720-5220 cal BP)	Low	No
4490-3280 BP (5220-3470 cal BP)	Moderate, variable	Yes - 3770-3730 BP (4110-4020 cal BP)
3280-2870 BP (3470-2960 cal BP)	High	Yes - 3200-3040 BP (3390-3230 cal BP)
2870-2260 BP (2960-2320 cal BP)	Consistently moderate	No
2260-1660 BP (2320-1540 cal BP)	Consistently high	No
1660-780 BP (1540-680 cal BP)	Moderate	No
780-720 BP (680-660 cal BP)	Moderately high	Yes
670-400 BP (650-480 cal BP)	High and variable	Yes
400-190 BP (480-150 cal BP)	Very high, peak at 350 BP (360 cal BP)	No
190-0 BP (150 cal BP-present)	Gradually decreasing	No

Table 30. Results of charcoal size class regression analysis at Camban.

Charcoal size classes	R^2	Charcoal size classes	R^2
10-25 μm *vs.* 26-50 μm	0.92	26-50 μm *vs.* 51-75 μm	0.94
10-25 μm *vs.* 51-75 μm	0.86	26-50 μm *vs.* >75 μm	0.91
10-25 μm *vs.* >75 μm	0.81	51-75 μm *vs.* >75 μm	0.93

Table 31. Sediment stratigraphic description for the Morvich sequence.

Depth (cm)	Description
0-7	Poorly humified, predominantly *Sphagnum* peat with occasional monocot stems and frequent roots with *Myrica* leaves near the surface; Tb3 Th1
7-12	Slightly more humified detrital and *Sphagnum* peat; Tb1 Th2 Sh1
12-16	Lighter moss peat with *Sphagnum* and *Polytrichum*; Tb3 Th1 Sh+
16-26	More amorphous *Sphagnum* and detrital peat with monocot leaves; Dh+ Tb1 Th1 Sh2
26-101	Dark brown, well-humified peat with fine rootlets, occasional lignified twigs and *Phragmites* leaf sheaths between 77-89 cm; Dl+ Dh+ Dg+ Th1 Sh3
101-109	Diffuse inwash with wood fragments in amorphous peat; Th1 Sh3
109-125	Well-humified peat with fine roots and occasional lignified twigs; Dl+ Th1 Sh3
125-149	Woody, amorphous peat, wood decreasing with depth; Dl1 Th+ Sh3
149-184.5	Well-humified peat with occasional monocot leaves, twigs and wood; Dl1 Dh+ Th+ Sh3
184.5-201.5	Sedge peat with twigs and occasional black roots; Dl+ Dh1 Th+ Sh3
201.5-223	Amorphous peat with twigs, black roots; Dl+ Dh + Th1 Sh3
223-280	Dark, amorphous, woody peat with fine roots and twigs, becoming denser with depth; Dl1/2 Th+ Sh2/3
280-301	Softer amorphous peat, still with wood, lower boundary gradual; Dl1 Th+ Sh3
301-361	Amorphous, woody peat with black roots and monocot leaves; Dl1/2 Dh+ Th+ Sh2/3
361-377	Amorphous peat with occasional wood; Dl+ Th+ Sh4
377-415.5	Amorphous peat with wood, especially 402-415.5 cm; Dl1 Th+ Sh3
415.5-438	Softer amorphous peat with wood; Dl1 Sh3
438-477	Gradual transition to firmer, amorphous peat with wood, large fragment 431-434 cm; Dh1 Dh+ Th+ Sh3
477-497.5	Gradual transition to very firm, woody amorphous peat; large wood fragment at 477-479 cm; Dl2 Sh2
497.5-502	Coarse, silty grey sand with mica, charcoal flecks at the upper boundary; Ag+ Ga1 Gs3 Sh+

Table 32. Radiocarbon assays for Morvich.

Lab. Code	**Depth (cm)**	**Age (^{14}C BP)**	**Age (cal BP)**	**Age (cal BC/AD)**	**$\delta^{13}C_{PDB}$ (± 0.1 ‰)**
AA-33331	498	9540 ± 75	1σ - 10891-10425 2σ - 10951-10358	1σ - 8941-8475 2σ -9001-8408	-30.0
AA-33332	472	7105 ± 70	1σ - 7939-7815 2σ - 8052-7724	1σ - 5989-5865 2σ - 6102-5774	-29.3
AA-33333	468	7065 ± 65	1σ - 7918-7785 2σ - 7950-7695	1σ - 5968-5835 2σ - 6000-5745	-29.0
AA-33334	378	5685 ± 60	1σ - 6526-6410 2σ - 6641-6314	1σ - 4576-4460 2σ - 4691-4364	-29.6
AA-33335	270	4210 ± 50	1σ - 4835-4645 2σ - 4861-4566	1σ - 2886-2696 2σ - 2912-2617	-29.3
AA-33336	220	3935 ± 75	1σ - 4503-4263 2σ - 4560-4099	1σ - 2553-2313 2σ - 2610-2149	-29.5
AA-33337	146	3500 ± 50	1σ - 3834-3691 2σ - 3887-3631	1σ - 1885-1742 2σ - 1938-1682	-29.5
AA-33338	118	2630 ± 50	1σ - 2768-2741 2σ - 2839-2716	1σ - 819-792 2σ - 890-767	-28.5
AA-33339	70	1365 ± 45	1σ - 1299-1268 2σ - 1331-1179	1σ - 651-682 2σ - 619-771	-29 (estimated)
AA-33340	50	modern (post-1950)	-	-	-28.9

Table 33. Temporal resolution of data from Morvich.

Depth (cm)	Sampling interval (cm)	Age range (^{14}C BP)	Age range (cal BP)	Resolution (^{14}C years/ sampling interval	Resolution (cal years/ sampling interval)	Sediment accumulation rate (^{14}C years/cm)	Sediment accumulation rate (cal years/cm)
0-4	2.0	*c*.0-78	modern	39.0	36.7	19.5	18.4
4-68	4.0	*c*.78-1326	modern-*c*.1274	78.0	73.5	19.5	18.4
68-72	4.0	*c*.1326-1418	*c*.1274-1302	91.7	97.8	22.9	24.5
72-116	4.0	1418-2577	1302-2741	105.4	122.2	26.4	30.5
116-120	4.0	2577-2692	2741-3772	114.9	135.4	28.7	33.8
120-144	4.0	2692-3438	3772-3688	124.3	148.6	31.1	37.1
144-148	4.0	3438-3512	3688-3762	73.9	90.9	18.5	22.7
148-168	4.0	3512-3629	3762-3921	23.5	33.2	5.9	8.3
168-172	2.0	3629-3641	3921-3957	11.8	16.6	5.9	8.3
172-176	6.0	3641-3676	3957-3982	35.3	49.9	5.9	8.3
176-220	4.0	3676-3935	3982-4407	23.5	33.2	5.9	8.3
220-268	4.0	3935-4199	4407-4728	22.0	26.9	5.5	6.7
268-270	2.0	4199-4210	4728-4743	11.0	13.4	5.5	6.7
270-272	2.0	4210-4237	4743-4830	27.3	31.8	13.7	15.9
272-376	4.0	4237-5658	4830-6417	54.6	63.6	13.7	15.9
376-380	4.0	5658-5716	6417-6487	58.0	62.8	14.5	15.7
380-392	4.0	5716-5900	6487-6732	61.3	62.0	15.3	15.5
392-394	2.0	5900-5930	6732-6749	30.7	31.0	15.3	15.5
394-400	6.0	5930-6022	6749-6868	92.0	93.0	15.3	15.5
400-468	4.0	6022-7065	6868-7856	61.3	62.0	15.3	15.5
468-472	2.0	7065-7105	7856-7907	20.0	25.5	10	12.8
472-500	4.0	7105-9727	7907-10960	374.6	439.1	93.7	109.8
500-502	2.0	9727-9915	10960-11006	187.3	219.5	93.7	109.8

Table 34. Summary of local pollen assemblage zones and sub-zones for Morvich.

Local pollen assemblage zones		**Depth (cm)**	**Subzones**		**Depth (cm)**	**Age (^{14}C BP)[1]**	**Age (cal BP)**
MOR4	Poaceae-*Betula*-Cyperaceae	0-46	MOR4b	Poaceae-Cyperaceae	0-6	0-*c.*120	0-*c.*110
			MOR4a	*Betula*-Poaceae-Cyperaceae	6-46	*c.*120-900	*c.*110-790
MOR3	*Betula*-Poaceae-*Alnus*	46-269	MOR3b	*Betula*-Poaceae-*Alnus*-*Corylus*	46-146	*c.*900-3480	*c.*790-3710
			MOR3a	*Betula*-Poaceae-*Alnus*	146-269	3480-4200	3710-4730
MOR2	*Alnus*-*Betula*-*Ulmus*	269-471	MOR2c	*Alnus*-*Betula*	269-378	4200-5690	4730-6470
			MOR2b	*Alnus*-*Betula*-*Ulmus*-*Corylus*	378-446	5690-6730	6470-7540
			MOR2a	*Betula*-*Corylus*-*Alnus*-*Ulmus*	446-471	6730-7100	7540-7910
MOR1	*Betula*-*Salix*-*Corylus avellana*-type	471-502	-	-	-	7100-9920	7910-11010

[1] '*c.*' denotes estimated age based on extrapolation from 70 cm to surface; see Section 8.1.3.3 for discussion of chronological uncertainties.

Table 35. Dimensions of cereal-type and large Poaceae pollen grains from Morvich. Italics denote minimum size estimates from damaged or partially concealed grains.

Depth (cm)	**Age ^{14}C BP (cal BP)**	**Annulus diameter (μm)**	**Grain length x width (μm)**	**Average diameter (μm)**	**Identification**
0	present	8.75	33.75 x 32.5	33.125	*Hordeum* group
2	modern	13.75	37.5 x 38.75	38.125	?*Hordeum* group
		11.25	32.5 x 32.5	32.5	?*Hordeum* group
		10.0	37.5 x 35.0	36.25	*Hordeum* group
		8.75	36.875 x 32.5	34.688	*Hordeum* group
		8.75	35.0 x *33.75*	*34.375*	*Hordeum* group
4	80 (modern)	11.25	37.5 x 36.875	37.188	? *Hordeum* group
		10.0	37.5 x 35.0	36.25	*Hordeum* group
		10.0	*37.5 x 31.25*	*34.375*	*Hordeum* group
		10.0	36.25 x *31.25*	*33.75*	*Hordeum* group
		10.0	35.0 x 30.0	32.5	*Hordeum* group
		9.375	33.75 x 33.75	33.75	*Hordeum* group
		9.375	30.0 x 28.75	29.375	Poaceae anl-D>8 μm
		8.75	37.5 x 32.5	35.0	*Hordeum* group
		8.75	33.75 x 32.5	33.125	*Hordeum* group
		8.75	31.875 x 28.75	30.313	Poaceae anl-D>8 μm
		8.75	*31.25* x 36.25	*33.75*	*Hordeum* group
		8.75	*? x 28.75*	?	Poaceae anl-D>8 μm
8	160 (140)	11.25	*40.0 x 43.75*	*41.875*	*Avena/Triticum* group
		11.25	36.25 x 35.625	35.938	*Hordeum* group
		11.25	32.5 x 35.0	33.75	*Hordeum* group
		10.0	37.5 x 32.5	35.0	*Hordeum* group
		10.0	36.25 x *28.125*	*32.188*	*Hordeum* group
		10.0	35.0 x 40.0	37.5	*Hordeum* group
		10.0	32.5 x 30.625	31.563	Poaceae anl-D>8 μm
		8.75	35.625 x 33.125	34.375	*Hordeum* group
		8.75	32.5 x 32.5	32.5	*Hordeum* group
		8.75	31.25 x 26.25	28.75	Poaceae anl-D>8 μm
		8.75	? (broken)	?	Poaceae anl-D>8 μm
12	*c.*230 (290)	11.25	48.75 x 43.75	46.25	*Avena/Triticum* group
		11.25	*42.5 x 28.75*	*35.625*	*Hordeum* group
		11.25	37.5 x 36.25	36.875	*Hordeum* group
		11.25	36.25 x 33.75	35.0	*Hordeum* group
		11.25	36.25 x 32.5	34.375	*Hordeum* group
		11.25	*36.25 x 32.5*	*34.375*	*Hordeum* group
		11.25	35.0 x 40.0	37.5	*Hordeum* group
		11.25	35.0 x 36.25	35.625	*Hordeum* group
		11.25	*35.0* x 32.5	*33.75*	*Hordeum* group
		11.25	*27.5* x 36.25	31.875	Poaceae anl-D>8 μm
		10.625	36.25 x 35.0	35.625	*Hordeum* group
		10.0	43.75 x *30.0*	*36.875*	*Hordeum* group
		10.0	*37.5 x 31.25*	*34.375*	*Hordeum* group
		10.0	36.25 x 36.25	36.25	*Hordeum* group
		10.0	36.25 x 35.0	35.625	*Hordeum* group
		10.0	35.0 x 32.5	33.75	*Hordeum* group
		10.0	33.75 x 32.5	33.125	*Hordeum* group

Table 35. Continued.

Depth (cm)	Age ^{14}C BP (cal BP)	Annulus diameter (µm)	Grain length x width (µm)	Average diameter (µm)	Identification
12	*c.*230 (290)	10.0	33.75 x 31.25	32.5	*Hordeum* group
		10.0	? (broken)	?	Poaceae anl-D>8 µm
		9.375	32.5 x 33.75	33.125	*Hordeum* group
		8.75	36.25 x 32.5	34.375	*Hordeum* group
		8.75	36.25 x 31.25	33.75	*Hordeum* group
		8.75	35.0 x *31.25*	*33.125*	*Hordeum* group
		8.75	35.0 x *31.25*	*33.125*	*Hordeum* group
		8.75	33.75 x 33.75	33.75	*Hordeum* group
		8.75	33.125 x 31.25	32.188	*Hordeum* group
		8.75	*32.5 x 33.75*	*33.125*	*Hordeum* group
		8.75	29.375 x 31.25	30.313	Poaceae anl-D>8 µm
16	*c.*310	11.875	35.0 x 37.5	36.25	*Hordeum* group
		11.25	42.5 x *32.5*	*37.5*	*Hordeum* group
		11.25	31.25 x 31.875	31.563	Poaceae anl-D>8 µm
		11.25	*30.0 x 33.75*	*31.875*	Poaceae anl-D>8 µm
		10.625	*41.25 x 37.5*	*39.375*	*Hordeum* group
		10.0	33.75 x 33.75	33.75	*Hordeum* group
		9.375	32.5 x 32.5	32.5	*Hordeum* group
		9.375	*25.0 x 32.5*	*28.75*	Poaceae anl-D>8 µm
		8.75	*35.0 x 31.25*	*33.125*	*Hordeum* group
		8.75	32.5 x *32.5*	*32.5*	*Hordeum* group
		8.75	32.5 x 30.625	31.563	Poaceae anl-D>8 µm
		8.75	31.25 x *30.0*	*30.625*	Poaceae anl-D>8 µm
20	*c.*390 (470)	10.0	45.0 x 43.75	44.375	*Avena/Triticum* group
		10.0	36.25 x 36.25	36.25	*Hordeum* group
		10.0	34.375 x 33.75	34.063	*Hordeum* group
		10.0	32.5 x 35.0	33.75	*Hordeum* group
		10.0	32.5 x 30.0	31.25	Poaceae anl-D>8 µm
		10.0	*? x 36.25*	? (crumpled)	Poaceae anl-D>8 µm
		8.75	36.25 x 35.0	35.625	*Hordeum* group
		8.75	31.25 x 33.75	32.5	*Hordeum* group
		8.75	*31.25* x 33.75	*32.5*	*Hordeum* group
24	*c.*470 (510)	8.75	41.25 x *31.25*	*36.25*	*Hordeum* group
		8.75	32.5x *32.5*	*32.5*	*Hordeum* group
28	550 (540)	10.0	41.25 x *33.75*	*37.5*	*Hordeum* group
		10.0	40.0 x 38.75	39.375	*Hordeum* group
		10.0	37.5 x *28.75*	*33.125*	*Hordeum* group
		10.0	*25.0 x 43.75*	*34.375*	*Hordeum* group
		8.75	33.75 x 31.25	32.5	*Hordeum* group
32	620 (600)	10.0	33.75 x 33.75	33.75	*Hordeum* group
		10.0	*33.75 x 32.5*	*33.125*	*Hordeum* group
		10.0	32.5 x 35.0	33.75	*Hordeum* group
		8.75	32.5 x 30.0	31.25	Poaceae anl-D>8 µm
		8.125	33.75 x 33.75	33.75	*Hordeum* group
36	700 (660)	11.25	33.75 x 33.75	33.75	*Hordeum* group
		10.625	36.25 x 33.75	35.0	*Hordeum* group
		10.0	38.75 x 40.0	39.375	*Hordeum* group
		10.0	*35.0 x 35.0*	*35.0*	*Hordeum* group
		8.75	36.25 x 33.75	35.0	*Hordeum* group

Table 35. Continued.

Depth (cm)	**Age ^{14}C BP (cal BP)**	**Annulus diameter (μm)**	**Grain length x width (μm)**	**Average diameter (μm)**	**Identification**
36	700 (660)	8.75	33.75 x 31.25	32.5	*Hordeum* group
40	780 (680)	11.25	33.75 x 32.5	33.125	*Hordeum* group
		11.25	31.875 x 36.875	34.375	*Hordeum* group
		8.75	35.0 x 31.25	33.125	*Hordeum* group
		8.125	32.5 x 26.25	29.375	Poaceae anl-D>8 μm
44	860 (740)	11.25	41.25 x 36.25	38.75	*Hordeum* group
		11.25	40.0 x 35.0	37.5	*Hordeum* group
		11.25	36.25 x 36.25	36.25	*Hordeum* group
		8.75	33.75 x 33.75	33.75	*Hordeum* group
		8.75	33.75 x *30.0*	*31.875*	Poaceae anl-D>8 μm
		8.125	37.5 x 33.75	35.625	*Hordeum* group
48	940 (830)	10.0	40.0 x 37.5	38.75	*Hordeum* group
		10.0	*33.75 x 33.75*	*33.75*	*Hordeum* group
		10.0	*? x 35.0*	? (crumpled)	Poaceae anl-D>8 μm
52	1010 (930)	10.0	43.75 x 36.875	40.313	*Avena/Triticum* group
		10.0	36.25 x 36.25	36.25	*Hordeum* group
		9.375	33.75 x 32.5	33.125	*Hordeum* group
56	1090 (970)	8.75	*36.25 x 37.5*	*36.875*	*Hordeum* group
60	1170 (1060)	10.0	32.5 x 31.25	31.875	Poaceae anl-D>8 μm
		8.75	32.5 x 32.5	32.5	*Hordeum* group
64	1250 (1170)	10.0	*38.75 x 33.75*	*36.25*	*Hordeum* group
		10.0	37.5 x *36.25*	*36.875*	*Hordeum* group
		10.0	32.5 x 32.5	32.5	*Hordeum* group
		8.125	35.0 x 37.5	36.25	*Hordeum* group
68	1330 (1270)	11.25	42.5 x 40.0	41.25	*Avena/Triticum* group
		8.75	*36.25 x 36.25*	*36.25*	*Hordeum* group
		8.75	40.0 x 33.75	36.875	*Hordeum* group
72	1420 (1300)	10.0	*38.75 x 32.5*	*35.625*	*Hordeum* group
		8.75	41.25 x 32.5	36.875	*Hordeum* group
80	1630 (1530)	10.0	46.25 x 40.0	43.125	*Avena/Triticum* group
		10.0	36.25 x 33.75	35.0	*Hordeum* group
		8.75	33.75 x 33.75	33.75	*Hordeum* group
84	1730 (1670)	11.25	36.25 x 36.25	36.25	*Hordeum* group
		10.0	38.75 x 33.75	36.25	*Hordeum* group
88	1840 (1740)	10.625	*33.75 x 33.75*	*33.75*	*Hordeum* group
		10.0	36.875 x 35.0	35.938	*Hordeum* group
		10.0	36.25 x 36.25	36.25	*Hordeum* group
		10.0	36.25 x 32.5	34.375	*Hordeum* group
		10.0	36.25 x 31.25	33.75	*Hordeum* group
		10.0	33.75 x *31.25*	*32.5*	*Hordeum* group
		9.375	36.25 x 33.75	35.0	*Hordeum* group
		8.75	35.0 x 35.0	35.0	*Hordeum* group
		8.75	32.5 x 35.0	33.75	*Hordeum* group
92	1950 (1880)	11.25	*40.0 x 37.5*	*38.75*	*Hordeum* group
		11.25	38.75 x 37.5	38.125	*Hordeum* group
		10.0	*33.75* x 42.5	*38.125*	*Hordeum* group
		8.75	*32.5 x 32.5*	*32.5*	*Hordeum* group
		8.75	30.0 x 36.875	33.438	*Hordeum* group
		8.125	*36.25 x 30.0*	*33.125*	*Hordeum* group

Table 35. Continued.

Depth (cm)	**Age ^{14}C BP (cal BP)**	**Annulus diameter (μm)**	**Grain length x width (μm)**	**Average diameter (μm)**	**Identification**
92	1950 (1880)	8.125	33.75 x 30.0	31.875	Poaceae anl-D>8 μm
96	2050 (1990)	11.25	33.75 x 36.25	35.0	*Hordeum* group
		10.0	38.75 x *30.0*	*34.375*	*Hordeum* group
		10.0	36.25 x 36.25	36.25	*Hordeum* group
		10.0	36.25 x 32.5	34.375	*Hordeum* group
		10.0	33.75 x 37.5	35.625	*Hordeum* group
		8.75	30.0 x 30.0	30.0	Poaceae anl-D>8 μm
		8.75	35.0 x 31.25	33.125	*Hordeum* group
		8.75	33.75 x 35.0	34.375	*Hordeum* group
		8.75	32.5 x 31.25	31.875	Poaceae anl-D>8 μm
		8.125	36.25 x *28.75*	*32.5*	*Hordeum* group
100	2160 (2140)	15.0	48.75 x 45.0	46.875	*Avena/Triticum* group
		12.5	36.25 x 36.25	36.25	*Hordeum* group
		11.25	40.0 x 37.5	38.75	*Hordeum* group
		11.25	*35.0* x 37.5	*36.25*	*Hordeum* group
		10.0	32.5 x 36.25	34.375	*Hordeum* group
		8.75	37.5 x *32.5*	*35.0*	*Hordeum* group
		8.75	*36.25* x 38.75	*37.5*	*Hordeum* group
104	2260 (2320)	11.25	42.5 x 41.25	41.875	*Avena/Triticum* group
		10.0	36.25 x 28.75	32.5	*Hordeum* group
		10.0	35.625 x 32.5	34.063	*Hordeum* group
		10.0	35.0 x 32.5	33.75	*Hordeum* group
		10.0	*31.25 x 33.75*	*32.5*	*Hordeum* group
		9.375	33.75 x 38.75	36.25	*Hordeum* group
108	2370 (2350)	8.75	36.25 x *38.75*	*37.5*	*Hordeum* group
		8.75	33.75 x *32.5*	*33.125*	*Hordeum* group
112	2470 (2640)	11.25	37.5 x 38.75	38.125	*Hordeum* group
		10.0	37.5 x 36.25	36.875	*Hordeum* group
		8.75	*40.0 x 38.75*	*39.375*	*Hordeum* group
116	2580 (2740)	10.0	35.625 x 28.75	32.188	*Hordeum* group
		10.0	35.0 x 33.75	34.375	*Hordeum* group
		8.75	*26.25 x 30.0*	*28.125*	Poaceae anl-D>8 μm
120	2690 (2770)	10.0	33.75 x 37.5	35.625	*Hordeum* group
124	2820 (2920)	8.75	*35.0 x 38.75*	*36.875*	*Hordeum* group
		8.75 (corroded)	35.0 x 33.75	34.375	*Hordeum* group
128	2940 (3070)	8.75	38.75 x 33.75	36.25	*Hordeum* group
136	3190 (3380)	10.0	*36.25* x 40.0	*38.125*	*Hordeum* group
		10.0	*33.75* x 36.25	*35.0*	*Hordeum* group
140	3310 (3510)	12.5	38.125 x 33.75	35.938	*Hordeum* group
		11.25	37.5 x 37.5	37.5	*Hordeum* group
		10.0	37.5 x 37.5	37.5	*Hordeum* group
		8.75	*33.75* x 32.5	*33.125*	*Hordeum* group
148	3510 (3760)	10.0	38.75 x 36.25	37.5	*Hordeum* group
		10.0	37.5 x 35.0	36.25	*Hordeum* group

Table 35. Continued.

Depth (cm)	**Age ^{14}C BP (cal BP)**	**Annulus diameter (µm)**	**Grain length x width (µm)**	**Average diameter (µm)**	**Identification**
152	3540 (3920)	8.75	33.75 x 31.25	32.5	*Hordeum* group
156	3560 (3840)	8.75 7.5	36.25 x *31.25* 38.75 x *36.25*	*33.75* *37.5*	*Hordeum* group Poaceae >37 µm
160	3580 (3860)	8.75	42.5 x *33.75*	*38.125*	*Hordeum* group
164	3610 (3890)	8.75	36.25 x 31.25	33.75	*Hordeum* group
168	3630 (3920)	10.0	37.5 x 33.75	35.625	*Hordeum* group
172	3640 (3960)	11.25 11.25 10.0 9.375 8.75 8.125	*36.25 x 46.25* 38.75 x 36.25 33.75 x 32.5 36.25 x 33.75 40.0 x 33.75 35.0 x 32.5	*41.25* 37.5 33.125 35.0 36.875 33.75	*Avena/Triticum* group *Hordeum* group *Hordeum* group *Hordeum* group *Hordeum* group *Hordeum* group
176	3680 (3980)	11.25 9.375	31.25 x 35.0 32.5 x 33.75	33.125 33.125	*Hordeum* group *Hordeum* group
180	3700 (4030)	8.75 8.75	41.25 x 33.75 36.25 x 33.75	37.5 35.0	*Hordeum* group *Hordeum* group
184	3720 (4020)	11.25	36.25 x 35.0	35.625	*Hordeum* group
196	3790 (4150)	8.75	37.5 x 37.5	37.5	*Hordeum* group
204	3840 (4230)	10.0 10.0 8.75	*38.75 x 35.0* 33.75 x 28.75 *40.0 x 33.75*	*36.875* 31.25 *36.875*	*Hordeum* group Poaceae anl-D>8 µm *Hordeum* group
212	3890 (4330)	8.125	*31.25 x 33.75*	*32.5*	*Hordeum* group
220	3940 (4410)	8.75 8.125	35.0 x 32.5 33.75 x 32.5	33.75 33.125	*Hordeum* group *Hordeum* group
228	3980 (4420)	11.25	31.25 x *38.75*	*35.0*	*Hordeum* group
244	4070 (4530)	8.75	*35.0 x 33.75*	*34.375*	*Hordeum* group
252	4110 (4740)	8.75	*42.5 x 35.0*	*38.75*	*Hordeum* group
264	4180 (4720)	10.0	38.75 x *30.0*	*34.375*	*Hordeum* group
272	4210 (4740)	8.75	35.0 x 36.25	35.625	*Hordeum* group
280	4350 (4870)	11.25	*36.25* x 42.5	*39.375*	*Hordeum* group
296	4570 (5290)	11.25 8.75	38.75 x 38.75 32.5 x 32.5	38.75 32.5	*Hordeum* group *Hordeum* group
300	4620 (5310)	9.375 8.75	35.0 x 36.25 40.0 x 35.0	35.625 37.5	*Hordeum* group *Hordeum* group
304	4670 (5410)	8.75	37.5 x 32.5	35.0	*Hordeum* group
340	5170 (5920)	10.0	36.25 x 35.0	35.625	*Hordeum* group
364	5440 (6220)	8.75	*36.25* x 35.0	*35.625*	*Hordeum* group
428	6450 (7330)	10.0	33.75 x 32.5	33.125	*Hordeum* group
460	6940 (7710)	10.0	35.0 x *32.5*	*33.75*	*Hordeum* group
470	7090 (7850)	10.0	36.25 x 32.5	34.375	*Hordeum* group
476	7480 (8250)	10.0	43.75 x 43.75	43.75	?*Avena/Triticum* group
484	8230 (9210)	8.75	38.75 x 37.5	38.125	*Hordeum* group

Table 36. Summary of charcoal data from Morvich.

Age of charcoal peaks	Relative magnitude
9730-7090 BP (10960-7850 cal BP)	Very high; peaks at 9730, 8600-8230 and 7090 BP (10960, 9520-9210, 7850 cal BP)
7090-6760 BP (7850-7550 cal BP)	High; peaks at 6940, 6820-6760 BP (7710, 7620-7550 al BP)
6760-6570 BP (7550-7400 cal BP)	Moderate values
6570-5380 BP (7400-6460 cal BP)	Low, consistent values; slightly higher at 5440-5380 BP (6220-6460 cal BP)
5380-3310 BP (6460-3510 cal BP)	Very low and intermittent; small peaks at 5110, 4890, 4620, 3910, 3720, 3640-3630 BP (5900, 5610, 5310, 4370, 4020, 3960-3920 cal BP)
3310-1520 BP (3510-1400 cal BP)	Consistent record, rising to 2160 BP (2140 al BP) before declining gradually
1520-0 BP (1400 cal BP-present)	Rising values, with peaks at *c.*700, *c.*470 and *c.*160 BP (*c.*660, *c.*510, *c.*140 cal BP), before declining to the surface

Table 37. Results of charcoal size class regression analyses at Morvich.

Charcoal size classes	R^2	Charcoal size classes	R^2
10-25 μm *vs.* 26-50 μm	0.91	26-50 μm *vs.* 51-75 μm	0.87
10-25 μm *vs.* 51-75 μm	0.76	26-50 μm *vs.* >75 μm	0.73
10-25 μm *vs.* >75 μm	0.64	51-75 μm *vs.* >75 μm	0.80

Table 38. Comparison of local pollen assemblage zones from study sites in Glen Affric and Kintail.

Date (^{14}C BP)	Torran Beithe	Carnach Mór	Camban	Morvich
0	Cyperaceae-Poaceae-*Calluna*	Cyperaceae-*Calluna*	Poaceae-Cyperaceae-*Potentilla*-type Poaceae-Cyperaceae	Poaceae-Cyperaceae
-	*Calluna*-Cyperaceae	Poaceae-*Calluna*-Cyperaceae	Poaceae-Cyperaceae-*Calluna*-*Betula* *Betula*-Poaceae-*Salix*-*Calluna*-*Myrica*	*Betula*-Poaceae-Cyperaceae
1000			*Betula*-Poaceae-*Salix*-Cyperaceae *Salix*-Poaceae-*Betula*	
-				
2000		Poaceae-*Myrica*-*Calluna*	*Calluna*-Poaceae-*Betula*-Cyperaceae-*Potentilla*-type	*Betula*-Poaceae-*Alnus*-Corylus
-	*Calluna*-Cyperaceae-*Pinus*		Poaceae-*Betula*-Cyperaceae-*Filipendula*	
3000		*Calluna*-Cyperaceae-*Betula*		*Betula*-Poaceae-*Alnus*
-			*Salix*-*Betula*-Poaceae-*Calluna* *Alnus*-Poaceae-*Betula*	
4000		Cyperaceae-*Betula*-*Alnus*-*Pinus*	*Betula*-*Alnus*-Poaceae-*Calluna*	
-			*Betula*-*Salix*-Poaceae	
5000	*Pinus*-*Calluna*-*Betula*	*Betula*-*Pinus*-*Alnus*-Cyperaceae		*Alnus*-*Betula*
-				
6000				*Alnus*-*Betula*-*Ulmus*-*Corylus*
-	*Pinus*-*Betula*-Cyperaceae			*Betula*-*Corylus*-*Alnus*-*Ulmus*
7000	*Betula*-*Pinus*-*Calluna*-*Corylus*	*Betula*-*Salix*-*Corylus*		
-				
8000	*Betula*-*Corylus avellana*-type			
-				*Betula*-*Salix*-*Corylus avellana*-type
9000		*Betula*-*Sorbus*-Cyperaceae		
-				

Table 39. Dates for *Pinus* expansion and decline in West Affric and Kintail.

Site	**Marked percentage and absolute increase**	**Main rise & maximum values (where different)**	**Decline**
Torran Beithe	7205 BP* (7950 cal BP)	6790 BP* (7580 cal BP)/4390-3765 BP* (4410-4110 cal BP) (35%)	3765 BP (4410 cal BP)
Carnach Mór	7420 BP (8160 cal BP)	5880 BP (4560 cal BP) (29%); local growth at 5340 BP (6140 cal BP) and 4100-3840 BP (4560-4230 cal BP)	3840 BP (4230 cal BP)
Camban	Pre-dating sedimentation	absent/4390-4110 BP* (4930-4600 cal BP) (10%)	*c.*3630 BP (3920 cal BP)
Morvich	*c.*7105 BP (7910 cal BP) (hiatus)	6760 BP (7550 cal BP) (15%)	*c.*3910 BP (4270 cal BP)

* Local growth inferred from presence of *Pinus* stomata.

Table 40. Dates for *Alnus* expansion and decline in West Affric and Kintail.

Site	**Rational limit**	**Maximum**	**Decline**
Torran Beithe	6360 BP (7230 cal BP)	5630 BP (6410 cal BP) (18%)	3600 BP (3890 cal BP) (stepped)
Carnach Mór	6080 BP (6900 cal BP)	4460 BP (5040 cal BP) (32%)	3840 BP (4230 cal BP) (stepped)
Camban	Pre-dating sedimentation	3700 BP (4030 cal BP) (48%)	3630 BP (3920 cal BP)
Morvich	c.7065 BP (7860 cal BP) (above hiatus)	6150 BP (6930 cal BP) (75 %)	4210 BP (4740 cal BP)

Table 41. Comparison of Holocene climatic inferences from West Affric and Kintail with selected literature data. Carnach Mór (CAR), Camban (CAM), Morvich (MOR). Disparities noted in italics.

Climatic inference from Affric data	**Evidence from Glen Affric & Kintail**	**Other**
Drier *c.*7400-6500 BP (8140-7380 cal BP)	**TOR**: prolonged erosion & slight rise in charcoal at *c.*7400-6540 BP (8140-7390 cal BP). **MOR**: short hiatus at *c.*7100 BP (7910 cal BP)	Dubois & Ferguson (1985): between inferred 'pluvials' at 7300 BP (8040 cal BP) & 6200 BP (7090 cal BP). Bridge *et al.* (1990): major *Pinus* expansion (6800-6600 BP,7580-7380 cal BP) Anderson (1996, 1998): major dry/warm shift, promoting *Pinus* expansion, rise in charcoal at Glen Carron at 6850-6775 BP (7400-7225 cal BP) Binney (1997): high treelines at 7250-6600 BP (8030-7470 cal BP) Alley *et al.* (1997): 7700-7200 BP (8400-8000 cal BP) - widespread, short-lived cool, dry or windy event.
Drier *c.*5500-4900 BP (6290-5630 cal BP)	**TOR**: *Quercus-Pinus* competition (*c.*5520-4960 BP, 6300-5690 cal BP), rise in charcoal (5240 BP/5970 cal BP & 5070 BP/5820 cal BP) **MOR**: increased *Betula*, lower *Alnus*, *C. avellana*-type & *Salix* (5490 BP, 6290 cal BP)), rise in charcoal (5380-4890 BP, 6460-5610 cal BP)	Pennington *et al.* (1972): *c.6000-5000 BP (6800 5730 cal BP)- natural retrogressive succession to blanket bog.* Bridge *et al.* (1990): drier (trough in *Pinus* macrofossils) at *c.*5700-5250 BP (6480-5960 cal BP). Anderson (1996, 1998): major dry/warm shift, favouring *Pinus*, increased charcoal at 5300-5100 BP (6090-5780 cal BP) Binney (1997): *5400-5300 BP (6260-6090 cal BP)- regional decline in tree-line/canopy density* Smith (1996, 1998): 5600 BP (6380 cal BP) - drier (loch level reduction), *Pinus reduction c.5700-4800 BP (6500-5600 cal BP)*
Wetter *c.*4900-4300 BP (5630-4860 cal BP)	**TOR**: *Alnus-Pinus* competition (4620-4330 BP) **CAR**: maximum *Alnus* (4460 BP) **CAM**: peat accumulation commenced (c.4980 BP, 5730 cal BP), fall in *Betula* (4740 BP, 5550 cal BP); slight *Alnus* rise (4530-4220 BP, 5150-4740 cal BP); expansion of open ground (4480 BP, 5060 cal BP) **MOR**: 4270 BP (4840 cal BP) - decline in *C. avellana*-type & ferns	Bridge *et al.* (1990): *4970-4660 BP (5710-5420 cal BP) - second major expansion of Pinus wood & pollen throughout region* Anderson (1996, 1998): wet/cold shift at 4800-4200 BP (5500-4860 cal BP)
Warmer/drier/ continental *c.*4300-4000 BP (4860-4440 cal BP)	Maximum/higher *Pinus* (see Table 39) & increased *Quercus* in uplands. **MOR**: short-lived hiatus around 4200 BP (4730 cal BP)	Williams (1977), Birks & Williams (1983) – brief *Pinus* expansion at Loch Ashik, S. Skye Dubois & Ferguson (1985): *4200-3940 BP (4730-4410 cal BP)- 'pluvial'* Gear & Huntley (1991): 4400-4000 BP (4920-4440 cal BP)- warmer, *Pinus* range expansion northwards Anderson (1996, 1998): dry/warm shift at 4100-4000 BP (4560-4440 cal BP) Binney (1997): higher *Pinus* treeline/canopy density at 4300-4000 BP (4860-4440 cal BP)
Wetter/more oceanic from *c.*4200-3600 BP (4730-3890 cal BP)	**TOR**: high *Alnus* (3765-3320 BP, 4410-3510 cal BP), fall in *Pinus* (3765 BP, 4410 cal BP), fall in other AP & blanket peat spread from 3600 BP (3890 cal BP) **CAR**: mire-woodland fluctuations (4190-3870 BP, 4720-4280 cal BP) **CAM**: max. *Alnus* (3700-3630 BP, 4030-3920 cal BP), more open woods **MOR**: shift from *Alnus* to *Betula* shortly after 4200 BP (4730 cal BP)	Dubois & Ferguson (1985): 3300 BP (3470 cal BP)'pluvial' Gear & Huntley (1991): 4000 BP (4440 cal BP)- climatic deterioration, *Pinus* range contraction southwards in Britain & Fennoscandia Dixon (1994): 3700 BP (4030 cal BP)- wetter on valley side at Lairg. Anderson (1996, 1998): major shift to wetter/colder conditions at 3600-3500 BP (3890-3790 cal BP) Proxy pollen evidence from many Highland sites for wetter conditions (see Section 1.12).

Table 42. Comparison of tree and shrub pollen sums in surface samples and comparable subfossil records.

Site	**Tree & shrub pollen in surface sample (%TLP)**	**Age of comparable subfossil record**
Torran Beithe	44% (22% pre-plantation rise)	*c.*44% - 2030-1890 BP (1970-1830 cal BP), from 1460 BP (1330 cal BP) *c.*22% - single spectra at 1890 BP (1830 cal BP) & 1110 BP (980 cal BP); 230-120 BP (290-130 cal BP)
Carnach Mor	19%	From 3000 BP (3190 cal BP)
Camban	15% (3-6% pre-plantation rise)	*c.*15% - 2470-1960 BP (2650-1880 cal BP), from 640 BP (590 cal BP) *c.*6% - 320-70 BP (410 cal BP-modern)
Morvich	27%	3310 BP (3510 cal BP) (single spectrum), from *c.*780 BP (*c.*680 cal BP)

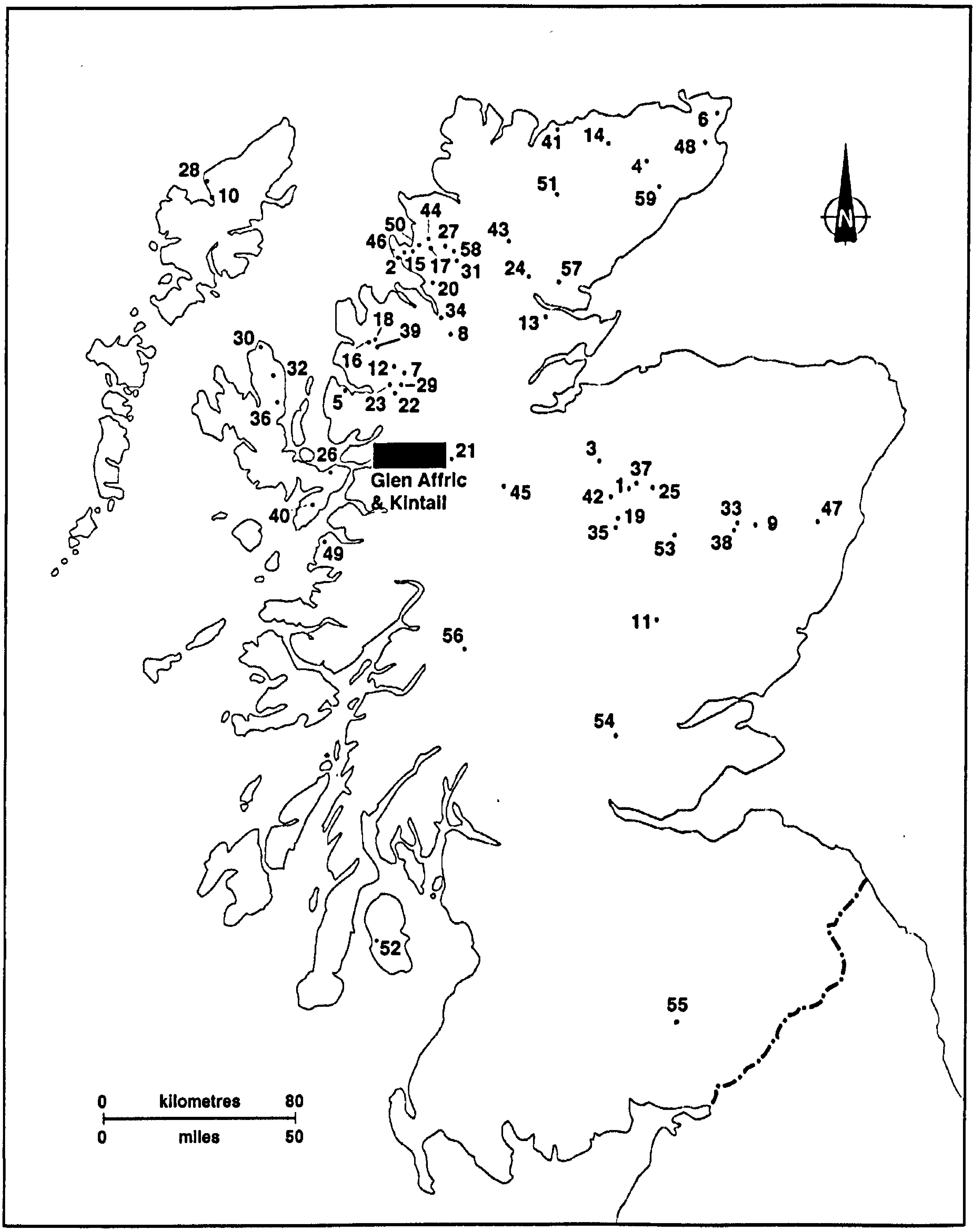


Figure 1. Location of study area in Glen Affric with palaeoecological and other sites mentioned in the text. See over for key; sites are listed in alphabetical order.

Key to Figure 1.

Site	Reference
1. Abernethy Forest	Birks (1970), Birks & Mathewes (1978)
2. Achiltibuie & Badentarbet	Bunting & Tipping (1997), Johansen in Pennington *et al.* (1972)
3. Allt na Feithe Sheilich	Birks (1975)
4. Altnabreac	Blackford *et al.* (1992)
5. Ardheslaig Loch & Bog	Bennett & Hill (1998)
6. Aukhorn	Robinson (1987)
7. Beinn Eighe	Durno & McVean (1959)
8. Beinn Dearg	Binney (1997), Anderson *et al.* (1998)
9. Braeroddach Loch	Edwards (1978), Edwards & Rowntree (1980), Edwards & Whittington (1993)
10. Callanish	Bohncke (1988)
11. Carn Dubh	Tipping (1995a)
12. Coille na Glas Leitre	Durno & McVean (1959), Kerslake (1982)
13. Coire Bog	Birks (1975)
14. Cross Lochs	Charman (1992, 1994)
15. Druim Bad a'Ghaill (peat)	Johansen in Pennington *et al.* (1972)
16. Eilean Dubh na Sroine	Kerslake (1982)
17. Eilean Mor	Kerslake (1982)
18. Eilean Subhainn (Subhainn Bog & Subhainn Lochan)	Kerslake (1982)
19. Gleann Einich	Binney (1997)
20. Glen Achall	Welsh (1999)
21. Glen Affric I, II, III	Tate (1995)
22. Glen Carron	Anderson (1996, 1998), Anderson *et al.* (1998)
23. Glen Torridon	Anderson (1996, 1998), Anderson *et al.* (1998)
24. Lairg (Achany Glen)	Smith (1996, 1998), Anderson *et al.* (1998), McCullagh & Tipping (1998)
25. Loch a'Chnuic	O'Sullivan (1974a)
26. Loch Ashik	Williams (1977), Birks & Williams (1983)
27. Loch Borralan	Pennington *et al.* (1972)
28. Loch Buailaval Beag	Fossitt (1990, 1996)
29. Loch Clair	Pennington *et al.* (1972)
30. Loch Cleat	Williams (1977), Birks & Williams (1983)
31. Loch Craggie	Pennington *et al.* (1972)
32. Loch Cuithir	Vasari & Vasari (1968), Birks & Williams (1983)
33. Loch Davan	Edwards (1978), Edwards & Whittington (1993)
34. Loch Droma	Kirk and Godwin (1963)
35. Loch Einich	Birks (1975)
36. Loch Fada	Vasari & Vasari (1968), Birks & Williams (1983)
37. Loch Garten	O'Sullivan (1974a)
38. Loch Kinord	Vasari & Vasari (1968)
39. Loch Maree	Birks (1972)
40. Loch Meodal	Williams (1977), Birks & Williams (1983)
41. Loch Mer	Gear (1989), Gear & Huntley (1991)
42. Loch Pityoulish	O'Sullivan (1976)
43. Loch Shin	Daniell (1997)
44. Loch Sionascaig (loch & peat profiles)	Pennington *et al.* (1972)
45. Loch Tarff	Pennington *et al.* (1972)
46. Loch Vatachan	Daniell (1997)
47. Loch of Park	Vasari & Vasari (1968)
48. Loch of Winless	Peglar (1979)

49. Lochan Doilead	Williams (1977)
50. Lochan Dubh	Kerslake (1982)
51. Lochstrathy	Gear (1989), Gear & Huntley (1991)
52. Machrie Moor, Arran	Boyd & Dickson (1987), Haggarty (1991), Barber (1997)
53. Morrone Birkwoods	Huntley (1994)
54. North Mains, Strathallan	Romans and Robertson (1983), Barclay (1989)
55. Over Rig	Tipping (1997)
56. Rannoch Moor	Bridge *et al.* (1990)
57. Rogart	Tipping pers. comm.
58. Strath Oykell (peat)	Johansen in Pennington *et al.* (1972)
59. Suisgill	Barclay (1985)

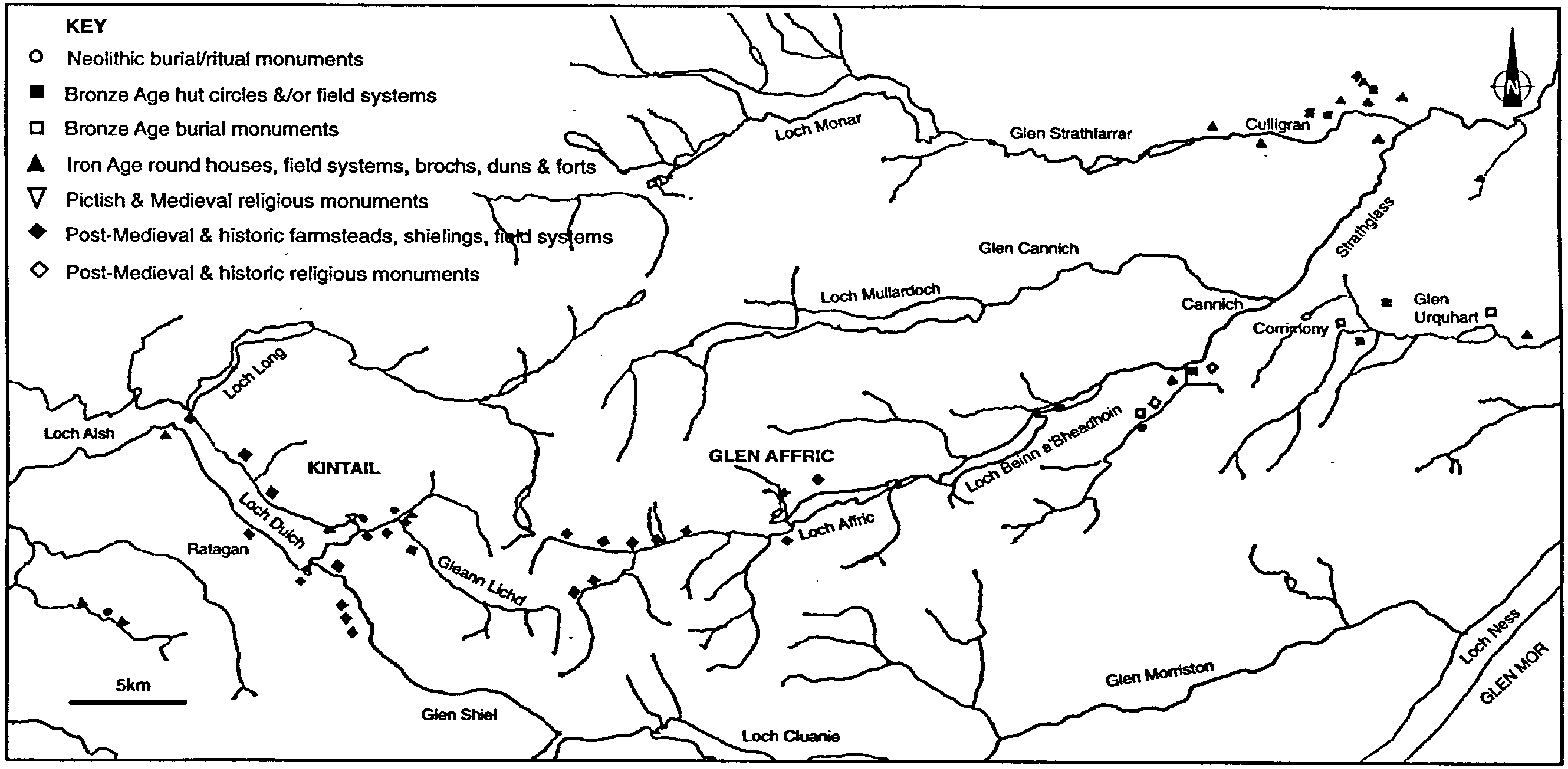


Figure 2. The location of Glen Affric in relation to geomorphological and archaeological sites named in the text. See Table 1 for more information.

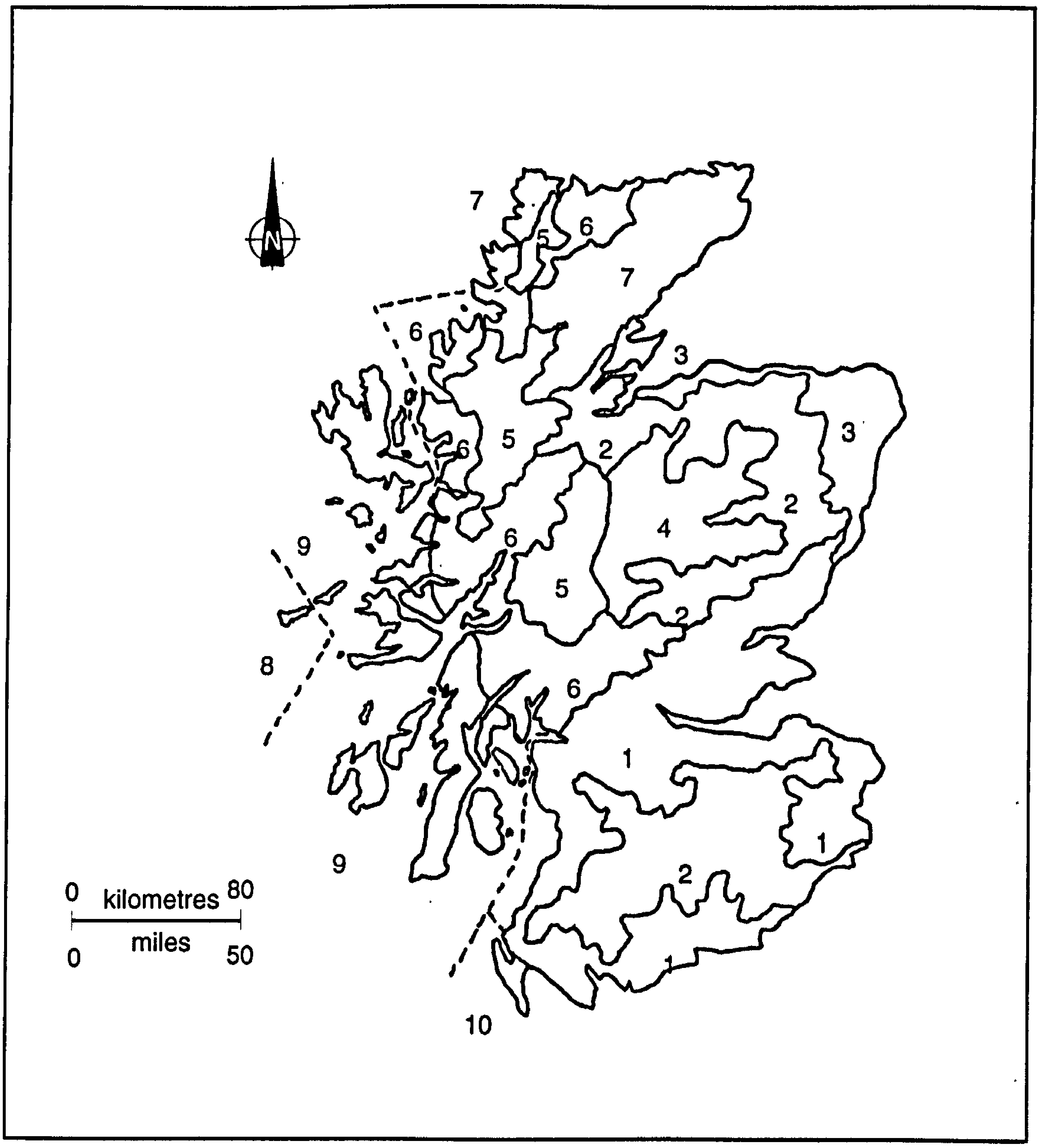


Figure 3. Biogeographical zonation of Scotland (after Usher and Balharry 1996), showing 10 zones defined for mainland Scotland and the Inner Hebrides. **1.** Central and Southern Lowlands, **2.** Grampian Fringe and Southern Uplands, **3.** East Coast, **4.** Cairngorm, **5.** Western Highlands, **6.** Western Highlands Fringe, **7.** Western Isles (north) and North Mainland, **8.** Barra and Tiree, **9.** Argyll and Inner Hebrides, **10.** Galloway Coast.

