The Late-Holocene palaeoecology of Scots pine (Pinus sylvestris L.) in north-west Scotland.

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The Late-Holocene Palaeoecology of Scots Pine (*Pinus sylvestris* L.) in North-West Scotland

by

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Frontispiece. Native Scots pine by Loch Maree. Note the dead standing trunk and the pine regeneration in the foreground.

Declaration

The material contained within this thesis has not previously been submitted for a degree at the University of Durham or at any other University. The research reported within this thesis has been conducted by the author unless indicated otherwise.

Abstract

The distribution of subfossil *Pinus sylvestris* L. stumps preserved in blanket peat was surveyed across northern Scotland within an area north of the Cromarty Firth and west of Strathy Point. Three main sites with large numbers of stumps and a number of other locations with smaller numbers of subfossils were selected across the region and investigated dendrochronologically to establish the relative times of the growth of pine within and between the sites. Tree-ring data from two other previously studied sites were incorporated. Peat monoliths were recovered from two of the main sites (Loch Vatachan and Loch Shin) and one other at Srath Dionard, and were investigated palynologically for peaks in pine pollen and layers of tephra. Twenty radiocarbon dates were obtained for subfossil wood, of which ten were used in conjunction with dendrochronological data to derive a wiggle matched date for one site at Loch Shin.

From these data something of the nature of the pine woodlands on the peat is reconstructed. It is shown that Scots Pine spread northwards onto the blanket peat beyond the present day limits of its distribution reaching the north coast by around 3000 BC. It is further shown that the pine began to die out on the blanket peat at around 2900-2800 calendar years BC, well before the date of the Hekla 4 eruption (2310 ± 20 BC) sometimes invoked as a possible cause for this demise. A regional climatic change, causing drying of the peat surfaces, is proposed to explain the speed and scale of the pine spread. This change is linked to rapid and wide fluctuations in levels of atmospheric ^{14}C at about this time and it is suggested that these fluctuations are linked to changes in solar activity causing climate change on a global scale.

Acknowledgements

Firstly I would like to express my gratitude to Prof. Brian Huntley and Dr. Judith Turner, my supervisors, for all their help, advice and support during this project. I am also very grateful to Dr. Judy R.M. Allen for all her help, particularly with the pollen analysis and proof reading.

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Chapter 1 - INTRODUCTION

1.1 Historical context

Despite the near treelessness of vast tracts of the far north of Scotland, the presence of tree remains buried in the blanket bogs that cover so much of the region has been known for centuries, certainly for as long as peat has been used for fuel or the bogs drained for agricultural purposes. It was recorded that these remains were mainly of oak and pine, with the less frequent occurrence of rowan, hazel, willow, birch, alder and juniper (Steven and Carlisle, 1959) and that oak tended to occur in lowland bogs and pine in the uplands and in the north.

Various explanations of the destruction of these northern pine forests and the subsequent growth of the peat were proposed from the 18th century onwards, including clearance by the Romans and burning during Viking raids. For example Rackham (1986) quotes J. Sinclair of Applecross in Wester Ross, who wrote in the Statistical Account of Scotland for 1791-9:

> 'There are trunks of trees found at a considerable depth under ground, in hills and meadows, where there is no vestige of any kind of wood remaining; many of them have suffered visibly from fire, which the traditional history of the country reports to have been occasioned by the Danes burning the forests.'

Rackham goes on to point out that the blackening mentioned in this extract, and widely supposed to be the product of burning, was probably caused by the natural processes of drying after removal of the timber from the bogs.

Certainly sources such as the Icelandic Sagas would seem to confirm the presence of substantial pockets of woodland in the far north, at least on the coast, as late as the middle of the 13th century. Laxdæla Saga tells of Unn the Deep-minded, daughter of Ketil Flat-nose, a Norse settler in Scotland, having a ship built secretly in the forest in Caithness in about 950 AD (Magnusson and Palsson, 1969). This would have required large quantities of straight timber more than 6 m long (probably from at least thirty trees). The frames were usually oak and pine was frequently used for the planking and for spars, though other materials might have been used if available (Olsen and Crumlin-Pedersen, 1967). The Saga of Haakon Haakonsson describes a skirmish near Loch Eriboll after the Battle of Largs in 1263 AD, recording the presence of woods around the shore (Steven and Carlisle, 1959), these woods being of sufficient density to hide the fleeing Scots. However these woods were probably birch, as this species persists in the area to this day.

1.2 Previous scientific work

The earliest climatic explanations of the demise of the forest and the growth of peat came with the ideas of James Geike (1866, summarised in Steven and Carlisle, 1959). He endeavoured to link the climatic evidence of changes in vegetation with variations in sea-level since glaciation. At the turn of the century F.J. Lewis was studying the stratigraphic sequence of the northern Scottish peats. He too invoked climatic change as the cause of the vegetation changes he described (summarised in Lewis, 1907) and suggested the occurrence of two "genial" forest periods separated by a more "Arctic" period. His findings were interpreted by Samuelsson (1910) as supporting the Blytt and Sernander scheme of climatic periods proposed for Scandinavia. These, based mainly on macrofossil remains, but employing some early pollen analysis, reflected the warming of climate towards a post-glacial maximum (the sub-Boreal of Blytt and Sernander) through episodes of varying continental or oceanic influence. The two forest beds found by Lewis (1907), the upper containing pine, the lower predominantly birch, were identified with the sub-Boreal and Boreal periods, both described as warm and dry.

Subsequent workers examined the evidence (both macrofossils and pollen) for the presence of Scots Pine beyond its present day northern limits (shown in Figure 1.1). Interpretations of this evidence varied. For instance, G. Manley (1945) recorded the finding by T.G. Longstaff of a Scots Pine trunk in peat at Badantarbet Lodge (Nat. Grid Ref. NC(29)013101) near Loch Vatachan in Wester Ross (close to a site in the present study). Dr. Longstaff suggested a date of about 1700 AD for its growth and noted the failure of a nearby plantation of Scots Pine made in 1915, arguing that this suggested an increase in wind and reduction in sun in recent times. Manley suggested the use of dendrochronology to date the find against architectural timbers of known date. However, the advent of radiocarbon dating overtook this proposal, and Lamb (1964), applying this technique to the same trunk, dated it to 4400 radiocarbon years before the present, much earlier than previously suspected. He discussed at length the changes in climate that might have permitted its growth and that of the other stumps found in the area, and also the processes by which they might have been preserved in the bogs.

Further locations of subfossil pine in the region were mapped by H.H.Birks (1975) who also suggested a northerly limit for the present distribution of pine in Scotland assuming no interference by man (Figure 1.1). She obtained radiocarbon dates for the subfossil pine, noting the narrow range of dates (4000-4500 BP) for what she referred to as the north-west Highland group of stump samples. Through this and a review of other work, she concluded that there was a marked decline in the presence of *Pinus sylvestris* in the north and west of Scotland and Ireland at about 4000 BP. Quoting in particular the work of McVean (1963a, b), she attributed this to an increase in wetness of the blanket bog surface on which the trees were growing. This could inhibit the regeneration of Scots pine or produce a rising water table that would kill the trees outright. Birks also discussed the conditions necessary for the preservation of subfossil pine stumps, concluding as others before her that their presence indicated that the drier conditions permitting their growth had been succeeded by a wetter period allowing rapid peat development to cover and preserve them. She further noted the synchronism of this decline at the edge of the pines' range in the north and west, but felt that as this did not tally chronologically with the Boreal/Atlantic and sub-Boreal/sub-Atlantic boundaries of Blytt and Sernander (c. 7000 and 2500 BP respectively) it was not evidence for the overall scheme of these authors. However this did not rule out climate change as a possible cause of the pine decline in the region, but further evidence was required before any overall palaeoclimatic significance could be attributed to it.

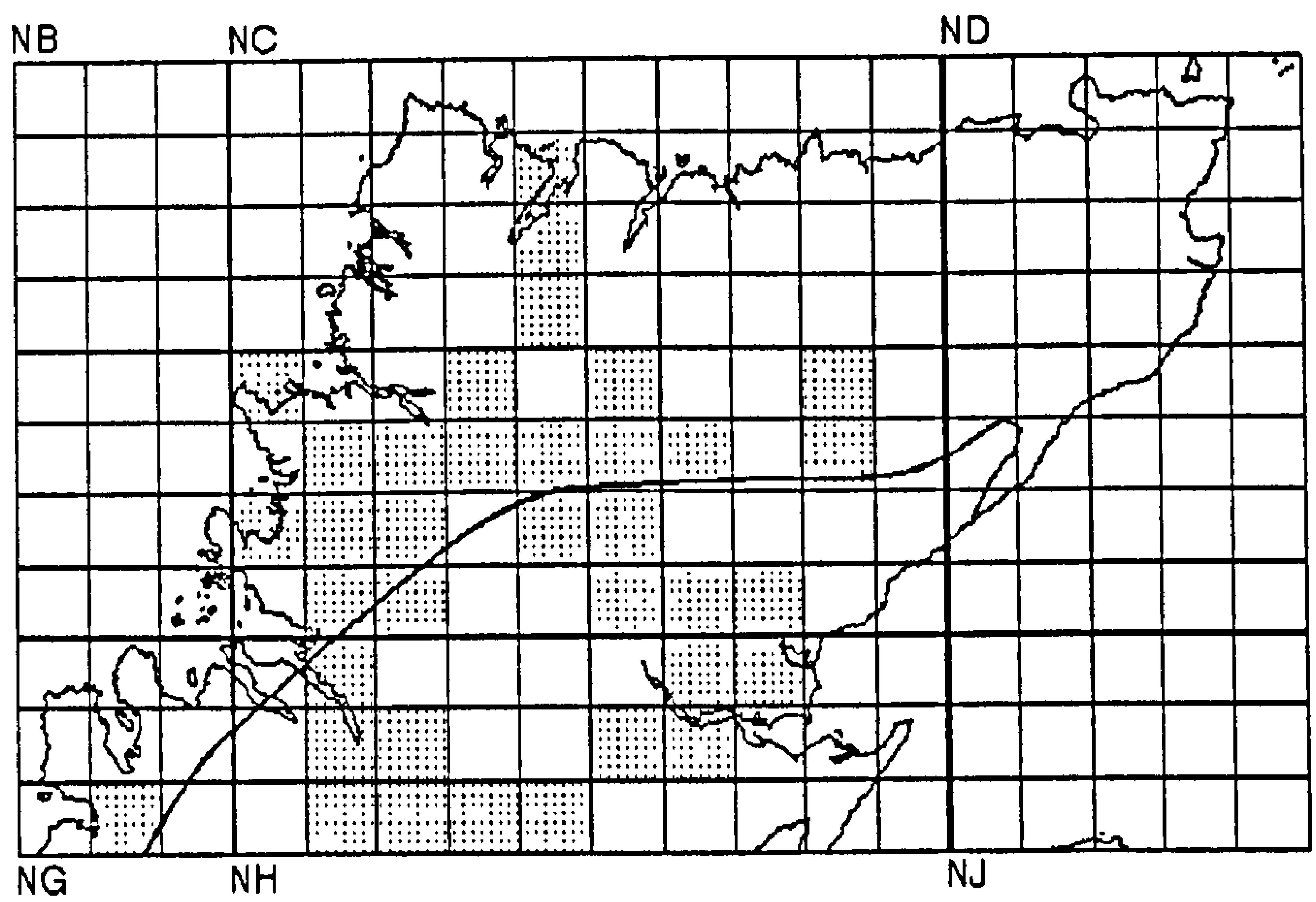


Figure 1.1 H.H.Birk's (1975) map of 10 km grid squares in northern Scotland containing subfossil pine stumps in peat (shaded squares). The solid line represents her theoretical present northern limit for natural pine distribution.

Bennett (1984), using available pollen and macrofossil records, mapped the distribution of *Pinus sylvestris* since the last glacial, suggesting that Scots Pine had reached its maximum northwards limit in Britain at about 4000 BP. He also differentiated between the evidence from pollen diagrams and that from radiocarbon dated macrofossils, arguing that a pollen frequency greater than 20% of total tree and shrub pollen was required to indicate a significant presence of Scots Pine in a locality, whilst macrofossils rarely occurred in sufficient density in a stratified sequence to give any indication of changes in abundance. On this basis he suggested that the presence of subfossil stumps in the far north of Scotland coupled with the apparent absence of any significant pollen record indicated either a sparse distribution in favourable sites through chance long-distance dispersal, or low pollen production from trees at the edge of their range. He also concluded that it was impossible to determine whether the decline in Scots Pine around 4000 BP caused the spread of blanket bog or vice versa, though he recognised that the overall range of the species was controlled climatically.

H.J.B.Birks (1989) summarised the available pollen evidence and published the isochrone map of the Holocene distribution of *Pinus sylvestris* reproduced here (Figure 1.2). Rather than Bennett's (1984) 20% criterion for the local presence of pine he used the 'rational limit' of Smith and Pilcher (1973), which those authors defined as 'the point at which the pollen curve [for a particular taxon] begins to rise to sustained high values'. Birks also suggested different apparent sources of expansion into the British Isles for different populations of the tree, from the south east of England for the English population, from the south-west of Ireland for the Irish population, and from the west to north-west for the north-west Scottish trees (Figure 1.2). He described various hypotheses to account for this latter expansion. The first of these, suggested by Huntley and Birks (1983) proposed refugia to the west and south west in which scattered small populations of pine survived the last glacial. This was supported to some extent by the evidence of Kinloch *et al.* (1986) who identified populations of pines in Wester Ross that were genetically distinct from each other and from the rest of the Scottish trees. The second hypothesis, which Birks suggested was untestable, invoked random 'jump dispersal' of seed from great distances, from southern Britain or Europe. The third hypothesis was that a very rapid, sparse expansion of pine into poor habitats, where competition from deciduous trees was low, occurred early on (about 8500 - 8000 BP) through western Ireland and south-west Scotland. However it seemed from the absence of fossil evidence that pine didn't spread into the Kintyre region or the south-western islands of Scotland. On balance however, Birks decided the most likely explanation was dispersal from Ireland, certainly into Galloway, and possibly via the Hebrides into north-west Scotland. Finally, in the same paper Birks gave spread rates for pine based on his isochrones, that for the Scottish pines being approximately 150 m yr^{-1}.

All this probably marked the limit of the information obtainable from conventional broad scale pollen analysis. That it was possible to miss evidence of substantial spreading of pine on a short time scale was shown by the studies of pollen (Birks and Madsen, 1979) and macrofossil evidence (Wilkins, 1984) from the Isle of Lewis. The pollen study indicated very low pollen values for trees other than *Betula* or *Corylus* on the island throughout the Flandrian whereas study of the macrofossils revealed the presence of pine in significant quantity between 4000 and 5000 BP. Wilkins (1984), in his paper,

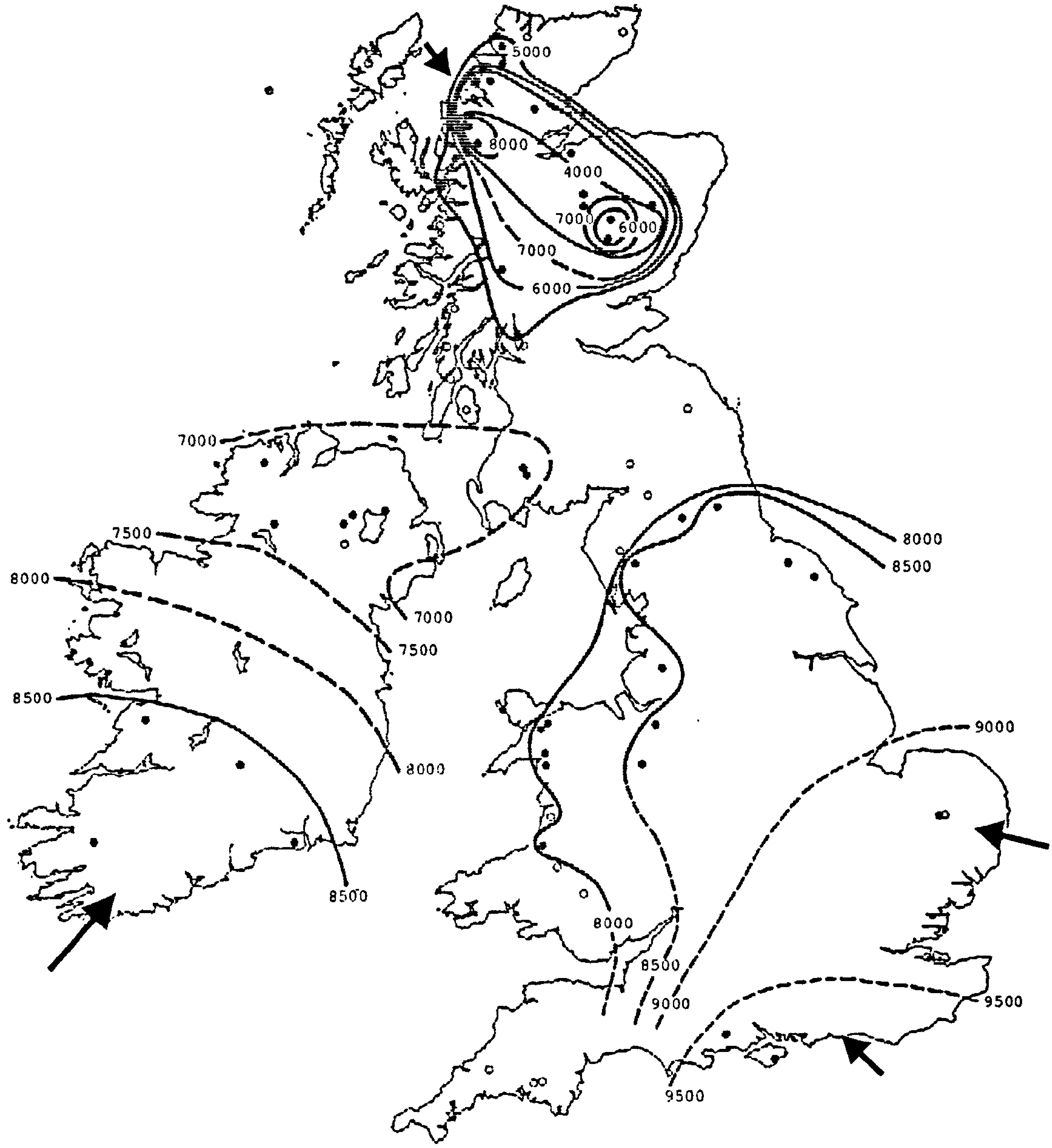


Figure 1.2. Isochrone map based on the 'rational limit' of *P. sylvestris* pollen in the British Isles. The isochrones are based on pollen diagrams from the sites indicated by dots. The open circles indicate sites where there is no pollen evidence of local presence. The isochrone dates are are radiocarbon years BP. The arrows indicate Birks' suggested directions of arrival of pine. Redrawn from Birks (1989).

suggested the low pollen count could have been due to most of the pollen being dispersed by offshore winds or that the macrofossils were from trees scattered in time, though this latter idea was contradicted by dense assemblages of stumps at the same stratigraphic level. With hindsight it seems more likely that episodes of high pine pollen levels were missed within the sampling intervals used by Birks and Madsen (1979).

In order to test whether Scots pine had occurred sparsely over the far north of the Scottish mainland through thousands of years, or whether pine forest had extended northwards for a period brief enough to have been overlooked in previous conventional pollen studies, Gear and Huntley (1991) mapped occurrences of subfossil pine stumps across the region, obtaining radiocarbon dates and making detailed palynological studies. They found evidence that pine had been widespread throughout the area with the exception of the extreme north east (Figure 1.3).

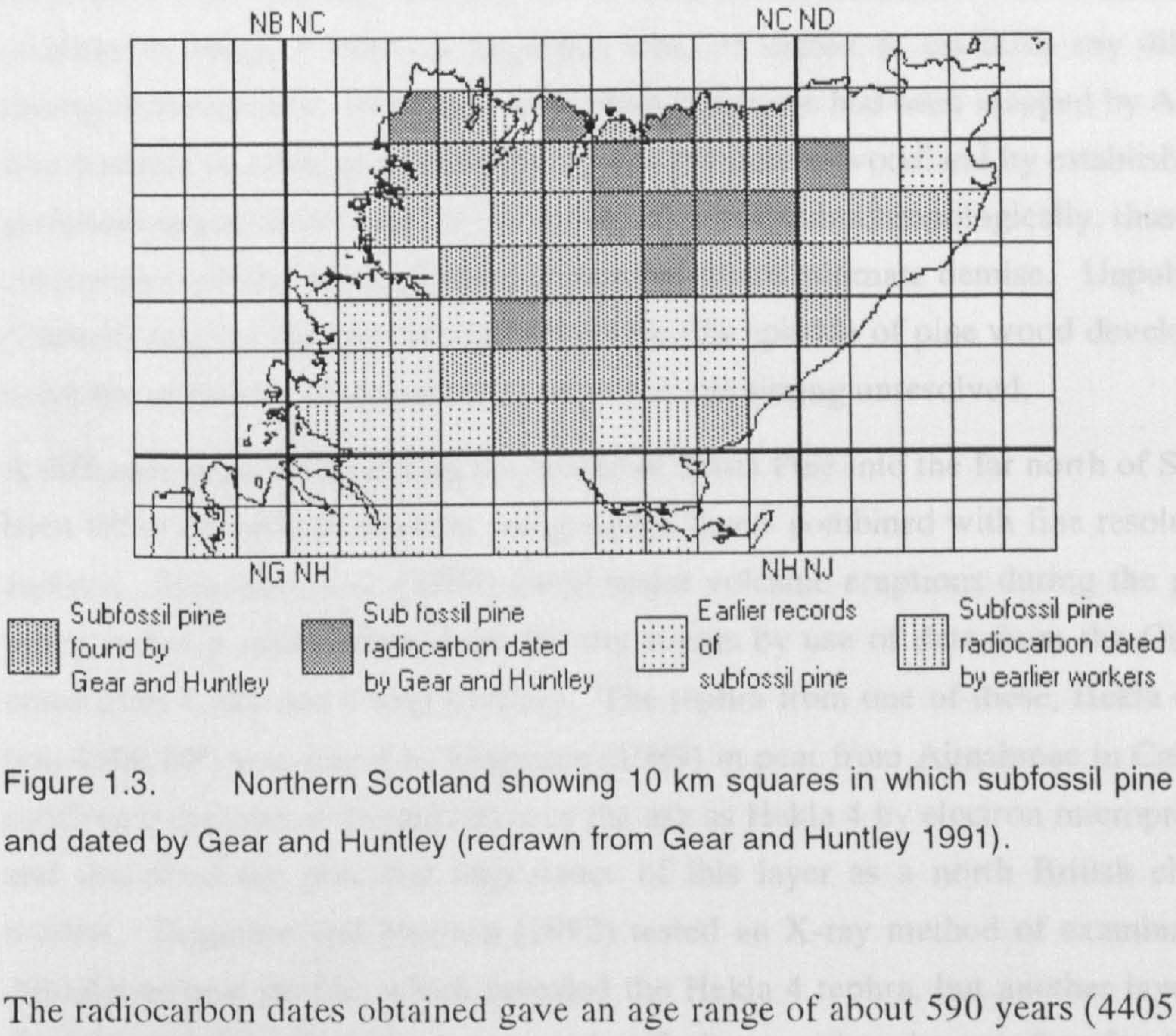


Figure 1.3. Northern Scotland showing 10 km squares in which subfossil pine was located and dated by Gear and Huntley (redrawn from Gear and Huntley 1991).

The radiocarbon dates obtained gave an age range of about 590 years (4405 - 3815 BP) for the stumps across the region, each site tending to span a period of approximately 350 - 400 years. For one site, Lochstrathy (Nat. Grid Ref. NC(29)796491) this was confirmed dendrochronologically, and a fine resolution pollen study was made. This revealed a very narrow phase of high pollen values (>30% of the total terrestrial pollen sum across about 68 mm of peat) confirming the local presence of pines for the short time span (about 325 years) in question. Stratigraphic analysis of charcoal from the samples, together with changes in the presence of other pollen taxa suggested that considerable variation had taken place in the wetness of the blanket bog. This, coupled with the regional scale (about 70-80 km) and synchronism of the range of expansion and contraction of the pine forest was seen to be evidence of climatic influence. Gear and Huntley (1991) estimated the rate of forest boundary movement from their data and found it to be around 375 - 800 m yr^{-1}, which was consistent with estimates for larger scale post-glacial migrations and probably represents the maximum rate attainable. This agreed well with similar events elsewhere in northern Europe, suggesting the effects of a broad-scale change in atmospheric circulation, probably a northwards shift of the jet-stream.

Daniell (1992), working on stumps collected from the loch shore at Badanloch by A. J. Gear, described similar population dynamics and dating to those found at Lochstrathy by Gear (1989). But as the sites were close together (15 km) and radiocarbon dates obtained for the subfossil wood were all lying within each other's error limits it was not possible to assign a value to migration rate, or indeed to establish any differences in timing with certainty. However, as the Badanloch site had been mapped by A. J. Gear, it was possible to attempt a reconstruction of the palaeo-woodland by establishing relative germination and death dates of the different trees dendrochronologically, thus tracing the colonisation of the site and possible reasons for its ultimate demise. Unpublished data (Daniell) support the climatic hypothesis for this episode of pine wood development, but leave the questions of spread rates, sequence and timing unresolved.

A different approach to dating the spread of Scots Pine into the far north of Scotland has been taken by various workers using tephra layers combined with fine resolution pollen analysis. Hammer *et al.* (1980) listed major volcanic eruptions during the past 10,000 years, refining radiocarbon dates for the events by use of data from the Greenland ice cores from Crête and Camp Century. The tephra from one of these, Hekla 4 in Iceland (ca. 4000 BP) was found by Dugmore (1989) in peat from Altnabreac in Caithness. He confirmed the optical identification of the ash as Hekla 4 by electron microprobe analysis and described the potential importance of this layer as a north British chronological marker. Dugmore and Newton (1992) tested an X-ray method of examination on the Altnabreac peat profile, which revealed the Hekla 4 tephra, but another layer higher up (known as "Glen Garry", as yet unidentified) proved to be too fine for this method. Further work by Dugmore *et al.* (1992) confirmed the geochemical stability of the Icelandic tephras and hence the possibility of positively identifying events from which stratigraphic marker horizons could be established.

J.R. Pilcher, V.A. Hall and others (Pilcher and Hall, 1992: Hall *et al.*, 1993) began the work of constructing a tephrochronology for the north of Ireland, correlating tephra layers, including one believed to be from the eruption Hekla 4, in blanket peats across the province. They also discussed the possibility of spread of the tephra layer in time down through the peat, questioning whether pollen might spread in the same way, limiting the maximum resolution of pollen analytical techniques. In north east Scotland, Blackford *et al.* (1992) in a fresh study at Altnabreac also raised these questions, but more importantly found a sharp decline in pine pollen coinciding with the Hekla 4 tephra layer. They noted that radiocarbon dates for subfossil pine stumps did not always coincide with the pine peak in the accompanying pollen diagrams in other studies (Bridge *et al.*, 1990: Gear and Huntley, 1991), and pointed out that the stumps represented "a period of tree-growth rather than demise", particularly as the outer rings were frequently missing. They therefore felt dating of the pine decline in this way to be ambiguous. They concluded from their data that the eruption of Hekla 4 may have played a key climatic rôle in the pine decline in the Altnabreac area.

Whereas this finding may be true for north-east Scotland, Hall *et al.* (1994) have demonstrated that there is no correlation between pine pollen values and the Hekla 4 tephra in northern Ireland. They have obtained a more precise date of 2310±20 BC for the eruption itself by a 'wiggle-matching' technique and shown that, when calibrated, the dates for pine given by Bennett (1984) and Gear and Huntley (1991) reveal a pine decline preceding Hekla 4 in the north and west of Scotland.

1.3 Description of the region

1.3.1 Geography and geology

The sites studied in this investigation are in the western half of the far north of Scotland, an area bounded to the east by a line approximately midway between Strathnaver and Strath Halladale, and stretching south to a line between Loch Maree in the west and the Cromarty Firth in the east. Figure 1.4 shows the main geographical features of the region, including place names mentioned in the text, and Figure 1.5 shows the general relief. The eastern half of the region is made up largely of an extensive undulating plateau lying at about 300 m above sea level, while the landscape to the west is more rugged, with a number of peaks over 700 m, and a few rising to over 900 m. The reasons for this division can be seen clearly in the underlying geological structure of the area, shown in Figure 1.6. This is a generalised map, but shows clearly the Moine Thrust which splits the region. To the east of this the Moine Schists underlie the peat-covered plateau, while to the west occur the Torridonian sandstones and grits, with Lewisian gneisses in the north, the latter giving rise to a typical 'knob and lochan' landscape. Following the line of the Moine Thrust itself is a band of quartzite with occasional outcrops of limestone. This broadens to the west along the northern portion of the

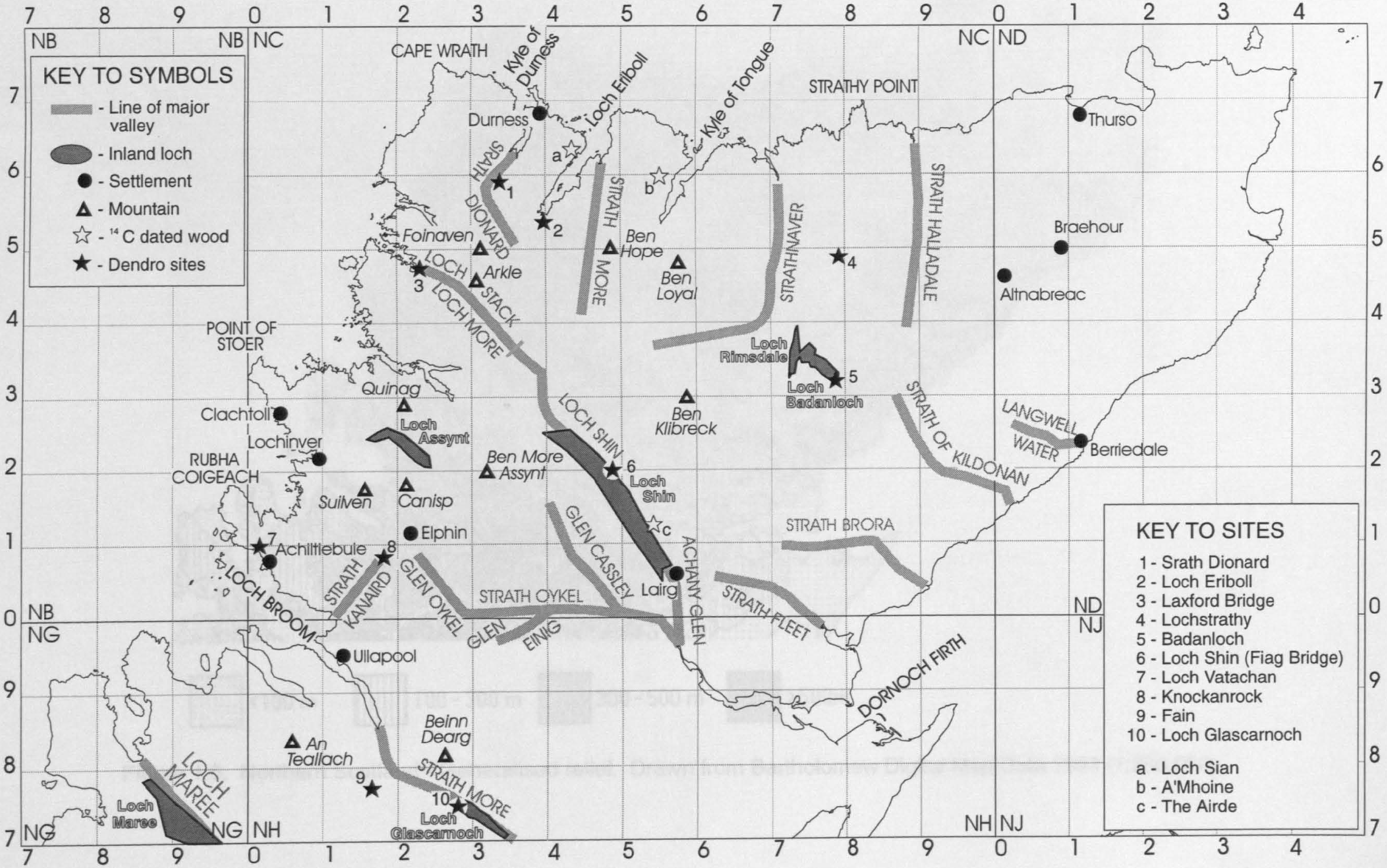


Figure 1.4 Northern Scotland showing main valleys, other geographical features and places mentioned in the text

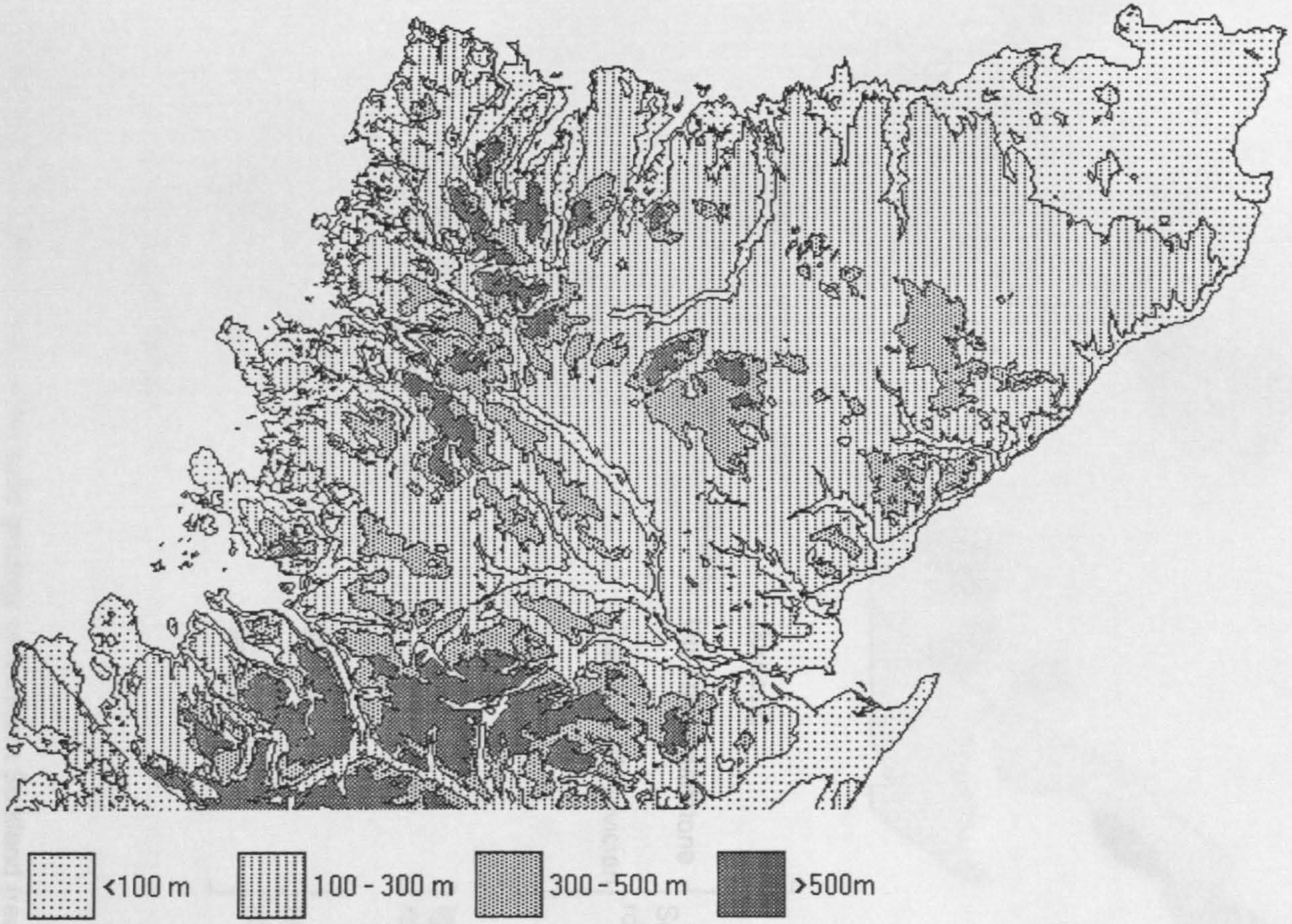


Figure 1.5. Northern Scotland - Generalised relief. Drawn from Bartholomew Digital Map Data 1993 (1:250,000)

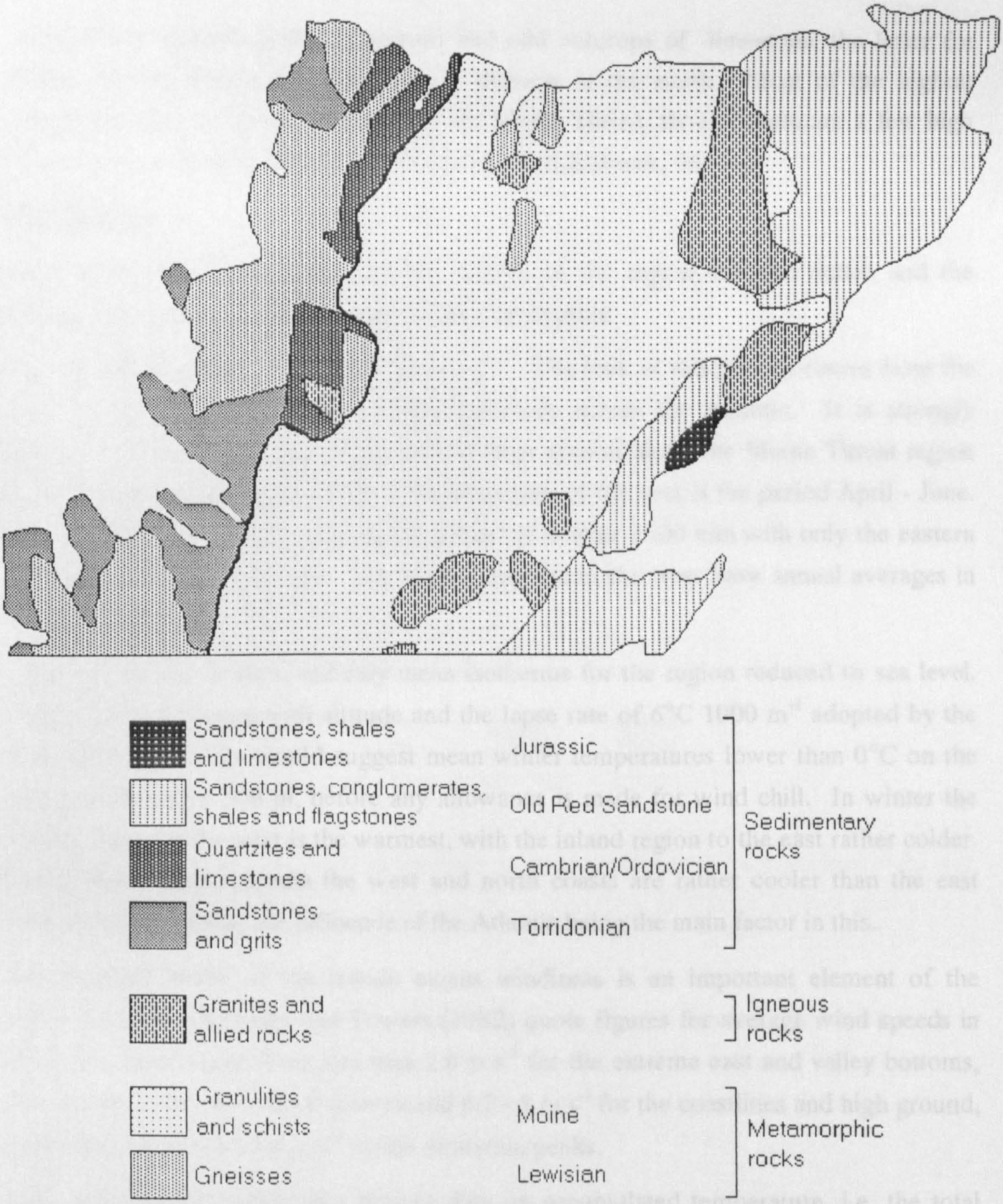


Figure 1.6. Generalised map of the solid geology of Northern Scotland (redrawn from Futty and Towers, 1982).

thrust line to include granite intrusions and odd outcrops of limestone, the latter for instance around Elphin and especially at Durness in the north. Most of the highest ground lies along or just to the west of the Moine Thrust, though there are a few high hills to the east (notably Ben Loyal, 764 m and Ben Klibreck, 961 m).

1.3.2 Climate

Futty and Towers (1982) analysed the climate of the region in some detail, and the summary given here is based largely on their description.

Average annual rainfall is shown in Figure 1.7. The bulk of this rainfall comes from the west, brought by depressions tracking eastwards across the Atlantic. It is strongly related to altitude (cf. Figure 1.5), with the high ground along the Moine Thrust region creating a rain-shadow to the east. The driest part of the year is the period April - June. Most of the region receives an annual rainfall of at least 1000 mm with only the eastern part of Caithness getting less. The higher summits in the west have annual averages in excess of 3000 mm.

Figure 1.8 shows January and July mean isotherms for the region reduced to sea level. Temperature decreases with altitude and the lapse rate of 6°C 1000 m^{-1} adopted by the Meteorological Office would suggest mean winter temperatures lower than 0°C on the high ground above 500 m, before any allowance is made for wind chill. In winter the coastal region of the west is the warmest, with the inland region to the east rather colder. During the summer months the west and north coasts are rather cooler than the east coast and inland areas, the influence of the Atlantic being the main factor in this.

The exposed nature of the terrain means windiness is an important element of the regional climate and Futty and Towers (1982) quote figures for average wind speeds in the area. These range from less than 2.6 m s^{-1} for the extreme east and valley bottoms, 2.6 - 4.4 m s^{-1} for the central plateau and 6.2 - 8 m s^{-1} for the coastlines and high ground, with values in excess of 8 m s^{-1} on the mountain peaks.

Futty and Towers (1982) also present data on accumulated temperature, i.e. the total temperature above or below a particular threshold for an average year. The thresholds quoted are days below 0°C (frost days) and days above 5.6°C, both limits of importance to plant growth. It should be noted that their limit of 5.6°C, taken as the point at which plant growth becomes significant is perhaps geared more towards the agricultural context in which they are writing, and may be a trifle high for wild plants, particularly montane species. For the frost day limit they give values of less than 20 day-degrees for the north and west coasts increasing to 50 - 110 day-degrees inland and increasing with altitude to values of 230 - 470 day-degrees on the mountain tops. For the 5.6°C threshold they present a map of climate regions (reproduced here as Figure 1.9)

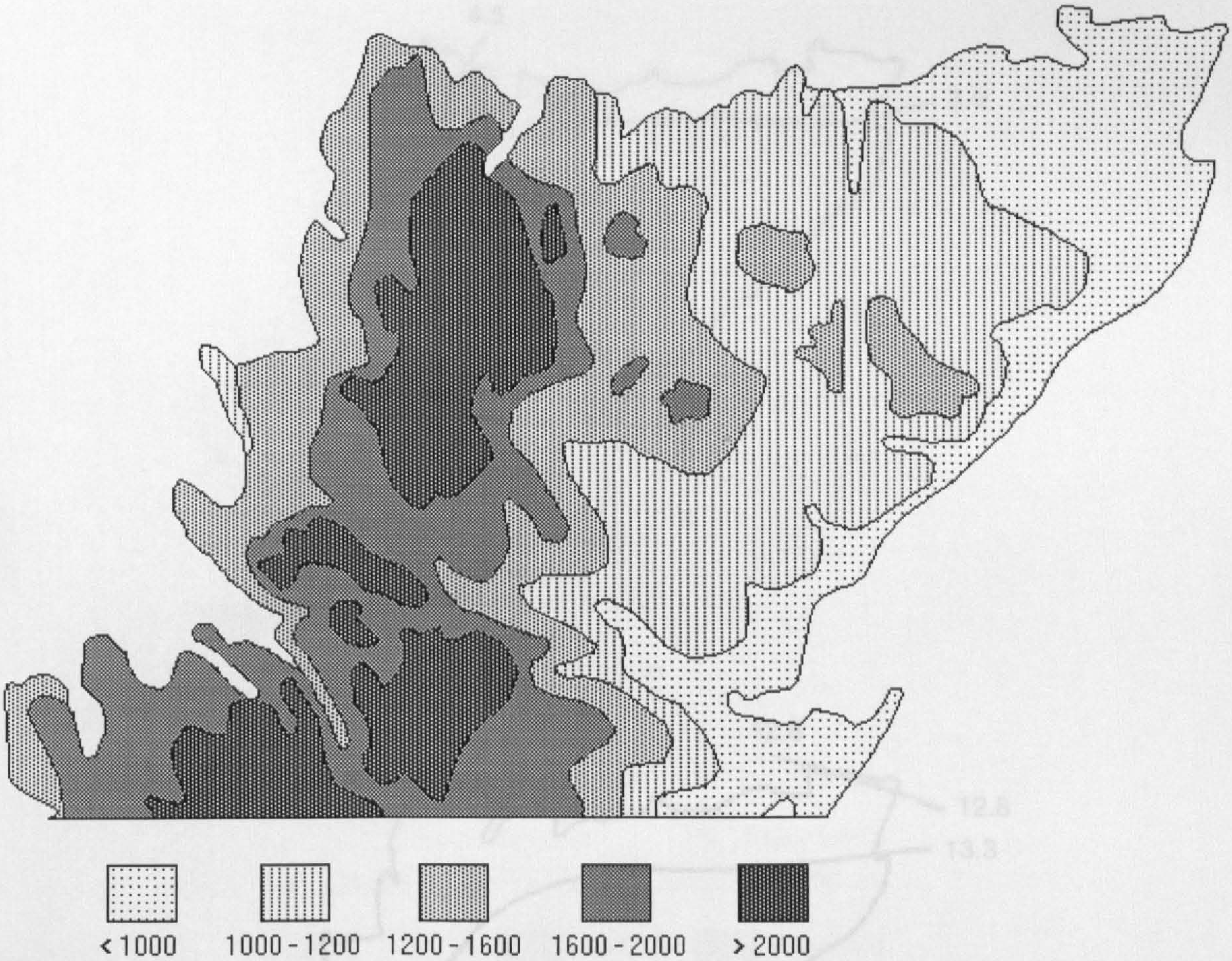


Figure 1.7. Average annual rainfall for Northern Scotland in millimetres (redrawn from Futty and Towers, 1982).

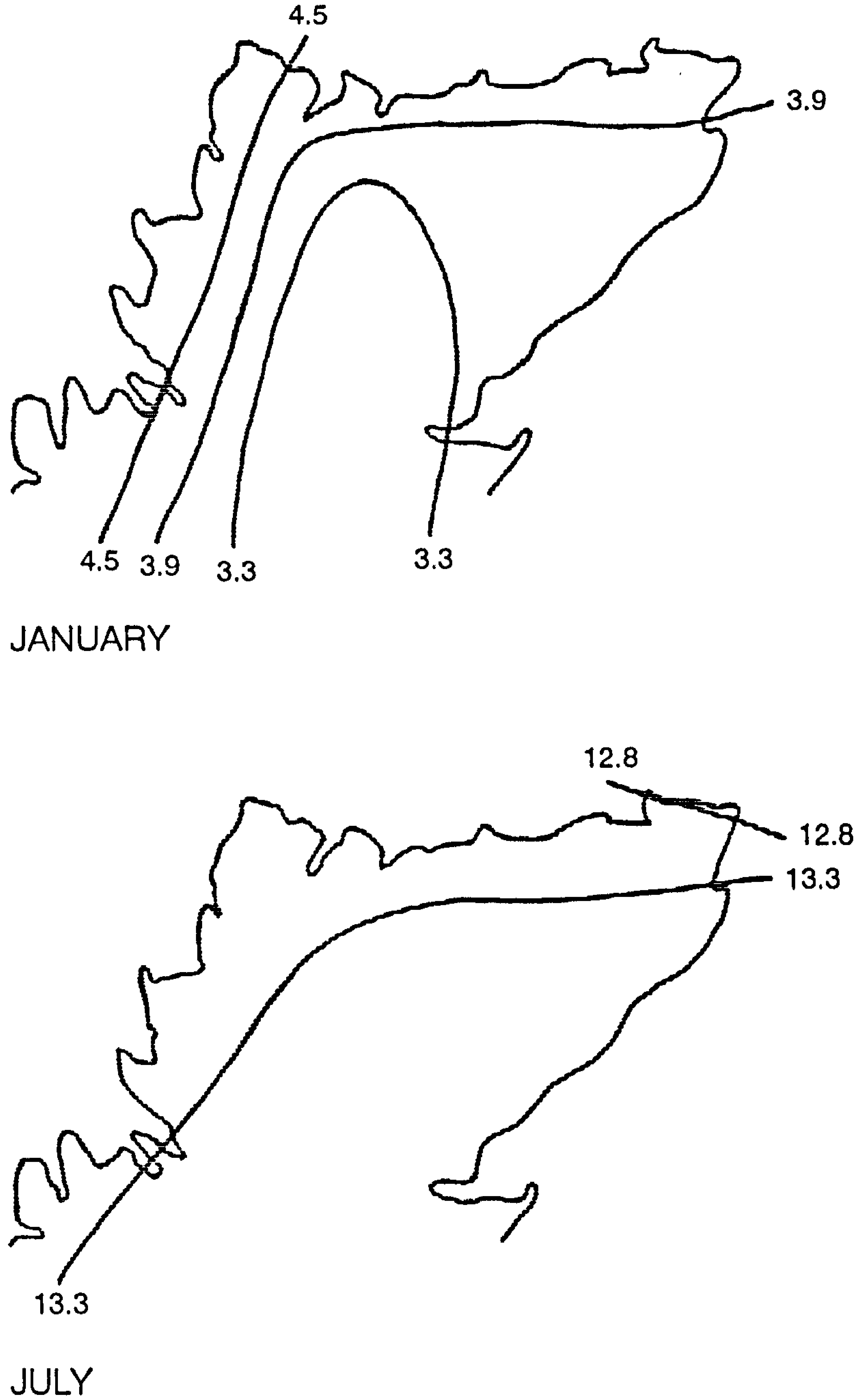
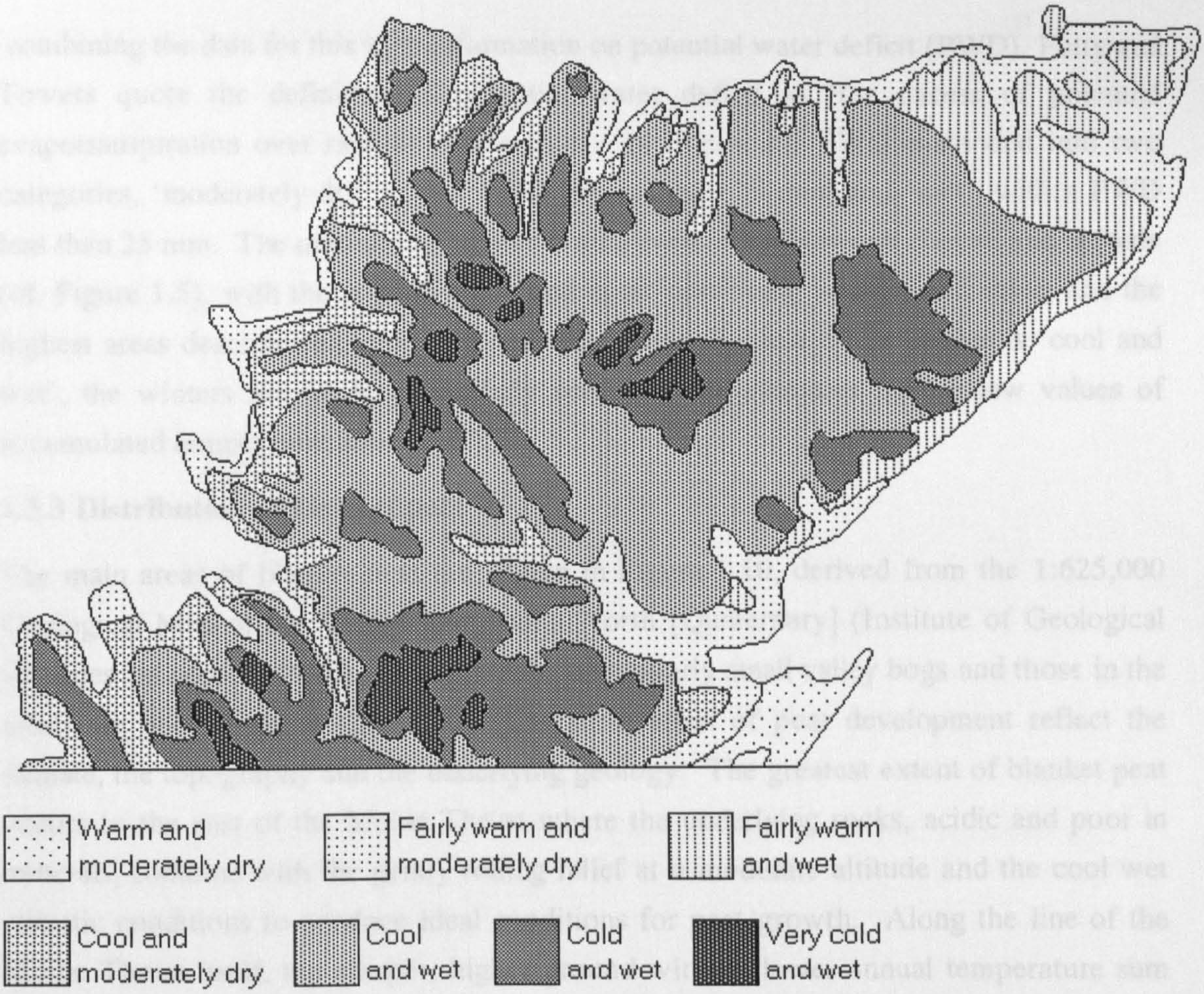


Figure 1.8. January and July isotherms (reduced to sea level) in °C. Redrawn from Fraser Darling 1947.



Accumulated Temperature Divisions		Potential Water Deficit Divisions	
RANGE (day °C)	DESCRIPTION	RANGE (mm)	DESCRIPTION
>1375	warm	>25	moderately dry
1100 - 1375	fairly warm	<25	wet
825 - 1100	cool		
550 - 825	cold		
0 - 550	very cold		

Figure 1.9. Climate regions of northern Scotland (redrawn from Futty and Towers 1982). The accumulated temperature is day-degrees above 5.6 °C.

combining the data for this with information on potential water deficit (PWD). Futty and Towers quote the definition of potential water deficit as 'the excess of potential evapotranspiration over rainfall in one year'. In Figure 1.9 PWD is divided into two categories, 'moderately dry' with a PWD greater than 25 mm, and 'wet', with a PWD less than 25 mm. The map shows again a strong correlation between climate and altitude (cf. Figure 1.5), with the coastal fringe and north east being warmer and drier, and the highest areas described as very cold and wet. Overall, most of the region is 'cool and wet', the winters not being particularly cold, but the summers having low values of accumulated temperature above 5.6°C.

1.3.3 Distribution of blanket peat

The main areas of blanket peat are shown in Figure 1.10, derived from the 1:625,000 Geological Map of the United Kingdom - North [Quaternary] (Institute of Geological Sciences 1st edition, 1977). Smaller areas, particularly small valley bogs and those in the west, are not shown at this scale. The main areas of peat development reflect the climate, the topography and the underlying geology. The greatest extent of blanket peat occurs to the east of the Moine Thrust where the underlying rocks, acidic and poor in minerals, combine with the gently rolling relief at a moderate altitude and the cool wet climatic conditions to produce ideal conditions for peat growth. Along the line of the Moine Thrust itself, the steeper, higher ground with its lower annual temperature sum and rapid drainage has a thin soil or peat cover with large areas of exposed rock on the summits of the north and west. On the west coast, particularly on the Torridonian sandstones and grits, there are small areas of blanket peat. The 'knob and lochan' terrain of the Lewisian gneisses gives rise to thin soils, peats and patches of bare rock, with occasional deeper peats in the hollows where drainage is poor. In this respect these bogs are more properly regarded as valley bogs (soligenous mires *sensu* McVean and Ratcliffe, 1962) rather than blanket bogs (ombrogenous bogs or mires *sensu* McVean and Ratcliffe, 1962) which depend upon high precipitation and low evapotranspiration (low PWD) for its formation. This has implications for the possibility of climate driven drying of bog surfaces which will be discussed later.