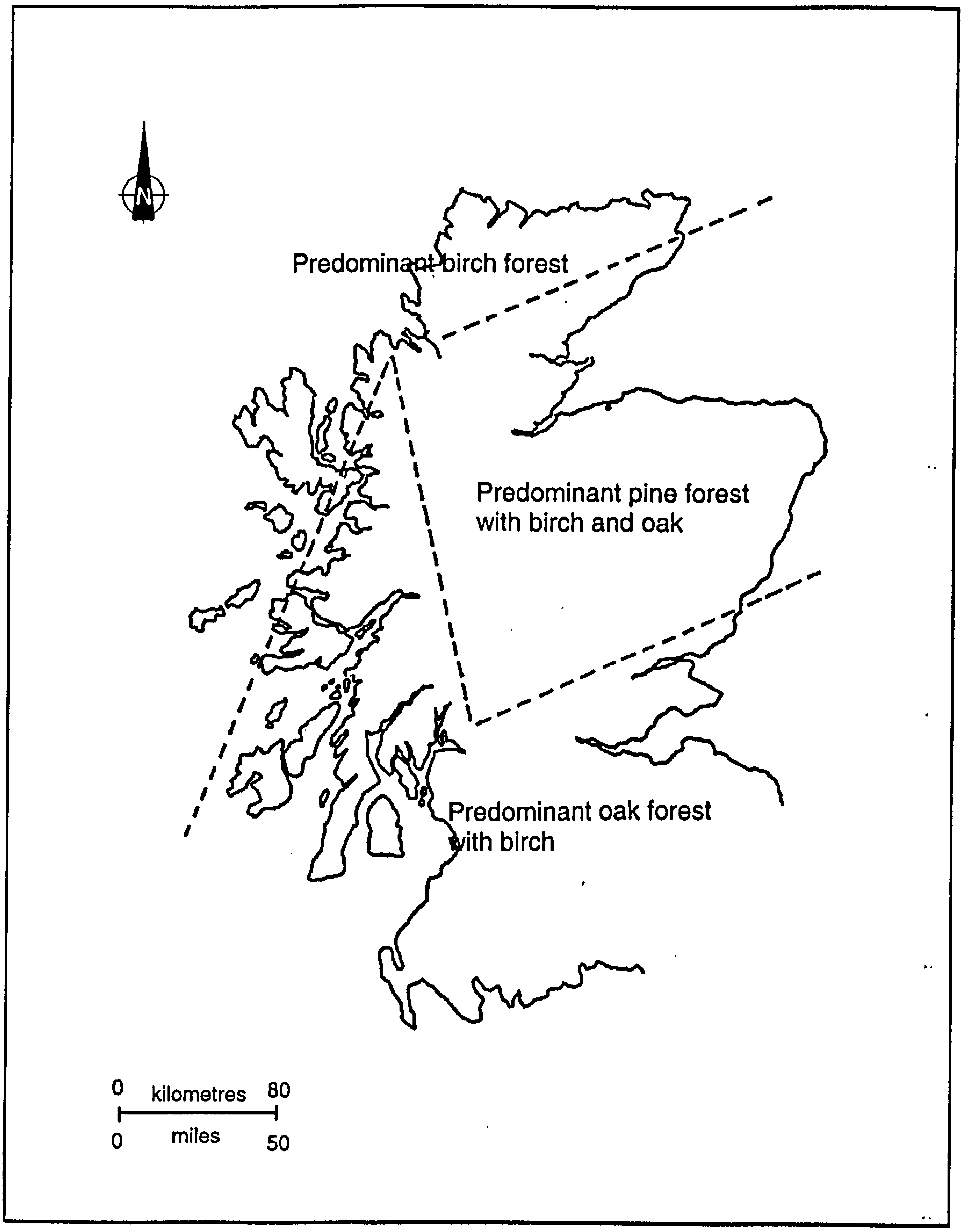


Figure 4. Potential woodland distribution map (after McVean and Ratcliffe 1962).

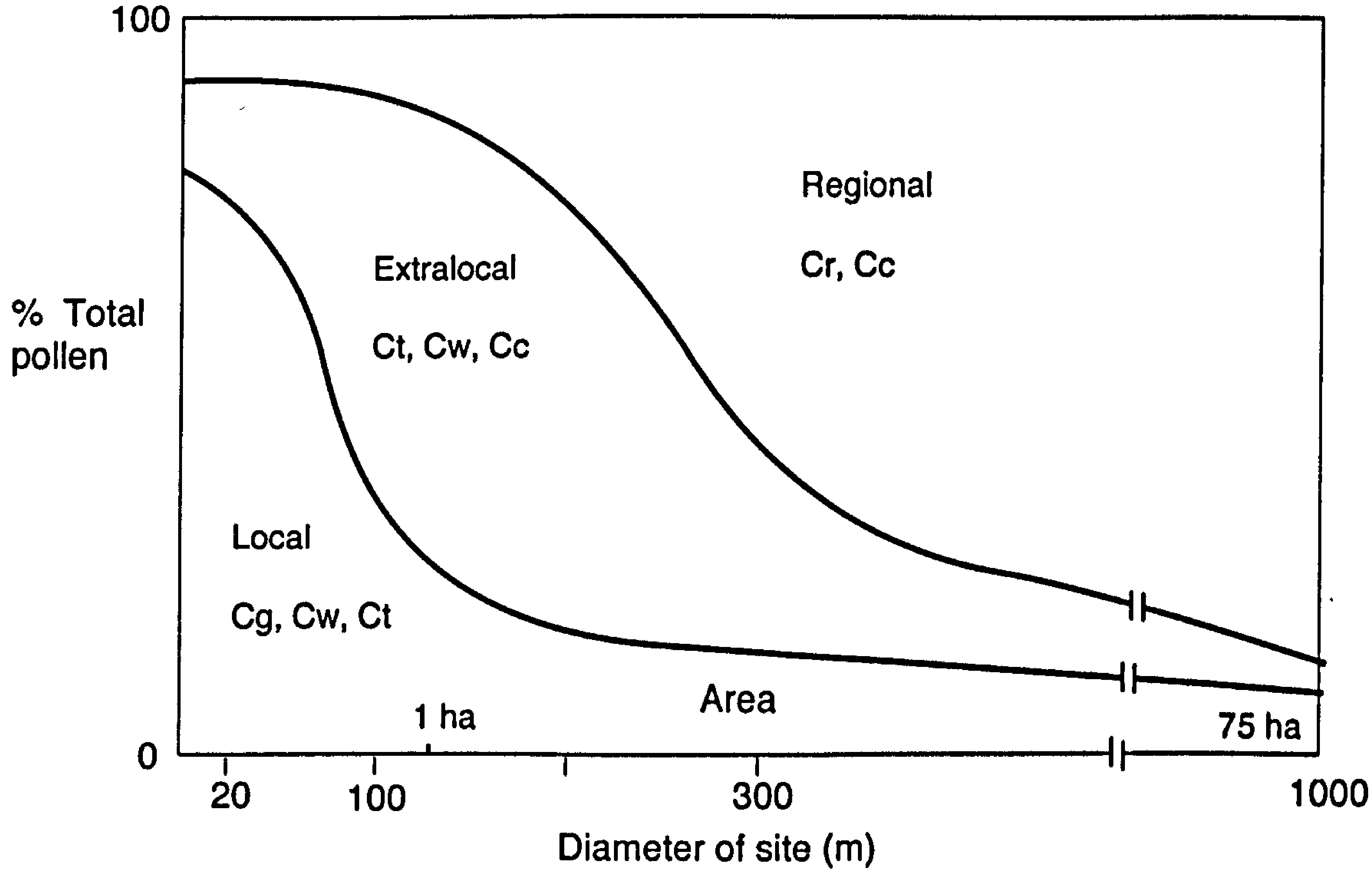


Figure 5. Jacobson and Bradshaw's (1981) model describing the relationship between the size of a site that has no inflowing streams, and the relative proportions of pollen originating from different areas around the site. See text for details.

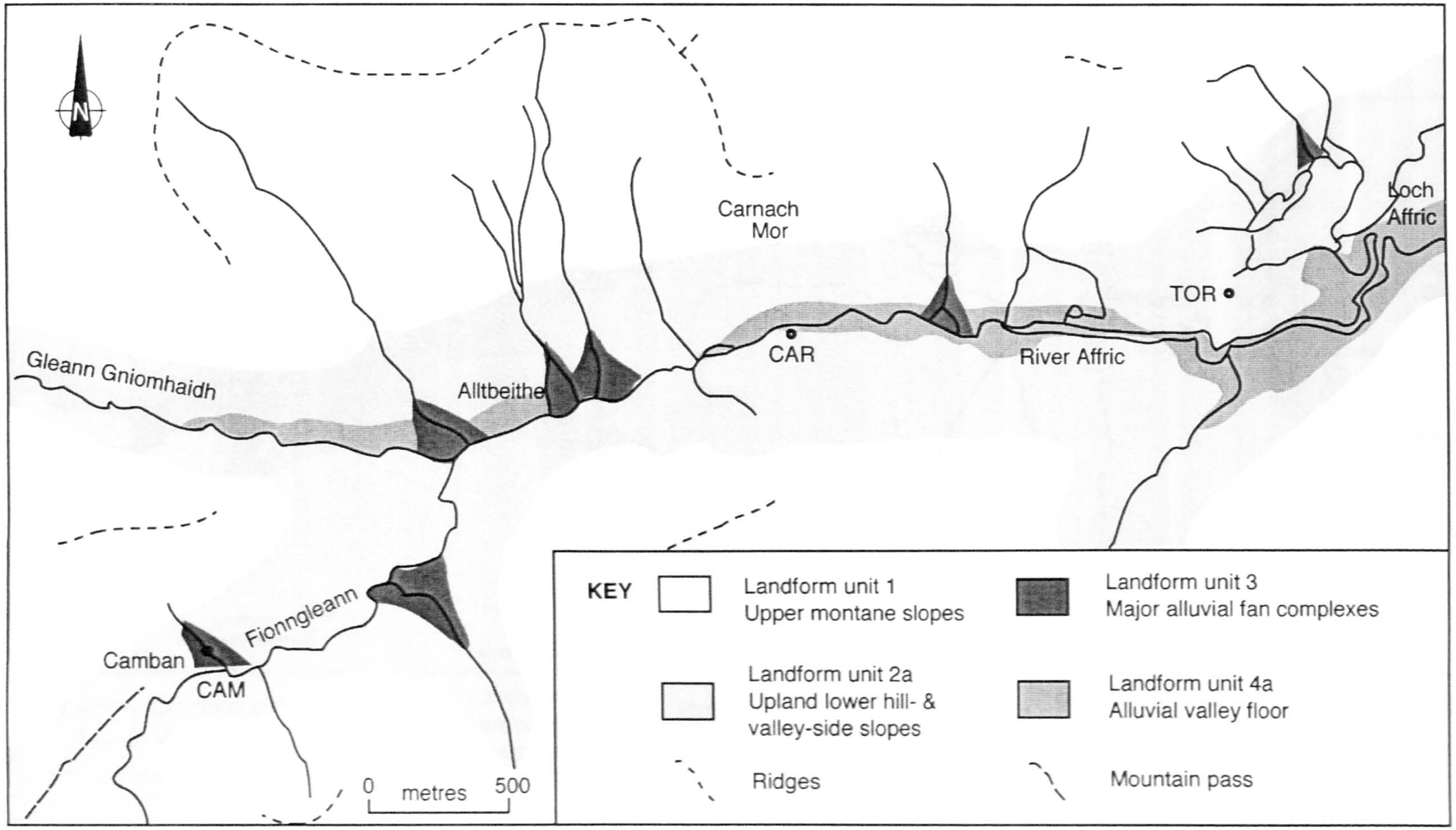


Figure 6 (a). Map of 'landform' units in Central and West Affric. See text for explanation.

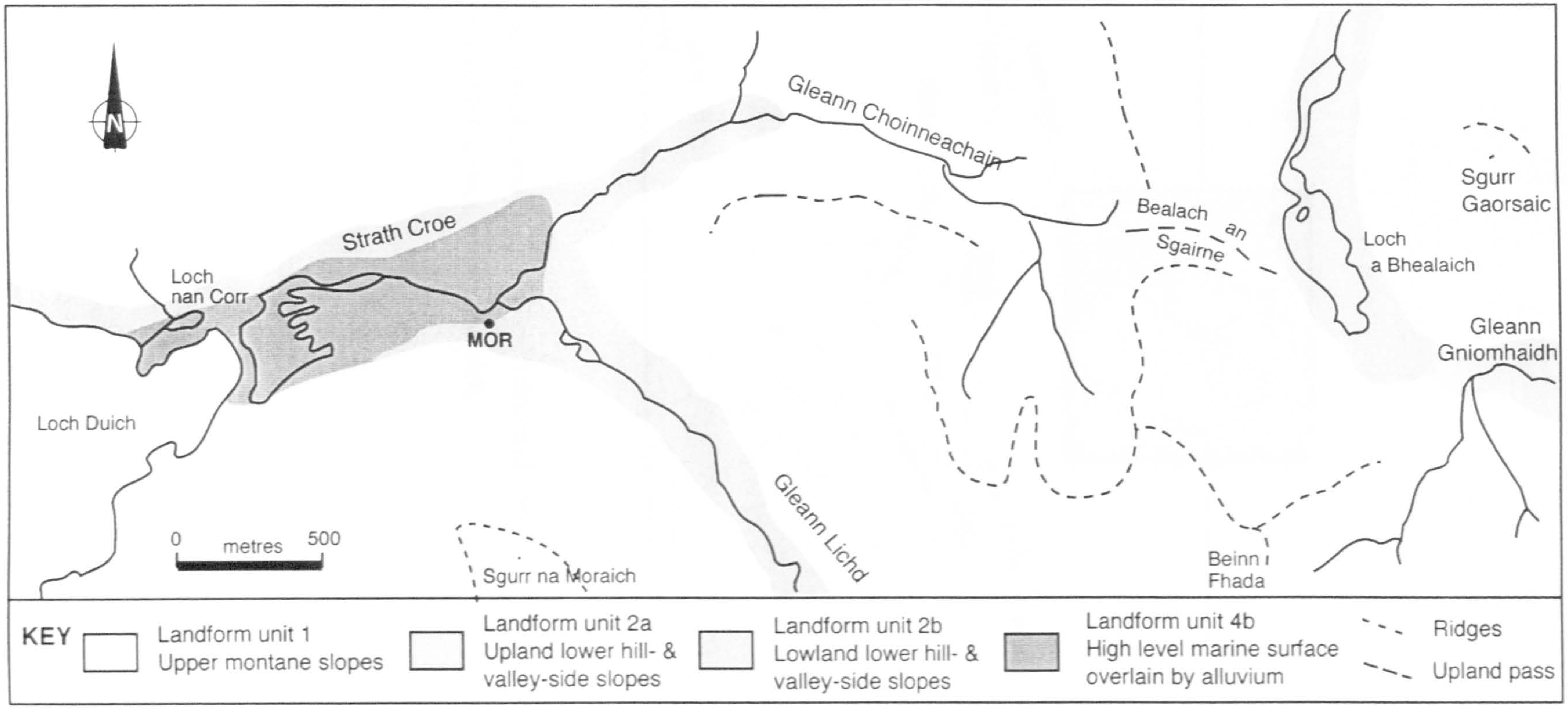


Figure 6 (b). Map of 'landform' units in Kintail. See text for explanation.

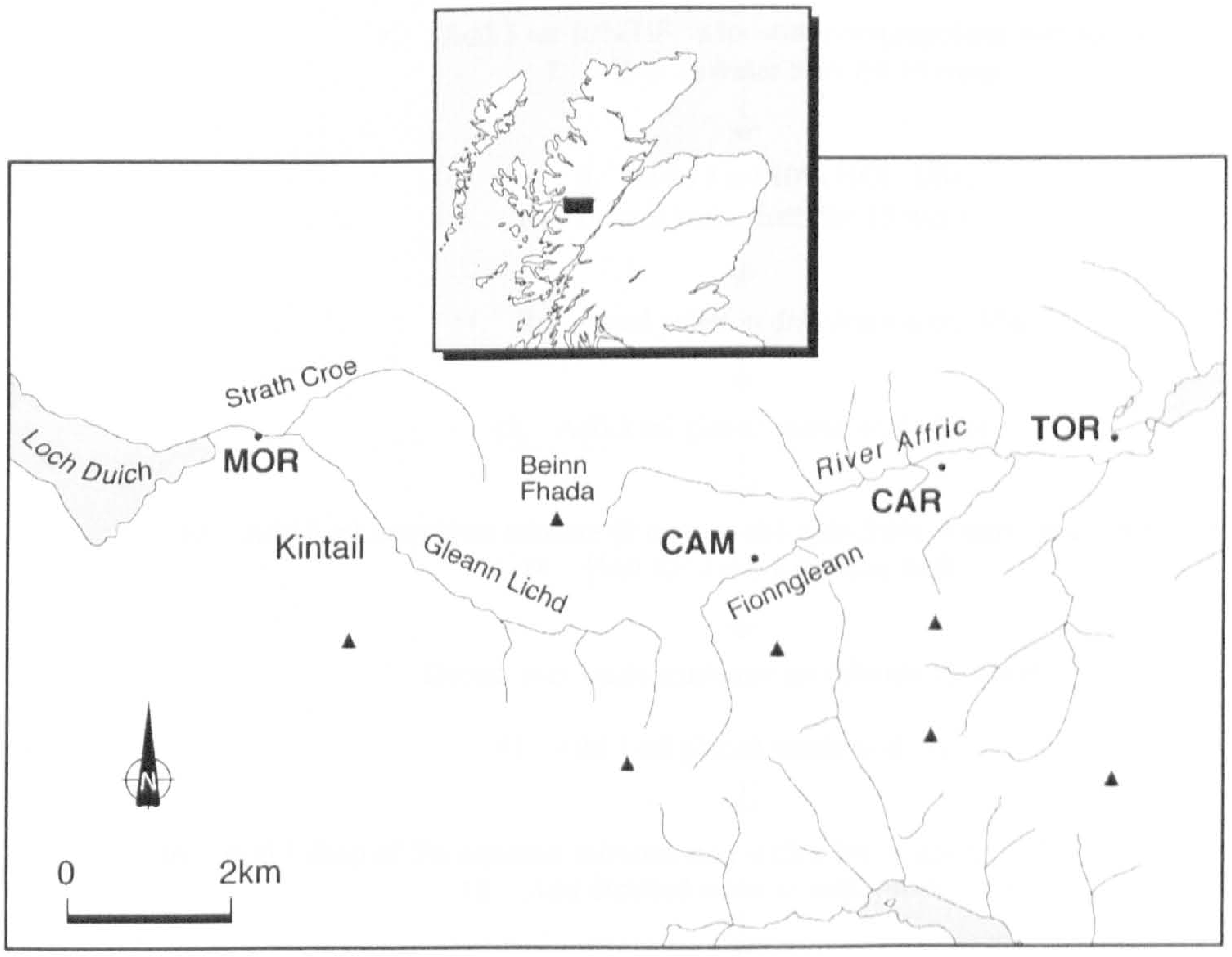


Figure 7. Location of pollen sites in Glen Affric and Kintail. TOR: Torran Beithe, CAR: Carnach Mór, CAM: Camban, MOR: Morvich.

1. Sub-sample cores at 0.5 cm vertical thickness,
0.5 cm^3 volumetric displacement into 3 ml of 10% HCl, at intervals of 2-8 cm
2. Add *Lycopodium* tablets and mix.

↓

Centrifuge at 3500 rpm for 3 minutes. Decant.

3. Add 3 ml 10% KOH, mix
4. Heat in boiling water bath on hotplate for 15 mins.
5. Sieve through 150 µm mesh into clean 15 ml graduated centrifuge tubes.

↓

Centrifuge in distilled water. Repeat until suspension is no longer dark.

6. If siliceous, add 3 ml 10% HCl. Mix.

↓

7. Add 3 ml 10% HF. Mix with polypropylene stirring rods.
8. Heat in water bath for 30 mins.

↓

9. Add 3 ml 10% HCl. Mix.
10. Heat in water-bath for 15 mins.

↓

11. Resuspend pellet in distilled water. Mix.

↓

12. Add 3 ml glacial acetic acid. Mix.

↓

13. Add 3 ml acetolysis mixture (9 parts acetic anhydride: 1 part concentrated H_2SO_4). Mix.
14. Heat for 2 mins in water bath.

↓

Decant into waste container on calcium carbonate.

15. Add 3 ml glacial acetic acid. Mix.

↓

16. Add 1 drop of 5% aqueous safranin, mix with a few drops of 10% KOH and leave for 1 min
17. Add distilled water to make up to 3 ml.

↓

18. Resuspend pellet in distilled water.

↓

19. Add 3 ml TBA. Mix.

↓

20. Add 1 ml TBA and mix.

↓

21. Add approximately 1 ml TBA and transfer to labelled 13 mm glass vial. Stopper.
22. Wrap each in paper towelling to protect.

↓

Centrifuge at 4000 rpm for 2 mins. Decant.

23. Add a minimum volume of silicone oil (12 500 cc viscosity).
24. Cover and place in drying cabinet overnight to evaporate remaining TBA.
25. Samples ready for mounting and sealing under a cover slip using nail polish.

Figure 8. Pollen processing procedure for fossil samples. Each arrow indicates centrifugation at 3500 rpm for 3 minutes, unless otherwise indicated, followed by decanting supernatant into waste bucket for neutralisation with calcium carbonate for safe disposal.

1. Place c.100 ml wet moss in a 150 ml conical flask.
2. Cover with 10% KOH.
3. Heat on hotplate for 30 mins, stirring frequently.
4. Sieve through 150 µm mesh into clean 15 ml graduated centrifuge tubes.

↓

Centrifuge in distilled water.

5. Repeat sieving, washing and centrifuging in distilled water until all moss has been well-washed.

↓

6. Sieve test-tube residue through 150 µm mesh.

↓

7. Resuspend pellet in distilled water. Mix.

↓

8. Add 3 ml glacial acetic acid. Mix.

↓

9. Add 3 ml acetolysis mixture (9 parts acetic anhydride: 1 part concentrated H_2SO_4). Mix.
10. Heat for 2 mins in water bath.

↓

Decant into waste container on calcium carbonate.

11. Add 3 ml glacial acetic acid. Mix.

↓

12. Add 1 drop of 5% aqueous safranin, mix with a few drops of 10% KOH and leave for 1 min
13. Add distilled water to make up to 3 ml.

↓

14. Resuspend pellet in distilled water.

↓

15. Add 3 ml TBA. Mix.

↓

16. Add 1 ml TBA and mix.

↓

17. Add approximately 1 ml TBA and transfer to labelled 13 mm glass vial. Stopper.
18. Wrap each in paper towelling to protect.

↓

Centrifuge at 4000 rpm for 2 mins. Decant.

19. Add a minimum volume of silicone oil (12 500 cc viscosity).
20. Cover and place in drying cabinet overnight to evaporate remaining TBA.
21. Samples ready for mounting and sealing under a cover slip using nail polish.

Figure 9. Pollen processing procedure for surface samples. Each arrow indicates centrifugation at 3500 rpm for 3 minutes, unless otherwise indicated, followed by decanting supernatant into waste bucket for neutralisation with calcium carbonate for safe disposal.

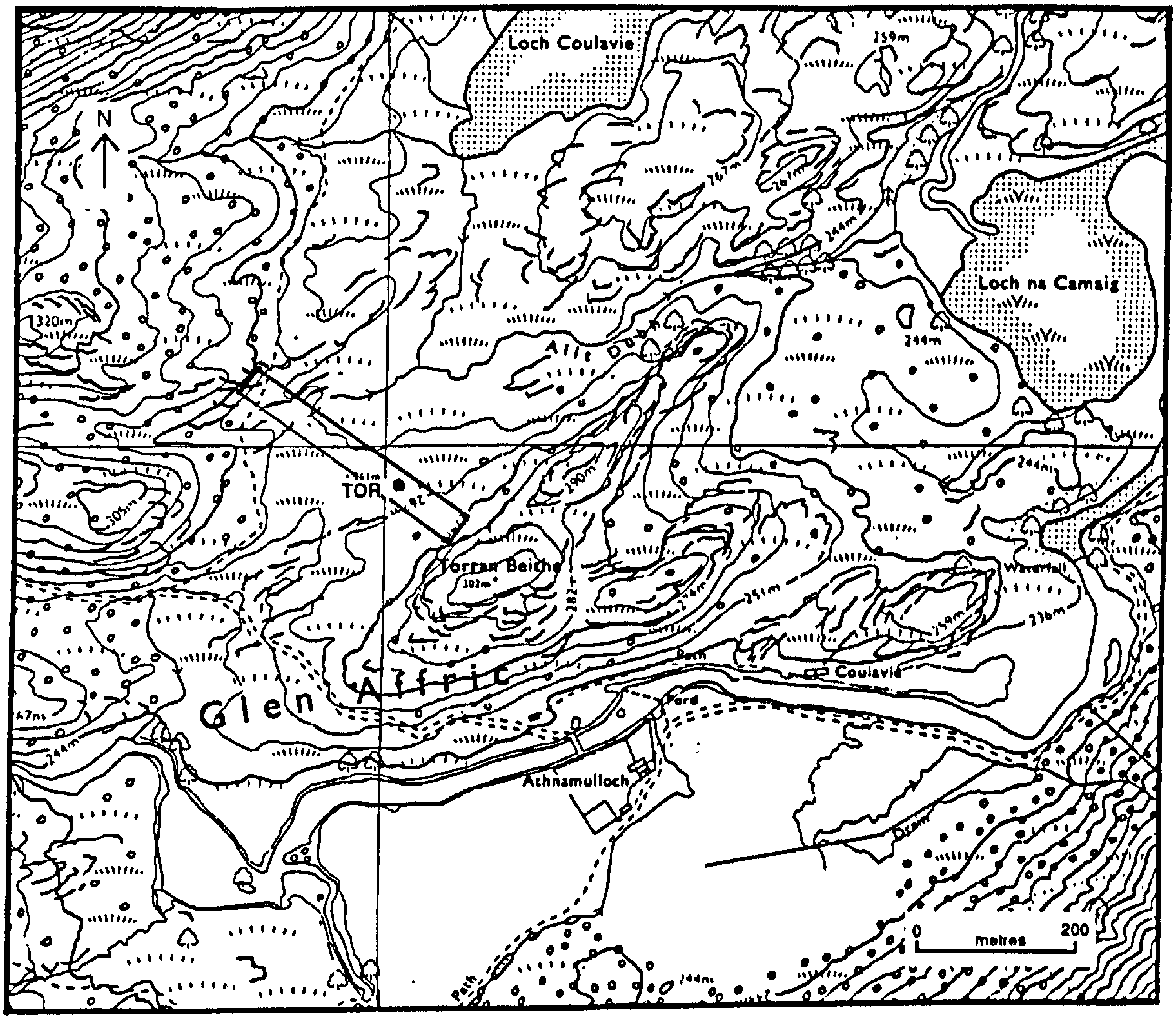


Figure 10. Location of transect survey and sampling site at Torran Beithe. © Ordnance Survey.

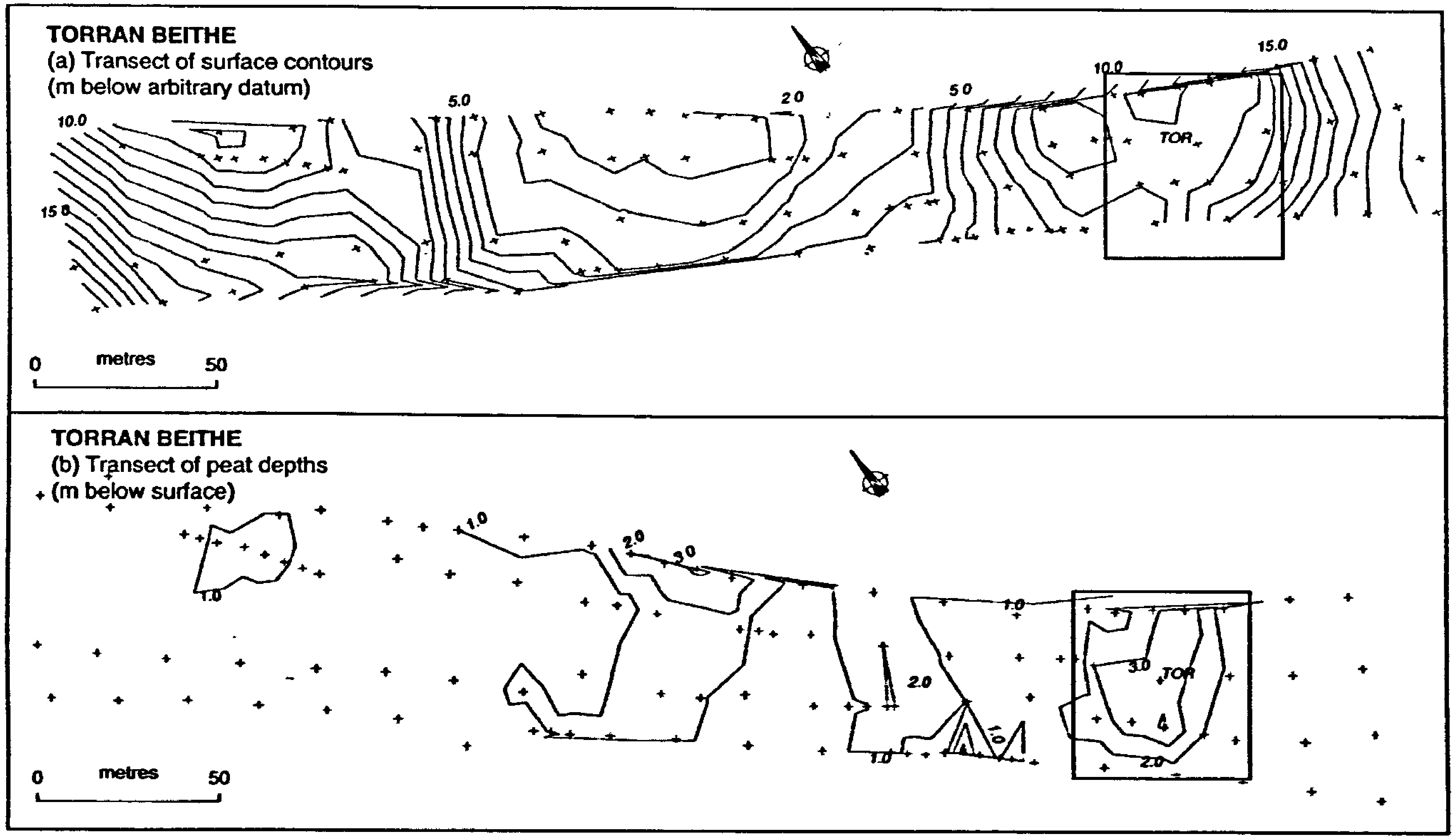


Figure 11. Torran Beithe transect survey results (a) surface contours, (b) peat depths in metres at arbitrary intervals below arbitrary datum.

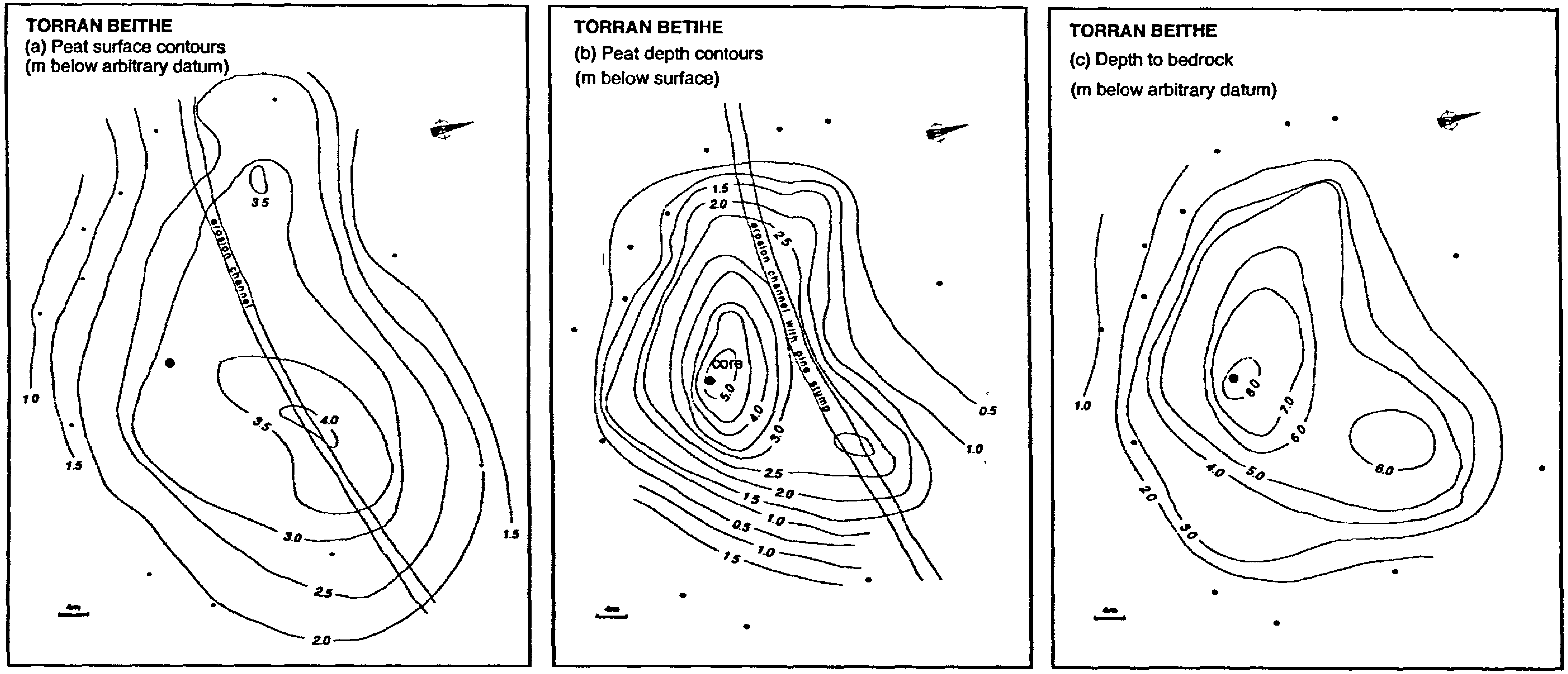


Figure 12. Basin contour maps for Torran Beithe: (a) peat surface, (b) peat depth, depth to bedrock (m). Surface and bedrock contours recorded as depth below arbitrary datum.

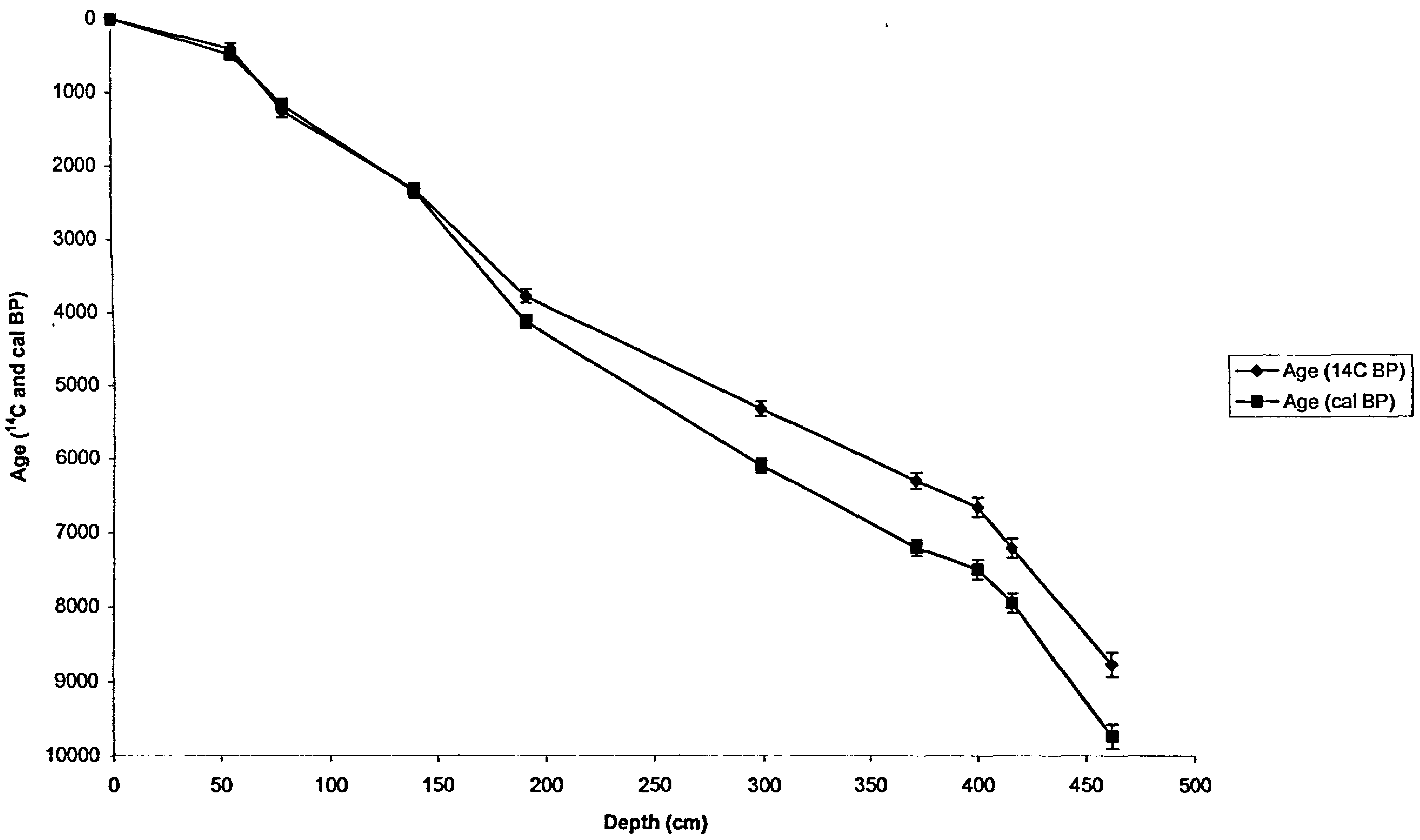


Figure 13. Radiocarbon and calibrated time-depth curves for Torran Beithe with 2σ error ranges.

Figure 14. Full percentage data for Torran Beithe.
Sum = %TLP/%TLP + group; exaggeration x10.

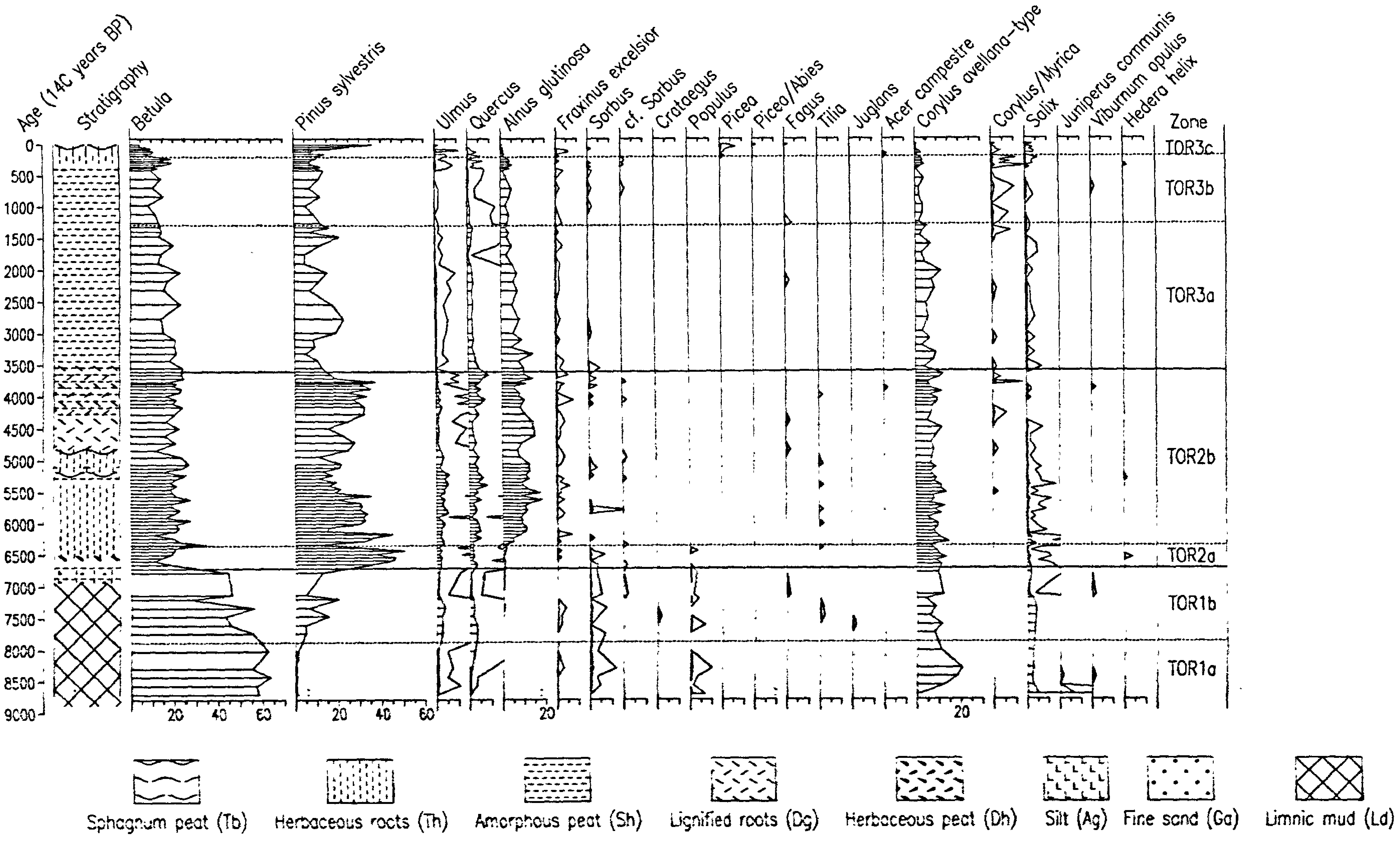
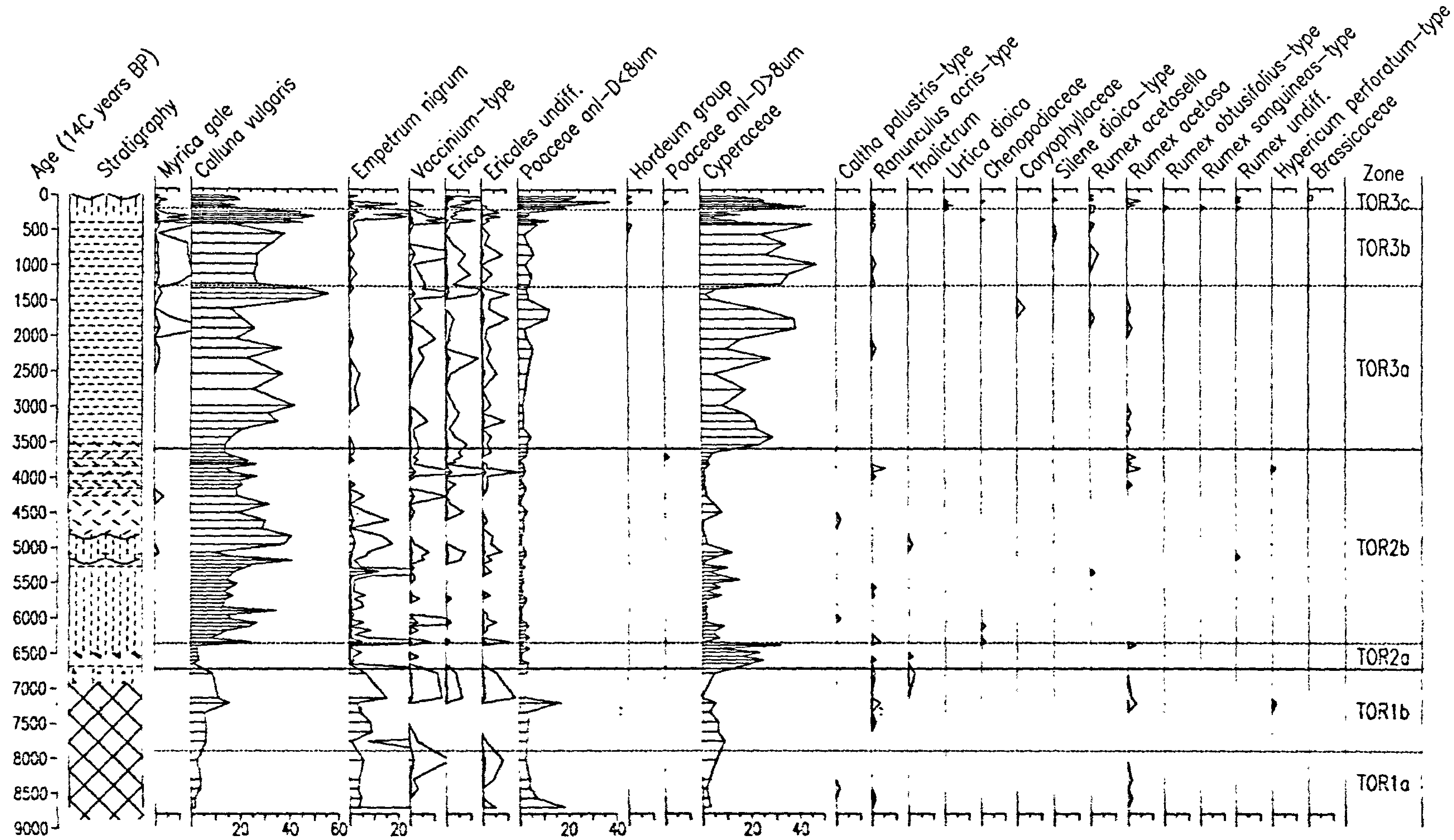


Figure 14. Full percentage data for Torran Beithe (continued).
Sum = %TLP/%TLP + group; exaggeration x10.



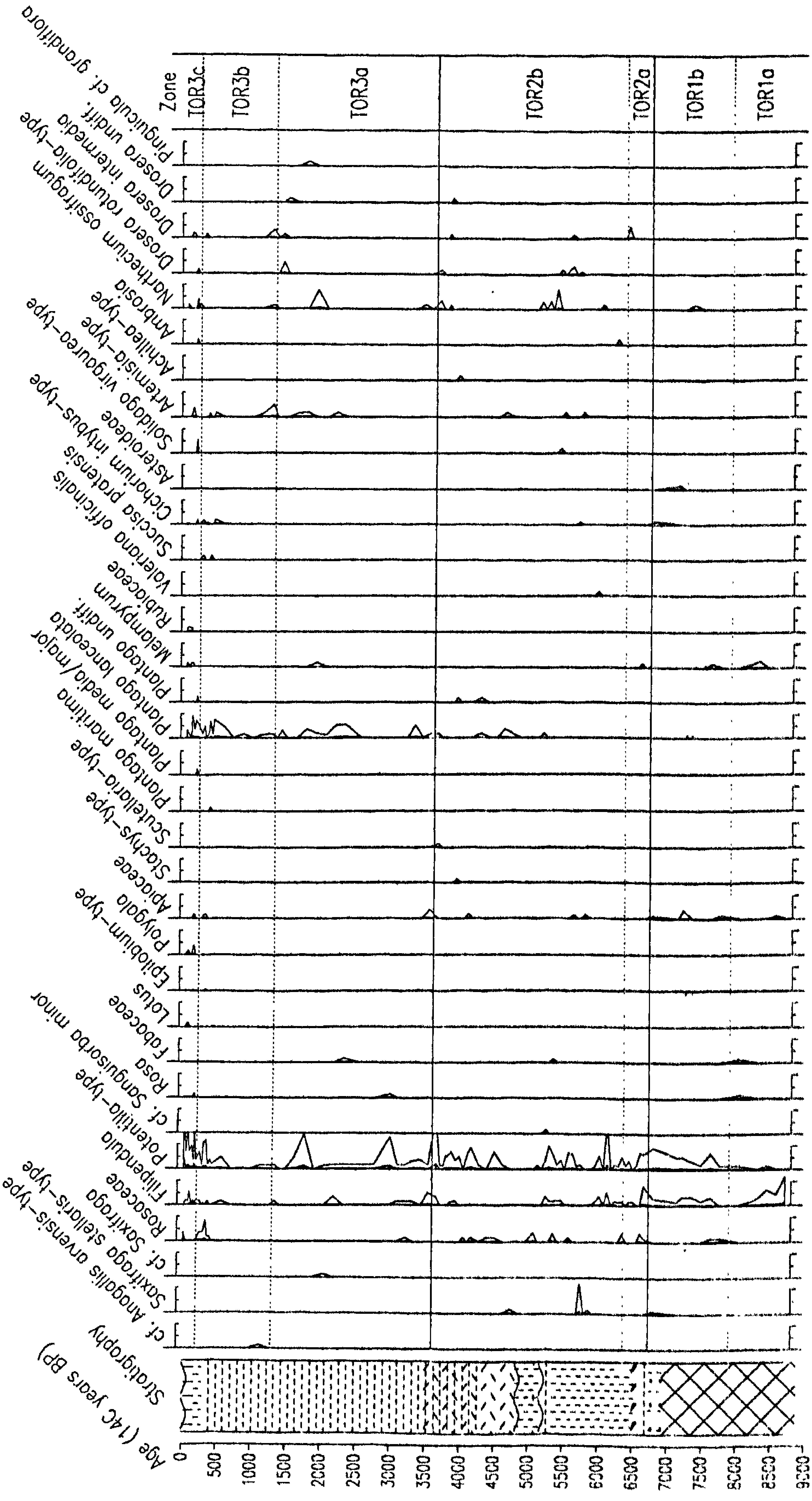


Figure 14. Full percentage data for Torran Beithe (continued).
Sum = %TLP/%TLP + group; exaggeration x10.

Figure 14. Full percentage data for Torran Beithe (continued).
Sum = %TLP/%TLP + group; exaggeration x10.

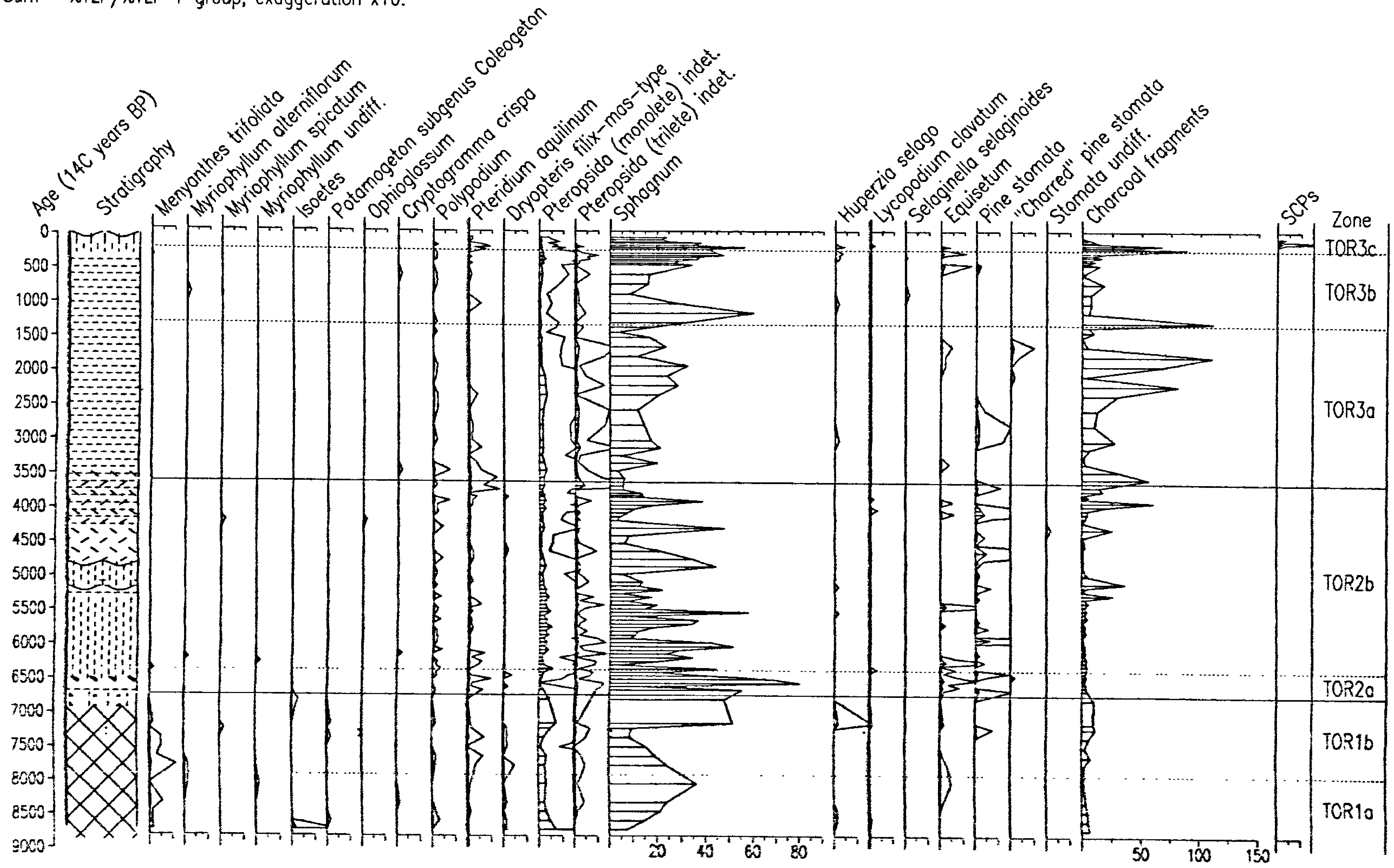
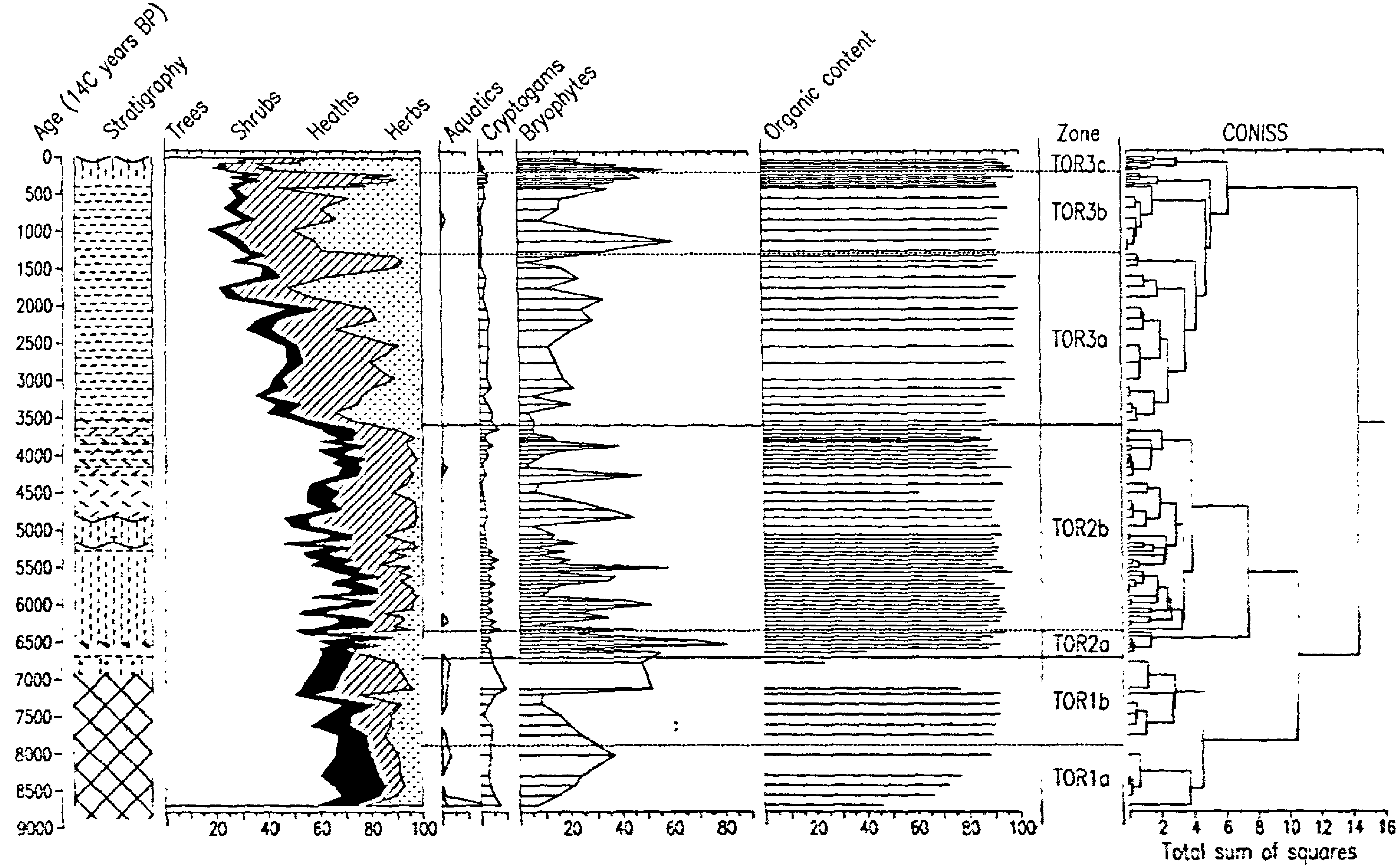


Figure 14. Full percentage data for Torran Beithe (continued).
Sum = %TLP/%TLP + group; exaggeration x10.