1.3.4 Present vegetation

The principal plant communities of northern Scotland are described in detail by McVean and Ratcliffe (1962) and in Burnett (1964). The following very brief summary is taken from these sources. On the blanket peats the vegetation is dominated by *Sphagnum* spp. in the wetter areas with *Trichophorum cespitosum* and *Eriophorum* spp. growing on the drier patches. On the driest ground there are extensive patches of heather (*Calluna vulgaris*), frequently managed for grazing or shooting by burning. Considerable drainage of the peat and planting of timber has taken place in recent years, particularly of exotic

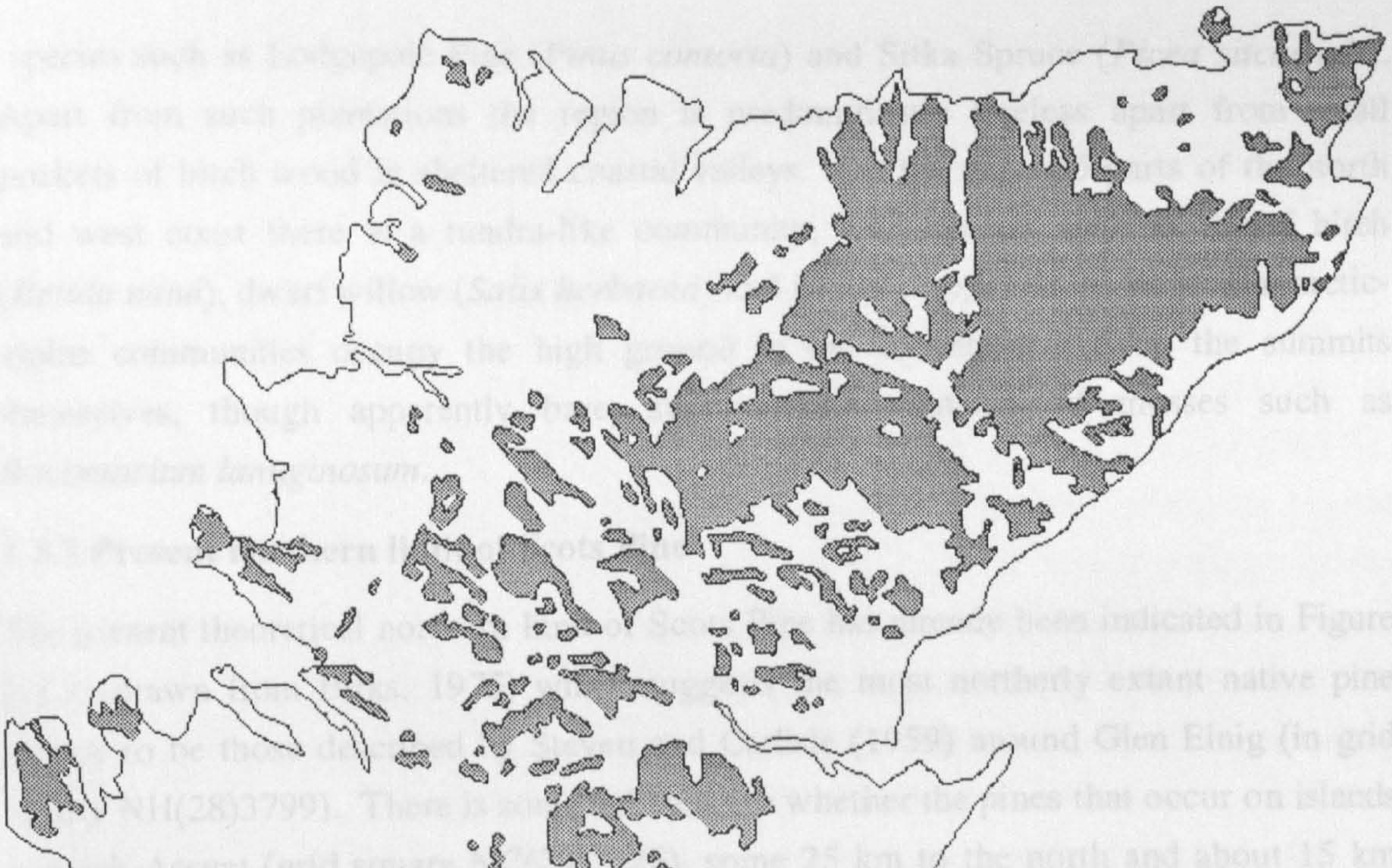


Figure 1.10. Distribution of main areas of blanket peat in northern Scotland. Redrawn and simplified from the 1:625,000 Geological Map of the United Kingdom - North [Quaternary] (IGS 1979).

species such as Lodgepole Pine (*Pinus contorta*) and Sitka Spruce (*Picea sitchensis*). Apart from such plantations the region is predominantly treeless apart from small pockets of birch wood in sheltered coastal valleys. On the exposed parts of the north and west coast there is a tundra-like community, with species such as dwarf birch (*Betula nana*), dwarf willow (*Salix herbacea*) and *Dryas octopetala*, while similar arctic-alpine communities occupy the high ground in the mountains. Even the summits themselves, though apparently bare, support small patches of mosses such as *Racomitrium lanuginosum*.

1.3.5 Present northern limit of Scots Pine

The present theoretical northern limit of Scots Pine has already been indicated in Figure 1.1 (redrawn from Birks, 1975) which suggests the most northerly extant native pine woods to be those described by Steven and Carlisle (1959) around Glen Einig (in grid square NH(28)3799). There is some debate as to whether the pines that occur on islands in Loch Assynt (grid square NC(29)2125), some 25 km to the north and about 15 km west of Glen Einig, are native (T. Clifford, Ben Eighe nature reserve, pers. comm.). However Steven and Carlisle (1959), on the basis of old parish records, suggest that they are seeded from 18th century plantation. Birks (1975) also proposed the theoretical northern limit shown in Figure 1.1. This was derived from McVean and Ratcliffe (1962) and is reproduced here in its more detailed form as Figure 1.11.

Figure 1.11. Potential present pine distribution. The shaded area represents the theoretical northern limit of *P. sylvestris*, the black areas major lochs (redrawn from McVean and Ratcliffe 1962).

McVean and Ratcliffe (1962) based their theoretical limit for pine on the known present distribution of woodland types together with their ecological requirements, on pollen analysis, subfossil remains and recorded history. They suggested that free from human interference *P. sylvestris* would spread north along the east coast as far as Berriedale and the Langwell Water, and inland north-westwards along the major valleys, Strath Oykel, Glen Cassley, by Loch Shin, Strath Brora and the Strath of Kildonan (see Figure 1.4). In two cases at least this has been born out by the present study. Firstly, about halfway up the northern side of Loch Shin, there is a plantation of Scots Pine (NC(29)506176), dating from the 19th century. This plantation is noted in Walker (1985) as 'recent woodland', i.e. not on the 1747-55 Military Survey of Scotland (the Roy maps) or the 1868-73 OS 6" First Edition. Its importance in this context is that the landowner reports that natural regeneration takes place when grazing pressure is removed. The second case is of a stand in Glen Cassley (NC(29)397136) where pine appears to be regenerating naturally on a bog surface between two groups of established trees on mineral soils. The size of the trees indicates that this regeneration may have been a single episode. In marked contrast to the trees on the mineral substrate, the trees on the bog are growing poorly.

1.3.6 Vegetation history since the last glacial

Current knowledge of the vegetation history of northern Scotland is based on relatively few studies. The majority of these are pollen and macrofossil studies of sediment cores taken from lake beds. The information from these is presented here in the form of a table (Table 1.1) derived from a review by Birks (1977) and data from two more recent studies.

From this it can be seen that a broadly similar pattern of vegetation history occurs across the region, the major differences lying in the timing, and in the occurrence of *Pinus sylvestris*. By and large the vegetation changed from open heathland and scrub at around 9000-10,000 radiocarbon years ago (years BP), through birch/hazel woodland, and then with deteriorating climate and soils (from about 4000 years BP onwards) to treeless heath and blanket bog. Pine appeared first in the south west of the region (around Loch Maree where it still persists today) about 8000 years BP and had less significance to the north and east, being virtually absent from Caithness. The appearance of alder is roughly synchronous across the region at about 6000 years BP, again being slightly earlier in the west. The final disappearance of pine is also synchronous across northern Scotland at about 4000 years BP. There is some evidence of clearance and the development of agriculture around the coast, particularly in the north and east from about 5000 years BP onwards.

Radiocarbon years BP	Wester Ross (Birks 1972, Durno McVean 1959, Pennington *et al.* 1972)	SW Sutherland (Moar 1969, H.H. Birks unpub.)	NW Sutherland (H.H. Birks unpub.)	Central Northern Scotland (Gear 1989)	Caithness (Peglar 1979)
1000				↑	
		Deforestation			
2000	↑			Blanket bog and grassland increasing	
3000	Expansion of blanket bog			*Betula* declines *Calluna, Graminae* increasing	Clearance and evidence of farming
4000	Rapid decline in *Pinus*	Rapid decline in *Pinus*		Small *Pinus* peak *Betula*/*Corylus* pollen increasing	*Plantago* increasing
5000		*Pinus* expanding locally	Deforestation, evidence of farming ?	Low *Pinus* values Rise in *Alnus*	*Ulmus* decline
6000			*Alnus* rise		
	Alnus frequent	*Alnus* expansion		*Betula, Corylus* dominant	
7000	Slow decline in *Pinus* begins				*Pinus* maximum *Betula* and *Pinus* increasing
8000	*Pinus* replacing *Betula* on drier and poorer soils	Small *Pinus* rise long distance pollen ?		*Juniperus* declining	Patchy woodland
9000	*Betula, Corylus* *Salix. Ulmus* and *Quercus* rare	Rise in *Corylus*, herb pollen *Betula* replaces *Juniperus* scrub	*Betula, Corylus* replacing *Juniperus*	*Juniperus* scrub, treeless heath	*Calluna* peak *Betula, Corylus* expansion
10,000					
	Juniperus scrub				

Table 1.1. Vegetation history of northern Scotland reconstructed from pollen analysis of lake sediments across the region (based on information from Birks 1977, Peglar 1979 and Gear 1989).

1.3.7 Distribution of subfossil pine

Despite the scarcity of pine in the pollen record in northern Scotland, there is very clear evidence from the distribution of subfossil remains that it had once reached all of the region apart from the mountain tops and the extreme north-east. Various possible explanations of this have been quoted earlier in this chapter, but the clustering of all the dated material around 4000 years BP suggests a single, fairly rapid phase of expansion of Scots pine onto the blanket peat which now preserves its remains. This is supported by a high resolution pollen study (Gear, 1989: Gear and Huntley, 1991) which shows a narrow peak of pine pollen previously missed in the region. Earlier mapping of the distribution of subfossil pine has been described already, but the most up to date 10 km map is shown in Figure 1.12.

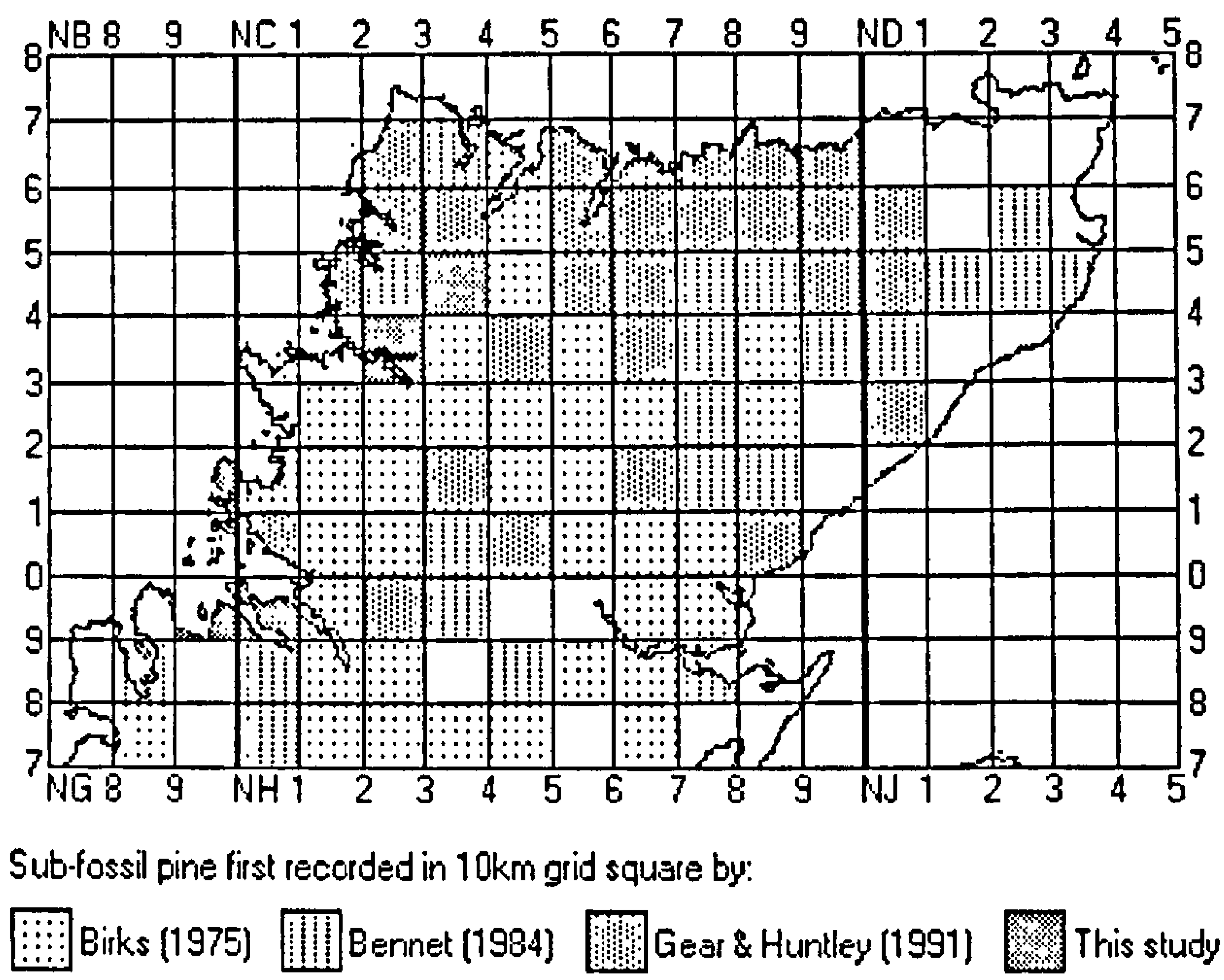


Figure 1.12. The known distribution (10 km grid squares) of subfossil *Pinus sylvestris* in northern Scotland at the time of writing. This includes locations found during the present study.

Both the extent and timing of this expansion suggests a climatic cause, a brief spell of drier, more continental conditions within the context of a climate steadily deteriorating over a longer time span.

1.4 Objectives of the present study

Against the background outlined in this chapter, the present study set out to investigate in more detail the spread of *Pinus sylvestris* L. on to the blanket peats of north west Scotland, both in terms of origin and timing. An attempt was also made to reconstruct the ecology, population dynamics and structure of these subfossil woodlands. The primary technique used to attain these objectives was the collection of dendrochronological data from groups of subfossil stumps from sites across the western half (Sutherland and Wester Ross) of the study area. These data were used in conjunction with the data gathered in Gear's (1989) and Daniell's (1992) study from the central part of the region to analyse the timing and direction of the spread of the pines onto the blanket peat, as well as for examination of the individual sites.

As a supplement to the dendrochronology, pollen analysis of peat from selected sites was used to identify the pine pollen peaks corresponding to the period that pine was occupying these sites, and to locate any tephra layers that might serve as chronological markers. This was done to confirm the timing of the pine occupation of the peat and to examine the rôle of volcanic activity in its demise. Changes in vegetation on the peat surface around the time of the pine occupation were also assessed.

During the process of locating suitable sampling sites, a general survey was made of the western half of the region and those 10 km grid squares in which subfossil pine had not previously been recorded checked for its presence (see Figure 1.12).

Chapter 2 - FIELD AND LABORATORY METHODS

This chapter describes the methods used in conducting this study, together with the theoretical background of these where appropriate. It covers the identification and selection of the different sampling sites, the selection, collection, processing and ^{14}C dating of the dendrochronological samples, and the collection of material for pollen and tephra analysis. It also includes a discussion of the statistical principles employed in the analyses and crossmatching of the tree-ring sequences obtained. All computer programs used in the processing of the data are listed together with their functions in Appendix 1.

2.1 Survey of region

Areas accessible by road in the region bounded roughly by a line from Strathy Point (Nat. Grid Ref. NC(29)828698) to Loch Glascarnoch (Nat. Grid Ref. NH(28)310730) were searched by vehicle for subfossil pine sites suitable for sampling. Amongst these were included locations described by previous workers and various sites identified by locals. As well as the search for sampling sites, the presence of subfossil pine was established in Grid Square NC(29)34 by exploring on foot from Loch Eriboll in the north and Loch Stack to the south east. The area of 'knob and lochan' country to the east of Clachtoll (Nat. Grid Ref. NC(29)043275) was also searched on foot, together with the peninsula culminating in the Point of Stoer (NC(29)022356). Various stretches of peatland around Loch Shin were also covered in this way.

2.2 Site selection criteria

2.2.1 Geographical location

The first criterion in the selection of potential sites was their geographical location. In order to assess the rate and direction of pine spread across the region, sites were required in the area from the west coast east to Strathnaver, and from around Ullapool in the south to the north coast. Thus an area overlapping the present northern limit of *P. sylvestris* in the south (see Figure 1.1) and including all the recorded 10 km grid squares with subfossil pine to the north coast and east as far as Strathnaver would be covered. Data from groups of stumps at two sites, Lochstrathy (Gear, 1989: Gear and Huntley, 1991) and Badanloch (Daniell, 1992), were already available. These two sites marked the eastern limit of the study area (see Chapter 3, Figure 3.1). A range of altitudes would have been desirable, but in the end this was governed by the availability of suitable sites in any particular location, rather than any overriding strategy.

2.2.2 Accessibility/exposure

It was important that any site selected for sampling should be reasonably accessible in order to be able to get cutting and digging equipment on to it easily and to be able to transport a considerable weight of samples away from it. This usually meant that sites had to be within a few hundred yards of a road or track, though in one case access by boat was the easiest method. The stumps themselves also had to be reasonably well exposed, with at least twenty visible, for a potential site to be recognised, let alone be worth exploiting. These considerations led to two types of site being selected. The first of these were waterside sites, such as reservoirs, where recent changes in water level had eroded the peat cover of the preserved stumps, revealing them on the shore in their original positions of growth. The second were various forms of excavation, usually peat cuttings but including banks on roadsides, ditches and forestry tracks, and also streams and rivers where there were eroded peat banks. For any attempt at reconstruction of the palaeo-woodland the first type of site was the most suitable, as it was much more likely that any sampling would include most if not all the trees present within the bounds of the chosen area. The problem with the second type of site was that it was difficult to be sure of locating every stump in a given area without very extensive excavation, thus any estimates of density etc. would be less certain.

2.2.3 Quality of samples

Finally it was important to consider the overall quality of the preserved remains. Firstly they had to have at least a short portion of trunk remaining above the root system. Without this it was extremely difficult to obtain samples with ring patterns sufficiently undistorted for crossmatching. Secondly the bulk of stumps on the site had to be reasonably undecayed. This was usually the case where the stumps had been exposed in relatively recent years, or had remained fairly wet. However, on exposure to air, the processes of decay halted by their original burial in peat recommenced, and in the older exposures many stumps were extremely rotten and impossible to sample.

2.2.4 Sites selected

On the basis of the above criteria three main sites were chosen where a large number of stumps were sampled and mapped. At two of these a peat monolith was cut for pollen and tephra analysis. In addition a number of other sites were chosen where a smaller number of samples were collected; at one of these a monolith was cut. Details of all these sites appear in Chapter 3 - Results; their locations are shown in Figures 3.1 and 3.2.

2.3 Dendrochronological samples - Collection and Measurement

2.3.1 General measurements and sample selection

At the main sites a simple plan was drawn to record the relative positions of the subfossil stumps. This was done by measured triangulation or a simple 'chain and tape' technique, one tape being used for the line of survey (the chain), the other to measure the offsets. The data were converted to Cartesian co-ordinates and the plans drawn from these using a commercial CAD program, DANCAD3D v. 2.5. These plans were used to calculate stump density at the different sites. In one case (Loch Vatachan) no plan was drawn but the subfossil stumps in a known area were counted.

In terms of sample selection, the object was to get as complete an impression of the subfossil woodland as possible within a small area of each study site. To this end as many as was feasible of the stumps present were sampled. Only those where cutting would have been impossible were rejected, the reason being usually that the stump had decayed too far, either with only the roots remaining, or having broken into a series of concentric 'shells' of harder wood. Even so great variability was found in the preservation of the stumps sampled, some disintegrating on cutting, others yielding solid wood which still smelt perceptibly of pine. Sections were cut from even the most unpromising looking stumps as it proved difficult to judge the quality and ring span until the samples had been further prepared in the laboratory.

2.3.2 Cutting

The sampling was done using a Stihl Woodboss 024 chainsaw with a 16 inch bar and a chisel chain, biodegradable chain oil being used to reduce any contamination of the environment. To improve the ease of horizontal cutting, particularly of markedly conical stumps, the saw was modified by the addition of an extra bumper spike on the outside of the bar.

The cutting was done as high as possible into the remains of the trunk to minimise the effects of root buttress distortion on the ring patterns. Ideally two cuts were made, producing a section of the tree between 2 and 4 cm thick. Where this was not possible because of the fragility of the stump, one cut was made on site to separate the sample, a second being made later with a bandsaw prior to polishing. The samples were wrapped in polythene to prevent drying, labelled and returned to Durham where they were stored at 4°C to inhibit decay until needed.

2.3.3 Identification

For the most part it was apparent from the morphological characteristics and location of the stumps that they were *Pinus sylvestris*. Their overall appearance is quite typical as are details such as the flattening in a vertical plane of the main roots. The only other remains found were those of birch and alder which are clearly very different (see Plate 12). The stumps were of trees that had been growing on the peat surface and had been buried after death by subsequent peat development, and thus were of great antiquity.

The field identification was clearly confirmed in the sampled stumps by the appearance of the cross-sections after polishing, where the characteristic cell structure and ring boundaries of pine were visible, along with the resin canals frequent in this genus. However, by way of confirmation, transverse, radial and tangential sections were prepared in one case and identified using a computer key based on Phillips (1948), modified by Wheeler *et al.* (1986). The characters distinguished in the subfossil samples (see Appendix 2) yielded three possible identifications, *Pinus sylvestris*, *P. nigra* and *P. resinosa*. Neither of the last two are native to Britain, both being introduced in the 1750s (Mitchell, 1978), far too late to be preserved in the manner of the collected samples. This supported the identification as *P. sylvestris*, the only species of its genus known to be native to the British Isles in this interglacial (Carlisle and Brown, 1968).

2.3.4 Sample Processing

Before the samples could be polished they first had to be dried. In the absence of any purpose-built facility this was achieved by unwrapping the samples and allowing them to dry naturally, first for about a week in an outside store where the humidity was fairly high, then for a further week in a normally heated room with mechanical ventilation. This process resulted in some splitting of the wood but did not impair the quality of the samples for finishing and subsequent ring measurement.

When the samples were sufficiently dry one surface was polished. This method of revealing the ring structure was favoured over the alternative of cutting a track with a sharp blade sometimes used, because of the need to see the entire section of the tree to identify areas of distortion and locate any missing rings (Schweingruber, 1988: Pilcher, 1990). The polishing was done by using progressively finer sanding disks (36 - 400 grit) on a Bosch PEX 125AE orbital sander, continuing until the cell structure of the wood was visible, with a final finish being given with a lambswool bonnet. No polishing compounds were used as it was intended to use some of the samples for ^{14}C dating.

2.3.5 Measurement of ring-widths

Before measurement each sample was examined for areas of damage or distortion and if these were too serious the sample was discarded at this point. Samples were also rejected if there appeared to be too few rings (less than 30) to be worth measuring. Cracks in the samples were checked for charcoal. The little charcoal found was associated with radial splits, with no ring distortion or scarring, and therefore was assumed to be the result of damage after the tree's death rather than from fire during its life.

Three radii for measurement were then marked on the selected samples. This was done in pencil, the three directions being chosen to pass through areas of least distortion or damage in the ring patterns. Particular attention was also paid to zones where very narrow rings occurred, and to ensure as far as possible correct counting and measurement of these the following procedure was adopted. A prominent ring just before and just after the narrow ring sequence was selected, traced round the sample, and marked where it intersected each of the marked radii. This was done for all narrow sequences, areas of damage, and also at regular intervals throughout each radius, thus providing a check for miscounting, discontinuous or false rings. In point of fact only one example of the last category was found, whereas at the sites sampled, where the trees were growing under stress, discontinuous rings indicating a poor growing season in that particular year were very common.

The ring-widths were then measured from the centre of the sample along each of the three radii. To do this the sample was placed on a travelling stage and moved past a fixed stereo microscope head (a Russian OGM3-P2). This was equipped with a graticule in one eyepiece, which at the usual working magnification ($\times 56$) provided a scale of 14 microns (μ) per division, permitting measurement to $\pm 7\,\mu$. Occasionally when a sample with consistently wider rings was found a lower magnification was used for measurement ($\times 32$, thus measuring to $\pm 12.5\,\mu$). The graticule eyepiece could be rotated to ensure all measurements were normal to the ring boundaries.

Where a ring was missing from one radius, an estimated value, based upon the width of the ring in the other radii relative to its adjacent rings, was inserted at that point. For example, if the i th ring ${}_a w_i$ was missing in radius a but not in radius b or c then it would be estimated from its values in b and c as follows:

$$_{a(est)}w_i = \frac{{}_b w_i\left(\dfrac{{}_a w_{i+1}}{{}_b w_{i+1}} + \dfrac{{}_a w_{i-1}}{{}_b w_{i-1}}\right) + {}_c w_i\left(\dfrac{{}_a w_{i+1}}{{}_c w_{i+1}} + \dfrac{{}_a w_{i-1}}{{}_c w_{i-1}}\right)}{4} \qquad (1)$$

where: ${}_{a(est)}w_i$ = the estimated value of the missing i th ring in radius a

and ${}_{b}w_i, {}_{c}w_i$ = the corresponding i th values in radii b and c

Although such a value clearly did not represent the actual growth of the tree in that particular radius it was more advantageous from the computational point of view than inserting a zero or missing value code.

The individual ring-widths in eyepiece graticule units were recorded by hand on sample sheets. These data were then entered into computer files and converted to integer values in microns for use in subsequent processing.

2.3.6 Comparison of radii.

The next stage was to plot the ring-widths from each of the radii as separate curves and compare them with each other, both as a further check for discontinuous rings, and to ensure that they corresponded sufficiently well to be used to construct a valid mean radius. This was done on a purely visual basis, as both long term and short term features of the curves were relevant, and it was immediately clear if the patterns of the three radii were appreciably different (Figure 2.1). In cases where this was so the sample was rejected, or where the cause (knots, scarring etc. unavoidable in measurement) was apparent from inspection of the sample, only two radii were averaged.

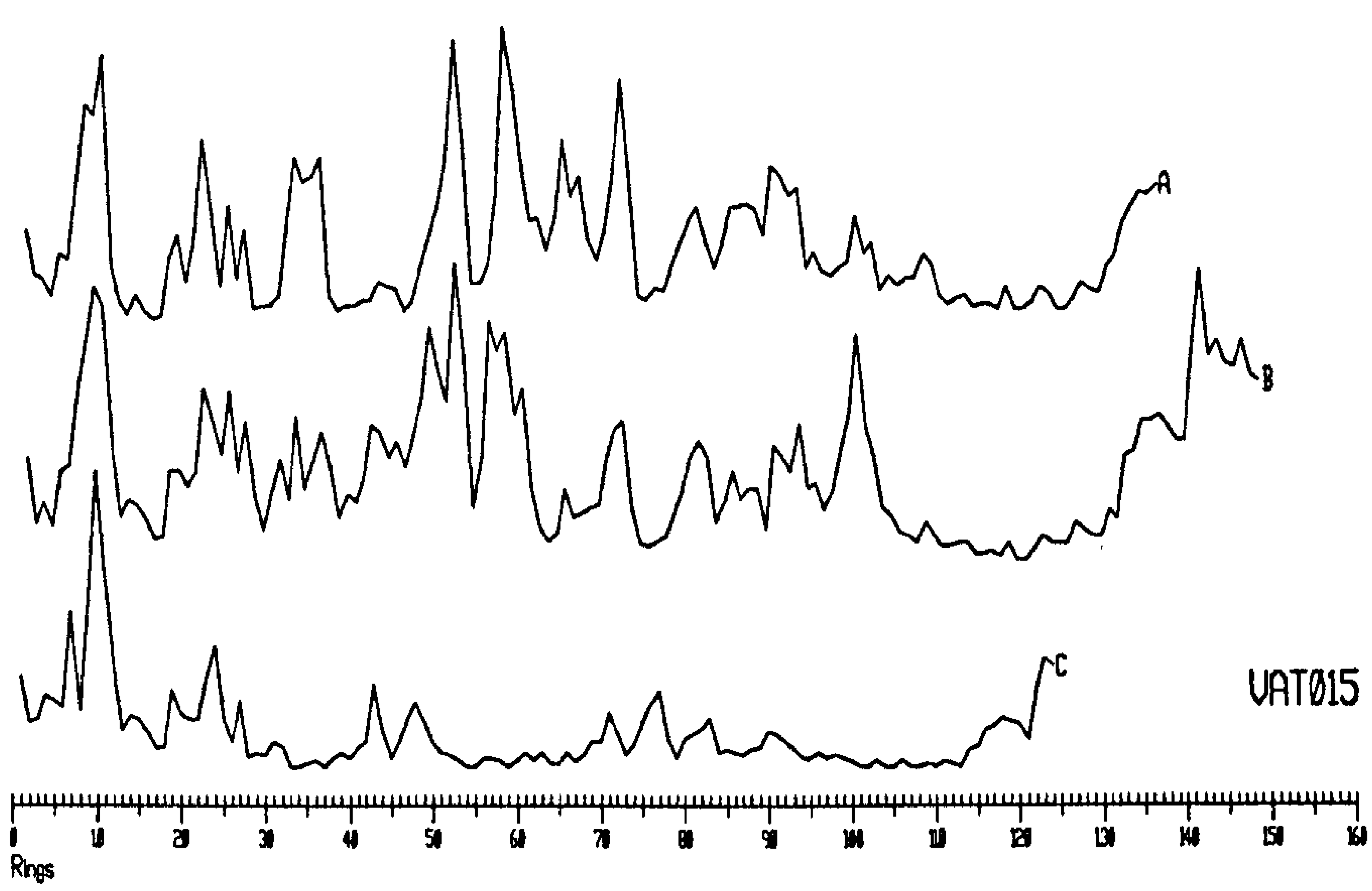


Figure 2.1. Three radii from VAT015 plotted in raw values. Radius C was rejected.

Because of the large number of samples involved, rather than plotting these curves on squared paper and inspecting them on a light box, a computer program, TREERING (see Apppendix 1), was written which permits comparisons between the curves to be made on a video screen, with the facility to 'slide' them past each other for comparison at different overlaps. This program, as well as allowing the display of the radii as raw ring-width values, also plots them as standardised values. These latter are a set of values expressed in standard deviation units and with a mean of zero for each radius, the overall shape of the curve being unchanged. This makes visual crossmatching easier in that the variations in different curves are presented on the same scale. The standardised values were calculated within TREERING using the following expression:

$$ {}_r w_s = \frac{({}_r w - {}_r \overline{w})}{SD_r w} \tag{2} $$

where: ${}_r w$ is the measured width of an individual ring for radius r

${}_r \overline{w}$ is the mean width for rings along radius r

$SD_r w$ is the standard deviation of ring-widths along radius r

and ${}_r w_s$ is the standardised width of the individual ring for radius r

It should be noted that this is not the 'standardisation' usually referred to by dendrochronologists, who use the term to describe the removal of long-term growth trends from ring-width sequences to create tree-ring indices. In the present study the process described in Equation 2 above will be referred to as 'simple standardisation'.

2.3.7 Calculation of a Mean Radius for each sample.

Next a mean ring-width sequence for each tree was calculated using only those samples or radii not rejected in the previous stage. As radii sometimes differed markedly in mean ring-width, and frequently extended over different numbers of rings, a simple arithmetic mean of the widths of corresponding rings on the individual radii was considered inappropriate. In particular different radius lengths could lead to 'steps' occurring in a series of values computed as an arithmetic mean when a radius dropped out of the calculation. In order to overcome these problems a 'robust' mean of the simple standardised ring-widths was calculated. This then was transformed back into measurement units by inverting the simple standardisation. The calculation was done (using the program TREEMEAN - see Appendix 1) as follows:

$$ {}_t w = ({}_r \overline{w}_s . SD_t w) + {}_t \overline{w} \tag{3} $$

where: ${}_t w$ is the width of an individual ring averaged for the tree

${}_r \overline{w}_s$ is the mean simple standardised width of that ring in the several radii, and is computed as:

$$ {}_r\overline{w}_s = \frac{\sum_{r=1,n} ({}_r w_s)}{n} \tag{4} $$

where: n is the number of radii in which the ring is represented

${}_r w_s$ is the simple standardised width of the ring in radius r (see Equation (2))

$SD_t w$ is the weighted mean standard deviation of ring-widths for the tree and is computed as:

$$ SD_t w = \frac{\sum_{r=1,n} (SD_r w \cdot {}_r N)}{\sum_{r=1,n} ({}_r N)} \tag{5} $$

where: ${}_r N$ is the number of rings measured for radius r

and ${}_t\overline{w}$ is the mean width of all rings measured for the tree.

These 'robust' mean sequences for each tree were used in all subsequent comparisons.

2.3.8 Statistics for individual trees

Finally, various statistics were calculated and listed for each of these mean sequences using a computer program TREESTAT (see Appendix 1) written for the purpose. These statistics were as follows: ring total (i.e. number of rings), ring sum (equivalent to length of radius), mean, standard deviation, average mean sensitivity and 1st-order autocorrelation.

The first four are straightforward but the last two require further explanation. The average mean sensitivity is an indication of the degree of change on a year-to-year basis in the ring-widths of a particular series (Fritts 1976: Schweingruber 1988). It is calculated as follows :

$$ {}_t\overline{ms} = \frac{1}{{}_t N - 1} \sum_{i=1,{}_t N-1} \left| \frac{2({}_t w_{i-1} - {}_t w_i)}{{}_t w_{i+1} + {}_t w_i} \right| \tag{6} $$

where: ${}_t\overline{ms}$ = average mean sensitivity

${}_t w_i$ = ring-width of the i th ring

and ${}_t N$ = number of rings in the sequence

The values of ${}_t\overline{ms}$ lie between 0 if the series is complacent (i.e. all the ring-widths are the same) and 2 if the ring series is extremely sensitive (this maximum value occurs if a zero value is next to a non-zero one, clearly not attained in a tree-ring sequence).

The 1st-order autocorrelation of a tree-ring series is an indication of the non-randomness of a series, showing the degree of dependence of each term upon its predecessor (Fritts, 1976). It is calculated in TREESTAT as follows:

$$_{t}ar_{1} = \frac{\sum_{i=1,_{t}N-1}\left(_{t}w_{i+1} - _{t}\overline{w}\right)\left(_{t}w_{i} - _{t}\overline{w}\right)}{\left(_{t}N - 1\right)\sum_{i=1,_{t}N}\left(_{t}w_{i} - _{t}\overline{w}\right)^{2}} \tag{7}$$

where: $_{t}ar_{1}$ = 1st-order autocorrelation

and other symbols are as for equations (5) and (6).

As might be expected 1st-order autocorrelation is usually high in tree-ring series where early season growth depends at least in part on reserves from the previous year for example oak (Shiyatov *et al.*, 1990).

2.4 Dendrochronological Samples - Crossmatching

2.4.1 Theoretical Considerations - De-trending

In order to correctly crossmatch two sequences of tree-rings some signal has to be found common to the two sequences in question. Signal in this study is defined as information relevant to the task in hand, 'noise' is used of all other information (Briffa *et al.*, 1987). The common signal must clearly be generated by a simultaneous influence on the trees from which the ring sequences are drawn, and must therefore be external to them, acting on either a stand-wide or regional basis, and on a short-term year-by-year time scale. In order to use this information to maximum effect it must be separated from the noise in the series, especially that due to growth trends within each tree itself.

More formally, Cook (1990) summarises this as follows. He describes the tree-ring series (a time series) as a sum of several subseries:

$$R_t = A_t + C_t + \delta\, D1_t + \delta\, D2_t + E_t \tag{8}$$

where:

R_t = the observed ring-width series.

A_t = the tendency for ring-width to decrease with increasing girth and other growth related trends.

C_t = the climatically related environmental signal common to all trees in a stand caused by changes in moisture, temperature and other environmental variables.

$D1_t$ = a disturbance pulse affecting the individual tree, the δ indicating that this is not always present.

$D2_t$ = a disturbance pulse affecting the stand, the δ indicating that this is not always present.

E_t = other year-to-year variability not related to the other signals.

Clearly from Cook's definition, the environmental signal C_t is going to be the one of prime importance for crossmatching, though one-off stand-wide events ($\delta D2_t$) will be significant in within-stand matches. Cook describes C_t as incorporating 'all climatically related environmental variables except for those associated with stand disturbances', giving amongst others precipitation and temperature as examples of these variables. He assumes all these variables to be broad scale, affecting all the trees in a stand. A large part of C_t will be in the form of year by year, i.e. high frequency, variation and to extract this the tree-ring series may be detrended, a process described below.

A tree-ring series may be divided into different components on the basis of frequency, detrending being used for the removal of long-term cyclical information, leaving the high frequency, year by year signal. This, as described above is assumed to be largely the environmental signal C_t and is used for crossmatching. Use of this high frequency signal is essential in any form of crossmatching based on comparison of absolute values rather than trends (see Theoretical Considerations - Crossmatching below) as any long term trend will add a component to the value which might mask year-by-year changes. Detrending also has the effect of stabilising the variance in a tree-ring series, the variance in a raw sequence being positively correlated to the mean ring-width in that section of the sequence.

In practice methods of detrending can be divided into two broad classes described as 'deterministic' or 'stochastic' by Cook *et al.* (1990) who review the advantages and disadvantages of both approaches.

Deterministic methods consist fundamentally of fitting a curve to the long term trend in the series and expressing the individual ring-widths as a departure from this. Expressed mathematically:

$$I_t = \frac{R_t}{G_t} \qquad (9)$$

where: I_t = the de-trended tree-ring index

R_t = the observed ring-width (see equation 8 above)

and G_t = the 'expected' ring-width from the fitted curve.

(Cook *et al.* 1990)

These curves may be fitted visually, either by flexible ruler, or using more sophisticated methods such as the 'corridor' method described by Shiyatov and Mazepa (1987). More recently various forms of computer fitted curve have been used. One group of these employs exponential functions based on the geometric nature of the growth trend, reflecting the decrease in ring-width as the girth of the tree increases (Fritts 1976). This works well for relatively undisturbed trees, but does not take account of any sudden increase or decline in growth brought about by external events in the tree's environment. One way of overcoming this is by the fitting of a polynomial curve (in effect a mathematical flexible ruler) to the sequence (Fritts 1976: Graybill *et al.* 1982), a technique embodied in the widely used INDEX and SUMAC computer programs of the Laboratory of Tree-Ring Research, Arizona (Graybill 1979). Clearly this is somewhat arbitrary, especially as functions of progressively higher orders are used. Warren (1980) tried to combine the advantages of both methods by fitting a series of exponential functions to different sections of the ring-width curve. This seemed to work quite well compared with fitting a single exponential function, particularly where stands of trees had been disturbed by thinning etc. However, taken overall the results did not seem to justify the additional mathematical complexity involved (Warren and MacWilliam 1981).

Deterministic methods can work well where the mechanisms producing the long-term trends are apparent, but their inability to deal with random perturbations lasting longer than a few years frequently found in tree-ring series (Cook *et al.* 1990) has led to the investigation of more data-dependent, stochastic approaches.

One of the most widely used of these is the symmetrical digital filter, which can be used to extract groups of frequencies from the series. A low-pass filter, as its name suggests passes lower frequencies and suppresses higher ones, and a high-pass filter *vice versa.* The precise cut-off point is determined by the nature of the filter and selected for the purpose in hand. For crossmatching a high-pass filter with a cut-off at around 10 years (to suppress sun-spot driven cycles for example) is frequently applied to the logarithms of the original series (Fritts, 1976: Munro, 1984). The general form of such a filter is:

$$ {}_fR_i = \sum_{k=-m,0,+m} s_k R_{i+k} \qquad (10)$$

where: $\quad {}_fR_i$ = the transformed value from the i th ring-width.

R_i = the log of the i th ring-width.

and $\quad s_{-m}...0...s_m$ = the weights of the filter with $s_j = s_{-j}$

Such a filter has the disadvantage that a number of values (m) are lost from the beginning and end of the filtered series, but in most tree-ring sequences this represents a negligibly small proportion of the total number of rings.

Theoretically a one-sided, non-symmetrical filter would better reflect the nature of a tree-ring series, allowing previous but not subsequent values to generate each successive term. The fitting of autoregressive-moving average (ARMA) models to the individual tree-ring series is one way of achieving this. Guiot (1987, 1991) describes the operation in detail. Where the order of the components is low, i.e. reflecting only the influence of recent past ring-width values (2 to 3 years at most) ARMA models are a good reflection of biological processes. However higher orders of such a model become at best an individually tailored high-pass filter. The method was tested on some of the tree-ring series in the present study, but appeared to show no great advantages over the three methods finally adopted.

These methods were two symmetrical digital filters, Fritts' (1976) 13-term 8 year cut-off high-pass filtered log widths and Munro's (1984) 23-term 10 year cut-off high-pass filtered log widths, plus Baillie and Pilcher's (1973) 5 point filtered normalised values based on a 5 year rolling mean. The weight values for Fritts' and Munro's high-pass filters are given in the references cited and in Appendix 3.

The Baillie and Pilcher values are calculated by taking a 5 year rolling mean throughout the ring sequence and expressing each ring as a percentage of the mean of the 5 rings of which it is the centre. The Baillie and Pilcher values are taken as the natural log of these percentages (to approximately normalise the data). This is expressed mathematically below:

$$ {}_fR_i = \log_e \left\{ \frac{{}_tw_i}{\frac{1}{5} \sum_{k=-2,0,+2} {}_tw_{i+k}} \times 100 \right\} \tag{11} $$

where: $\quad {}_tw_i$ = the i th ring-width

and $\quad {}_fR_i$ = the transformed value from the i th ring-width

Clearly 2 values are lost at the beginning and end of the sequence. This is effectively a high-pass filter producing a cut-off at about 6 years, but tending to emphasise cycles with 2.5 to 5 year periods (Munro 1984). Figure 2.2 shows a raw ring-width sequence and the corresponding values for each of the 3 filters.

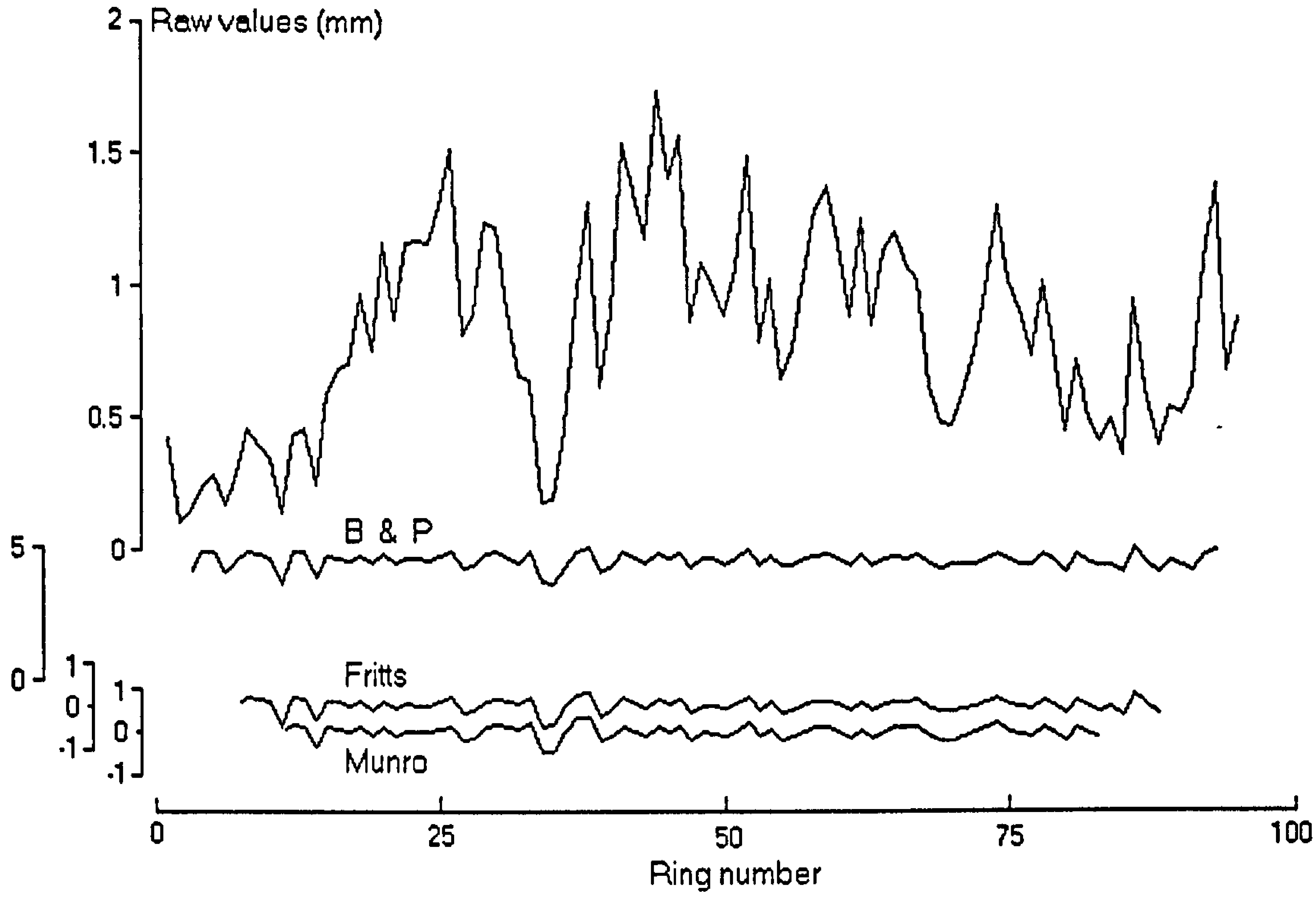


Figure 2.2. BAD157 showing raw values and the effects of the three filters used.

2.4.2 Theoretical Considerations - Crossmatching

For a crossmatch between two tree-ring sequences to be acceptable there has to be not only a good visual correspondence between the sequences, but a statistically significant one as well. In terms of the former the eye notes overall shape and pattern, and also prominent features such as particularly wide or narrow rings and their spacing. Early American dendrochronologists exploited these in their use of skeleton plots in which they recorded on graph paper any markedly narrow rings in the ring sequences, allowing the synchronisation of groups of these rings and hence the crossmatching of the sequences (Schweingruber, 1988). Skeleton plotting can be computerised, and the program TREERING, referred to above, provides this option based on the method proposed by Cropper (1979). However, though skeleton plotting has the advantage of effectively de-trending the sequences (i.e. removing long-term growth trends), in this study there were so many narrow rings in the tree-ring series that it was of little help in crossmatching. The frequency of these narrow rings was almost certainly due to the stress under which the trees were growing near the northern limit of their distribution, and in the end a clearer picture was gained by plotting curves for crossmatching. The use of simple standardisation in plotting these curves aided this by displaying the two sequences for matching on similar scales of amplitude (see section 2.3.6 above).

The assessment of the statistical quality of crossmatches is rather more complicated. Broadly speaking, there have been two approaches to this. The first of these is based on the degree of agreement in increase or decrease from point to point of the plots of the sequences being compared. For this, European dendrochronologists have used a statistical indication of percentage agreement in trend called Gleichläufigkeit (Schweingruber, 1988) which provides a numerical indication of similarity, but takes no account of ring-width values, either in absolute magnitude or in terms of the standard deviation (SD) of the sequence. Thus high values for Gleichläufigkeit can occur in many cases where the series are not correctly crossmatched.

The second option is to examine the correlation between the corresponding pairs of ring-width values at each position where the sequences overlap and assess the statistical quality of this correlation, calculating the probability of it arising by chance. This is usually done by first calculating the correlation coefficient (Pearson's r) between the two sets of ring-width sequences for all overlapped positions. There are then various ways of assessing the significance of this. In the original Belfast tree-ring crossmatching program CROS (Baillie and Pilcher, 1973) the raw ring-width series were first filtered using the Baillie and Pilcher filter described above (Equation 11). The correlation coefficient r was then calculated for each overlap position and Student's t derived from it. The program took the highest value of t as the best match position (empirically values greater than 3.5 (Baillie 1982) were taken as significant) and the probability level of the match arising by chance could then be derived from tables. This was found to be more satisfactory than the calculation of percentage agreement (Gleichläufigkeit) described above, both in isolation of the best match position and in assessment of confidence limits. However, as Orton (1983) and Munro (1984) pointed out, a single value of t, or its derived probability, p, does not take account of the number of tests performed in the crossmatching process, and thus gives a falsely high value. They suggested using the following expression to calculate a significance probability, P, derived from the individual probability and the number of tests made:

$$P = 1 - (1 - p)^m \qquad (12)$$

where: P = the probability taking into account the number of tests (the multiple probability)
p = the individual probability
and m = the number of tests

Munro also suggested the use of Fisher's z statistic, the values of which are normally distributed, rather than Student's t. These changes were incorporated in the Queen's University of Belfast Palaeoecology Centre program CROS84.

Wigley *et al.* (1987) performed a number of tests comparing different methods of digital filtering together with the original Baillie and Pilcher algorithm. The filters used were 10, 20 and 30 year Gaussian types applied to both raw and log values, and 1st and 2nd order autoregressive (AR) models again applied to both log and raw values. They found that the performance of the filters varied according to the test data used and no particular type emerged as superior overall. On this basis they suggested that various filters should be tried to find the one giving best results with the material at hand. They also recommended the procedures proposed by Orton (1983) and Munro (1984) and further suggested the calculation of an indicator of the distinction of the best match probability from the next best. They called this the isolation factor or IF, and defined it as the ratio of the multiple probability (P) of the best match to that of the second best:

$$IF = \frac{P_2}{P_1} \tag{13}$$

where: IF = isolation factor
P_1 = the multiple probability of the best match (i.e. the lowest P)
and P_2 = the multiple probability of the next best match

They suggested that a value of $P < 0.1$ combined with an $IF > 5.0$ indicated a sound crossmatch, while stressing that any such statistical indication could only support, and not replace a good visual crossmatch. They also noted that with very short overlaps (as low as 10 years in their tests) the chances of spurious crossmatches were high.

In view of these considerations it was decided to adopt the following procedure. First the data were detrended using the Baillie and Pilcher, Fritts, and Munro methods described earlier. These filtered sequences were then used for crossmatching, producing three best match positions, one for each detrending method in turn. The significance of each of these was assessed using Fisher's z, from which the multiple probability P and isolation factor IF were derived as described above. As an example Figure 2.3 shows the crossmatch between two trees (GLA014 and GLA013) based on one of the filters, Munro's (1984) 23-term 10 year cut-off high-pass filtered log widths. The Baillie and Pilcher and the Fritts filter would appear very similar but of different lengths as in Figure 2.2. In Figure 2.3 the statistical result of the crossmatch is shown in the heavy box. From the short sections of raw and filtered values enclosed in the lighter vertical box it can be seen that though the corresponding raw sequences from the two trees appear very different at this particular stage (in amplitude rather than Gleichläufigkeit at any rate) their filtered values are very similar. The raw values suggest that GLA014 at this point is much the more sensitive of the two trees.

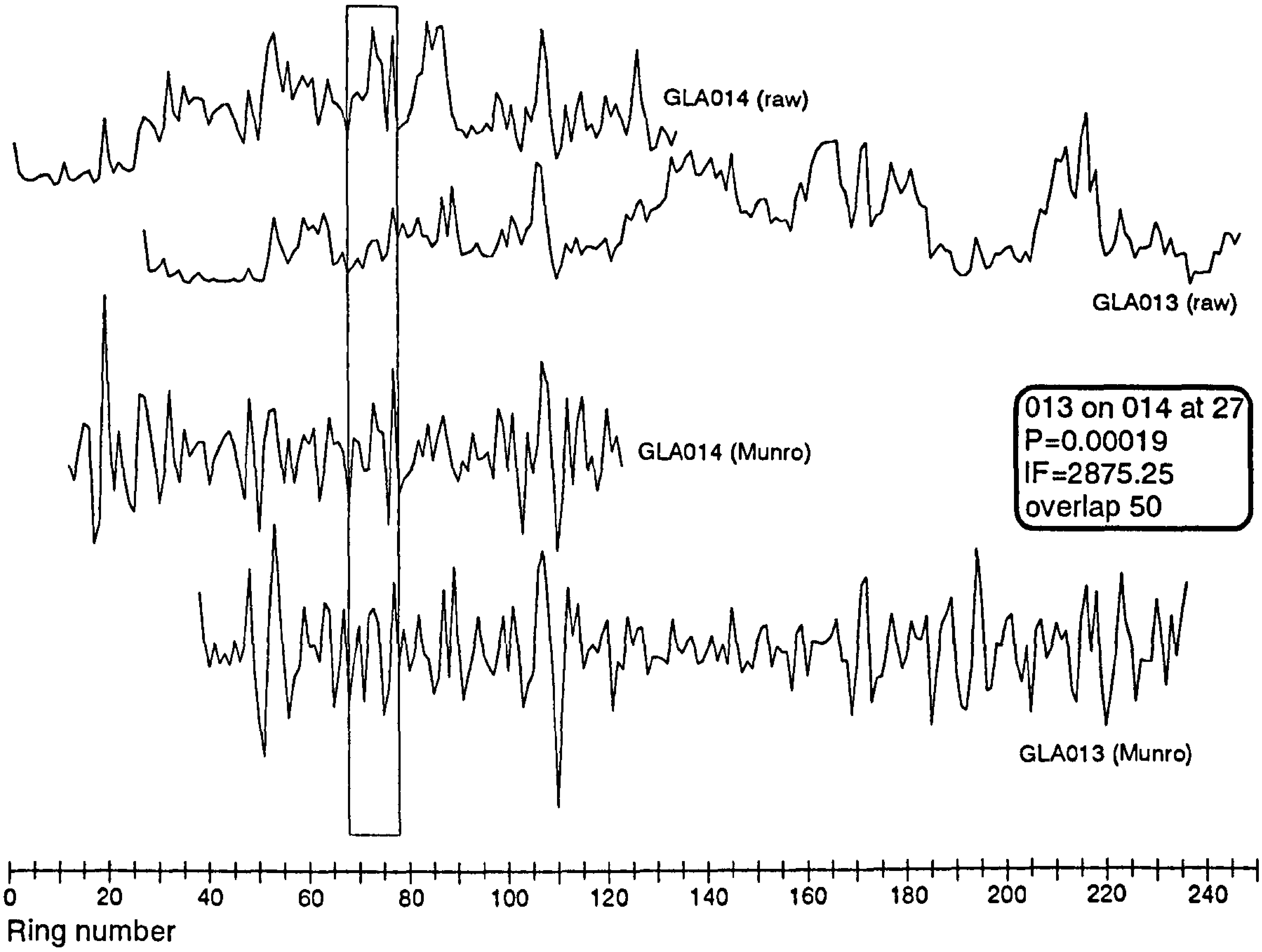


Figure 2.3. Crossmatching between GLA014 and GLA013, raw and Munro filtered values. The figures in the box are the statistics for the crossmatch using the Munro filter.