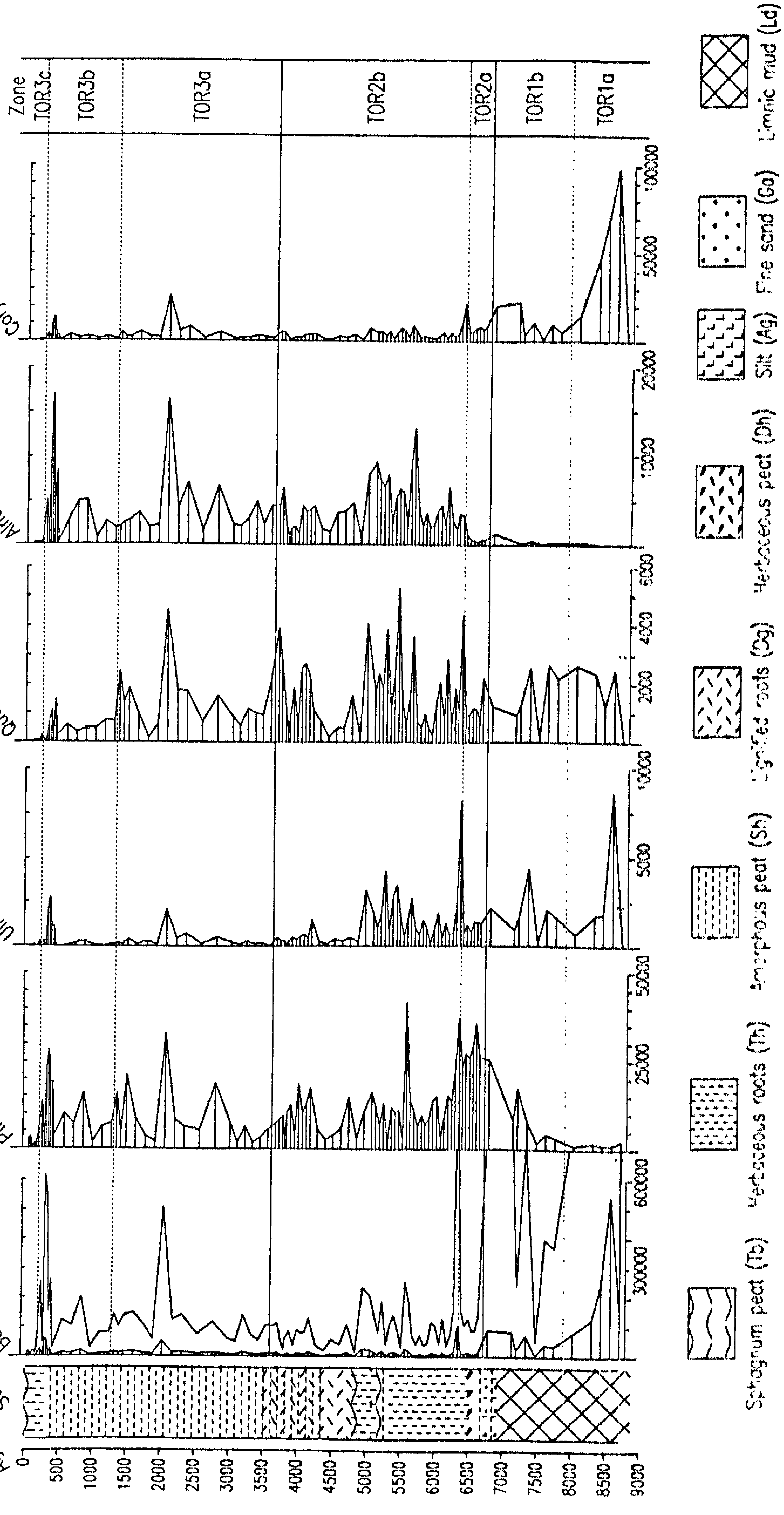


Figure 15. Selected concentration data from Torran Beithe.
NB Changes in scale; exaggeration x10.

Figure 15. Selected concentration data from Torran Beithe (cont.).
NB Changes in scale; exaggeration x10.

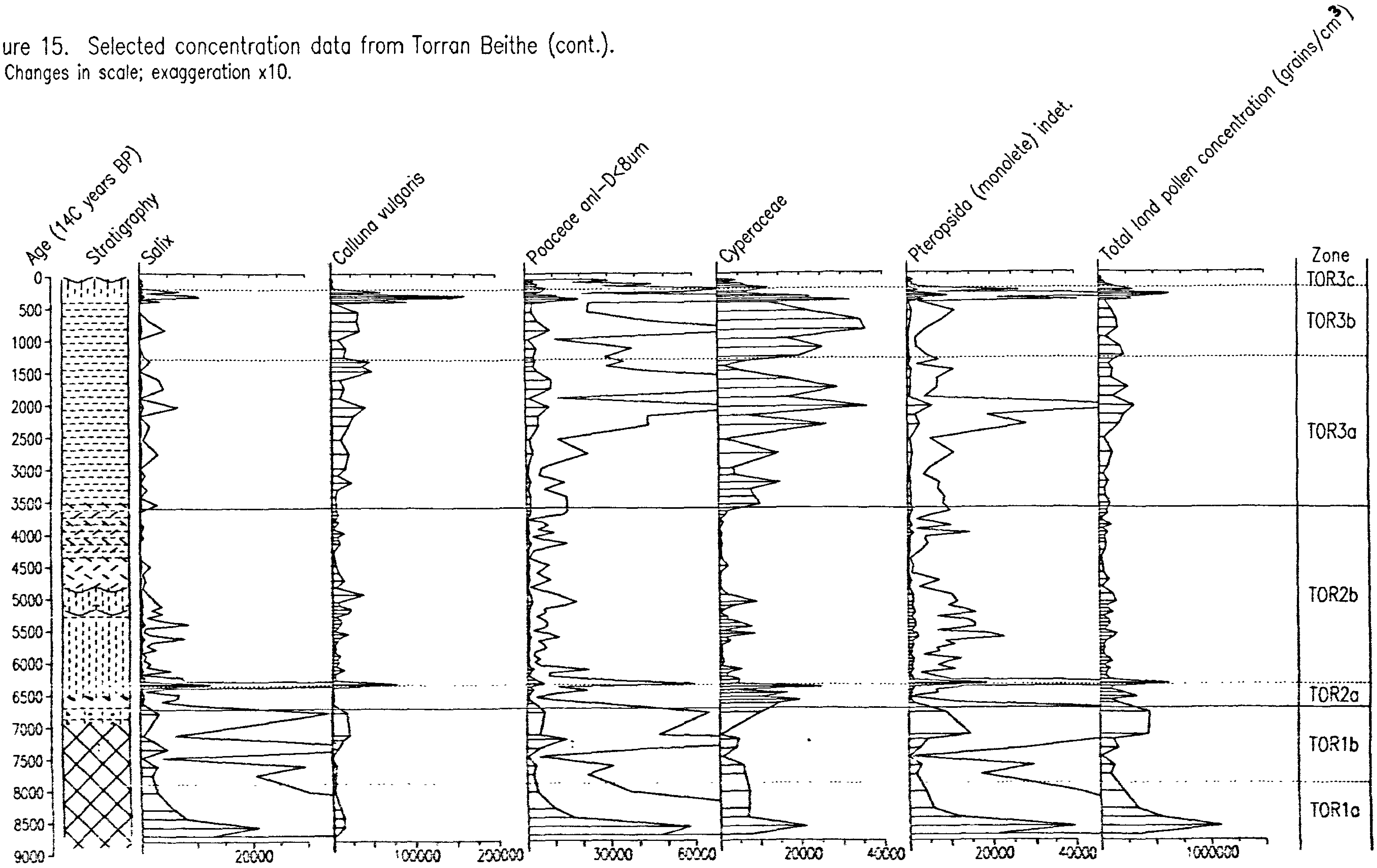


Figure 16. Selected accumulation rates from Torran Beithe.
(grains/cm^2/14C year BP)
NB Changes in scale; exaggeration x10

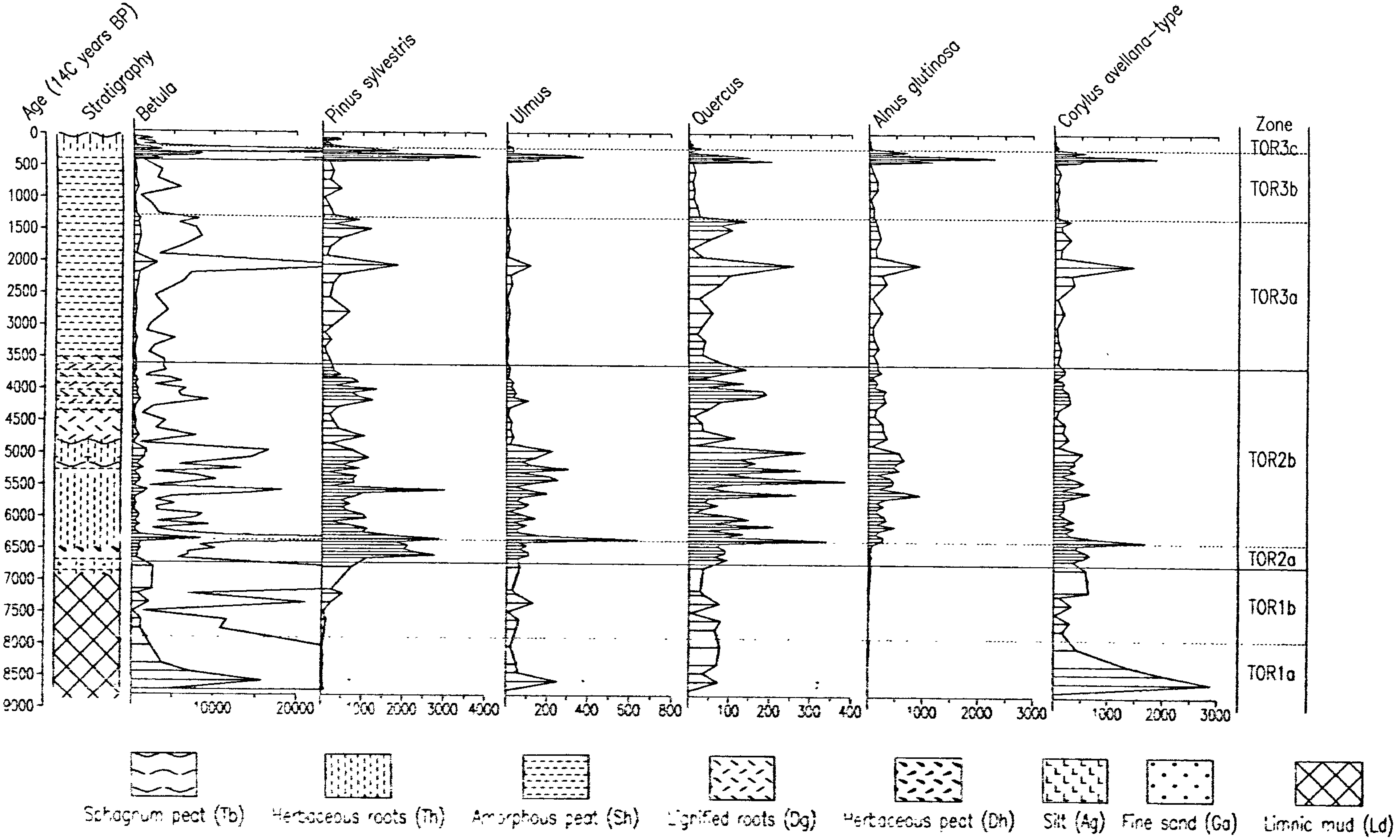
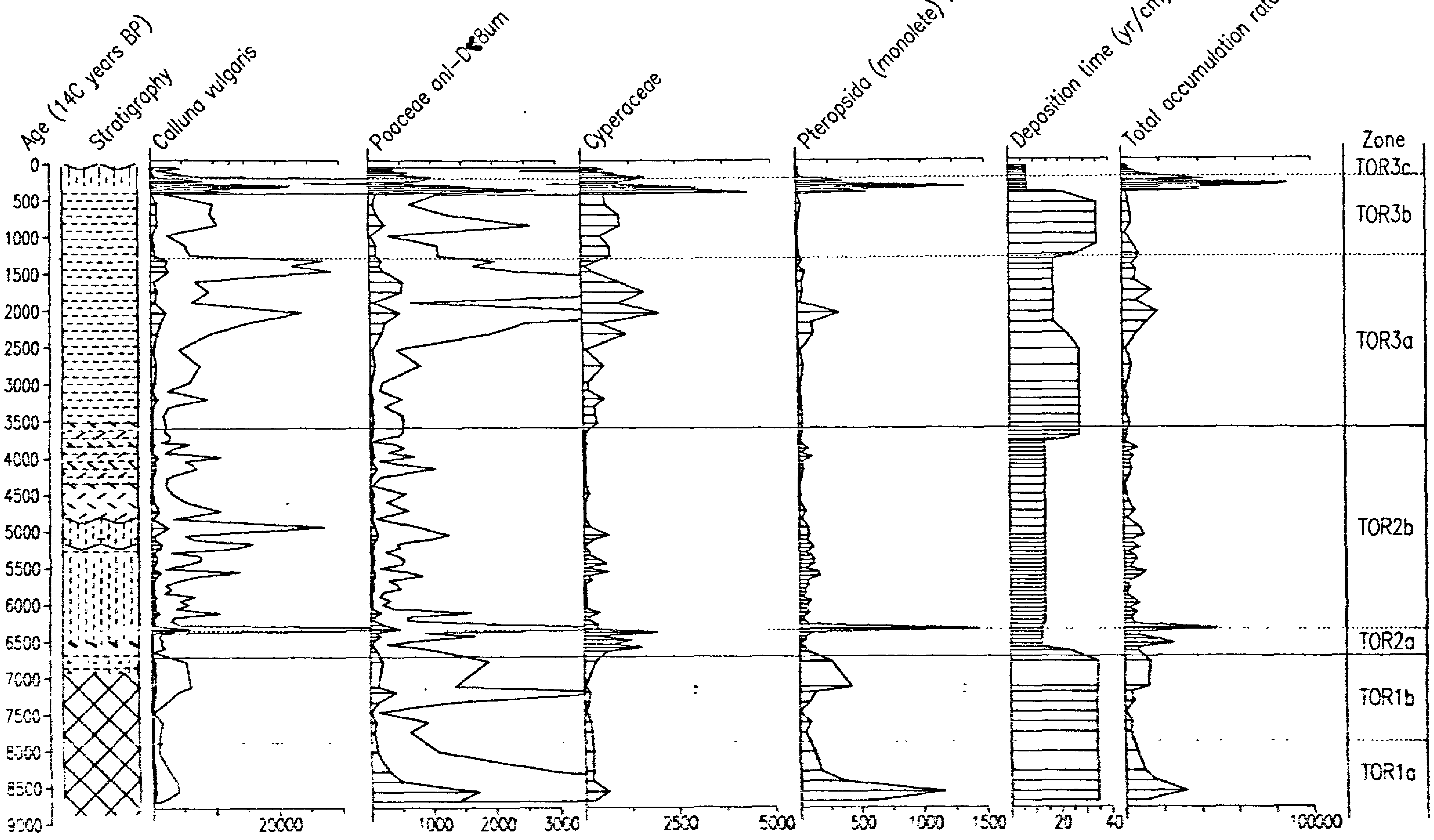


Figure 16. Selected accumulation rates from Torran Beithe (cont.).
(grains/cm^2/14C year BP)
NB Changes in scale; exaggeration x10



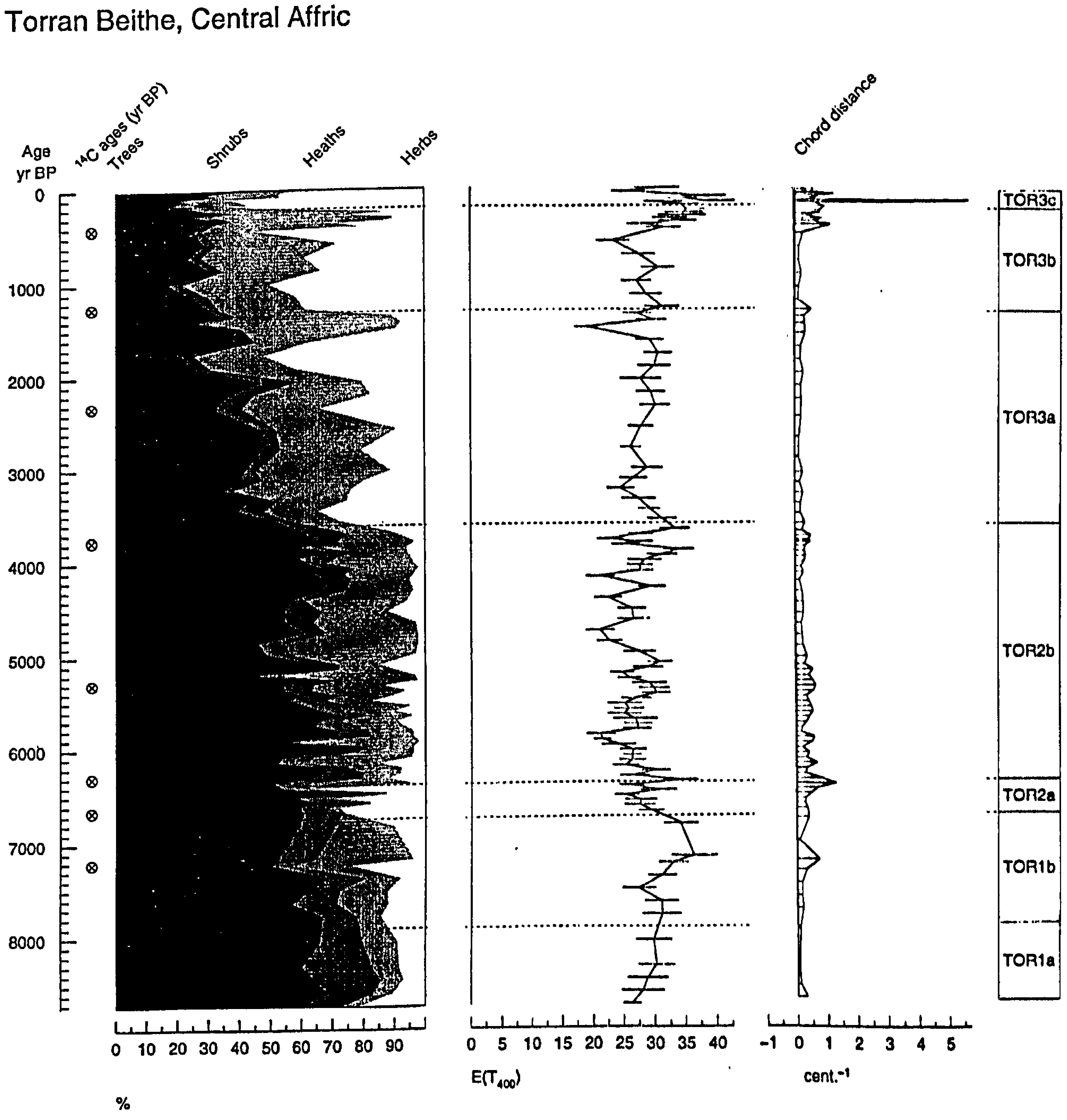


Figure 17. Rarefaction data and rates of change for Torran Beithe plotted against age in ^{14}C years BP.

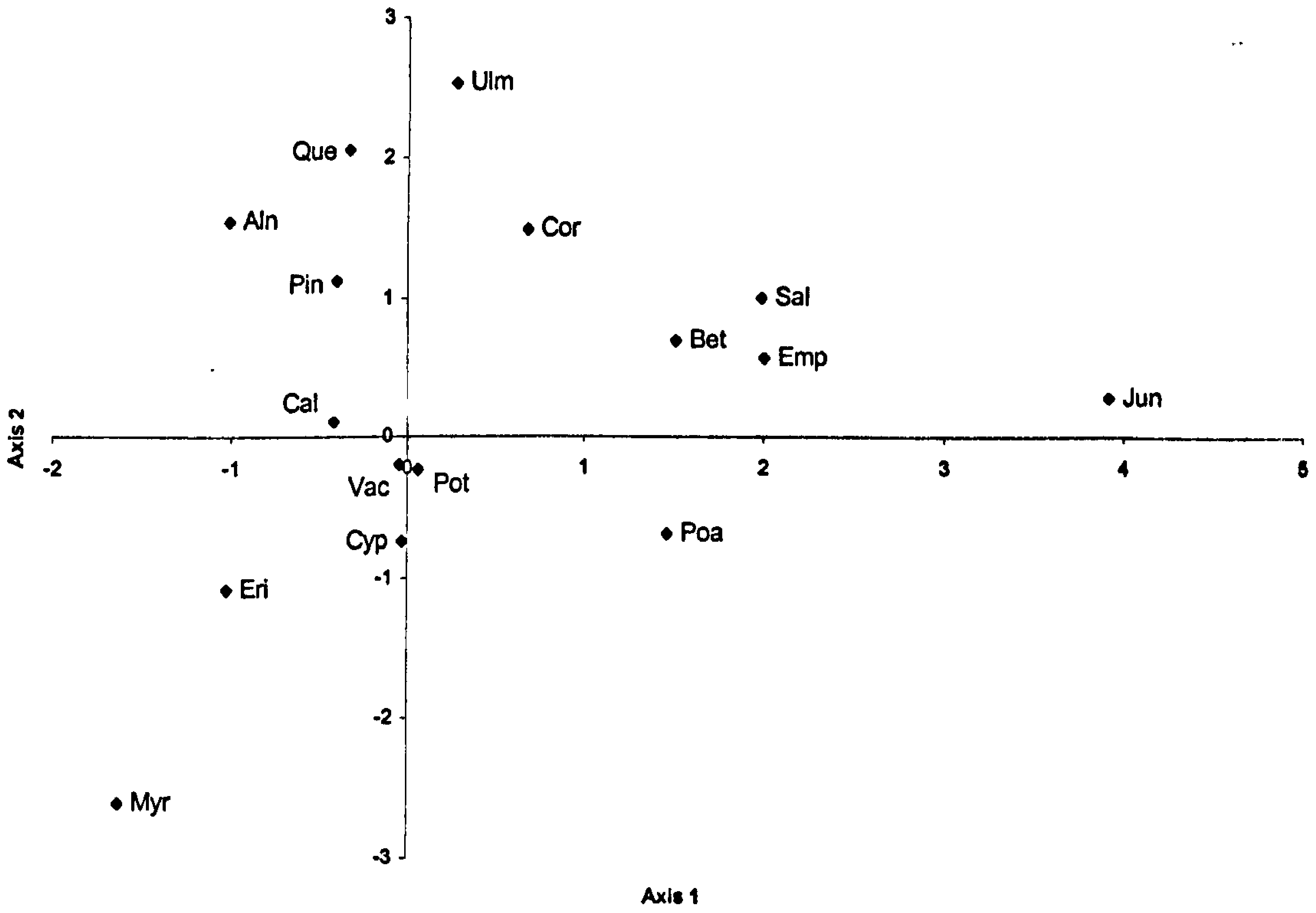


Figure 18a. DCA taxon scores on first two axes for Torran Beithe. Aln = *Alnus glutinosa*, Bet = *Betula*, Cal = *Calluna vulgaris*, Cor = *Corylus avellana*-type, Cyp = Cyperaceae, Emp = *Empetrum nigrum*, Eri = *Erica*, Jun = *Juniperus communis*, Myr = *Myrica gale*, Pin = *Pinus sylvestris*, Poa = Poaceae anl-D<8 µm, Pot = *Potentilla*-type, Que = *Quercus*, Sal = *Salix*, Ulm = *Ulmus*, Vac = *Vaccinium*-type.

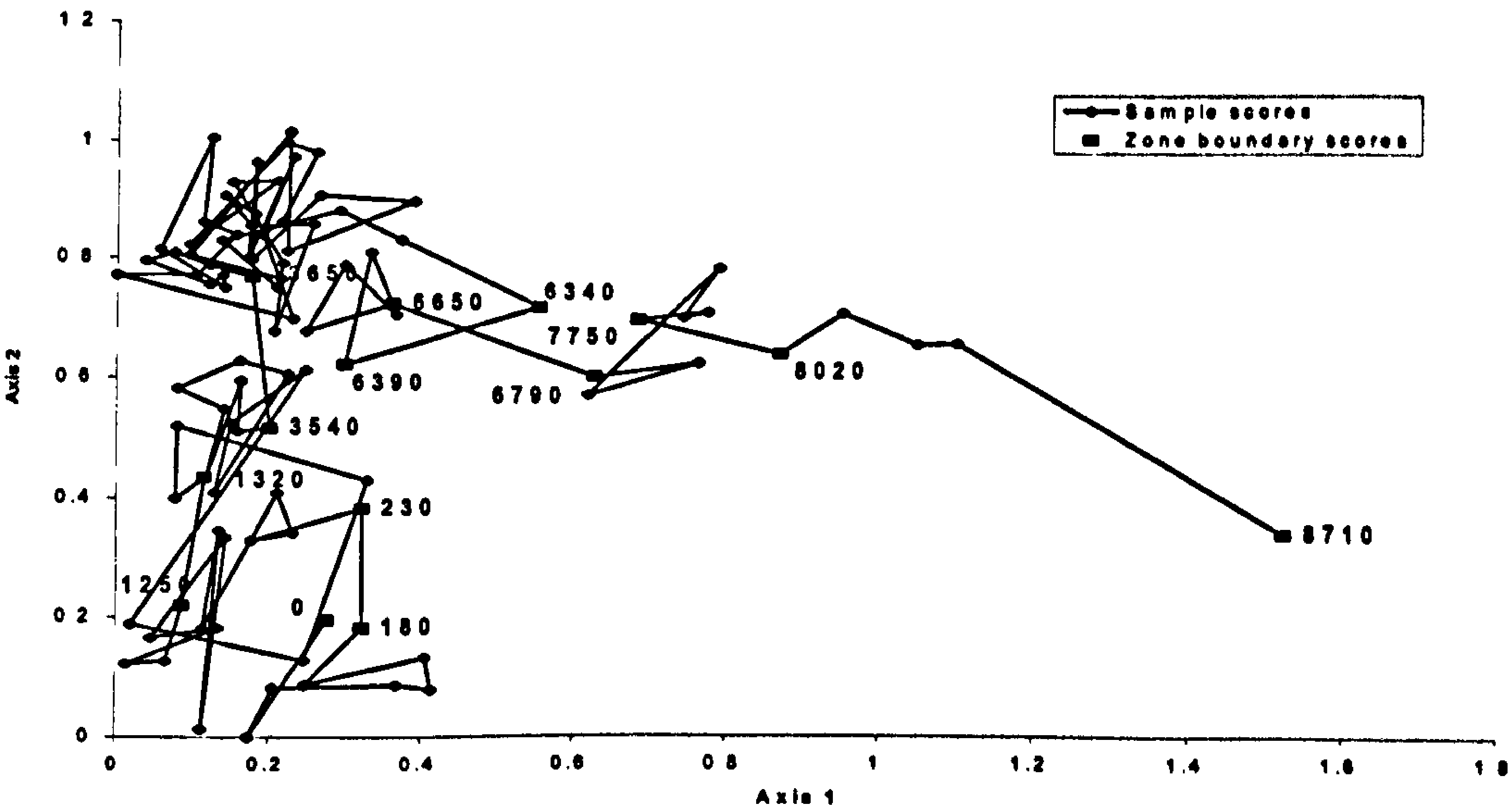


Figure 18b. DCA sample scores on first two axes for Torran Beithe with top and basal levels, and samples either side of zone boundaries labelled in ^{14}C years BP.

Figure 19. Summary preservation data from Torran Beithe.
Sum = %TLP/%TLP + indeterminate; exaggeration x10.

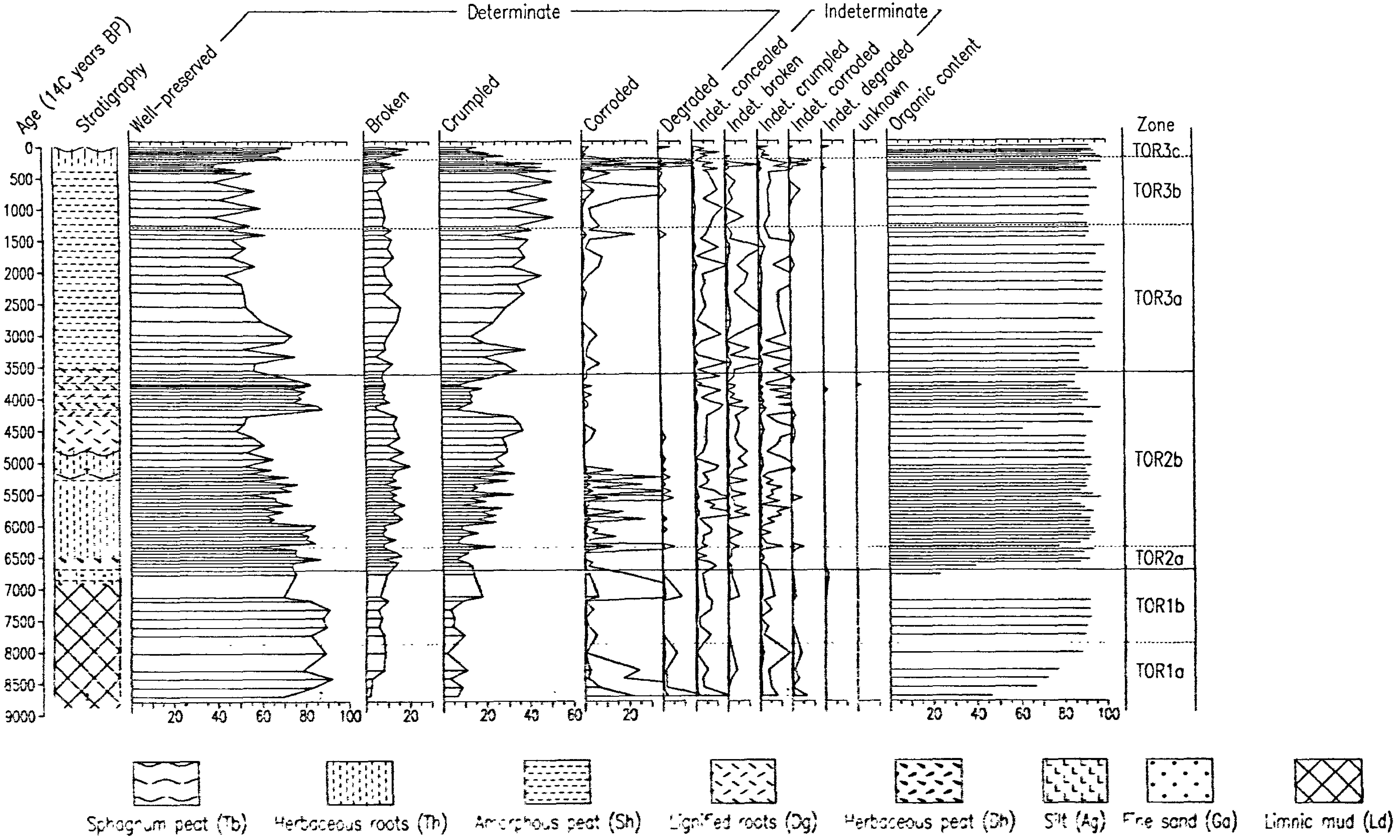
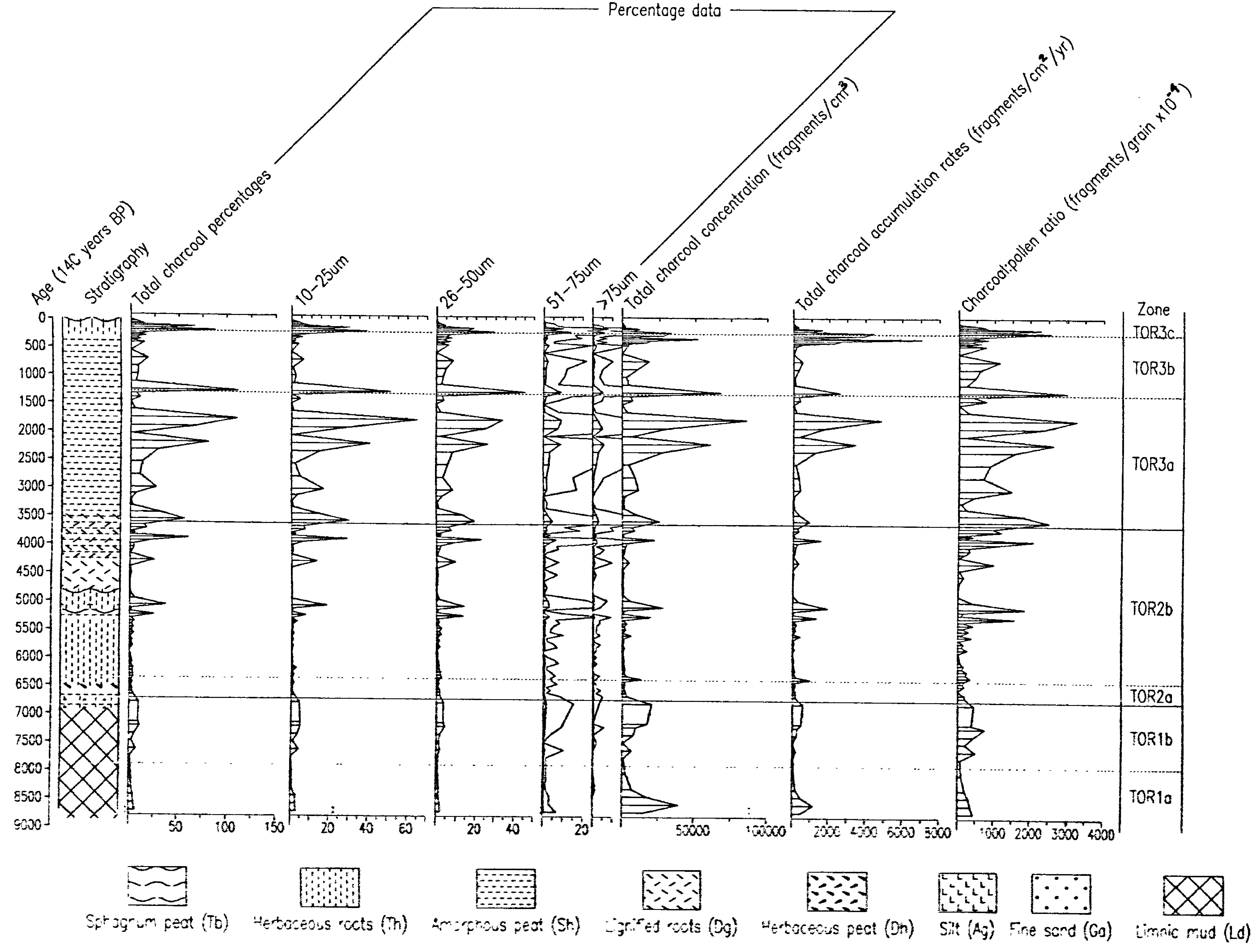


Figure 20. Charcoal data from Torran Beithe.
Sum = %TLP; exaggeration x10



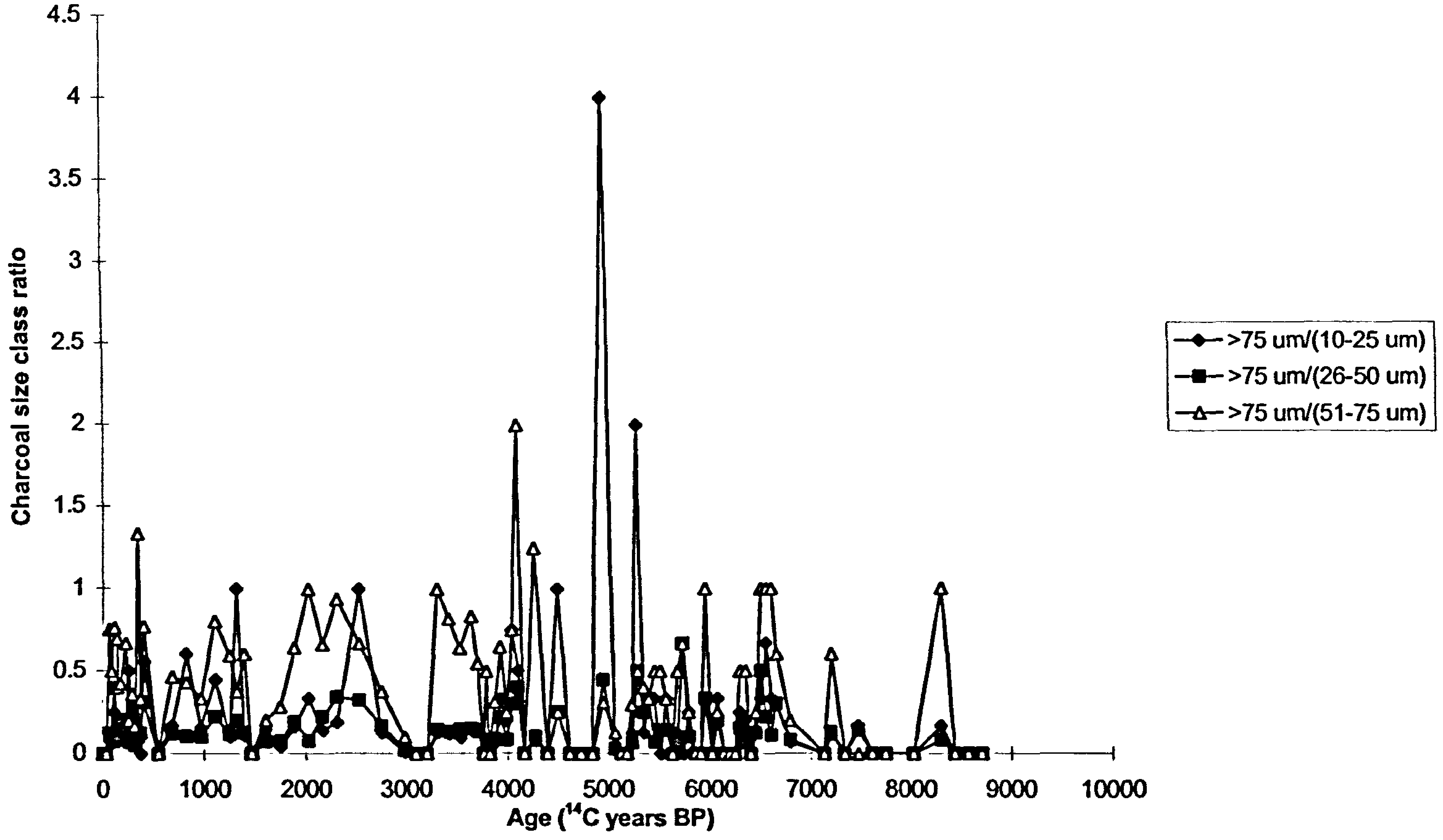
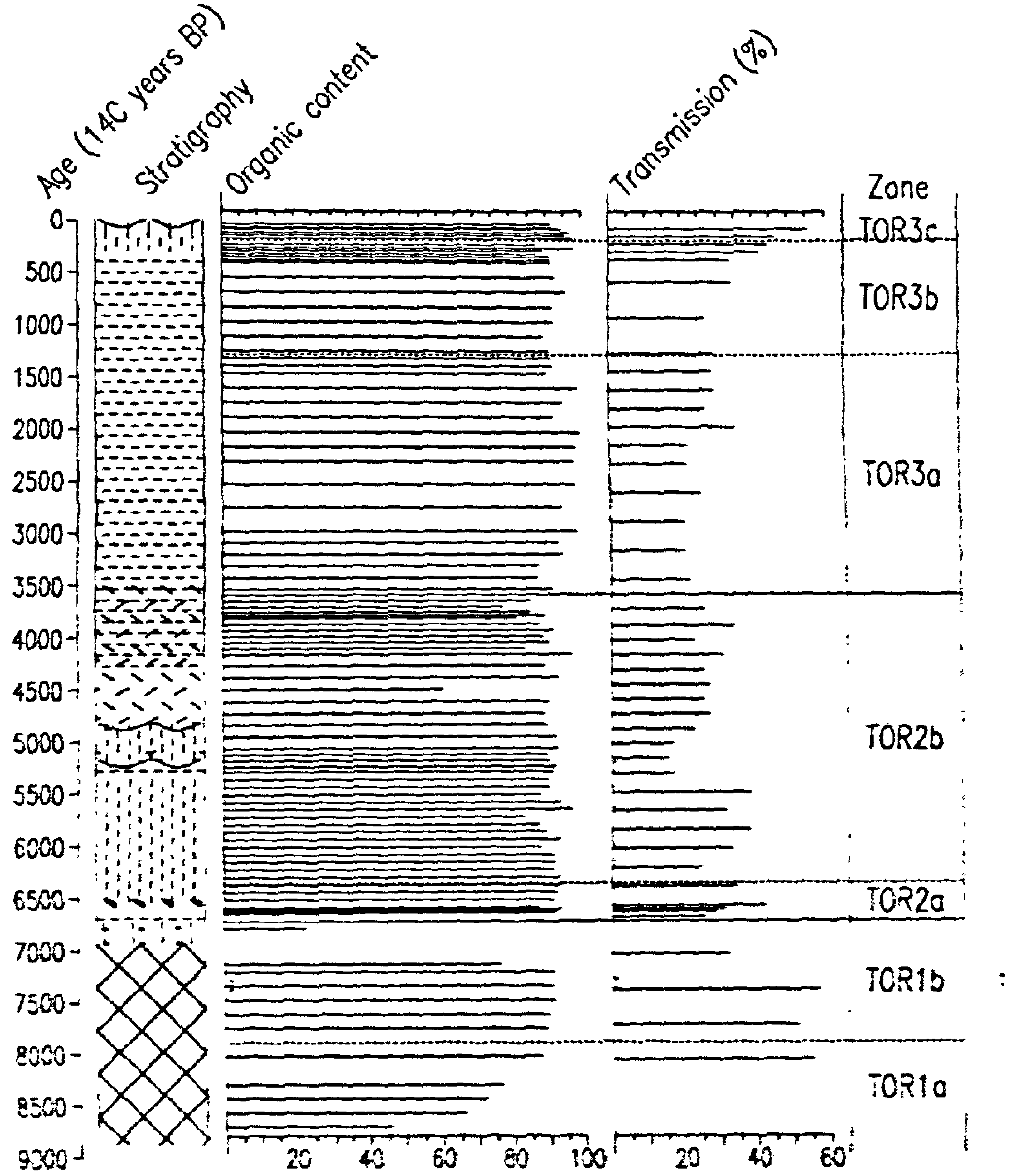


Figure 21. Charcoal size class analysis for Torran Beithe - ratio of percentage of large (>75 µm) to smaller (10-25 µm, 26-50 µm, 51-75 µm) fragments, plotted against age in ^{14}C years BP.

Figure 22. Humification data from Torran Beithe.
With organic content.



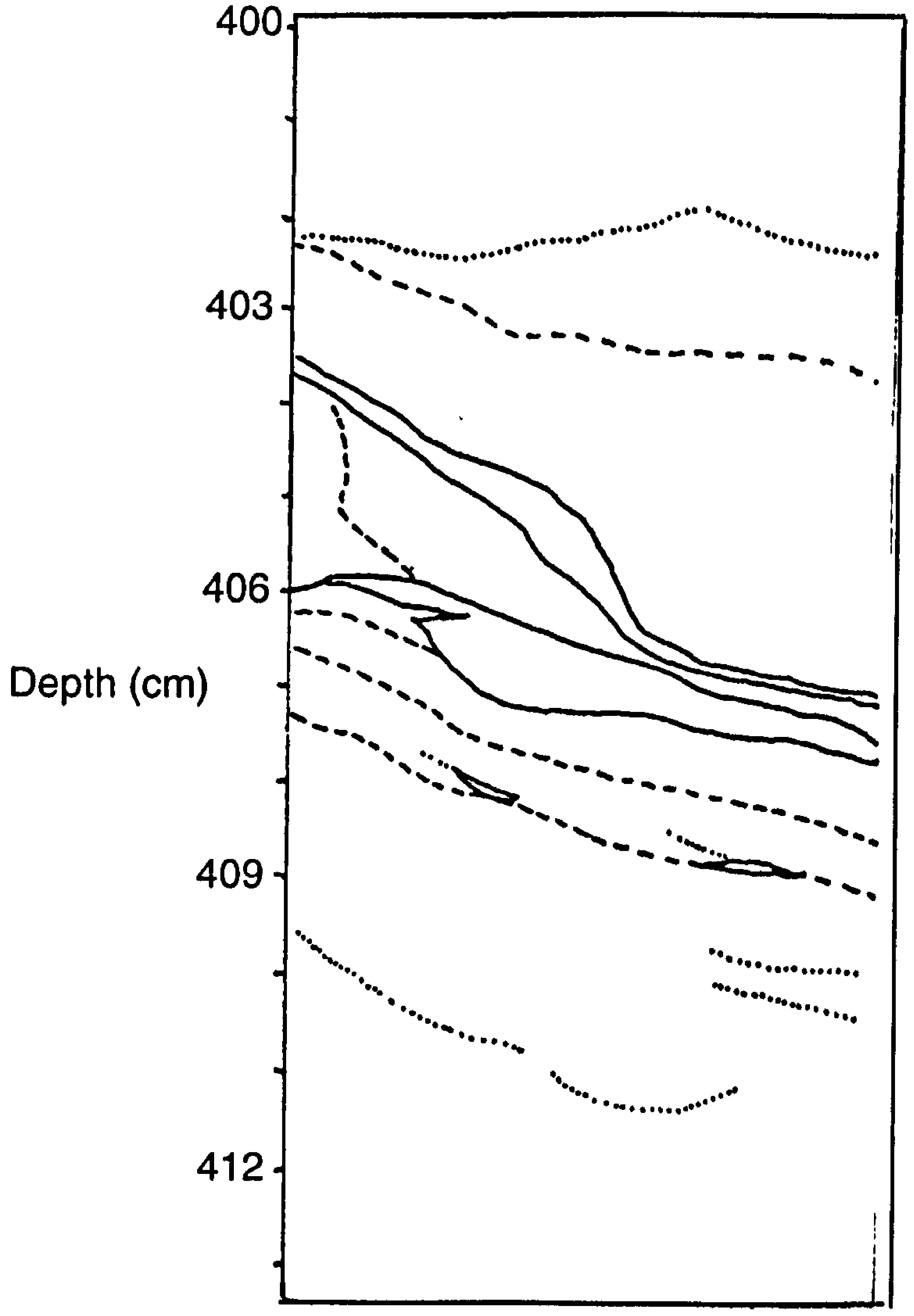


Figure 23. X-radiography analysis of inwashing at 408-403 cm (*c*.7400-6540 BP (8140-7390 cal BP)) in Torran Beithe sequence. Solid line delimits main inwash bands, broken line delimits high proportions of mineral grains, and dotted lines define sediment with lower proportion of mineral grains.

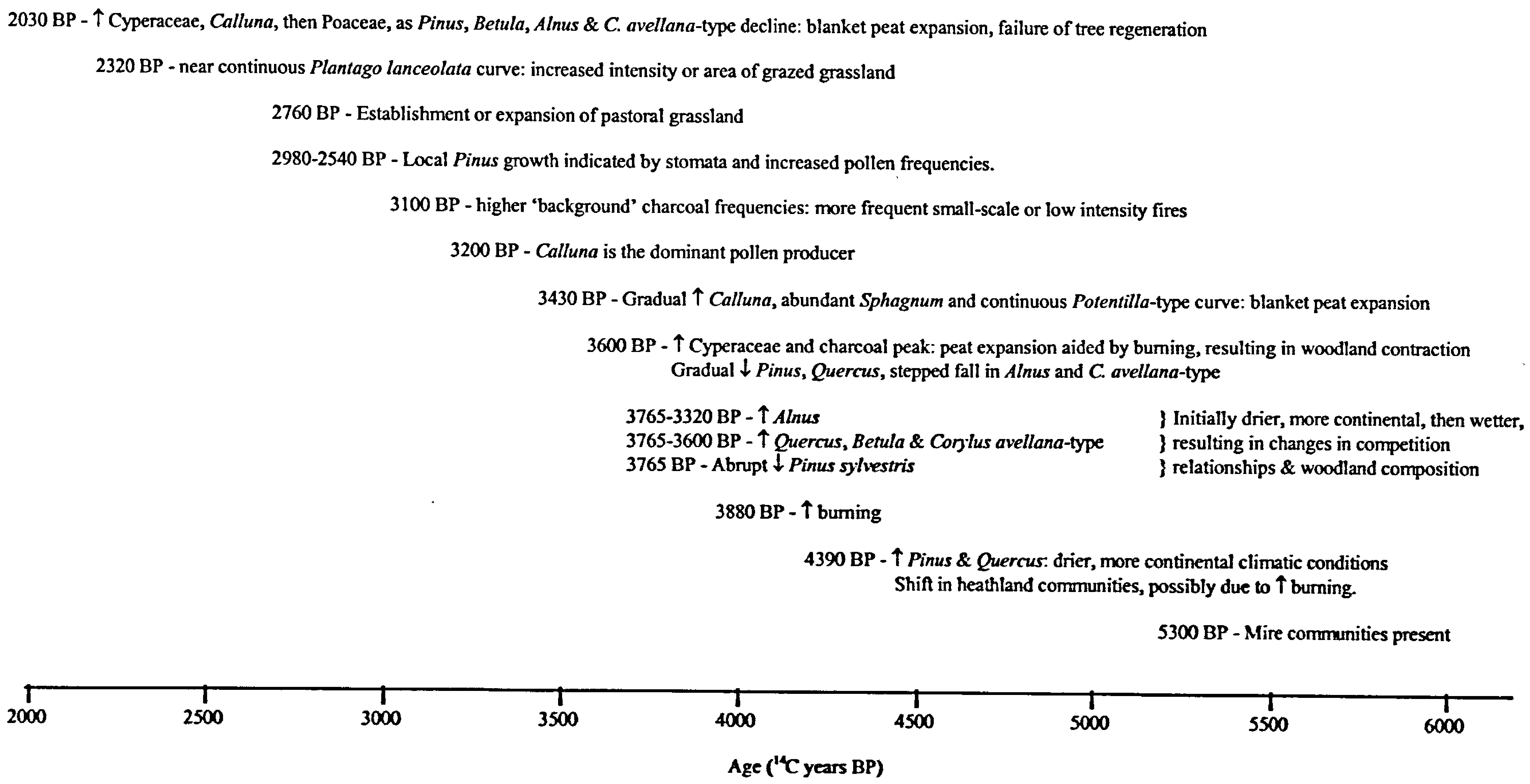


Figure. 24. Summary of inferred mid-Holocene vegetational and environmental changes around Torran Beithe. Arrows denote increasing/decreasing pollen and charcoal values.

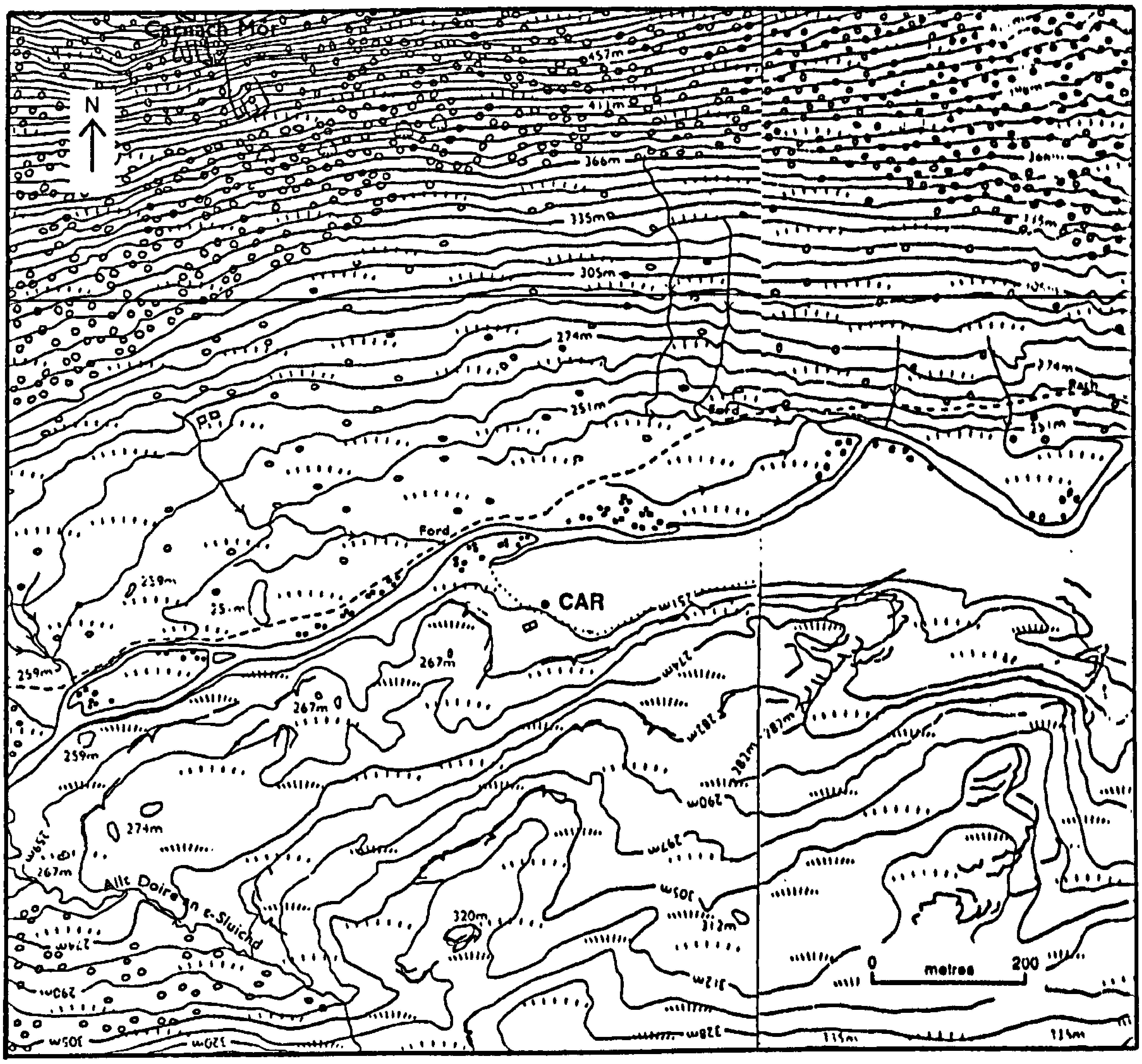


Figure 25. Sampling site at Carnach Mór. © Ordnance Survey.