From the results of this crossmatching procedure a hierarchy of match qualities was established as described in detail below.

2.4.3 Crossmatching procedures followed in the present study

In view of the large number of samples (over 200) used in this study it was necessary to screen large amounts of tree-ring data rapidly for possible crossmatches. As crossmatches finally accepted would have to be both visually satisfactory and statistically significant it was considered valid to reverse the traditional dendrochronological method, using a computer to identify statistically significant matches and then confirming them visually rather than the other way about.

The program MULTCROS (Huntley, unpublished) was used for the statistical crossmatching. This was developed from the programs RINGWID7 and CROSDAT5 (Huntley, unpublished) to permit crossmatching between numbers of trees in all possible combinations automatically. A variant, MULTCROS-T (Huntley, unpublished), was used to calculate values of Student's 't' where required.

The input data for the program are ASCII files of raw integer tree-ring values (in this study usually the 'robust' mean sequences in microns described above) and an ASCII file listing the names and extension of the files to be processed. Also required for each run are threshold values for the multiple probability P, the isolation factor IF, the minimum overlap value at which to start and end crossmatching, and the minimum length of tree-ring sequence to be considered (expressed as a multiple of the minimum overlap value).

The minimum overlap and sequence length are important in the light of Wigley *et al.*'s (1987) observation on spurious crossmatches above, indeed most workers consider any overlap below 50 or even 80 insufficient (Pilcher and Baillie, 1987). However, where a number of short sequences have been recovered from a single site it may be valid to attempt to match these to investigate the internal relationships within that site, although these sequences should not be used for chronology construction or absolute dating (Hillam *et al.*, 1987). Clearly context is all important in these cases.

MULTCROS only lists as output crossmatches which satisfy the preset criteria for P and IF for at least one of the filters it uses (a page of this output is shown in Appendix 4). The values for these criteria were varied slightly depending on the samples being tested; the values adopted are described in the appropriate sections below.

Within MULTCROS the raw data are first detrended as described in the preceding sections, providing the three separate sets of indices from each original tree-ring sequence. All possible pairs of trees are then tested for crossmatches within the preset limits using each set of indices in turn.

Visual confirmation of the matches was done using the program TREERING. This, in addition to providing the visual display described earlier, can also be used for statistical crossmatching between individual pairs of ring sequences, the output being best match position, second best, their individual (p) and multiple (P) probabilities and the isolation factor (IF) of the best match, calculated as in MULTCROS. The program also displays the correlation coefficient (r), Fisher's z, the individual probability (p), t and the Gleichläufigkeit value for each match position as the curves are slid past each other, the last two statistics being calculated mainly for comparison with other workers' results. However any filtering has to be applied to the data before running the program and short routines, BPLOG2, FRITTS2 and MUNRO2 (see Appendix 1) were written to do this using listing files to process batches of data.

2.4.4 Crossmatching within sites

When the measurement of the samples from a particular site was completed, MULTCROS was run with the data from them. Based on experience from the site at Badanloch (Daniell, 1992) the criteria for a significant crossmatch were made a little more stringent than those of Wigley *et al.* (1987), the multiple probability being reduced to $P \leq 0.05$ from their suggested value of 0.1, the minimum isolation factor remaining at 5.0. It was also felt that for the highest quality of matching all three filters used should indicate the same match position. Though this had no formal statistical significance it gave an added confidence in the results. Where different matches did arise from different filters the cause was either the matches were not statistically robust, or, in the case of some of the shorter sequences, that the number of rings left, after application of the longer filters plus the minimum overlap, were too short to match at the best position found by the shorter filter.

For within-site matches two runs were usually made, one with a minimum overlap of 50 rings, the other with a minimum of 30. In each case the shortest sequence accepted was the same as the value of the overlap, 50 and 30 rings respectively. The second run with the shorter overlap was made to allow the possible matching of shorter sequences (30 - 50 rings) as a number of the samples fell within this range. This was felt to be justified on a within-site basis where visual matching and replication (consistency with other results from the site) made it possible to be reasonably confident of the result. However, as explained in the previous section, such samples could not justifiably be used in isolation or for any chronology.

The results of the first (50 ring) run were sorted to identify crossmatches where all three filters gave the same, significant, result for the year of match. These high quality matches were then checked visually (both as raw and filtered data) and for consistency with each other. The matches that passed these tests formed the basis of the crossmatching for the site. The results of the second (30 ring) run were checked on the same basis, except that some of the samples and/or overlaps were too short for the Fritts or Munro filter to operate properly, with potential matches being missed by these filters because of their filter length (13 and 23 terms respectively). Instead these filters would give either the best match within the limited range the overlap allowed or none at all. However, if the Baillie and Pilcher filter gave a highly significant result and the visual match was very strong, these crossmatches, if consistent with the others for the site, were included in the results for the that site.

On completion of the matching process, the successfully crossmatched sequences were plotted against a site year time scale, year 1 of which was taken as year 1 of the earliest crossmatched tree on the site. A table was constructed based on this scale giving the start and end year of each ring sequence together with its length, and a chart prepared showing the crossmatching and its quality. These are presented with the results for each site.

2.4.5 Crossmatching between sites

This was done using ring sequences selected from those that formed the core of the crossmatching at each site on the basis of length of overlap, quality of match (both visual and statistical) and replication. This is described in detail for each site in Chapter 3. A robust mean chronology of these ring sequences placed in their crossmatched positions was calculated site year by site year using the same algorithm as for the calculation of the mean radii (Section 2.3.7 above) in a variant of the program TREEMEAN, ROBCRON. The robust mean was again used to eliminate sudden 'steps' as sequences dropped out of the calculated mean, although in practice the results differed little from an ordinary mean.

The chronologies thus produced were then matched against each other and against two Irish pine chronologies, Garry Bog Pine 1 (Brown, 1991) and Sharvogues (both kindly provided by the Palaeoecology Centre of the Queen's University of Belfast) using MULTCROS and MULTCROS-T (this applied the Baillie and Pilcher, Fritts and Munro filters to the chronologies before matching as described in Section 2.4.3 above). The results of this matching were checked visually and for consistency with the various ^{14}C dates obtained (see below) and are presented in Chapter 3.

2.5 Dendrochronological Samples - ^{14}C dating

2.5.1 Sampling strategy

Radiocarbon dates for 20 samples of subfossil *P. sylvestris* collected during the study were sought from and allocated by NERC. 10 of these samples were taken from the main, subsidiary, and other sites listed below:

Loch Glascarnoch, Loch Vatachan, Laxford Bridge, Srath Dionard, Knockanrock, Fain, Loch Eriboll, Loch Sian, A'Mhoine, The Airde.

These were used to provide dates for the periods of occupation by pine of the sites in question and to confirm the inter-site crossmatching.

In addition a further 10 samples from the crossmatched material from Loch Shin (Fiag Bridge) were dated. These were used to obtain more precise dates for this site by 'wiggle matching' (Pearson, 1986) and by extension for other sites crossmatched to it. The 10 samples were taken from 8 trees spanning 219 years; details are given with the site results. Dates were not sought for material from Badanloch and Lochstrathy as they were available from previous studies (Gear, 1989: Gear and Huntley, 1991). Again details are given with other information from the individual sites.

2.5.2 Sample preparation

The sampling was done by using a clean chisel to split sections of rings from the sample along ring boundaries, the cuts perpendicular to the rings being made with a cleaned fine hacksaw (Eclipse Junior type). Thus a specimen of known ring-span could be separated for dating. The samples were cut to weigh between approximately 20 and 100 g, obviously trying to keep the number of rings spanned by the sample to a minimum. All rough surfaces were sanded or cut with a scalpel to ensure cleanliness and the samples were wrapped in foil, labelled, placed in polythene bags and sent to the NERC facility at East Kilbride for dating. There, prior to isotope analysis, the samples were broken into matchstick sized pieces and digested in 2M KOH (80°C) until all alkali solubles were extracted before being rendered to cellullose. The material was washed with distilled water, filtered and dried in a drying oven (B.F. Miller, pers.comm.).

2.5.3 Calibration of ^{14}C dates.

This was done with the calibration program CALIB rev. 3.0 (Stuiver and Reimer, 1993; Stuiver and Pearson, 1993), using Dataset 1 - bidecadal tree-ring data. The calendar dates obtained are quoted in years BC and are given in the relevant sections of Chapter 3.

2.6 Peat monoliths - Collection and processing

2.6.1 Location

Peat monoliths for pollen and tephra analysis were collected from three sites, Loch Vatachan, Loch Shin and Srath Dionard. Although the selection of these sites was dictated to some extent by the nature of the sites themselves and the need for a good depth of apparently undisturbed peat containing, or adjacent to, the pine stumps used in this study, the sites were chosen to give a good geographical spread across the region. Details are given in the results for each site.

2.6.2 Cutting and storage

With the exception of Loch Shin where it was not possible, the monoliths were cut next to a sampled pine. At the Loch Shin site the monolith was cut from a nearby peat bank.

The face of the peat was cleaned by cutting back with a spade as far as necessary to avoid cracks and surface oxidation. A sketch was made of the cleaned surface to show the different colours and textures of the peat and the position of any visible macrofossils. The relative position of the adjacent pine stump was also indicated. The monoliths were cut with a spade and kitchen knife in 50 cm lengths, about 20 cm by 20 cm in section, the surface vegetation being retained on the top of the upper section. The cutting was continued downwards to well below the level of the embedded stumps, usually to within the layer of birch macrofossils found at the sites below the pine.

The sections of monolith were wrapped in cling film and aluminium baking foil to exclude both air and light as far as possible. Each section was labelled with its orientation, depth and other relevant details. On return to Durham the sections were stored in a cold room at 4°C until required for study.

2.6.3 Preparation for sub-sampling

On removal from storage the monolith sections were unwrapped and one face was cleaned (the same face for each section of a complete monolith). A detailed drawing of this was made indicating changes in the nature of the peat and any other features (macrofossils, cracks etc.). Each distinct layer of peat was sampled, and the samples examined with a binocular and a compound microscope to determine their composition. These details were recorded using the notation of Troels-Smith (1955). Also noted were any shards of 'glass' of possible volcanic origin and any obvious pollen grains. This information was used to determine a sampling strategy for subsequent detailed analysis.

2.6.4 X-raying of sections for tephra

Slices from each monolith section were then X-rayed for tephra layers, following the methods of Dugmore and Newton (1992) and the advice of P. Clogg at the Department of Archaeology at the University of Durham.

A slice about 2 cm thick and 10 cm wide was cut from the cleaned face of each section of the monolith. This 50 cm long section was divided into three roughly equal sections, the cut between these being stepped to avoid complete loss of information at the junctions (Figure 2.4).

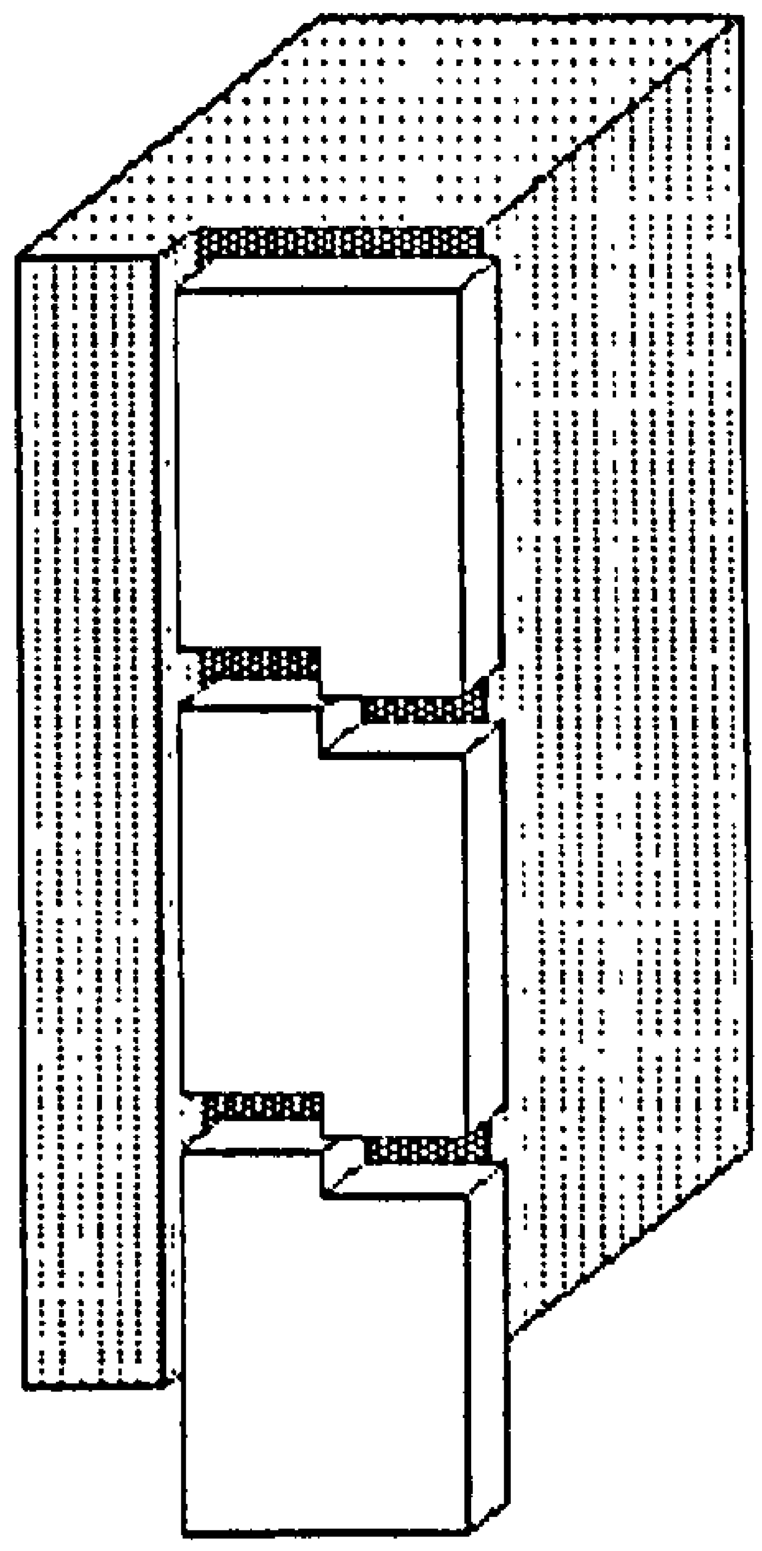


Figure 2.4
Peat monolith showing cutting of slabs for X-ray analysis.

Two measured horizons were marked on each of the resulting slabs using ordinary wire staples, the purpose of this being to create shadows on the X-ray film thus providing measured points of reference on the final image. Because the point source of the X-rays was fairly close (about 50 cm) to the film plane, these markers had to be placed on the side of the sample next to the film to avoid geometric distortion, the peat slab being placed on top of the film below the X-ray source.

The machine was a bench-top industrial machine, a Hewlett Packard Faxitron Series 43806 X-Ray System. The film used was Agfa Structurix D4 Pb in 10 × 24 cm sheets. This film is an industrial type, designed to be exposed within the manufacturer's packing. However, for this application the thin lead sheets on either side of the film in its envelope were removed prior to exposure to reduce the exposure time required. This, after various tests was found to be about 2 minutes (varying slightly with the thickness of the samples) at a potential of 30 kV. Development was by hand in a deep tank using the manufacturer's recommended developer for 5 minutes at 20°C with intermittent agitation.

Once dry, the films were examined for clear bands indicating the presence of X-Ray opaque material. In the present study these were generally found to be caused by either layers of tephra or wind-blown sand, usually the latter. Again the information was used to determine the strategy for subsequent sub-sampling.

2.6.5 Tephra identification

By and large the results of the X-ray photography were disappointing, only one substantial tephra layer being found by this method, that at Srath Dionard. A tenuous layer was found in the Loch Shin profile, but its identity has yet to be confirmed. The tephra from Srath Dionard were identified by J.J. Blackford (Department of Geography, University of Durham) as being almost certainly from the Icelandic eruption Hekla 4. The material was extracted by an acid digestion process (Dugmore, 1989) by J.J. Blackford and its identity confirmed by electron microprobe analysis (J.J. Blackford, pers. comm.- see Appendix 6). This type of analysis reveals the chemical composition of the tephra which permits identification of its source (Dugmore, 1989: Dugmore *et al.*, 1992).

2.6.6 Pollen extraction and counting

The main purpose of the pollen analysis in this study was to locate any peaks in pine pollen corresponding to the occupation of each site by pine, and the vegetation changes on the peat surface immediately prior to, and just after this occupation. The samples were taken from the cleaned slabs used for X-ray analysis at widely spaced intervals (16 cm usually). In the sections where the pine peaks were expected, samples were taken at smaller intervals (1 cm). With the sampler used samples taken at 1 cm intervals were effectively continuous. The end result was thus continuous sampling through the areas of principal interest albeit at a resolution of ± 0.5 cm.

The samples taken were 0.5 ml in volume. 0.5 ml of a suspension of exotic pollen (*Eucalyptus* sp.) of known concentration was added in order to estimate pollen concentrations on counting. Preparation followed the protocol given by Huntley and Allen (1992) based on Faegri and Iversen (1989) and Moore *et al.* (1991). The hydrofluoric acid step was omitted in order not to destroy any tephra present, though the low mineral content of the peats involved made it unnecessary anyway. Because of the humification of the peat a 10 minute hot NaOH stage was used, and acetolysis was carried out for 10 minutes to reduce the amount of plant debris in the samples. The pollen was stained with safranin and mounted in silicon oil for counting. The counting was done using an Olympus EHC-TR microscope with a ×40 fluorite objective, a ×100 oil immersion objective being used for difficult determinations. Each slide was scanned by traverses at 1 mm intervals, pollen being counted to a total of between 300 and 500 grains per slide (excluding the exotic 'spike'). Identification was done mainly from the key of Moore *et al.* (1991) and from reference material held at the Department of Biological Sciences, Durham. The results were plotted using TILIA and TILIAGRAPH (E.C. Grimm, unpublished) and are presented with the other results from the individual sites.

Chapter 3 - RESULTS

This chapter begins with a brief description of new locations for subfossil pine found during the outline surveys of the region. Next the results from each of the sites studied are presented in turn, followed by the results of inter-site comparisons. The main sites are dealt with first, followed by the two sites with previously available data, then other subsidiary sites and odd samples. For each site a general description is given, followed by the results of the dendrochronological work, with the statistics for individual trees preceding the results of crossmatching within the site; then details of ^{14}C dates are recorded where these are available and finally any data from pollen and tephra studies at each site are presented.

Within each site description the geological details are based on the 1:625,000 Geological Map of the United Kingdom - Solid, North Sheet (Institute of Geological Sciences 3rd edition, 1979) and the 1:625,000 Geological Map of the United Kingdom - Quaternary, North Sheet (Institute of Geological Sciences 1st edition, 1977). The soil descriptions are based on those of Futty and Towers (1982). Each site has a three letter code which is used in all references to data from that location. Thus each tree and its ring sequence are identified by a three letter code followed by a number (with the exception of the data from Lochstrathy (Gear, 1989) which are referred to by their original codes). These and other details of the sites are summarised in Table 3.1, their locations being shown in Figure 3.1.

In considering the dendrochronological results, three things should be borne in mind.

- Firstly, with respect to the death dates, two assumptions have to be made. The first of these is that a substantial part of the tree cross-section has been recovered, with only a few of the outer rings missing through decay (only one tree, VAT025 from Loch Vatachan, appeared to have any bark still attached). The second assumption is that this loss is roughly the same for all the trees involved in the study. It is on this basis that comparisons of life spans etc. are made.
- Secondly, it should be remembered that all reconstructions and comparisons are made with the data from successfully crossmatched, or at least measured, trees. No account could be taken of trees that were not recoverable, not measurable or not crossmatched as in any of these cases a relationship with other successfully crossmatched trees cannot be proved. Failure of a successfully measured tree to show a significant match with any other trees suggests at first sight that it grew at a different time from those others, but there is also the possibility that the ring pattern has been so distorted by factors unique to that particular tree that it is unmatchable

Table 3.1. Sampled sites with location, altitude, number of samples collected (tree-ring data sets available for Badanloch and Lochstrathy), and site code.

Site name	1:50,000 O/S Sheet	National Grid Reference	Altitude (metres)	Code	No. of dendro samples
Main sites					
Loch Glascarnoch	20	NH(28)289739	250	GLA	25
Loch Vatachan	15	NC(29)020098	20	VAT	28
Loch Shin (Fiag Bridge)	16	NC(29)476197	95	SHI	32
Sites with data from previous work					
Badanloch	17	NC(29)786330	122	BAD	(54)
Lochstrathy	10	NC(29)796491	157	S, STR, SNK	(34)
Subsidiary sites					
Laxford Bridge	9	NC(29)227468	10	LAX	12
Srath Dionard	9	NC(29)338585	20	DIO	15
Other locations with fewer than 10 samples					
Knockanrock	15	NC(29)177067	210	KNO	2
Fain	20	NH(28)160767	300	FAI	6
Loch Eriboll	9	NC(29)394541	10	ERI	2
Loch Sian	9	NC(29)441635	50	SIA	1

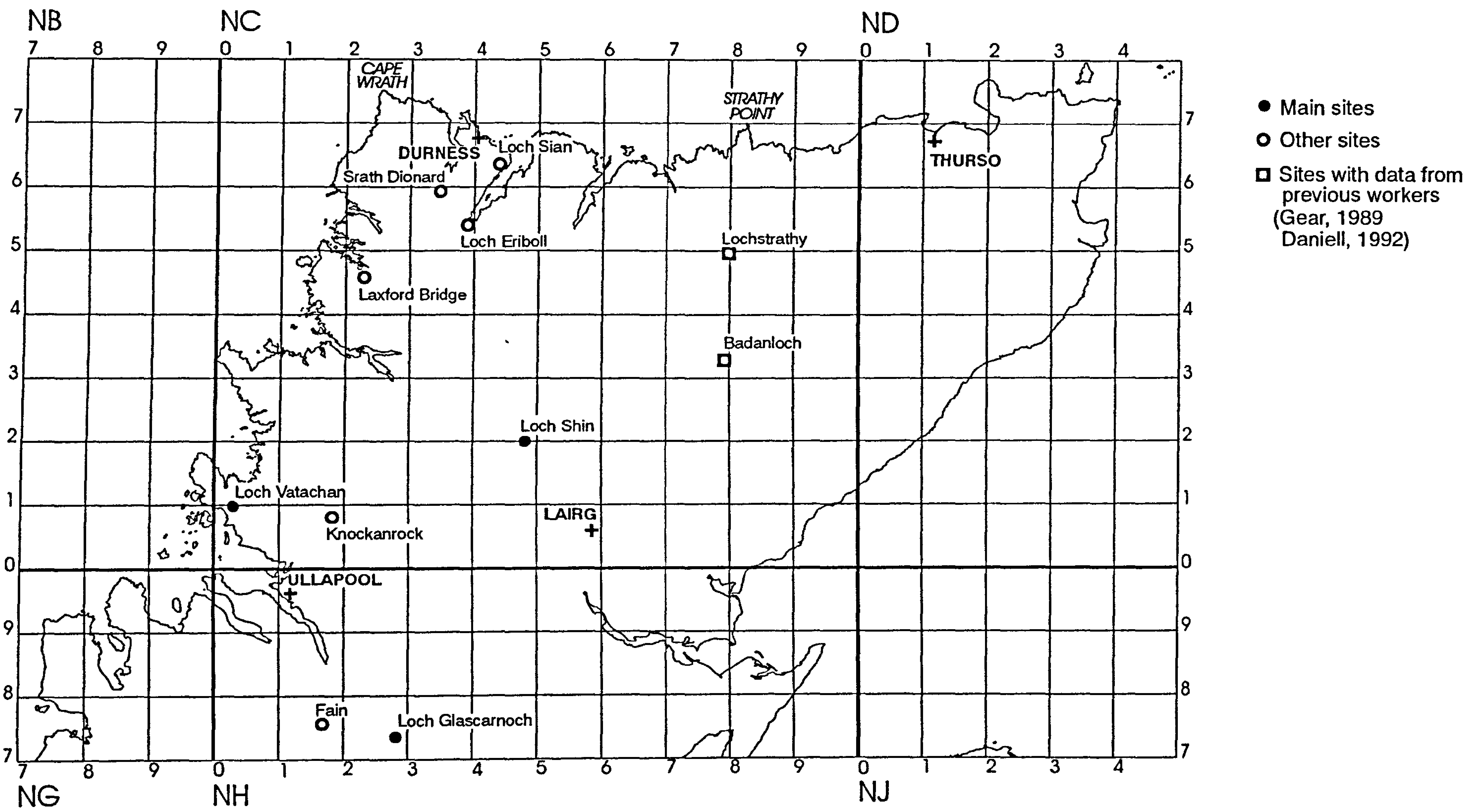


Figure 3.1. Northern Scotland showing the dendrochronological sampling sites in the study.

even though growing at the same time. This latter possibility is made more likely by the fact that the trees in this study were growing at the edge of their range under difficult conditions and therefore were particularly sensitive to local interaction and disturbance (Fritts, 1976). Also sensitivity to exogenous influences tends to be more marked in gymnosperms than angiosperms (Schweingruber, 1988).

- Finally, it should be noted that no seedlings were found, and that for the statistical reasons outlined in Chapter 2, no ring sequences under 30 years could be crossmatched with any confidence. This means that in any considerations of population density, age distribution etc. no trees in the age range 1 - 30 years are included. It also means that in any discussion of reproduction it is 'established' trees that are being considered, and that here (unless otherwise stated) 'established' therefore means greater than 30 years old.

3.1 Locations of subfossil Scots Pine recorded during the surveys

Details of the locations of subfossil Scots Pine other than the dendrochronological sites are given in Table 3.2 and Figure 3.2.

Taken with the 10 km resolution distribution maps for subfossil pine presented earlier (Figs. 1.1, 1.3, 1.12), the results of the surveying confirm that the remains are widely distributed across the far north west of Scotland, seeming to occur wherever peat of sufficient depth is found, from sea level up to at least 300 m. Gear (1989) confirms this altitude range for subfossil pine in the eastern half of Northern Scotland.

The absence of pine stumps in the shallower peats and soils of the 'knob and lochan' country, particularly between Quinag and the coast at Clachtoll and Lochinver (grid squares NC(29)02, 12), suggests two possibilities:

a) Pines were growing there, but the conditions were not suitable for preservation of the stumps.

b) These drier, better drained soils were occupied by other species such as birch, pine being excluded by competition and confined to poorer habitats on the drying surfaces of the blanket peats.

It is probable that the hollows in the 'knob and lochan' areas remained too wet for colonisation by trees.

Five new 10 km squares containing subfossil pine were identified during the survey (Fig. 3.2). Four of these are on the western and south-western fringes of the region confirming the distribution of subfossil pine right to the coast. The fifth, NC(29)34, covers an area of high ground, relatively inaccessible from public roads, containing the

Table 3.2. Sub-fossil pine locations. The number in column 1 refers to Figure 3.2

No.	Location	Altitude (metres)	Nat. Grid Ref.	Comments
1	Srath Coille na Feàrna	30	NC(29)384514 - 379509	Pine in peat cut back by river, peat depth 2 m +
2	A'Mhoine	130	NC(29)545600	Pine stumps in peat cutting, blanket peat, 54 cm peat depth below stumps, ^{14}C date
3	Achinahuach	70	NC(29)580643	Blanket peat, decayed stump in peat cutting
4	Loch Stack	40 - 60	NC(29)299402 - 306405	Pine above birch, isolated clumps, blanket peat, new 10 km square
5	Garbh-allt	260	NC(29)788414	Pine fragments in stream bank in blanket peat
6	Near Unapool	150	NC(29)238303	In peat hag, peat depth 70-80 cm, buttress root about 15cm down
7	Near Achnahaird	70	NB(19)995136	New peat cutting
8	Aird of Coigach	70 - 130	NC(29)074126 - 074116	Old peat hag, blanket peat about 1.1 m deep, exposed col
9	The Airde, Loch Shin	95	NC(29)521150, 523139	Large trees on edge of loch, on peat under shingle, total peat depth about 1.5 m, ^{14}C date
10	Achnairn	140 - 150	NC(29)558140 - 563146	Drainage ditches on blanket peat
11	Badluarach	170	NG(18)998927	Peat cutting, peat about 50 cm deep, group of stumps
12	Badrallach	160 - 230	NH(28)104893 - 100919	Peat about 75 cm deep
13	Allt an t-Strathain	30	NH(28)112969	Stumps in valley bog
14	Oykel Bridge	50	NC(29)395008	Blanket peat
15	Meall a' Gruididh	300	NC(29)531039	Drainage ditch in blanket peat. Trunk (2.1m) with branch, very weathered
16	Loch Bad an Scalaig	110	NG(18)849719	Reservoir drained for maintenance revealing pine stumps on bottom
17	Abhainn Droma	210	NH(28)220772	Stumps and trunk in drainage channel in blanket peat

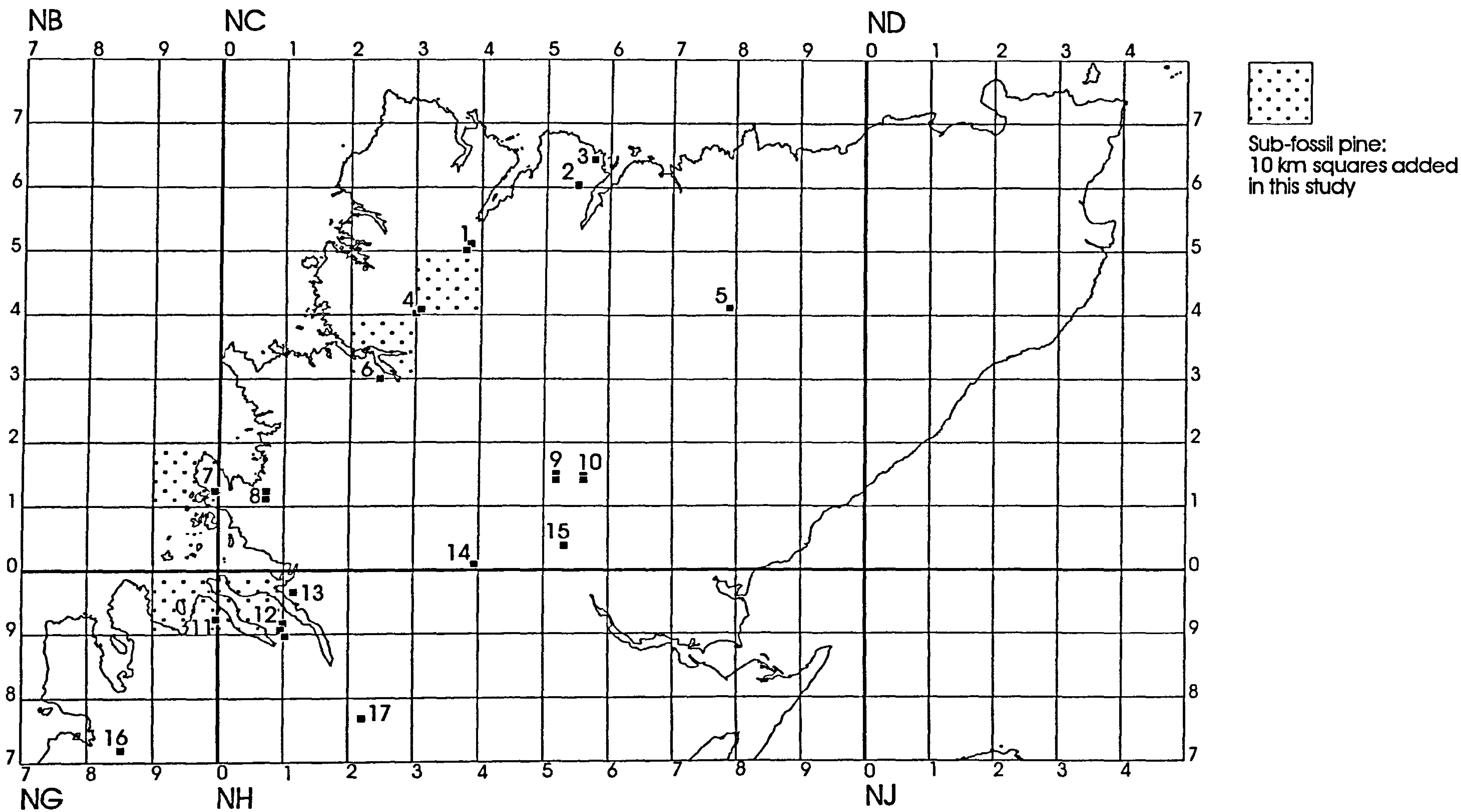


Figure 3.2. Subfossil pine locations: the numbers refer to Table 3.2. Sites sampled for dendrochronology are shown in Figure 3.1. Overlapping squares indicate a group of locations close together as shown by the Grid References in Table 3.2.

peaks of Arkle and Foinaven. However subfossil pine is certainly present in peat on the lower ground at the south-west of this grid square, and further searching would probably reveal its presence at the head of Srath Dionard and in the other glens below about 300 m or so.

3.2 Loch Glascarnoch

57° 43' 23" N 4° 52' 25" W, Nat. Grid Ref. NH(28)289739

Figure 3.3, Plate 1.

3.2.1 Site Description

Loch Glascarnoch is the most southerly of the sampled sites, and as such lies about 25 km south of the present northern limit of *Pinus sylvestris* at Glen Einig, and about 85 km south of the most northerly sampled site at Srath Dionard. The loch itself is a hydro-electric reservoir about 6 km long and over 1 km wide at its broadest point. It lies about 250 m above sea level just to the east of the summit (279 m) of a low pass which forms the head of Strath More to the west. The valley below the reservoir to the east continues downwards to the head of Loch Garve and thence to the sea near Dingwall. Thus the head of Loch Glascarnoch is about 1 km from, and about 30 m below, the highest point of a narrow corridor connecting the sea loch Loch Broom in the west to the Cromarty Firth in the east (Figure 1.4).

The loch is to the east of the Moine Thrust (Fig. 1.6), which crosses Loch Broom about 15 km to the west. The underlying rocks are the Moine Group, mainly quartz-feldspar-granulite, with a narrow band of schists at the eastern end of the loch. The area beyond the head of the loch contains hummocky moraine which is bounded by areas of smooth relief rising to *ca* 650 m to the south of the valley. The soils in the area are peaty gleys and podzols with occasional areas of deep peat on the level and gently sloping sections, dominated by deer grass (*Trichophorum cespitosum*) with heather (*Calluna vulgaris*) in the drier areas. To the north a barrier of high ground, rising to over 1000 m at the summit of Beinn Dearg, cuts the valley off from Strath Oykel and Loch Shin some 25 km to the north. There are a few narrow plantations of exotic conifers along the southern shore of the western end of the loch (Fig. 3.3a).

As the loch is a hydro-electric reservoir, there are fairly marked fluctuations in level throughout the year, and during periods of low level a wide shore is revealed at its head. Here the flooding of the reservoir and consequent erosion of the shore has removed the covering of blanket peat which was probably originally part of an extensive valley bog,

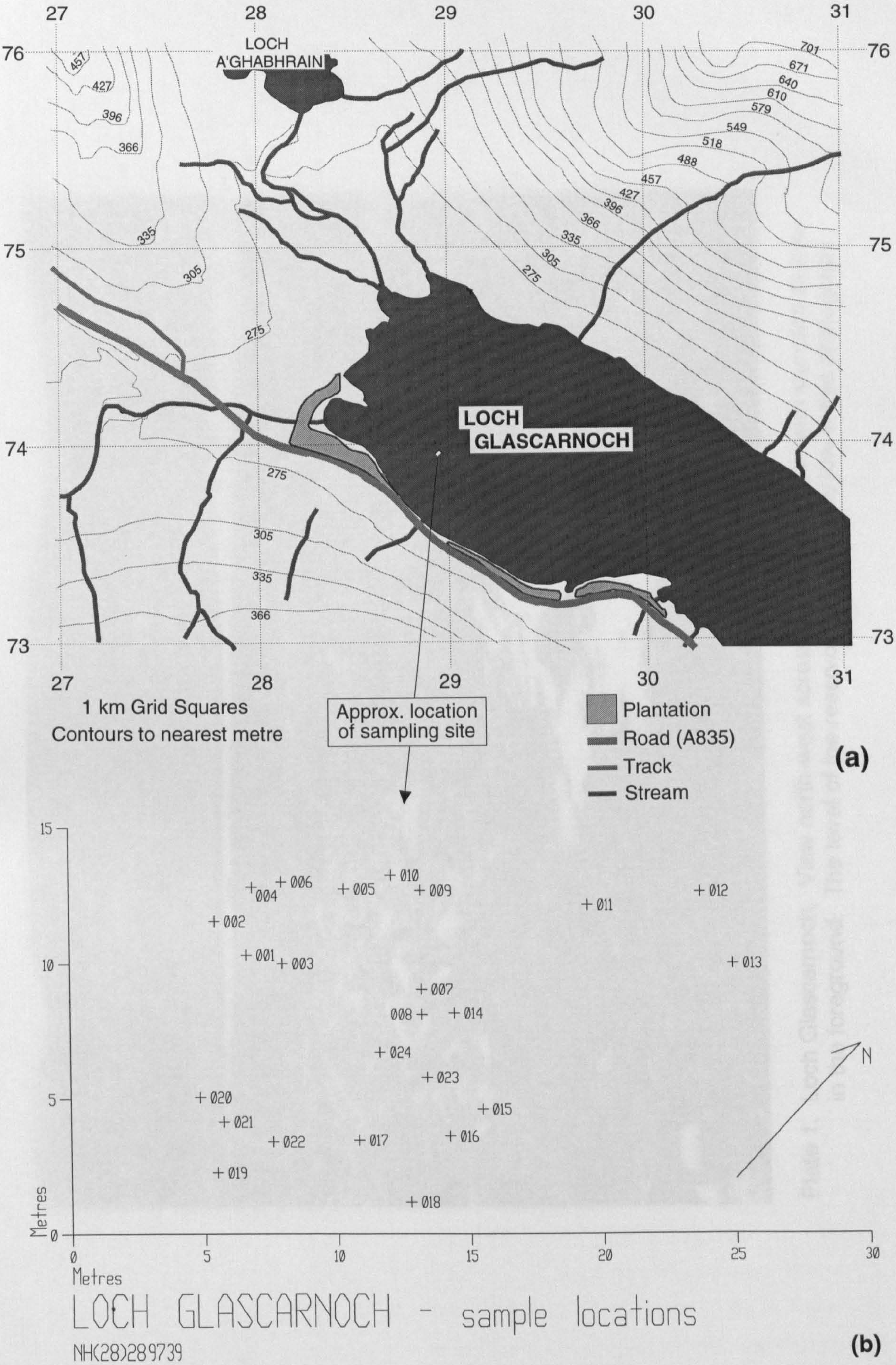


Figure 3.3.
Loch Glascarnoch - showing the location (a) and a plan of the sampling site (b)

Plate 1. Loch Glascarnoch. View north-west across the sampling site with sampled stumps in the foreground. The level of the reservoir is particularly low in this photograph.

exposing a large number of pine stumps in their original positions of growth. A small group of these just beyond the line of the old road on the reservoir floor were selected for sampling. These were chosen on the basis that it was possible to recover usable samples from virtually all the stumps from a single group which occupied an area approximately 15 by 30 m. The location of the sampled area is shown in Figure 3.3a and the layout of the stumps together with their sample numbers in Figure 3.3b. The depth of peat below the stumps is at the most about 0.5 m, and taking into account the height of the old road bed above the reservoir floor and stumps embedded in a peat bank at the western end of the loch, it seems there was originally about 1 m of peat above them before the reservoir was filled. This however can only be an estimate.

3.2.2 Dendrochronological Results

These are given in various tables and figures, comparisons between sites being presented in Inter-site Comparisons (Section 3.10) below.

3.2.2.1 General statistics

Table 3.3 lists the individual statistics for each sample derived as described in Section 2.3.8. From these it can be seen that of the total of 24 stumps recovered, 21 proved measurable. For this particular site the trees are divided into the groups revealed by crossmatching, with overall figures for the site at the bottom of the table. There is no significant difference between the overall statistics for the individual groups, though it is worth noting that two of the three most long-lived trees (in excess of 220 years) on the site are in Group 1, giving rise both to the greater mean number of rings and the large SD for that mean.

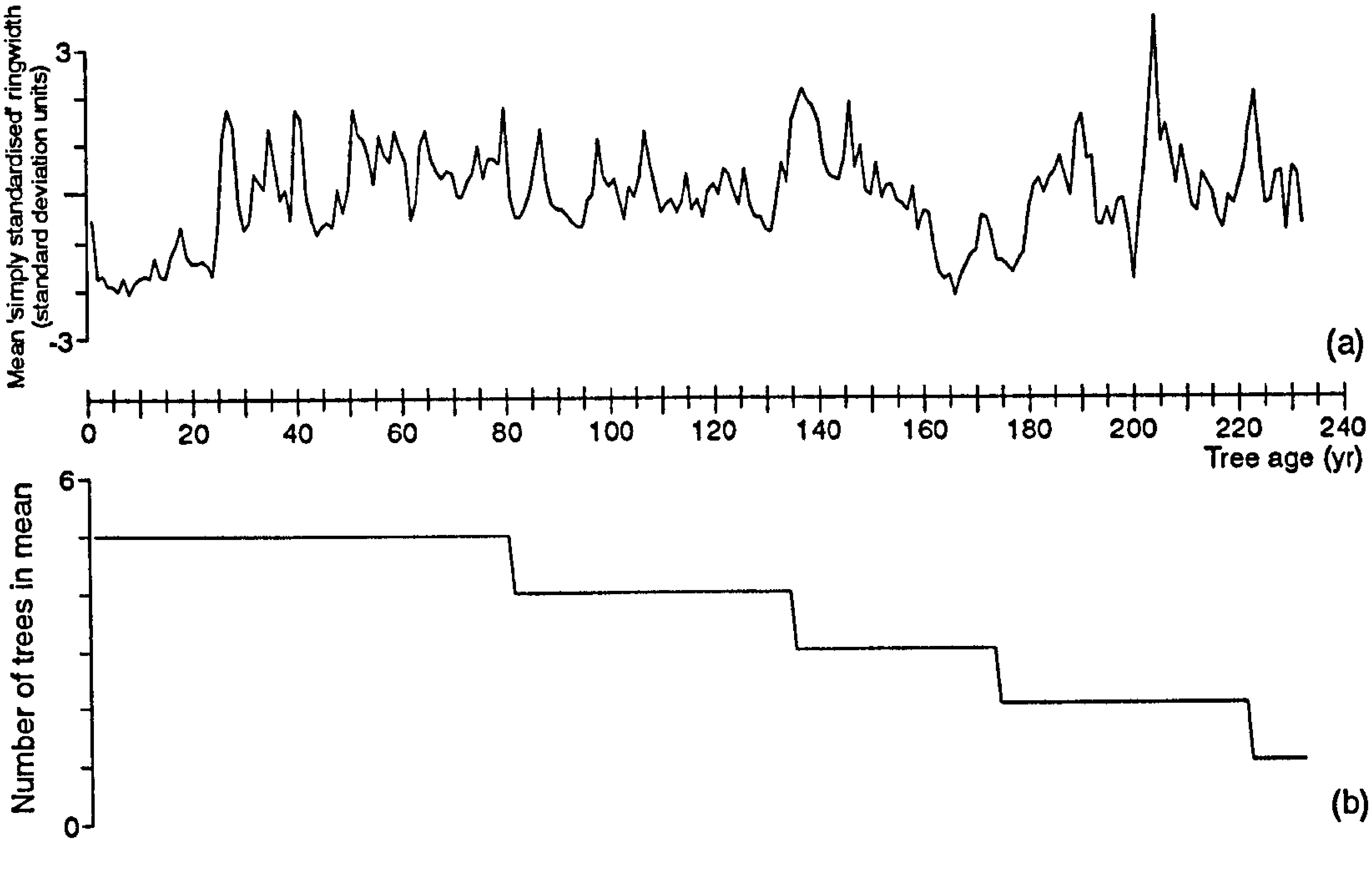
The last two columns in Table 3.3 give values for the mean sensitivity of each tree and the first order autocorrelation for each ring series. These figures, and their comparison with other sites are discussed later.

3.2.2.2 Mean growth curve

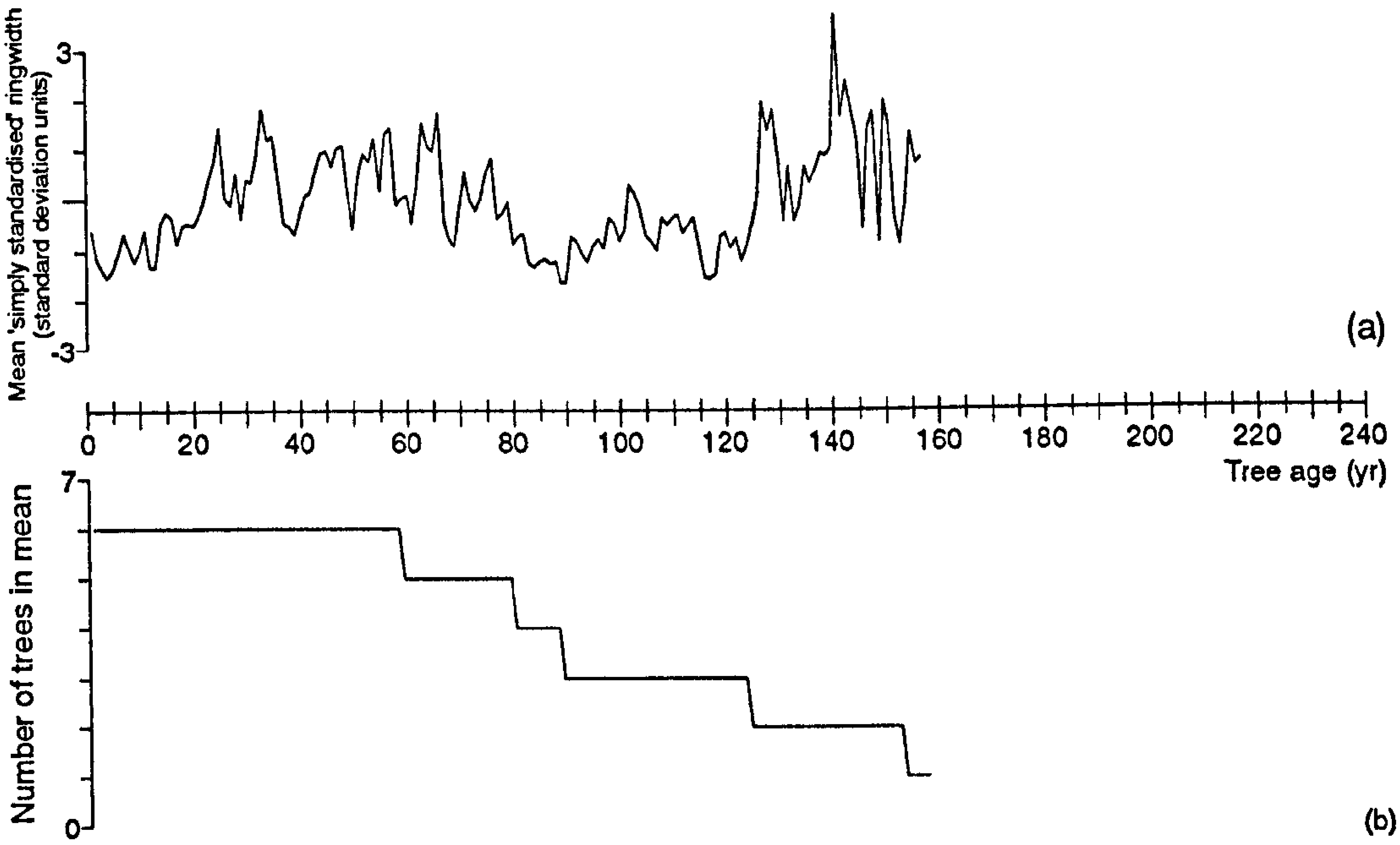
Figure 3.4 shows the mean growth (the (a) curves) for trees in Groups 1 and 2 at the Loch Glascarnoch site. This is calculated as the year by year mean of the raw ring-widths from all those trees measured which had intact centres (see Table 3.4), with year 1 for each sequence placed at year 1 on the x-axis (Pilcher *et al.*, 1995). These year by year means are plotted as simply standardised values as defined in Section 2.3.6. The (b) curves in Figure 3.4 are plotted on the same horizontal axis and indicate the number trees present in the means at any one time. Both Groups 1 and 2 show a rise in ring-width over the first *ca* 40 years of the trees' lives followed by a steady decline until about 170

Table 3.3 Loch Glascarnoch: summary statistics based on the mean radius for each sample measured

Tree	Number of rings	Mean radius (cm)	Mean ring-width (mm)	SD of ring-widths	Sensitivity	First order autocorr.
Unmatched						
GLA001	222	11.8	0.53	0.29	0.24	0.85
GLA004	99	7.4	0.75	0.37	0.30	0.72
GLA009	135	7.3	0.54	0.45	0.42	0.66
GLA012	107	8.1	0.76	0.42	0.23	0.86
GLA015	100	5.5	0.55	0.30	0.33	0.71
Group 1						
GLA008	232	11.1	0.48	0.31	0.33	0.75
GLA011	159	9.8	0.62	0.36	0.28	0.82
GLA013	221	9.8	0.44	0.27	0.26	0.85
GLA014	134	7.2	0.54	0.28	0.30	0.72
GLA016	173	9.2	0.53	0.33	0.33	0.67
GLA017	80	6.8	0.85	0.46	0.30	0.72
GLA021	65	5.0	0.77	0.34	0.26	0.62
GLA022	168	10.4	0.62	0.40	0.25	0.86
Mean	*154.0*	*8.66*	*0.606*		*0.289*	*0.752*
SD	*59.7*	*2.08*	*0.141*		*0.034*	*0.085*
Group 2						
GLA002	79	7.0	0.88	0.68	0.28	0.81
GLA003	123	6.2	0.50	0.23	0.26	0.73
GLA005	123	8.3	0.68	0.31	0.26	0.71
GLA006	79	5.7	0.72	0.39	0.35	0.64
GLA007	88	7.0	0.79	0.47	0.30	0.76
GLA010	58	4.8	0.82	0.32	0.23	0.69
GLA019	157	8.5	0.54	0.23	0.29	0.58
GLA020	152	5.9	0.39	0.32	0.42	0.78
Mean	*107.4*	*6.68*	*0.667*		*0.298*	*0.713*
SD	*36.6*	*1.30*	*0.172*		*0.060*	*0.076*
Overall						
Mean	**131.1**	**7.75**	**0.634**		**0.296**	**0.739**
SD	**51.9**	**2.00**	**0.145**		**0.054**	**0.081**



Group1



Group 2

Figure 3.4. Growth of trees at Loch Glascarnoch (Groups 1 and 2)
(a) - Mean growth curve (see Section 3.2.2.2).
(b) - Number of trees included in the mean.

years in the case of Group 1 and about 120 years in Group 2. These first sections of the curves suggest that the bulk of the trees are showing the initial rise followed by the exponential decrease (induced by the growth geometry) in annual increment found in many pine populations. In the later sections the variance seems to increase, with some large increment values in the last 40 to 60 years or so. However by this time there are only two trees left in each of the means, in Group 1 GLA008 and GLA013 (plotted as part of Figure 3.8 below) having their widest rings in the last few years of their span as do GLA019 and GLA020 in Group 2 (Figure 3.9 below).

3.2.2.3 GLA001 - Stump and trunk

An entire trunk, believed from its position on the exposed peat surface to be that of the stump GLA001, was also recovered (Plate 2). The ring sequence from the trunk matched that of GLA001 particularly well ($P \leq 0.00001, IF > 10{,}000$ for the for all filters at ring 23 on GLA001, Figure 3.5), confirming this relationship. The section used for the match was cut at an estimated 80 cm up the trunk, the precise height being indeterminable because of decay both in the stump and base of the trunk. Allowing for a possible 5 rings or so missing from the decayed centre of GLA001, this match would suggest a maximum height of about a metre after 30 years growth. This low initial growth rate compares well with that found by Ågren *et al.* (1983) for *Pinus sylvestris* regenerating naturally on mire surfaces in northern Sweden about 5° south of its northern limit in that country, and is not uncommon in the Scottish pine woods of today (Goodier and Bunce, 1977). Overall the trunk was 7.4 m long and straight for the first 6.5 m or so, bending to one side about 1 m from the top and there appear to have been branches for most of its length. As with the stumps, some of the outer layers were missing, representing around 50 years based on the ring counts for the stump and trunk (222 and 149 respectively), so it was not possible to determine if the outer surface of the trunk had been clean, or whether the lower branches had persisted throughout the tree's life. However, the branches appear to have been horizontal or ascending in habit, and the crown skewed to one side, possibly due to the effects of strong winds. The radius of the sample was at least 8.4 cm (compared with 11.8 cm for the stump) at the point where the cross-section was taken.

Plate 2. Loch Glascarnoch. Subfossil trunk from GLA001 (see Section 3.2.2.3)

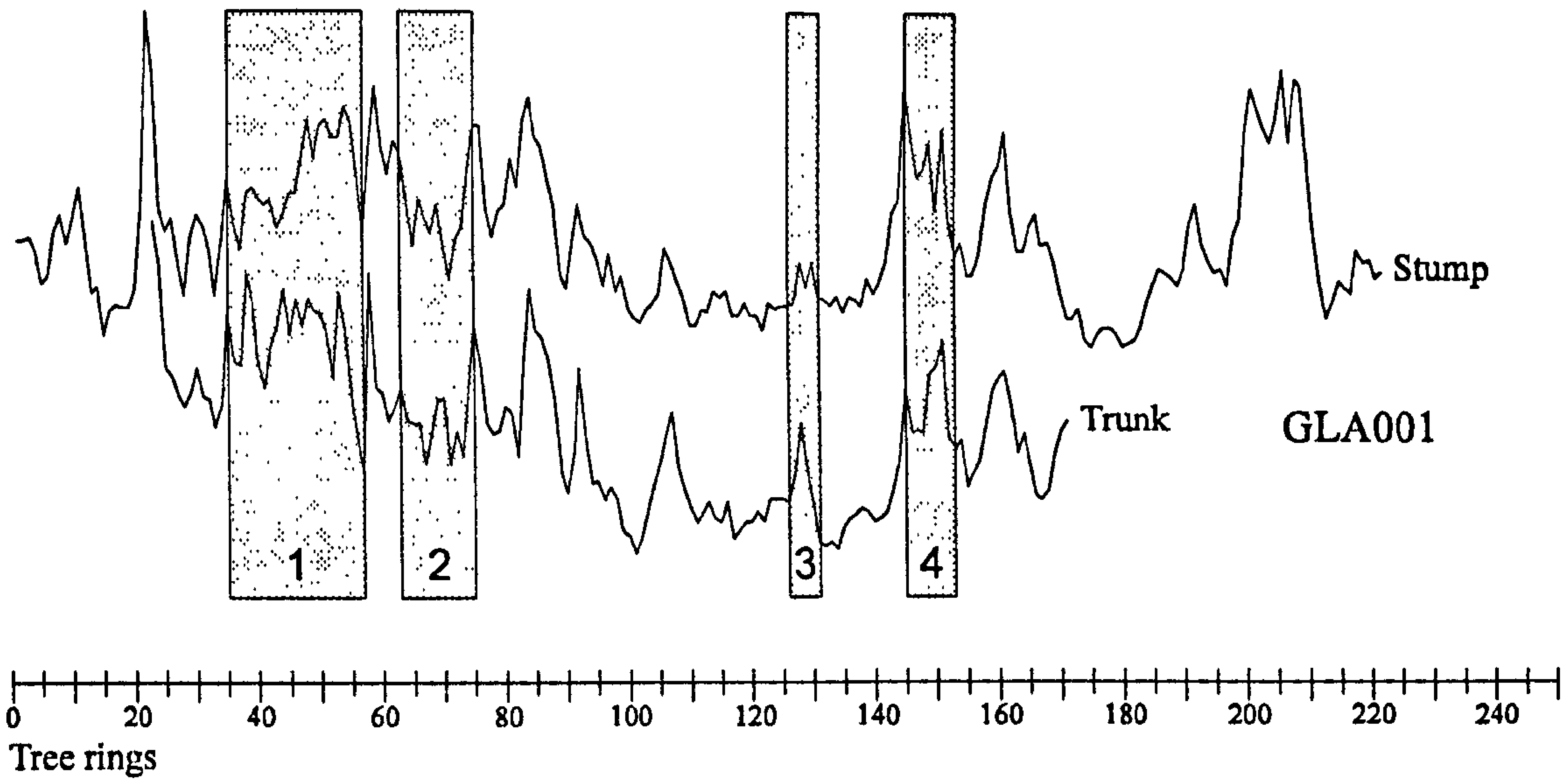


Figure 3.5. GLA001 stump and trunk at their matched position. The curves are in raw values and plotted at the same scale (for 1, 2, 3, 4 see text).

The very high quality of the matching between stump and trunk confirmed the suspicion that distortion in the cross-section caused by the growth of the root buttress was not greatly affecting the signal from the ring-widths. Thus the distortion was behaving either as a long-term trend and as such would be removed by high pass filtering, or as an offset affecting each ring equally. However the shaded sections in Figure 3.5 are worth closer examination. They all show sections of the trunk and stump mean tree-ring curves where there are differences between these. In section 1 the trunk curve seems to be rather more sensitive than that for the stump with the middle of this section and there is a a phase difference between the two. In sections 2 and 4 the sensitivities are much the same in both curves, but there are differences in emphasis. In section 3 the trunk shows a single large increase in ring-width where the stump shows two smaller peaks.

All this suggests that tree-ring sequences obtained from stumps are giving much the same environmental information as would those from trunks (which are anyway relatively rarely found in the Scottish peat deposits), although growth effects in the stumps, due to stresses on the root buttresses etc., are adding a certain amount of extra noise to this environmental signal.

3.2.2.4 Site crossmatching

Table 3.4 gives a summary of the crossmatching results for Loch Glascarnoch. The table lists all the samples recovered, the minimum age where the sample has been measured, the crossmatch date where this has been established, and thence the earliest death date of that particular tree relative to the others in its group. At this site two separate groups of

Table 3.4. Loch Glascarnoch - summary of crossmatching positions.

TREE	MIN AGE	MATCH POSITION (Group 1 or 2 site years)	DEATH (minimum - Group 1 or 2 site years)	
Unmatched				
GLA001	222			Centre damaged
GLA002	79			Centre damaged
GLA004	99			Centre missing
GLA009	135			Centre indistinct
GLA012	107			
GLA015	100			
GLA018				Not counted
GLA023				Not counted
GLA024				Not counted
Group 1				
GLA008	232	1	232	
GLA011	159	50	208	Centre missing
GLA013	221	59	279	
GLA014	134	33	166	
GLA016	173	12	184	
GLA017	80	113	192	
GLA021	83	111	193	Centre damaged
GLA022	168	123	290	Centre damaged
Group 2				
GLA003	123	11	133	
GLA005	123	12	134	Knots in centre
GLA006	79	1	79	
GLA007	88	20	107	
GLA010	58	4	61	
GLA019	157	20	176	
GLA020	152	49	200	
GLA00t1	149			Centre split - Trunk (on GLA001 at 23)

Samples recovered: 24. Samples successfully crossmatched: 15 (63%) (not including GLA00t1 - trunk matched to GLA001)

Density of stumps on site: 533 ha^{-1}.

crossmatchable trees were found. This information is presented graphically in Figure 3.6 which represents the minimum life-span of each crossmatched sample as a line, these lines being plotted in their relative matched positions against the relevant scale of 'Group site years'. These scales have their origins (0 position) 1 year before year 1 of the earliest crossmatched sample in each group. From the table and figure it can be seen that the matched trees in Group 1 span a period of 290 years, the earliest established tree being GLA008, and the last (and also the last survivor) being GLA022. Similarly the trees in Group 2 span 200 years, the first being GLA002, the last to be established and last survivor being GLA020. No dendrochronological link was established between the two groups, based either on the individual trees or on robust mean chronologies from each group. Figure 3.6 also shows in Group 2 that all but one of the trees were established within 30 years of the first tree in that group. This suggests a rapid colonisation or expansion, rather than the slower development in Group 1. In both groups it can be seen that the death dates are widely scattered over at least 100 years, and that therefore it would appear that no single catastrophic incident was responsible for the death of the trees in either case.

Figure 3.7 shows the quality of the crossmatching for the two groups of trees. Significant crossmatches are indicated by a letter in the appropriate box with a key to the quality of the match included in the chart. Values of 't' for the Baillie and Pilcher filter are given, with stars indicating the multiple probability for that match. Also indicated is the replication of the matches, a minimum of two significant matches being required for a tree to be included at all. Apart from variation peculiar to the individual trees, the principal cause of poor quality or absent (where they might be expected) matches is probably the small overlap between some of the shorter sequences.

Figures 3.8 and 3.9 show plots of the ring sequences of the trees in the two groups in their suggested match positions. The plots are of the raw values, not the filtered sequences, and are simply standardised. The vertical dotted lines indicate years in which prominent peaks or troughs occur in the sequences, not all the trees showing the same degree of response. Although these reactions must have been produced by site-wide phenomena, clearly different trees by virtue of their own particular environmental circumstances were less or more sensitive to them. For clarity only the major common features have been marked on the diagrams.

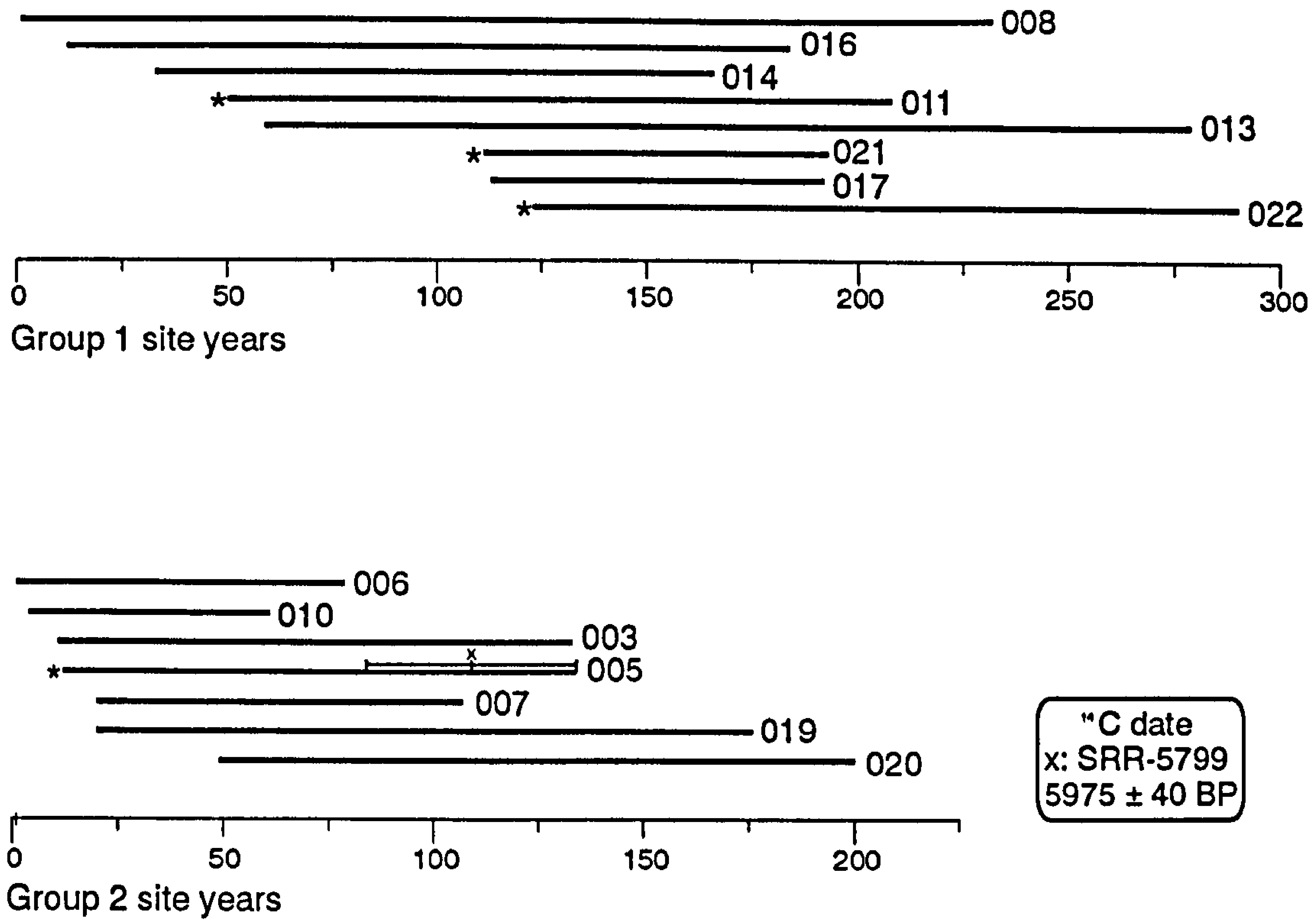


Figure 3.6. Loch Glascarnoch - the two groups of crossmatched trees.

The lines represent individual lifespans, the asterisks indicating a missing centre to the tree. The numbers are the sample numbers (the prefix GLA is omitted). The double line indicates the span of rings used for ^{14}C dating, with x indicating the point taken as the centre (see text).

TREES GROUP 1

GLA	016	011	021	017	022	014	013
008	5.7***	n/s	n/s	n/s	n/s	4.17*	n/s
A	016	n/s	s/o	n/s	n/s	4.46**	n/s
n/s	n/s	011	n/s	3.45*	3.59*	4.2*	7.78***
n/s	s/o	n/s	021	4.3**	5.91***	4.11*	n/s
n/s	n/s	C	A	017	10.32***	n/s	4.45**
n/s	n/s	C	B	A	022	s/o	n/s
A	A	A	B	n/s	s/o	014	4.35**
n/s	n/s	A	n/s	C	n/s	A	013
008	016	011	021	017	022	014	GLA

TREES

TREES GROUP 2

GLA	005	010	003	007	019	020
006	7.73***	6.71***	n/s	n/s	n/s	s/o
B	005	s/o	5.07**	5.19***	6.35***	3.96*
A	s/o	010	s/o	s/o	s/o	s/o
n/s	A	s/o	003	4.53**	5.48***	n/s
n/s	A	s/o	A	007	5.15**	n/s
n/s	A	s/o	A	A	019	5.95***
s/o	A	s/o	n/s	n/s	A	020
006	005	010	003	007	019	GLA

TREES

CROSSMATCHING QUALITY

UPPER RIGHT
Values of 't' and multiple probabilityfor Baillie and Pilcher filter.
* - 0.1>P>0.01 ** - 0.01>P>0.001 *** - P<0.001

LOWER LEFT
Match significant if P < 0.05 and IF > 5.0
A - All 3 filters give the same match position and all matches are significant Minimum overlap is 50 rings.
B - As A but minimum overlap is 30 rings.
C - As B but only 1 or 2 matches significant.

n/s - not significant
s/o - short overlap (< 54 rings, ie 50 rings plus those lost in the B & P filter)

REPLICATION: This table shows the number of significant matches in which the tree is present.

TREE	MATCHES	TREE	MATCHES	TREE	MATCHES
GLA008	2	GLA014	5	GLA007	3
GLA016	2	GLA013	3	GLA019	4
GLA011	4	GLA006	3	GLA020	2
GLA021	3	GLA005	6		
GLA017	4	GLA010	3		
GLA022	3	GLA003	3		

Figure 3.7 Loch Glascarnoch crossmatching. This diagram shows the significant crossmatches between trees with the quality and replication of those matches.

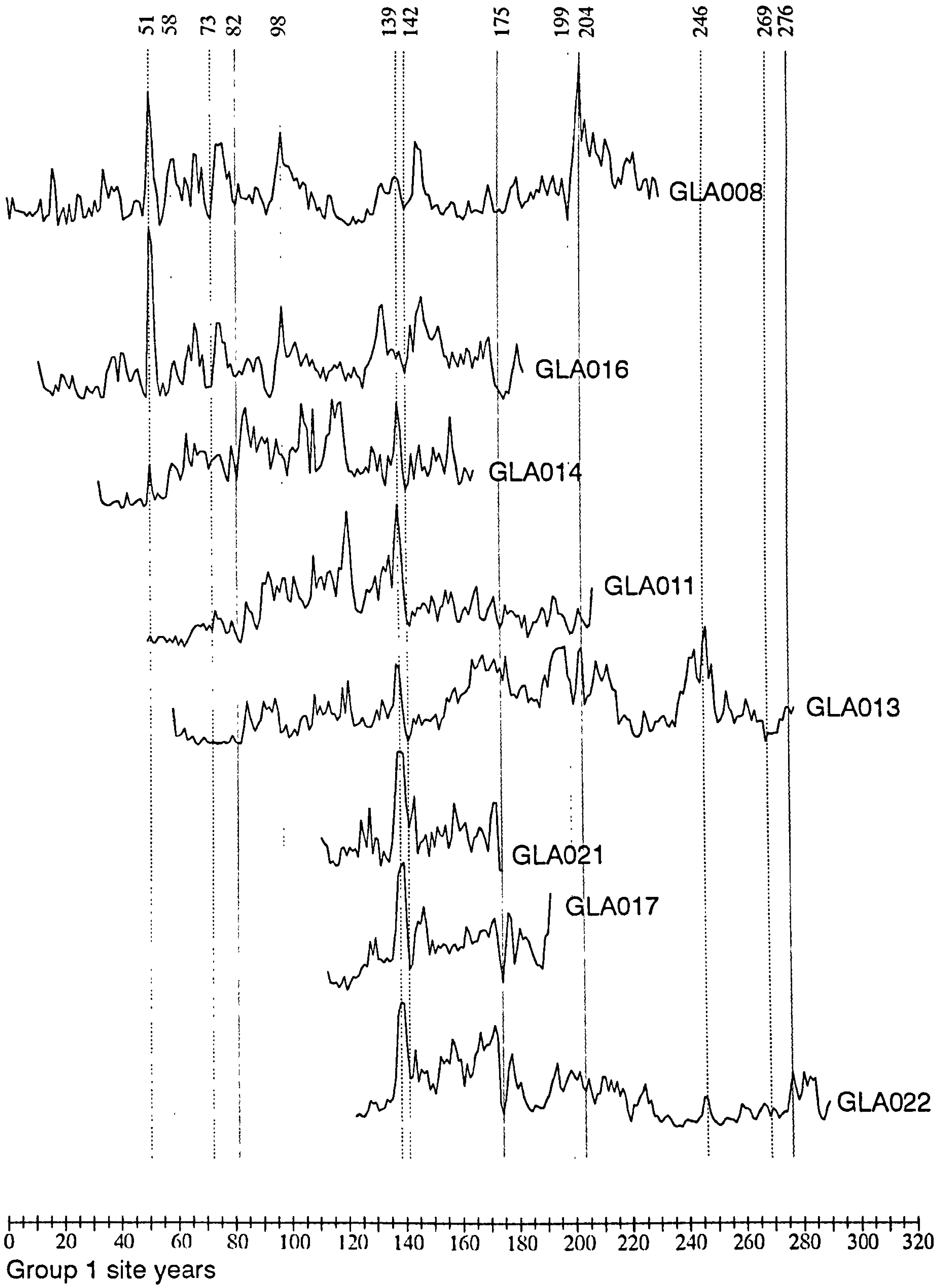


Figure 3.8. Loch Glascarnoch Group 1.
Raw value curves in their crossmatched positions.

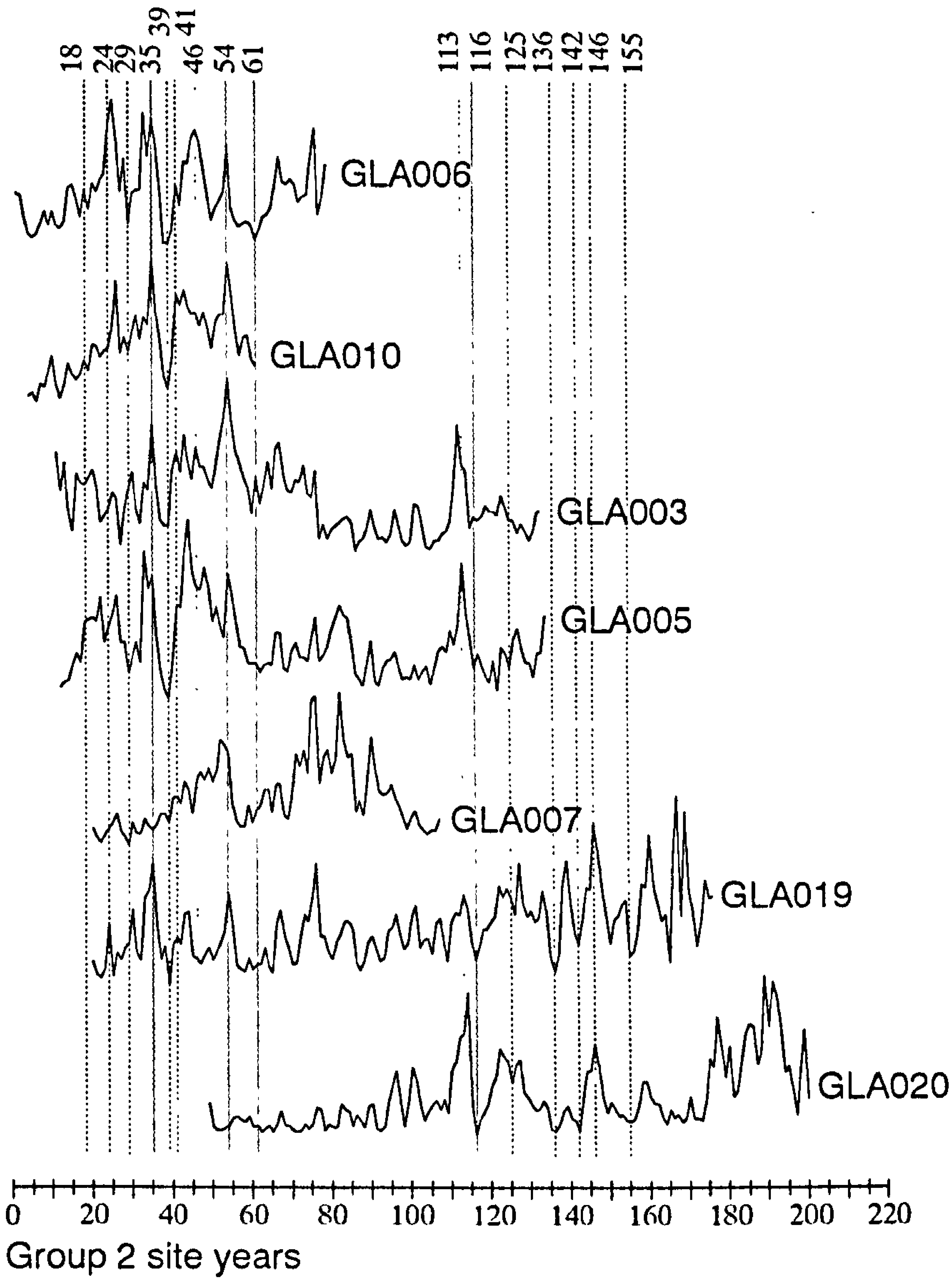


Figure 3.9. Loch Glascarnoch Group 2.
Raw value curves in their crossmatched positions.

3.2.3 ^{14}C dating

One ^{14}C date (SRR-5799) was obtained for subfossil wood at this site. This sample was taken from rings 77-127 of GLA005 (Group 2 site years 98-148). This yielded an uncalibrated age of 5975 ± 40 radiocarbon years, and a calibrated age range as follows:

Cal BC 4940 (4896, 4882, 4845) 4778 (2σ)

This would suggest the following 2σ range of dates for the origin of the first tree in Group 2:

5063 - 4901 Cal years BC

and a 2σ range of:

4853 - 4691 Cal years BC

for the death of the last tree in the group, based on the centre ring of the sequence at Group 2 site year 123. Group 1 remains undated.

These dates are about 1500 calendar years earlier than the other dates in this study and previous dates from subfossil wood in the far north, thus placing Loch Glascarnoch apart from the other sites investigated here. Though Group 1 is undated its stratigraphical context suggests that it lies nearer in time to Group 2 than to the other sites studied. Comparisons of the characteristics of the individual trees with those on the other sites are in Inter-site Comparisons (Section 3.10) as is a fuller discussion of the significance of the ^{14}C dates.

3.3 Loch Vatachan

58° 02' 5" N 5° 21' 14" W, Nat. Grid Ref. NC(29)020098

Figure 3.10, Plate 3.

3.3.1 Site Description

Loch Vatachan is the most westerly of the sampled sites, about 10 km to the north and about 45 km west of the most northern present-day natural pines at Glen Einig. The site lies in a shallow valley that runs about 5 km from north to south, joining the sea at Achnahaird Bay (on the edge of the much larger Enard Bay) in the north, to the sea at Badentarbat Bay in the south (Fig. 3.10). The highest point of the valley is at 27 m OD at its southern end, about 500 m from the sea. The bulk of the valley floor to the north lies below the 10 m contour and contains, in order from the south, Loch Vatachan, Loch Raa and the extensive sandy beach and dune system in Achnahaird Bay. Because of its

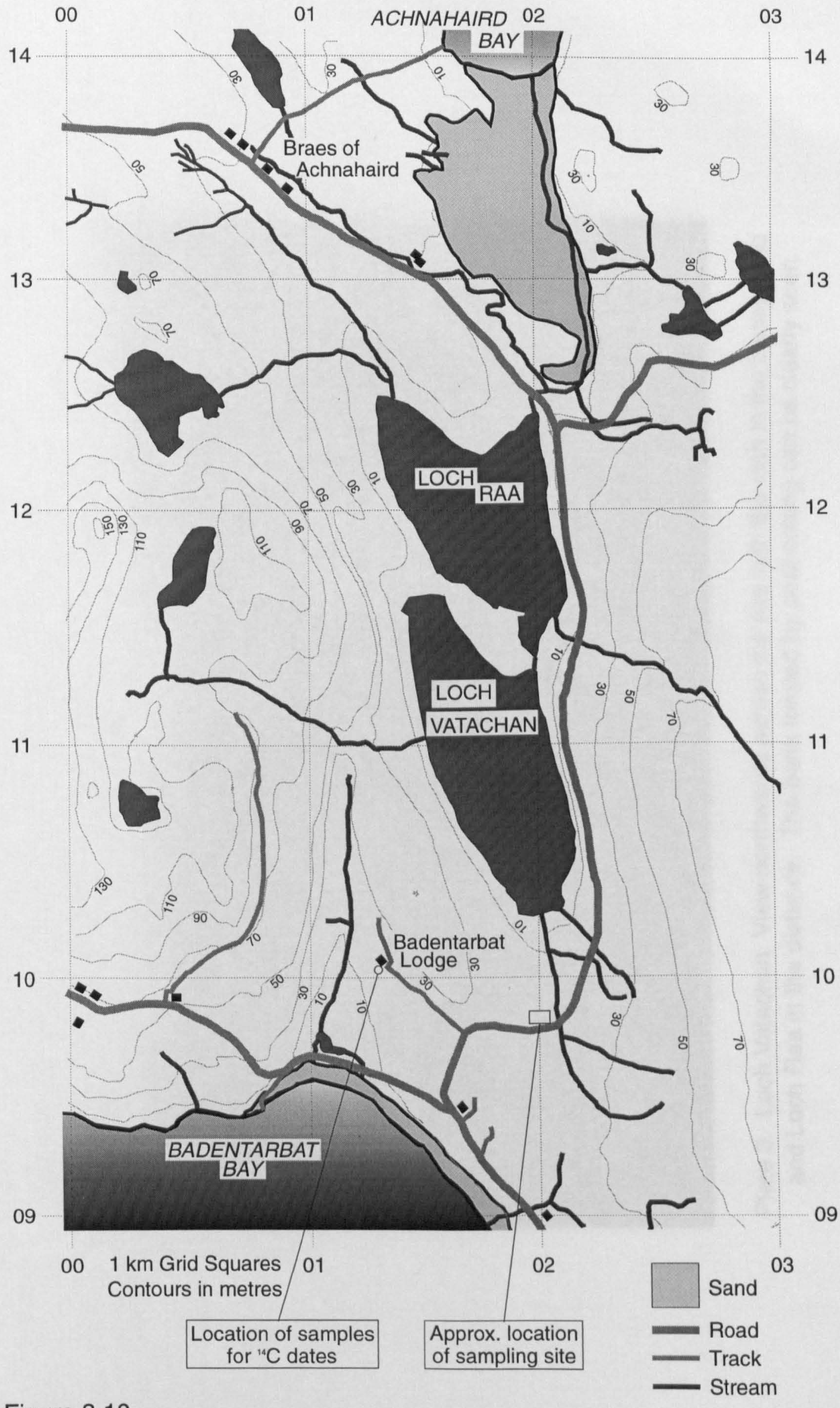


Figure 3.10.
Loch Vatachan - showing the location of the sampling site
For ^{14}C dates (NPL-13, NPL-14) see Section 3.3.3.

Plate 3. Loch Vatachan. View northwards across the site with the loch in the background and Loch Raa in the distance. The bank formed by peat cutting can be clearly seen.

low altitude it has been suggested that the valley once formed a southwards extension of the sea at the time of the Main Postglacial Transgression (Lawson, 1995). To the west the valley is sheltered by peat covered hills lying within 1 km and rising to a height of 200 m in places; to the east the ground rises steadily to the mountains of the Inverpolly National Nature reserve with peaks above 700 m about 12 km away. This rising ground is split by a long glen which links Achnahaird Bay and the mouth of Strath Kanaird 35 km to the south east. To the north and west of the valley a low peninsula, covered with blanket peat and containing a number of small lochs stretches to the point of Rubha Coigeach about 7 km away.

The underlying rocks of the area are Torridonian sandstones and grits, but the valley floor itself is on Cambrian pipe-rock and basal quartzite covered with peaty gleys, peat, and some peaty podzols. The vegetation around the sampling site is dominated by heather (*Calluna vulgaris*) in the drier areas, deer grass (*Trichophorum cespitosum*), with *Erica tetralix* and *Spagnum* spp. in the wettest patches. Today the area is treeless and extremely exposed to winds from off the sea both to the north and south (Lamb, 1964).

There is some evidence of early human settlement in the area, particularly the hut circles and enclosures at Achiltibuie about 1 km south of the sampling site. However Pennington *et al.* (1972) suggest that the earliest evidence of anthropogenic influence on the vegetation of the region dates from 1520 ± 100 BC, rather later than the final decline of pine in the region. These authors also comment on the pine from nearby Badentarbat (Lamb, 1964, and see Section 1.2 above and Fig. 3.10) and in a small pollen profile from there they found no evidence of human involvement in the decline of pine locally.

The site itself is an area of old cuttings in blanket peat, at an altitude of just below 20 m on a gentle slope that runs down to the shore of Loch Vatachan about 500 m to the north. Where the surface peat has been removed, pine stumps are visible amongst the vegetation that has colonised the exposed surface. As is usual in this kind of cutting, banks have been left between the areas of extraction, and stumps and roots can also be seen protruding from the sides of these. From the top of one of these banks the total depth of peat was 1.75 m. A monolith was cut from the upper 90 cm of the peat at this point. However, it is not certain that the top of the bank represents the original peat surface, though there is no evidence that cut material has been dumped there.

The remains of 37 trees were counted in a measured area of 2360 m^2 (0.236 ha) on the site suggesting a minimum density of about 157 stumps ha^{-1}. From these remains 28 samples were recovered for dendrochronological analysis.

3.3.2 Dendrochronological Results

These, like those for Loch Glascarnoch above, are summarised in a series of tables and figures, the conventions of which are the same as for that site.

3.3.2.1 General statistics

Table 3.5 gives general statistics for the individual trees measured. Of the 28 samples recovered all but one (VAT023) proved measurable. The mean number of rings per sample was 85.6, with a maximum of 152 and a minimum of 36, the latter too short for crossmatching. The mean annual increment for the site is less than 1 mm though the variance is quite high with 3 trees having a mean ring-width greater than 1.5 mm.

3.3.2.2 Mean growth curve

The mean growth curve (Figure 3.11), based again on those trees with complete centres, shows a rise at the beginning of the trees' growth, peaking at about 20-25 years, with a subsequent decline till about 85 years. Thereafter the variance increases as the number of trees left in the mean decreases. Again some of the longer sequences, for instance VAT006 and VAT015, show increasing ring-widths at the end of their lives. However, in this context, VAT020 (Fig. 3.14), with extremely narrow rings from around ring 60 to its end at ring 141 (the smallest is only 0.02 mm) is worth noting, although it is not included in the mean growth curve as its centre is missing.

3.3.2.3 Site crossmatching

Table 3.6 summarises the crossmatching results for Loch Vatachan, in the same format as for the previous site. At the Loch Vatachan site the successfully matched trees formed a single group, unlike those at Loch Glascarnoch. The density of stumps on the site was calculated as indicated in Section 3.3.1 above, and from this and the proportion of stumps successfully crossmatched a figure of 124 ha^{-1} was derived for the maximum density of trees alive at any one time. This was calculated as follows:

$$D_{alv} = \frac{N_{mat}}{N_{coll}} \times D_{stu} \qquad (14)$$

where: D_{alv} = maximum density of stumps alive at any one time

N_{mat} = maximum number of crossmatched stumps alive at any one time

N_{coll} = number of stumps collected

and: D_{stu} = density of stumps on site

Also given in Table 3.6 is an establishment rate for the main recruitment phase on this site. The origin of this is more clearly seen in Figure 3.12, which shows the crossmatching graphically. From this figure it can be seen that the crossmatched trees show a single phase of recruitment spanning 38 years, though their apparent death dates

Table 3.5. Loch Vatachan: summary statistics based on the mean radius for each sample measured

Tree	Number of rings	Mean radius (cm)	Mean ring-width (mm)	SD of ring-widths	Sensitivity	First order autocorr.
VAT001	64	6.1	0.96	0.51	0.30	0.71
VAT002	49	7.0	1.44	0.93	0.31	0.79
VAT003	80	6.5	0.81	0.38	0.36	0.59
VAT004	76	10.4	1.37	1.00	0.26	0.85
VAT005	36	7.0	1.93	0.93	0.25	0.78
VAT006	152	9.8	0.65	0.37	0.34	0.55
VAT007	89	13.6	1.53	0.76	0.25	0.72
VAT008	81	3.4	0.42	0.27	0.44	0.34
VAT009	69	6.2	0.90	0.59	0.31	0.79
VAT010	75	6.8	0.91	0.61	0.36	0.83
VAT011	57	5.2	0.91	0.58	0.39	0.50
VAT012	109	6.6	0.61	0.40	0.36	0.68
VAT013	130	6.8	0.52	0.43	0.44	0.75
VAT014	95	7.1	0.74	0.47	0.32	0.71
VAT015	148	8.8	0.60	0.40	0.34	0.75
VAT016	61	4.7	0.77	0.48	0.39	0.53
VAT017	67	5.0	0.74	0.43	0.35	0.43
VAT018	78	6.8	0.87	0.71	0.44	0.59
VAT019	98	6.9	0.70	0.40	0.36	0.67
VAT020	142	21.7	1.53	1.36	0.22	0.93
VAT021	69	5.4	0.79	0.51	0.35	0.41
VAT022	61	5.9	0.96	0.77	0.35	0.80
VAT024	72	4.7	0.66	0.53	0.36	0.80
VAT025	111	6.2	0.56	0.40	0.37	0.72
VAT026	86	5.6	0.66	0.35	0.29	0.77
VAT027	87	6.6	0.75	0.71	0.38	0.73
VAT028	69	5.4	0.78	0.42	0.36	0.53
Mean	**85.6**	**7.27**	**0.891**		**0.342**	**0.676**
SD	**29.7**	**3.52**	**0.361**		**0.057**	**0.147**

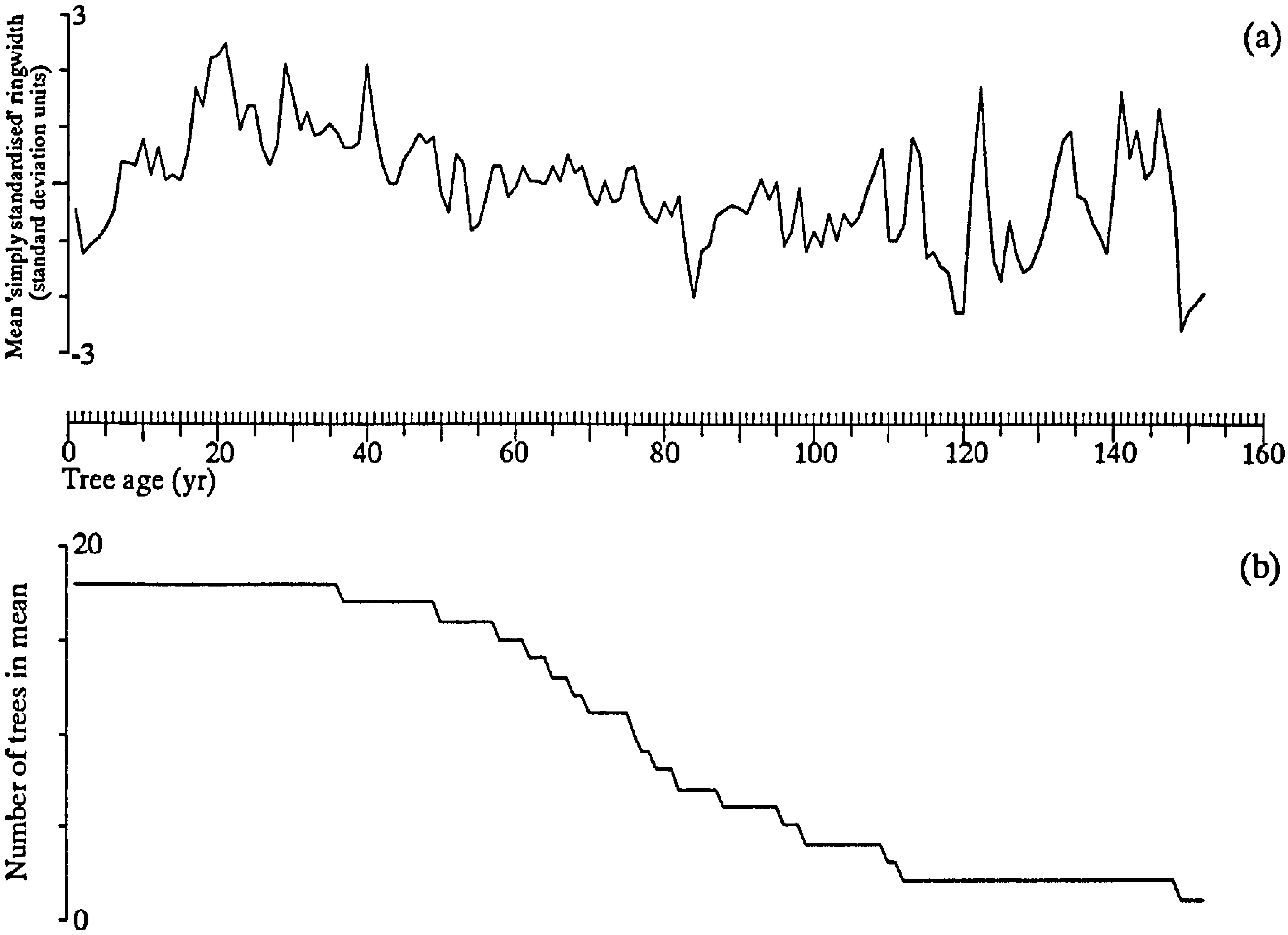


Figure 3.11. (a) - Mean growth curve for the trees at Loch Vatachan (see Section 3.3.2.2)
(b) - Number of trees included in the mean.

Table 3.6. Loch Vatachan - summary of crossmatching positions plus maximum recruitment rate and density.

TREE		MIN AGE	MATCH POSITION (site years)	DEATH (minimum - site years)	
VAT001		63			not matched
VAT002		48			not matched
VAT003		79	39	117	centre indistinct
VAT004	c	75	37	111	centre damaged
VAT005		35			not matched
VAT006	c	151	24	174	
VAT007	c	88	17	104	centre damaged
VAT008		80	21	100	
VAT009		69			not matched
VAT010		74	19	92	
VAT011		56	33	88	
VAT012		108	23	130	
VAT013		129	32	160	centre damaged
VAT014	c	94	6	99	
VAT015	c	147	1	147	
VAT016		60	32	91	
VAT017		66	24	89	
VAT018	c	77	13	89	
VAT019		97	34	130	
VAT020	c	141	11	151	centre missing
VAT021		68	22	89	centre distorted
VAT022		61			not matched
VAT023					not counted
VAT024		71	39	109	centre damaged
VAT025		110	4	113	bark present
VAT026		85	25	109	centre missing
VAT027	c	86	13	98	
VAT028		68	28	95	

(c denotes use in site chronology)

Samples recovered: 28. Samples successfully crossmatched: 22 (79%)

Establishment rate during recruitment phase (site years 1 - 38): 3.1 trees ha^{-1} $year^{-1}$.

Density of stumps on site: 157 ha^{-1}.

Maximum density of trees alive at any one time: 124 ha^{-1}

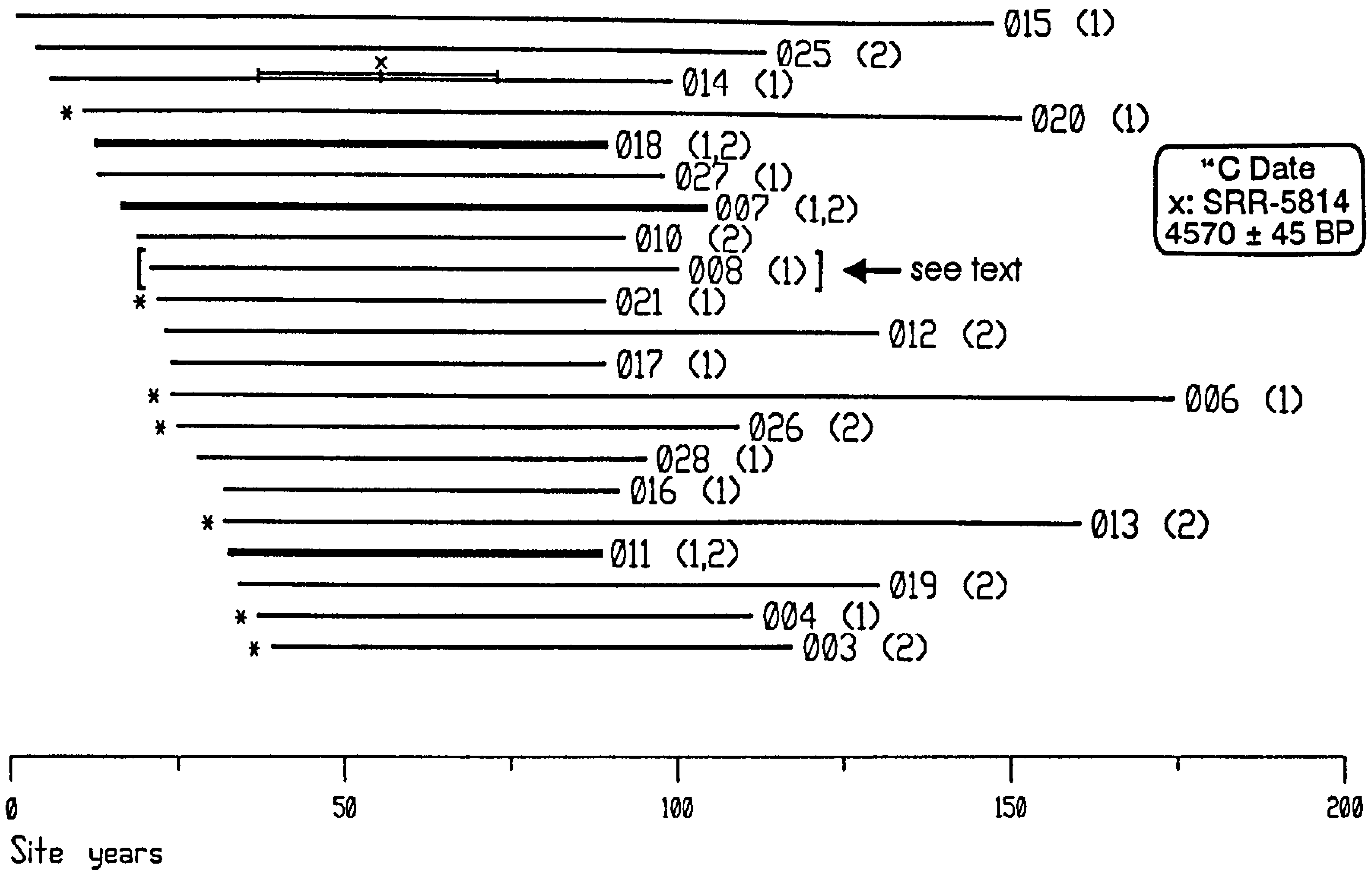


Figure 3.12. Loch Vatachan - crossmatched trees. The lines represent individual life spans, the asterisks indicating a missing centre to the tree. The numbers are the sample numbers (the prefix VAT is omitted) the numbers in brackets indicating the sub-group to which the tree belongs. The three heavy lines indicate the trees that belong to both sub-groups. The double line indicates the span of rings used for ^{14}C dating, with x indicating the point taken as the centre (see text).

are much more scattered. Overall occupation of the site by the crossmatched trees spanned a minimum of 174 years. The division of the trees into sub-groups is based on the main affinities in the crossmatching as shown in Figure 3.13, the raw sequences for the two sub-groups being shown in Figures 3.14 and 3.15. Figure 3.13 suggests that the sub-groups are linked by crossmatches based on VAT007, VAT011 and VAT018. These matches are weak (with the exception of VAT011/VAT019) and not well replicated. In sub-group 1 the quality of matching and replication are generally higher than at the previous site. VAT008 is included in Figures 3.12 and 3.14 because of its strong visual match, but is excluded from Figure 3.13 and calculations of means because of poor statistical crossmatching.

3.3.2.4 Mean ring-widths for site and site chronology

Figure 3.16a shows the ordinary mean ring-widths for the site based on all the crossmatched trees in both sub-groups, with the number of trees present in the mean year by year in Figure 3.16b. Of particular note are the peaks at 21-23 site years and 52 site years and the trough at 116-119 site years. The first of the peaks occurs in the most rapid section (see Fig. 3.12) of the recruitment phase when 10 of the crossmatched trees had become established. The second and largest peak occurs during the maximum occupancy of the site, and the trough when there are still 7 trees surviving. However similar low values to those in the trough do occur at the very beginning and towards the end of the sequence where few trees are included in the mean and the variance is high.

Figure 3.16c shows the robust mean chronology constructed for the site and used in subsequent attempts at inter-site crossmatching, with Figure 3.16d showing the number of trees in this mean. This chronology is based on the most securely matched trees indicated in Table 3.6 (see also Figure 3.13).

It should be born in mind that the ring sequences from this site are on the whole very short for crossmatching, the suggested matches relying heavily on visual matching (particularly the peak at site year 52) for confirmation.

3.3.3 ^{14}C dating

The ^{14}C date (SRR-5814), taken from rings 32-68 (site years 37-73) of VAT014, was 4570 ± 45 radiocarbon years, which on calibration gave the following calendrical estimated age range:

Cal BC 3494(3346)3099 (2σ)

This suggests the following 2σ range of dates for the origin of the site year axis:

3549 - 3154 Cal years BC

TREES — SUB-GROUP 1 / SUB-GROUP 1+2 / SUB-GROUP 2

VAT	014	020	027	021	017	006	028	016	004	018	007	011	025	010	012	026	013	019	003
015	4.31**	n/s	4.69**	3.42*	7.62***	5.99***	5.57***	5.13**	4.51**	n/s	5.1**	n/s							
A	014	5.31***	6.01***	7.15***	5.89***	4.67**	5.8***	4.48**	3.67*	n/s	6.36***	n/s							
n/s	A	020	n/s	4.21**	4.77**	n/s	n/s	n/s	3.97*	n/s	n/s	n/s							
C	A	n/s	027	6.0***	7.99***	5.11**	8.87***	7.28***	6.27***	4.13**	8.37***	3.96**							
C	B	B	B	021	5.91***	n/s	5.27***	n/s	n/s	3.83**	6.47***	n/s							
B	B	C	C	B	017	5.78***	6.55***	5.97***	n/s	5.65***	7.42***	s/o							
A	A	n/s	A	n/s	B	006	6.68***	7.22***	5.61***	5.62***	4.62**	n/s							
B	B	n/s	C	B	B	B	028	5.94***	6.97***	7.12***	5.31***	5.36***							
B	B	n/s	B	n/s	B	B	B	016	5.12***	4.75***	4.48**	3.77**							
C	C	C	B	n/s	n/s	A	B	B	004	s/o	4.01**	s/o	025	010	012	026	013	019	003
n/s	n/s	n/s	A	B	B	B	B	B	n/s	018	n/s	4.63***	n/s	n/s	n/s	n/s	n/s	3.92*	n/s
A	A	n/s	A	B	B	A	B	C	B	n/s	007	s/o	n/s	n/s	n/s	n/s	n/s	n/s	3.45*
n/s	n/s	n/s	B	n/s	s/o	n/s	B	B	B	B	s/o	011	n/s	3.91**	n/s	s/o	n/s	4.87***	n/s
015	014	020	027	021	017	006	028	016	004	n/s	n/s	n/s	025	5.39***	6.09***	6.73***	4.91**	n/s	5.28***
VAT										n/s	n/s	B	A	010	8.94***	7.81***	n/s	4.18**	n/s
										n/s	n/s	n/s	A	B	012	8.68***	4.44**	4.75**	4.09**
										n/s	n/s	s/o	A	B	A	026	4.48**	4.33**	n/s
										n/s	n/s	n/s	A	n/s	A	A	013	n/s	n/s
										C	n/s	B	n/s	C	A	A	n/s	019	n/s
										n/s	C	n/s	A	n/s	A	n/s	n/s	n/s	003
										018	007	011	025	010	012	026	013	019	003
																			VAT

TREES

CROSSMATCHING QUALITY

UPPER RIGHT
Values of 't' and multiple probabilityfor Baillie and Pilcher filter.
* - 0.1>P>0.01 ** - 0.01>P>0.001 *** - P<0.001

LOWER LEFT
Match significant if P < 0.05 and F > 5.0
A - All 3 filters give the same match position and all matches are significant. Minimum overlap is 50 rings.
B - As A but minimum overlap is 30 rings.
C - As B but only 1 or 2 matches significant.

n/s - not significant
s/o - short overlap (< 54 rings, ie 50 rings plus those lost in the B & P filter)

REPLICATION: This table shows the number of significant matches in which the tree is present.

TREE	MATCHES	TREE	MATCHES	TREE	MATCHES
VAT015	9	VAT028	11	VAT010	5
VAT014	10	VAT016	10	VAT012	6
VAT020	4	VAT004	9	VAT026	5
VAT027	11	VAT018	8	VAT013	3
VAT021	6	VAT007	10	VAT019	5
VAT017	10	VAT011	7	VAT003	3
VAT006	9	VAT025	5		

Figure 3.13 Loch Vatachan crossmatching. This diagram shows the significant crossmatches between trees with the quality and replication of those matches

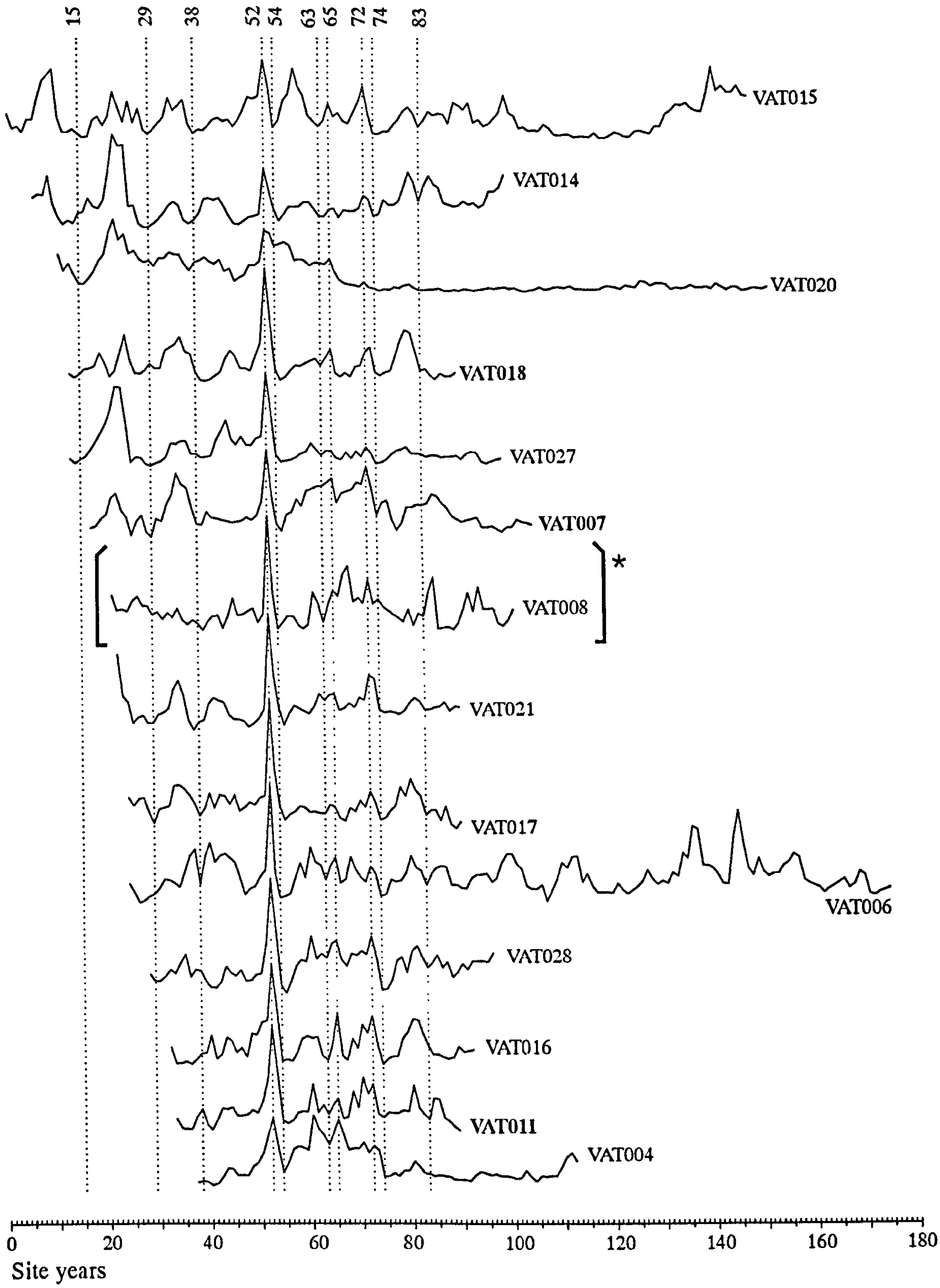


Figure 3.14. Loch Vatachan crossmatching - Sub-group 1
Trees numbered in bold link sub-groups 1 and 2
(* - see text.)