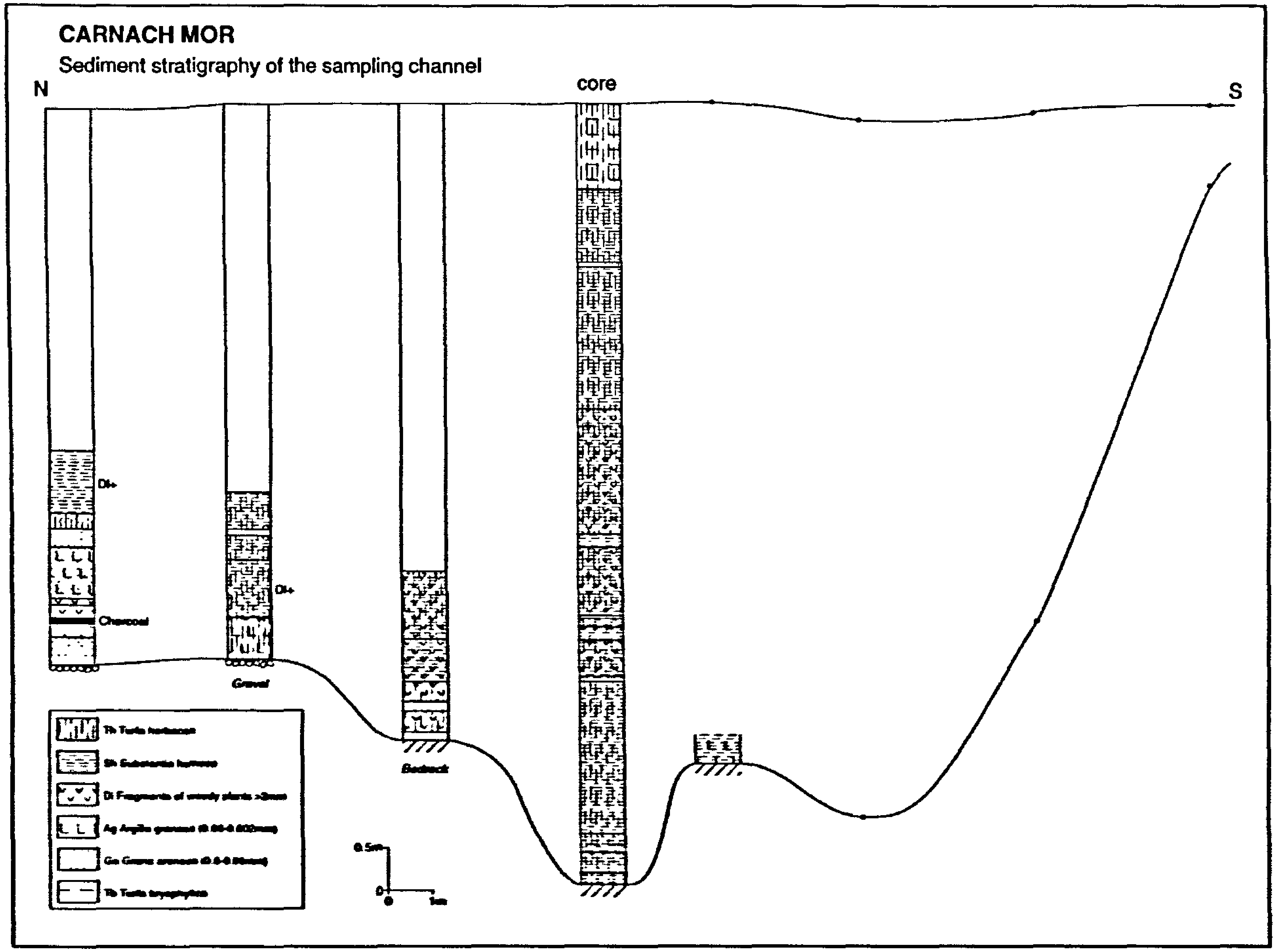


Figure 26. Sediment stratigraphy of sampling channel at Carnach Mór.

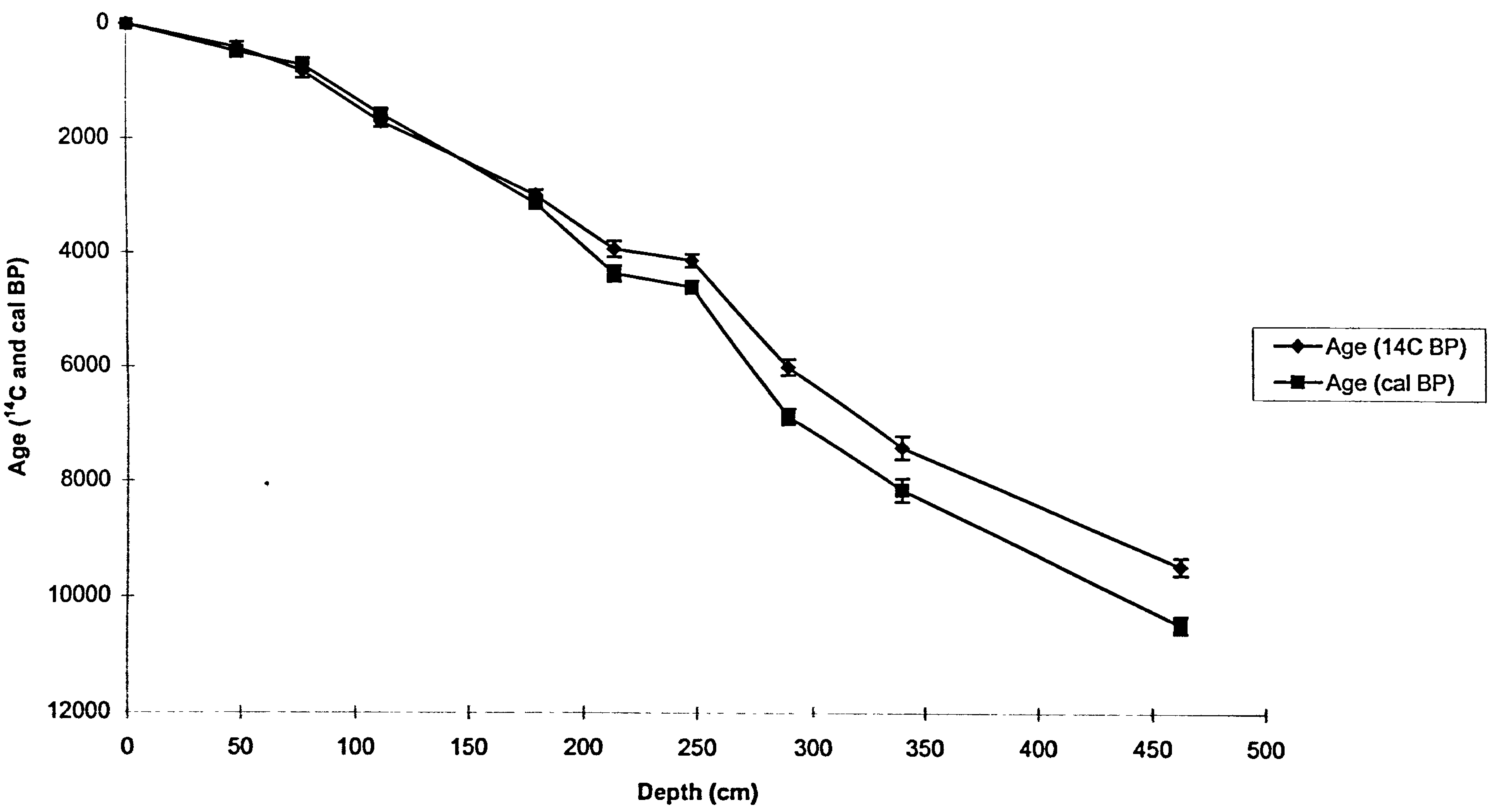


Figure 27. Radiocarbon and calibrated time-depth curves for Carnach Mór with 2σ error ranges.

Figure 28. Full percentage data from Carnach Mor.
Sum = %TLP/%TLP + group; exaggeration x10.

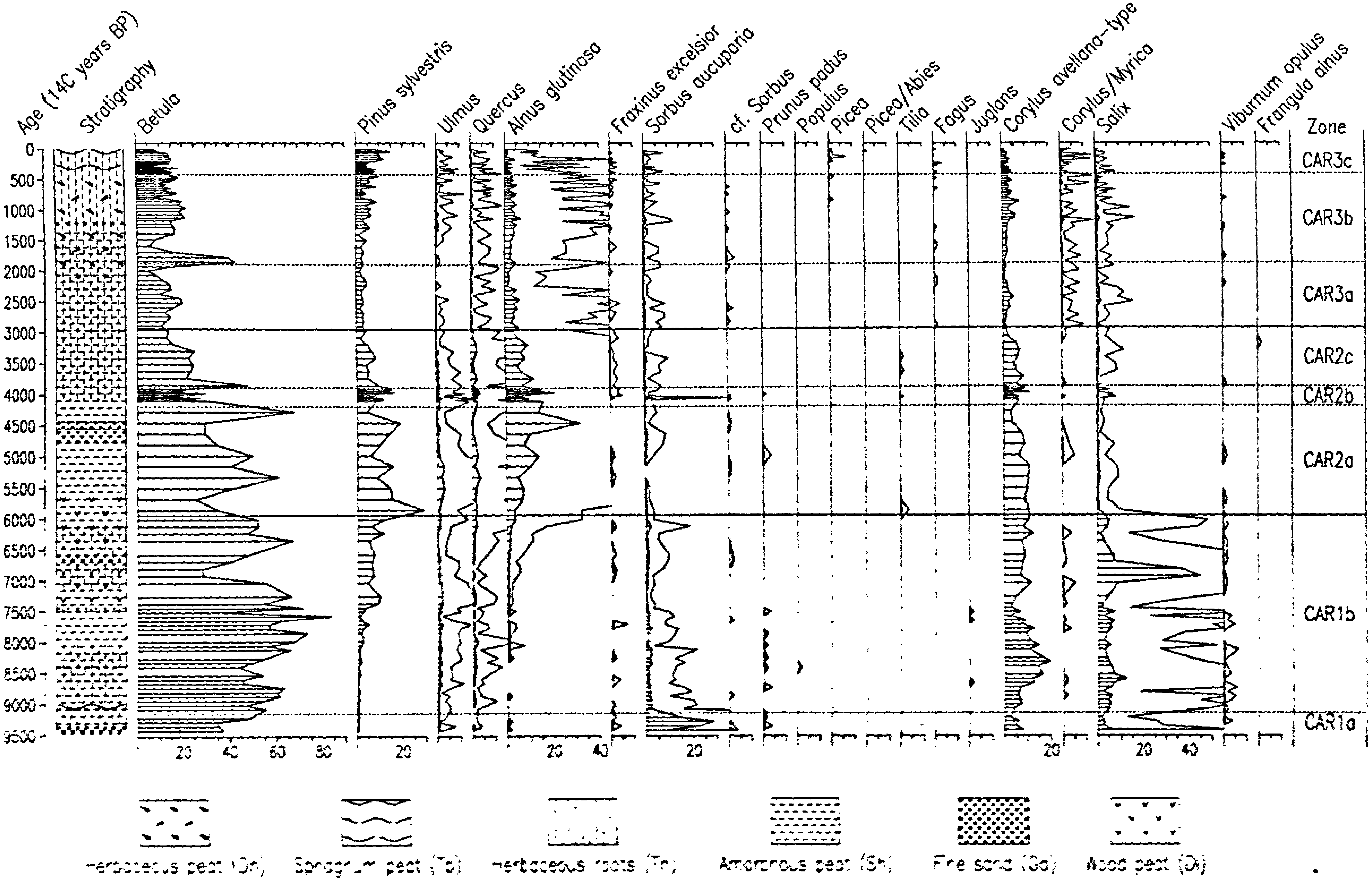


Figure 28. Full percentage data from Carnach Mor (continued).
Sum = %TLP/%TLP + group; exaggeration x10.

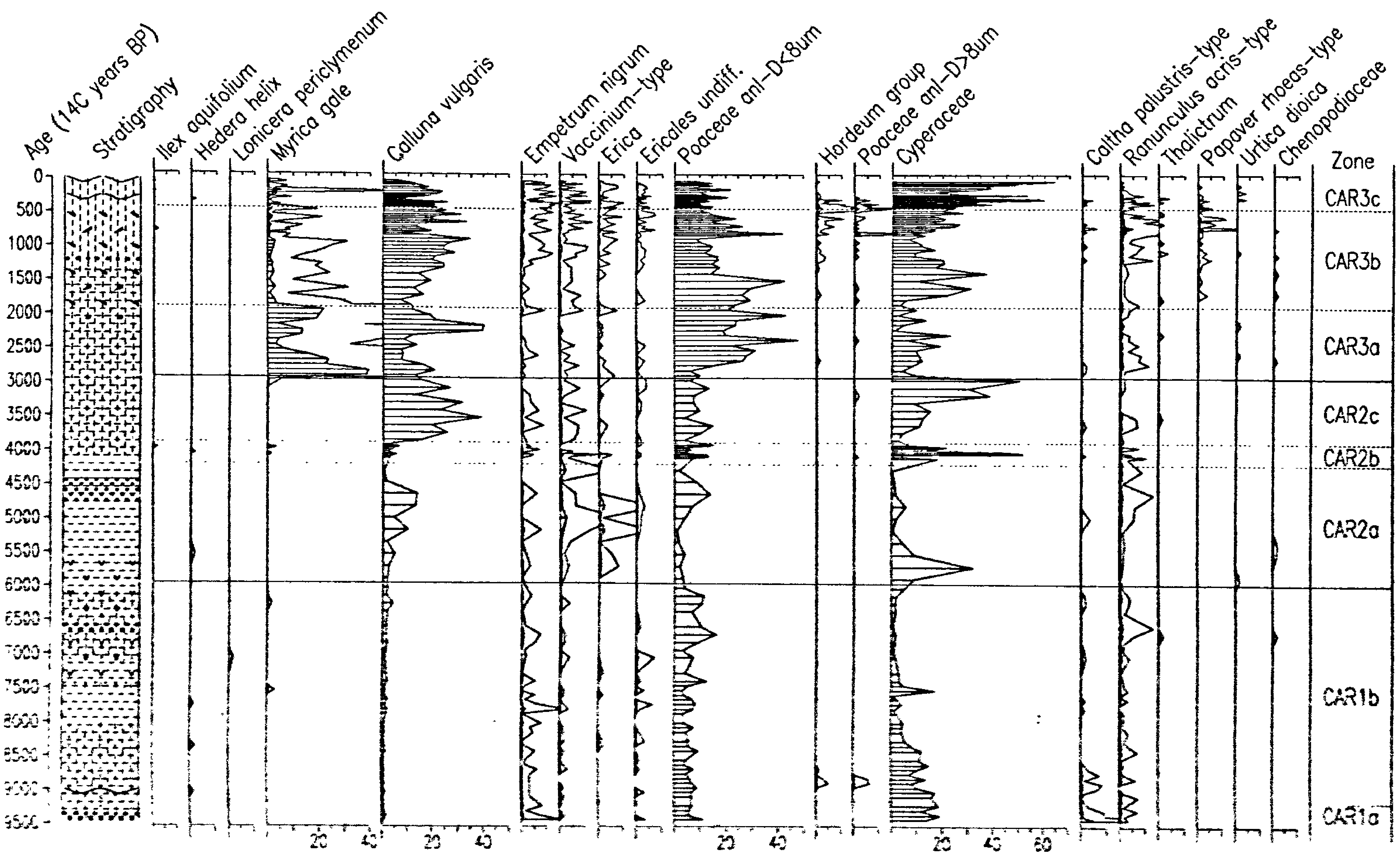


Figure 28. Full percentage data from Carnach Mor (continued).
Sum = %TLP/%TLP + group; exaggeration x10.

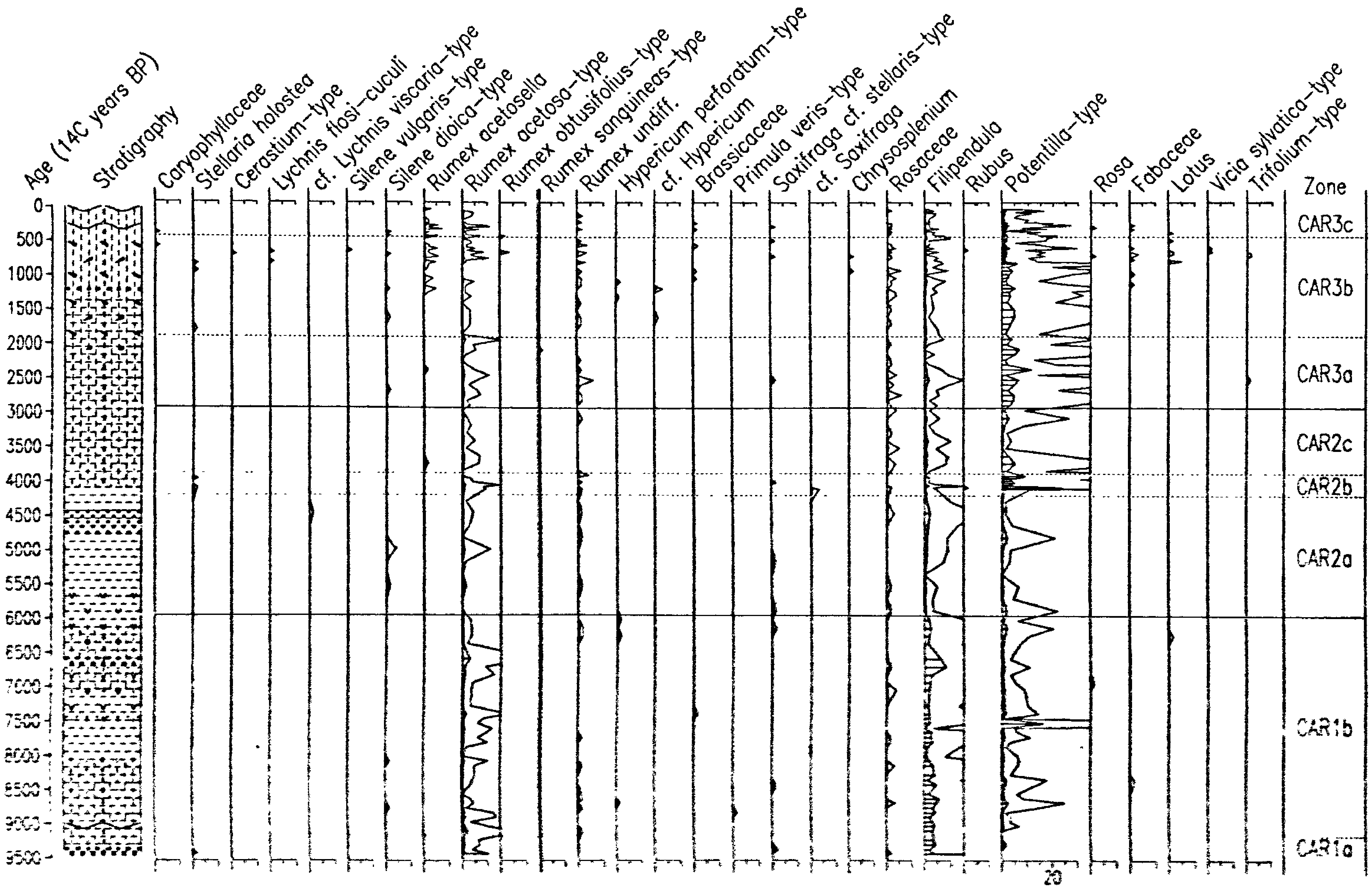


Figure 28. Full percentage data from Carnach Mor (continued).
Sum = %TLP/%TLP + group; exaggeration x10.

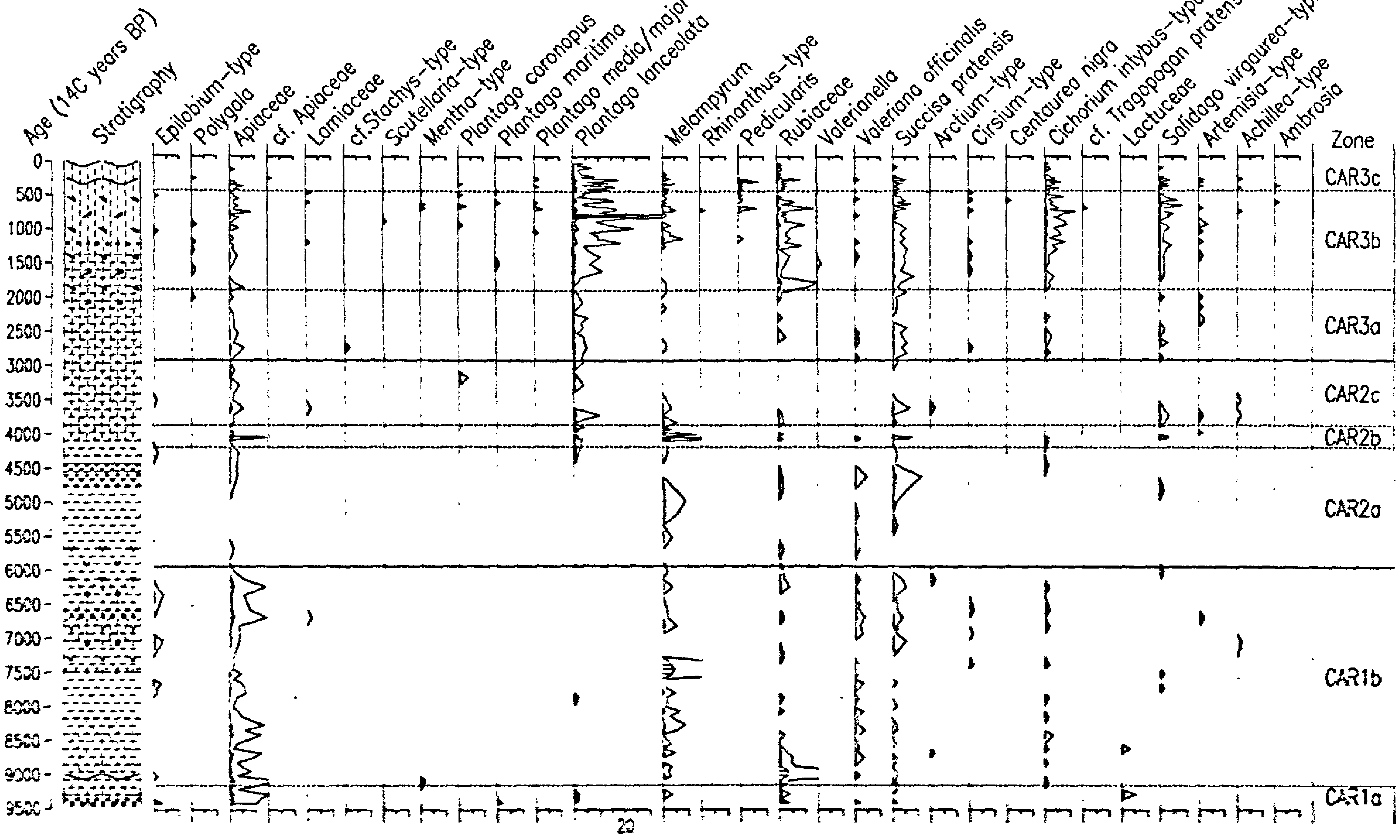


Figure 28. Full percentage data from Carnach Mor (continued).
Sum = %TLP/%TLP + group; exaggeration x10.

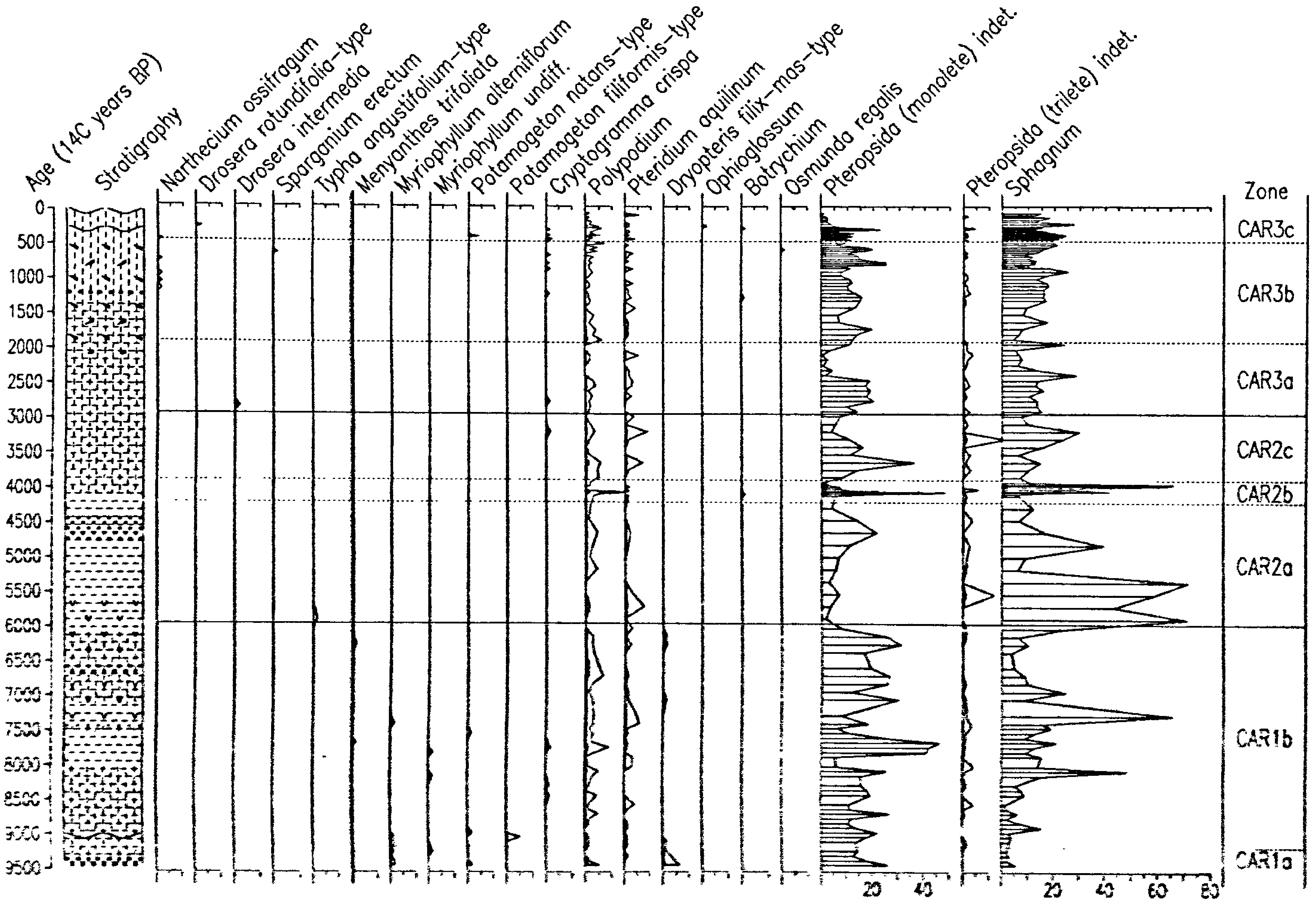


Figure 27. Full percentage data from Carnach Mor (continued).
Sum = %TLP/%TLP + group; exaggeration x10.

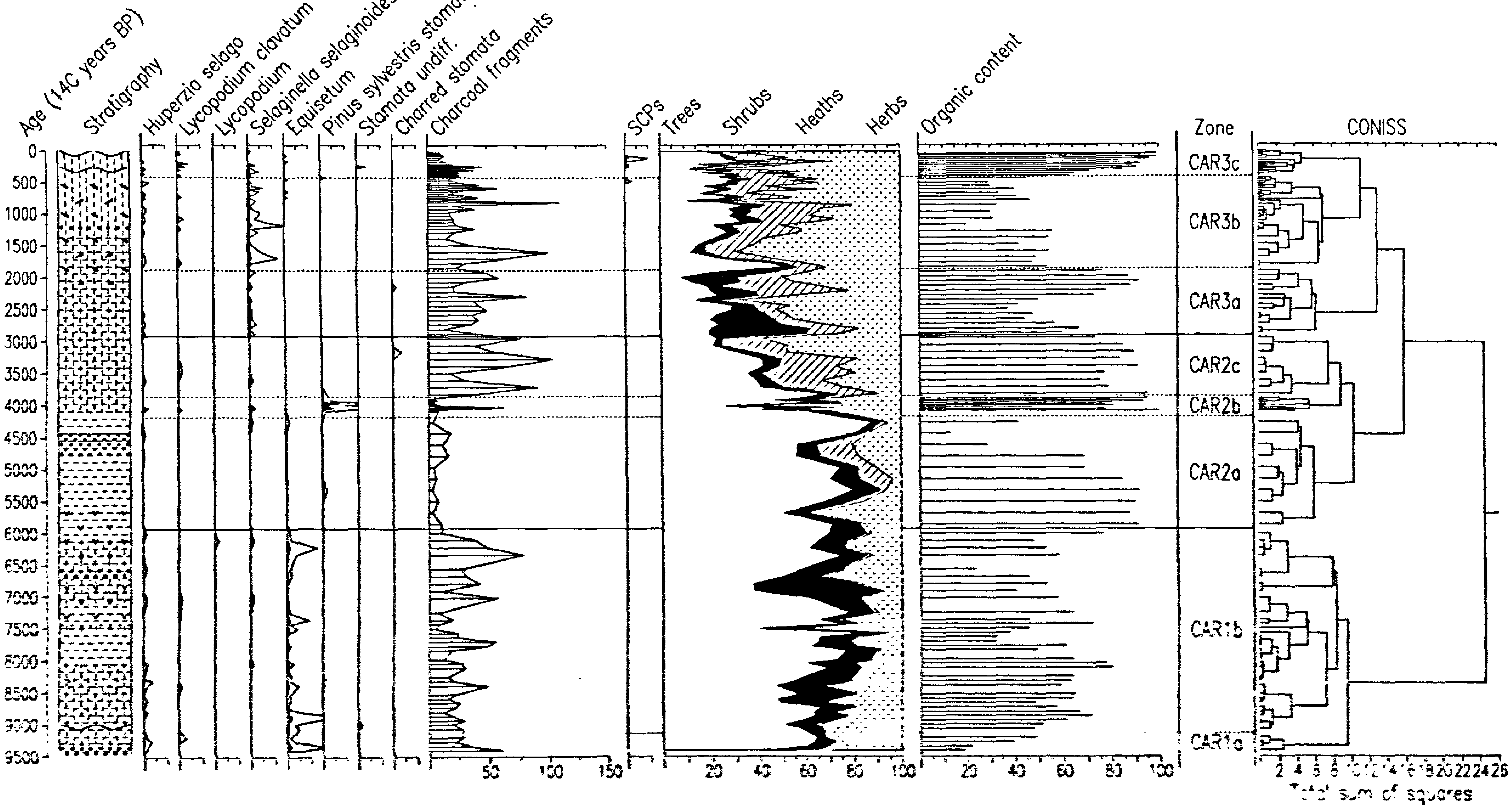


Figure 29. Selected concentration data from Carnach Mor.
NB Changes in scale.

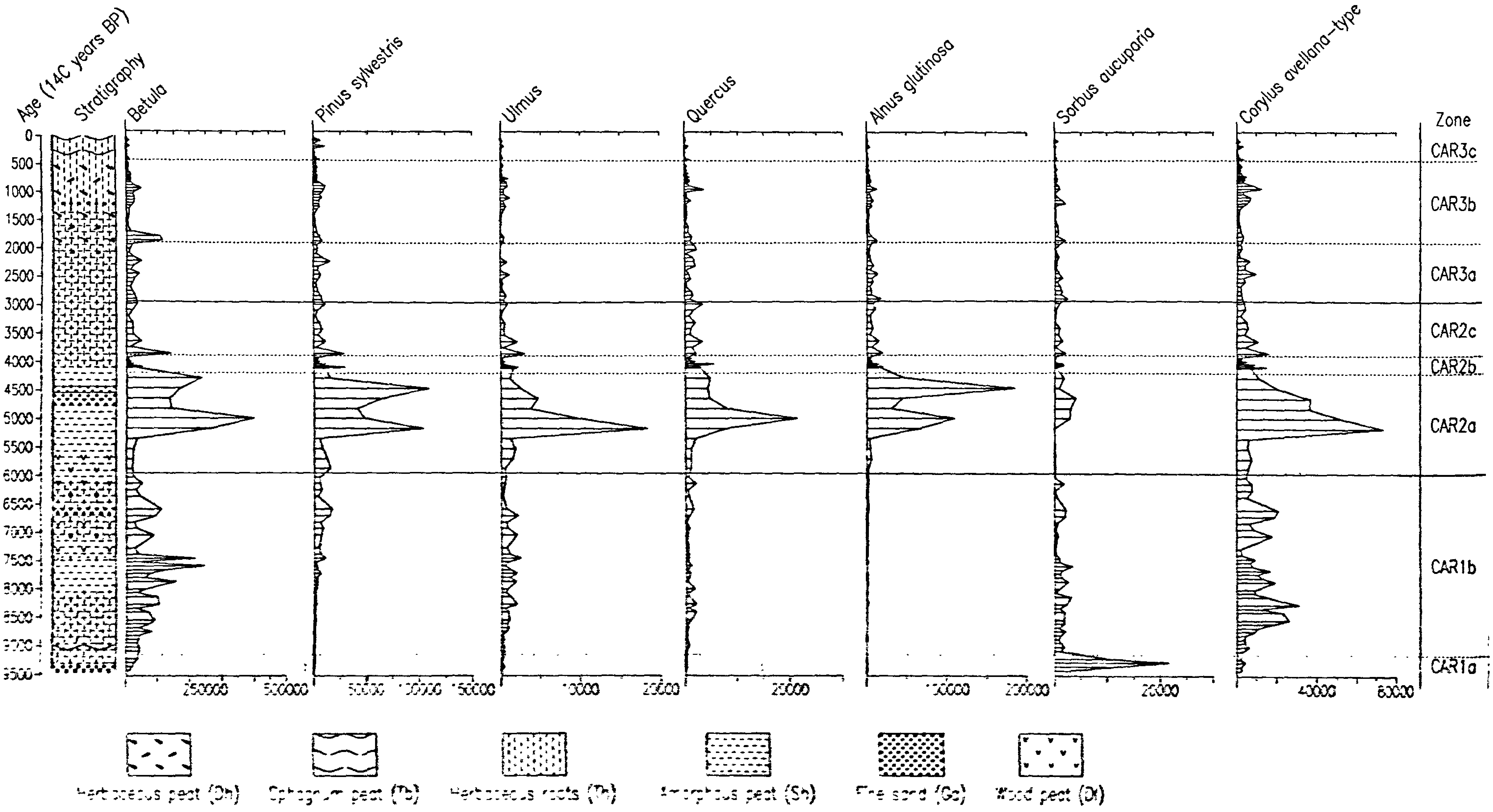
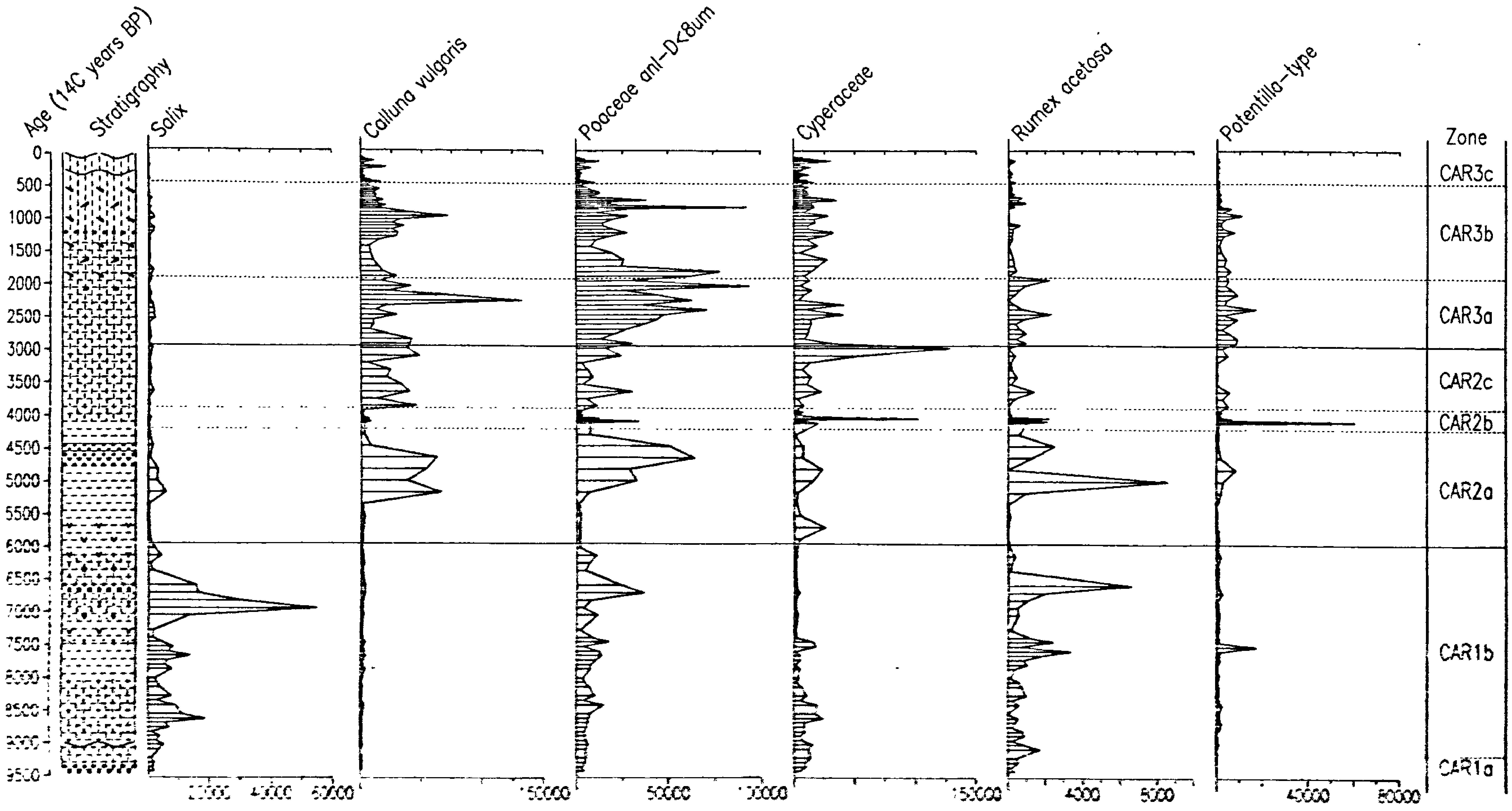


Figure 29. Selected concentration data from Carnach Mor (cont.).
NB Changes in scale.



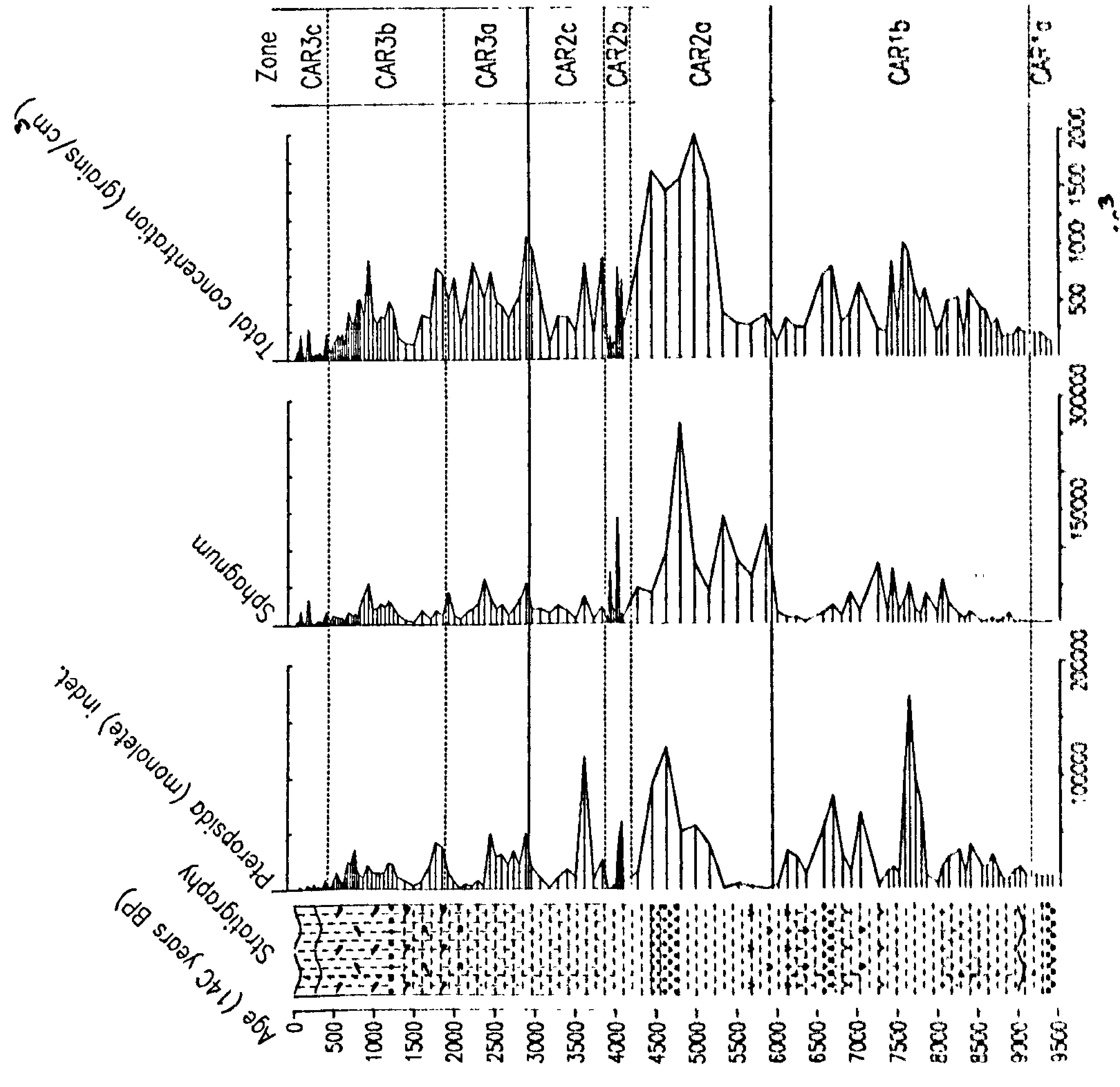


Figure 29. Selected concentration data from Carnach Mor (cont.).
NB Changes in scale.

Figure 30. Selected accumulation rate data from Carnach Mor.
NB Changes in scale.

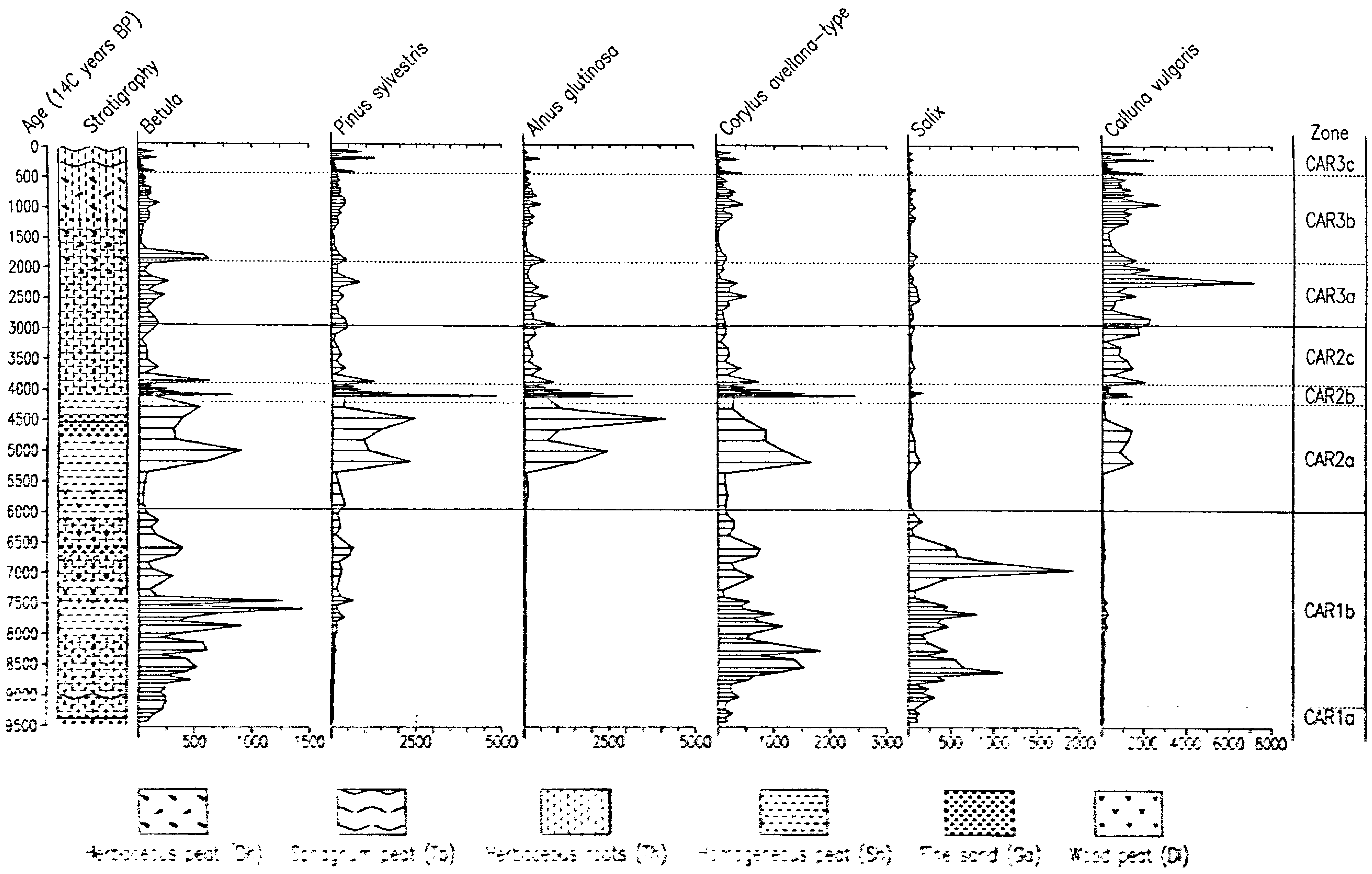
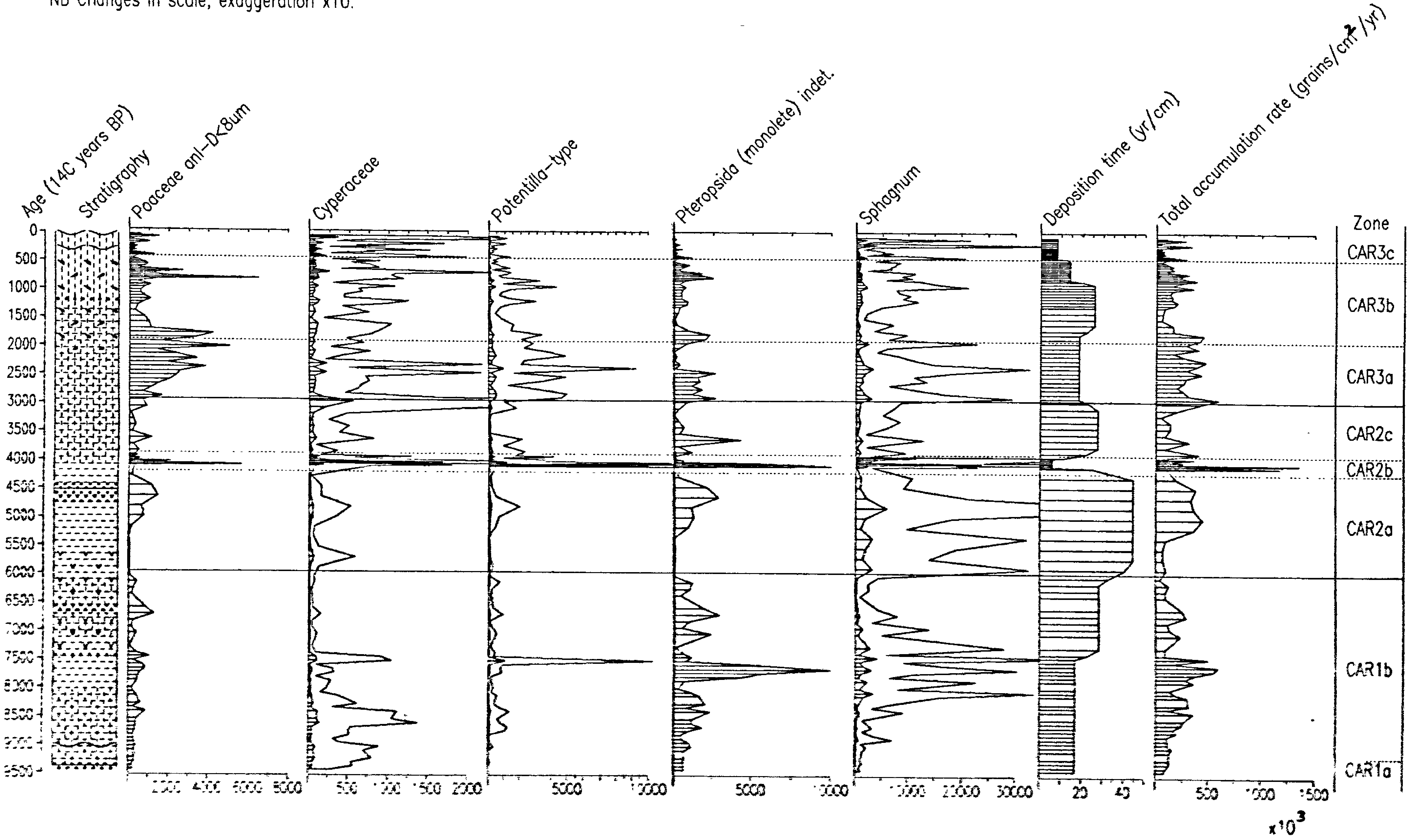


Figure 30. Selected accumulation rate data from Carnach Mor (cont.).
NB Changes in scale; exaggeration x10.



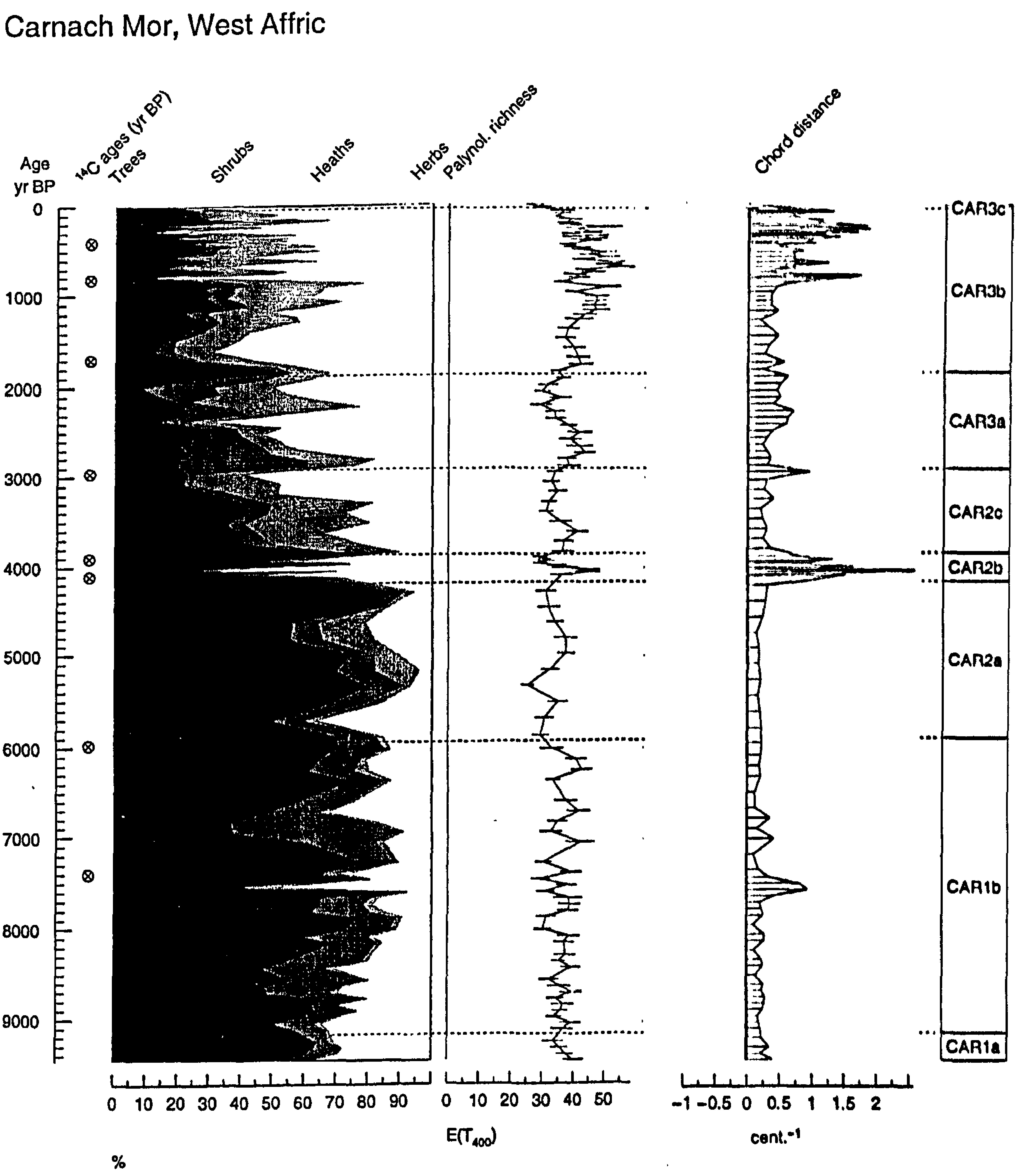


Figure 31. Rarefaction data and rates of change for Carnach Mór, plotted against age in ^{14}C years BP.

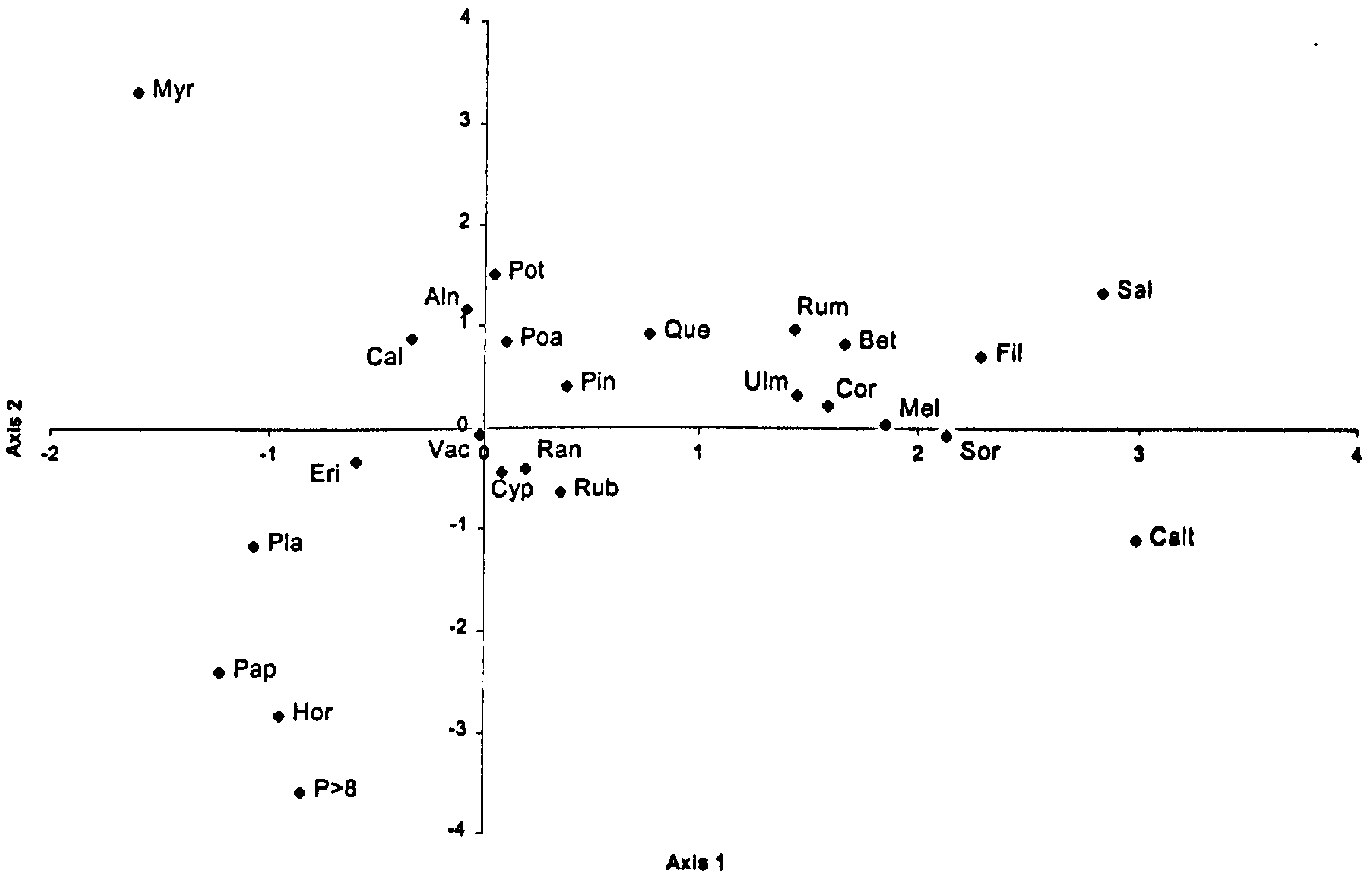


Figure 32a. DCA taxon scores on first two axes for Carnach Mór. Aln = *Alnus glutinosa*, Bet = *Betula*, Cal = *Calluna vulgaris*, Calt = *Caltha palustris*-type, Cor = *Corylus avellana*-type, Cyp = Cyperaceae, Eri = *Erica*, Fil = *Filipendula*, Hor = *Hordeum* group, Myr = *Myrica gale*, Mel = *Melampyrum*, Pap = *Papaver rhoeas*-type, Pin = *Pinus sylvestris*, Pla = *Plantago lanceolata*, Poa = Poaceae anl-D<8 µm, Pot = *Potentilla*-type, P>8 = Poaceae anl-D>8 µm, Que = *Quercus*, Ran = *Ranunculus acris*, Rub = Rubiaceae, Rum = *Rumex acetosa*, Sal = *Salix*, Sor = *Sorbus aucuparia*, Ulm = *Ulmus*, Vac = *Vaccinium*-type

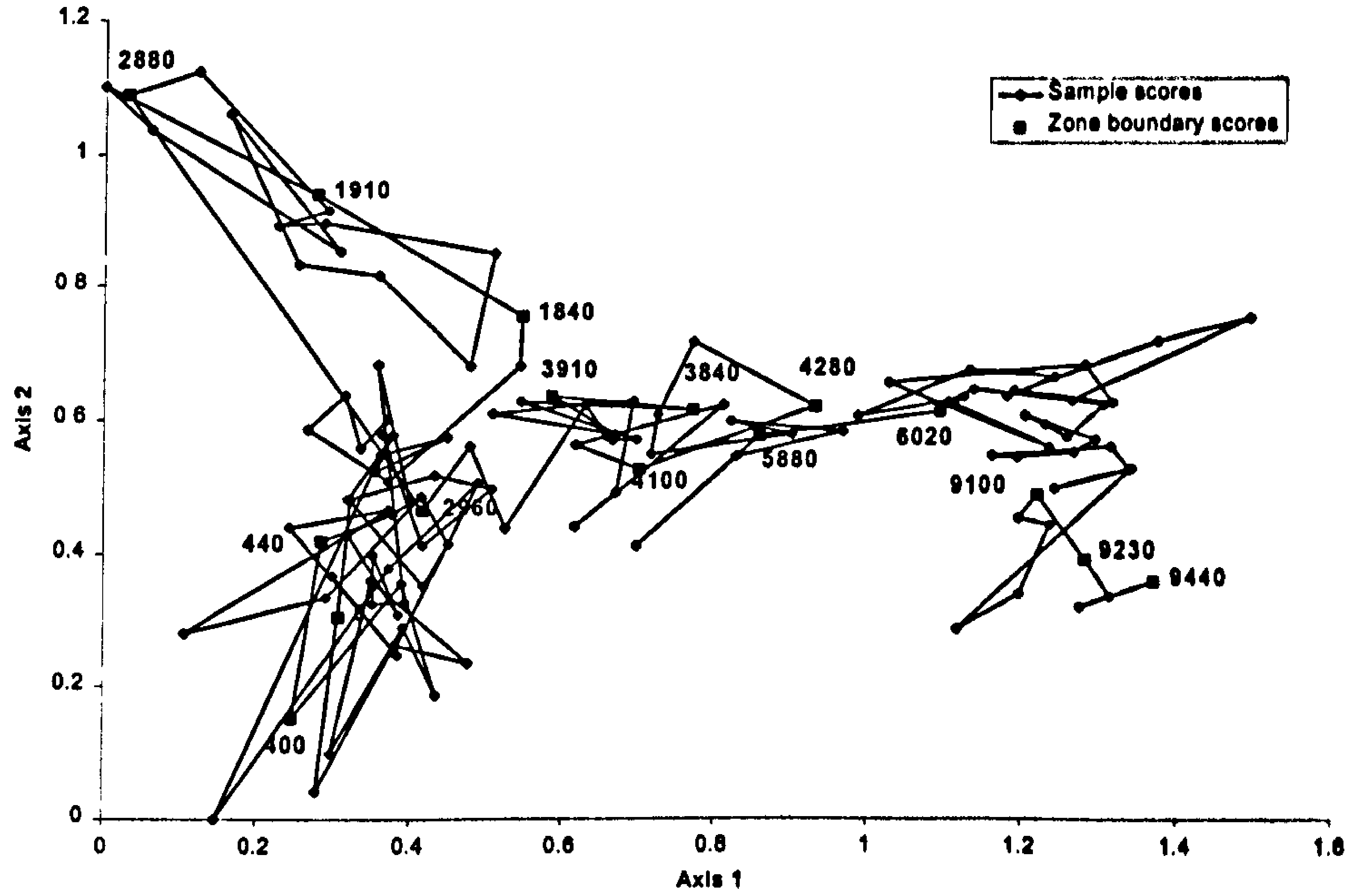
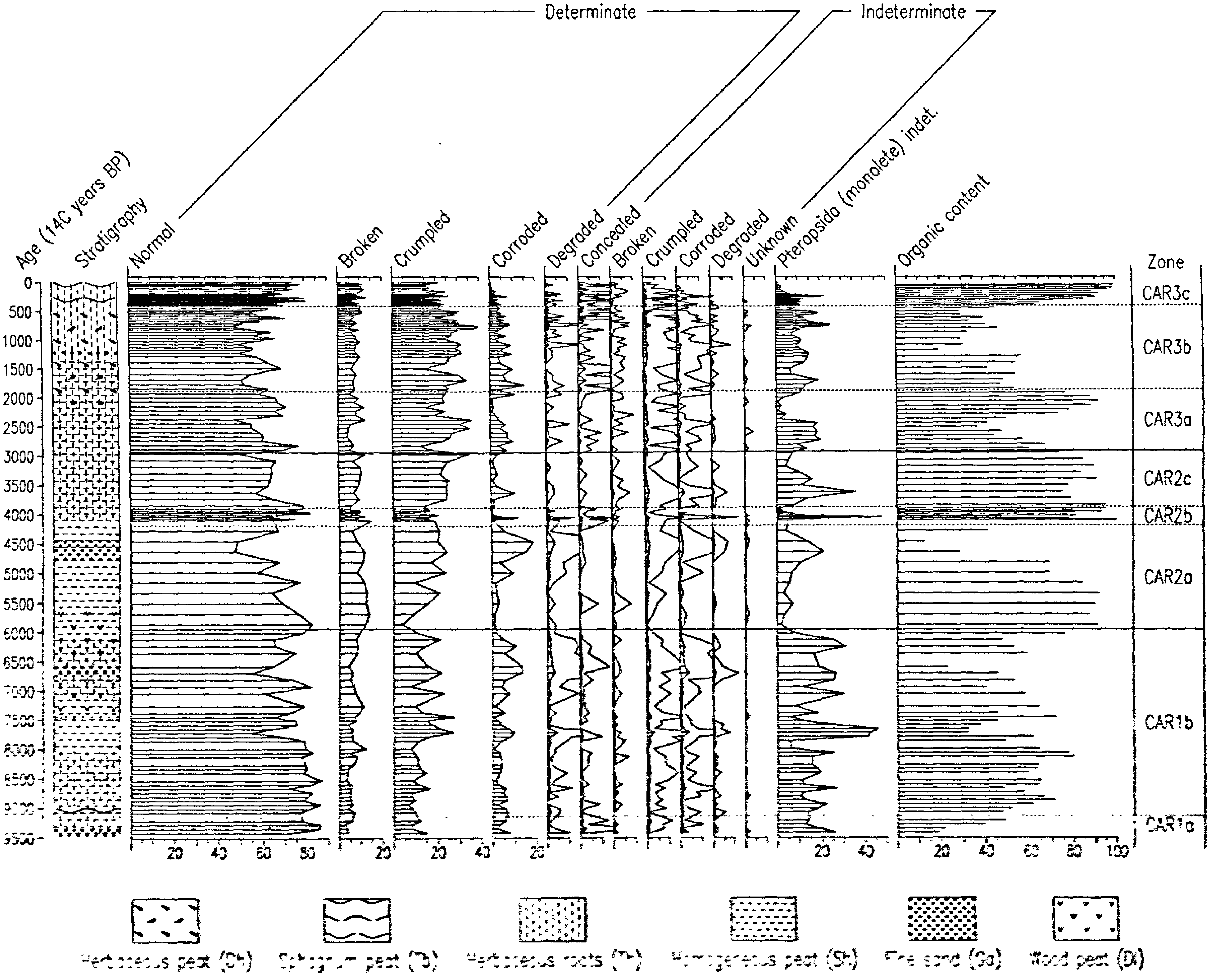


Figure 32b. DCA sample scores on first two axes for Carnach Mór with top and basal levels, and samples either side of zone boundaries labelled in ^{14}C years BP.

Figure 33. Summary pollen preservation data for Carnach Mor.
Sum = %TLP/%TLP + indeterminate; exaggeration x10.



[illegible] from [illegible]ach Mor.
[illegible] type
[illegible] layered

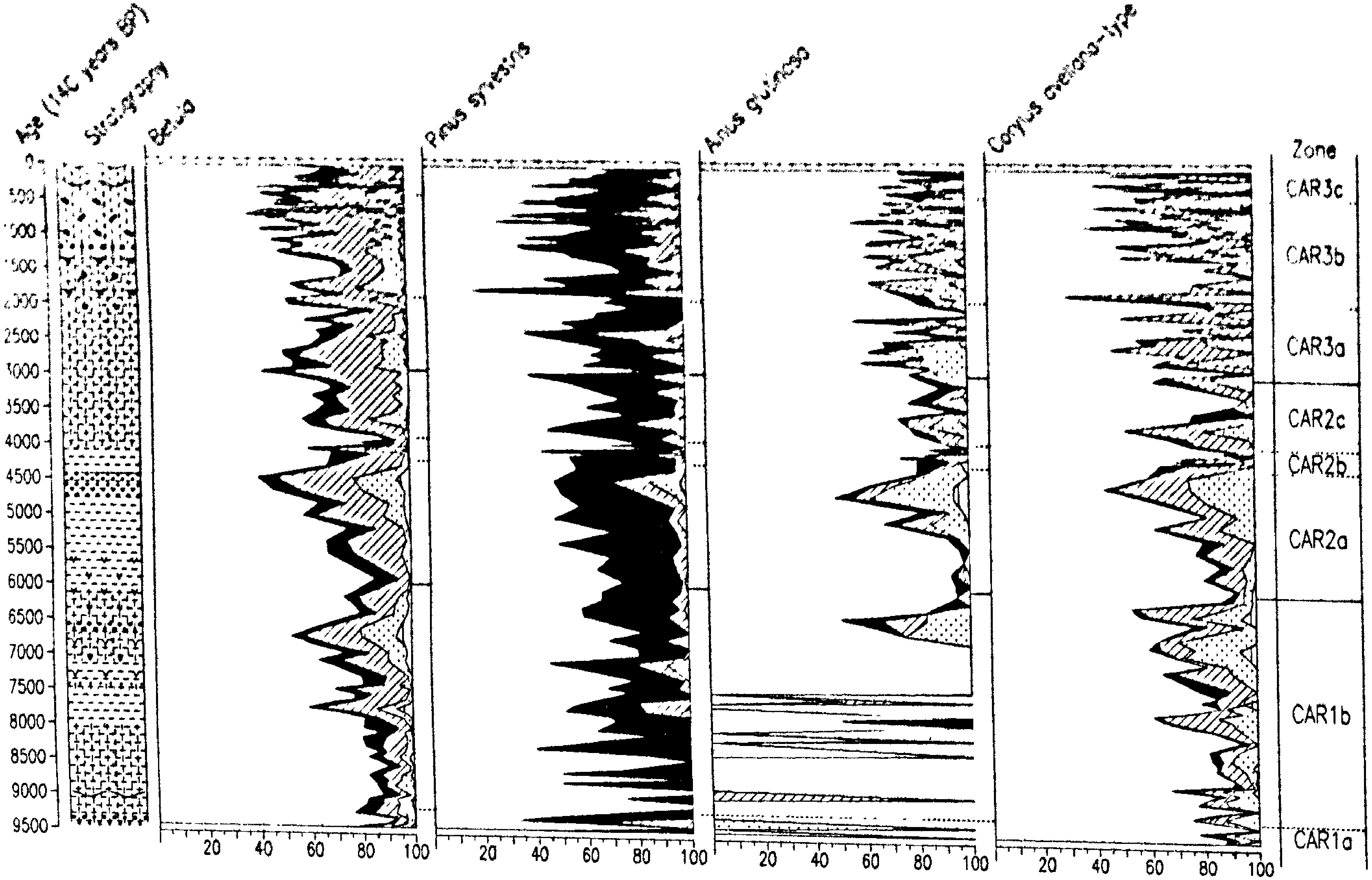


Figure 34. Selected pollen preservation data from Carnach Mor (cont.).
Sum = %total for each pollen type
Order: well-preserved, broken, crumpled, corroded, degraded.

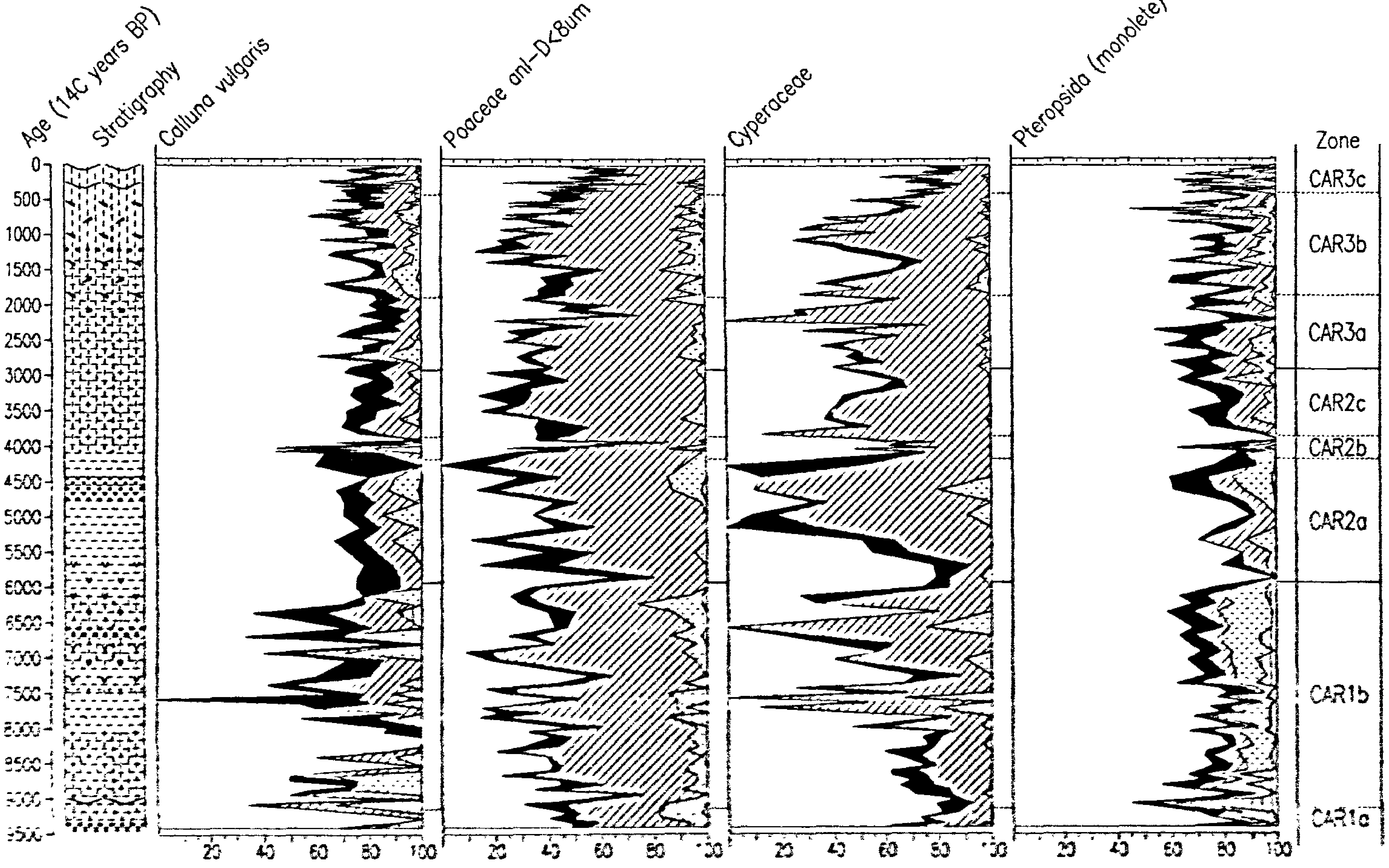
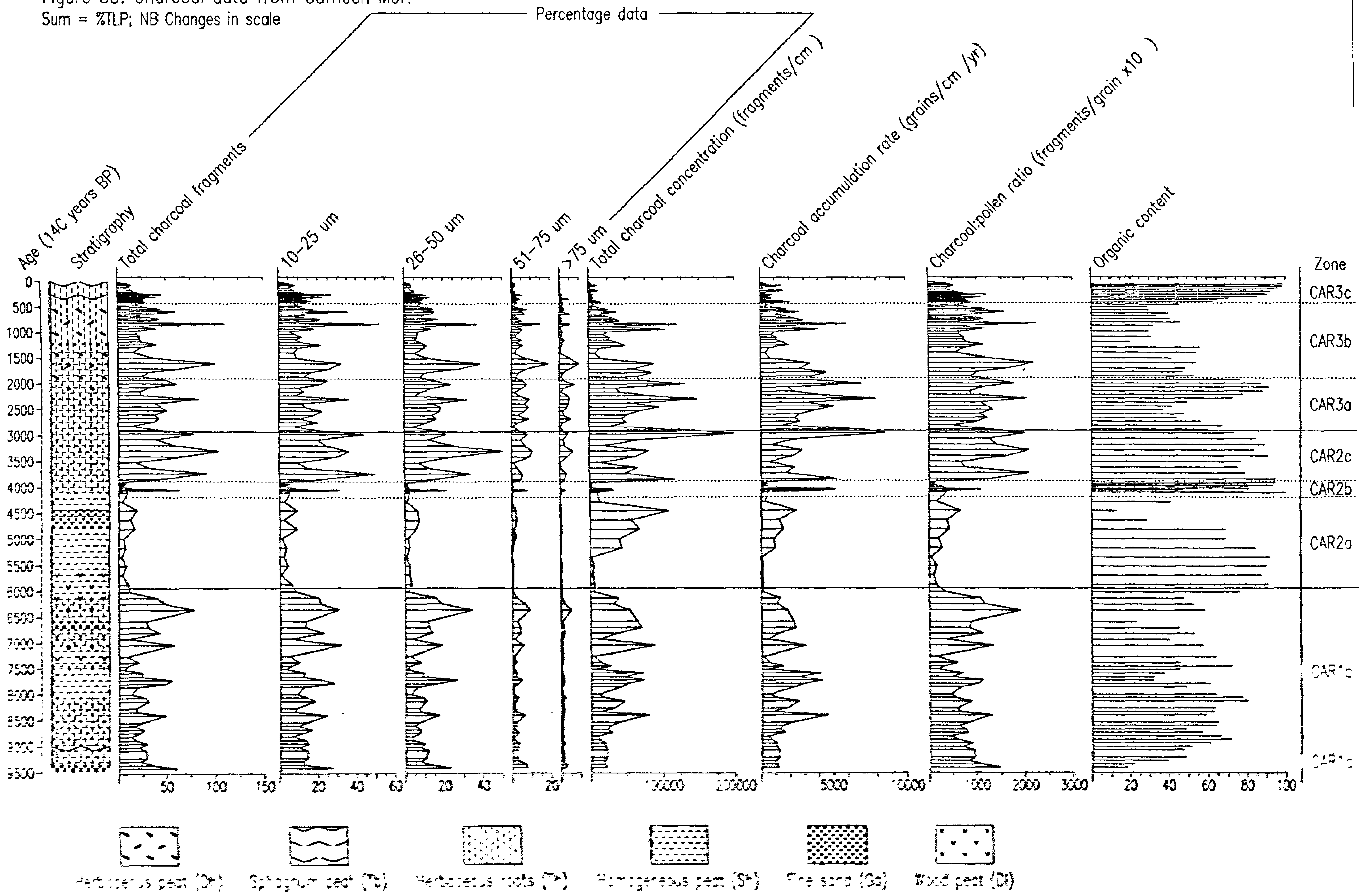


Figure 35. Charcoal data from Carnach Mor.
Sum = %TLP; NB Changes in scale



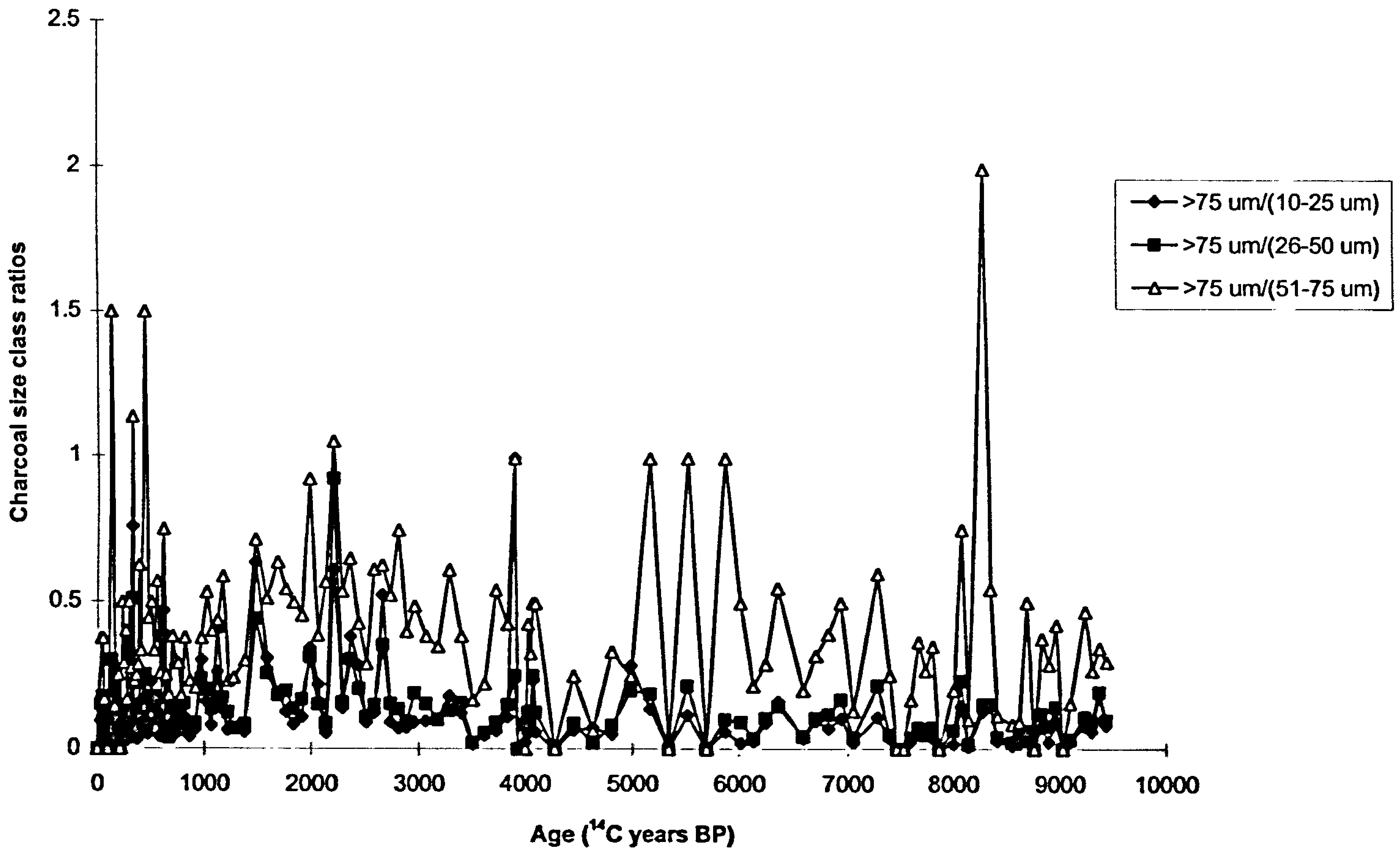


Figure 36. Charcoal size class analysis for Carnach Mór - ratio of percentage of large (>75 μm) to smaller (10-25 μm, 26-50 μm, 51-75 μm) fragments, plotted against age in ^{14}C years BP.

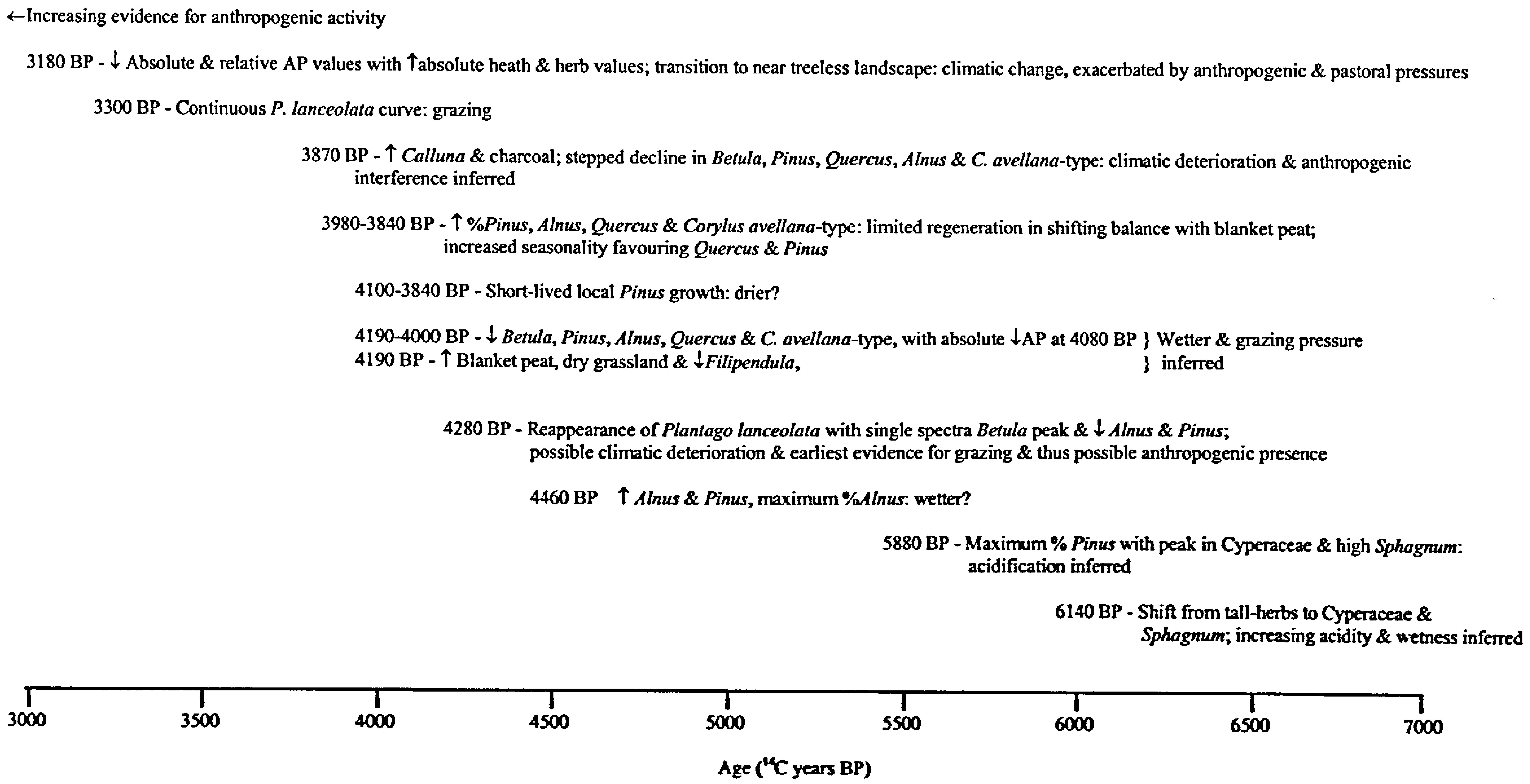


Figure 37. Summary of inferred mid-Holocene vegetational and environmental changes around Carnach Mór. Arrows denote increasing/decreasing pollen and charcoal values.

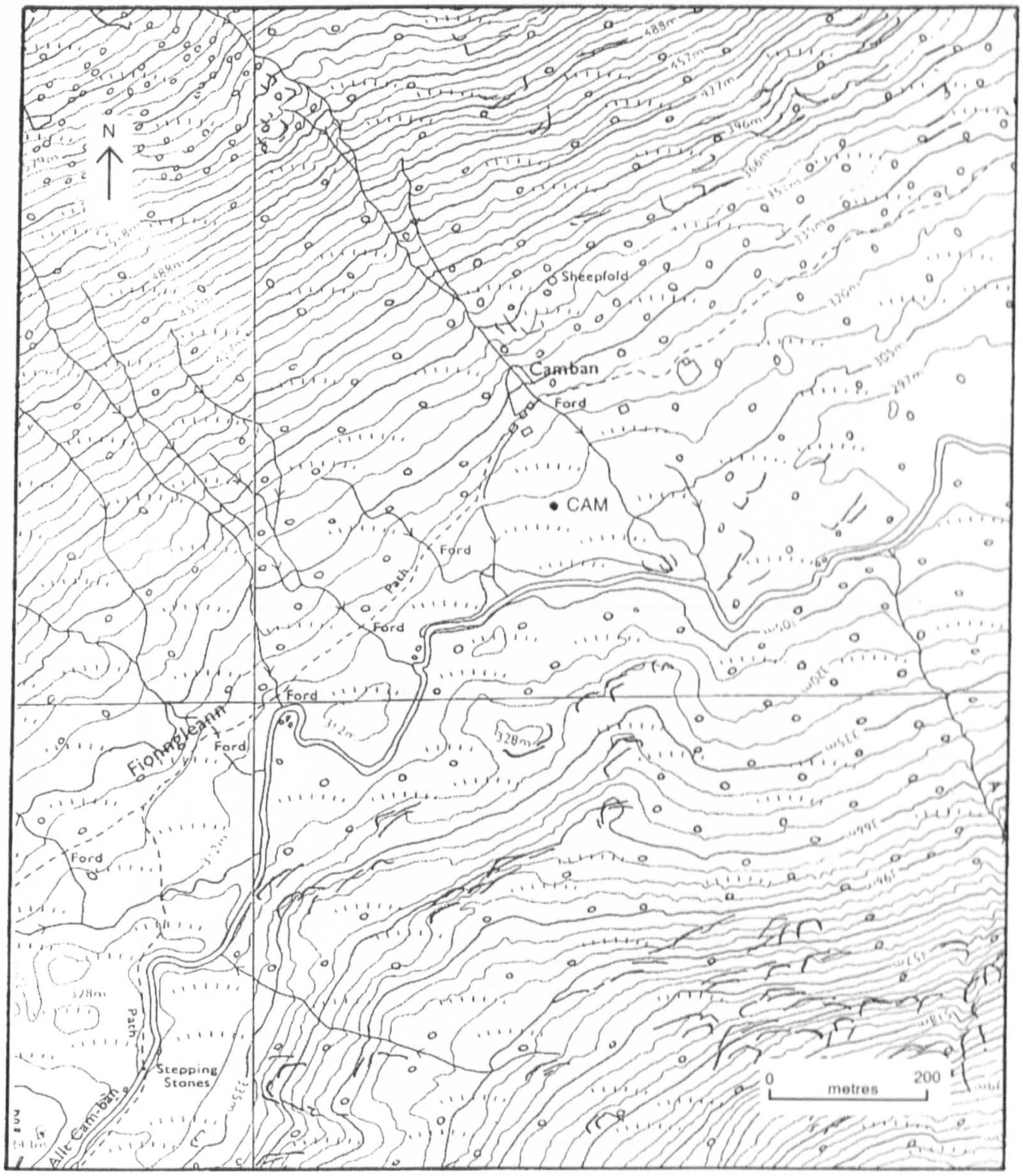


Figure 38. Sampling site at Camban. © Ordnance Survey.

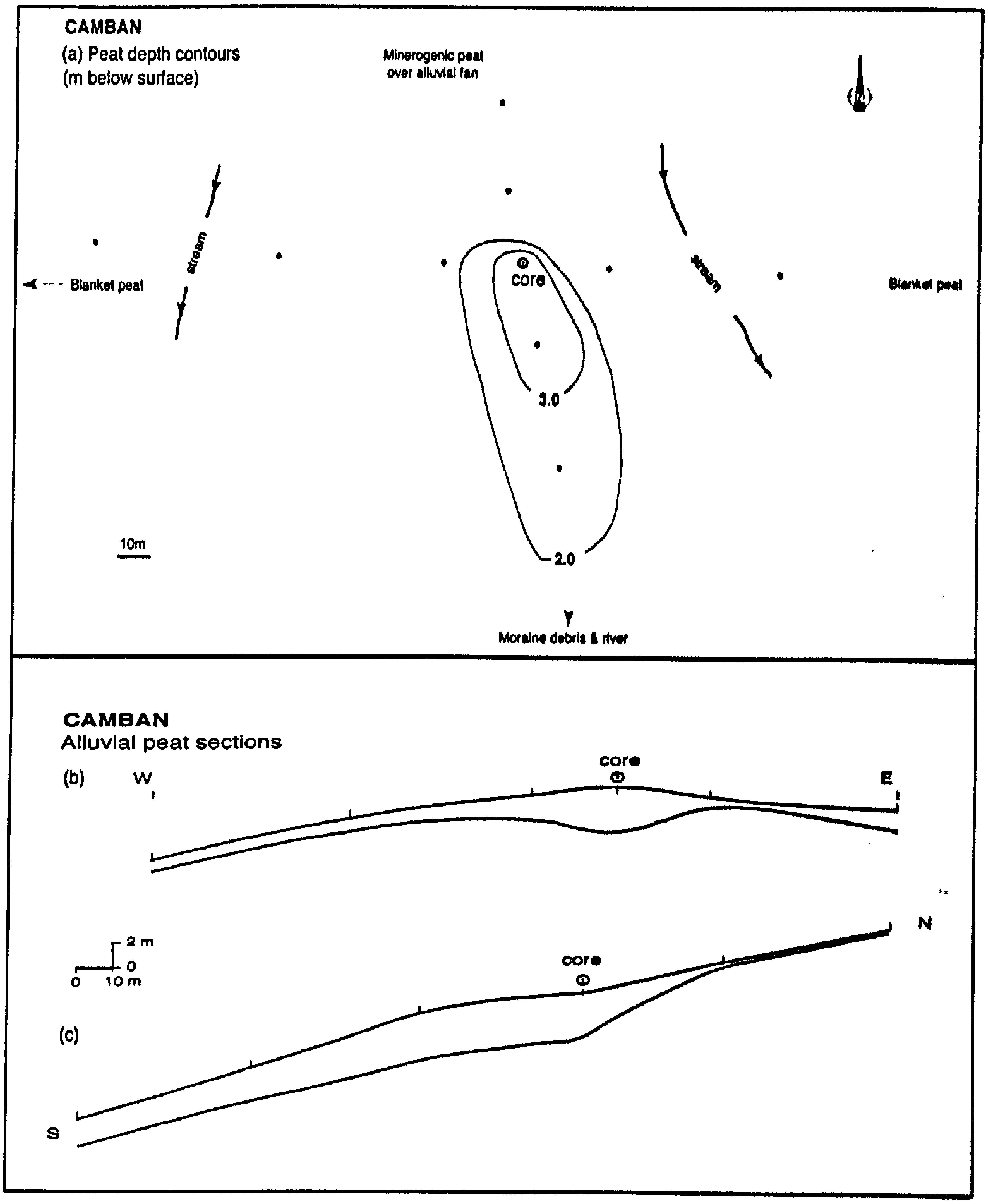


Figure 39. Site contour and section maps for Camban (a) peat depths (in metres below ground surface), (b) east-west section, (c) north-south section.

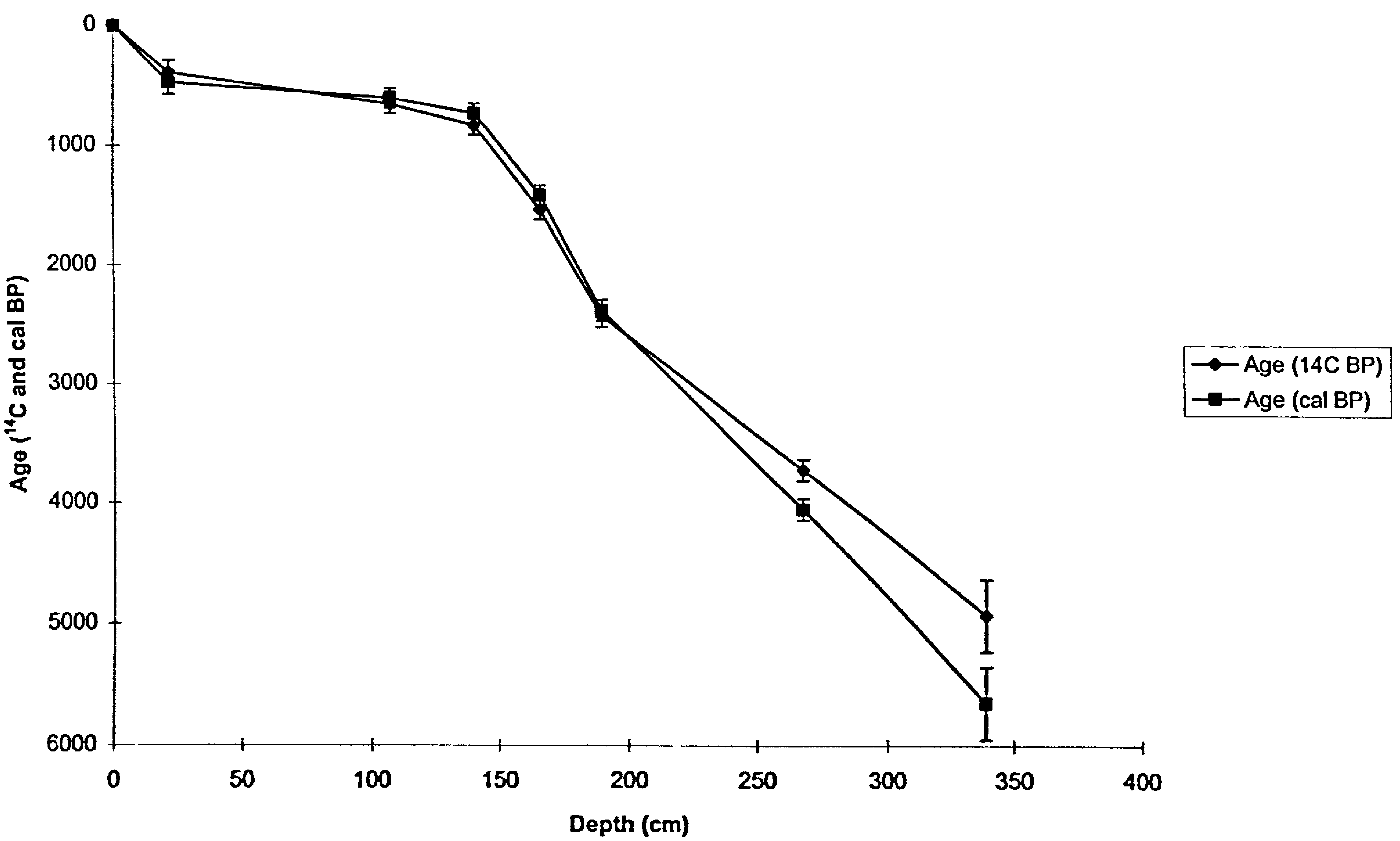


Figure 40. Radiocarbon and calibrated time-depth curves for Camban with 2σ error ranges.

Figure 41. Full percentage data from Camban.
Sum = %TLP/%TLP + group; exaggeration x10.

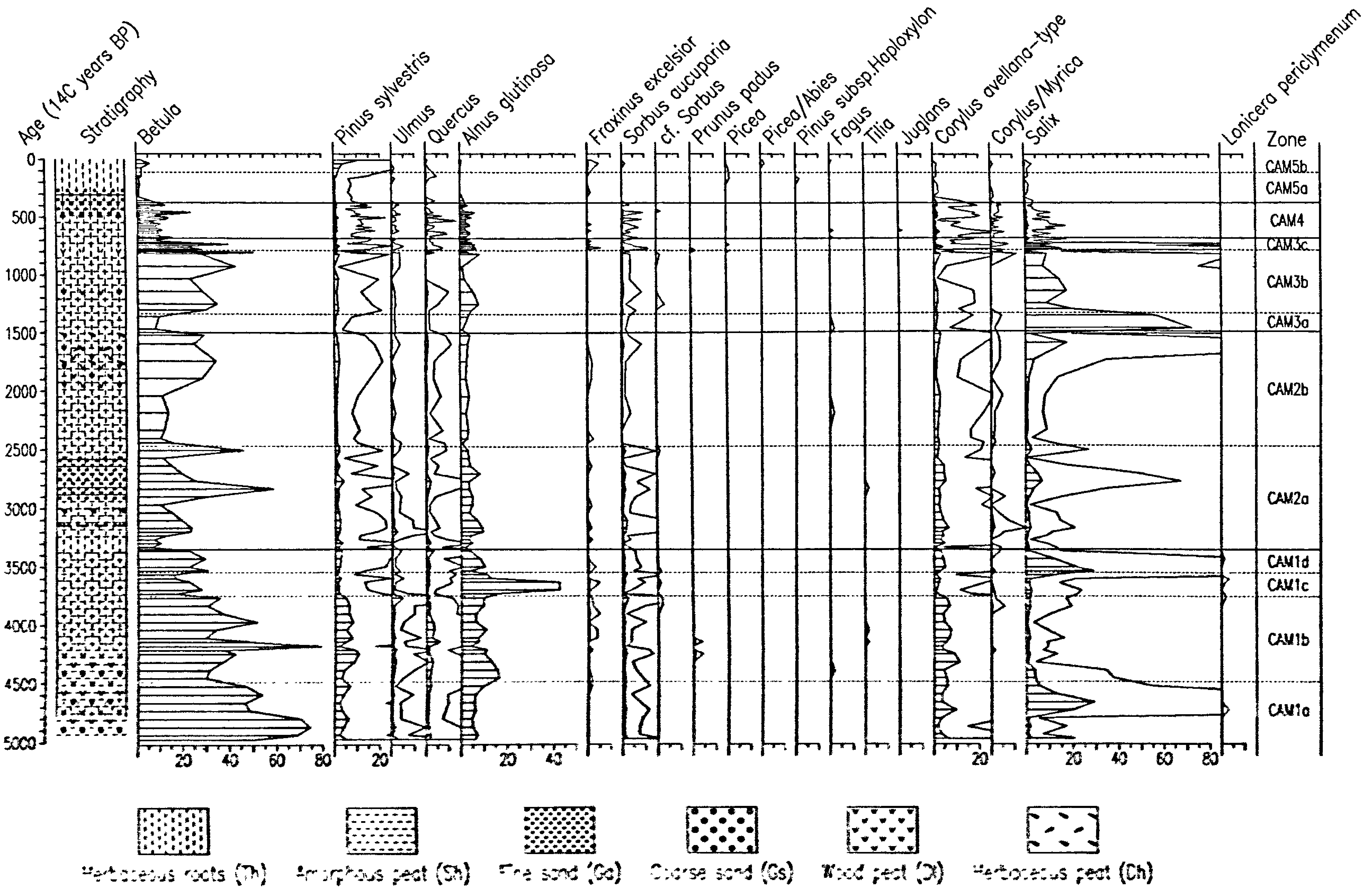


Figure 41. Full percentage data from Camban (continued).
Sum = %TLP/%TLP + group; exaggeration x10.

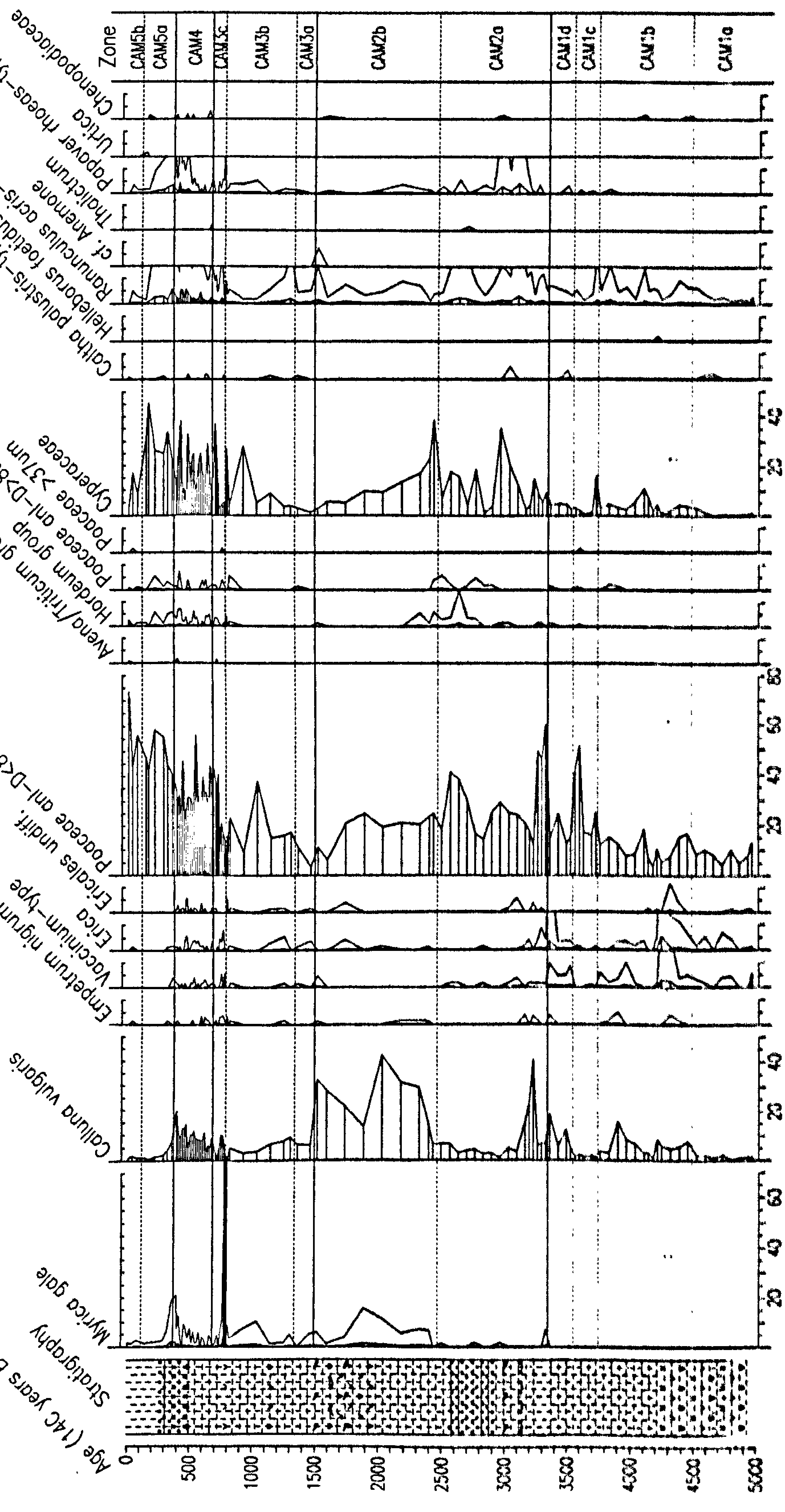


Figure 41. Full percentage data from Camban (continued).
Sum = %TLP/%TLP + group; exaggeration x10.

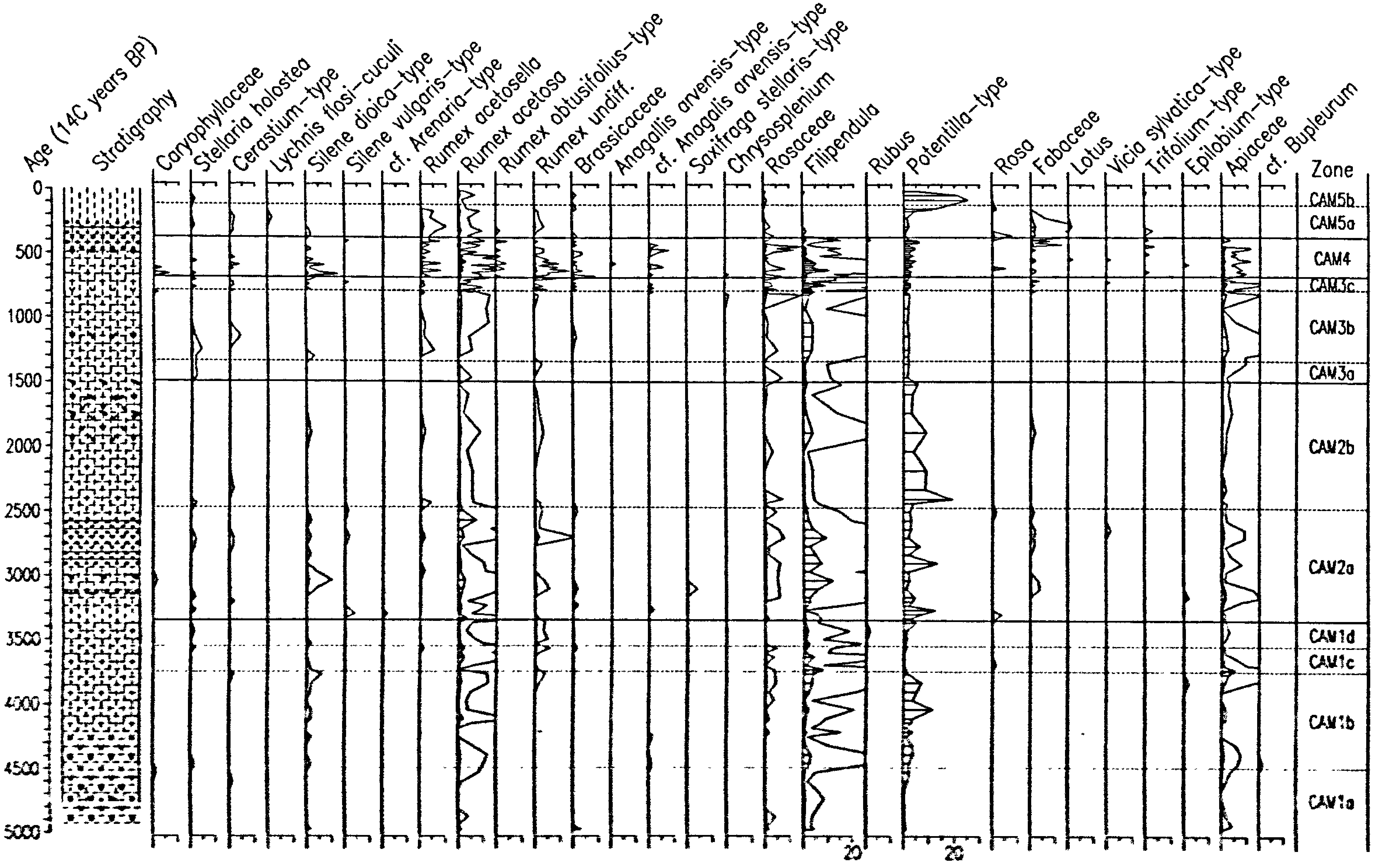


Figure 41. Full percentage data from Camban (continued).
Sum = %TLP/%TLP + group; exaggeration x10.