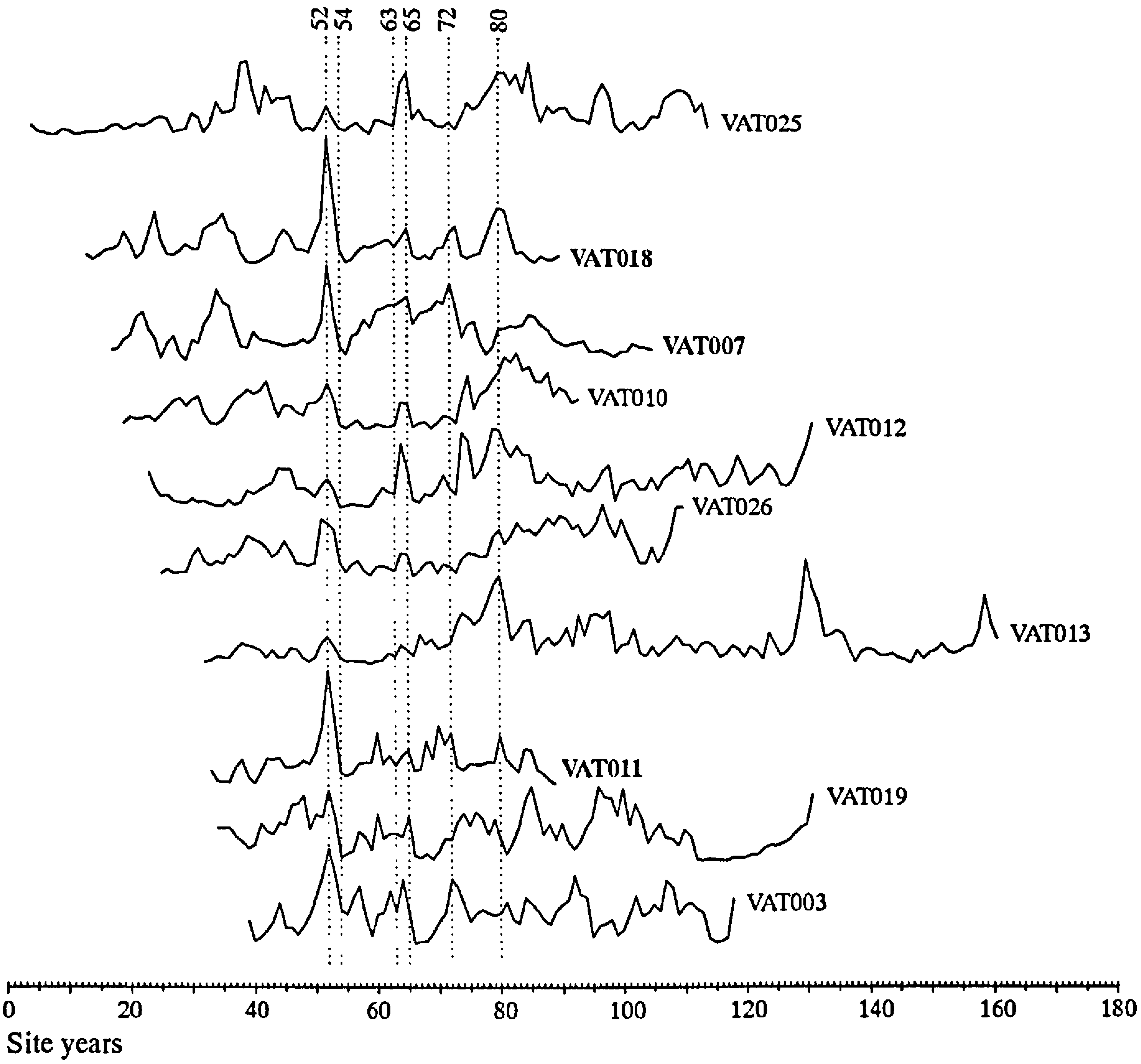


Figure 3.15. Loch Vatachan crossmatching - Sub-group 2
Trees numbered in bold link sub-groups 1 and 2

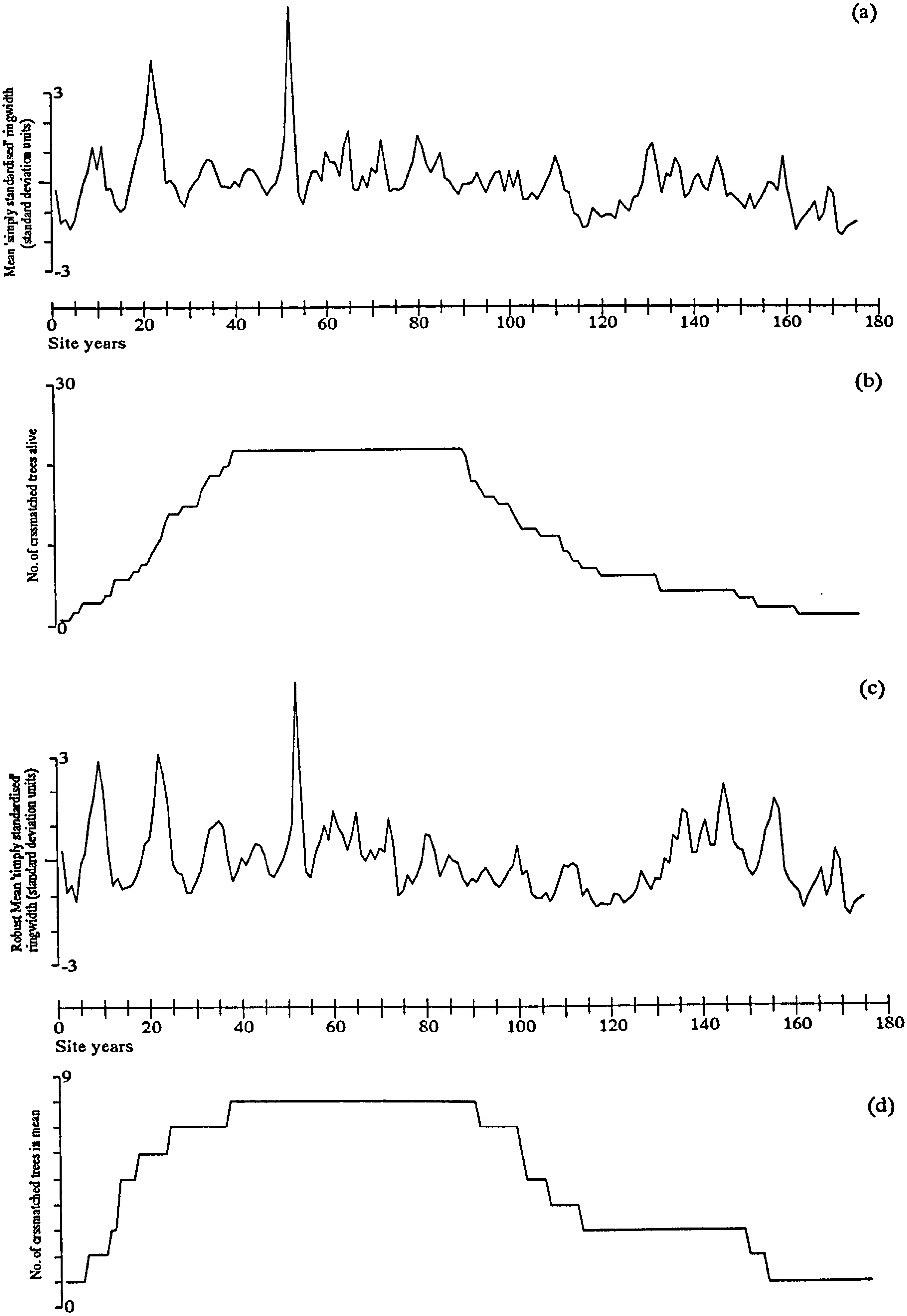


Figure 3.16. Loch Vatachan: (a) - mean ring-widths for the site. Each mean ring-width is the average of the ring-widths for that particular year from the mean radii of all the crossmatched trees. (b) Number of crossmatched trees alive on the site, i.e. the number present in the mean year by year. (c) Robust mean chronology from selected trees (see text). (d) Number of trees in robust mean chronology year by year.

and a 2σ range of:

3375 - 2980 Cal years BC

for the death of the last crossmatched tree, based on the centre ring of the dated sequence at site year 55.

Two other dates for subfossil pine are available from the site described by Lamb (1964) at Badentarbat Lodge about 750 m from the sampling site (Fig. 3.10). These are NPL-13 and NPL-14, with uncalibrated radiocarbon ages of 4420 ± 102 and 4220 ± 105 years BP respectively. These, calibrated as above, give calendar dates of:

Cal BC 3365 (3040) 2787 (2σ)

and:

Cal BC 3076 (2880, 2790) 2492 (2σ)

i.e. ranges of 3365 to 2787 and 3076 to 2492 calendar years BC.

The first of these, NPL-13 and the date obtained in the present study, SRR-5814, are statistically indistinguishable (Stuiver and Reimer, 1993). NPL-14 appears to be about 200 calendar years younger. Again these results are discussed in context in Section 3.10 later.

3.3.4 Pollen and Tephra Results

A monolith was cut from the face of one of the banks left between the old peat cuttings described in Section 3.3.1 as shown in Figure 3.17 below (see also Plate 3):

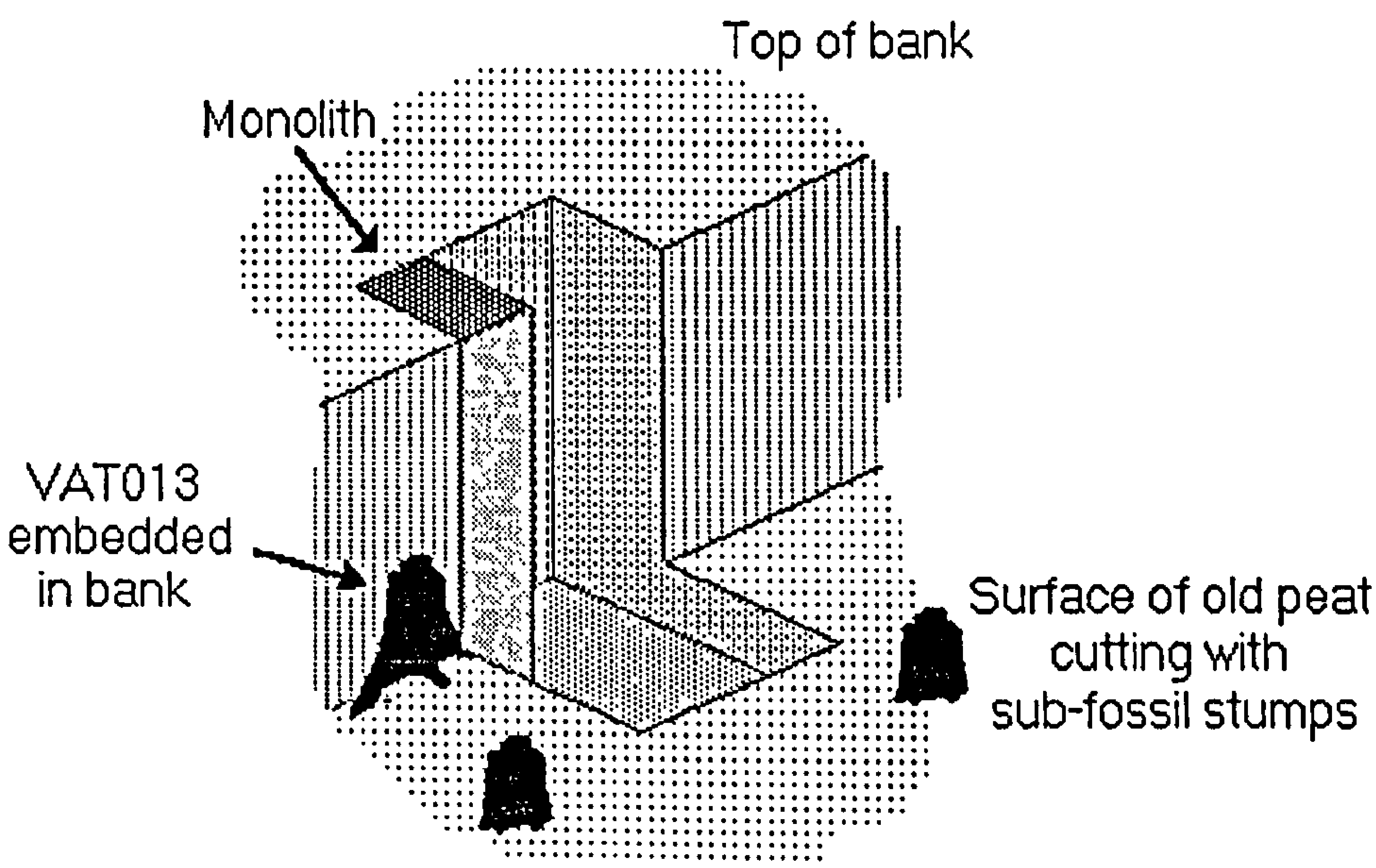


Figure 3.17. Cutting of peat monolith at Loch Vatachan.

This extended down to about 90 cm depth from the surface, but because of the peat workings it was not certain that this surface was original. The peat block was cut next to VAT013, the level of the base of the buttress root of the stump being shown in the outline stratigraphy, Figure 3.18. The monolith was stored and sampled as described in Section 2.6 and the results are shown as pollen percentages in Figure 3.19 and pollen concentrations in Figure 3.20. There is one *Pinus* pollen peak greater than 20% of the total pollen count centred on 77 cm, and its prominence on the pollen concentration diagram (Fig. 3.20) relative to the other taxa, none of which show any marked changes at the same level, suggests that it reflects the local pine indicated by the subfossil stumps. Looking in detail at events around this peak, the high level of *Betula* pollen shown at the bottom of the diagrams at 88 cm tallies with birch fragments found in the lowest 10 cm of the profile. The decline in the *Betula* above this is closely followed by a rise in *Sphagnum* and *Alnus* values at 86 cm which in turn give way to rising levels of *Calluna* (83 cm) and *Pinus* (80 cm and 77 cm). This suggests that the birch presence was reduced following a period of increased wetness on the peat surface (the *Sphagnum* peak) and that the birch was possibly replaced at the edge of the loch by alder. Then as the climate became drier again the peat was covered by heather with eventually pine. The high values of *Pinus* are succeeded by a period (73 - 65 cm) of markedly reduced pollen concentrations in all taxa except *Salix* (a peak at 71 cm) and a later peak in *Sphagnum* (67 cm).

The X-ray analysis shows little of note in the profile, the closeness of the sea suggesting that layers of opaque material in the top 25 cm are wind-blown sand. However a few shards of tephra, similar in appearance to those from the Srath Dionard site (see below) chemically identified as most likely from Hekla 4, were found at the 56 cm level during pollen counting. Though sparse, the presence of tephra in the pollen preparations suggests the potential for successful extraction and identification at some later date (J. Pilcher, pers. comm.) and their appearance and position in the sequence at Loch Vatachan relative to the *Pinus* pollen peak is consistent with their being from the Hekla 4 eruption. This supposition is further supported by comparisons with the other sites which are given later.

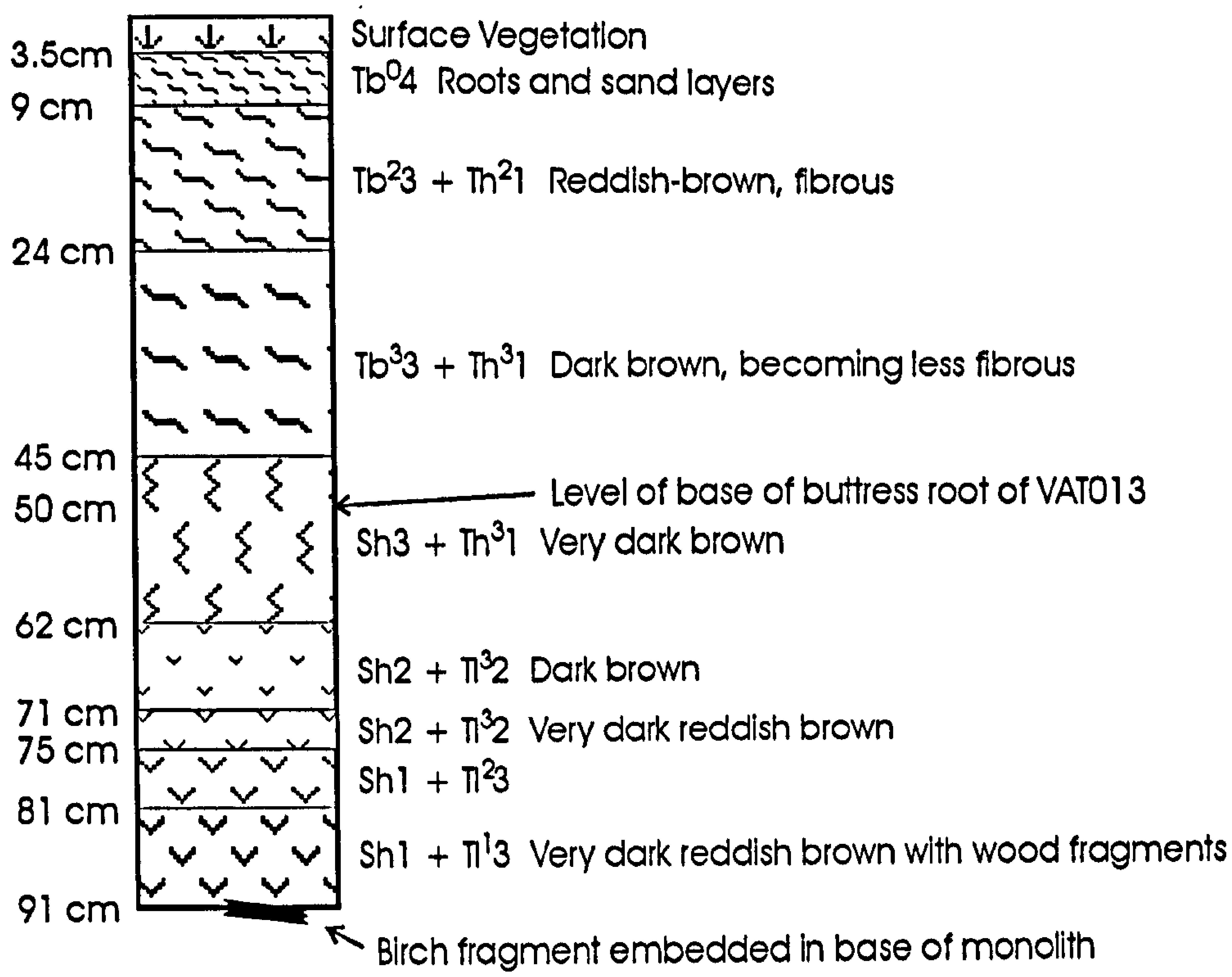


Figure 3.18. Loch Vatachan monolith - outline stratigraphy
Sediment description symbols as defined byTroels-Smith (1955)

Figure 3.19. Loch Vatachan pollen percentages. The 'T' horizon indicates the level at which tephra shards were found.

Figure 3.20. Loch Vatachan pollen concentrations - selected taxa. The 'T' horizon is the level at which tephra shards were found.

3.4 Loch Shin (Fiag Bridge)

58° 08' 27" N 4° 35' 24" W, Nat. Grid Ref. NC(29)476197

Figure 3.21, Plate 4.

3.4.1 Site Description

Loch Shin, over 27 km in length, is the largest loch in the north of Scotland. It lies at an altitude of just below 100 m above OD in a south-east to north-west orientation, in a long trough linking the west coast at Laxford Bridge to the east coast at Bonar Bridge and the Dornoch Firth. To the north and east of this trough, beyond a band of high ground which includes the summits of Ben Klibreck in the south and Foinaven and Arkle at its north-western end, lie the large expanses of blanket peat described in the introduction. The higher ground to the south and west includes the Ben More Assynt group of summits at its western end, but is divided by Glens Cassley and Oykel which run roughly parallel to the Loch Shin trough. Glen Einig, containing the most northerly group of surviving natural Scots Pines, is a branch of Glen Oykel about 20 km south of the north-western end of Loch Shin itself.

The underlying rocks of the area are predominantly quartz-feldspar-granulites of the Moine Group. The soils surrounding most of the loch are peat, peaty gleys and peaty podzols, though around the south-eastern shores of the loch by Lairg there is an area of better soils suitable for rough pasture. These may well include the remnants of previous attempts at land improvement. In this connection there is a small outcrop of marble on the Airde (NC(29)521150 - Table 3.2 and Figure 3.2)), a headland 9 km south-east of the main sampling site, Fiag Bridge (see Figure 3.21) on the northern shore of the loch near Shinness. This marble was quarried and roasted in lime kilns, which still survive on the site, and used for land improvement around Lairg in the nineteenth century.

Loch Shin was dammed at Lairg at its south-eastern end to form a reservoir in the late 1950s (the Act of Parliament was passed in 1953) and the level of the loch was raised 37 feet (about 11 m) in consequence. The resulting increase in surface area, especially where the slopes are gentler on the north-western shore has led to the erosion of large areas of the *Calluna* and *Trichophorum* covered blanket peat forming the shore. The edge of the loch is littered with washed-up tree roots and on inspection many of these appear to be remains of recent plantation, felled before the raising of the loch surface. However, where the blanket peat comes down to the shoreline on the north-western edges of the loch, stumps can be seen protruding from its eroded face. These are clearly of much greater antiquity than the plantation material, and from them a group was selected for study at a site near Fiag Bridge, about two thirds of the way up the loch on its northern shore (Figure 3.21).

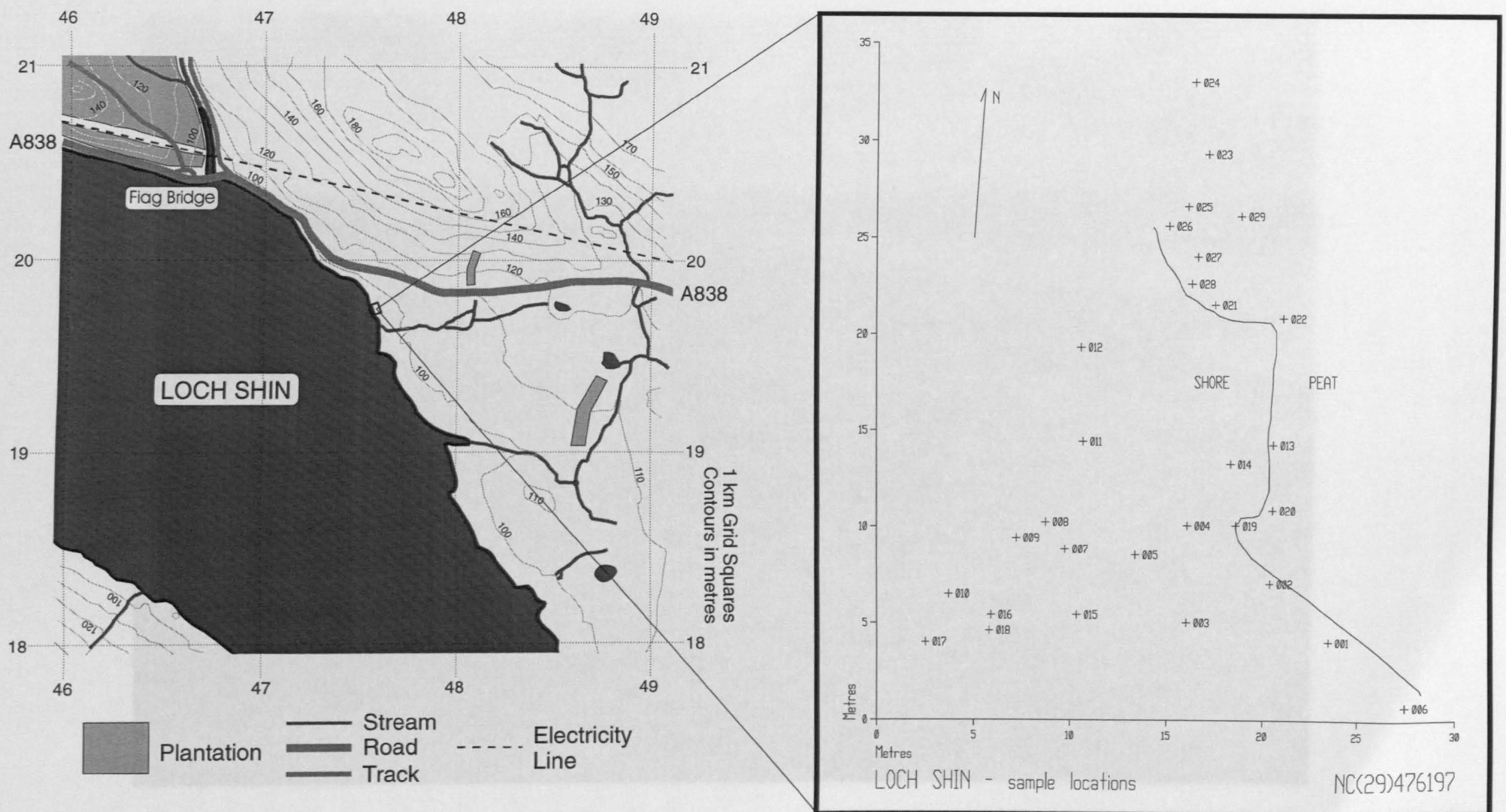


Figure 3.21. Loch Shin -location and plan of the sampling site

Plate 4. Loch Shin study site, looking west. The sampled stumps were embedded in the area of peat in the middle distance.

The plan of the site shows all the sampled stumps together with the apparent boundary of the peat surface. The shore is covered with stones, among which the tops of some of the stumps are visible. Probing revealed that, like the stumps protruding from the peat surface, those on the shore were actually rooted in peat, the stones having been washed in after the formation of the reservoir. A hypothetical section of the site is shown in Figure 3.22 below:

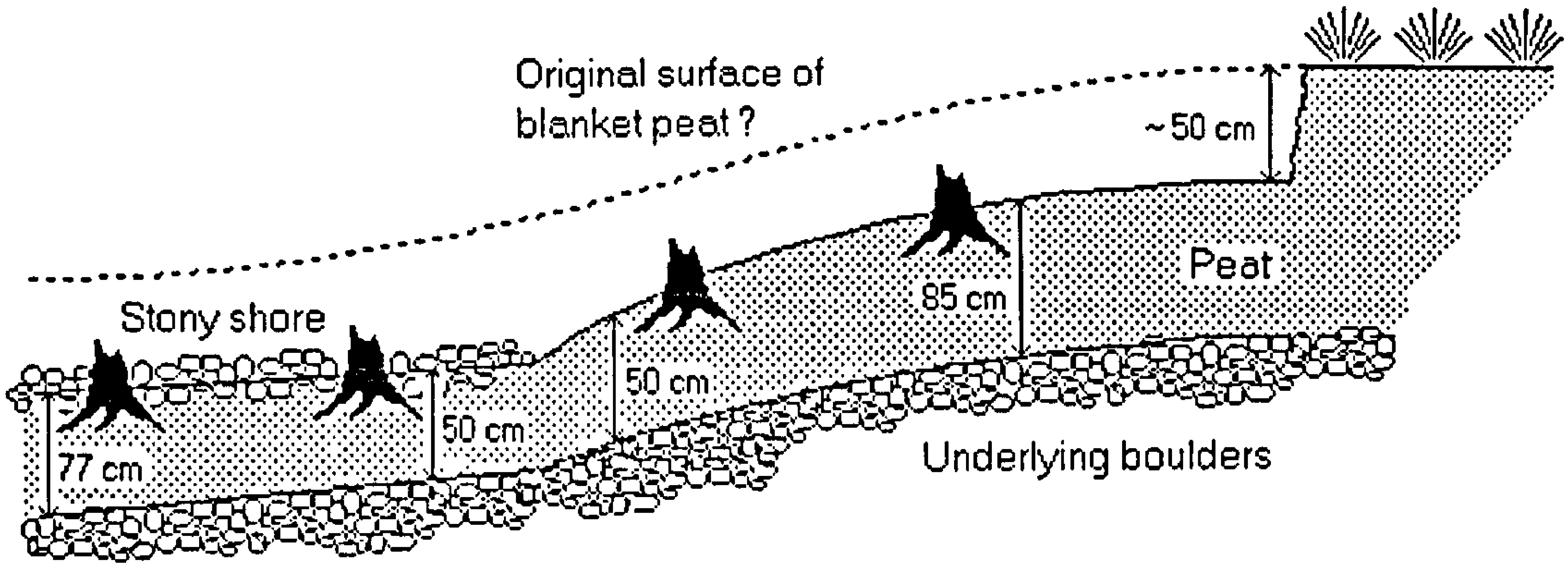


Figure 3.22. Hypothetical section through the sampling site at Fiag Bridge, Loch Shin.

Based on the plan in Figure 3.21, a density of 504 stumps ha^{-1} was estimated for the immediate area of the site. 29 samples were obtained and all proved measurable.

In addition, the stumps of about a dozen pines were found protruding from the peat on the beach at the Airde (Table 3.2 and Figure 3.2) close to the ruins of the lime kilns mentioned earlier. These were very large compared with those at Fiag Bridge, and an attempt was made to sample them for dendrochronology, but they were in very poor condition. However a ^{14}C age was obtained for one of these samples (see below).

Because of the eroded state of the peat bank at the site where the stumps were sampled at Fiag Bridge it was not possible to cut a monolith at the site itself, so this was done about 50 m back along the shore towards the road, where an exposed vertical section between embedded pine remains was found. Also near this point two stumps were found in the peat bank directly superimposed on each other. These were sampled (SHI030 and SHI031) in order to establish whether two distinct layers of pine subfossils were present. Crossmatching proved possible (SHI030 at 2 on SHI31: $t = 3.73^*$ for the Baillie and Pilcher filter) though the lower of the two stumps (SHI031) was very distorted, showing that the trees were growing at the same time, the distortion being caused by the pressure of the upper trunk on the lower as they grew. Crossmatching of these with the main site is described below.

3.4.2 Dendrochronological Results

3.4.2.1 General statistics

Table 3.7 lists these as for the other sites in this study. The mean number of rings for the site was 115.1, with a maximum of 215 and minimum of 43, slightly higher figures overall than for the site at Loch Vatachan. The mean ring-width is rather smaller than that for that site, though one tree, SHI012, has a mean annual increment of over 2 mm, about twice that of the three next largest at around 1 mm. However at 47 rings, SHI012 is one of the shortest sequences measured at Loch Shin and contains a few very wide rings; overall it is not representative of growth on the site.

3.4.2.2 Mean growth curve

The mean growth curve is shown in Figure 3.23, and is of the same general form as for the previous sites. The curve rises to a peak at around 35 years, then falls off over the next 70 or so. Then, as for the other sites, the variance increases with a few long-lived trees left in the mean. Figures 3.26 and 3.27 show the individual tree curves, several of the longer ones showing a tendency to increase in ring-width towards the end of their lives, with narrower sequences before this. Notable exceptions are SHI001, 003, 004 and 006 with very narrow rings throughout the latter half of their lives.

3.4.2.3 Site crossmatching

Table 3.8 summarises the results of the site crossmatching for Loch Shin. As at Loch Vatachan all the crossmatched trees form a single group, with a high proportion (66%) of the samples collected successfully matched. The trees in parentheses in this table are those which show a possible match in the indicated position, but because of shortness or other causes these matches are not well replicated or statistically of high quality. Also as for the previous site, a maximum density of trees alive was calculated using Equation 14, yielding a value of 452 trees ha^{-1}. This figure may be somewhat high as an indication of the general tree cover in the area as the distribution may have been fairly uneven (it also includes the less securely matched trees described above). A recruitment rate was calculated for the main phase of establishment, this emerging as considerably higher than at Loch Vatachan at 22.3 trees ha^{-1} yr^{-1}.

The crossmatching is shown graphically in Figure 3.24 and suggests a recruitment phase, involving all the crossmatched trees on the site, lasting about 25 years. The overall span of occupation was at least 228 years, rather longer than at Loch Vatachan, and as at the other sites the apparent death dates are very scattered. Figure 3.25 shows the quality and replication of the crossmatching, which is generally of a higher quality than the other sites in this study. As at the previous sites, Figures 3.26 shows the raw value curves for the individual trees in their suggested matched positions. SHI011 is included for the

Table 3.7. Loch Shin: summary statistics based on the mean radius for each sample measured.

Tree	Number of rings	Mean radius	Mean ring-width (mm)	SD of ring-widths	Sensitivity	First order autocorr.
SHI001	183	11.4	0.62	0.39	0.25	0.73
SHI002	133	11.0	0.83	0.54	0.32	0.84
SHI003	134	9.7	0.72	0.45	0.29	0.76
SHI004	131	7.9	0.60	0.39	0.26	0.77
SHI005	123	7.2	0.58	0.31	0.32	0.68
SHI006	126	8.4	0.66	0.62	0.28	0.84
SHI007	78	6.6	0.85	0.51	0.22	0.89
SHI008	215	8.3	0.39	0.24	0.37	0.63
SHI009	100	7.1	0.71	0.42	0.29	0.67
SHI010	133	6.0	0.45	0.25	0.25	0.82
SHI011	96	7.8	0.82	0.34	0.26	0.73
SHI012	47	10.2	2.17	1.10	0.26	0.78
SHI013	76	6.8	0.90	0.53	0.27	0.62
SHI014	144	8.6	0.60	0.33	0.28	0.78
SHI015	73	6.2	0.85	0.38	0.25	0.76
SHI016	100	6.5	0.65	0.31	0.27	0.62
SHI017	149	6.7	0.45	0.24	0.27	0.82
SHI018	135	5.6	0.41	0.26	0.33	0.74
SHI019	126	7.4	0.59	0.36	0.31	0.74
SHI020	162	6.9	0.43	0.26	0.29	0.77
SHI021	167	9.5	0.57	0.28	0.27	0.67
SHI022	152	10.0	0.66	0.39	0.25	0.80
SHI023	52	4.7	0.90	0.37	0.26	0.70
SHI024	52	4.7	0.90	0.44	0.32	0.71
SHI025	59	6.1	1.04	0.95	0.33	0.88
SHI026	81	8.3	1.03	0.64	0.34	0.78
SHI027	56	3.8	0.68	0.34	0.24	0.61
SHI028	212	6.2	0.29	0.17	0.30	0.75
SHI029	43	4.4	1.01	0.40	0.25	0.62
Mean	**115.1**	**7.38**	**0.736**		**0.284**	**0.742**
SD	**48.3**	**1.95**	**0.341**		**0.036**	**0.078**

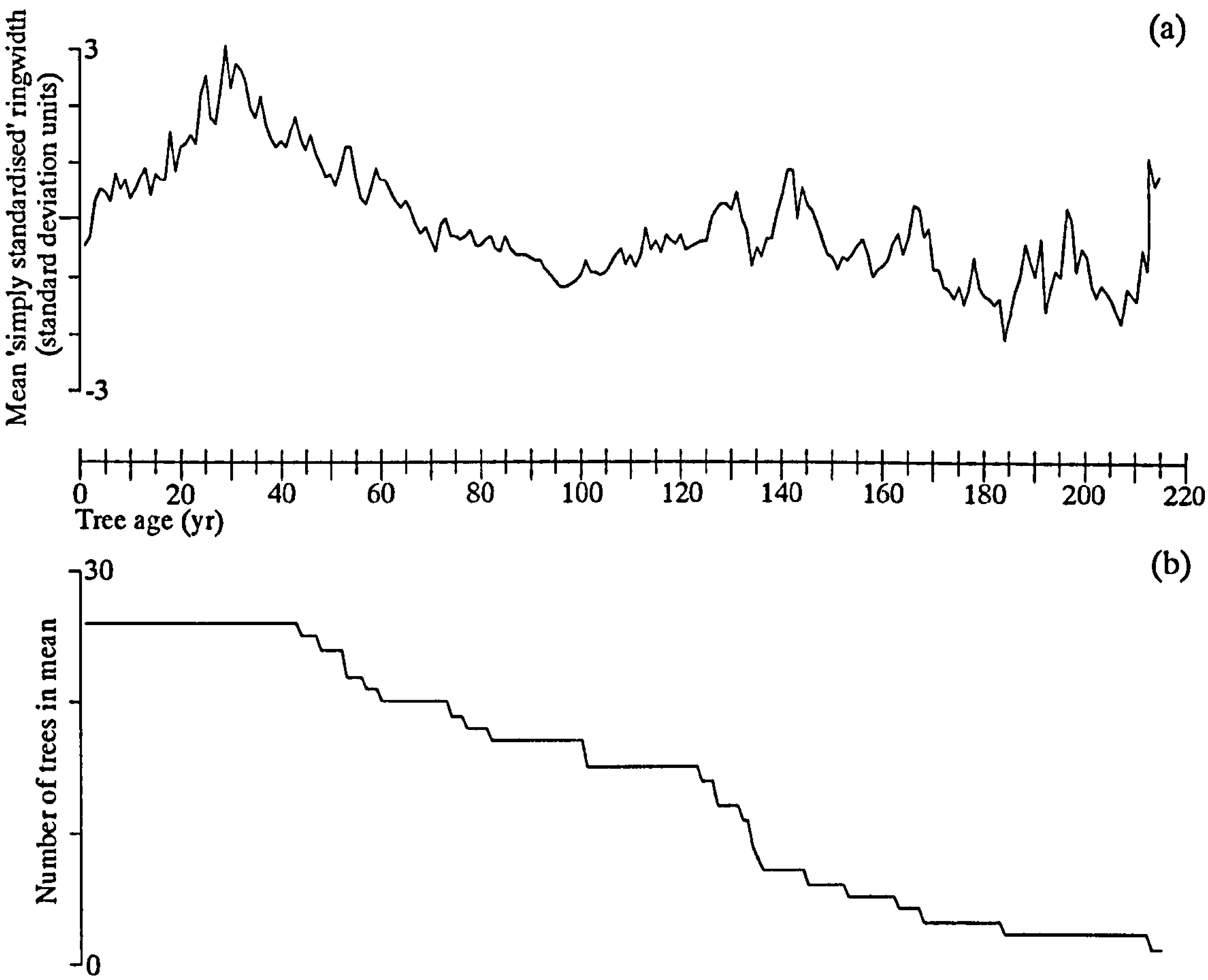


Figure 3.23. (a) - Mean growth curve for the trees at Loch Shin (see Section 3.4.2.2)
(b) - Number of trees included in the mean.

Table 3.8. Loch Shin - summary of crossmatching positions plus maximum recruitment rate and density.

TREE		MIN AGE	MATCH POSITION (site years)	DEATH (minimum - site years)	
SHI001	c	183	9	191	
SHI002		133			not matched
SHI003	c	134	13	146	
SHI004	c	131	12	142	
SHI005	c	123	20	142	
SHI006	c	126	11	136	
SHI007	c	78	15	92	centre damaged
SHI008	c	215	5	219	
SHI009	c	100	6	105	
SHI010	c	133	17	149	
(SHI011		96	28	123	centre damaged)
(SHI012		47	47	93)	
SHI013	c	76	7	82	
SHI014	c	144	16	159	
SHI015		73	16	88	
SHI016	c	100	1	100	
SHI017	c	149	13	161	centre missing
SHI018	c	135	9	143	
SHI019	c	125	17	141	
SHI020	c	162	18	179	
SHI021	c	167	16	182	
(SHI022		152	14	190)	
SHI023		52			not matched
(SHI024		52	21	97)	
(SHI025		59	11	94)	
SHI026		81			not matched
(SHI027		56	17	97)	
SHI028		212	17	228	
(SHI029		43	24	91)	

(c denotes inclusion in site chronology)

Samples recovered: 29. Samples successfully crossmatched: 19 (66%)
(excluding those in parentheses above - see text)

Establishment rate during recruitment phase (site years 5 - 23): 22.3 trees ha^{-1} $year^{-1}$.

Density of stumps on site: 504 ha^{-1}.

Maximum density of crossmatched trees alive: 452 ha^{-1}

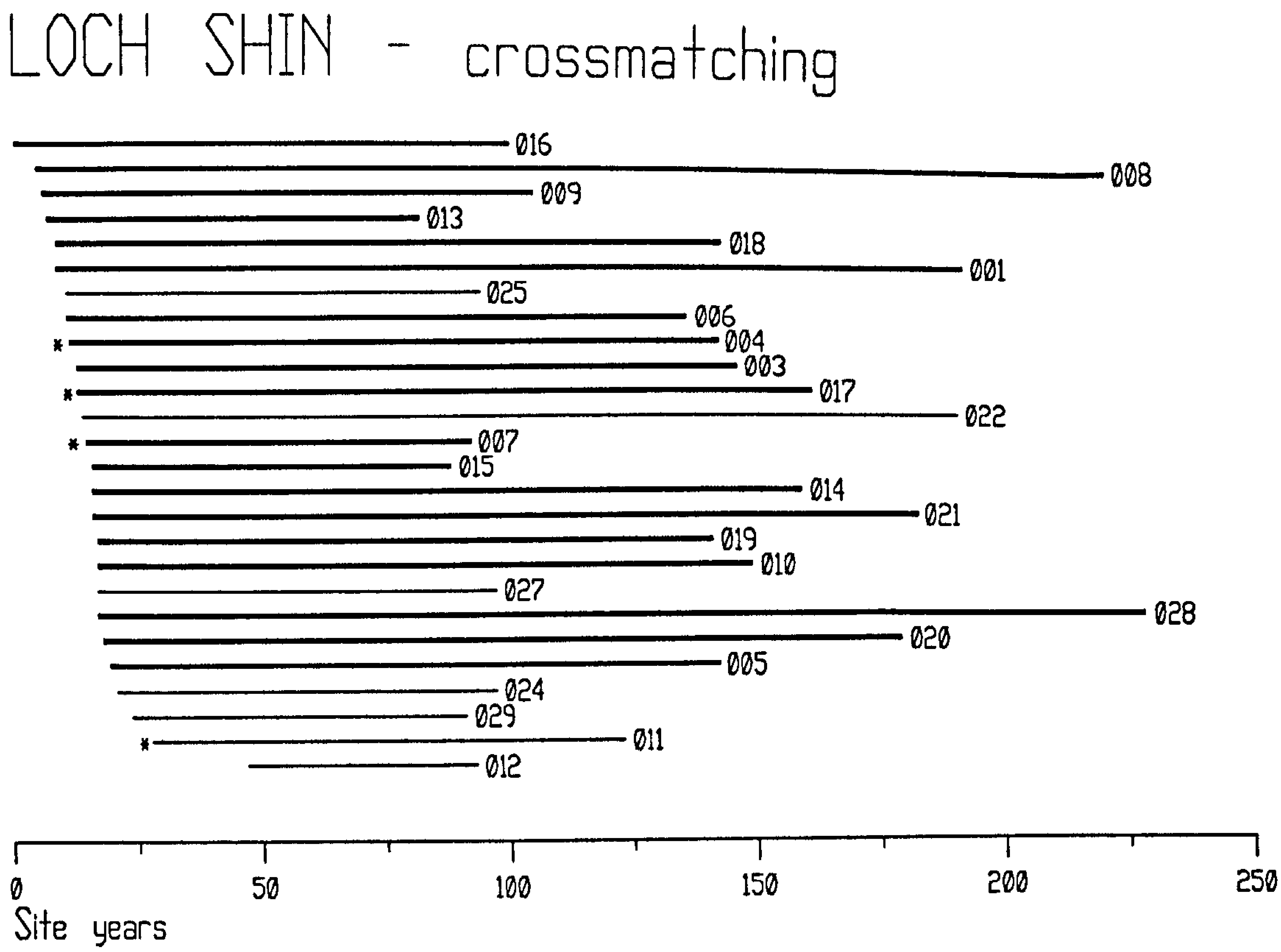


Figure 3.24. Loch Shin - crossmatched trees. The lines represent individual life spans, the asterisks a missing centre to the tree. The numbers are the sample numbers (the prefix SHI is omitted). The lighter lines indicate the trees that are not securely matched (see Section 3.4.2.3).

TREES SHI	009	013	018	001	006	003	017	015	014	019	010	028	020	016	004	007	021	005 SHI
008	11.01***	5.95***	6.32***	7.63***	6.29***	6.66***	10.42***	9.09***	7.66***	5.54***	7.35***	n/s	5.78***	8.17***	10.15***	7.41***	n/s	9.42***
A	009	7.06***	6.77***	8.65***	6.8***	7.25***	8.31***	5.67***	6.18***	6.17***	8.79***	4.67**	6.82***	10.91***	12.56***	7.86***	n/s	9.3***
A	A	013	5.75***	8.66***	5.75***	7.95***	5.85***	n/s	n/s	n/s	5.45***	n/s	5.26**	4.69**	11.17***	6.86***	n/s	6.92***
A	A	A	018	6.27***	6.33***	6.48***	7.14***	8.49***	6.09***	5.46***	5.58***	n/s	8.8***	8.4***	8.1***	5.86***	3.82*	7.08***
A	A	A	A	001	7.91***	7.63***	7.23***	7.14***	5.03**	8.68***	6.81***	4.27*	7.13***	7.52***	10.74***	5.18**	6.45***	8.64***
A	A	A	A	A	006	7.15***	6.75***	7.13***	3.65*	7.34***	7.37***	3.52*	6.1***	7.24***	7.99***	5.62***	5.54***	6.3***
A	A	B	A	A	A	003	7.22***	9.35***	7.48***	7.36***	6.46***	n/s	9.69***	5.89***	11.51***	5.48***	4.53**	7.06***
A	A	B	A	A	A	A	017	6.61***	7.29***	4.68**	7.4***	n/s	7.26***	9.22***	8.66***	7.41***	5.63***	8.68***
A	A	n/s	A	A	A	A	A	015	5.82***	10.43***	5.38***	3.69*	8.74***	5.76***	9.02***	5.46***	4.2**	6.7***
A	A	n/s	A	n/s	C	A	A	A	014	6.33***	7.98***	5.5***	10.32***	5.82***	7.34***	5.42***	5.54***	9.13***
A	A	n/s	A	A	A	A	A	A	A	019	6.05***	4.76**	8.97***	4.49**	7.92***	5.23***	5.34***	7.97***
A	A	B	A	A	A	A	A	n/s	A	A	010	6.25***	7.16***	6.81***	9.7***	5.49***	8.18***	13.13***
n/s	A	n/s	n/s	A	n/s	n/s	n/s	C	A	A	A	028	n/s	n/s	4.3*	n/s	4.51**	5.42***
A	A	B	A	A	A	A	A	A	A	A	A	n/s	020	6.19***	9.73***	6.52***	6.41***	9.85***
A	A	A	A	n/s	A	A	A	A	A	A	A	n/s	A	016	9.03***	7.43***	n/s	8.21***
A	A	B	A	A	A	A	A	A	A	A	A	A	A	A	004	9.48***	6.1***	11.97***
A	A	B	A	C	C	A	A	A	A	n/s	A	n/s	A	A	A	007	n/s	6.8***
n/s	n/s	n/s	C	A	A	A	A	n/s	A	A	A	A	A	n/s	A	n/s	021	7.47***
A	A	B	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	005
008 SHI	009	013	018	001	006	003	017	015	014	019	010	028	020	016	004	007	021	SHI TREES

CROSSMATCHING QUALITY

UPPER RIGHT
Values of 't' and multiple probability for Baillie and Pilcher filter.
* - 0.1>P>0.01 ** - 0.01>P>0.001 *** - P<0.001

LOWER LEFT
Match significant if P < 0.05 and IF > 5.0
A - All 3 filters give the same match position and all matches are significant.
Minimum overlap is 50 rings.
B - As A but minimum overlap is 30 rings.
C - As B but only 1 or 2 matches significant and/or giving the same match position.

n/s - not significant
s/o - short overlap (< 54 rings, ie 50 rings plus those lost in the B & P filter)

REPLICATION: This table shows the number of significant matches in which the tree is present.

TREE	MATCHES	TREE	MATCHES	TREE	MATCHES
SHI008	16	SHI017	17	SHI016	15
SHI009	17	SHI015	15	SHI004	18
SHI013	13	SHI014	16	SHI007	15
SHI018	17	SHI019	16	SHI021	12
SHI001	16	SHI010	17	SHI005	18
SHI006	17	SHI028	9		
SHI003	17	SHI020	17		

Figure 3.25. Loch Shin crossmatching. The diagram shows the significant crossmatches between trees with the quality and replication of those matches.

Figure 3.26. Loch Shin crossmatching (* - see text)

same reasons as VAT008 at the previous site, and is likewise not included in Figure 3.25 or any calculation of means etc.

3.4.2.4 Mean ring-widths for site and site chronology

As at Loch Vatachan, the mean ring-widths for the crossmatched trees on the site, including those less securely matched, are plotted in Figure 3.27. These show both high values and considerable fluctuation during the recruitment phase, and while the bulk of the trees are still alive. As the population decreases, so the mean site ring-widths become smaller, though a period of increased growth in the longer lived trees at the end of their spans can be seen at around 160 site years. The difference between the rapid increase in population at the beginning of the occupation of the site and the slow decline as the trees begin to die (Fig. 3.27b) is more marked than at Loch Vatachan.

The site chronology was constructed from the trees indicated in Table 3.8 which form the core of the high quality crossmatching. On comparison of the long sequence SHI008 with two of the others of similar length, SHI020 and SHI021, it appeared that a ring was missing at ring 105 on SHI008, and a dummy value was inserted. The resulting robust mean chronology is shown in Figure 3.28 and was used in attempts at inter-site crossmatching.

3.4.3 ^{14}C dating

Ten samples were taken from successfully crossmatched trees and submitted for ^{14}C dating in order to attempt a 'wiggle match' to improve the precision of the dating. The result of this was a date of 3495 +17 -40 Cal BC for the appearance of the first tree on the site and a date of 3257 +17 -40 Cal BC for the death of the last crossmatched tree on the site.

This result was obtained by following the procedure described in Pearson (1986). First it is necessary to have a series of ^{14}C dates for samples of known separation in calendrical years (in this case the ten dates from the crossmatched samples described above - see Table 3.9 below and Figure 3.29a and b). Ideally these samples should have spanned approximately equal numbers of rings, but the sample size required for dating, coupled with the very narrow rings found in the later years of the trees' lives, meant that in some cases (notably SHI008B) more rings than desirable were included.

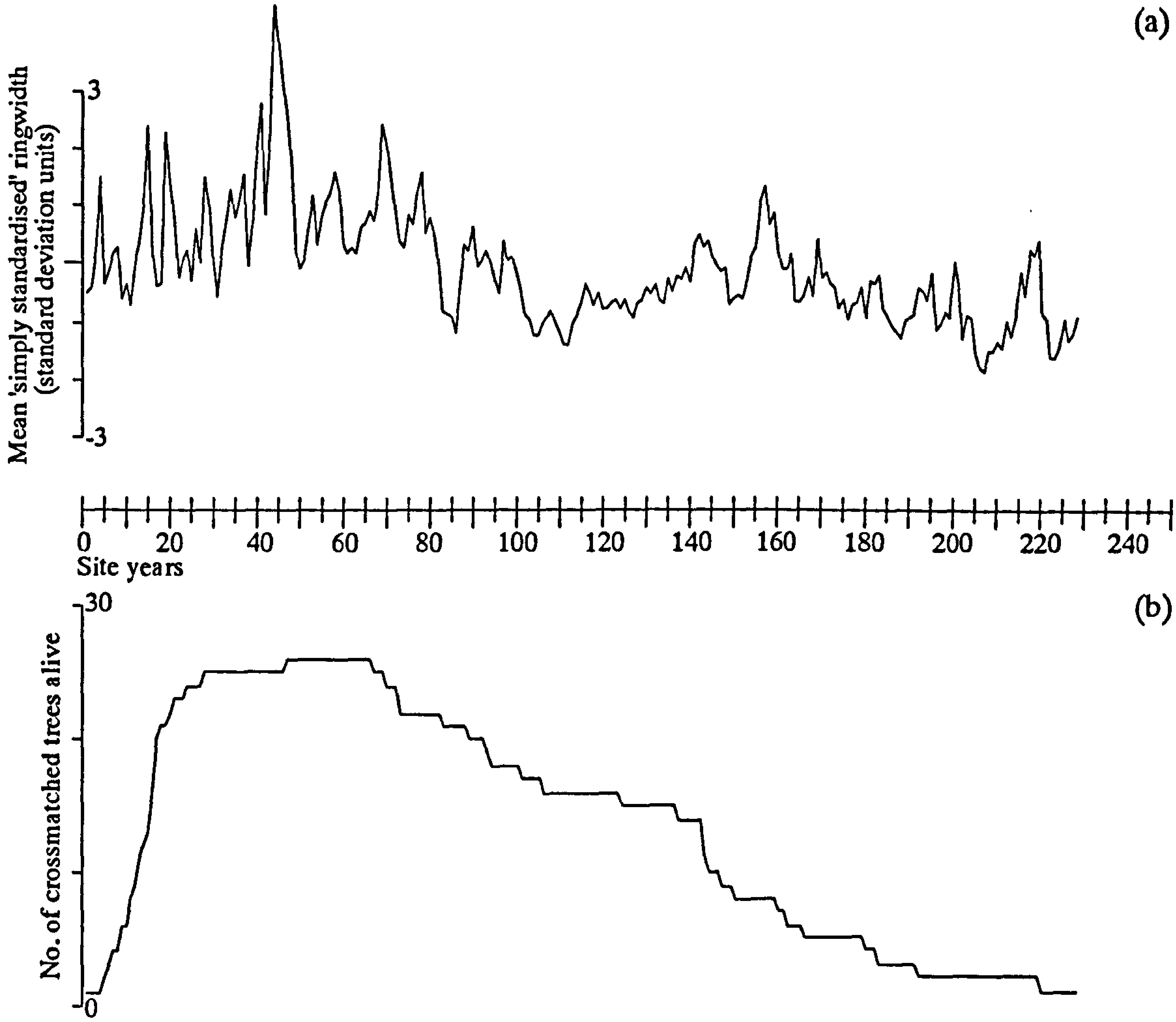


Figure 3.27. Loch Shin:

(a) - mean ring-widths for the site. Each mean ring-width is the average of the ring-widths for that particular year from the mean radii of all the crossmatched trees.

(b) - number of crossmatched trees alive on the site, *i.e.* the number present in the mean year by year.