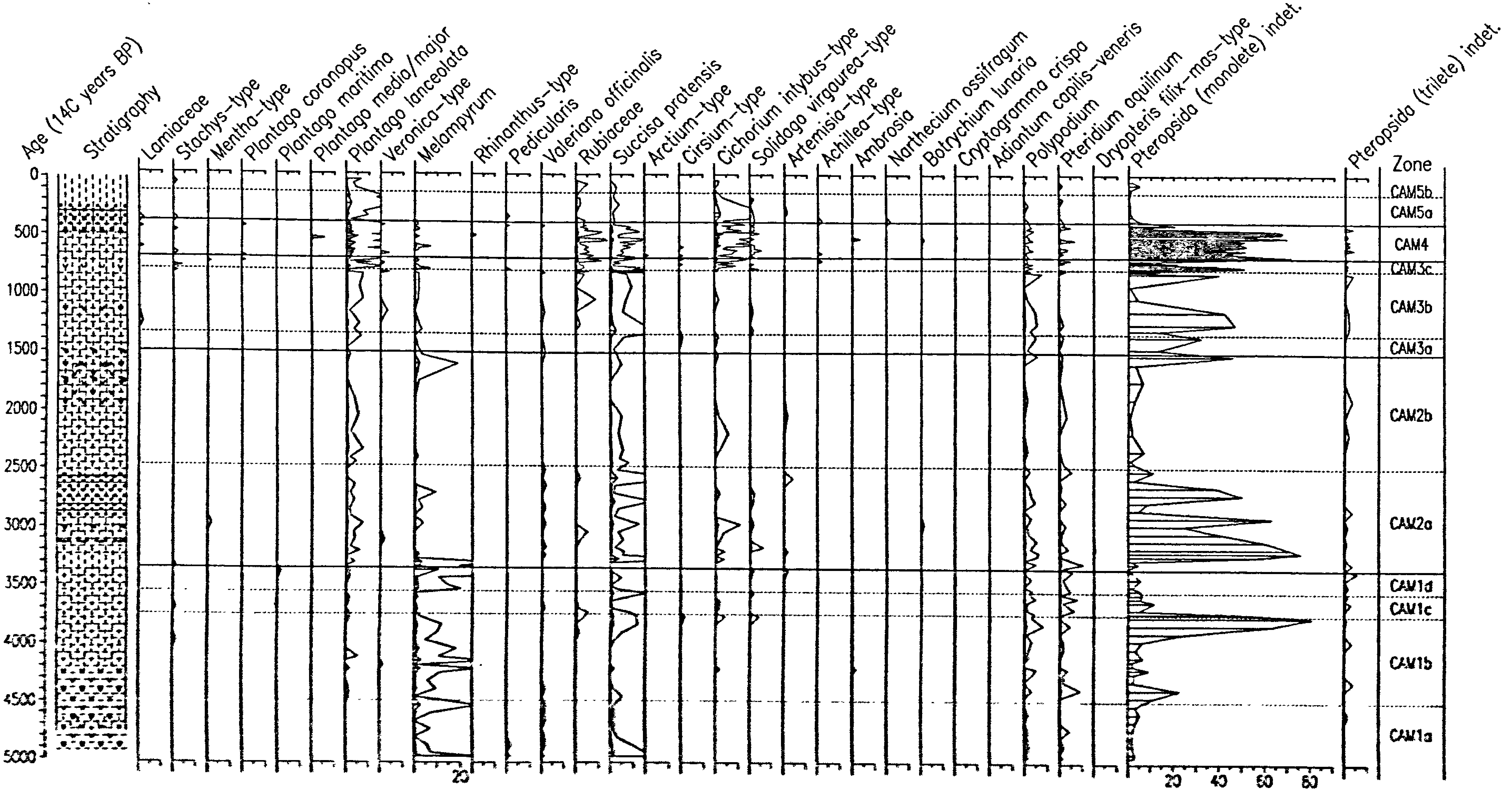


Figure 4'. Full percentage data from Camban (continued).
Sum = %TLP/%T_P + group; exaggeration x10.

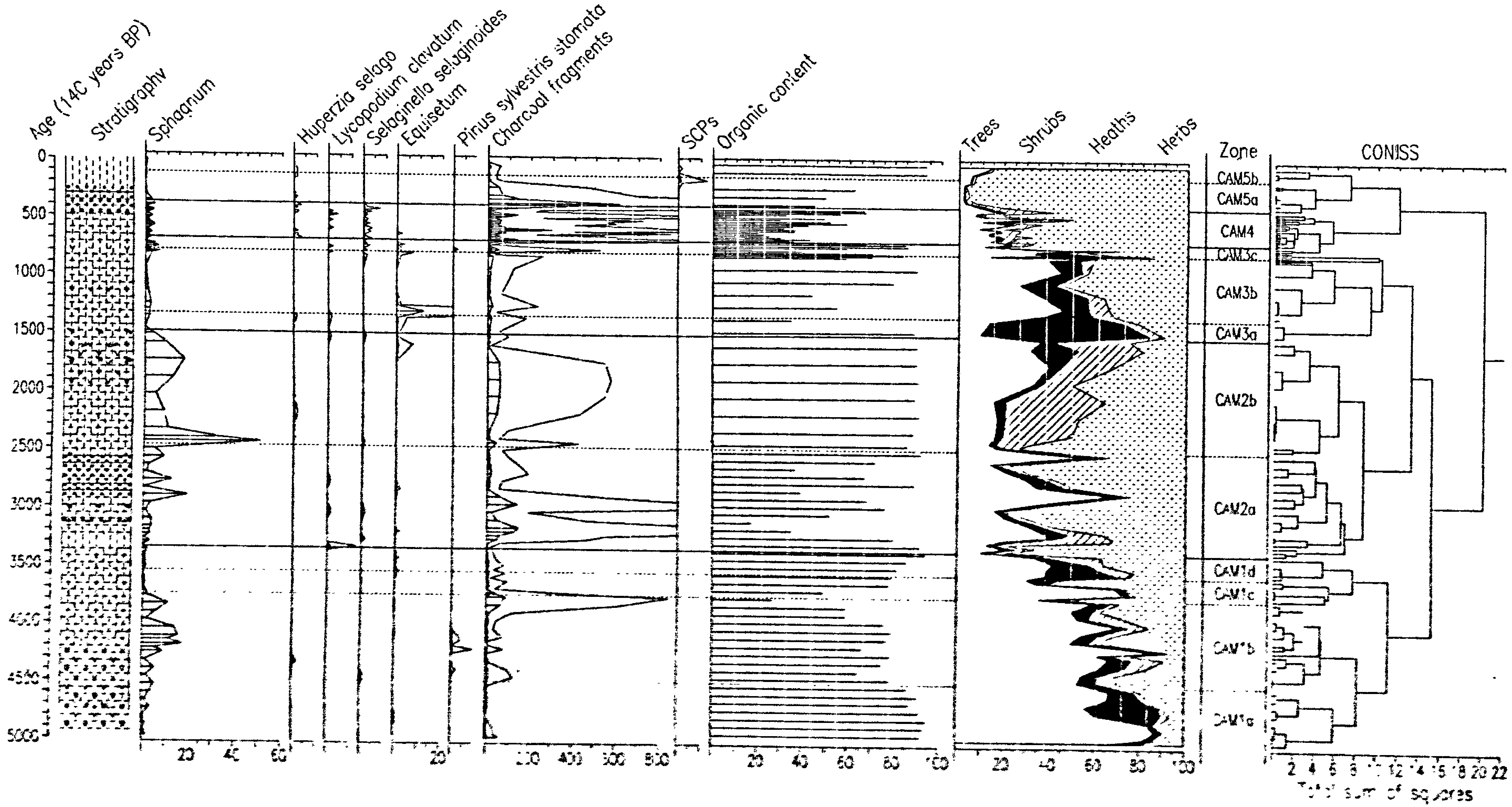


Figure 42. Selected concentration data for Camban.
NB Changes in scale.

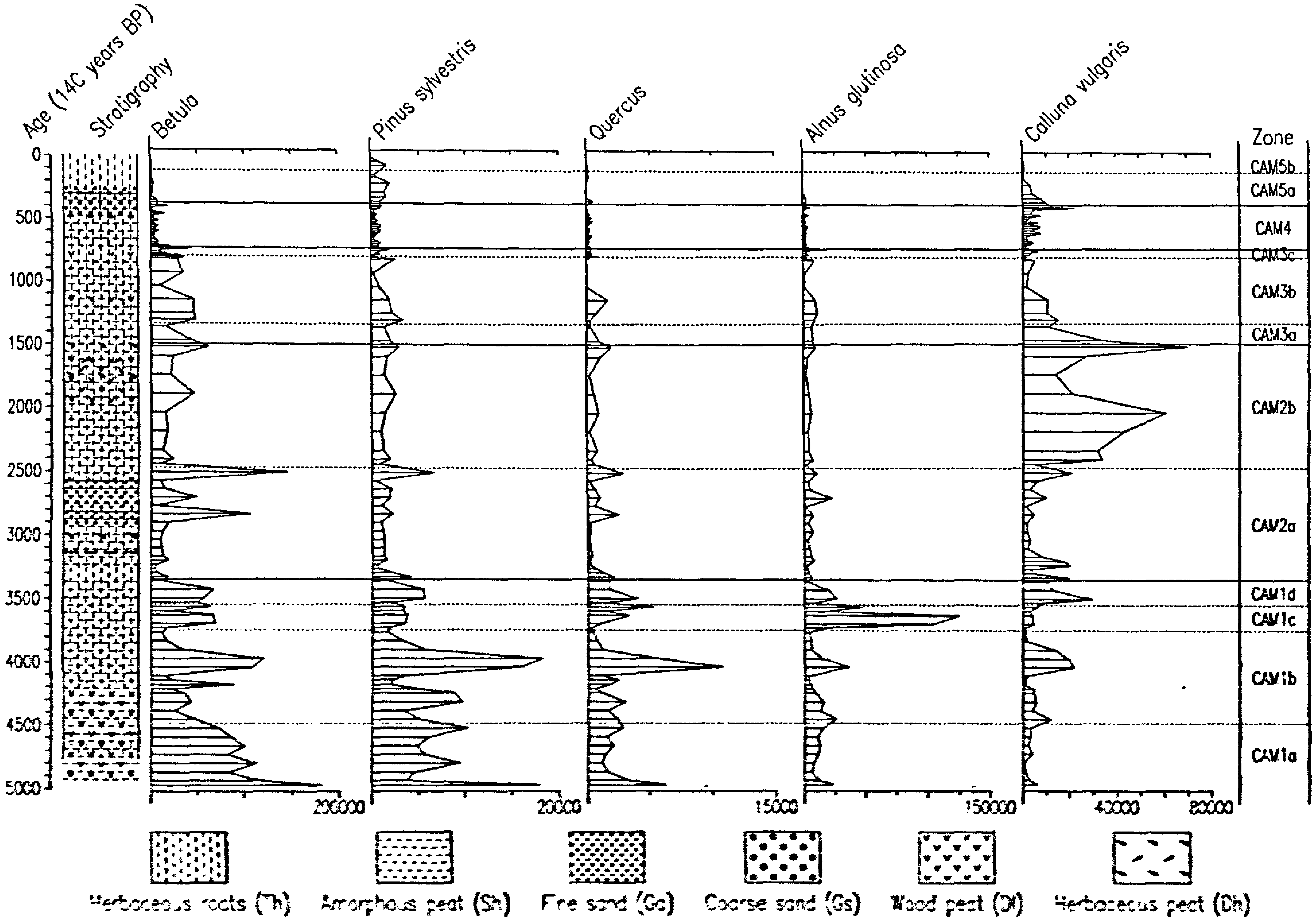


Figure 42. Selected concentration data for Camban (continued).
NB Changes in scale.

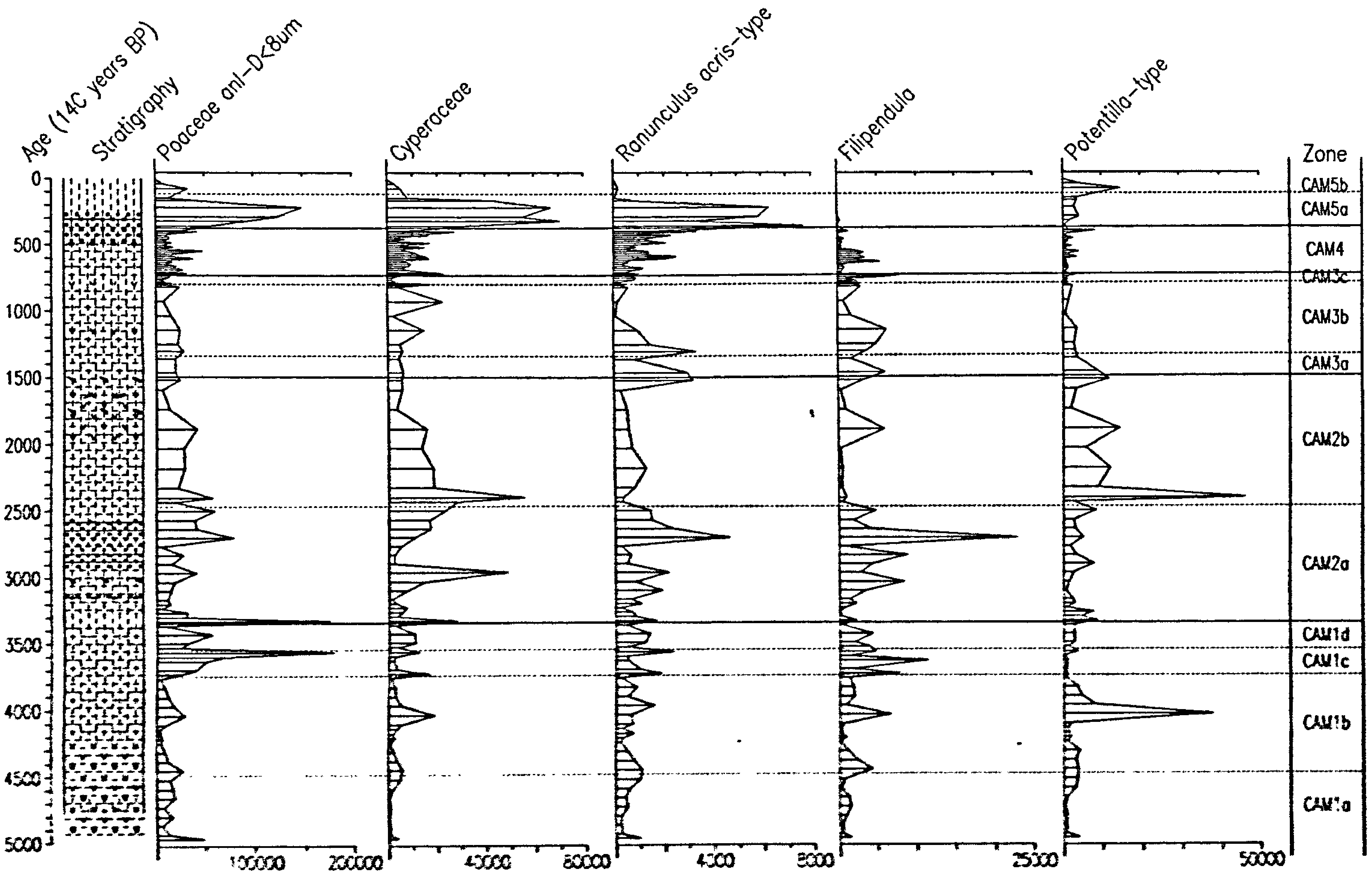
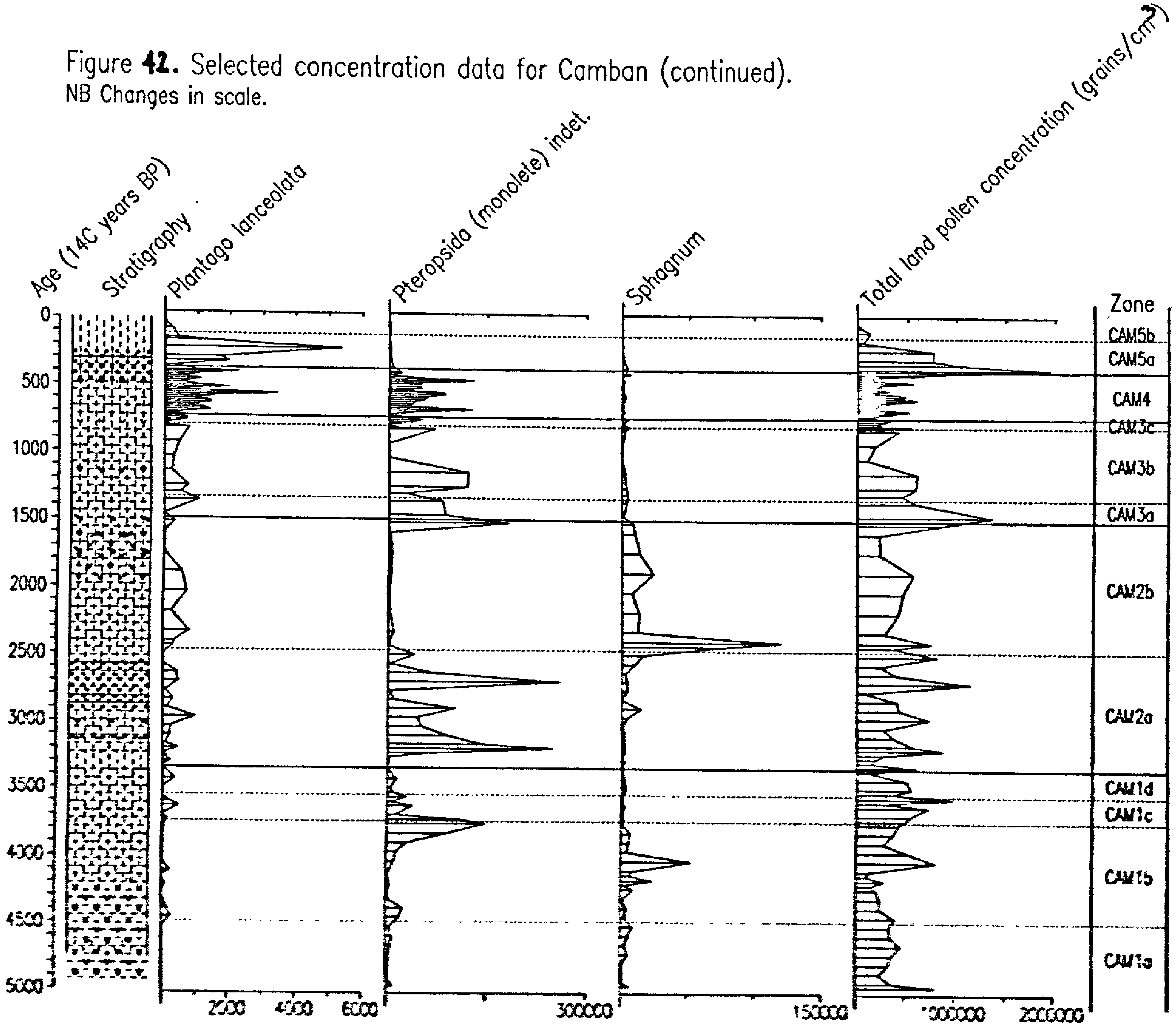


Figure **42.** Selected concentration data for Camban (continued).
NB Changes in scale.



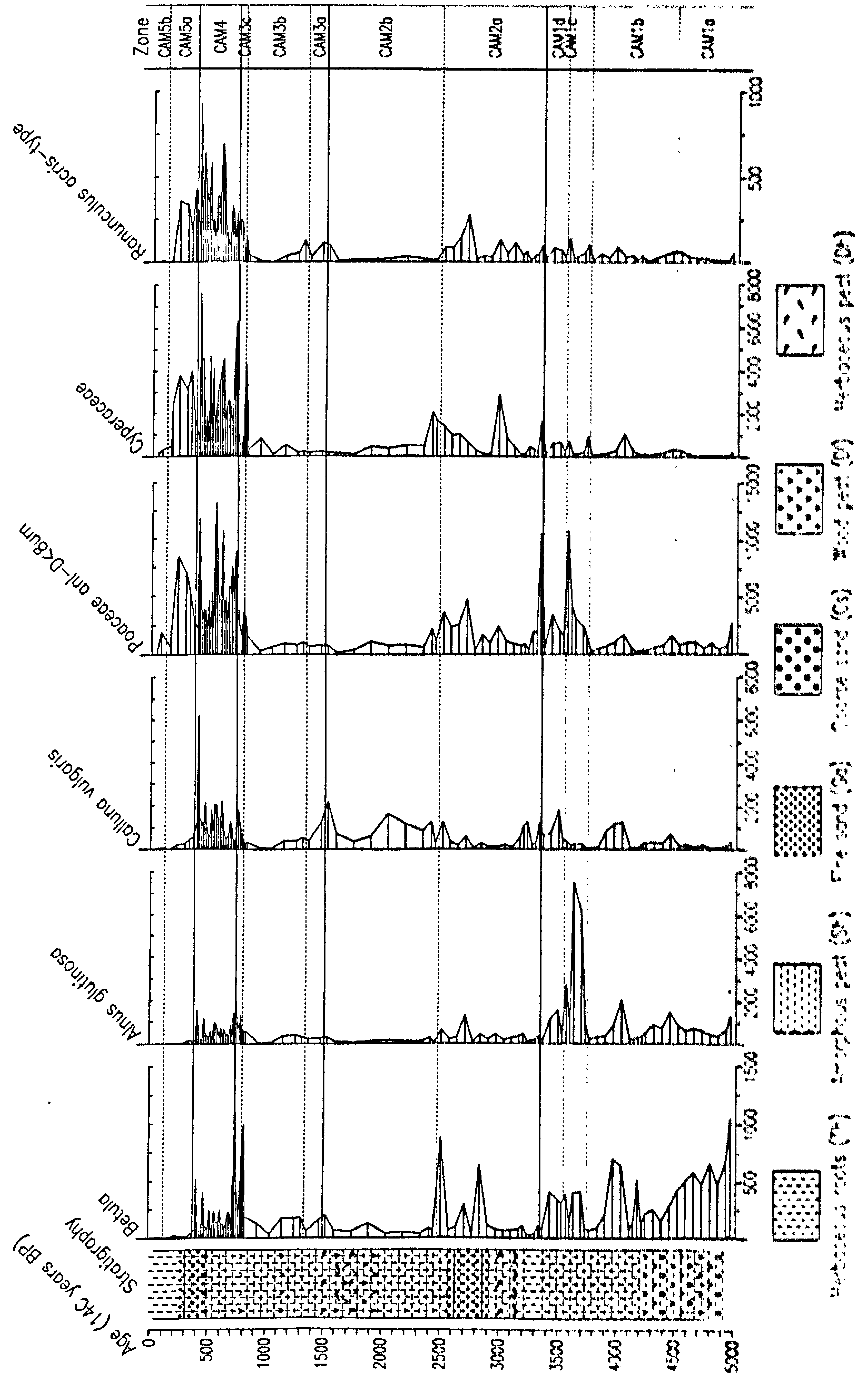


Figure 43. Selected pollen accumulation rates for Camban.
(grains/cm^2/yr)
NB Changes in scale.

Figure 43. Selected pollen accumulation rates for Camban (cont.).
(grains/cm^2/yr)
NB Changes in scale.

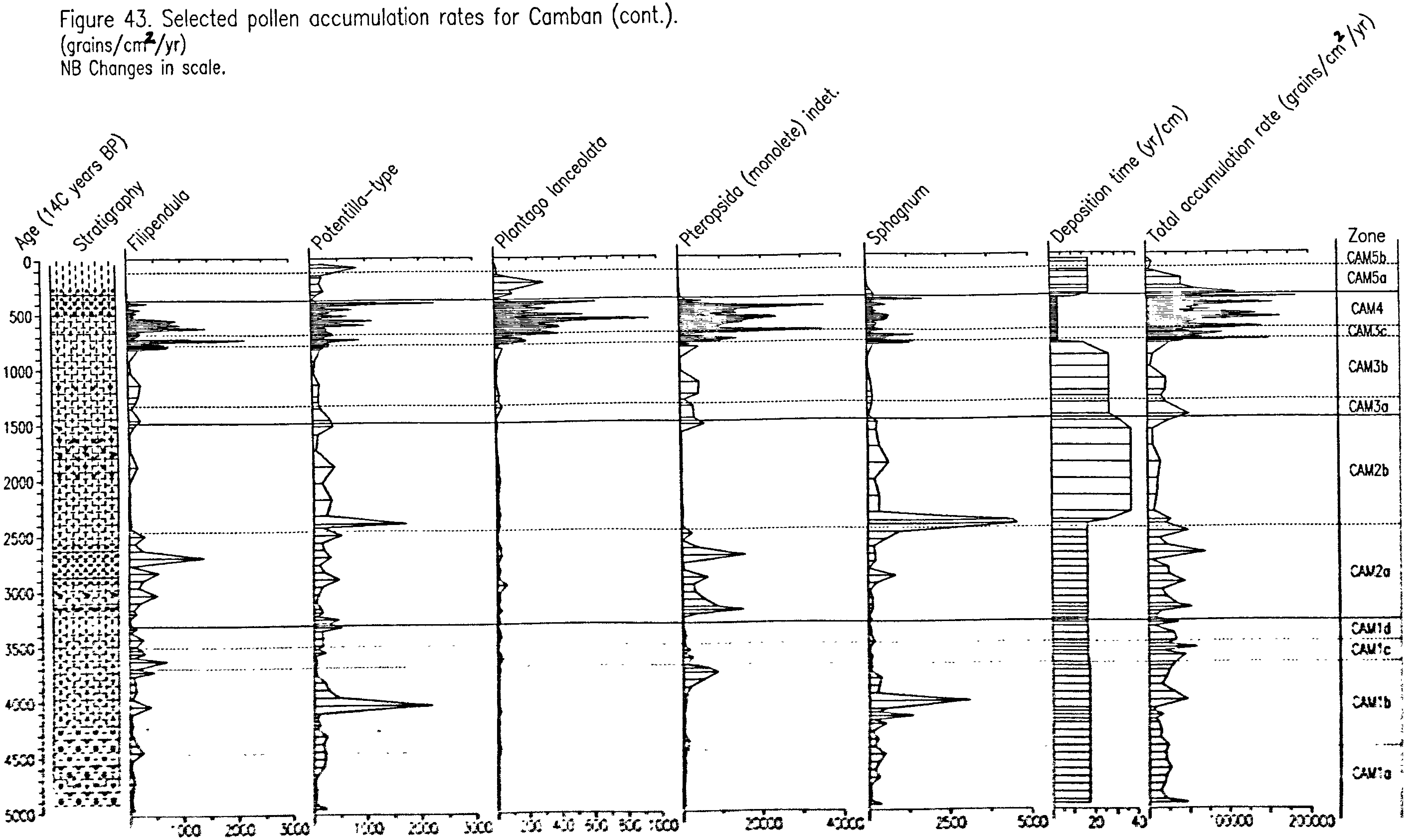
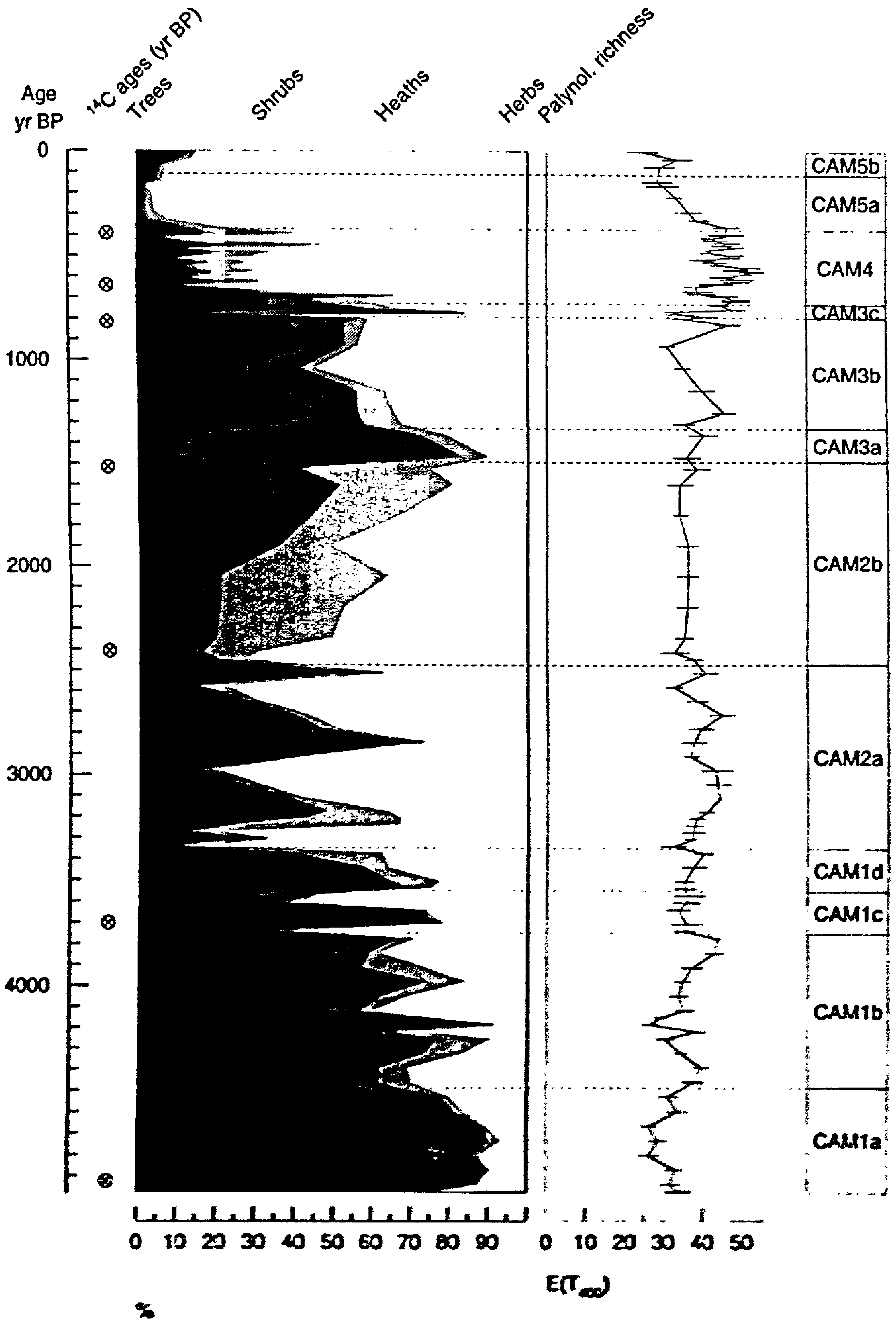


Figure 44. Rarefaction data for Camban.



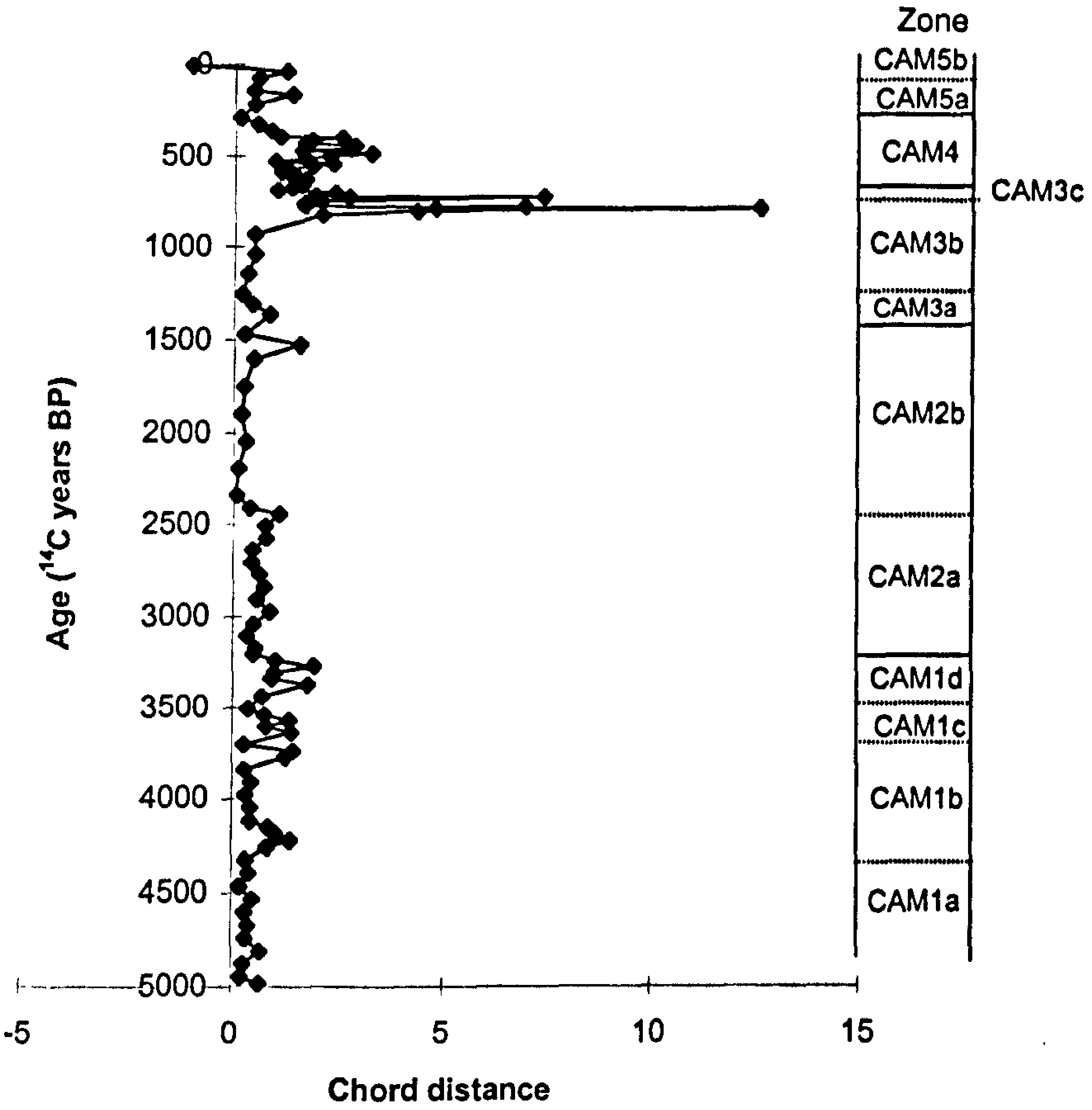


Figure 45. Rates of palynological change for Camban plotted against age in ^{14}C years BP.

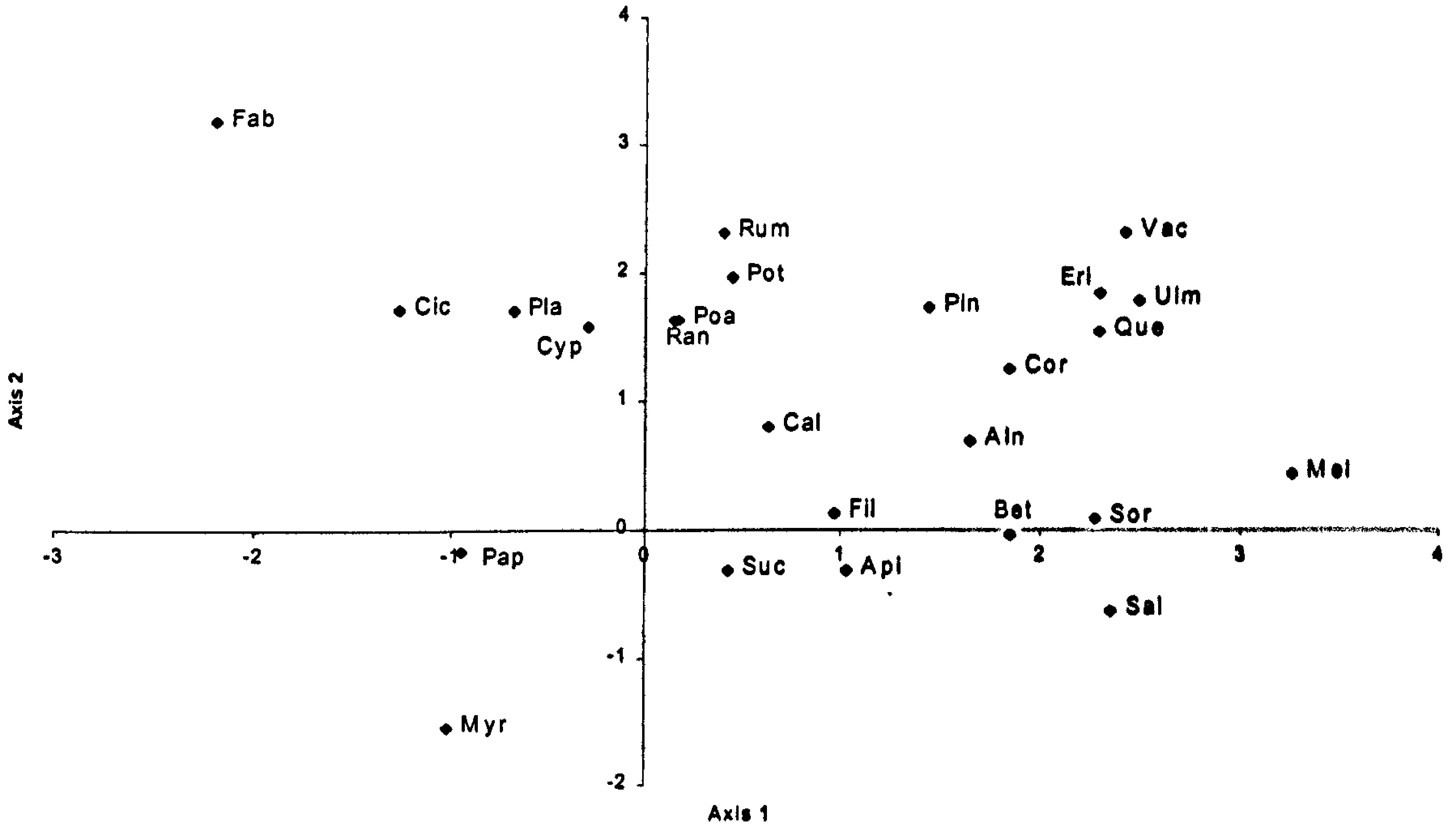


Figure 46a. DCA taxon scores on first two axes for Camban. Aln = *Alnus glutinosa*, Api = Apiaceae, Bet = *Betula*, Cal = *Calluna vulgaris*, Cic = *Cichorium intybus*-type, Cor = *Corylus avellana*-type, Cyp = Cyperaceae, Eri = *Erica*, Fab = Fabaceae, Fil = *Filipendula*, Mel = *Melampyrum*, Myr = *Myrica gale*, Pap = *Papaver rhoeas*-type, Pin = *Pinus sylvestris*, Pla = *Plantago lanceolata*, Poa = Poaceae anl-D<8 μm, Pot = *Potentilla*-type, Que = *Quercus*, Ran = *Ranunculus acris*, Rum = *Rumex acetosa*, Sal = *Salix*, Sor = *Sorbus aucuparia*, Suc = *Succisa pratensis*, Ulm = *Ulmus*, Vac = *Vaccinium*-type.

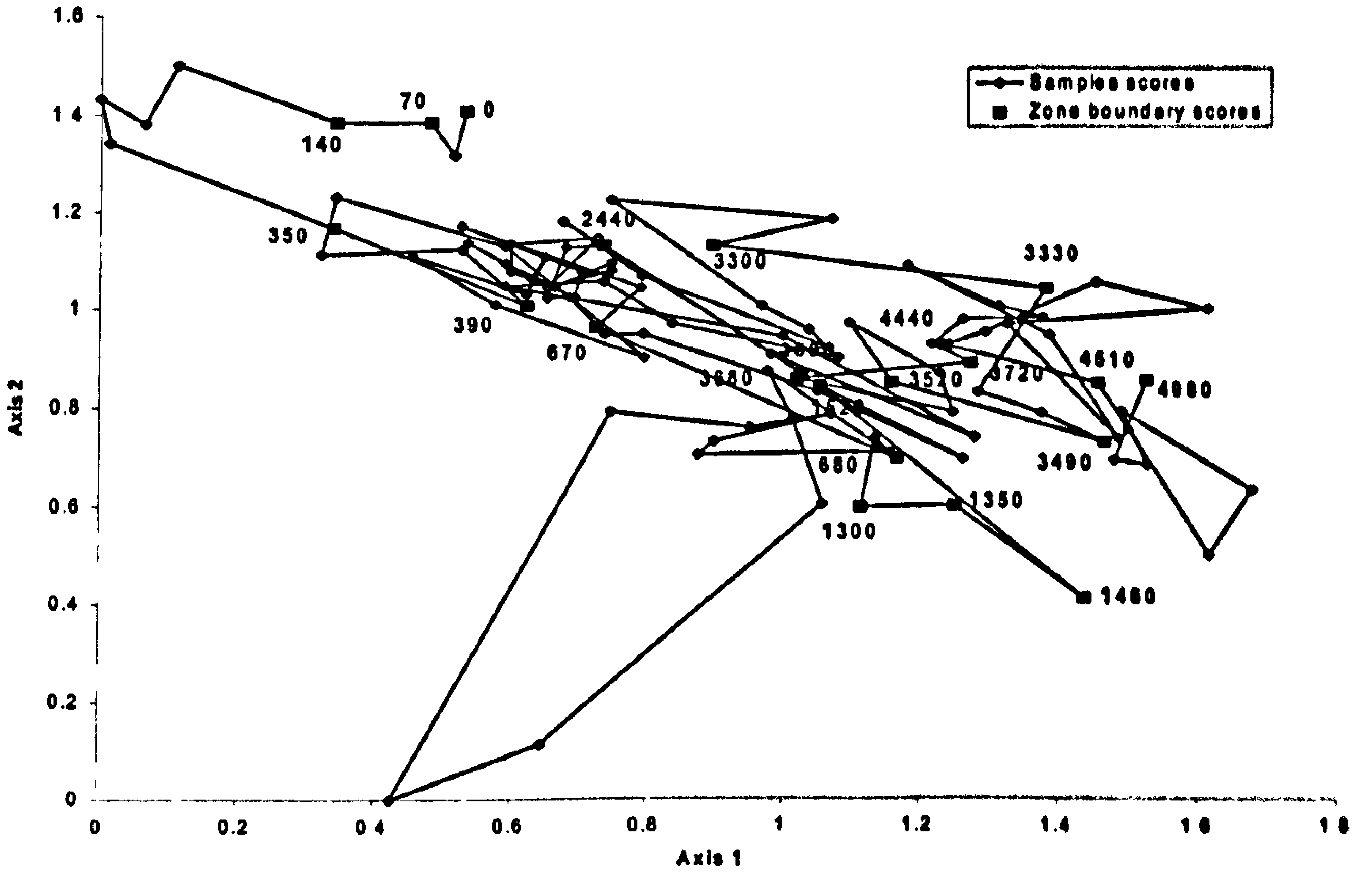


Figure 46b. DCA sample scores on first two axes for Camban with top and basal levels, and samples either side of zone boundaries labelled in ^{14}C years BP.

Figure 47. Summary pollen preservation data for Camban.
Sum = %TLP/%TLP + indeterminate/group; exaggeration x10.

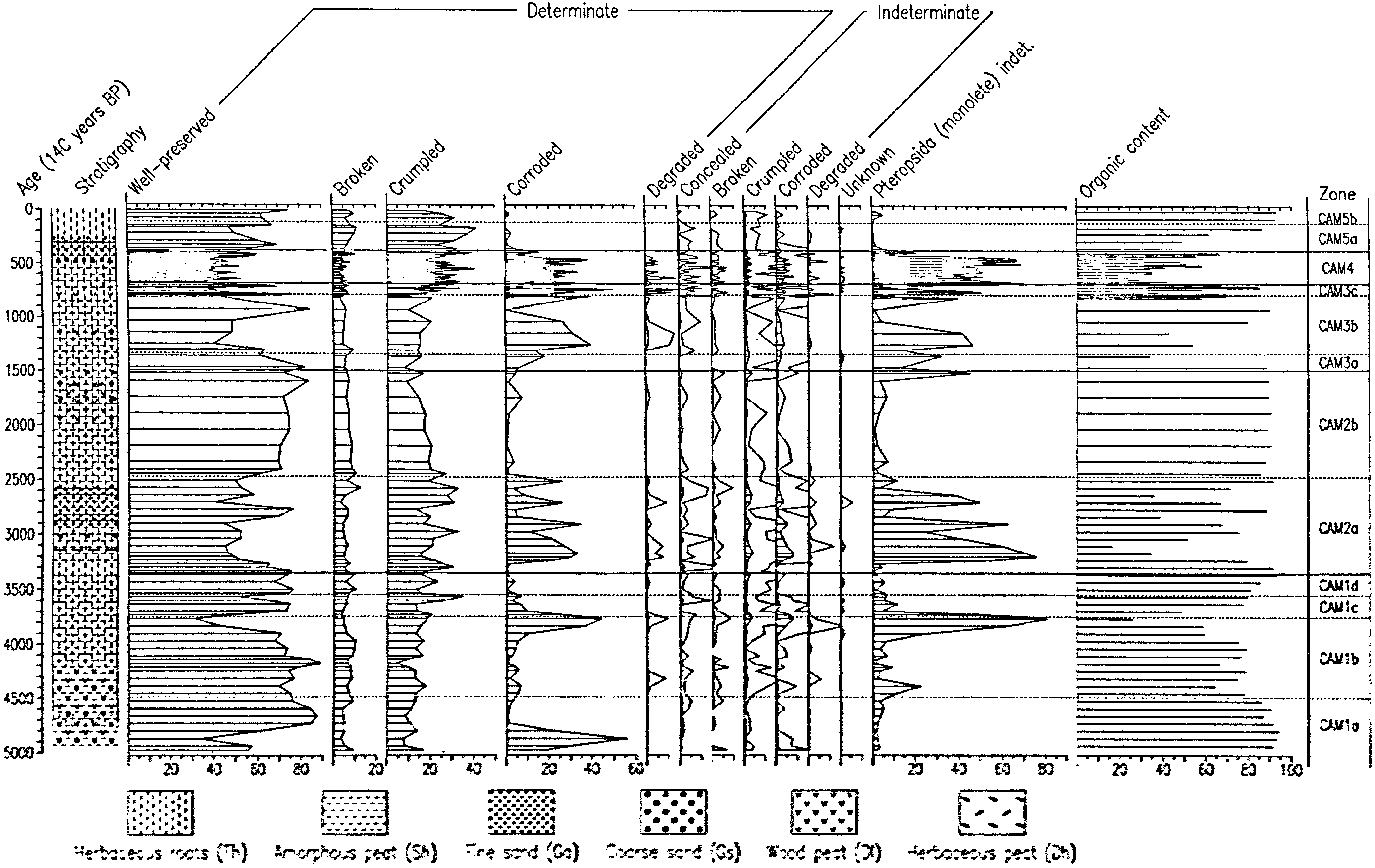


Figure 48. Pollen preservation data for selected taxa at Camban.
Sum = %taxon.
Order: well-preserved, broken, crumpled, corroded, degraded.

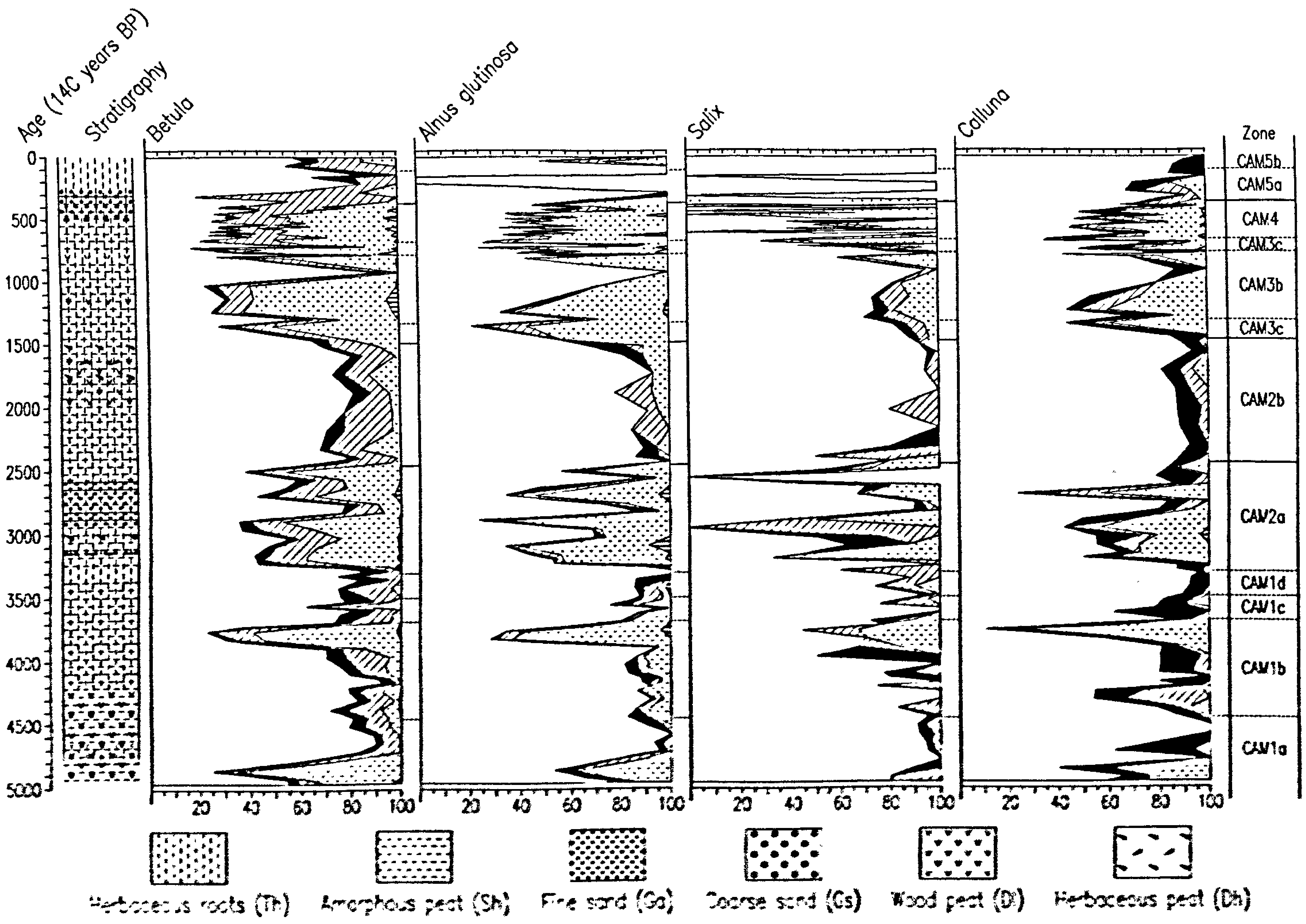


Figure 48. Selected pollen preservation data from Camban (cont.).
Sum = %taxon.
Order: well-preserved, broken, crumpled, corroded, degraded.

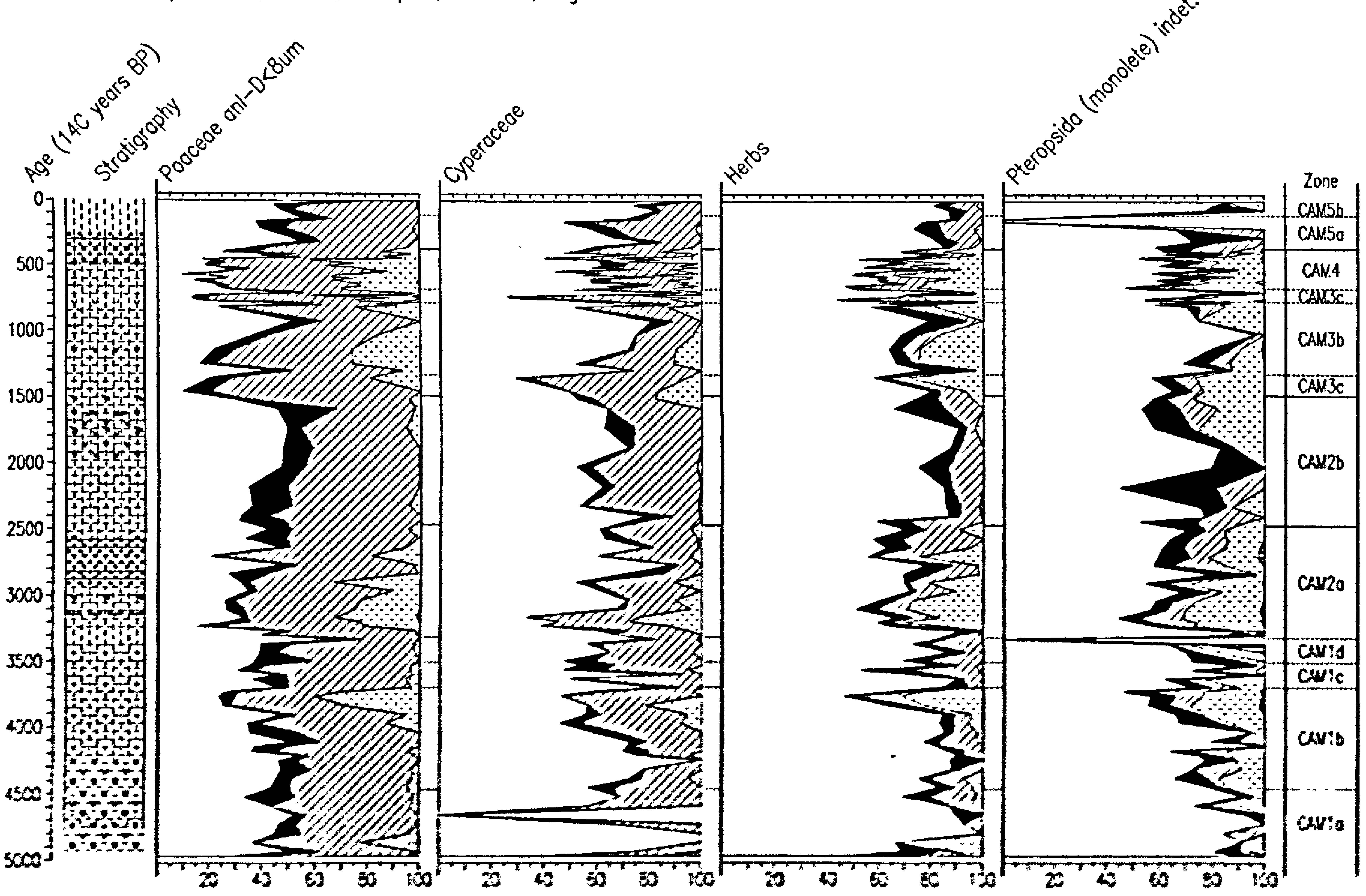
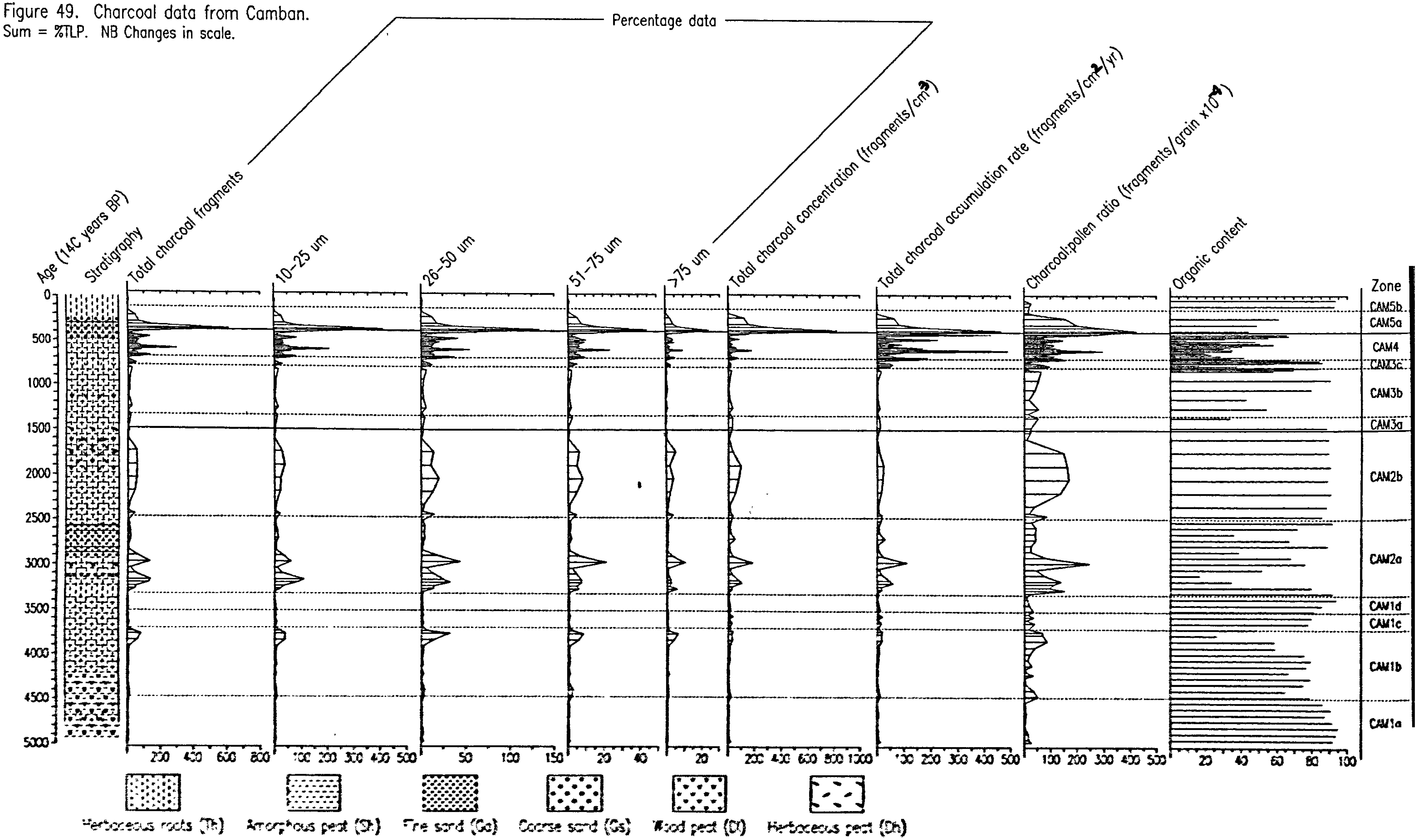


Figure 49. Charcoal data from Camban.
Sum = %TLP. NB Changes in scale.



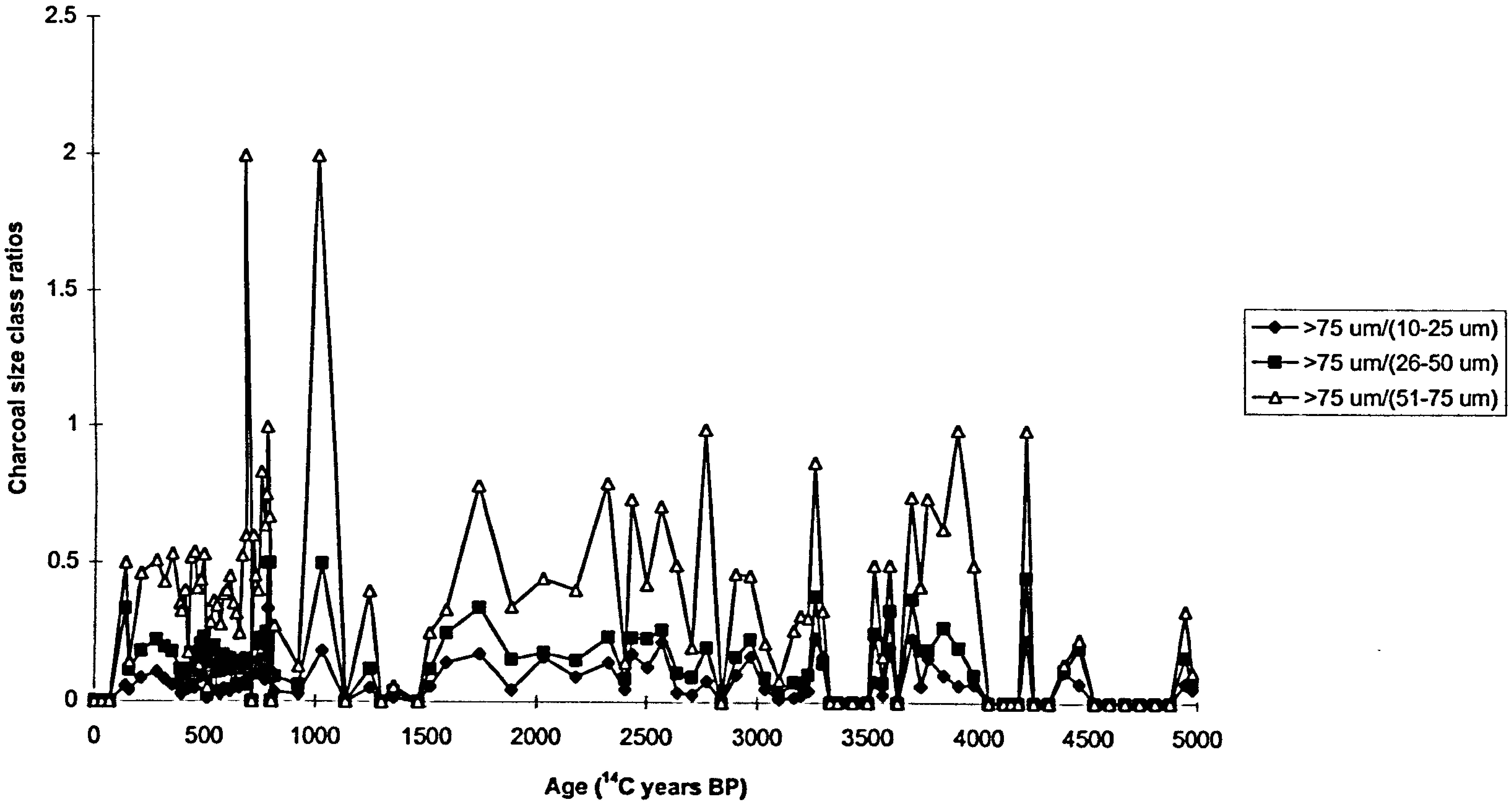


Figure 50. Charcoal size class analysis for Camban - ratio of percentage of large (>75 µm) to smaller (10-25 µm, 26-50 µm, 51-75 µm) fragments, plotted against age in ^{14}C years BP.

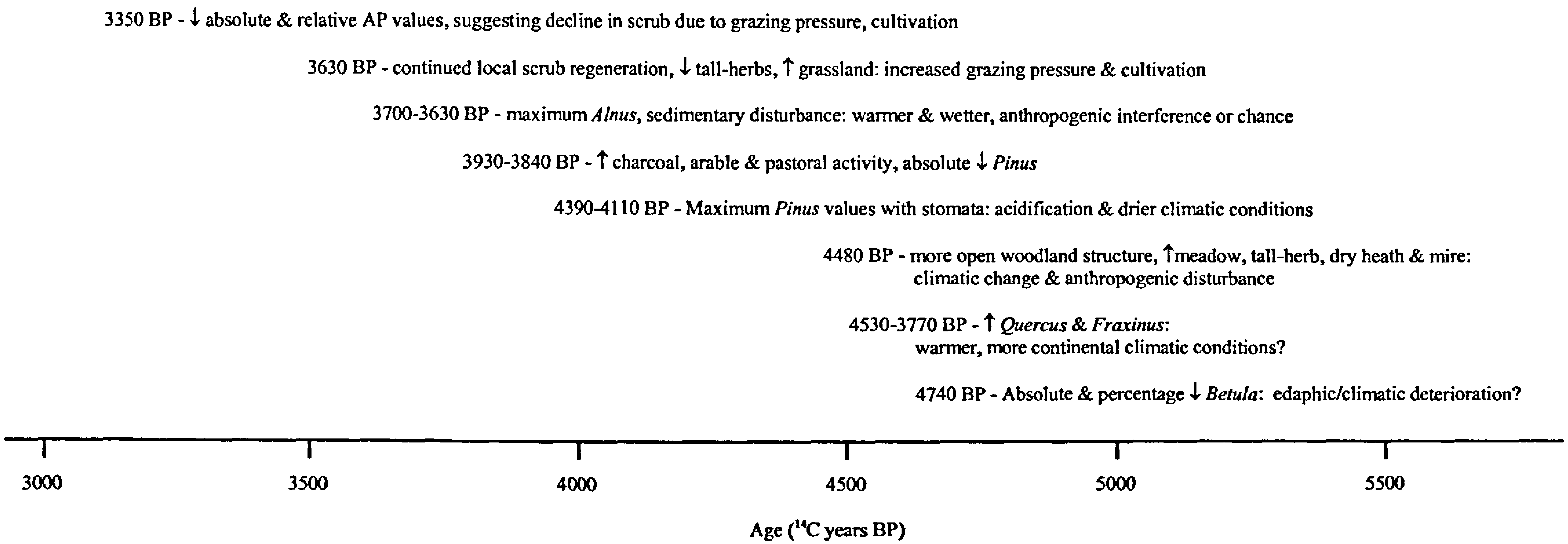


Figure 51. Summary of inferred mid-Holocene vegetational, climatic and anthropogenic changes at Camban. Arrows denote increasing/decreasing pollen and charcoal values.

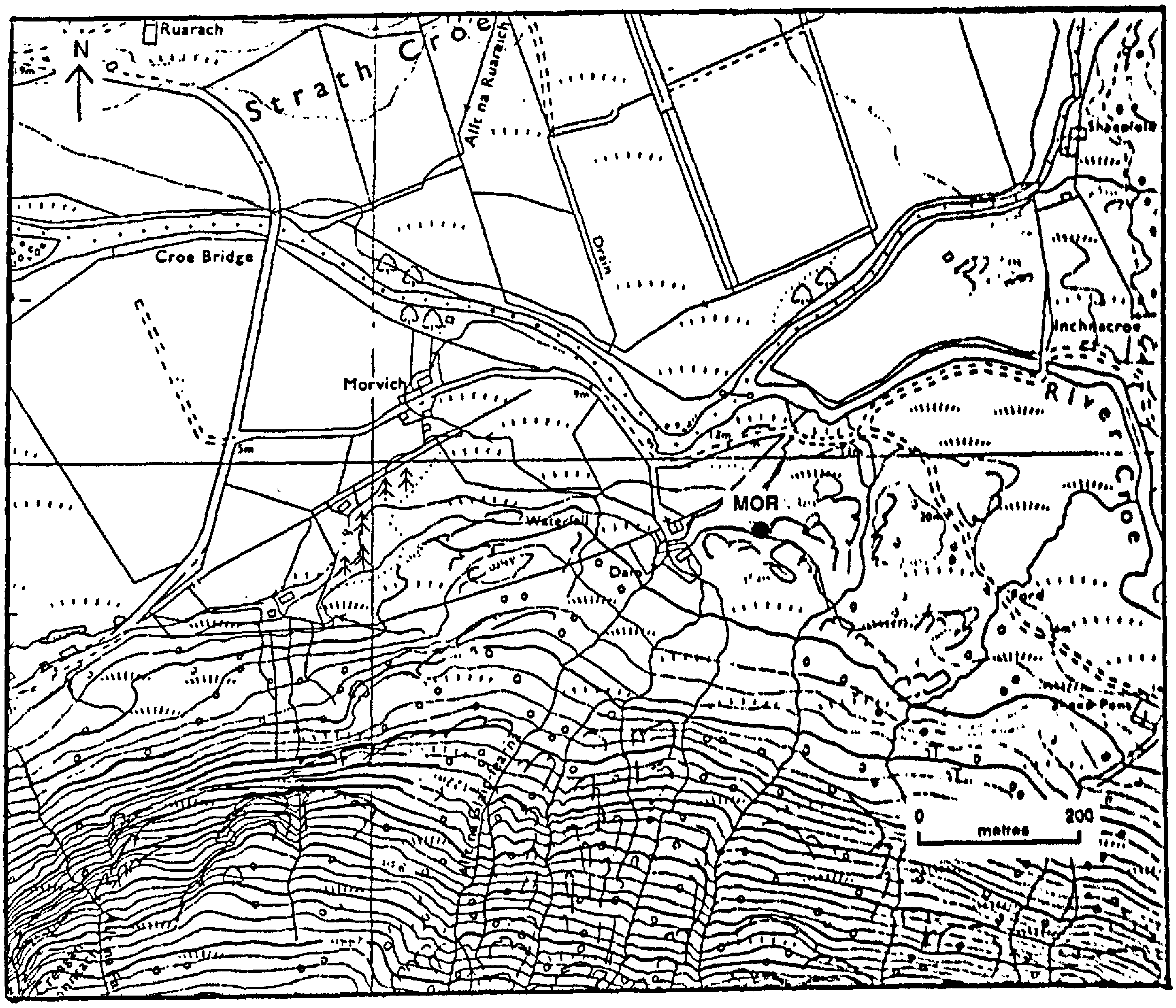


Figure 52. Sampling site at Morvich. © Ordnance Survey.

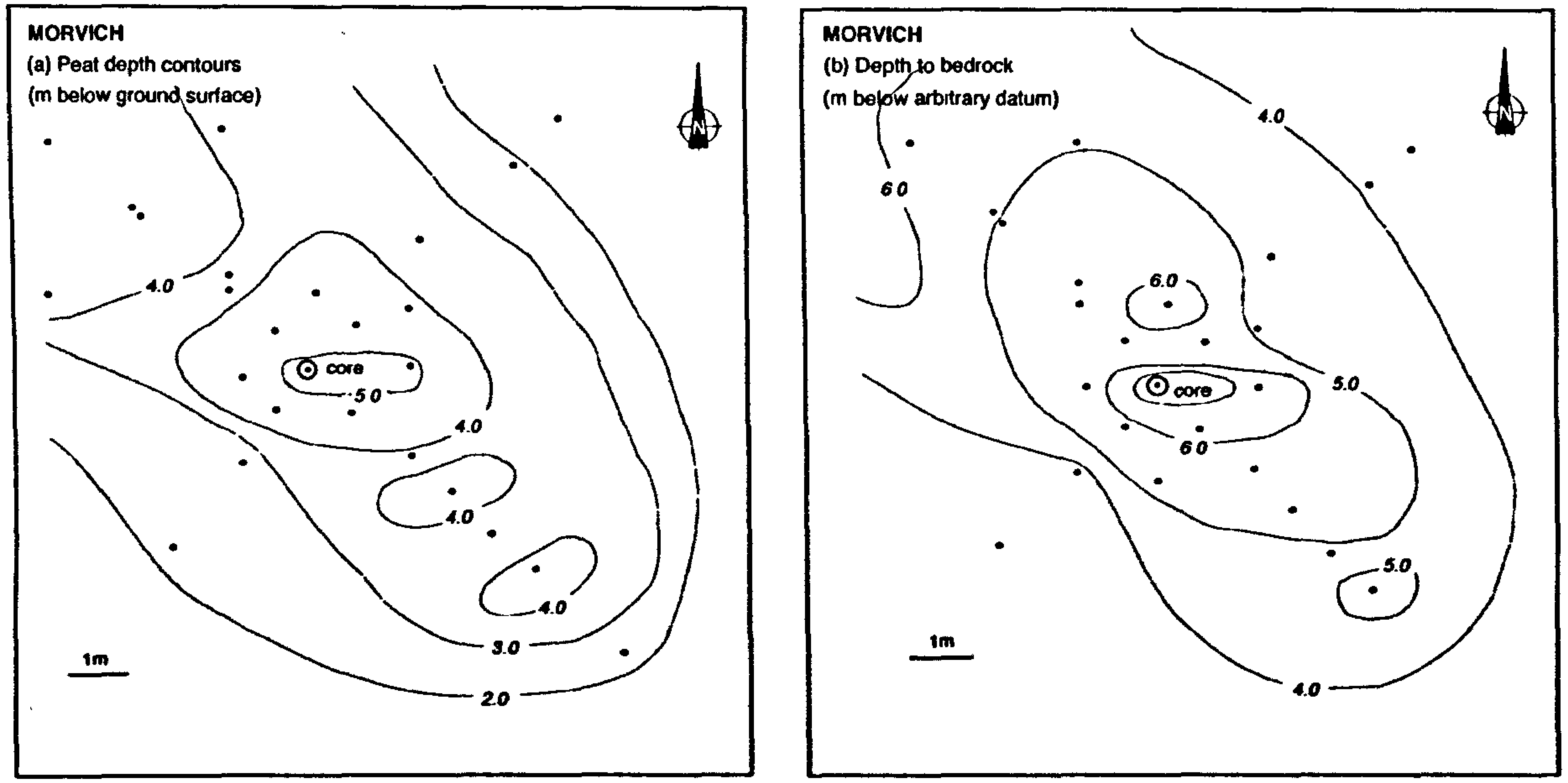


Figure 53. Basin contour maps from Morvich: (a) peat depth, (b) depth to bedrock (m). Surface and bedrock contours recorded as depth below arbitrary datum.

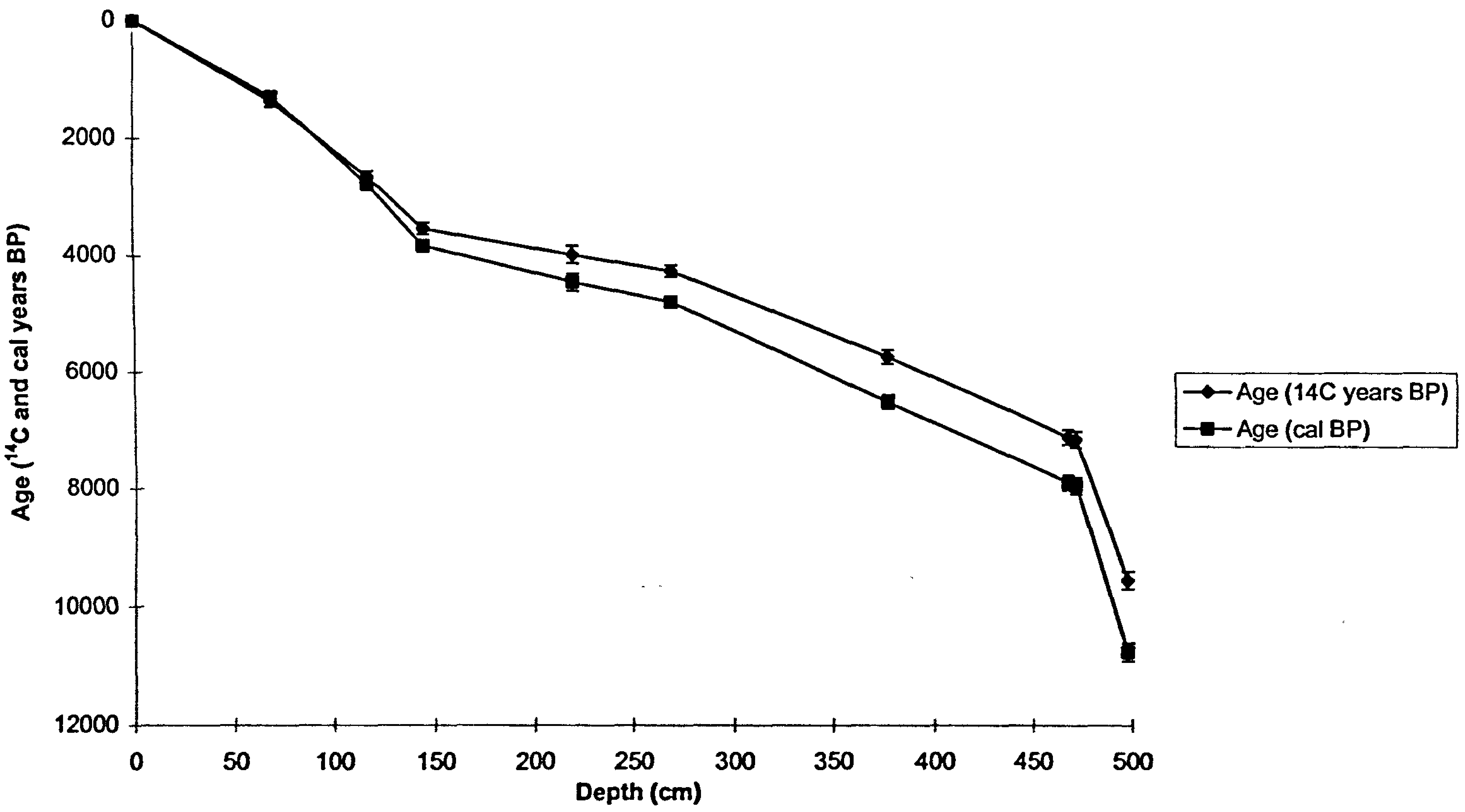


Figure 54. Radiocarbon and calibrated time-depth curves for Morvich with 2σ error ranges.

Figure 55. Full percentage data from Morvich.
Sum = %TLP/%TLP + group; exaggeration x10.

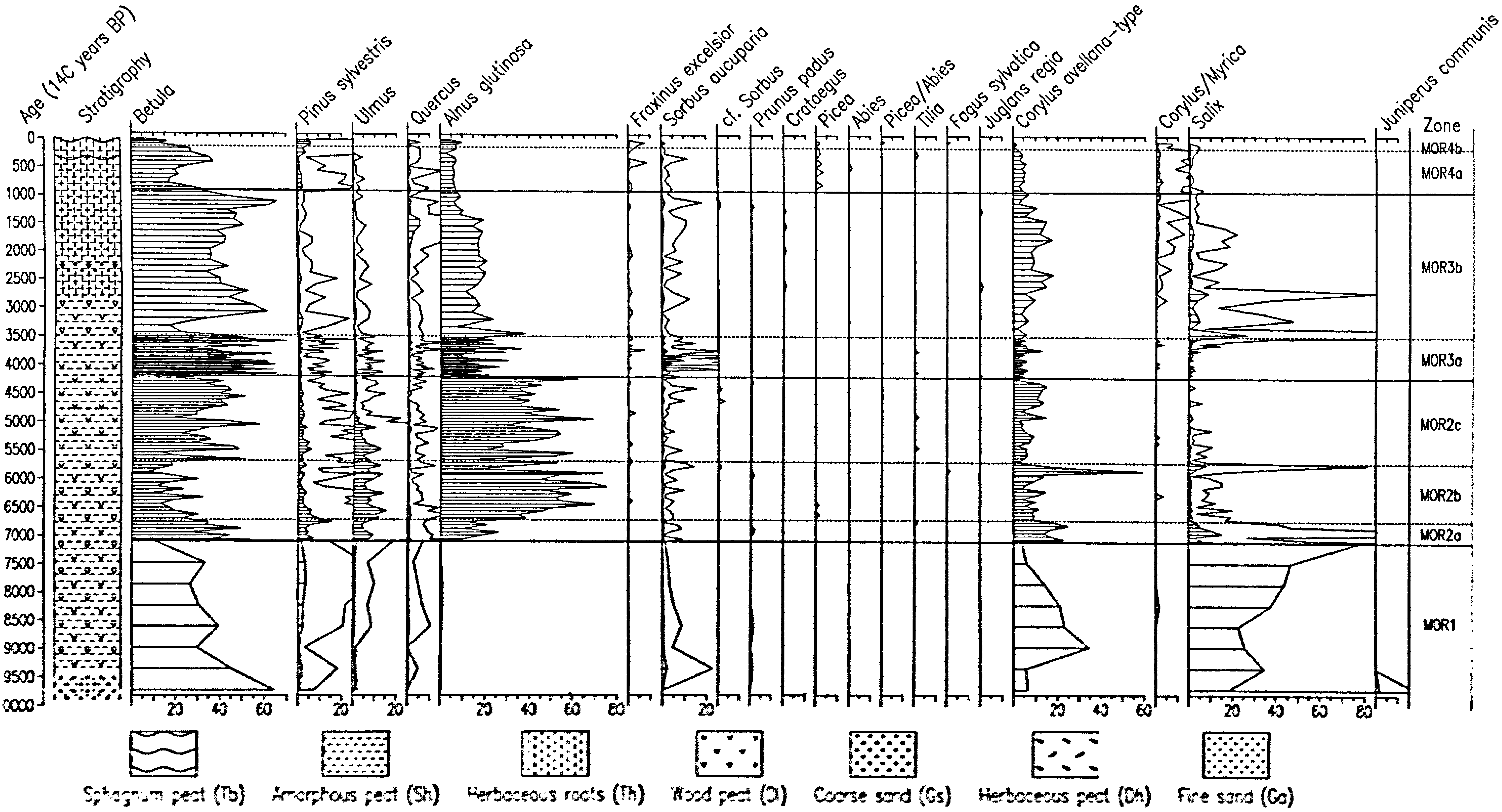


Figure 55. Full percentage data from Morvich (continued).
Sum = %TLP/%TLP + group; exaggeration x10.

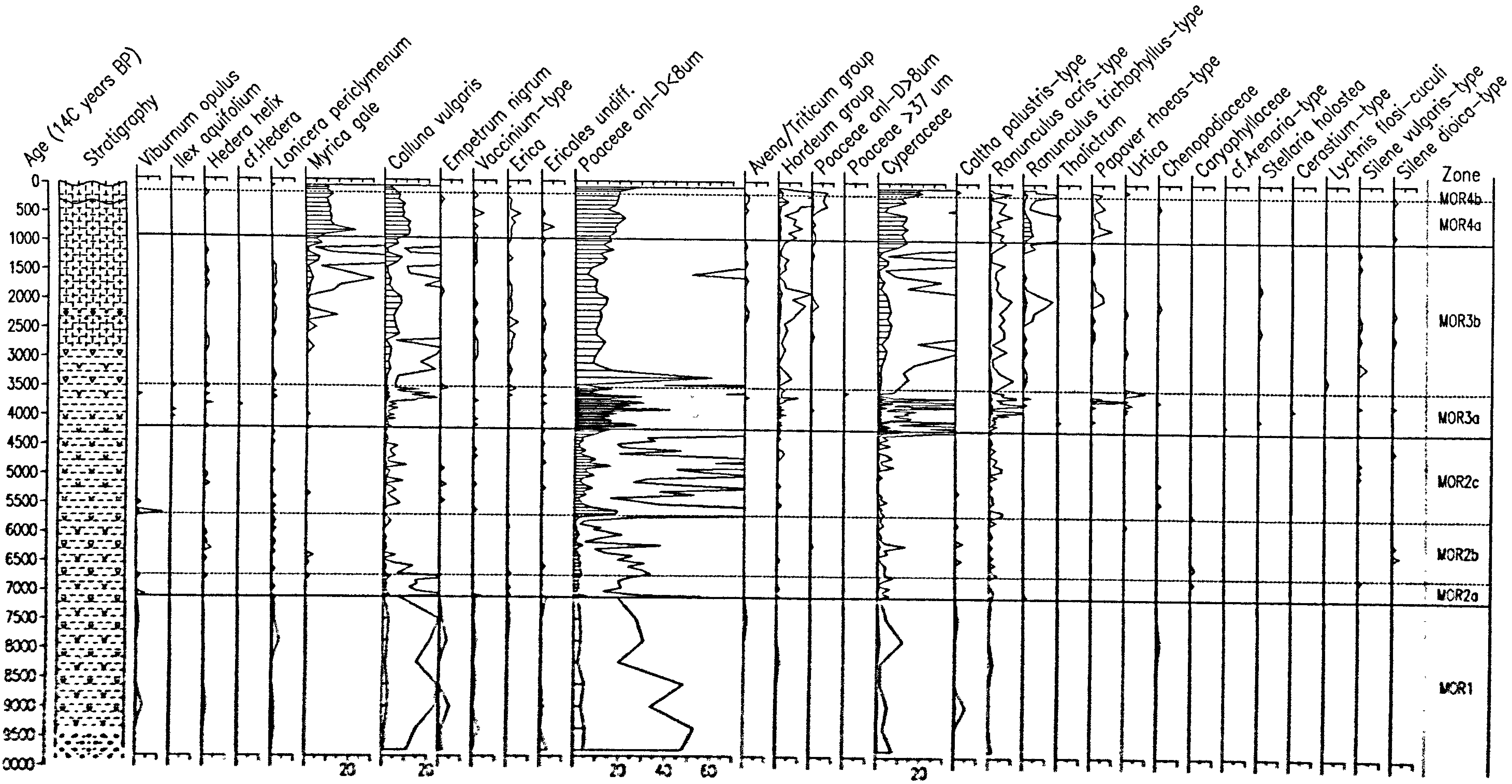


Figure 55. Full percentage data from Morvich (continued).
Sum = %TLP/%TLP + group; exaggeration x10.

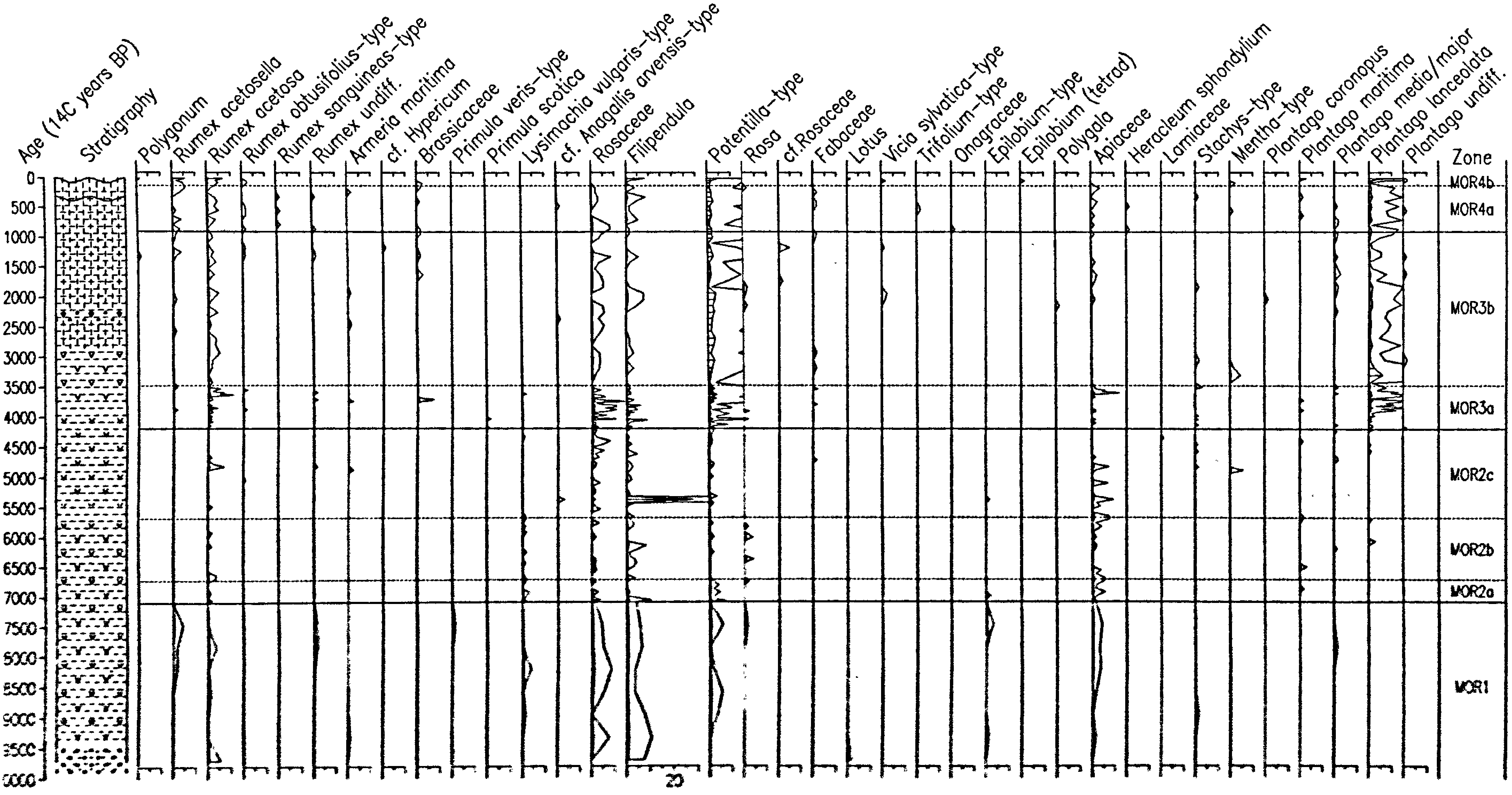


Figure 55. Full percentage data from Morvich (continued).
Sum = %TLP/%TLP + group; exaggeration x10.

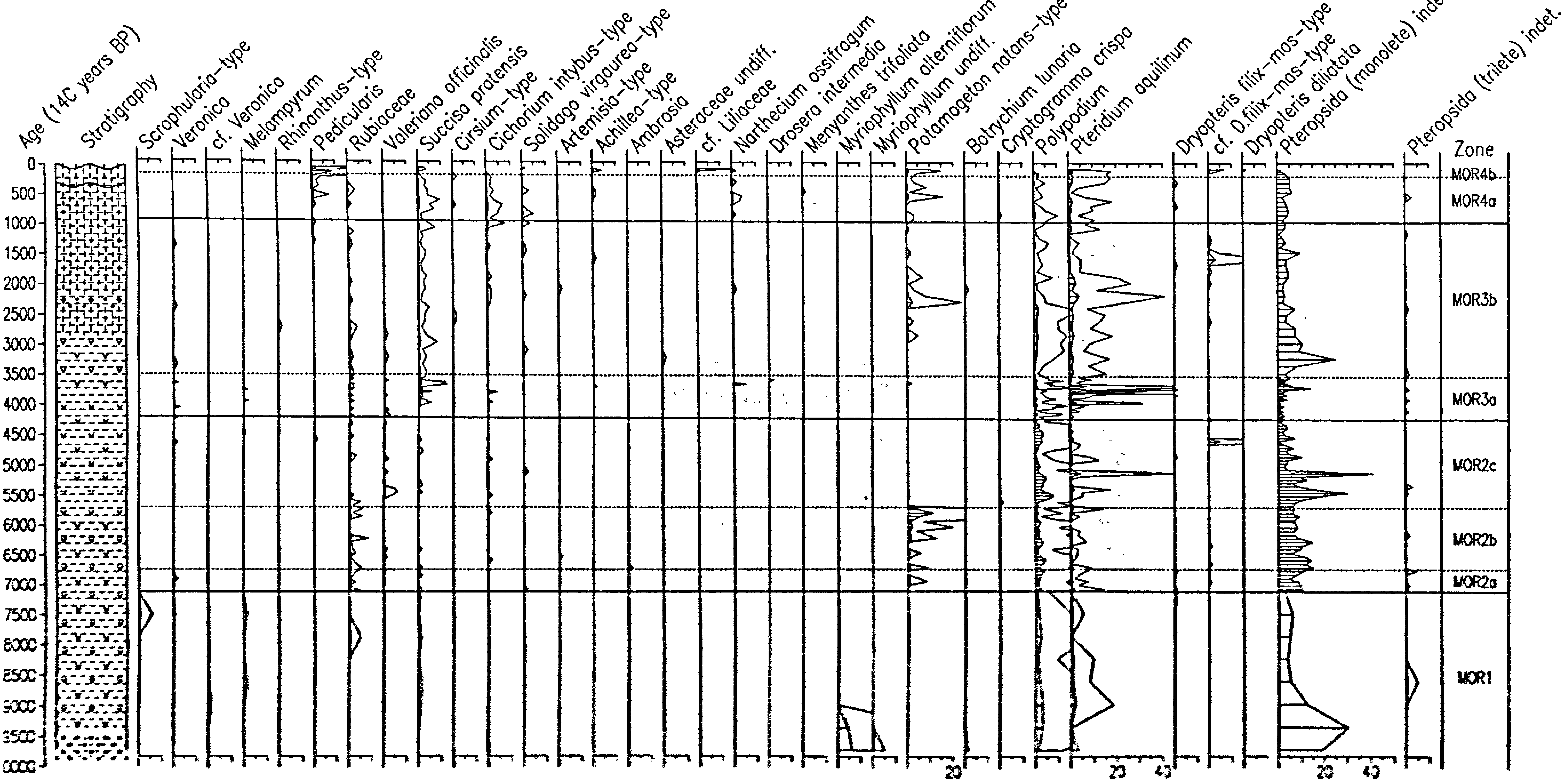


Figure 55. Full percentage data from Morvich (continued).
Sum = %TLP/%TLP + group; exaggeration x10.

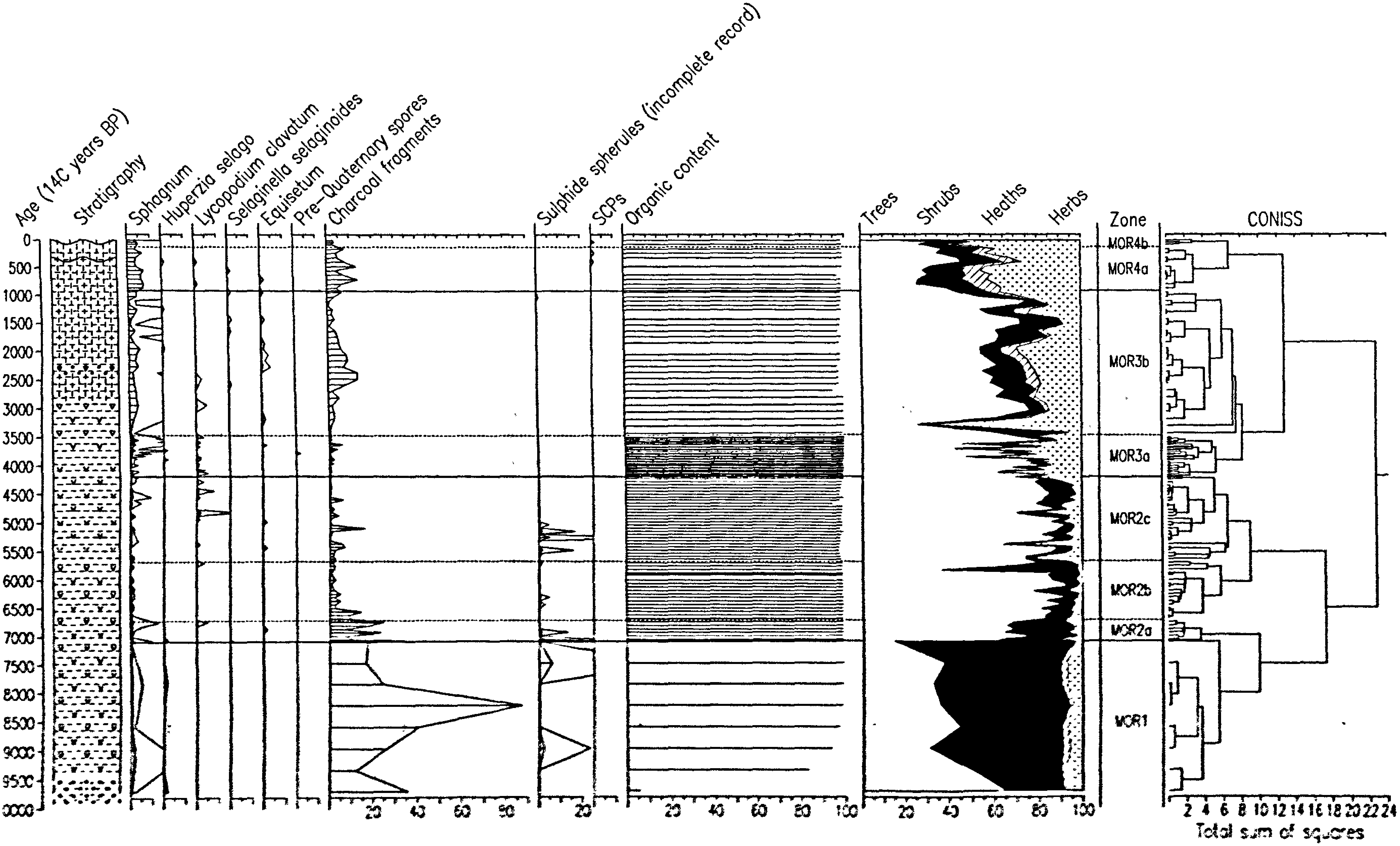


Figure 56. Selected concentration data for Morvich.
(grains/cm^3)
NB Changes in scale.

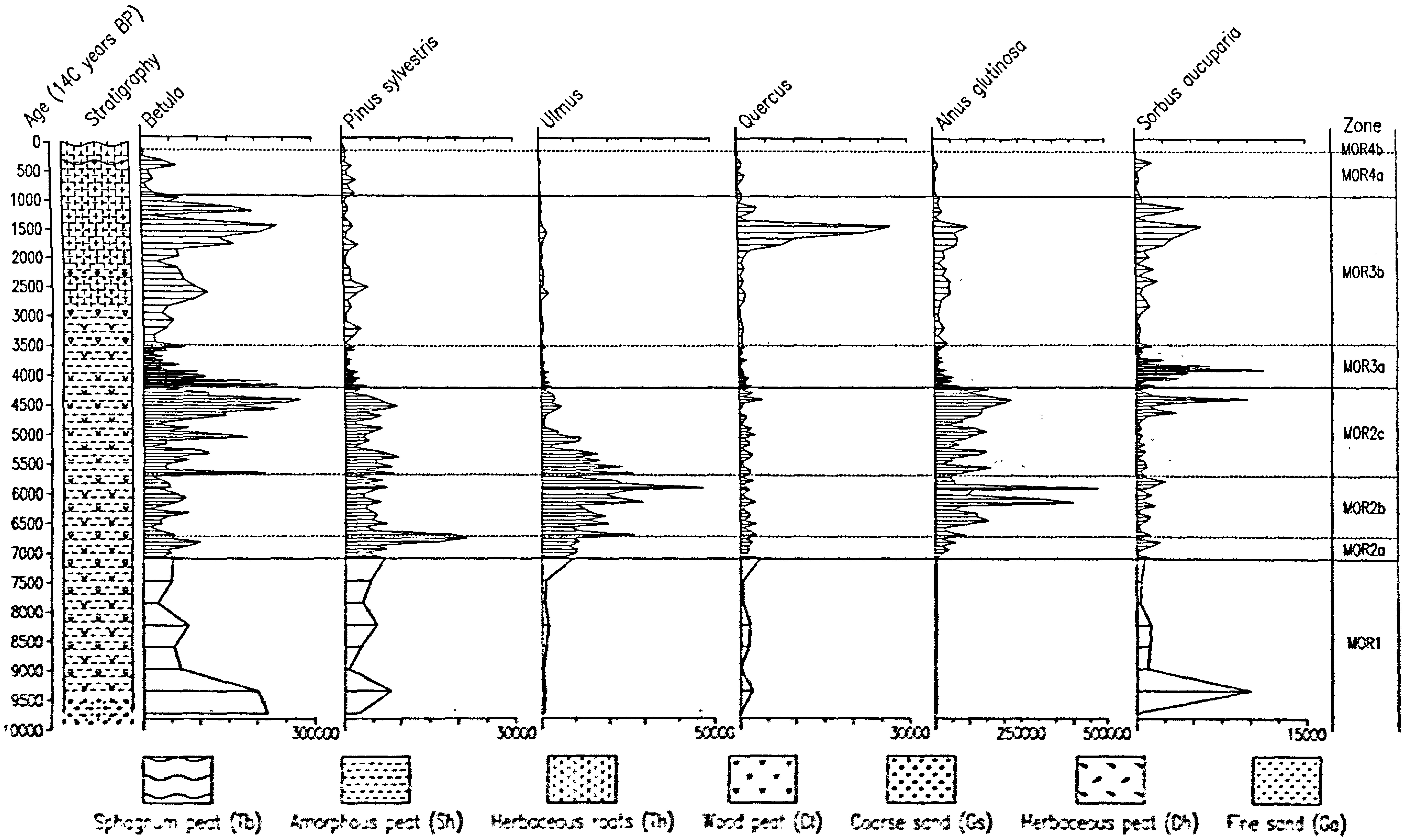


Figure 56. Selected concentration data for Morvich (continued).
(grains/cm^3)
NB Changes in scale; exaggeration x10.

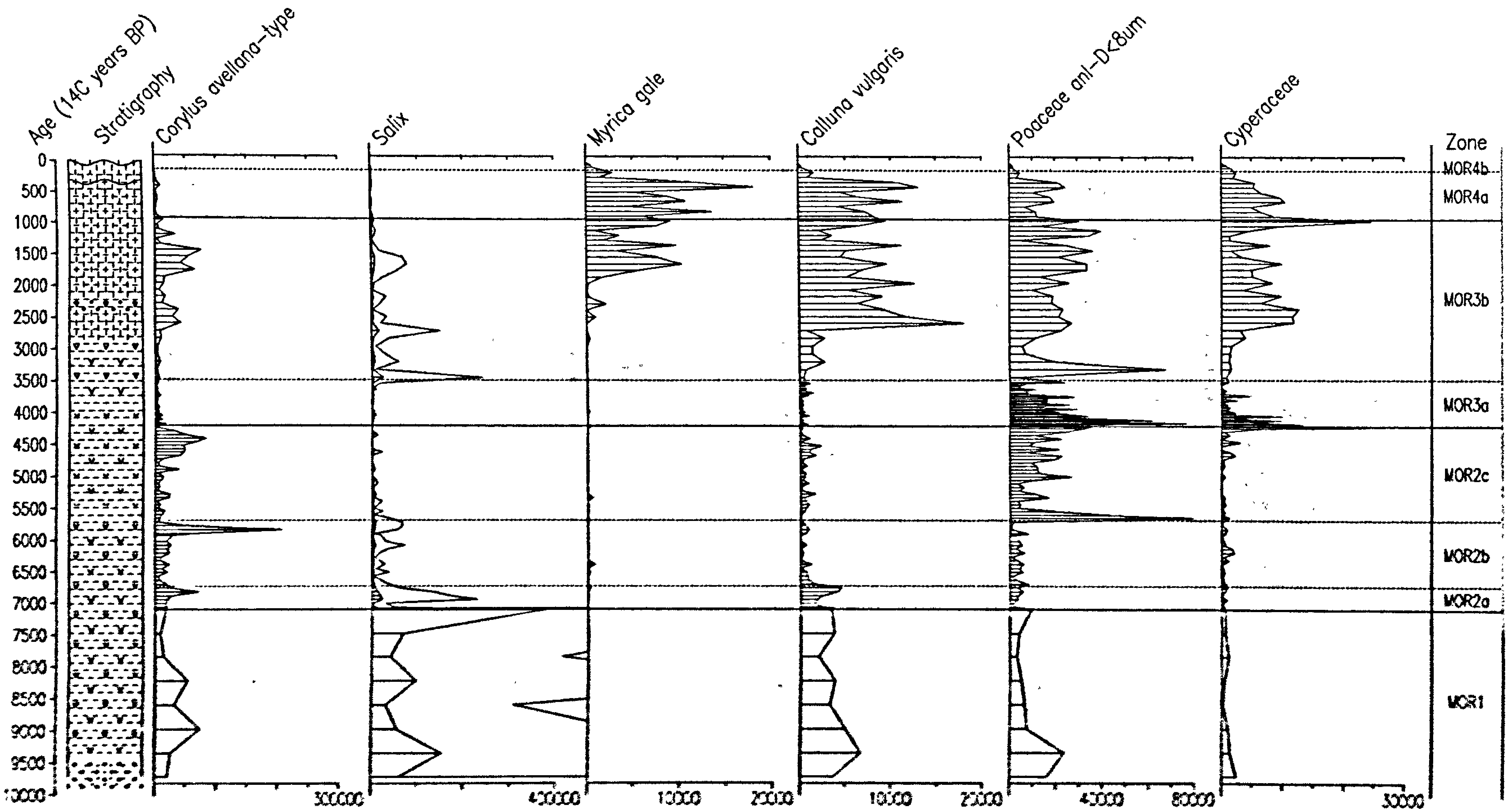


Figure 56. Selected concentration data for Morvich (continued). (grains/cm^3)
NB Changes in scale; exaggeration x10.

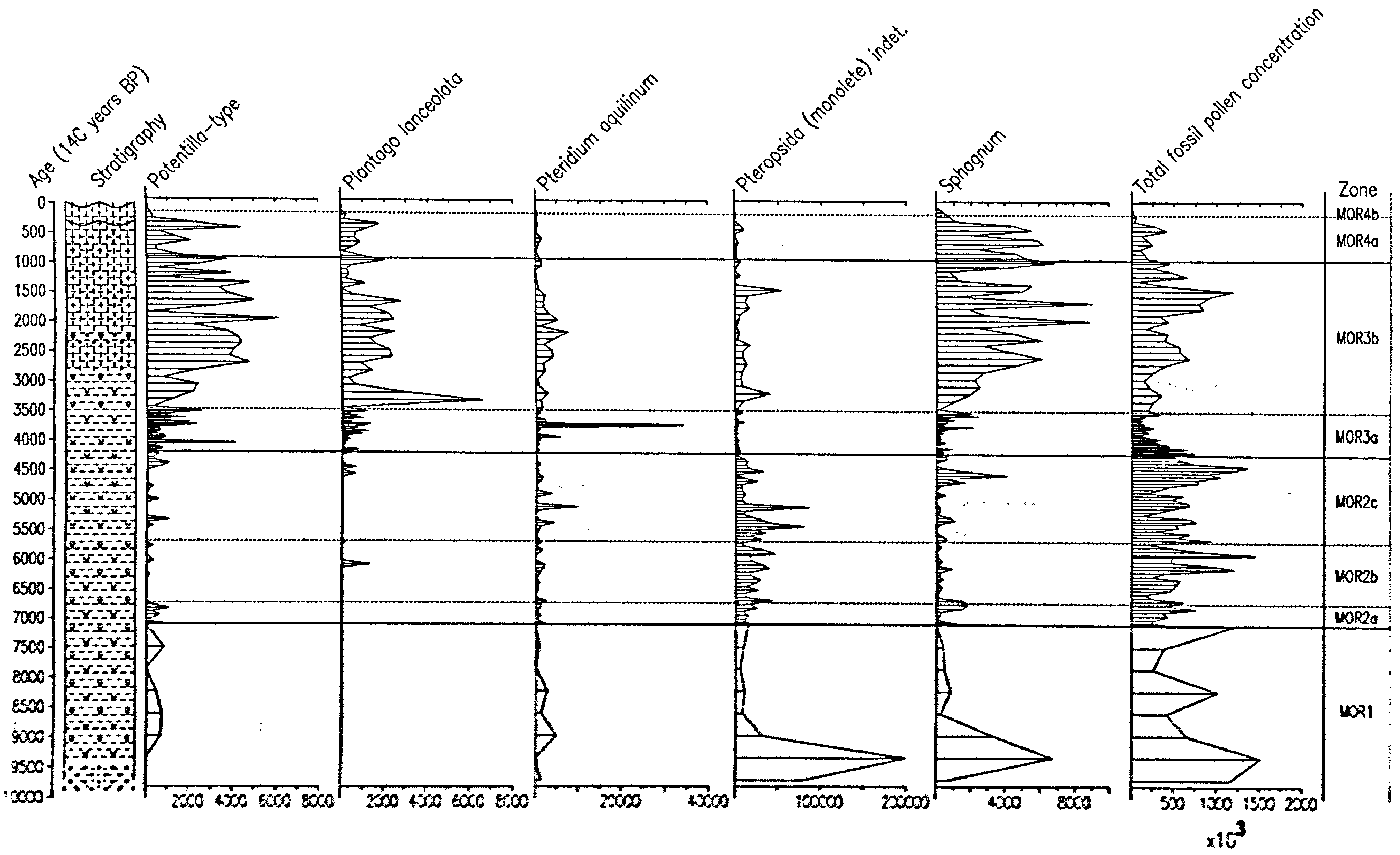


Figure 57. Selected pollen accumulation rate data for Morvich.
(grains/cm^2/yr)
NB Changes in scale.