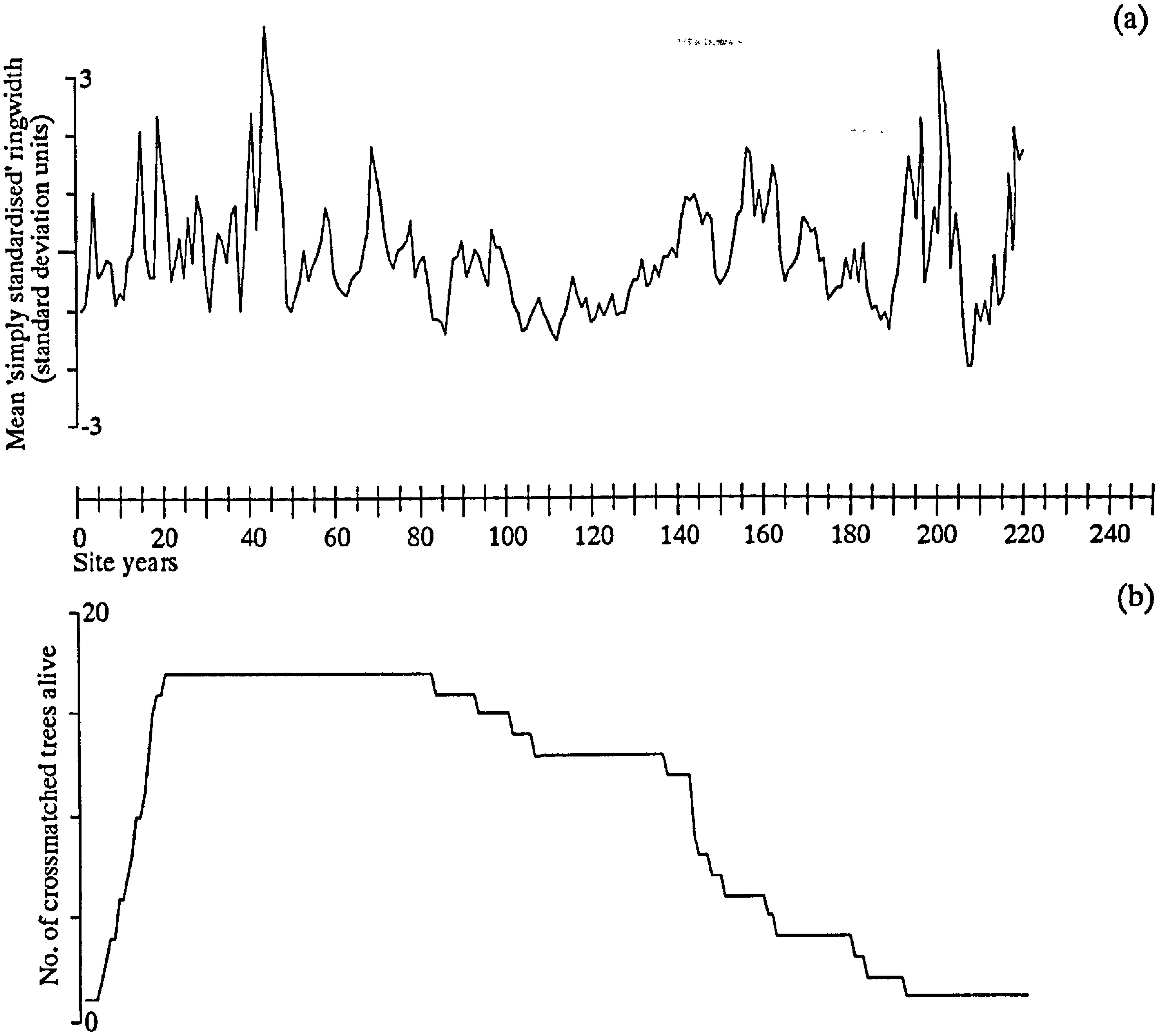
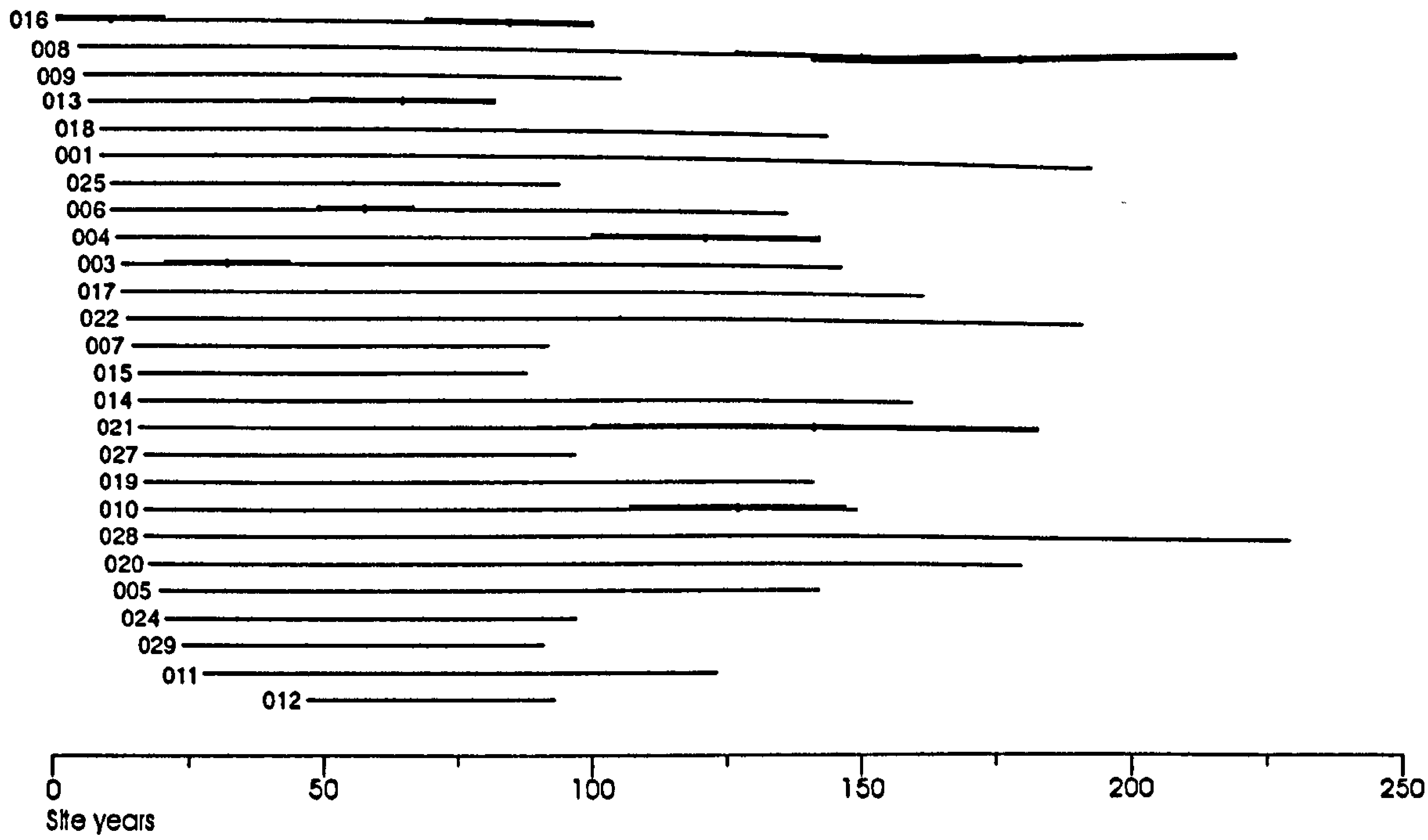
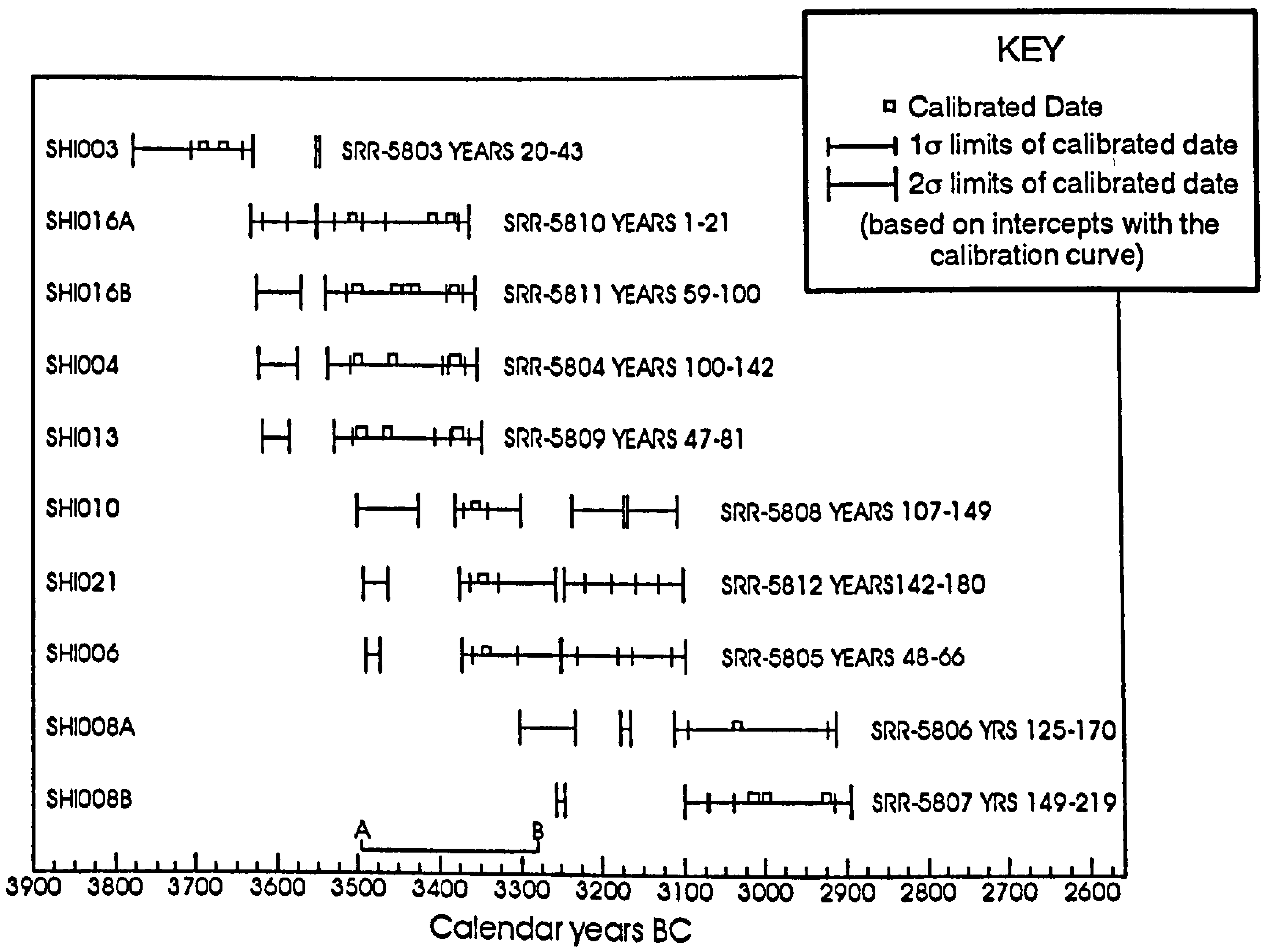


Figure 3.28. Loch Shin:
(a) Robust mean chronology from selected trees (see text).
(b) Number of trees in robust mean chronology year by year.



a) Ring spans from crossmatched trees at Loch Shin used for radiocarbon wiggle match dating.



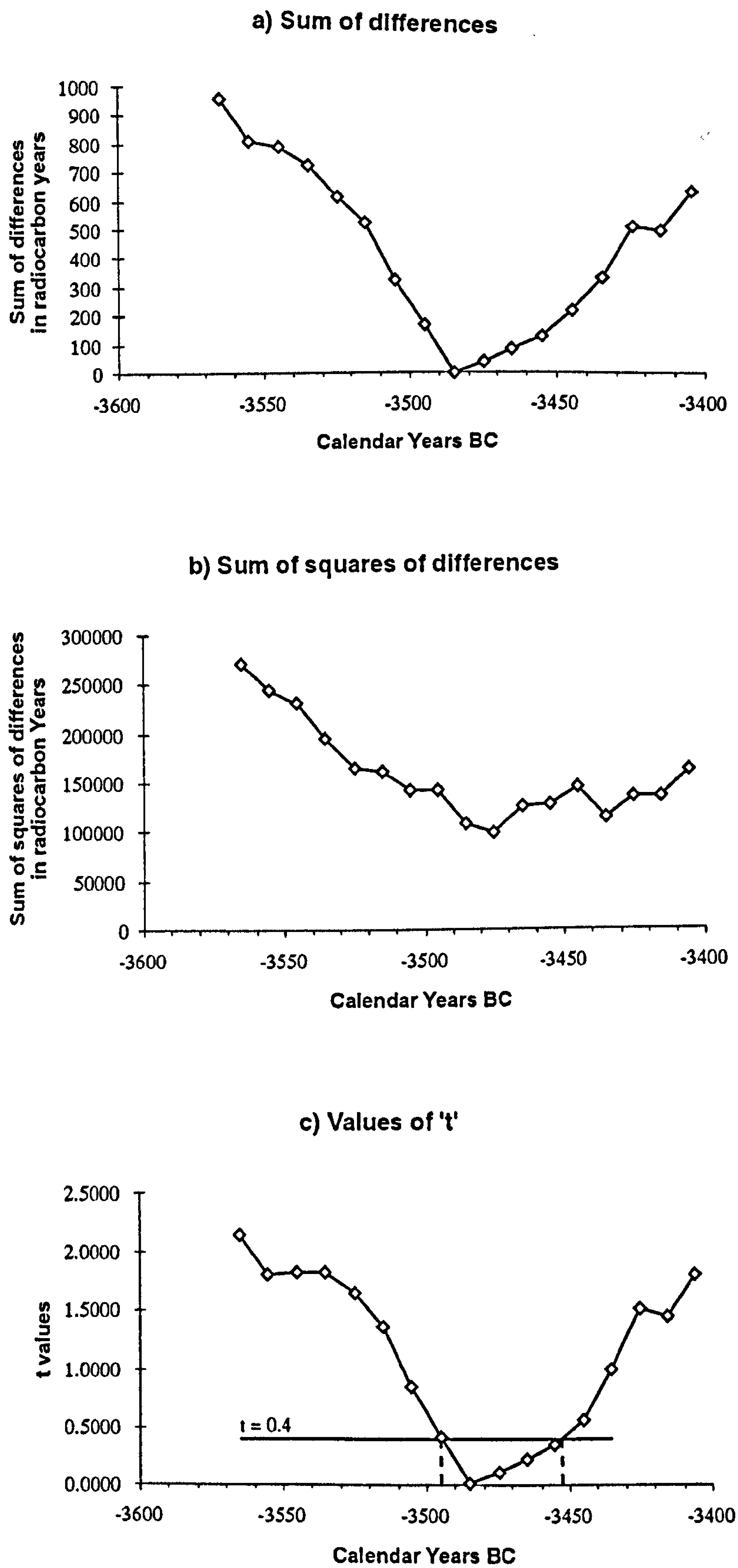
b) Calibration of 14C dates at Loch Shin. The line A-B represents the total span of tree rings wiggle match dated, placed at the position of best match.
Diagram based on the output from CALIB rev. 3 (Stuiver and Reimer, 1993; Stuiver and Pearson, 1993).

Figure 3.29. Radiocarbon dating at Loch Shin

SAMPLE	^{14}C AGE	SPAN OF RINGS DATED	CENTRE (site year)	LAB NO.
SHI016A	4710 ± 45	21	10	SRR-5810
SHI003	4895 ± 45	24	31	SRR-5803
SHI006	4560 ± 45	19	57	SRR-5805
SHI013	4665 ± 45	35	64	SRR-5809
SHI016B	4685 ± 45	32	84	SRR-5811
SHI004	4680 ± 45	42	120	SRR-5804
SHI010	4595 ± 45	41	126	SRR-5808
SHI021	4570 ± 45	39	140	SRR-5812
SHI008A	4415 ± 45	46	148	SRR-5806
SHI008B	4380 ± 45	80	178	SRR-5807

Table 3.9. Radiocarbon dates at Loch Shin used for 'wiggle matching'.

From these it is possible to construct a short curve of ^{14}C years plotted against the calendrical years of the separation between the samples. This can be compared with a calibration curve of ^{14}C against calendrical years to determine a position of best fit. In the present example this was done by taking the sequence of ^{14}C dates (the 'sample curve') from Loch Shin and comparing them with a section of the calibration curve Dataset 2, decadal tree-ring data from CALIB rev. 3.0 (Stuiver and Reimer, 1993; Stuiver and Pearson, 1993). This section of the calibration curve was defined by the earliest 2σ limit of the earliest ^{14}C date and the latest 2σ limit of the latest ^{14}C date in the sample curve. As the calibration curve used was decadal it was necessary to round the intervals between samples in the sample curve to the nearest 10 years. The comparison was then done by stepping the sample curve past the calibration curve in 10 year increments, calculating the sum of differences, sum of the squares of differences and 't' for each position using a short computer routine written for the purpose. The minimum values for the sum of differences and 't' were taken to indicate the best match position for the two curves and thence the best calendrical dating for the sequence as a whole. This was a date of 3485 calendar years BC for the beginning of the sample curve. Again following Pearson (1986), the values of the sums of differences, sum of the squares of differences and 't' for dates either side of this position were plotted (Figures 3.30 a, b and c) to confirm this finding. To determine the confidence limits a value of 't' was selected from tables (Fisher and Yates, 1963) to give a probability of around 70% (cf. Pearson 1986) and the intercepts from this on the calendar year axis used as confidence limits at the 1σ level (Figure 3.30c). These limits were +9 and -32 calendar years, but were regarded as minima as they did not allow for the span in time covered by the samples (i.e. the number of rings from each sample that are included in the material dated), the rounding of the intervals between samples in the sample curve and the 10



Figures 3.30 a, b, c. Statistical curve for 'wiggle match' positions either side of the minimum values. The dashed lines in c) indicate the limits of confidence at the 1σ level derived as suggested by Pearson (1986).

year increment of the matching steps. An allowance was made for the last two of these giving 1σ limits of +17 and -40.

Given this date of 3485 +17 -40 Calendar years BC for the beginning of the sample curve, the dates quoted at the start of this section for the occupation of the site were then calculated directly from the position of the samples on the site year scale derived from the crossmatching.

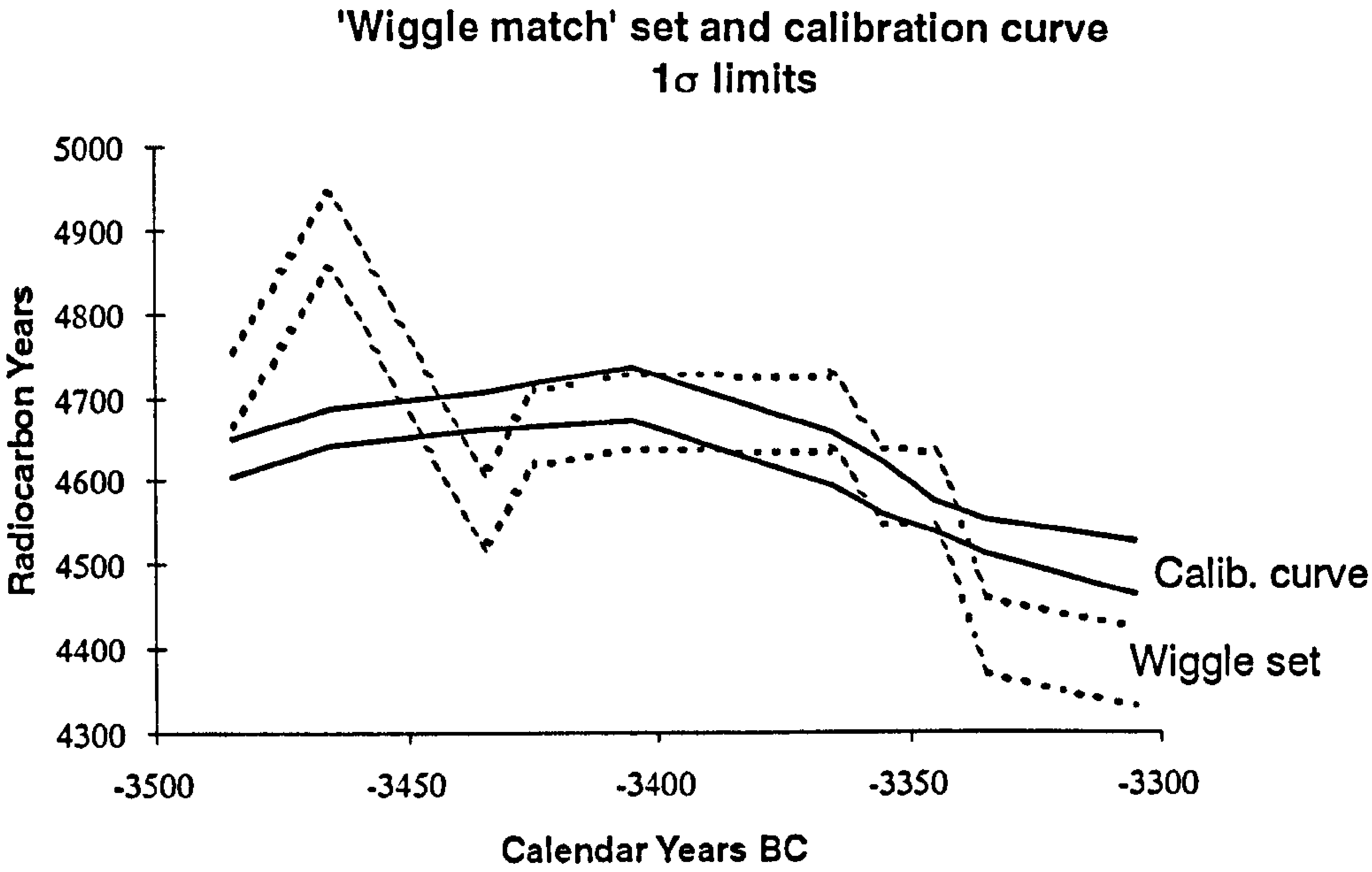
Finally, Figure 3.31 shows the 1σ and 2σ ranges of the ^{14}C dates in the calibration curve and sample curve superimposed on each other at the position of best match. All of the 2σ ranges for the corresponding points on each curve overlap with the exception of that for SRR-5803, which at 4895 ^{14}C years BP seems at least 100 ^{14}C years too old.

3.4.4 Pollen and Tephra Results

The stratigraphy is shown in Figure 3.32, and pollen percentage and concentrations in Figures 3.33 and 3.34 respectively. Figure 3.33 shows three peaks in the pine curve at 48 cm, 66 cm and 75 cm respectively. It is likely that only the pine peak at 66 cm represents the growth of pine on the site. The pollen concentration diagram (Fig. 3.34) shows a large peak at the 48 cm level, but this coincides with an increase in pollen concentration overall and can thus be discounted. The peaks at 66 cm and 75 cm are also shown in the pollen concentration diagram, but that at 75 cm is relatively small and occurs against a background of falling concentrations in the other taxa, so its significance in the percentage diagram (Fig. 3.33) is exaggerated.

Very broadly, the sequence at Loch Shin is the same as that at Loch Vatachan, with a decline in *Betula* pollen from the bottom of the profile, followed by a large peak in *Sphagnum* values at 79 cm. This in turn, unlike at Loch Vatachan, is followed by a period of low pollen concentrations (78 - 70 cm) against the background of which a slight increase in *Pinus* pollen at 75 cm shows as a high percentage figure. From about 68 cm *Calluna* increases followed by the *Pinus* peak at 66 cm, suggesting the same expansion with drier conditions of heather followed by pine as found at Loch Vatachan. There again follows a period of low pollen influx (64 - 52 cm) with *Sphagnum*, Cyperaceae and Graminae increasing slightly above this level.

X-ray analysis revealed a shadow caused by mineral material at 3.5 cm and a fainter one at 43 cm, well above the pine peak at 66 cm (this 43 cm horizon is shown in Figures 3.33 and 34). The upper shadow appeared on microscopic examination to be sand, but the lower one consisted of a quantity of vesicular glass shards similar in appearance to those found at Srath Dionard and identified chemically as most likely from the eruption Hekla 4. As yet, the Loch Shin shards have not been identified chemically, but their



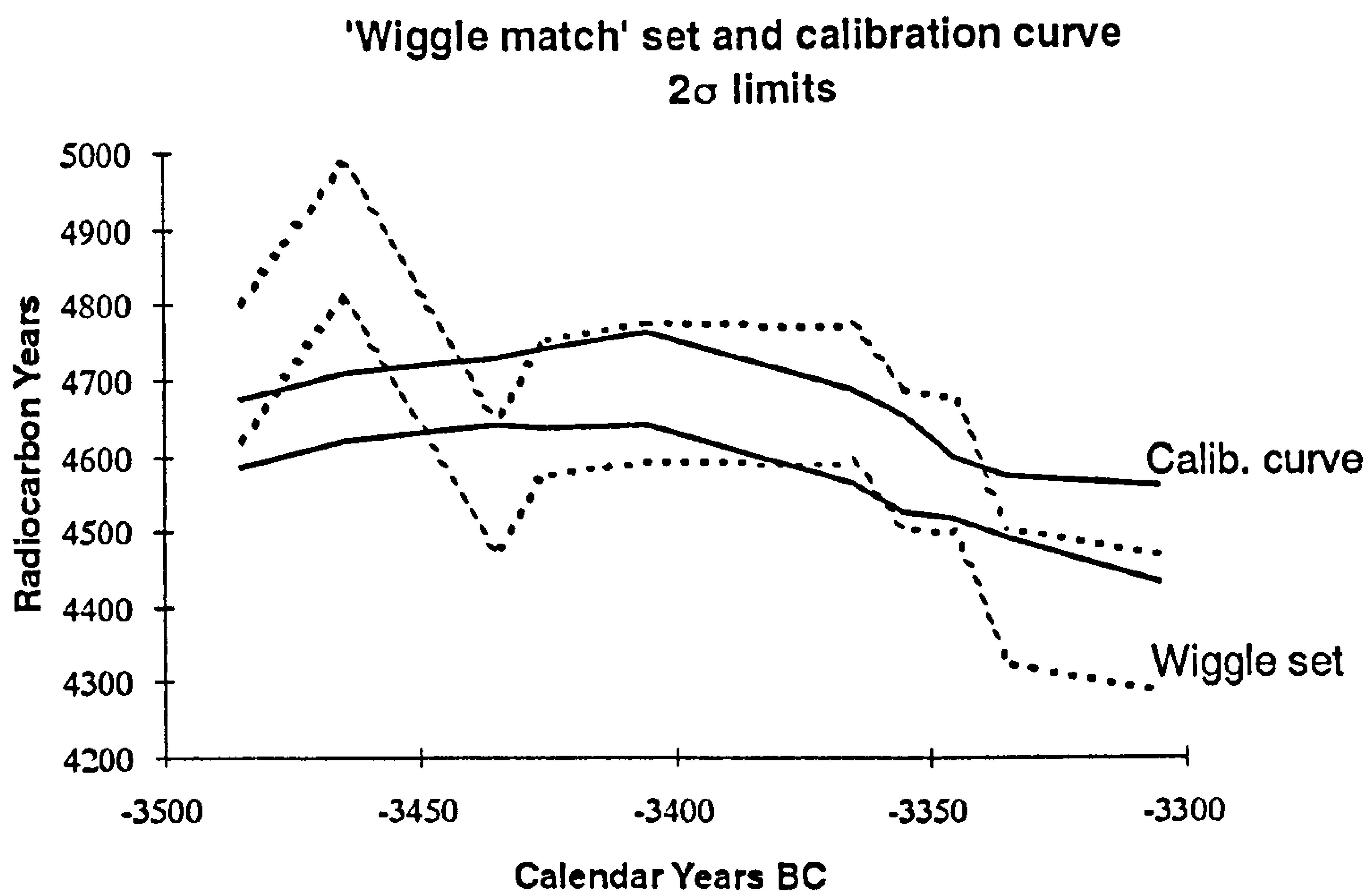


Figure 3.31. 1σ and 2σ limits of 'wiggle match' set and calibration curve at best match position.

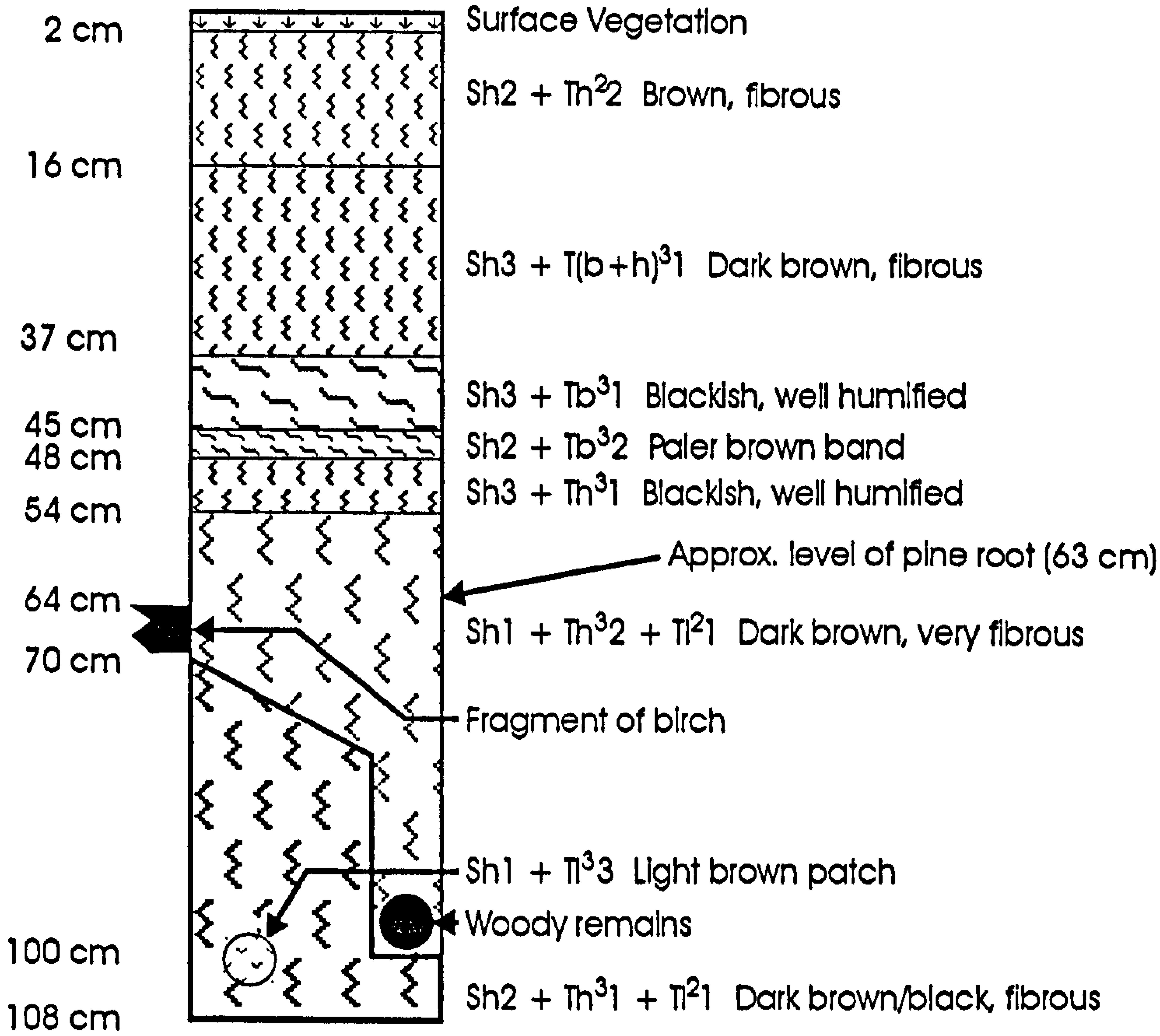


Figure 3.32. Loch Shin monolith - outline stratigraphy
Sediment description symbols as defined byTroels-Smith (1955)

Figure 3.33. Loch Shin pollen percentages. The 'T' horizon indicates the level at which tephra shards were found.

Figure 3.34. Loch Shin pollen concentrations - selected taxa. The 'T' horizon is the level at which tephra shards were found.

stratigraphic position and appearance strongly suggest the same origin. This is supported by the amount of peat formed (23 cm) between the pine and tephra horizons, which is consistent with the separation in time between the ^{14}C dates for the pines given above and that of the eruption, 2310 ± 20 BC (Hall *et al.*, 1994).

3.5 Badanloch

58° 16' 02" N 4° 04' 07" W, Nat. Grid Ref. NC(29)786330

Figure 3.35, Plates 5 and 6 .

3.5.1 Site Description

The site at Badanloch is the first of the two sites in this study from which data were already available (Table 3.1). It is one of the most striking sites in the region, having a large number of accessible well-preserved stumps. Samples of these stumps were collected in 1988 by A.J. Gear, stored at Durham and were the subject of an MSc. study by the author. The results of that work are re-assessed in the present study using a slightly different dendrochronological approach from that in 1992 and are presented below.

Badanloch lies at 122 m OD on a plateau between Strath Halladale to the east and Strathnaver to the west, both valleys running more or less south-north and opening onto the north coast, 30 km away (see Fig. 1.5). The whole area is underlain by acid metamorphic rocks, the Moine schists, which have given rise to rolling relief. The nearest higher ground, with an elevation of 270 m, is 1.5 km to the west; peaks of over 300 m lie within 4 to 5 km. Loch Badanloch, the southernmost extension of Loch Rimsdale, is exposed to winds from the north and east but sheltered to some extent from the west and south by mountains of over 700 m lying at a distance of about 10 km to the south-west. The site is surrounded by blanket peatland (deep blanket peat or peaty gleys and podzols), which is used predominantly for grazing, although there are some forestry plantations of exotic conifers to the north and west. The present vegetation on the peat is dominated by *Calluna vulgaris* and *Eriophorum* spp.

A small dam was built about 30 years ago to regulate the amount of water from the loch entering the River Helmsdale. During periods when the loch level is high, wave action erodes the pine stumps out of the adjacent blanket peat; when the level drops, as it does sometimes during dry periods, stumps may be seen along the southern shore.

In 1988 a plan was made of the positions of all the visible stumps along a section of the southern shore (Figure 3.35). Most of the stumps subsequently sampled occur within

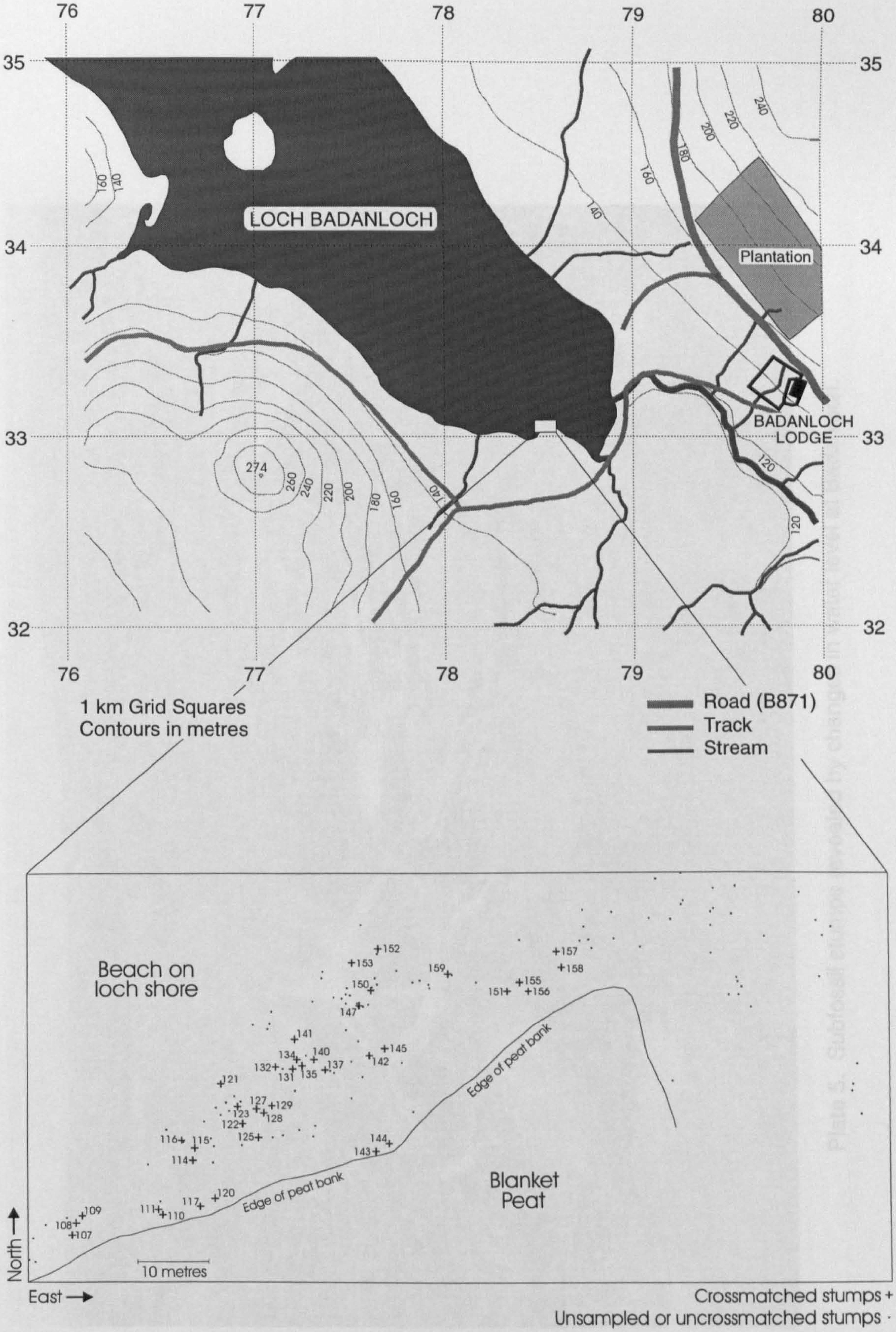


Figure 3.35. Badanloch - location and plan of sampling site.

Plate 5. Subfossil stumps revealed by changes in water level at Badanloch.

Plate 6. Pine stump embedded in blanket peat at Badanloch. Note the layer of birch macrofossils beneath it.

this area and are indicated on the plan, and from these data the density of stumps on the site was estimated as 431 ha^{-1}. When the site was revisited in 1992 it was apparent that further erosion had taken place. The level of the water was considerably lower (by up to a metre) and the number of stumps sticking out of the shallow water of the loch indicated that the group originally sampled was only part of a larger area of woodland. In the late summer of 1994 the water level was even lower and the original shoreline of the loch could be seen.

Although described as stumps, the tree remains at Badanloch consist primarily of a flat root system from around 1.5 m in diameter to in excess of 3 m in a few cases, and are generally slightly larger than those from the other sites in this study. As at the other sites the stump itself is the root buttress plus a few centimetres of the base of the trunk. Tap roots generally seem to be absent, suggesting that the water table was never very far below the surface. Only very occasionally are sections of trunk found, the longest noted at Badanloch being about 5 m (Plate 7). This had branches along all its length, but as at Loch Glascarnoch it was not possible to tell how much of the outside of the trunk had decayed and therefore whether the trunk had been clean or not.

3.5.2 Dendrochronological Results

3.5.2.1 General statistics

These are presented in the same format as for previous sites. Table 3.10 shows the summary statistics for Badanloch. Again the mean number of rings is low, despite one tree, BAD144, having a total of 363 rings. The next highest total is 154 rings, and the mean suggests that a count of around 100 rings is typical of the site. Allowing for unpredictable losses through decay, the true age of the trees may be rather greater. The mean ring-width is 0.935 mm, slightly greater than at the previous sites described, and in this context it is worth noting that BAD144, with its high ring count, has one of the lowest mean ring-widths, 0.41 mm, found on the site. Although this tree grew very slowly for most of the latter part of its life as shown in Figure 3.36, it does not appear to have 'switched off' in the way that some of the trees did, e.g. VAT020 (Figure 3.14) at Loch Vatachan and SHI006 (Figure 3.26) at Loch Shin.

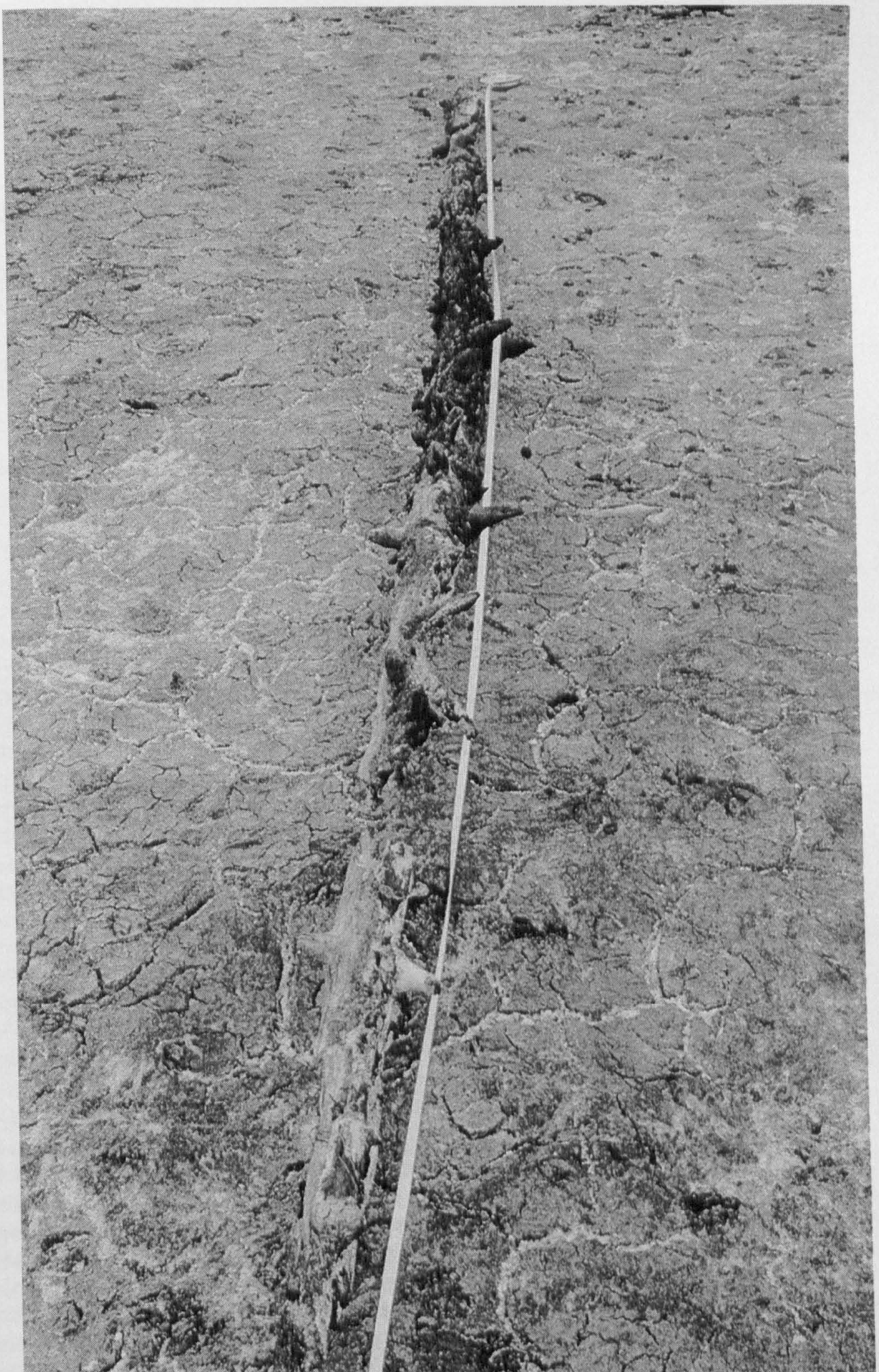


Plate 7. Subfossil trunk found at Badanloch. The overall length is 5 m, the base away from the camera.

Table 3.10. Badanloch: Summary statistics based on the mean radius for each sample measured.

Tree	Number of rings	Mean radius (cm)	Mean ringwidth (mm)	SD of ringwidths	Sensitivity	First order autocorr.
BAD009	110	9.3	0.85	0.50	0.29	0.86
BAD011	101	7.5	0.74	0.35	0.26	0.75
BAD012	76	7.2	0.94	0.37	0.29	0.54
BAD106	33	9.6	2.91	0.71	0.19	0.46
BAD107	139	19.1	1.37	0.70	0.27	0.75
BAD108	89	9.9	1.11	0.77	0.33	0.86
BAD109	99	10.6	1.07	0.88	0.33	0.83
BAD110	146	9.2	0.63	0.35	0.27	0.85
BAD111	77	3.8	0.50	0.33	0.40	0.66
BAD113	132	12.0	0.91	0.58	0.25	0.83
BAD114	154	8.0	0.52	0.31	0.23	0.85
BAD115	88	4.5	0.51	0.29	0.31	0.80
BAD116a	99	12.9	1.30	0.64	0.24	0.79
BAD116b	97	11.4	1.18	0.62	0.25	0.82
BAD117	35	4.8	1.36	0.66	0.21	0.80
BAD118	60	3.5	0.58	0.37	0.35	0.73
BAD119	36	3.6	0.99	0.47	0.31	0.51
BAD120	66	8.0	1.21	0.51	0.28	0.72
BAD121	99	7.0	0.71	0.49	0.27	0.81
BAD122	84	8.7	1.04	0.38	0.28	0.53
BAD123	67	6.8	1.01	0.59	0.24	0.76
BAD124	87	6.5	0.74	0.54	0.24	0.88
BAD125	78	7.3	0.93	0.41	0.27	0.74
BAD127	70	4.7	0.67	0.32	0.27	0.57
BAD128	118	8.1	0.69	0.44	0.37	0.75
BAD129	82	3.3	0.40	0.23	0.41	0.58
BAD131	96	4.9	0.51	0.38	0.31	0.76
BAD132	122	7.2	0.59	0.39	0.37	0.72
BAD133	78	13.0	1.67	0.68	0.18	0.84
BAD134	48	7.3	1.53	0.67	0.30	0.61
BAD135	92	5.5	0.59	0.34	0.35	0.61
BAD137	130	3.8	0.29	0.16	0.37	0.66
BAD140	46	6.2	1.34	0.67	0.34	0.51
BAD141	46	8.1	1.77	0.95	0.33	0.72
BAD142	133	5.4	0.41	0.28	0.38	0.78
BAD143	117	7.2	0.61	0.34	0.27	0.81
BAD144	363	14.8	0.41	0.30	0.26	0.88
BAD145	49	8.4	1.71	0.60	0.17	0.76
BAD147	54	1.9	0.35	0.29	0.50	0.53
BAD150	152	9.9	0.65	0.40	0.26	0.75
BAD151	128	10.7	0.83	0.62	0.27	0.88
BAD152	80	12.0	1.50	0.49	0.21	0.68
BAD153	126	13.1	1.04	0.57	0.25	0.83
BAD155	47	6.6	1.39	0.56	0.28	0.64
BAD156	124	6.6	0.53	0.21	0.30	0.51
BAD157	95	7.9	0.83	0.39	0.33	0.69
BAD158	77	13.2	1.72	0.87	0.21	0.89
BAD159	138	11.6	0.84	0.37	0.26	0.73
BAD272	125	4.2	0.33	0.20	0.34	0.73
BAD273	91	8.6	0.94	0.64	0.30	0.87
BAD341	116	4.7	0.41	0.19	0.29	0.70
Mean	**97.9**	**8.03**	**0.935**		**0.291**	**0.728**
SD	**49.9**	**3.42**	**0.493**		**0.062**	**0.118**

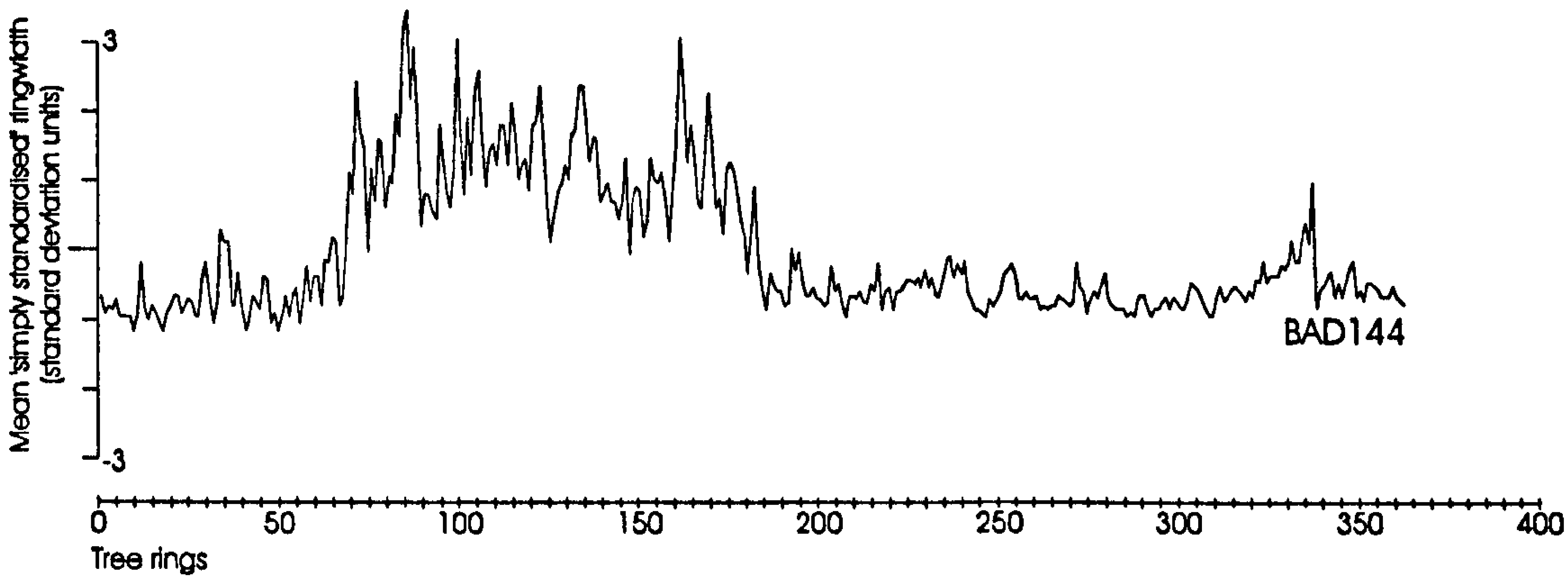


Figure 3.36. BAD144: ring-widths from mean radius.

The narrow rings from ring 185 onwards, until the apparent spurt in growth around ring 330, represent poor growing conditions for this particular tree. Unfortunately it has not proved possible to crossmatch the ring sequence with others on the site with a high degree of confidence, so whether these conditions were site wide or unique to this tree cannot be stated with absolute certainty.

3.5.2.2 Mean growth curve

This is shown in Figure 3.37. As at the other sites the curve is based on those trees with intact centres (see Table 3.11). BAD144 is excluded because of its great length. Overall the shape of the curve is similar to those of the other sites, with its rise to a maximum in the first 25 years, then a steady decline over the remaining 130 years or so. There is some sign of an increase in variance as the number of trees declines in the last 20 years of the plot, but overall the curve is rather smoother than those for Loch Vatachan and Loch Shin, probably because of the larger number of trees (36) included.

3.5.2.3 Site crossmatching

Table 3.11 summarises the crossmatching for the trees on the site, with the statistics for stump density, recruitment rate etc. The crossmatching is shown graphically in Figure 3.38. This diagram includes the core of securely crossmatched trees indicated in Figure 3.39, together with other trees linked by only one high quality match or several poorer ones (as at the other sites these are not included in any chronologies for inter-site matching or dating). The three trees at the bottom of the diagram include two ^{14}C dated samples and form a sub-group referred to here as the 'RC' Group. As Figure 3.39 suggests, this is linked to the main body of crossmatched trees by three matches with BAD156 and one with BAD114. To check this a separate robust mean chronology was formed from the 'RC' Group and matched against the robust chronology produced for

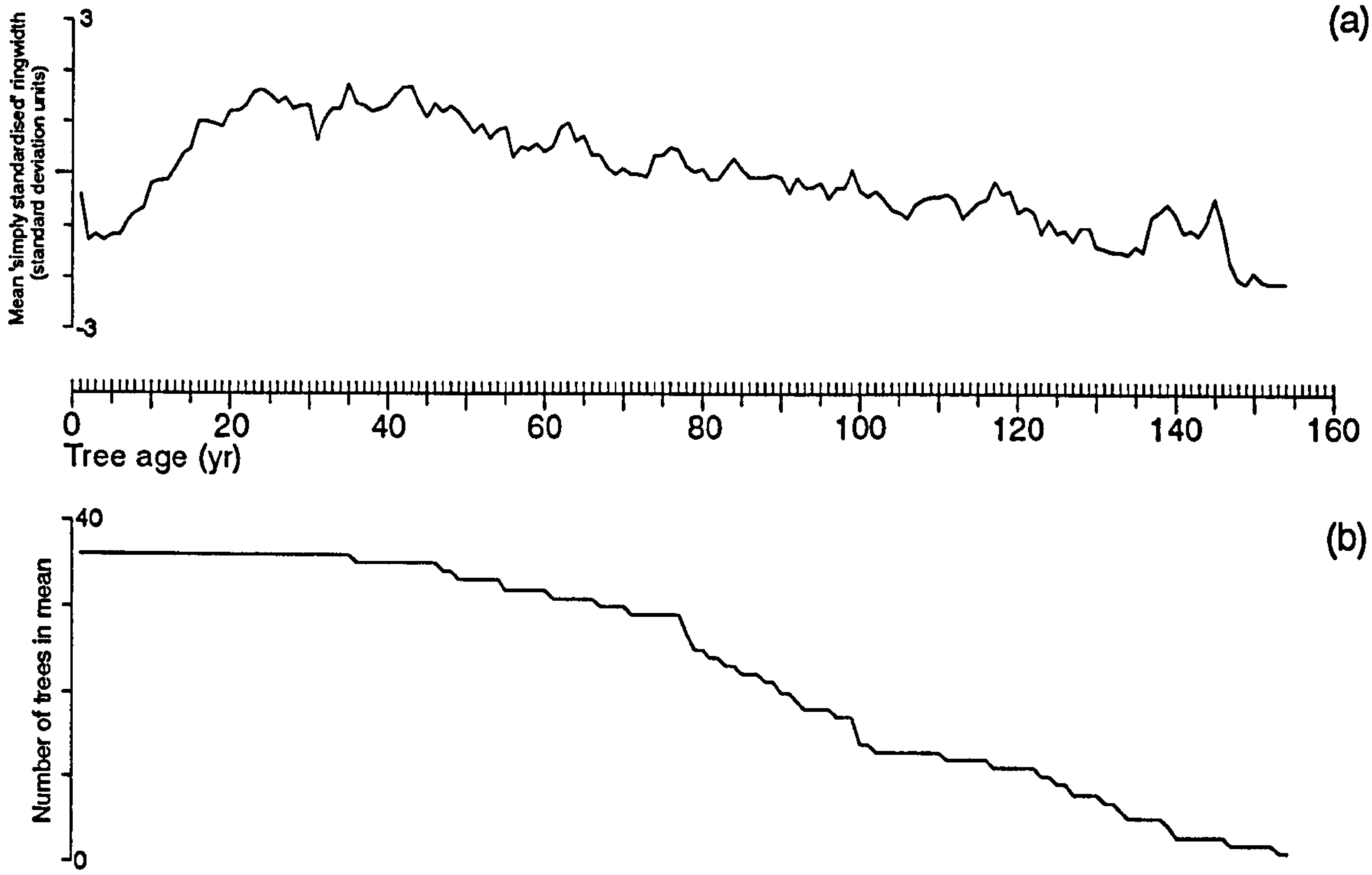


Figure 3.37. (a) - Mean growth curve for the trees at Badanloch.
(b) - Number of trees included in the mean.

Table 3.11. Badanloch - summary of crossmatching positions plus maximum recruitment rate and density.

TREE		MIN AGE	MATCH POSITION (site years)	DEATH (minimum - site years)	
(BAD009		110	43	152)	
(BAD011		101	50	150)	
(BAD012		76	84	159)	NC
BAD106		33			NC
(BAD107		139	7	145)	
BAD108		89			
BAD109		99			
BAD110		146			
BAD111		77			
BAD113		132			
BAD114	c	154	14	167	
BAD115		88	1	88	NC
BAD116A	c	99	3	101	
BAD116B	c	97	2	98	NC
BAD117		35			
BAD118		60			
BAD119		36			
BAD120		66			
BAD121		99			
BAD122		84			
BAD123		67	38	104	NC
BAD124		87			
(BAD125		78	26	103)	
BAD127		70	15	84	
BAD128	c	118	4	121	NC
BAD129		82			

TREE		MIN AGE	MATCH POSITION (site years)	DEATH (minimum - site years)	
(BAD131		96	25	120)	
(BAD132		122	22	143)	
BAD133		78			
BAD134		48			
(BAD135		92	33	124)	
(BAD137		130	26	155)	
BAD140		46			NC
BAD141		46			
BAD142		133			
BAD143		117	30	146	NC
(BAD144		363	86	448)	
BAD145		49			NC
BAD147		54			
BAD150	c	152	23	174	
BAD151		128	24	151	NC
BAD152		80	18	97	
BAD153	c	126	8	133	
BAD155		47			NC
BAD156	c	124	30	153	
(BAD157		95	12	106)	NC
BAD158		77			
BAD159	c	138	10	147	
BAD272		125			NC
BAD273		91			
BAD341		116			

Samples recovered: 58. Samples successfully crossmatched: 14 (24%)
(excluding those in parentheses - see text)
Establishment rate during main recruitment phase (site years 1-38):
approx. 2.7 trees ha^{-1} $year^{-1}$

Density of stumps on site: 431 ha^{-1}.
Maximum density of crossmatched trees alive: 130 ha^{-1}
NC denotes damaged or missing centre.
c indicates inclusion in site chronology.

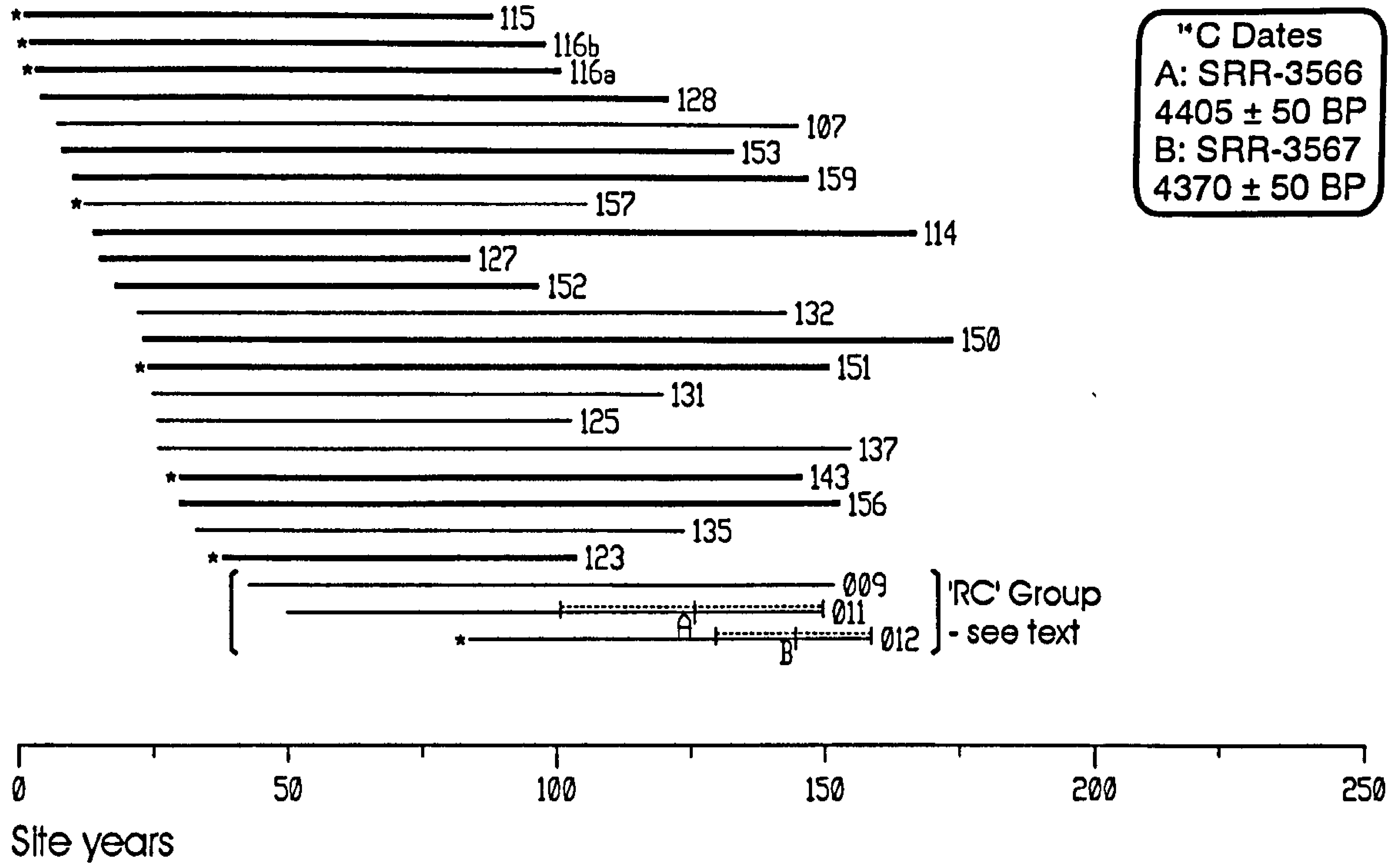


Figure 3.38 Badanloch - crossmatched trees. The lines represent individual lifespans. The numbers are the sample numbers (the prefix BAD is omitted). The lighter lines indicate the trees that are not securely matched (see Section 3.5.2.3). The dotted lines indicate the span of rings radiocarbon dated by Gear and Huntley (1991).
An asterisk indicates a missing or damaged centre in that tree.