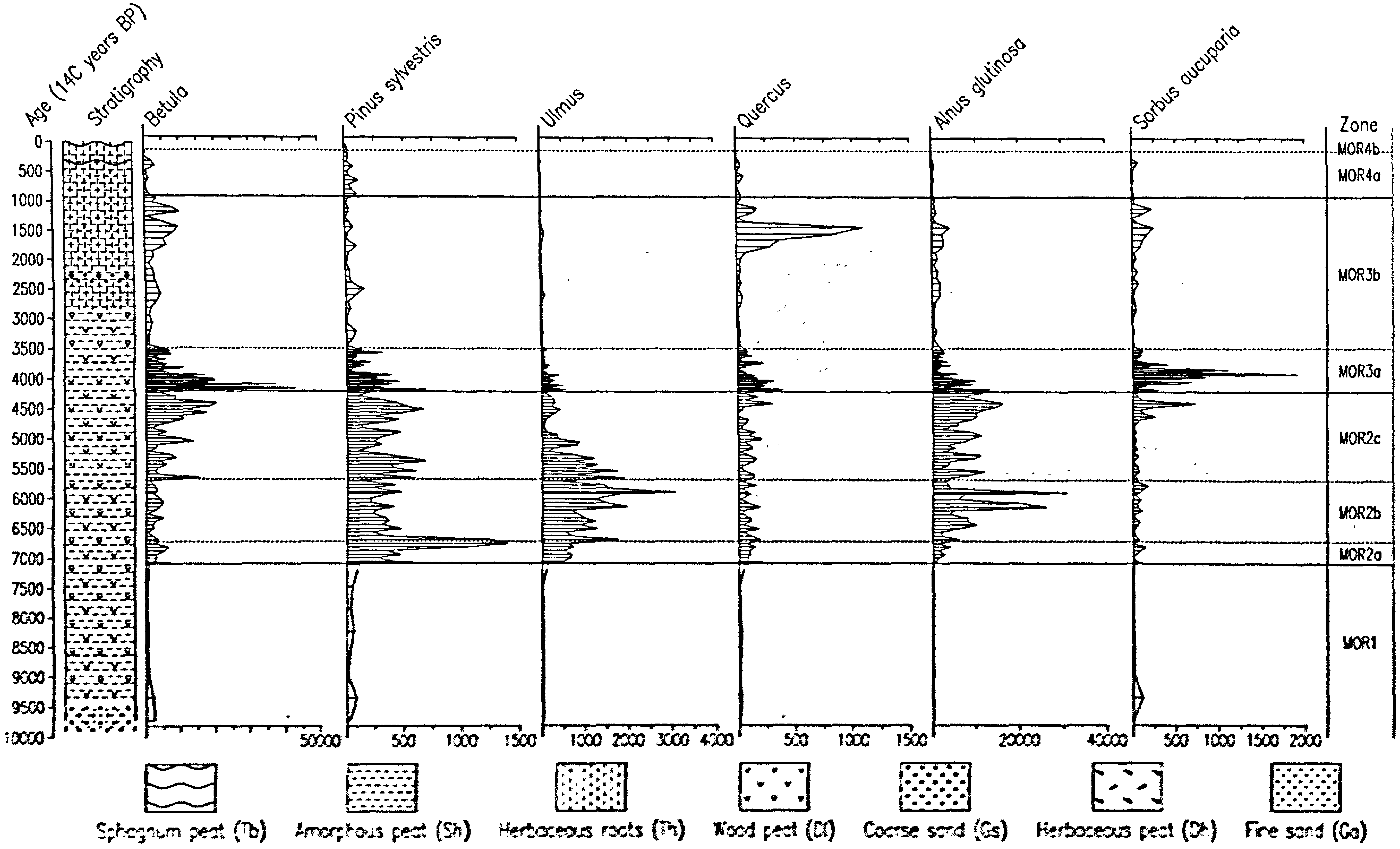


Figure 57. Selected pollen accumulation rate data for Morvich (cont).
(grains/cm^2/yr)
NB Changes in scale.

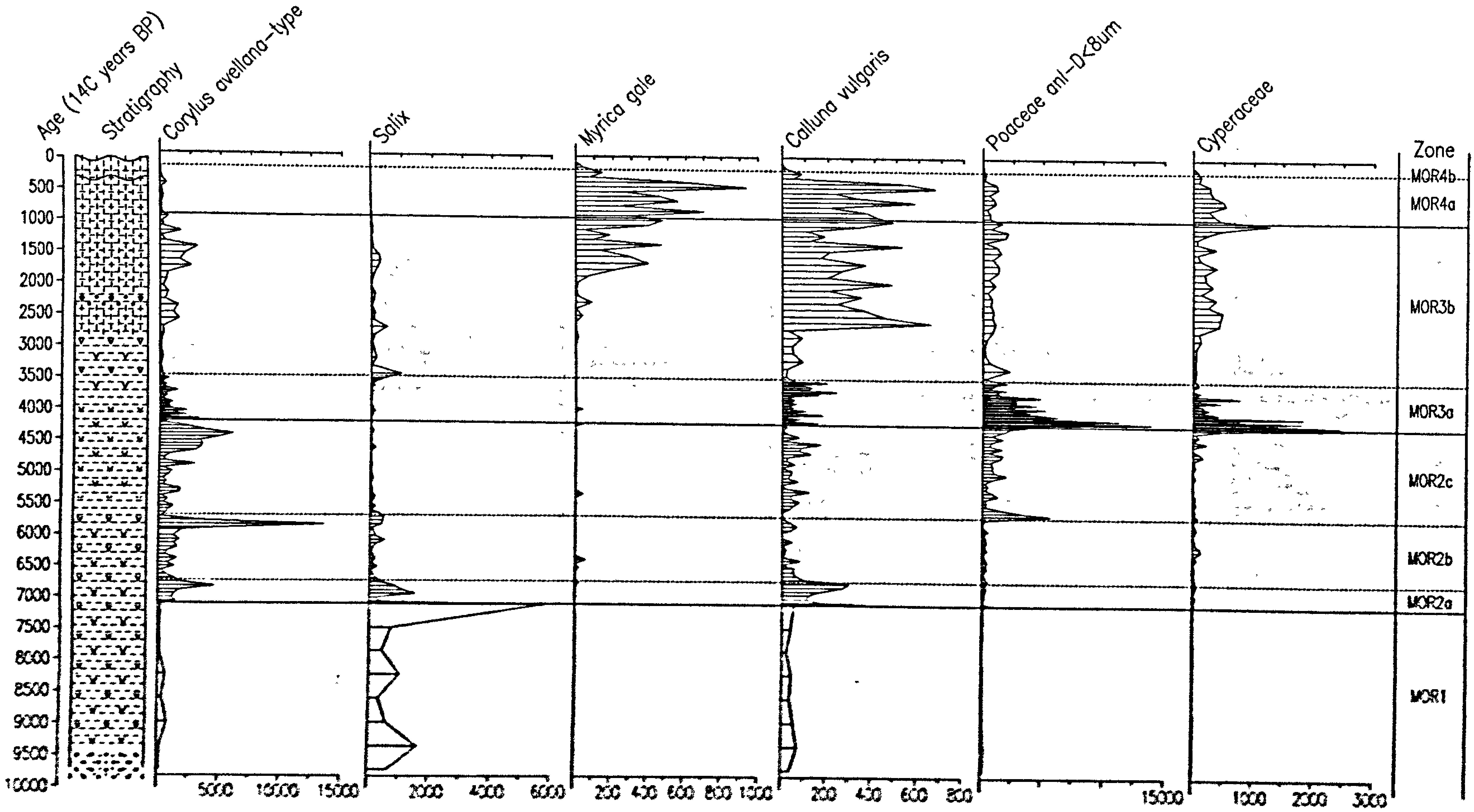


Figure 57. Selected pollen accumulation rate data for Morvich (cont).
(grains/cm^2/yr)
NB Changes in scale.

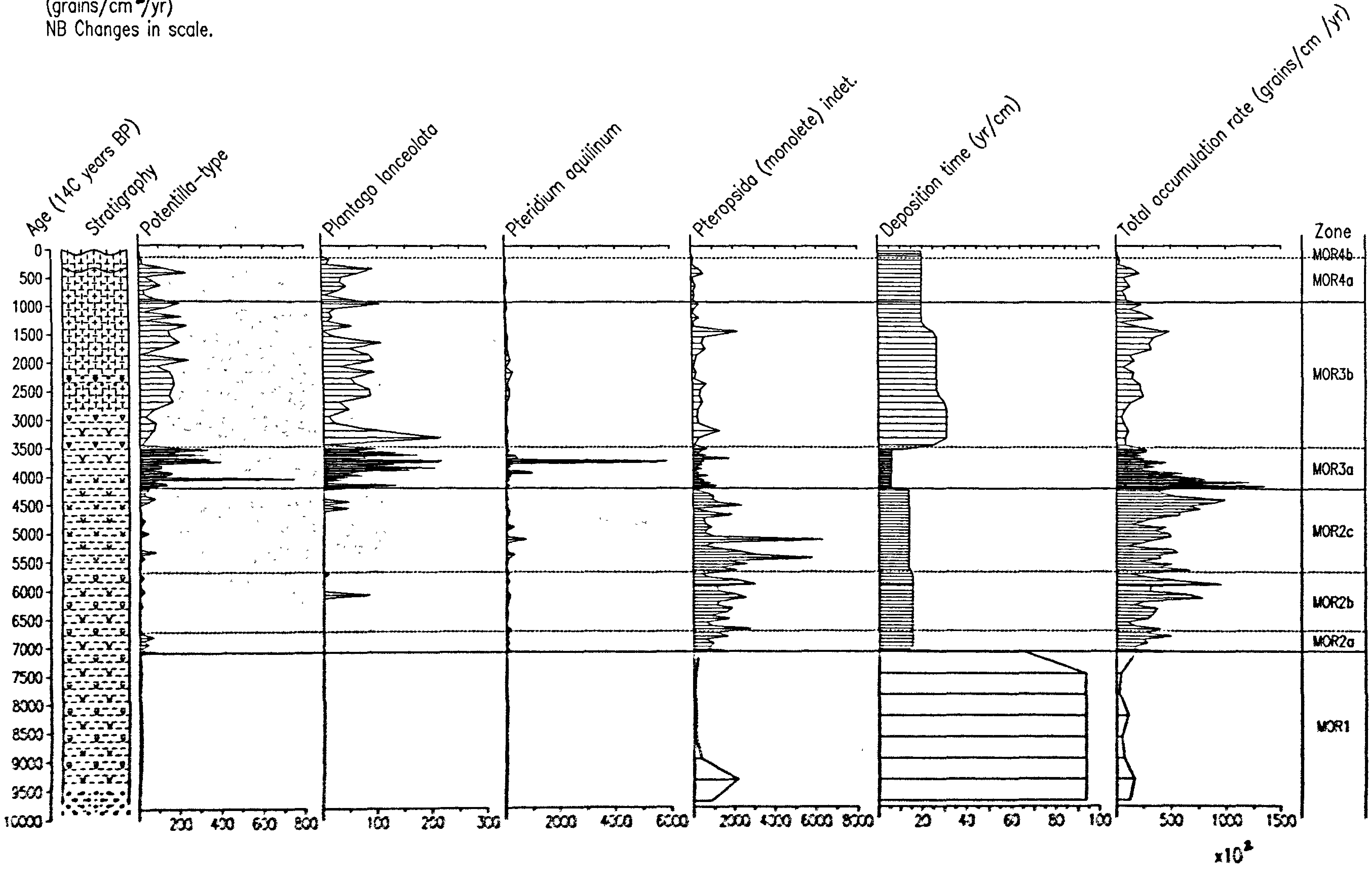
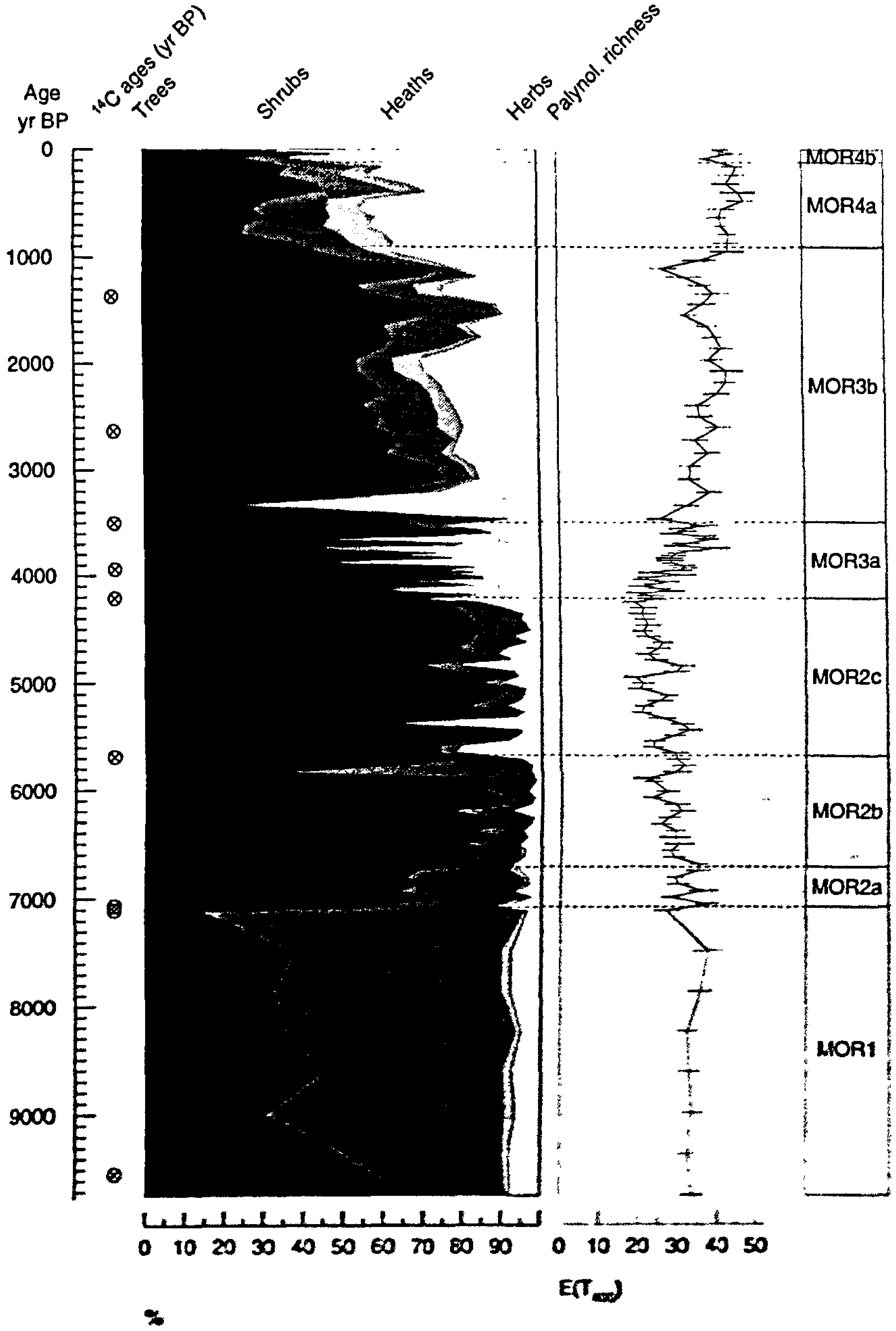


Figure 58. Rarefaction data for Morvich.



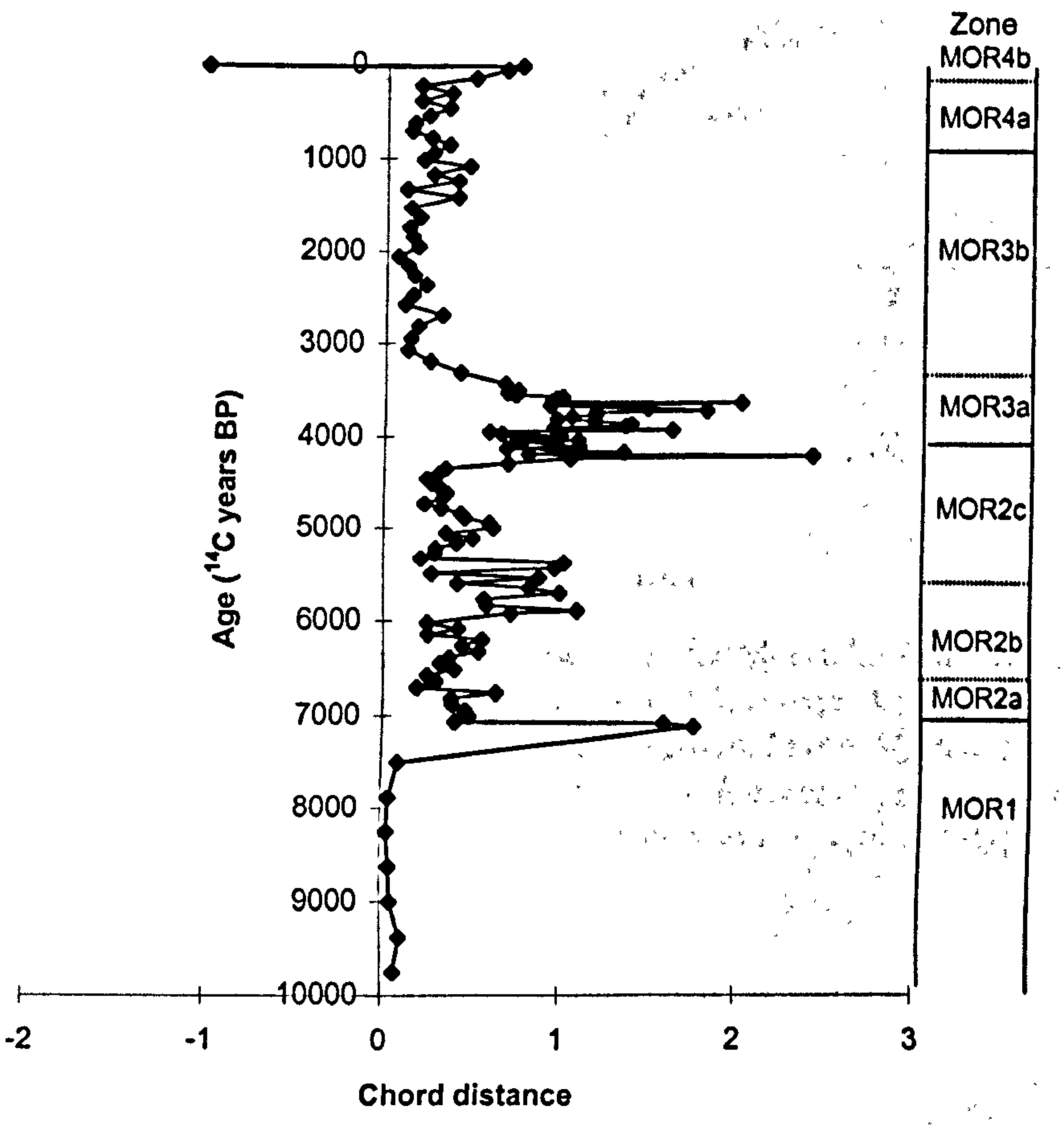


Figure 59. Rates of palynological change for Morvich plotted against age in ^{14}C years BP.

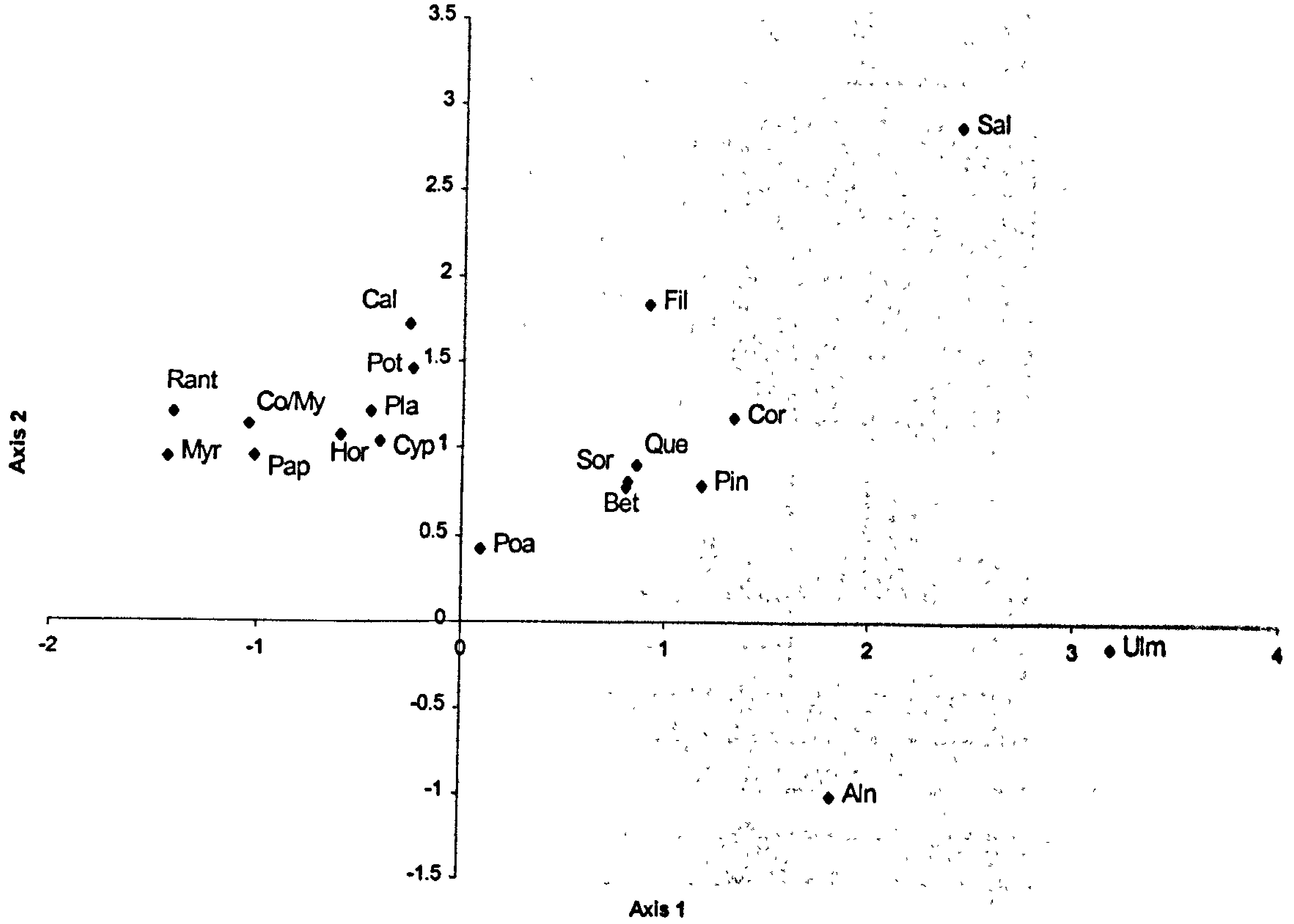


Figure 60a. DCA taxon scores on first two axes for Morvich. Aln = *Alnus glutinosa*, Bet = *Betula*, Cal = *Calluna vulgaris*, Cor = *Corylus avellana*-type, Co/My = *Corylus/Myrica*, Cyp = Cyperaceae, Fil = *Filipendula*, Hor = *Hordeum* group, Myr = *Myrica gale*, Pap = *Papaver rhoeas*-type, Pin = *Pinus sylvestris*, Pla = *Plantago lanceolata*, Poa = Poaceae anl-D<8 µm, Pot = *Potentilla*-type, Que = *Quercus*, Rant = *Ranunculus trichophyllus*-type, Sal = *Salix*, Sor = *Sorbus aucuparia*, Ulm = *Ulmus*.

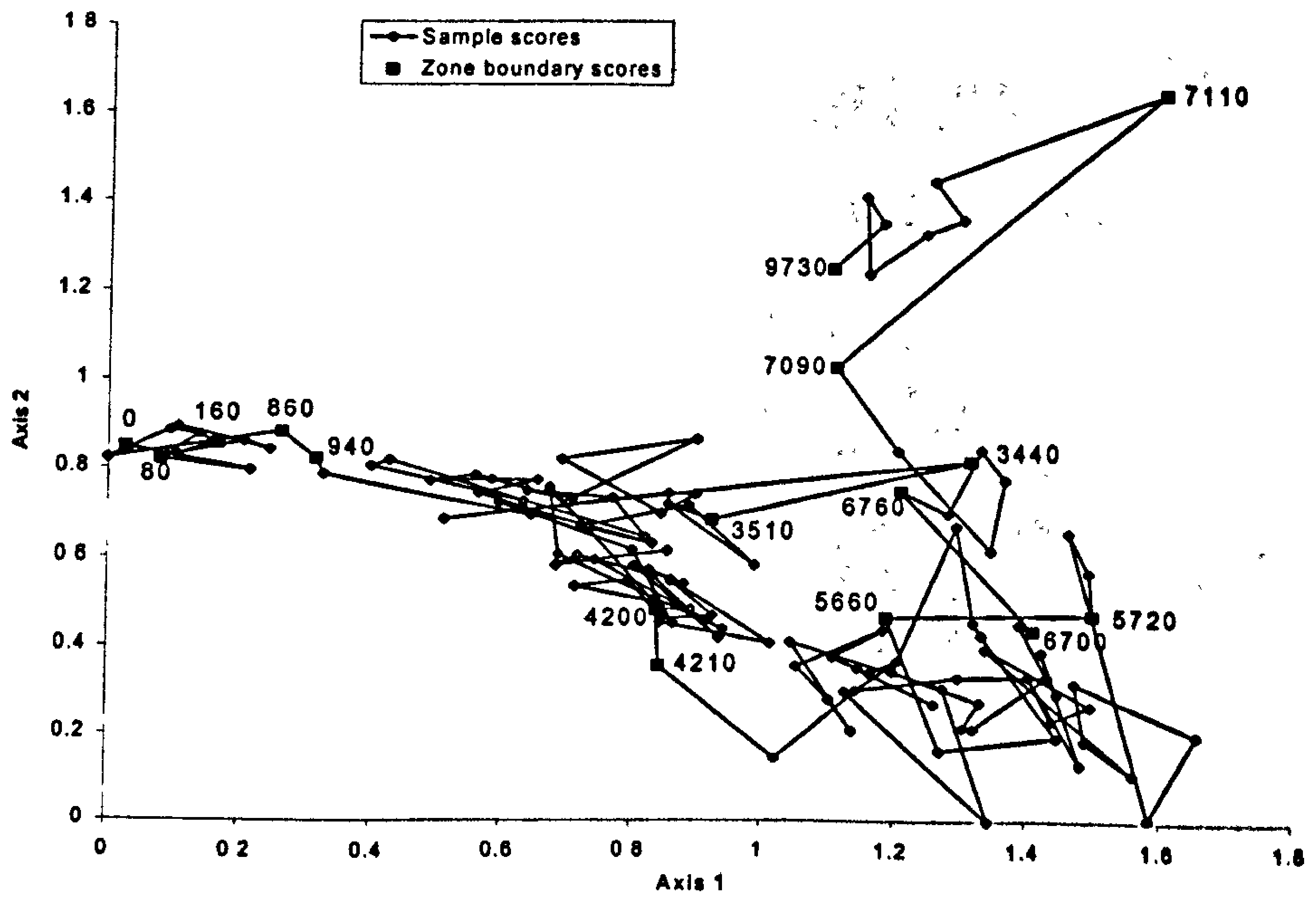


Figure 60b. DCA sample scores on first two axes for Morvich with top and basal levels, and samples either side of zone boundaries labelled in ^{14}C years BP.

Figure 61. Summary preservation data for Morvich.
Sum = %TLP/%TLP + group; exaggeration x10.

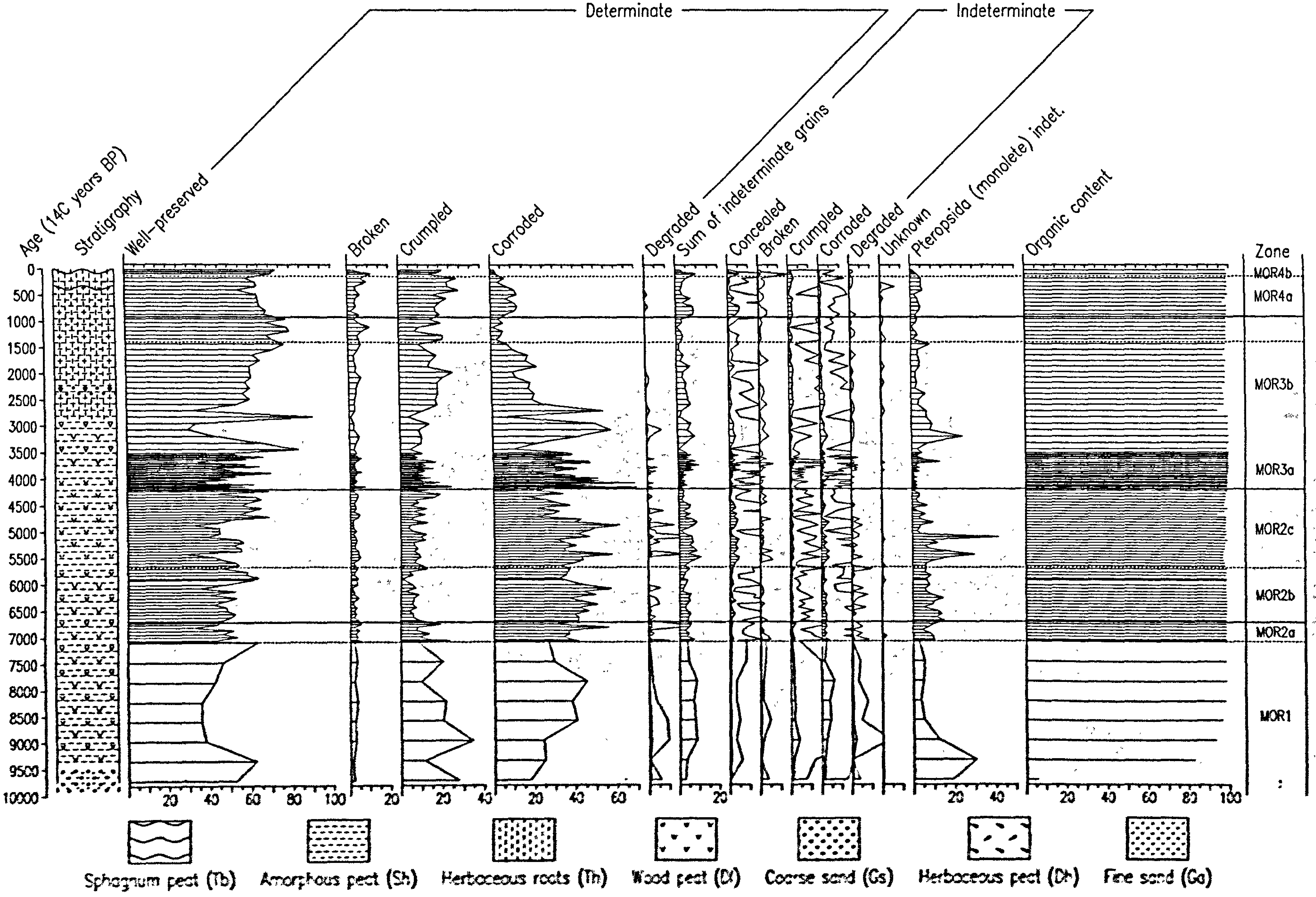


Figure 62. Pollen preservation data selected taxa at Morvich.
Order: well-preserved, broken, crumpled, corroded, degraded
Sum = %taxon.

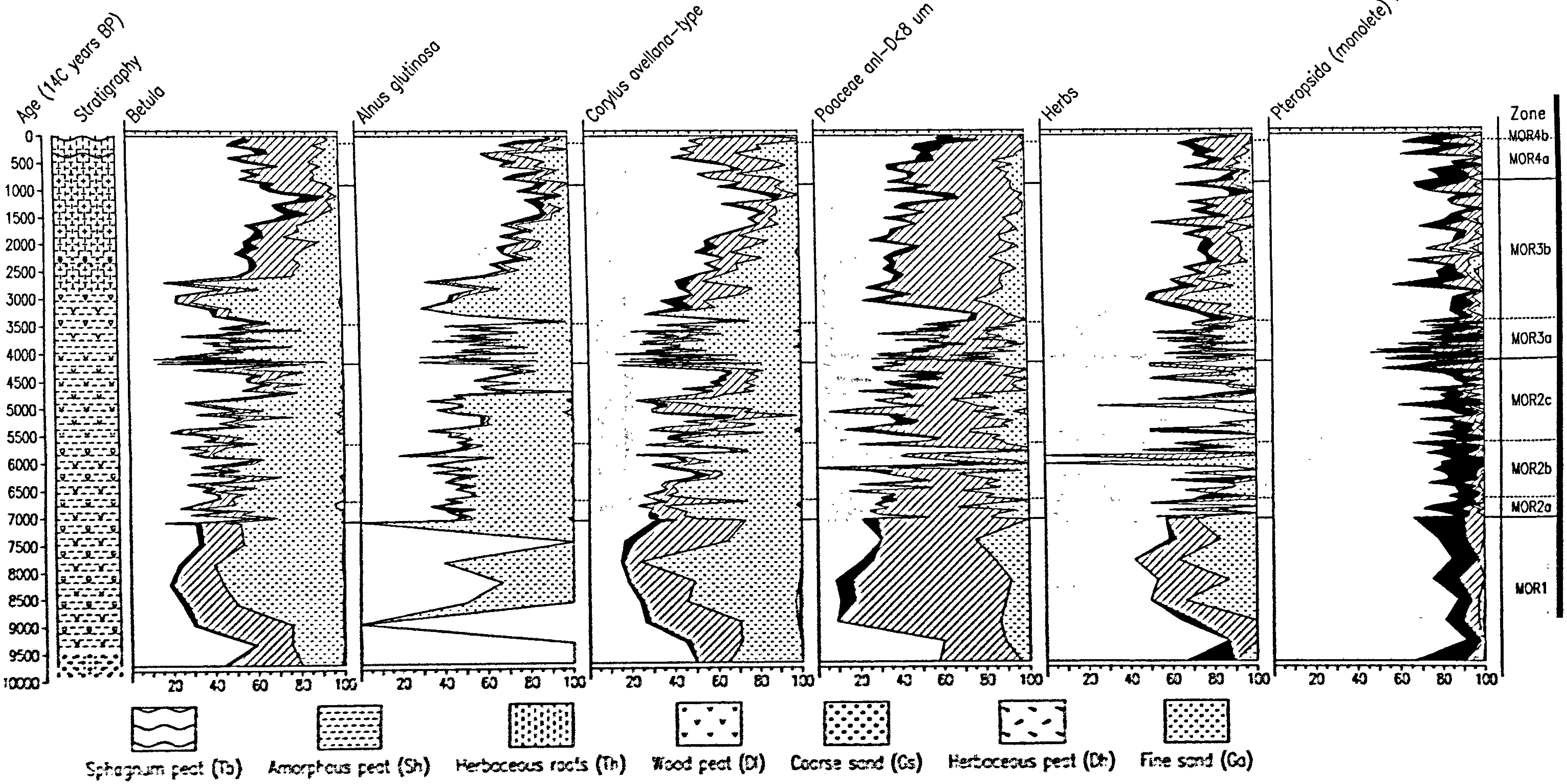
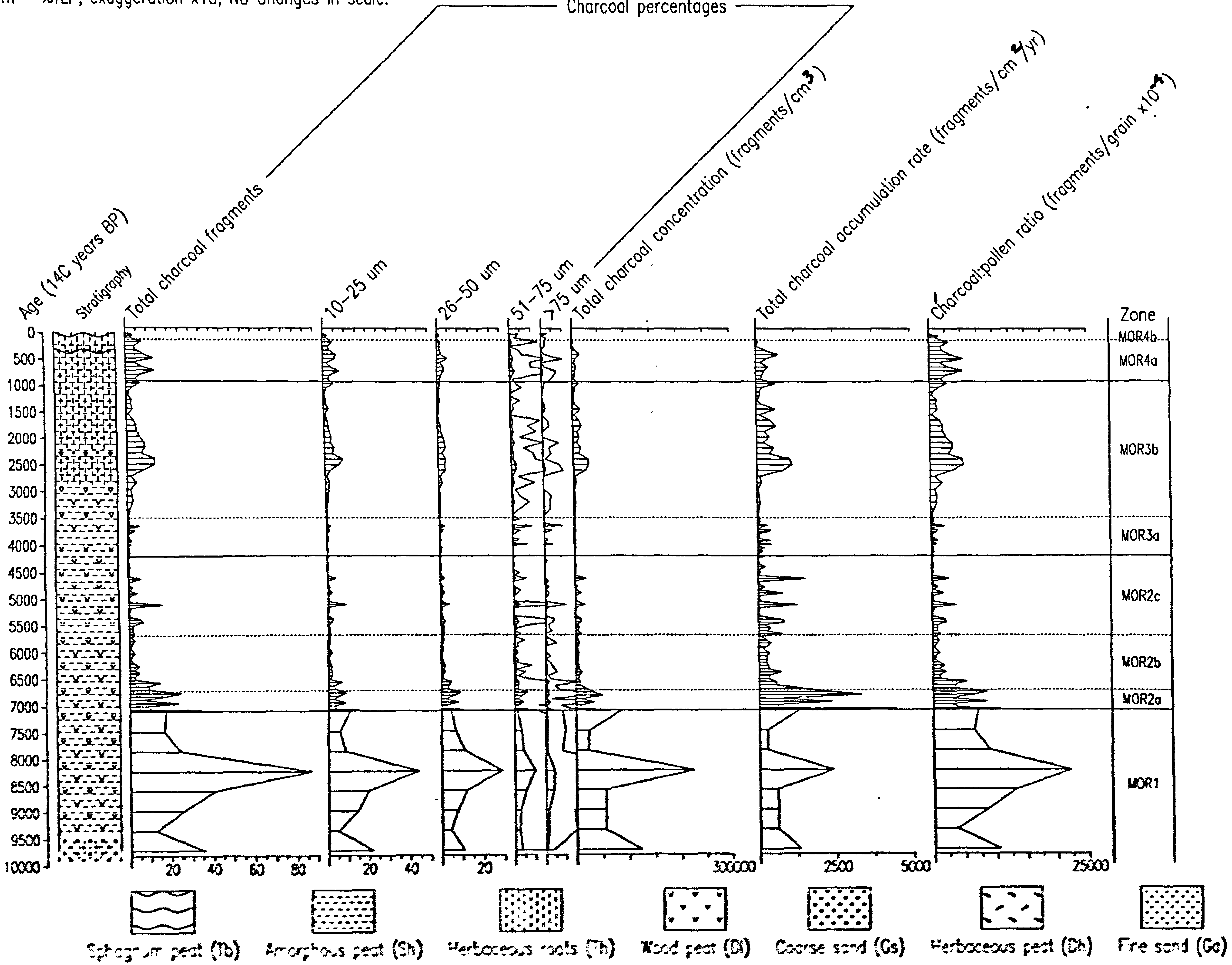


Figure 63. Charcoal data from Morvich.
Sum = %TLP; exaggeration x10; NB Changes in scale.



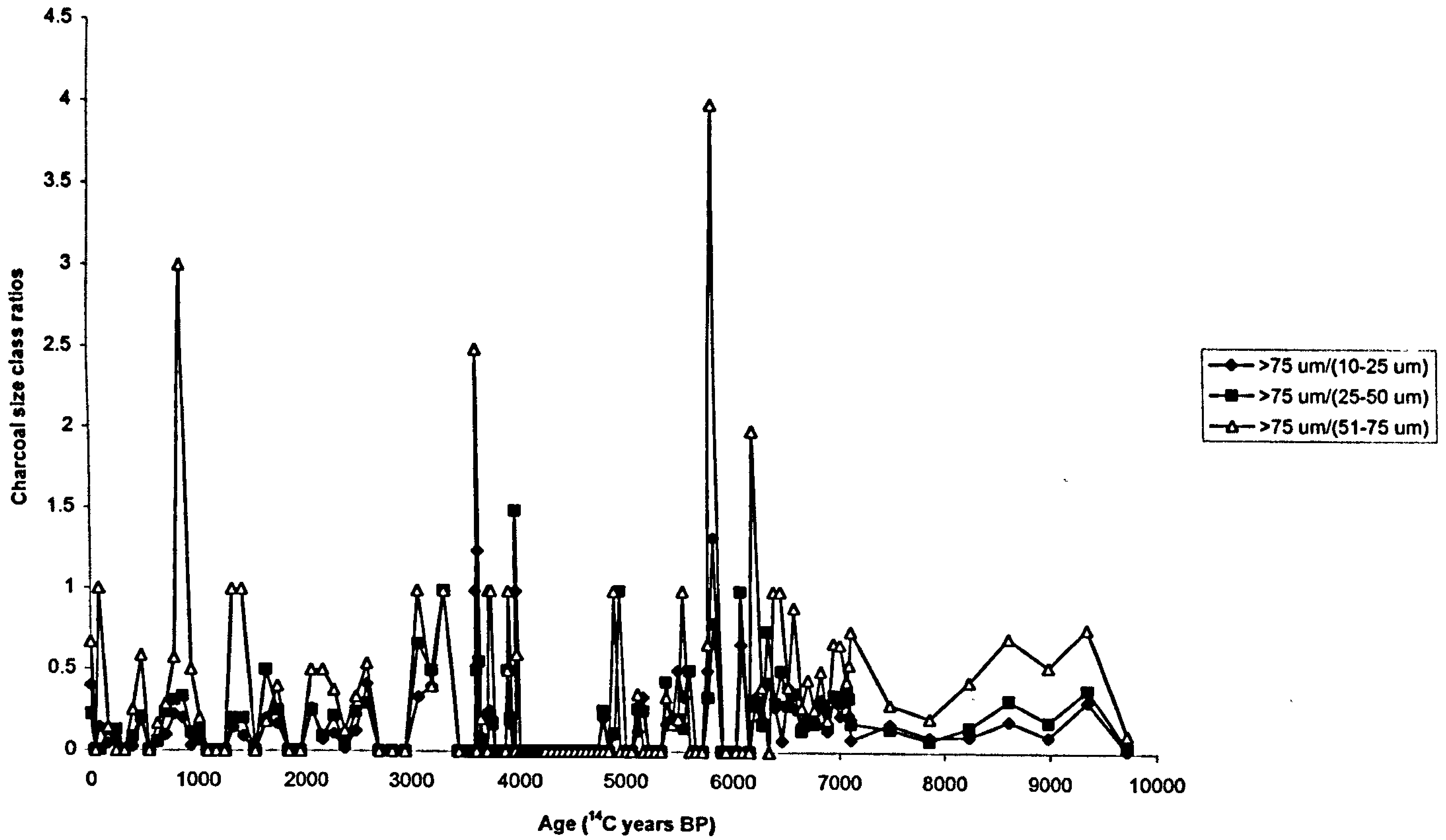
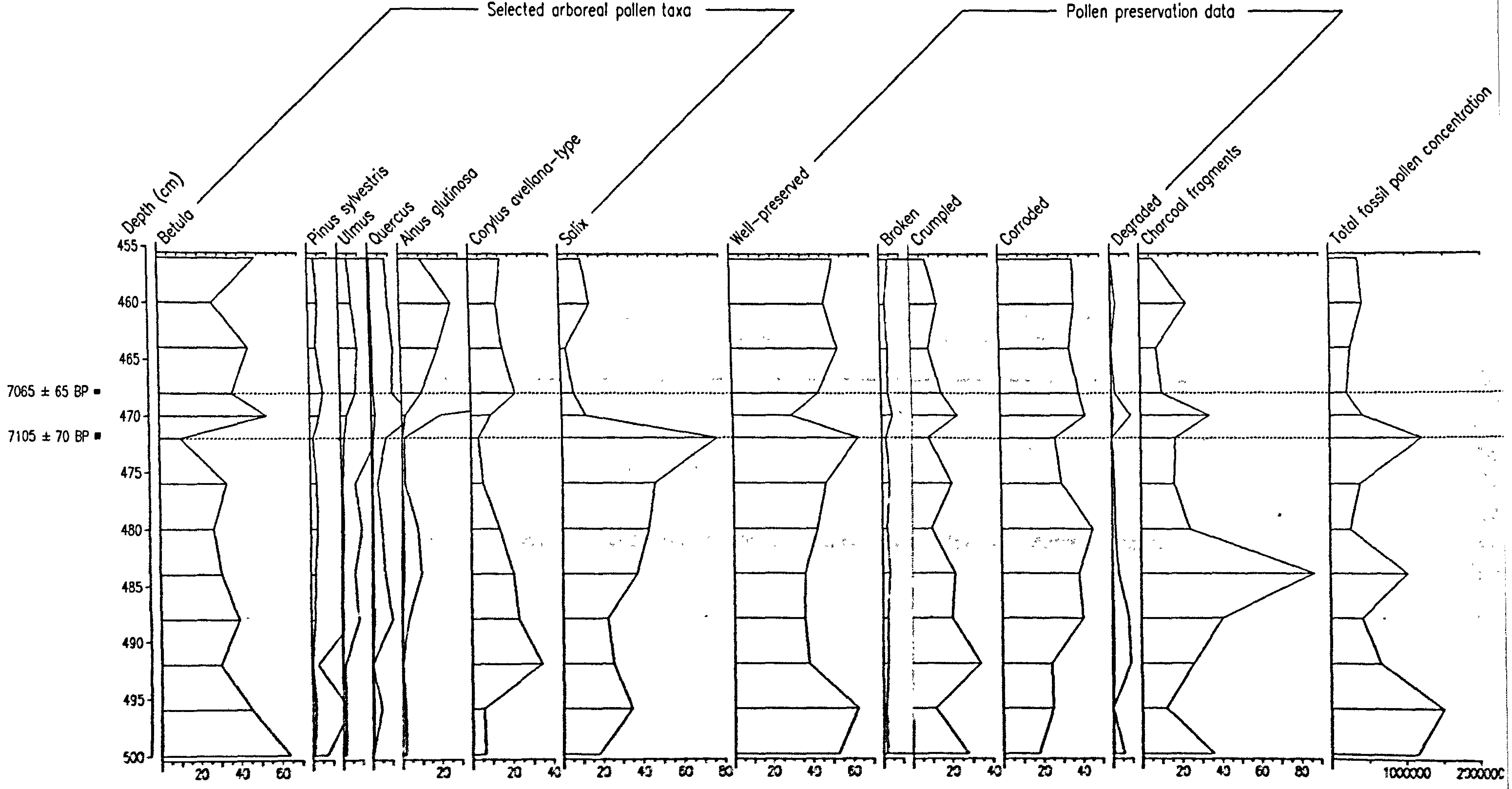
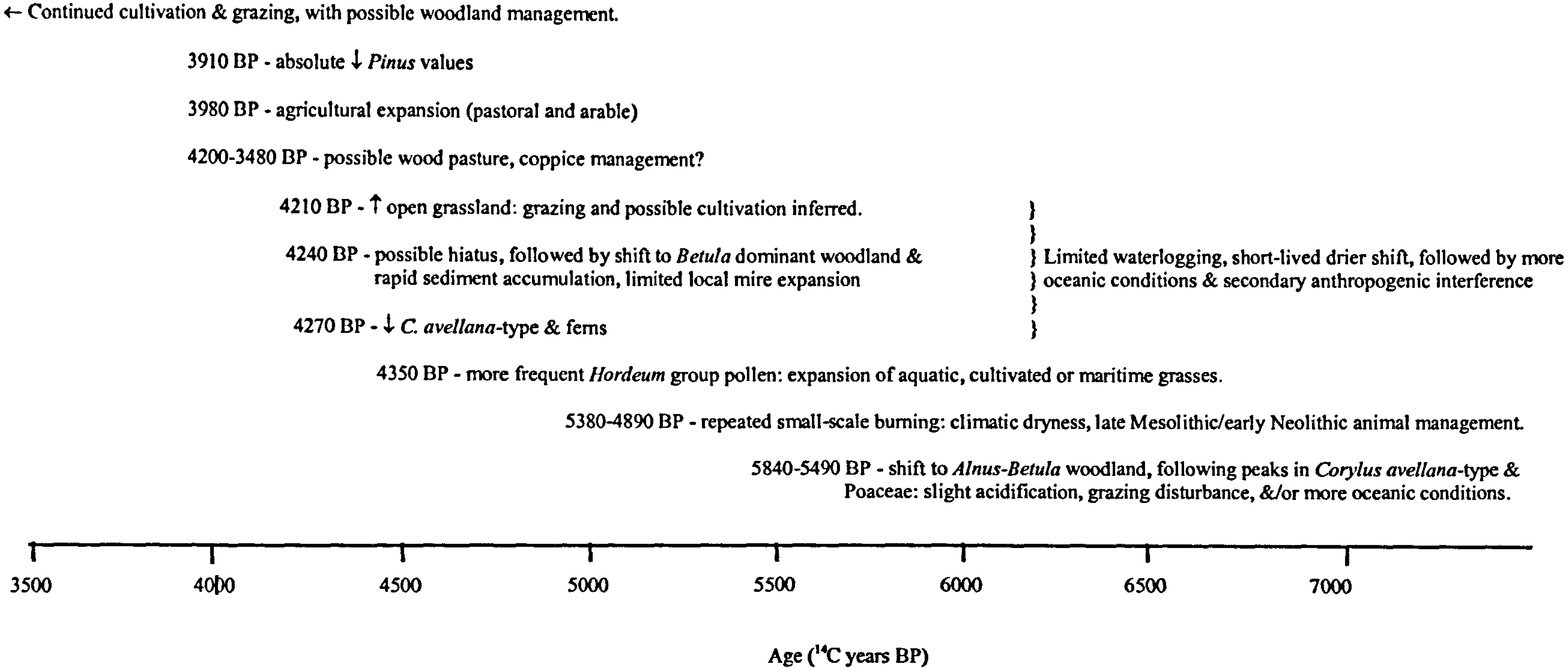


Figure 64. Charcoal size class analysis for Morvich - ratio of percentage of large (>75 μm) to smaller (10-25 μm, 26-50 μm, 51-75 μm) fragments, plotted against age in ^{14}C years BP.

Figure 65. Relationship between radiocarbon dates and inferred hiatus around 7100 BP with selected pollen data.
Sum = %TLP; exaggeration x10.





← Continued cultivation & grazing, with possible woodland management.

3910 BP - absolute ↓ *Pinus* values

3980 BP - agricultural expansion (pastoral and arable)

4200-3480 BP - possible wood pasture, coppice management?

4210 BP - ↑ open grassland: grazing and possible cultivation inferred.

4240 BP - possible hiatus, followed by shift to *Betula* dominant woodland & rapid sediment accumulation, limited local mire expansion

4270 BP - ↓ *C. avellana*-type & ferns

} Limited waterlogging, short-lived drier shift, followed by more oceanic conditions & secondary anthropogenic interference

4350 BP - more frequent *Hordeum* group pollen: expansion of aquatic, cultivated or maritime grasses.

5380-4890 BP - repeated small-scale burning: climatic dryness, late Mesolithic/early Neolithic animal management.

5840-5490 BP - shift to *Alnus-Betula* woodland, following peaks in *Corylus avellana*-type & Poaceae: slight acidification, grazing disturbance, &/or more oceanic conditions.

Figure 66. Summary of inferred early to mid-Holocene vegetational and environmental changes around Morvich. Arrows denote increasing/decreasing pollen values.

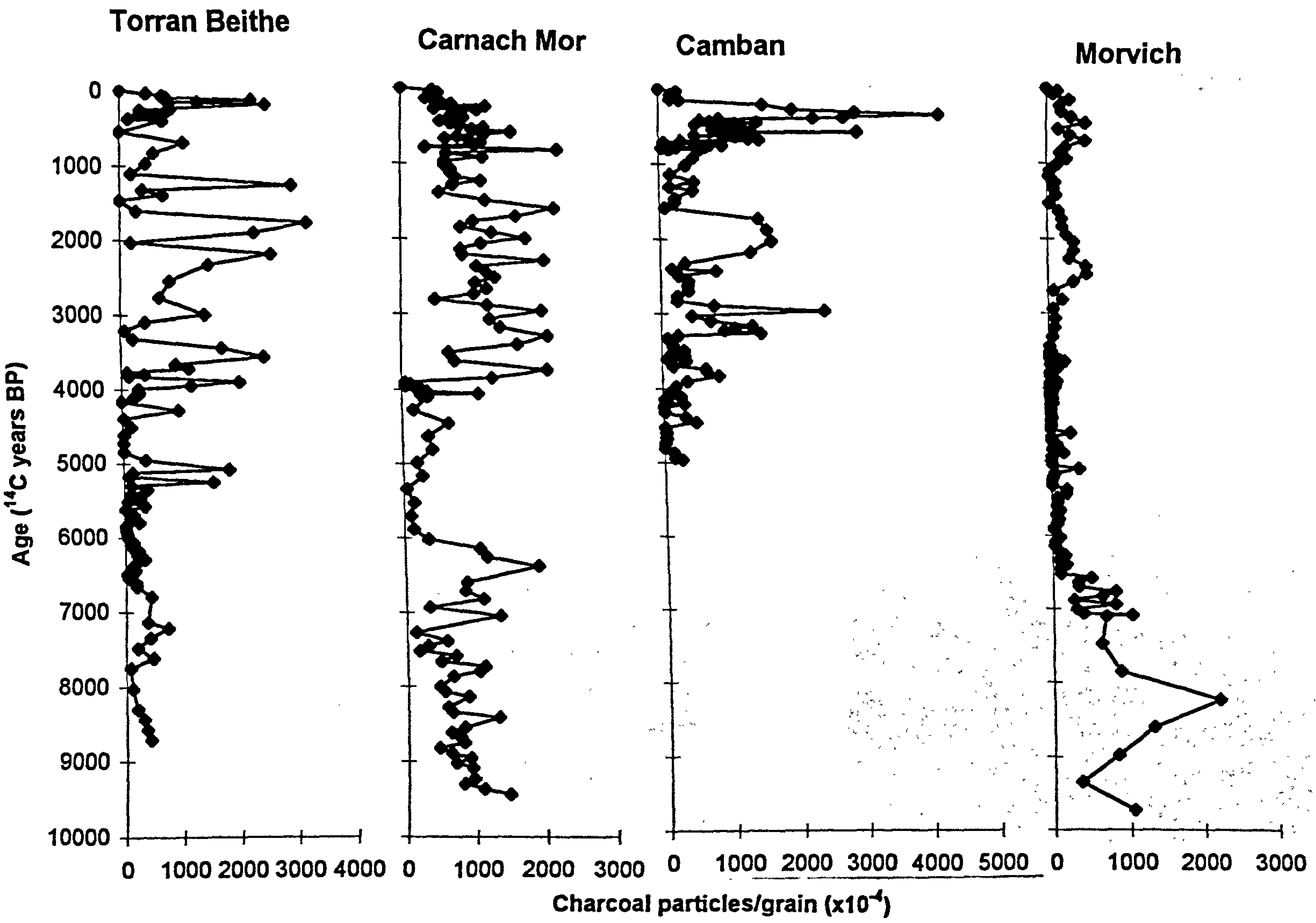


Figure 67. Comparison of charcoal data from Torran Beithe, Carnach Mor, Camban and Morvich. Plotted against ^{14}C years BP.

Photo 1. Putatively ancient Scots pine and birch woods in East Affric. Photo: M. Lloyd.

Photo 2. Sparse woodland near the head of Loch Affric. Photo: M. Lloyd.

Photo 3. Blanket peat communities on moraine sediment on the lower hillslopes around Torran Beithe in central Glen Affric. Photo: E. Tisdall.

Photo 4. The topography and vegetation of the flat alluvial floodplain grassland in West Affric contrast markedly with the undulating, blanket peat-covered morainic sediment. Photo: E. Tisdall.

Photo 5. Species-rich alluvial grassland communities around the sampling site at Carnach Mór in West Affric. Photo: E. Tisdall.

Photo 6. Characteristic unstable gravel bars and banks in the River Affric. Photo: E. Tisdall.

Photo 7. Alluvium and blanket peat surround the sampling site (marked by the augur in the centre) at Carnach Mór. Photo: E. Tisdall.

Photo 8. Ruins overlooking the sampling channel and valley floor at Carnach Mór. Photo: E. Tisdall.

Photo 9. The peat-covered alluvial fan with abundant *Juncus* at Camban in Fionngleann and the mountains flanking West Affric visible at top left. Photo: R. Tipping.

Photo 10. There is a marked contrast between alluvial soils with archaeological evidence, and surrounding blanket peat at Camban. Photo: R. Tipping.

Photo 11. Lying at the head of Loch Duich, the Strath Croe valley in Kintail is surrounded by steep mountains, connected with West Affric by upland passes. Photo: R. Tipping.

Photo 12. The sampling site at Morvich: view north across the basin towards the river, screened by a fringe of *Alnus glutinosa*. Photo: S. Bradley.

Photo 13. The sampling site at Morvich: view south over the sampling basin, up the gully and towards the hills. Photo: S. Bradley.

Photo 14. Possible evidence for tathing in Central Affric – a regular area of greener vegetation lies below the path. Photo: E.Tisdall.