TREES BAD	127	151	123	115	116a	116b	153	159	152	150	143	114	BAD 156			
128	n/s	n/s	n/s	4 12**	n/s	n/s	n/s	n/s	3 74*	4 42**	n/s	n/s	4 61***			
n/s	127	4 32***	n/s	n/s	n/s	n/s	n/s	n/s	n/s	n/s	n/s	4 5**	s/o			
n/s	B	151	5 37***	n/s	3 8*	4 02*	3 77*	n/s	4 89**	4 27**	n/s	n/s	n/s			
n/s	n/s	B	123	s/o	6 5***	7 78***	5 67***	5 08**	3 96**	4.44**	n/s	5 51***	n/s			
A	n/s	n/s	s/o	115	n/s	n/s	n/s	n/s	n/s	n/s	3.75*	n/s	s/o			
n/s	n/s	B	B	n/s	116a	15 22***	6 44***	4 49**	n/s	n/s	n/s	5.17**	n/s			
n/s	n/s	A	B	n/s	A	116b	4 98**	n/s	n/s	n/s	n/s	4 65**	n/s			
n/s	n/s	A	B	n/s	A	A	153	5 16**	n/s	7.8***	4.36**	8.05***	6 0***			
n/s	n/s	n/s	C	n/s	A	n/s	A	159	n/s	4.09*	n/s	n/s	n/s			
C	n/s	A	B	n/s	n/s	n/s	n/s	n/s	152	4 59**	n/s	n/s	n/s	'RC' SUB GROUP		
A	n/s	A	C	n/s	n/s	n/s	A	A	A	150	n/s	6.31***	6.88***			BAD
n/s	n/s	n/s	n/s	D	n/s	n/s	A	n/s	n/s	n/s	143	n/s	n/s	009	011	012
n/s	B	n/s	B	n/s	A	A	A	n/s	n/s	A	n/s	114	5.18**	3.61*	n/s	n/s
D	s/o	n/s	n/s	s/o	n/s	n/s	A	n/s	n/s	A	n/s	A	156	4.61**	4.16**	4.9**
128	127	151	123	115	116a	116b	153	159	152	150	143	C	A	009	3 53*	4.08**
BAD													A	C	011	n/s
													B	B	n/s	012
												114	156	009	011	BAD TREES

CROSSMATCHING QUALITY

UPPER RIGHT
Values of 't' and multiple probabilityfor Baillie and Pilcher filter.
* - 0 1>P>0.01 ** - 0.01>P>0.001 *** - P<0.001

LOWER LEFT
Match significant if P < 0 05 and IF > 5 0
A - All 3 filters give the same match position and all matches are significant Minimum overlap is 50 rings.
B - As A but minimum overlap is 30 rings
C - As B but only 1 or 2 matches significant.

n/s - not significant
s/o - short overlap (< 54 rings, ie 50 rings plus those lost in the B & P filter)

REPLICATION: This table shows the number of significant matches in which the tree is present

TREE	MATCHES	TREE	MATCHES
BAD128	4	BAD152	4
BAD127	2	BAD150	8
BAD151	7	BAD143	2
BAD123	9	BAD114	8
BAD115	2	BAD156	7
BAD116a	6	BAD009	4
BAD116b	5	BAD011	2
BAD153	9	BAD012	2
BAD159	4		

Figure 3.39. Badanloch crossmatching
This diagram shows the significant crossmatches between trees with the quality and replication of those matches.

inter-site matching (see Table 3.11 and below). This produced a best crossmatch at the position indicated by the matches of the individual trees with P = 0.012, IF = 17.77, t = 4.12* for the Baillie and Pilcher filter, confirming the position of this group.

Figure 3.40 shows the unfiltered ring-width sequences, expressed on the same scale in standard deviation units, for the main group of samples in their matched positions. Figure 3.41 similarly shows the 'RC' Group together with the two linking trees BAD114 and BAD156. The long sequences of low ring values in the second half of the series BAD114 and BAD151 should be noted, as should the marked low value in all the sequences at site year 46, and the two peaks visible in most trees at site years 49 and 52. Occupation of the site by the securely crossmatched trees appears to have spanned a minimum of 174 years with a main recruitment phase of about 40 years, and well scattered death dates.

3.5.2.4 BAD144 crossmatching

As described above, BAD144 is of particular interest because of its large number of rings. Although not replicated with other trees, one statistically significant match was found with BAD012 at year 3 on the latter. This is shown in Figure 3.42, which illustrates the match for the raw sequences and one of the filters. If this match is accepted then the occupation of the site is extended to a minimum span of 448 years. An attempt was also made to match BAD144 to the robust mean chronology for the site described below. BAD144 was found to match this chronology at year 18 with P = 0.0087, IF = 32.5 and t = 4.59** for the Baillie and Pilcher filter with an overlap of 155 rings. This alternative would suggest a minimum occupation span for the site of 382 years. Given the lack of corroborative evidence either way, it is not possible to place BAD144 with any confidence, though the match with the site chronology, with its longer overlap, seems on balance more likely.

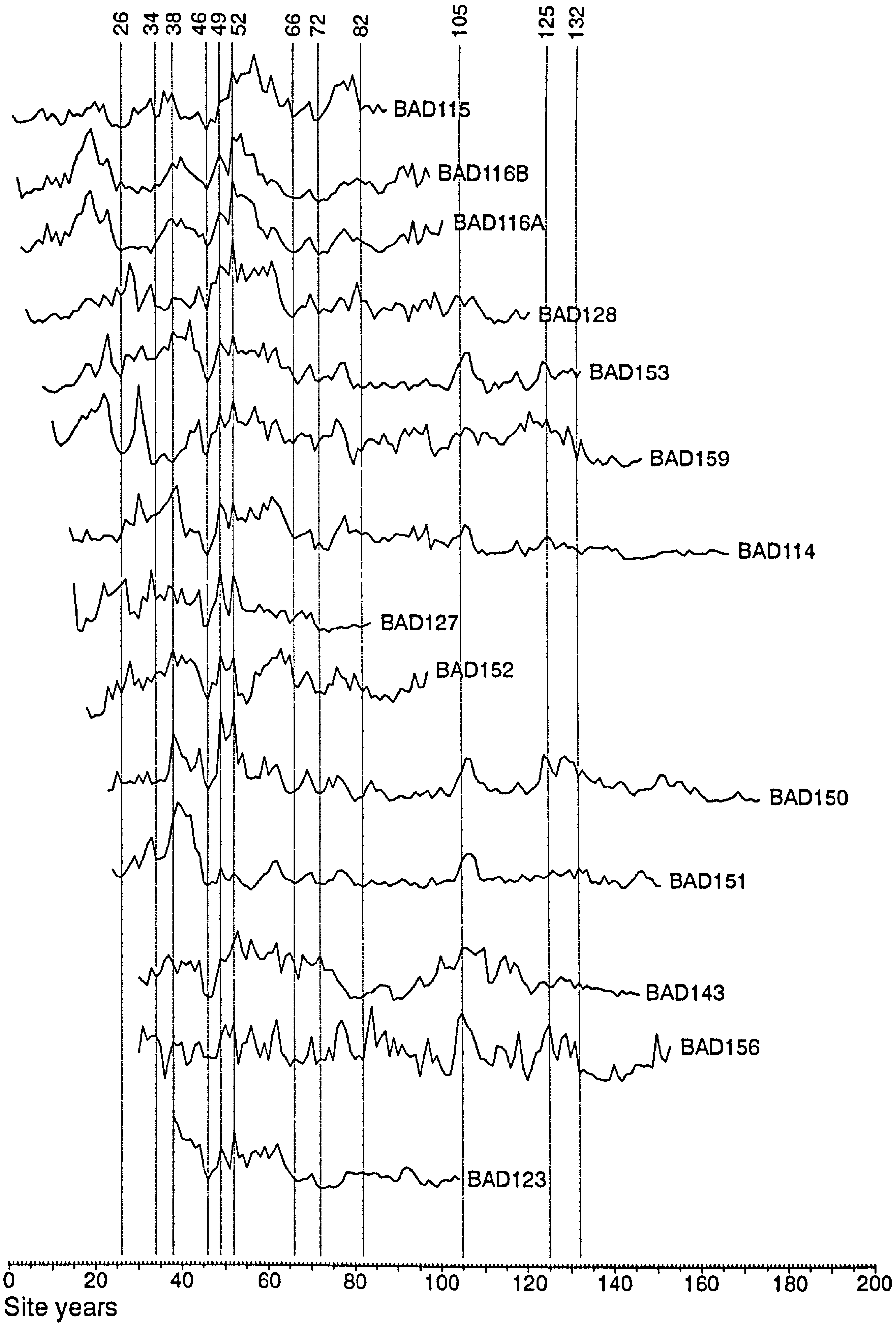


Figure 3.40. Badanloch crossmatching - Raw curves

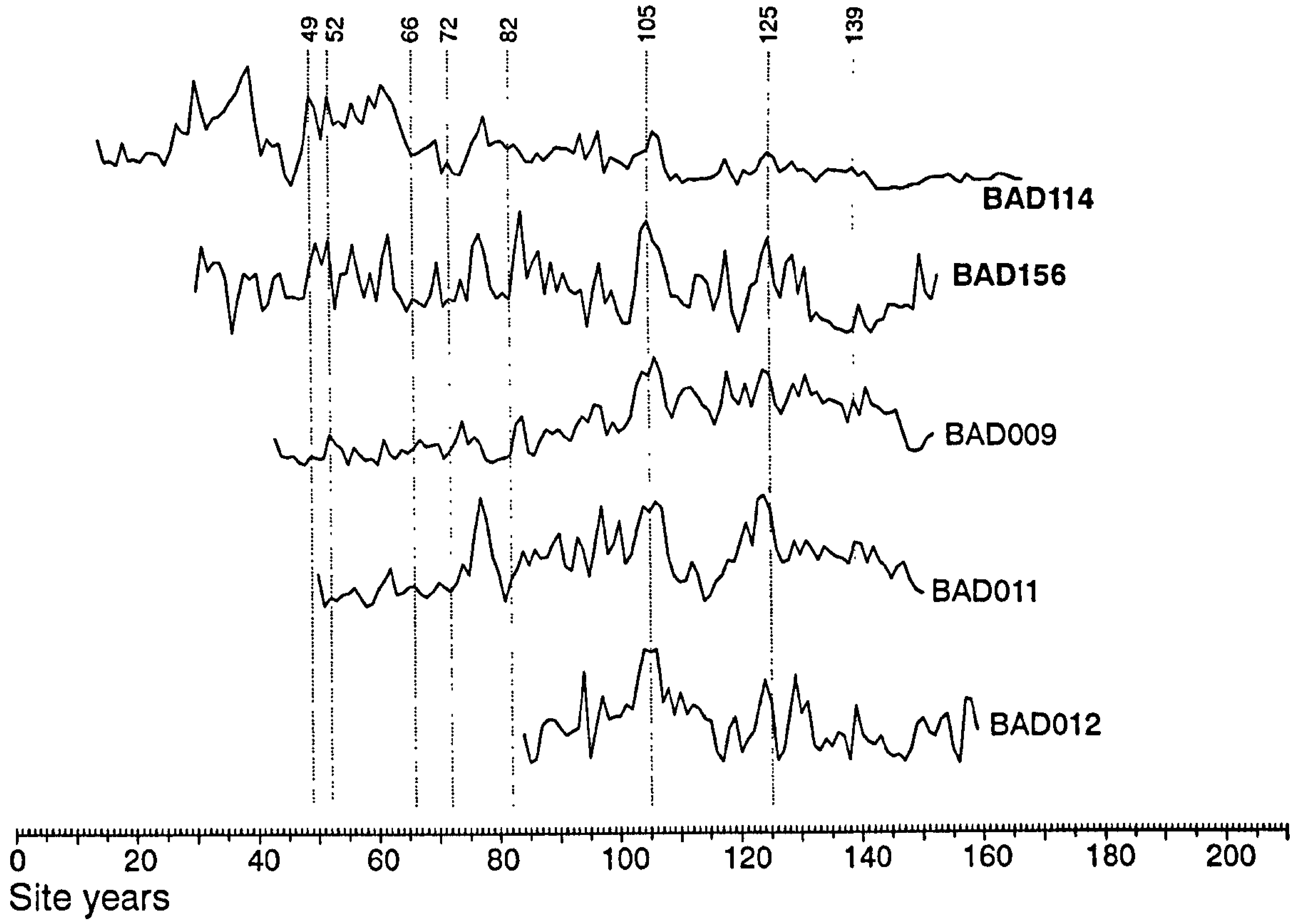


Figure 3.41 Badanloch crossmatching - 'RC' Group.
Trees numbered in bold link this group to Figure 3.40.

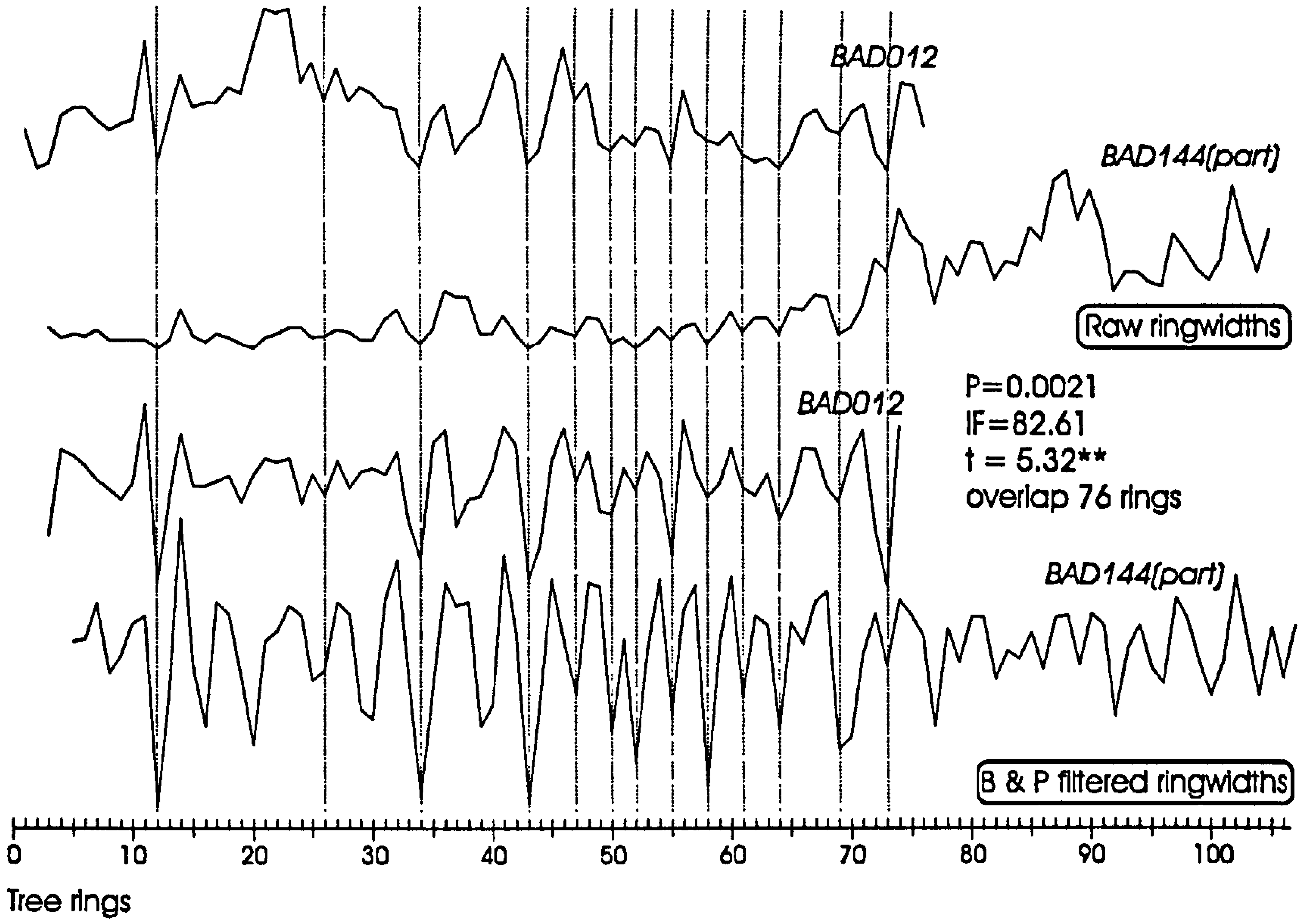


Figure 3.42. Crossmatching of BAD012 and BAD144. Only the raw curves (in standard deviation units) and the Baillie and Pilcher filtered values are shown (the Fritts and Munro filtered sequences are very similar but somewhat shorter).

3.5.2.5 Mean ring-widths for site and site chronology

The mean ring-widths for all the trees, including those less securely matched, are shown in Figure 3.43, their most striking feature being the narrow rings around site year 46 referred to above. Again there is a rise in mean ring-width coinciding with the phase of recruitment, and a gentler decline as the number of trees on the site decreases, the variance increasing as the number of trees alive grows less. Generally there is less year by year variation in the mean ring-widths than at Loch Shin or Loch Vatachan; this could be due to the greater number of trees in the mean and possibly also to less extreme conditions on the site from year to year. The latter explanation is to some extent supported by the apparent greater size of the Badanloch trees, as compared with the rather smaller trees seen at these other two sites.

Figure 3.44 shows the robust mean chronology for the site based on the most securely matched trees as indicated in Table 3.11. As may be seen from the trees incorporated it starts from site year 2 and spans 173 years to end at site year 174. It displays the major features shown in the mean site ring-widths of Figure 3.43, but with rather greater variance from site year 46 onwards. The chronology is used in all inter-site matching as described later.

3.5.3 ^{14}C dating

Two ^{14}C dates were obtained for samples from the Badanloch site by Gear (1989), 4405 ± 50 BP (SRR-3566) for a sample spanning fifty rings from BAD011, and 4370 ± 50 BP (SRR-3567) for a thirty ring section of BAD012; these two dates are statistically indistinguishable (Stuiver and Reimer, 1993). The spans of the ring sections used are shown diagrammatically in Figure 3.38. Dendrochronologically the central rings of the dated portions of these two samples are at 125 and 144 site years respectively, i.e. only 19 years apart. The mean of these two dendrochronological dates, i.e. 134 site years, was equated with the mean of the two ^{14}C dates, i.e. 4388 ± 36 BP, to provide an estimate of the absolute age of this point on the dendrochronological time scale. Calibration gives the following estimate of the calendar age:

Cal BC 3093(3020,2988,2934)2907 (2σ)

i.e. some time between 3093 and 2907 Cal BC. This places the origin of the dendrochronological time scale at between 3227 and 3041 Cal BC (i.e. 134 years earlier) and the demise of the last crossmatched tree at between 3053 and 2867 Cal BC.

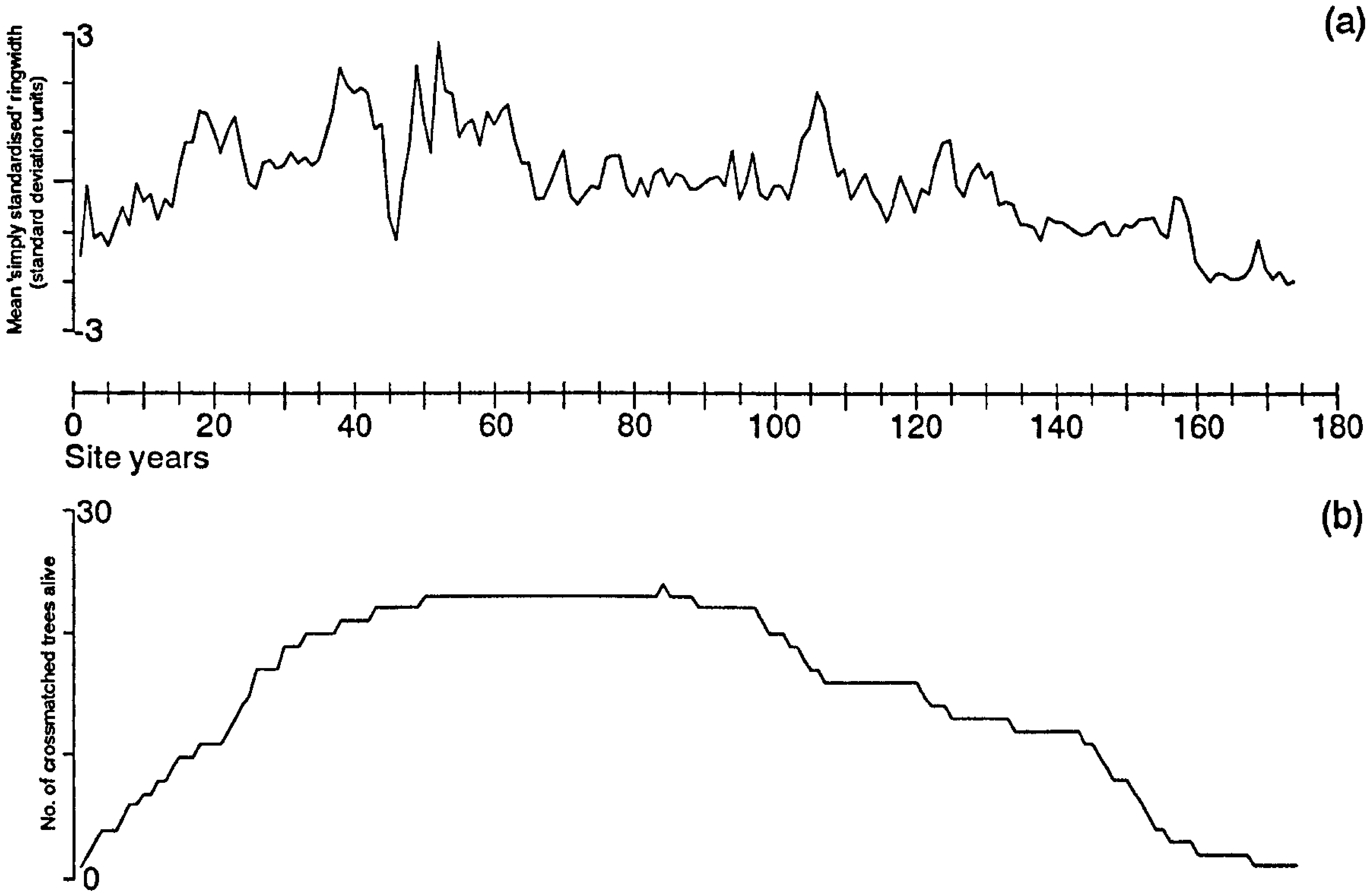


Figure 3.43. Badanloch: (a) - mean ringwidths for the site. Each mean mean ringwidth is the average of the ringwidths for that particular year from the mean radii of all the crossmatched trees.
(b) - Number of crossmatched trees alive on the site, i.e. the number present in the mean year by year.

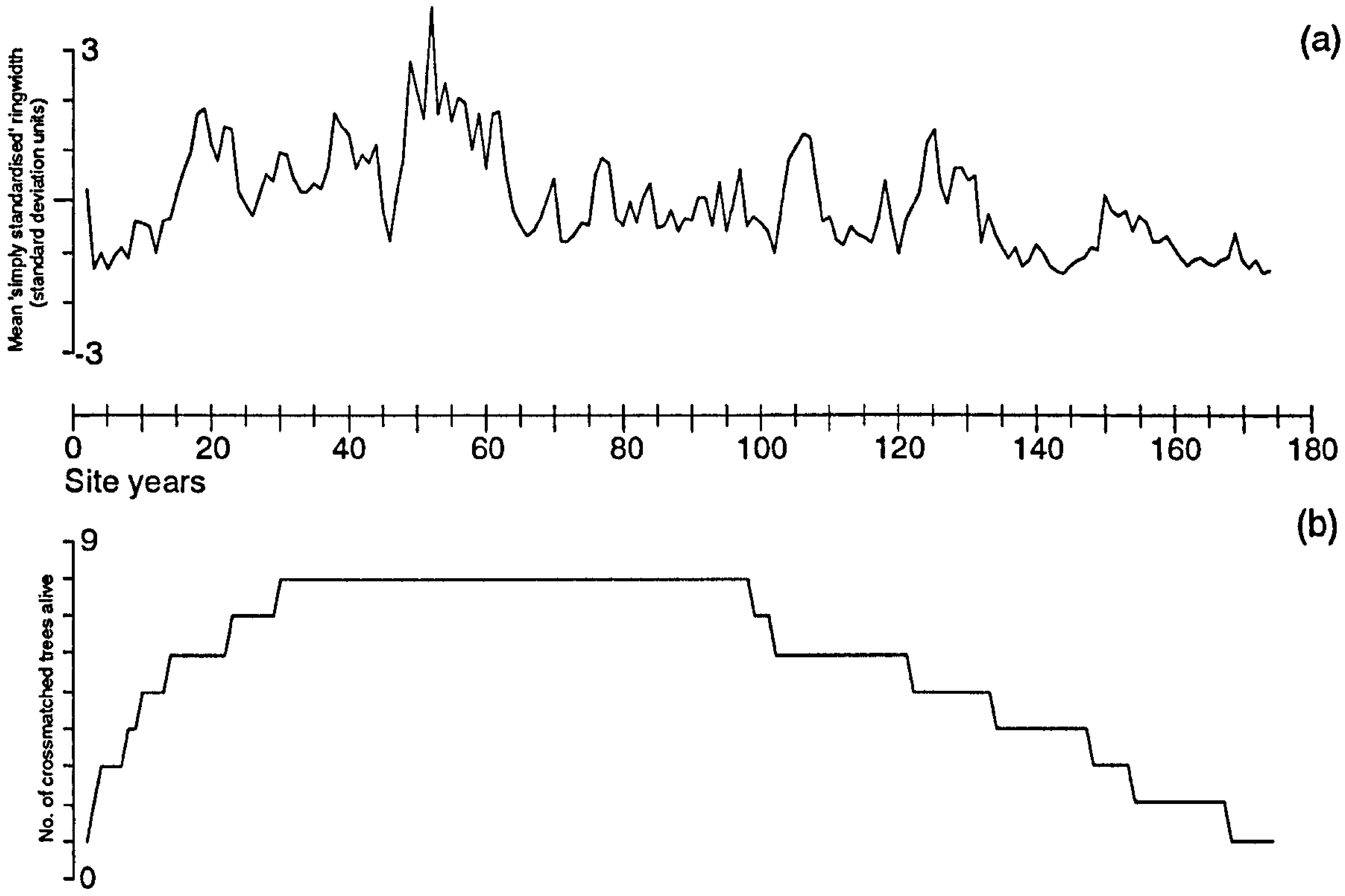


Figure 3.44. Badanloch:
(a) Robust mean chronology from selected trees (see text).
(b) Number of trees in robust mean chronology year by year

3.6 Lochstrathy

58° 24' 50" N 4° 03' 22" W, Nat. Grid Ref. NC(29)796491

(for location see Figure 3.1)

This, the second of the two sites for which data is available from previous studies, has been described fully by Gear (1989), who collected, prepared and measured the samples. To briefly place the site in context, it lies about 16 km to the north of, and about 20 m higher than Badanloch. The area surrounding the site is covered with blanket peat, and it was the cutting of a forestry road through it that revealed the buried subfossil stumps (Gear, 1989).

3.6.1 Dendrochronological Results

3.6.1.1 General statistics

Table 3.12 (next page) gives the individual statistics for the Lochstrathy trees calculated from mean ring sequences derived from those ring series in Gear's (1989) data that provided three crossmatchable radii. Table 3.13, reproduced in part from Gear (1989), gives her estimates for mean ring numbers, ring-widths, stumps per hectare and maximum density of trees alive per hectare for each of her four sampling sites at Lochstrathy. The first two of these means can be seen to be in broad agreement with the calculated figures in Table 3.12.

Table 3.13. Growth statistics for Lochstrathy (Gear, 1989)

	A	B	C	D
Mean no. of rings	57.0	54.0	64.9	63.1
Mean ring-width	0.788	0.595	0.738	0.843
Total stumps ha^{-1}	386.99	248.32	530.50	224.11
Estimated max. no. of stumps alive at any one time ha^{-1}	193	124	265	112

Table 3.12 shows that overall both the mean age and size of the trees at Lochstrathy are somewhat lower than at the other sites described, as is the mean ring-width. However the sensitivity and 1st order autocorrelation of the sequences are roughly the same as those for the other sites.

Table 3.12. Lochstrathy: summary statistics based on data from Gear (1989)

Tree	Number of rings	Mean radius (cm)	Mean ringwidth (mm)	SD of ringwidths	Sensitivity	First order autocorr.
s041	40	1.6	0.39	0.31	0.48	0.64
s043	53	2.4	0.45	0.29	0.21	0.90
s044	144	8.3	0.58	0.36	0.31	0.79
s045	40	1.5	0.38	0.15	0.31	0.54
s047	65	5.7	0.87	0.37	0.25	0.74
s050	221	9.2	0.42	0.30	0.24	0.90
s054	63	2.1	0.33	0.31	0.39	0.81
s060	37	3.1	0.83	0.26	0.17	0.75
s062	35	1.1	0.31	0.20	0.48	0.31
s066	57	6.0	1.05	0.50	0.20	0.87
s067	83	3.9	0.47	0.22	0.30	0.70
s068	62	3.3	0.54	0.28	0.26	0.74
s233	74	3.3	0.44	0.27	0.28	0.81
s234	50	3.4	0.68	0.21	0.22	0.65
s235	89	10.9	1.22	1.11	0.30	0.73
s237	73	4.2	0.58	0.28	0.24	0.79
s245a	160	8.3	0.52	0.50	0.35	0.89
s245b	85	5.0	0.58	0.44	0.39	0.82
s246	156	6.3	0.40	0.29	0.22	0.88
s249	39	1.5	0.38	0.20	0.27	0.81
s250a	43	6.3	1.46	0.67	0.25	0.78
s250b	54	7.7	1.43	0.67	0.24	0.71
s252	130	12.7	0.98	0.49	0.29	0.75
s253	152	5.9	0.39	0.22	0.26	0.66
s254	59	8.5	1.45	0.52	0.29	0.60
s256	89	4.9	0.55	0.23	0.25	0.61
s257	34	1.4	0.41	0.34	0.40	0.79
s260a	69	1.8	0.27	0.13	0.31	0.56
s260b	54	1.2	0.21	0.07	0.27	0.56
s264	77	8.4	1.09	0.62	0.32	0.65
snk1a	54	1.4	0.26	0.21	0.40	0.75
snk3	36	0.7	0.18	0.18	0.38	0.59
Mean	**77.4**	**4.75**	**0.629**		**0.298**	**0.721**
SD	**45.3**	**3.21**	**0.373**		**0.077**	**0.128**

3.6.1.2 Mean growth curve

As the samples were not retained, information as to their origin (branch, trunk, root etc.) and their condition (centre present or missing etc.) is not available, so a mean growth curve could not be produced.

3.6.1.3 Site crossmatching

Few samples could be successfully crossmatched with each other, and such significant matches as were found were not replicated. A major factor in this was the shortness of the sequences, many being less than 50 rings (see Table 3.12). In the absence of sufficient significant, replicated matches no site chronology was produced. However the individual samples were checked against the robust mean chronology from Badanloch, though again without result. It may well be that the high and exposed plateau of which Lochstrathy is a part was colonised by trees more widely scattered in space and time than at the other sites in this study. The wide spread of ^{14}C dates for the site described below would seem to support this view.

3.6.2 ^{14}C dating

Five dates for subfossil wood from Lochstrathy are quoted by Gear and Huntley (1991). These, SRR-3574 to SRR-3578 inclusive, are listed with their calibrated dates in the discussion on radiocarbon dates for the region below. The calibrated dates cover an overall span at the 2σ level from 3291 Cal BC to 2509 Cal BC.

3.7 Laxford Bridge

58° 22' 23" N 5° 02' 9" W, Nat. Grid Ref. NC(29)227468

Plates 8 and 9 (for location see Figure 3.1).

3.7.1 Site Description

As well as the main sites listed above, two subsidiary sites were investigated and about a dozen samples collected from each (Table 3.1). Plans were not made of either site as the stumps were scattered and relatively few in number.

The first of these sites, at Laxford Bridge, is an area of blanket peat in a sheltered valley on the coast at the head of Loch Laxford, a sea loch. The peat has been extensively cut for fuel in the past and is still being cut today. Originally the peat appears to have formed along the valley on the south side of the River Laxford, and to have been

Plate 8. Laxford Bridge. On the old peat cuttings, looking east, with a sampled stump in the foreground.

Plate 9. Laxford Bridge, subfossil pine exposed on the shore. Note the layer of birch below the pine. The tape is extended 1 m.

protected at its western, seaward limit by an outcropping granite dyke in the Lewisian gneiss of the area. The eastward extension of the dyke forms small outcrops amid the blanket peat. However, in the relatively recent past the sea appears to have crossed a low point in this dyke and eroded a roughly square area (about 0.5 km × 0.5 km) of the peat to form a bay, Tràigh Bad na Bàighe, which dries out at low water and has a narrow entrance at its north-east corner. As a result of this incursion the peat is now exposed at its western end in a 3 - 4 m vertical face cut by the sea. The upper 2 m is peat and the lower section consists of alluvial gravels. From this face two of the samples, LAX011 and LAX012, were recovered. The other ten, LAX001 - LAX010, were cut from stumps found among peat cuttings about 200m from the shore. Here the depth of the peat was 1.14 m at one point on the top of an apparently unworked area. The lower side of a pine stump buttress root was found to be 65 cm above the gravels at the base of this peat. In the profile exposed on the shore the peat depths were roughly the same, with a layer of birch visible beneath the pine.

3.7.2 Dendrochronological Results

3.7.2.1 General statistics

These are shown in Table 3.14. Of the twelve samples recovered all proved measurable, although four had missing centres. Generally the trees are larger, in age, mean radius and mean ring-width, than those at the other coastal site, Loch Vatachan. Figures for sensitivity and 1st order autocorrelation are roughly the same.

3.7.2.2 Mean growth curve

The mean growth curve, Figure 3.45, shows less of an early rise than at some of the other sites, a marked feature being the high degree of variance, due largely to the small number of samples, particularly in the last 60 years.

3.7.2.3 Site crossmatching

This is summarised in Table 3.15 and Figure 3.46. Nine of the trees proved matchable, this group spanning 217 years. There seems to have been an initial phase of recruitment spanning the first 30 years or so of the site's occupation, but with so few samples this cannot be certain. As at the other sites the apparent death dates are scattered. Figure 3.47 shows the statistical quality of the crossmatching. The core of the matched trees is formed by two groups, the first of which consists of LAX004, LAX005 and LAX007; with LAX001, LAX006 and LAX008 forming the second. These two groups appear to be linked by matches between LAX006 and LAX007 and between LAX008 and LAX005. Though these matches are not strong, the link was confirmed by forming

Table 3.14. Laxford Bridge: summary statistics based on the mean radius for each sample measured.

Tree	Number of rings	Mean radius (cm)	Mean ringwidth (mm)	SD of ringwidths	Sensitivity	First order autocorr.
LAX001	124	14.6	1.18	0.56	0.30	0.67
LAX002	69	2.7	0.39	0.21	0.40	0.55
LAX003	116	10.1	0.87	0.53	0.29	0.82
LAX004	96	11.6	1.21	0.50	0.25	0.74
LAX005	134	16.9	1.26	0.41	0.22	0.66
LAX006	174	10.6	0.61	0.38	0.29	0.82
LAX007	100	3.5	0.35	0.17	0.32	0.64
LAX008	178	15.8	0.89	0.45	0.24	0.84
LAX009	65	4.9	0.75	0.43	0.30	0.76
LAX010	116	10.2	0.88	0.55	0.34	0.74
LAX011	46	10.3	2.23	0.97	0.28	0.69
LAX012	103	15.2	1.48	0.89	0.36	0.77
Mean	**110.1**	**10.53**	**1.008**		**0.299**	**0.725**
SD	**40.1**	**4.77**	**0.516**		**0.050**	**0.085**

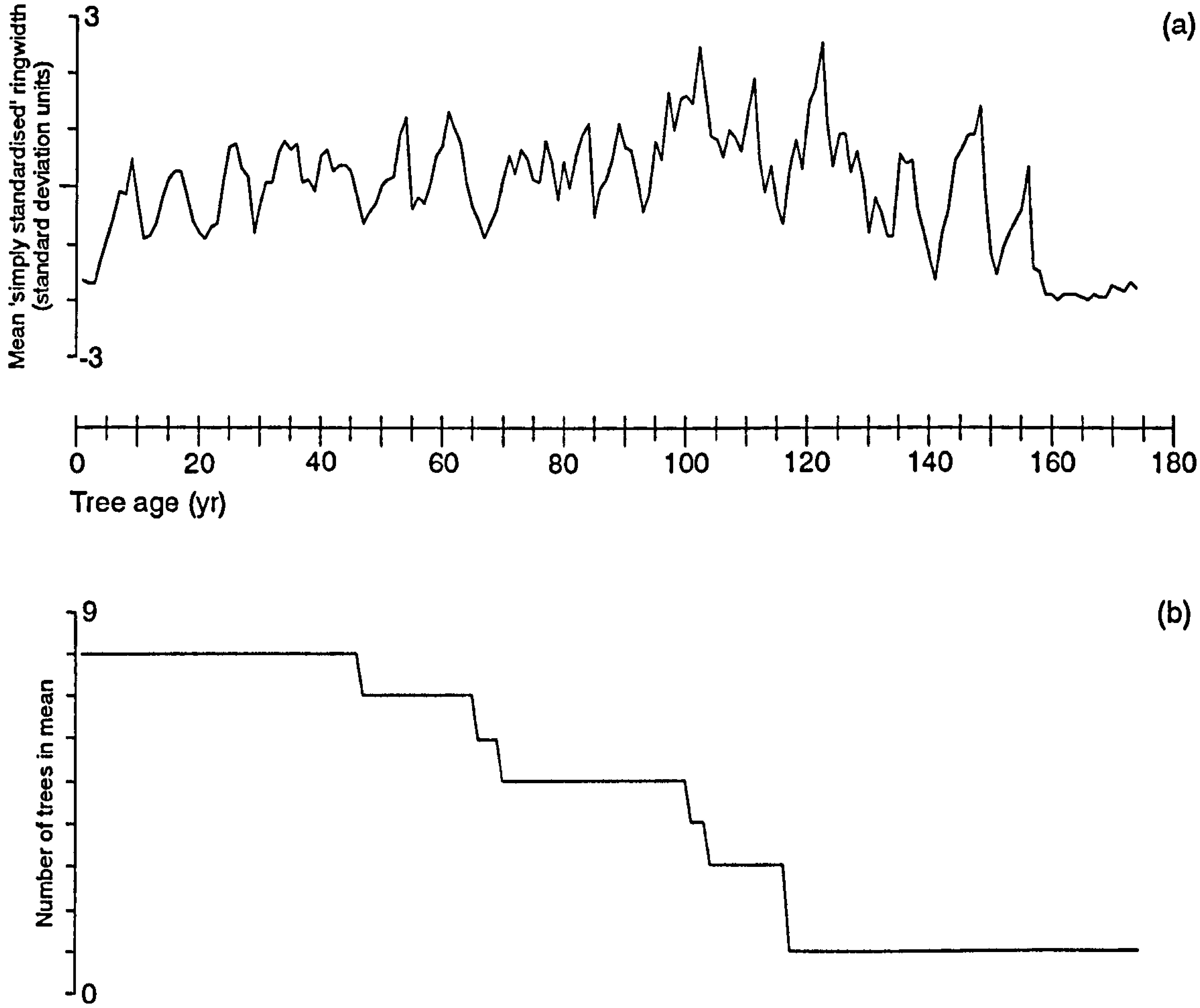


Figure 3.45. (a) - Mean growth curve for the trees at Laxford Bridge.
(b) - Number of trees included in the mean.

Table 3.15. Laxford Bridge - summary of crossmatching positions.

TREE		MIN AGE	MATCH POSITION (site years)	DEATH (minimum - site years)	
LAX001	c	124	29	152	NC
LAX002		69			
LAX003		116	10	125	
LAX004	c	96	24	119	NC
LAX005	c	134	19	152	NC
LAX006	c	174	18	191	
LAX007	c	100	1	100	
LAX008	c	178	40	217	NC
LAX009		65			
LAX010		116	66	181	
LAX011		46			Shore
LAX012		103	112	214	Shore

Samples recovered: 12. Samples successfully crossmatched: 9 (75%)
NC indicates a missing or damaged centre
c indicates inclusion in the site chronology

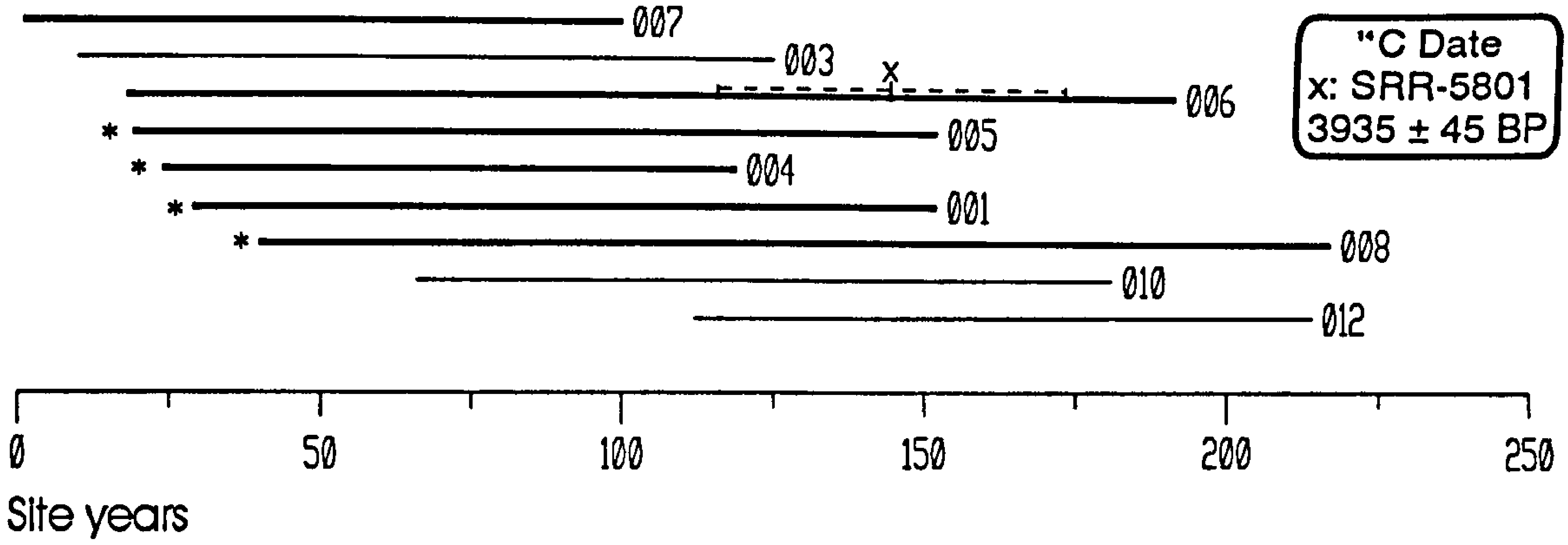


Figure 3.46. Laxford Bridge - crossmatched trees. The lines represent individual life spans, the asterisks indicating a missing centre to the tree. The numbers are the sample numbers (the prefix LAX is omitted). The heavy lines are the trees used to build the site chronology. The dotted line shows the ring span used for dating with X as its centre.

LAX								TREES
007	003	006	005	004	001	008	010	012
007	n/s	4.7**	5.01**	4.59**	n/s	n/s	s/o	n/o
n/s	003	6.47***	n/s	3.61*	n/s	3.82*	n/s	s/o
A	A	006	n/s	n/s	4.26**	4.77**	4.49**	4.25**
A	n/s	n/s	005	6.59***	n/s	3.8*	n/s	s/o
A	C	n/s	A	004	n/s	n/s	s/o	s/o
n/s	n/s	A	n/s	n/s	001	3.79*	n/s	s/o
n/s	C	A	C	n/s	A	008	4.0*	4.58**
s/o	n/s	A	n/s	s/o	n/s	C	010	n/s
n/o	s/o	A	s/o	s/o	s/o	C	n/s	012
007	003	006	005	004	001	008	010	012
TREES								LAX

REPLICATION: This table shows the number of significant matches in which the tree is present.

TREE	MATCHES	TREE	MATCHES
LAX007	3	LAX001	2
LAX003	3	LAX008	6
LAX006	6	LAX010	2
LAX005	3	LAX012	2
LAX004	4		

CROSSMATCHING QUALITY

UPPER RIGHT
Values of 't' and multiple probability for Baillie and Pilcher filter.
* - 0.1>P>0.01 ** - 0.01>P>0.001 *** - P<0.001

LOWER LEFT
Match significant if P < 0.05 and IF > 5.0
A - All 3 filters give the same match position and all matches are significant Minimum overlap is 50 rings.
B - As A but minimum overlap is 30 rings.
C - As B but only 1 or 2 matches significant.

n/s - not significant
s/o - short overlap (< 54 rings, ie 50 rings plus those lost in the B & P filter)
n/o - no overlap

Figure 3.47. Laxford Bridge crossmatching. This diagram shows the significant crossmatches between trees with the quality and replication of those matches.

chronologies from the two groups and testing the match between these. This yielded a best match in the correct position (for all three filters) to confirm the individual matches, with P = 0.00463, IF = 117.71 and t = 4.64** for the Baillie and Pilcher filter.

Figure 3.48 shows the raw ring sequences (in standard deviation units) in their crossmatched positions. The narrow ring values at site years 104 and 158 are very marked in all trees alive at those times, and the very narrow sequences spanning the first and last 20 years of LAX006 suggest particular environmental factors, possibly changes in the water table, affecting that tree.

3.7.2.4 Mean ring-widths for site and site chronology

These are shown in Figure 3.49a. From this it can be seen that the variance increases steadily throughout the occupation of the site, with the first 20 years or so being a period of low ring-width values. The years of narrow ring values noted in the previous section are clearly shown, that around 104 site years being at the time when most of the crossmatched trees were alive. It is possible that the death of LAX007 at this time was related to the conditions producing this poor growth. The low values from site years 175 to 190 should be noted even though only 3 trees are alive at this time. Again the death of LAX010 at the beginning of this interval may be related to this set-back.
Figure 3.49c shows the site chronology constructed from the trees indicated in Table 3.15 and Figure 3.46. These were selected as before on the basis of the quality and consistency of their crossmatching. This chronology was used for all attempts at crossmatching with other sites.

3.7.3 ^{14}C dating

One date of 3935 ± 45 years BP (SRR-5801) was obtained from a section of LAX006 spanning rings 99 - 156 (site years 116 - 173, see Fig. 3.46). On calibration this gave an overall 2σ range of 2561 to 2285 Calendar years BC. These limits give a date within the range 2718 - 2442 BC for the origin of the site year scale and a date in the range 2501 - 2225 BC for the death of the last crossmatched tree (both ranges based on the centre of the ring span dated). This is rather later than dates for the sites described earlier, but within the range obtained for other subfossil pine in the region (see Section 3.10.3).

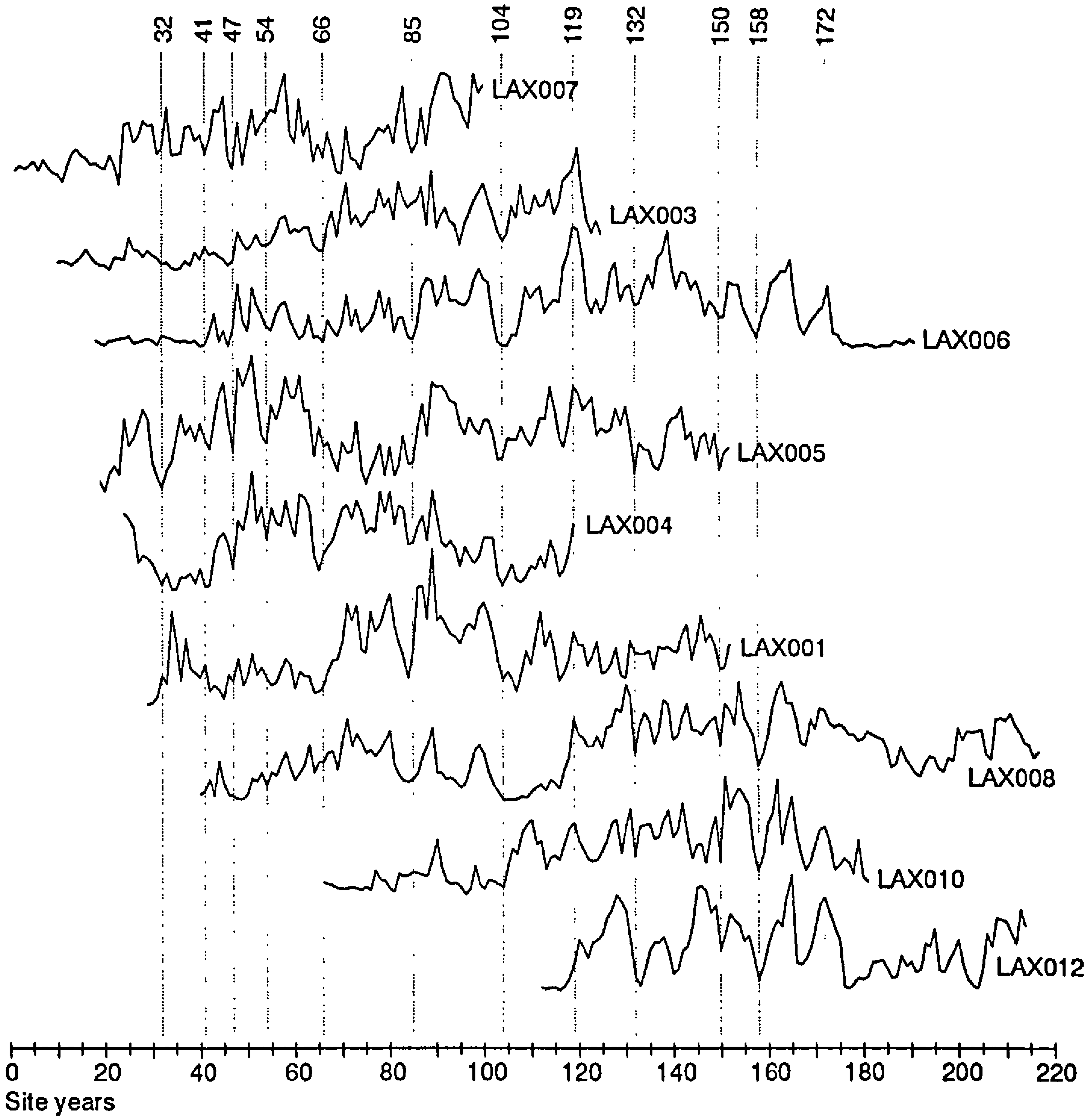


Figure 3.48. Laxford Bridge crossmatching

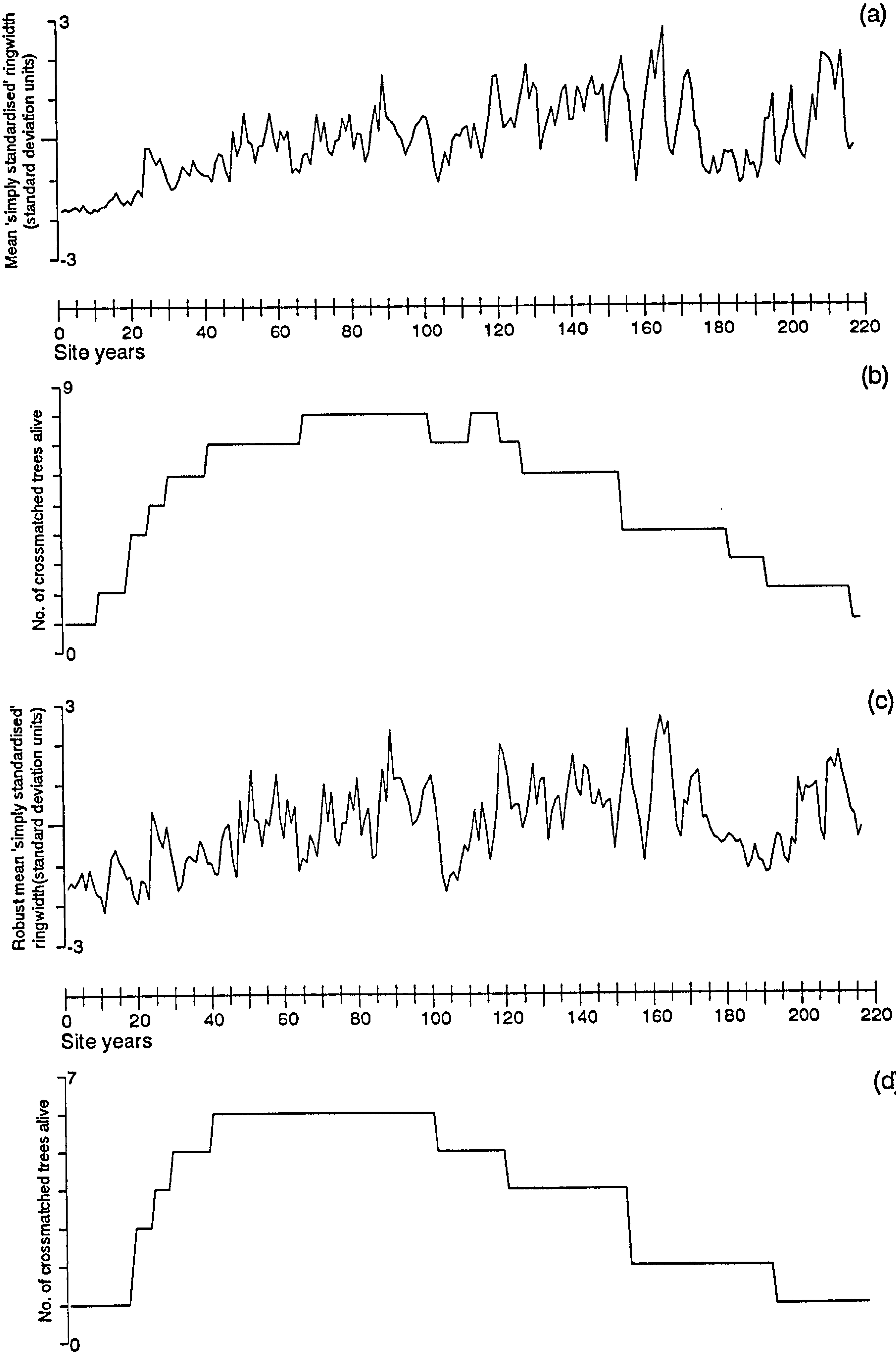


Figure 3.49. Laxford Bridge: (a) - mean ringwidths for the site. Each mean ringwidth is the average of the ringwidths for that particular year from the mean radii of the crossmatched trees. (b) Number of crossmatched trees alive on the site, i.e. the number present in the mean year by year. (c) Robust mean chronology from selected trees (see text). (d) Number of trees in robust mean chronology year by year.

3.8 Srath Dionard

58° 29' 3" N 4° 51' 8" W, Nat. Grid Ref. NC(29)338585

Plate 10 (for location see Figure 3.1)

3.8.1 Site Description

This, the second of the two subsidiary sites investigated, is the most northerly in this study. Srath Dionard is a broad, open, windswept valley which runs south-west from the Kyle of Durness, eventually turning inland along the north-eastern flank of Foinaven (908 m). At this turning point, about 6 km from the southern tip of the Kyle, the valley is separated from the west coast by a low col (160 m). The valley floor is a mixture of morainic and alluvial drift, overlying Lewisian gneiss, although at its northern end lie the Durness limestones and associated series. Much of the valley is covered with areas of deep blanket peat, and shallower peaty podzols occurring on the areas of moraine in the upper reaches. The area is predominantly treeless, the peat being covered with a mixture of *Calluna vulgaris* and *Trichophorum cespitosum*. The site investigated is at a point about 10 km south of Balnakiel Bay and the Kyle of Durness on the north coast, and about 10 km inland of Loch Inchard on the west coast. Here the River Dionard is crossed by the track to Rhigolter, and about 100m from the river's west bank to the north of the track, is an area of deep peat containing a number of scattered subfossil pines revealed by erosion. The tops of these stumps are about 50 cm below the present day peat surface and the base of their buttress roots at least a metre above the base of the peat. A more detailed profile is described in Section 3.8.4 below. Altogether 15 samples were taken from stumps (and one piece of trunk) scattered across an area of 1 - 2 ha. A monolith was dug out from beside DIO001.

3.8.2 Dendrochronological Results

3.8.2.1 General statistics

Table 3.16 lists these for this site. DIO004, 007, 009, 010 and 014 were not counted, either because they were too decayed, or as in the case of DIO004, too distorted. As at Laxford Bridge mean radius and ring-width are rather greater than those for the other sites studied. Sensitivity and 1st order autocorrelation are roughly the same as those at the other sites.

3.8.2.2 Mean growth curve

Figure 3.50 shows this curve for the trees at Srath Dionard. As at Laxford Bridge there is a large amount of variance, again probably because of the small number of trees

Plate 10. Srath Dionard, looking south-west, with various sampled stumps in the peat hag.

Table 3.16. Srath Dionard: summary statistics based on the mean radius for each sample measured.

Tree	Number of rings	Mean radius (cm)	Mean ringwidth (mm)	SD of ringwidths	Sensitivity	First order autocorr.
DIO001	117	14.6	1.25	0.58	0.28	0.80
DIO002	98	8.8	0.90	0.56	0.38	0.72
DIO003	173	12.7	0.73	0.37	0.25	0.75
DIO005	85	7.0	0.82	0.44	0.33	0.74
DIO006	82	9.4	1.14	0.53	0.24	0.77
DIO008	52	3.9	0.75	0.47	0.47	0.39
DIO011	141	18.4	1.30	0.64	0.27	0.77
DIO012	77	12.8	1.66	1.06	0.29	0.82
DIO013	85	14.0	1.65	0.88	0.18	0.87
Mean	**101.1**	**11.28**	**1.134**		**0.301**	**0.738**
SD	36.9	4.41	0.360		**0.085**	**0.136**

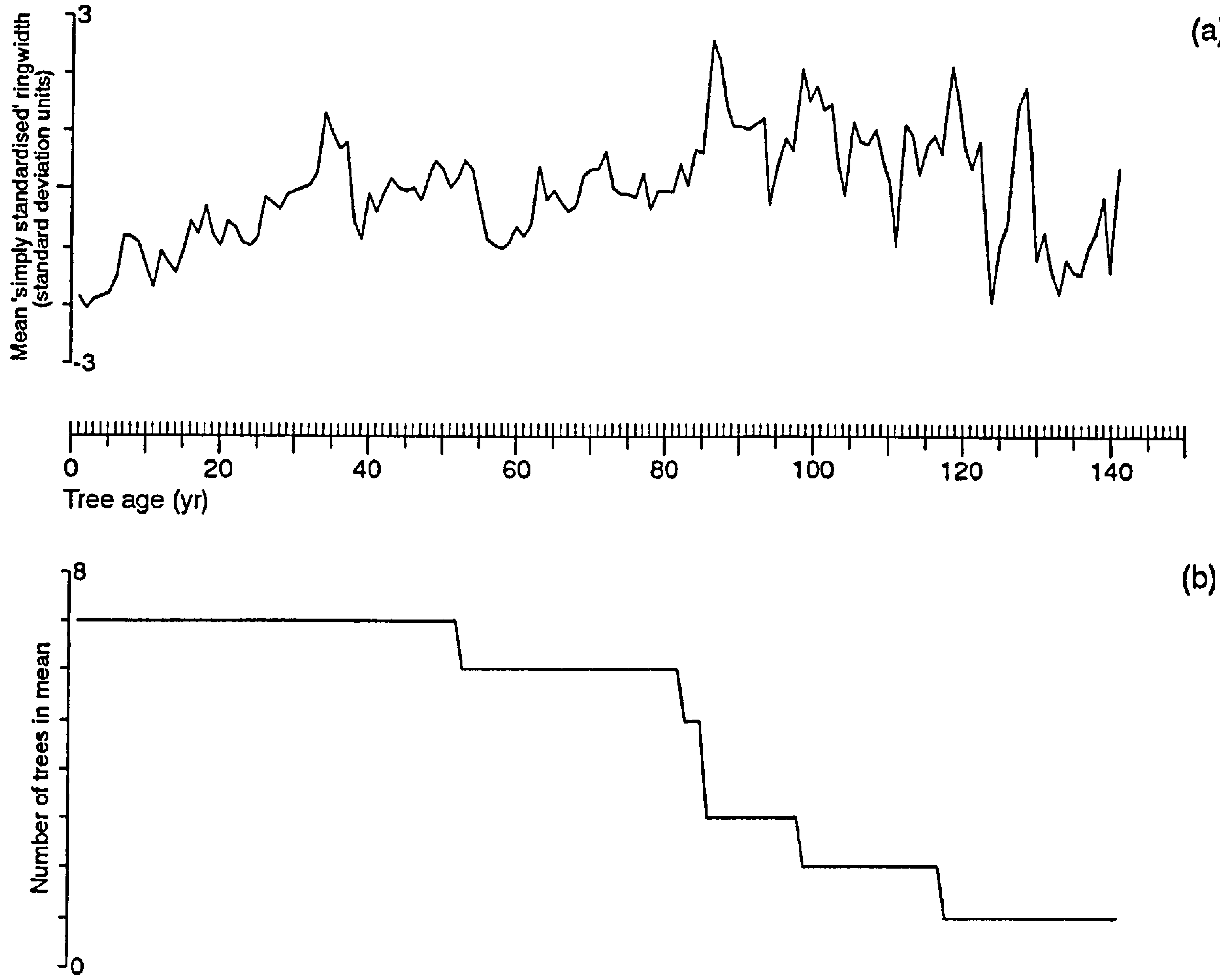


Figure 3.50. (a) - Mean growth curve for the trees at Srath Dionard.
(b) - Number of trees included in the mean.

included in the mean, particularly after about 85 years, and the overall shape of the curve is similar.

3.8.2.3 Site crossmatching

This is summarised in Table 3.17 and Figure 3.51. The total span of the crossmatched trees is 193 years, though as the centre is missing from DIO003, the earliest crossmatched tree on the site, this figure is a minimum. As at the previous site, there is no clear indication of a recruitment phase, as too few trees are present in the crossmatching to determine this. The death dates are scattered as at all the other sites, although the three most recent crossmatched trees all die within 25 years of each other. The quality of crossmatching is shown in Figure 3.52. DIO006 and DIO011 form the core of the group with DIO003 less well linked; the site chronology for attempts at inter-site crossmatching is formed from these three trees.

Otherwise the matching is poorly replicated, probably because of the shortness of some of the ring sequences and the wide spread of start dates. DIO001 and DIO012 are linked to DIO003 and DIO011 respectively by one significant match each (see Figure 3.52), these matches being supported by significant matching with the site chronology ($P = 0.00123$, $IF = 286.95$, $t = 5.21$**, overlap 117 and $P = 0.00376$, $IF = 41$, $t = 4.67$**, overlap 77 for the Baillie and Pilcher filter respectively). Similarly DIO002 matches DIO005 visually and with statistical significance (see Figure 3.52), but there is no strong match with the site chronology for either of these two trees.

The raw curves for the more confidently matched trees are presented in Figure 3.53

3.8.2.4 Mean ring-widths for site and site chronology

These are shown in Figure 3.54a. They exhibit the same high variance as those of the previous site, again almost certainly because of the small number of trees in the sample. Little can be inferred from the shape of the curve, but the maxima at around site years 85, 140, and 152 should be noted. Figure 3.54c shows the robust mean site chronology, the high variance again probably due to the few trees included in it (only one for nearly half its duration).

3.8.3 ^{14}C dating

A ^{14}C date was obtained from rings 96-122 (site years 148 - 174) of DIO011. This date, 4270 ± 45 (SRR-5796) on calibration yielded a 2σ range from 2922 Cal yr BC to 2702 Cal yr BC. This would imply a range of dates from 3083 Cal yr BC to 2863 Cal yr BC for the origin of the Srath Dionard site year axis, and a range from 2890 Cal yr BC to 2670 Cal yr BC for the death of the last crossmatched tree (both ranges based on the

Table 3.17. Srath Dionard - summary of crossmatching positions.

TREE		MIN AGE	MATCH POSITION (site years)	DEATH (minimum - site years)	
DIO001		117	4	120	
DIO002		98			
DIO003	c	173	1	173	NC
DIO004					
DIO005		85			
DIO006	c	82	56	137	
DIO007					
DIO008		52			
DIO009					
DIO010					
DIO011	c	141	53	193	
DIO012		77	100	176	NC
DIO013		85			
DIO014					
DIO00t		91			Trunk

Samples recovered: 14. Samples successfully crossmatched: 5 (36%).

NC indicates a missing or damaged centre

c denotes inclusion in the site chronology

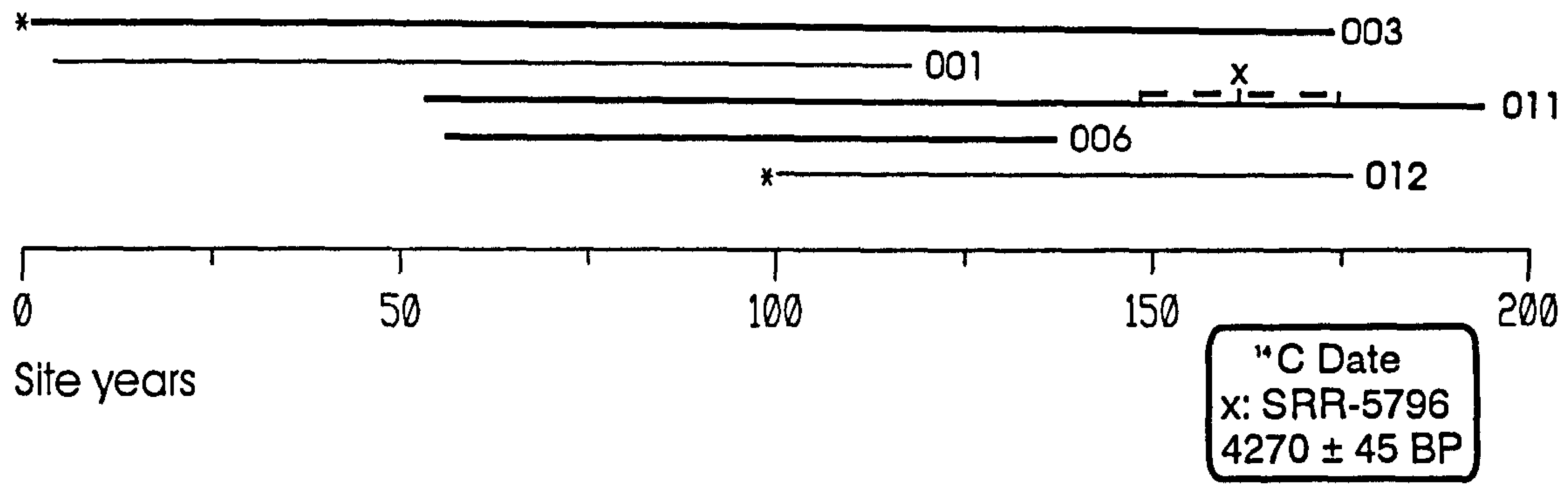


Figure 3.51. Srath Dionard - crossmatched trees. The heavy lines show the trees used in the site chronology, the lighter ones show trees linked by one good match only. The numbers are the sample numbers (the prefix DIO is omitted). The dotted line shows the rings used for ^{14}C dating, x being the centre.

		TREES
DIO	006	011
003	3.5*	4.29**
C	006	5.56***
C	A	011
003	006	DIO
TREES		

CROSSMATCHING QUALITY

UPPER RIGHT
Values of 't' and multiple probabilityfor Baillie and Pilcher filter.
* - 0.1>P>0.01 ** - 0.01>P>0.001 *** - P<0.001

LOWER LEFT
Match significant if P < 0.05 and IF > 5.0
A - All 3 filters give the same match position and all matches are significant Minimum overlap is 50 rings.
B - As A but minimum overlap is 30 rings.
C - As B but only 1 or 2 matches significant.

n/s - not significant
s/o - short overlap (< 54 rings, ie 50 rings plus those lost in the B & P filter)

REPLICATION:

TREE	MATCHES
DIO003	2
DIO006	2
DIO011	4

This table shows the number of significant matches in which the tree is present.

Significant single matches (Baillie and Pilcher filter, minimum overlap 50) - see text.

DIO001/DIO003 P = 0.00096, IF = 68.24, t = 5.28***, overlap 117
DIO002/DIO005 P = 0.00022, IF = 155.84, t = 5.74***, overlap 74
DIO005/DIO011 P = 0.00201, IF = 87.14, t = 4.84**, overlap 70
DIO011/DIO012 P = 0.00479, IF = 41.28, t = 4.39**, overlap 77

Figure 3.52. Srath Dionard crossmatching. This diagram shows the significant crossmatches between trees with the quality and replication of those matches.

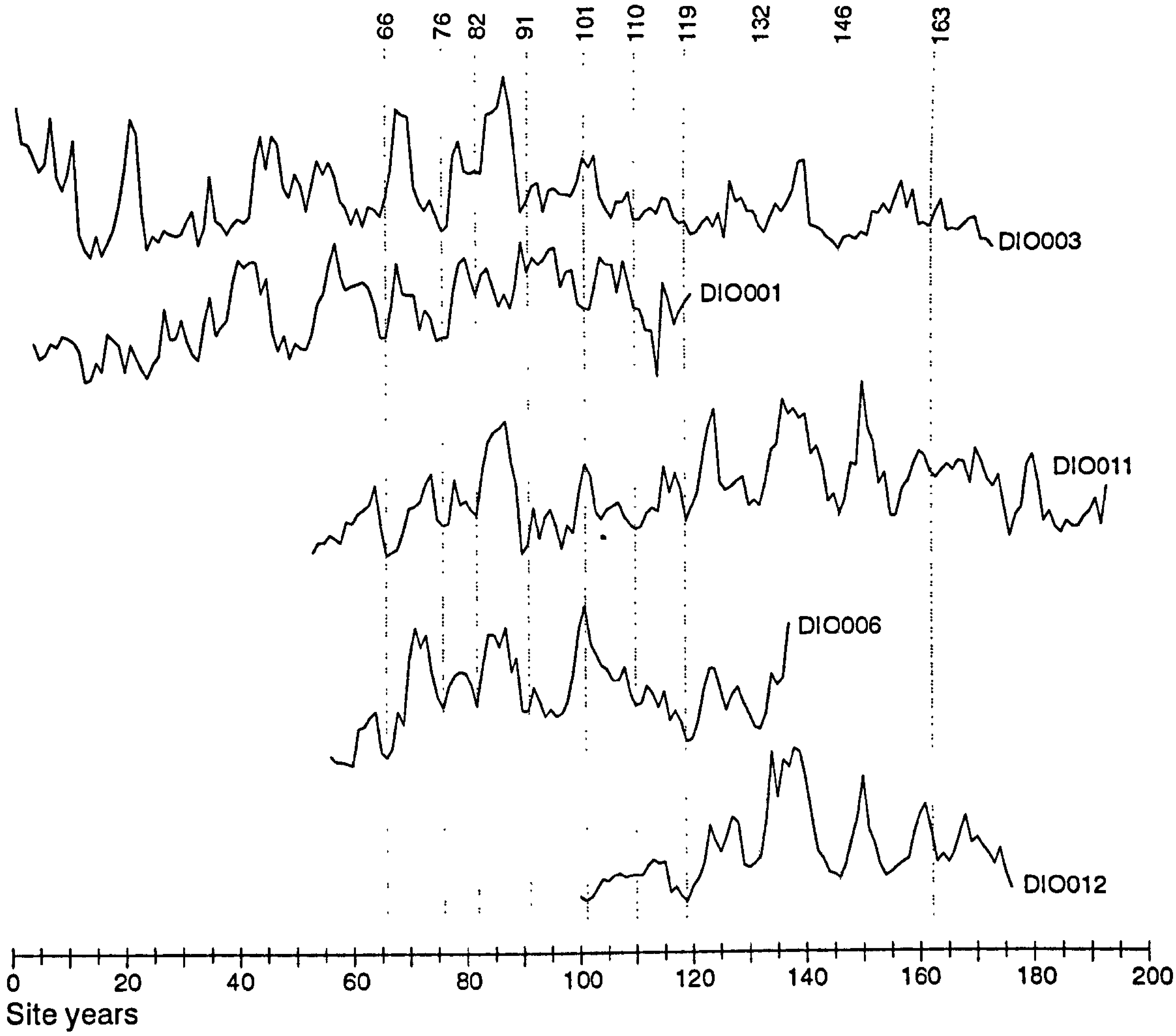


Figure 3.53. Srath Dionard crossmatching

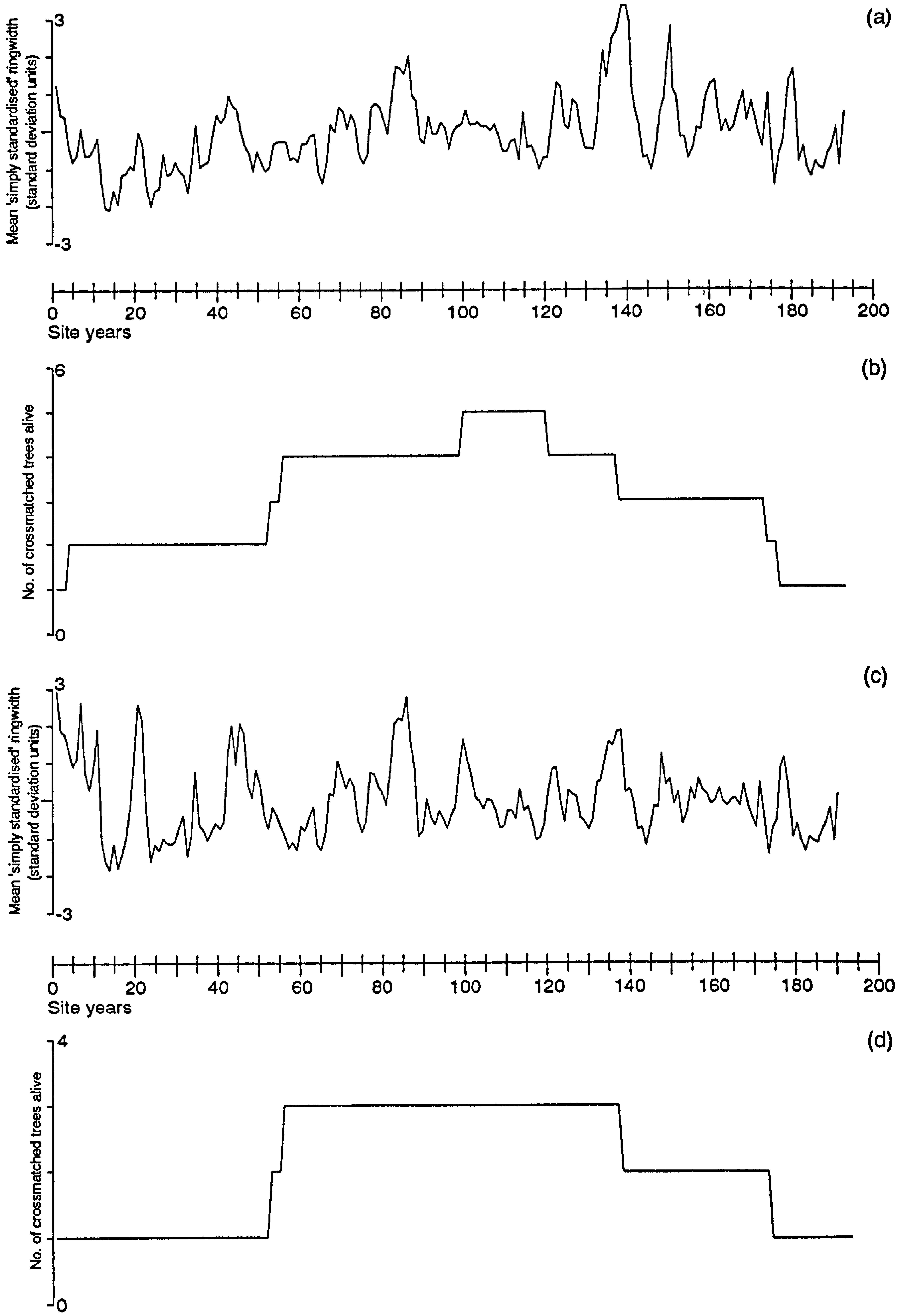


Figure 3.54. Srath Dionard: (a) - mean ringwidths for the site. Each mean ringwidth is the average of the ringwidths for that particular year from the mean radii of the crossmatched trees. (b) Number of crossmatched trees alive on the site i.e. the number present in the mean year by year. (c) Robust mean chronology from selected trees (see text). (d) Number of trees in robust mean chronology year by year.

centre of the ring span dated). These dates place the occupation of the site by pine in the same general period as the other dates available for the region and are discussed below.

3.8.4 Pollen and Tephra Results

A monolith was cut from next to DIO001 and sampled for pollen and tephra as detailed in Section 2.6. A substantial layer of opaque material was located by X-ray at about 74 cm from the surface in the monolith, and on extraction was identified (by J.J. Blackford as described in Section 2.6.5) as being almost certainly from the eruption Hekla 4 (2310 ± 20 BC - Hall *et al.* (1994), see Section 1.2), although some readings fell short of the 95% total oxides required (see Appendix 6) and further samples are awaiting analysis. The stratigraphy of the monolith is shown in Figure 3.55, and the pollen percentage and concentration diagrams in Figures 3.56a and 3.56b respectively. At this site only *Pinus*, *Calluna* and Ericales pollen grains were counted, percentages being of the total of these. Nevertheless, a prominent pine peak was found at 92 cm, 18 cm below the tephra. As the concentration diagram (Fig. 3.56b) shows, this is a real peak, and as such almost certainly represents the presence of pine on the site. This separation of the pine peak and tephra tallies well with that found at the other sites and is discussed below.

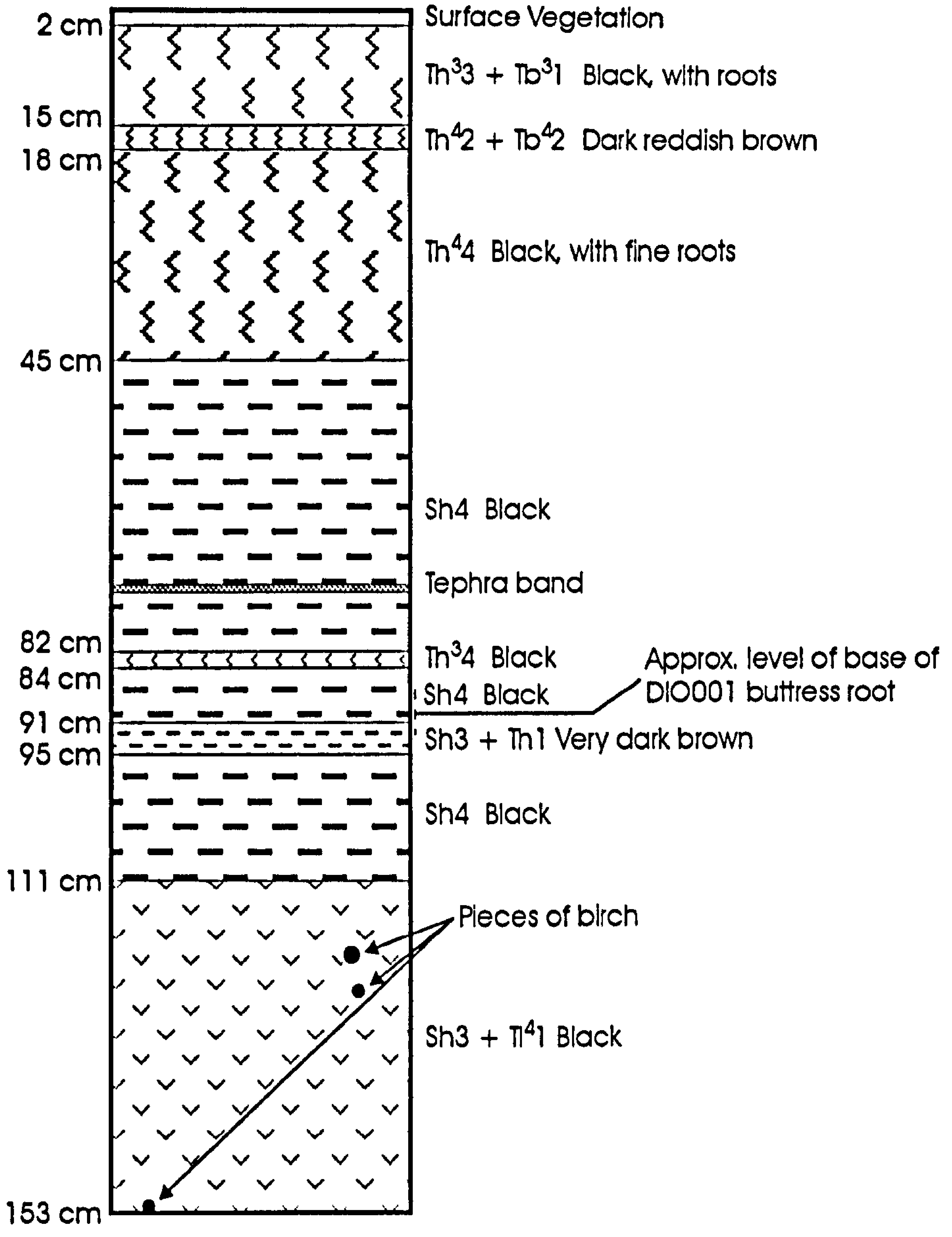
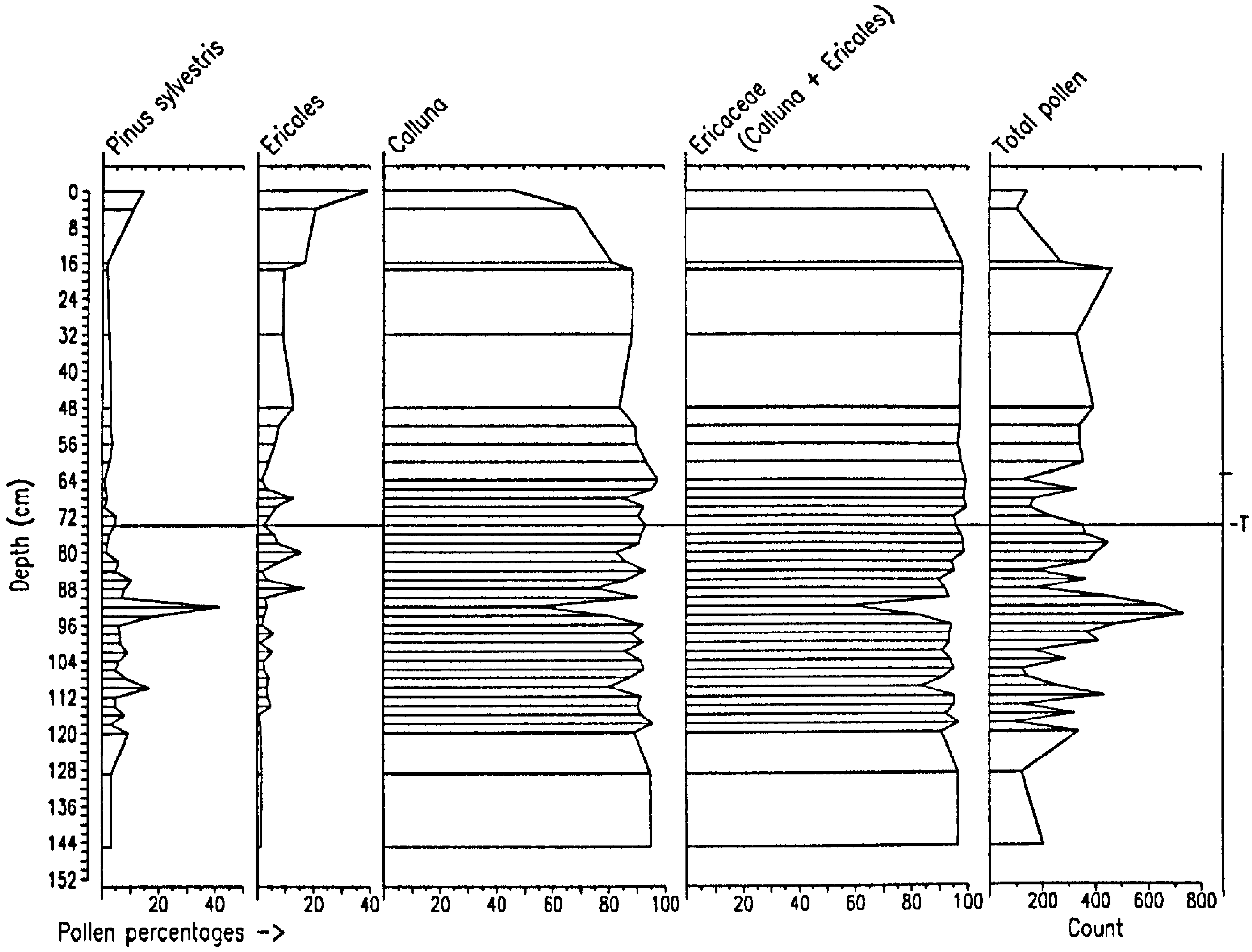
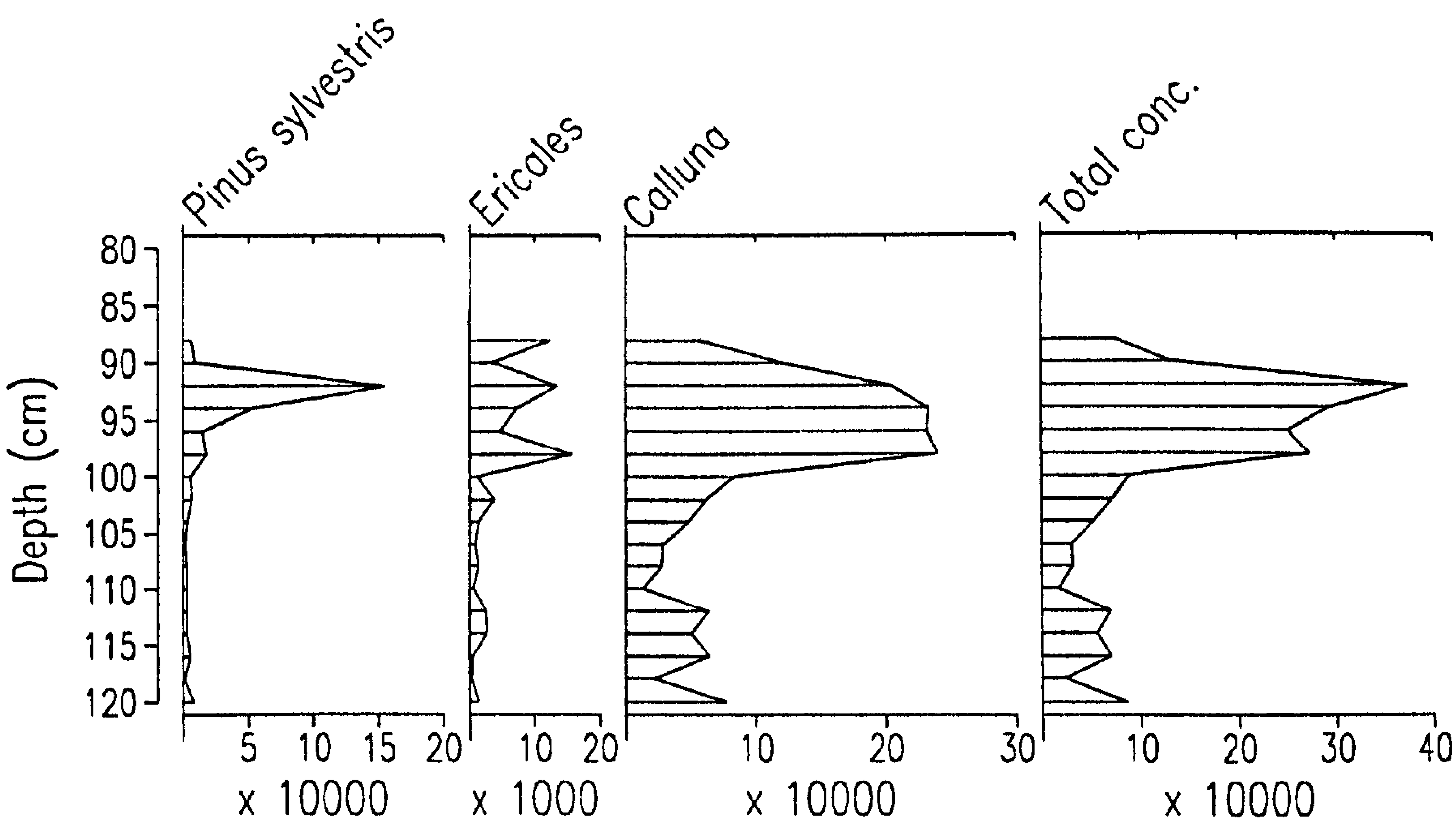


Figure 3.55. Srath Dionard monolith - outline stratigraphy
Sediment description symbols as defined byTroels-Smith (1955)



a) Pollen percentages. The 'T' horizon indicates the level at which tephra shards were found



b) Pollen concentrations.

Figure 3.56. Srath Dionard pollen counts

3.9 Samples from other locations.

As shown in Table 3.1 and Figure 3.1, samples were collected from four other locations during wider surveys of the region. Two of these locations, Knockanrock and Fain, were in the south of region, while the other two, both on the shores of the sea loch Loch Eriboll were in the extreme north. Also the two southern sites were fairly high up, 210 m and 300 m respectively, while the northern pair were at sea level. The dendrochronological results from these sites are summarised in Table 3.18 (next page). The samples from the two coastal sites, Loch Eriboll and Loch Sian, have particularly wide rings. At the Fain site, where 6 samples were collected, it proved possible to crossmatch FAI005 and FAI001, the latter at ring 55 on the former ($P < 0.005$, $IF > 130$ for all filters, overlap 108, $t = 4.66$** for the Baillie and Pilcher filter), but no others.

3.9.1 ^{14}C dating

^{14}C dates were obtained from samples from all of these sites and are summarised with their calibrated overall 2σ limits in Table 3.19 (fuller details are given in Table 3.22.):

Table 3.19. ^{14}C dates from other sites.

Sample	^{14}C date	Calibrated 2σ	limits	Lab. no.
Small sites				
ERI001	4460 ± 45	3340	2923	SRR-5797
SIA001	4360 ± 45	3092	2887	SRR-5813
KNO002	4365 ± 45	3094	2888	SRR-5800
FAI004	4165 ± 45	2885	2583	SRR-5798
Other samples not dendrochronologically measured				
AIR004	4070 ± 45	2863	2467	SRR-5795
MHO001	4530 ± 45	3365	3042	SRR-5802

Also shown in this table are two samples which have not been dendrochronologically measured. AIR004, is from the Airde, Loch Shin (see Section 3.4.1.) and was too fragile for polishing, MHO001 was recovered from an old peat cutting at A'Mhoine, NC(29)545600, near the north coast between Loch Eriboll and the Kyle of Tongue, and was too distorted to be studied dendrochronologically.

Table 3.18. Locations with fewer than 10 samples: summary statistics based on the mean radius. A mean and standard deviation has been calculated for the Fain samples.

Tree	Number of rings	Mean radius (cm)	Mean ringwidth (mm)	SD of ringwidths	Sensitivity	First order autocorr.
FAIN						
fai001	108	4.4	0.40	0.24	0.27	0.77
fai002	65	5.7	0.88	0.61	0.29	0.82
fai003	180	8.8	0.49	0.29	0.25	0.83
fai004	295	11.5	0.39	0.26	0.30	0.83
fai005	205	12.3	0.60	0.36	0.31	0.75
fai006	250	11.5	0.46	0.23	0.32	0.64
Mean	**183.8**	**9.03**	**0.54**		**0.292**	**0.775**
SD	**86.1**	**3.34**	**0.19**		**0.025**	**0.074**
eri002	119	14.1	1.19	0.52	0.26	0.71
kno001	92	6.1	0.66	0.47	0.33	0.80
kno002	129	12.7	0.98	0.42	0.22	0.79
sia001	82	16.6	2.02	1.11	0.18	0.90

3.10 Inter-site comparisons.

3.10.1 General statistics.

The summary statistics for each site are shown graphically in Figures 3.57 and 3.58, together with data from other individual samples. The bars on the charts are arranged in order of site altitude with those sites closest to sea level on the left. Overall there are no significant differences between the sites for any of the parameters measured. However it seems that the larger radii and ring-widths tend to be found at lower altitudes, whilst ring numbers at the higher sites are greater. Also at the highest (and most southerly) sites, Fain and Loch Glascarnoch, the variance in ring-width is lower. If the data are arranged by northing or easting no discernible pattern emerges, neither is there one if they are arranged by ^{14}C date.

Table 3.20 gives values for the summary statistics overall:

Site	Mean number of rings	Mean Radius (cm)	Mean Ring-width (mm)	Mean Sensitivity	Mean 1st order autocorrelation
GLA1	154.0	8.66	0.606	0.289	0.752
GLA2	107.4	6.68	0.667	0.298	0.713
BAD	97.9	8.03	0.935	0.291	0.728
DIO	101.1	11.28	1.134	0.301	0.738
LAX	110.1	10.53	1.008	0.299	0.725
SHI	115.1	7.38	0.736	0.284	0.742
STR	77.4	4.75	0.629	0.298	0.721
VAT	85.6	7.27	0.891	0.342	0.676
FAI	183.8	9.03	0.537	0.292	0.775
Others	105.5	12.36	1.213	0.249	0.798
Overall					
MEAN	113.79	8.597	0.8356	0.2942	0.7367
SE	31.94	2.293	0.2349	0.0227	0.0337
MAX	363	21.68	2.91	0.497	0.930
MIN	-	1.91	0.29	0.172	0.342

Table 3.20. Summary statistics: means for each site plus overall means, maxima and minima.

In terms of number of rings the overall mean of 114 compares well with those given by other authors for comparable sites. For example Bridge, Haggart and Lowe (1990) found most of their samples from Rannoch Moor had ring counts in the range 101-125, while McNally and Doyle (1984a) found an average count of 132 rings for subfossil pine recovered from bogs in the Irish Midlands. Pilcher *et al.* (1995) found the bulk of

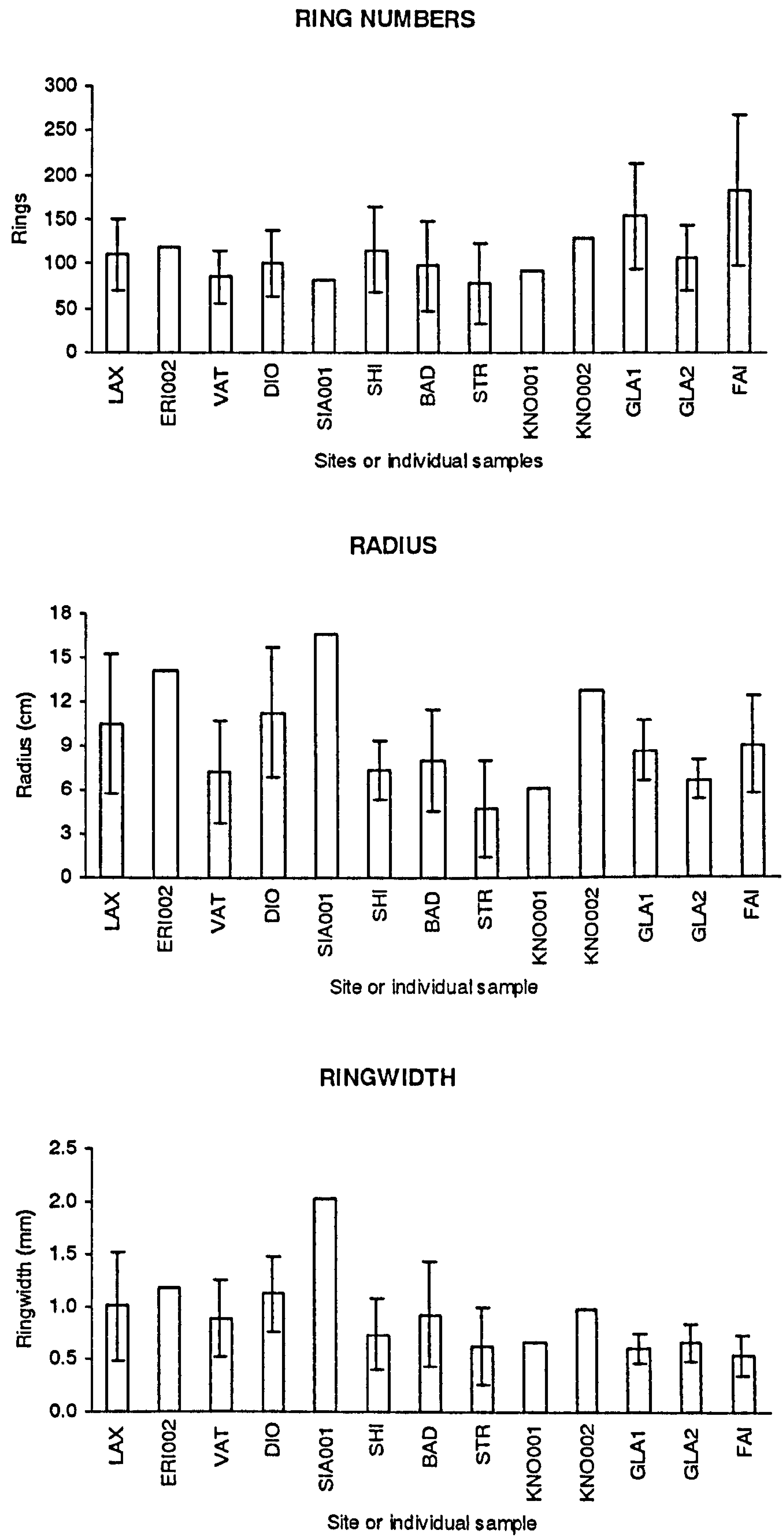
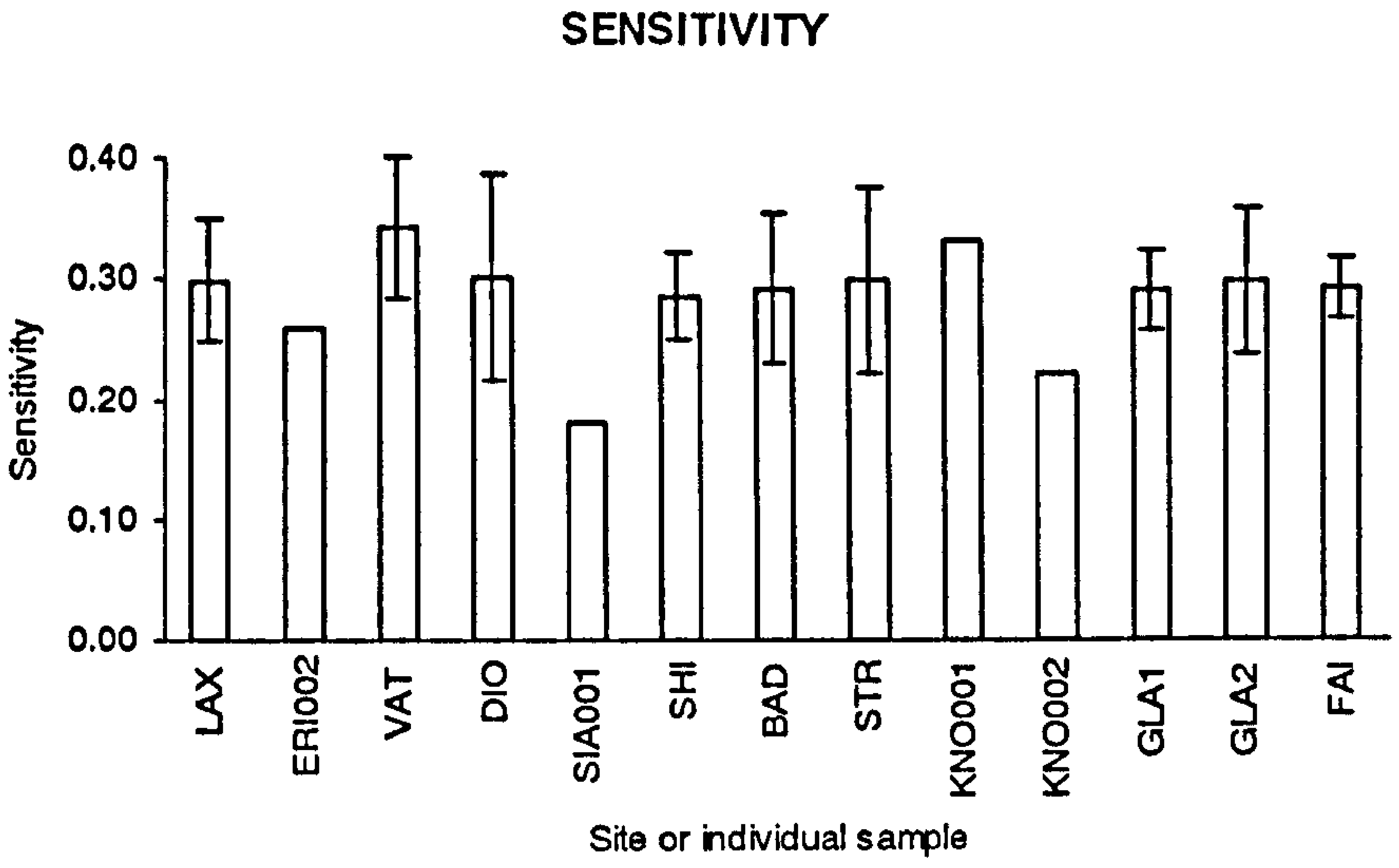


Figure 3.57. Mean summary statistics 1. Arranged by altitude, with the lowest sites to the left. The error bars are ± 1 SD. Where these are not shown the bar represents a single sample. Labels are as indicated in Table 3.1.



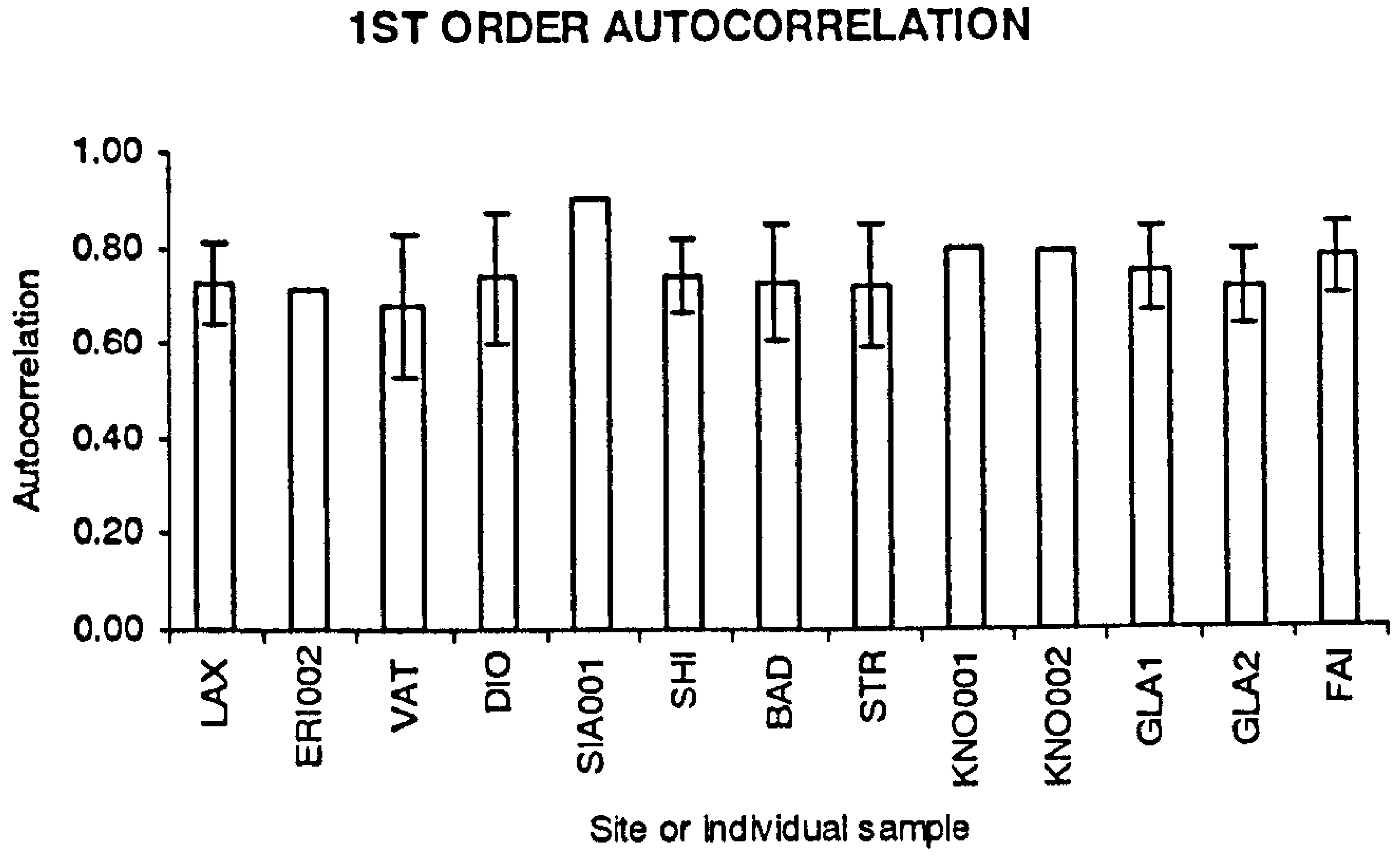


Figure 3.58. Mean summary statistics 2. Arranged by altitude, with the lowest sites to the left. The error bars are ± 1 SD. Where these are not shown the bar represents a single sample. Labels are as indicated in Table 3.1.

samples they recovered from raised bogs in Northern Ireland to have less than 200 rings. Ågren *et al.* (1983) in a study of present-day pine growth on mires in northern Sweden give a mean ring count of 41.7 for trees on their site, but this low value includes figures for seedlings not found on the subfossil sites. In the present study the maximum ring number found (363) is that for BAD144, described in Section 3.5.2; the minimum ring number is omitted as this is always the 30 ring minimum used for crossmatching (see Section 2.3.5 and the introduction to this chapter).

The overall mean ring-width of 0.84 mm found in this study was slightly smaller than those found by McNally and Doyle (1984a) which were in the range 1.125 - 2.25 mm, and the mean of 1 mm found by Pilcher *et al.* (1995), though some means for individual sites are as large as the values for these Irish sites (see Table 3.20). McNally and Doyle (1984a) also give mean ring-widths for modern pines growing on peatland, which at about 2.5 mm are greater than the subfossil values. Ågren *et al.*(1983), whilst not giving any figures for ring-width, say of their trees that 'their annual rings were narrow and often indistinct', a feature certainly found in the subfossil Scottish pines. The range of mean ring-widths for individual trees found in the present study was very wide, from 0.29 mm to 2.91 mm, and is reflected in the similarly wide range of radii, 1.91 cm to 21.68 cm.

The overall mean sensitivity and 1st order autocorrelation of the samples from northern Scotland are 0.29 and 0.74 respectively, with the highest mean sensitivity (0.50) belonging to BAD147, and the highest 1st order autocorrelation (0.93) belonging to VAT020. BAD147 is a very short (54 rings) sequence covering a period of fluctuating ring-widths at Badanloch (see Figure 3.40), while VAT020 from Loch Vatachan appears to have 'switched off' for the latter part of its life, the last 75 years of very small, relatively unchanging ring-widths giving rise to the high degree of autocorrelation (see Figure 3.14). Again at Badanloch, BAD145 shows the lowest mean sensitivity at 0.17, but as a fragment with no centre and wide rings (a mean of 1.71 mm) this is to be expected, as is the poor quality of its crossmatching (see Table 3.10 and Figure 3.39). As Badanloch shows the widest range of sensitivity values, so Loch Vatachan has the widest range of 1st order autocorrelation figures, VAT008 showing the lowest for the study, 0.34. Again this sample shows poor statistical crossmatching, though the very pronounced peak in its plotted raw value curve makes its visual crossmatching unambiguous (Figure 3.14). In comparison to these figures, Pilcher *et al.* (1995) give values of 0.18 for mean sensitivity and 0.7 for 1st order autocorrelation for subfossil pine at Sluggan Bog in northern Ireland. This value for sensitivity is rather lower than that for the Scottish trees, but the autocorrelation value is similar.

3.10.1.1 Age/radius plots

These are shown in Figure 3.59 as log/log scatter plots for six of the sites where there are sufficient trees. Additionally Figure 3.60 shows the Loch Glascarnoch trees plotted in the two separate groups indicated by their crossmatching (not including the unmatched trees from the site). With the exception of the Loch Glascarnoch plot, and to some extent that from Srath Dionard, only a small part of the variance in radius is explained by the regression against ring numbers. At Loch Glascarnoch, as Figure 3.60 shows, virtually all the variance in radius in Group 1 can be accounted for by age, but this not true of Group 2. The slopes of the regression lines in all the plots may indicate differences in growth rate between the sites, but the large amount of unexplained variance in the plots makes this difficult to assess. However Srath Dionard does seem to show a greater growth rate than at the other sites, as is borne out by its higher mean ring-width.

3.10.1.2 Survivorship curves

Although relatively few samples were recovered from most of the sites, survivorship curves (bearing in mind the assumptions made at the beginning of this chapter), shown in Figure 3.61, were plotted for the four sites with the most data. Since for these sites there was a single recruitment phase, it was felt valid to treat the trees as a single cohort, and to plot survivorship curves as described by Krebs (1985) for animal populations. Krebs describes Pearl's (1928) Types I, II and III survivorship curves, suggesting that Type I, closest in shape to those shown in Figure 3.61 for Badanloch, Loch Shin and Laxford Bridge, was indicative of a population with little loss for most of its life span, but with high losses of its older members. This reinforces the impression gained from the crossmatching diagrams that no single catastrophe or rapid deterioration of conditions brought about the deaths of the trees on these three sites, but rather that they lived out a natural span for the conditions under which they were growing. Since no indication of seedling mortality is available, the curve is flat for about fifty years in each case, mortality then beginning to increase. A slightly different picture emerged at Loch Vatachan, where the same flat section of the curve is followed by a section declining in a straight or even slightly convex line for the next fifty years. This is closer to Pearl's Type II curve which suggests a constant age-independent mortality amongst the trees after they reached an age of around fifty years. On this particular site this might have been due to foliage die-back caused by wind damage as the trees reached a certain size, though the lack of preserved trunks and displaced root buttresses would seem to rule out wind throw.

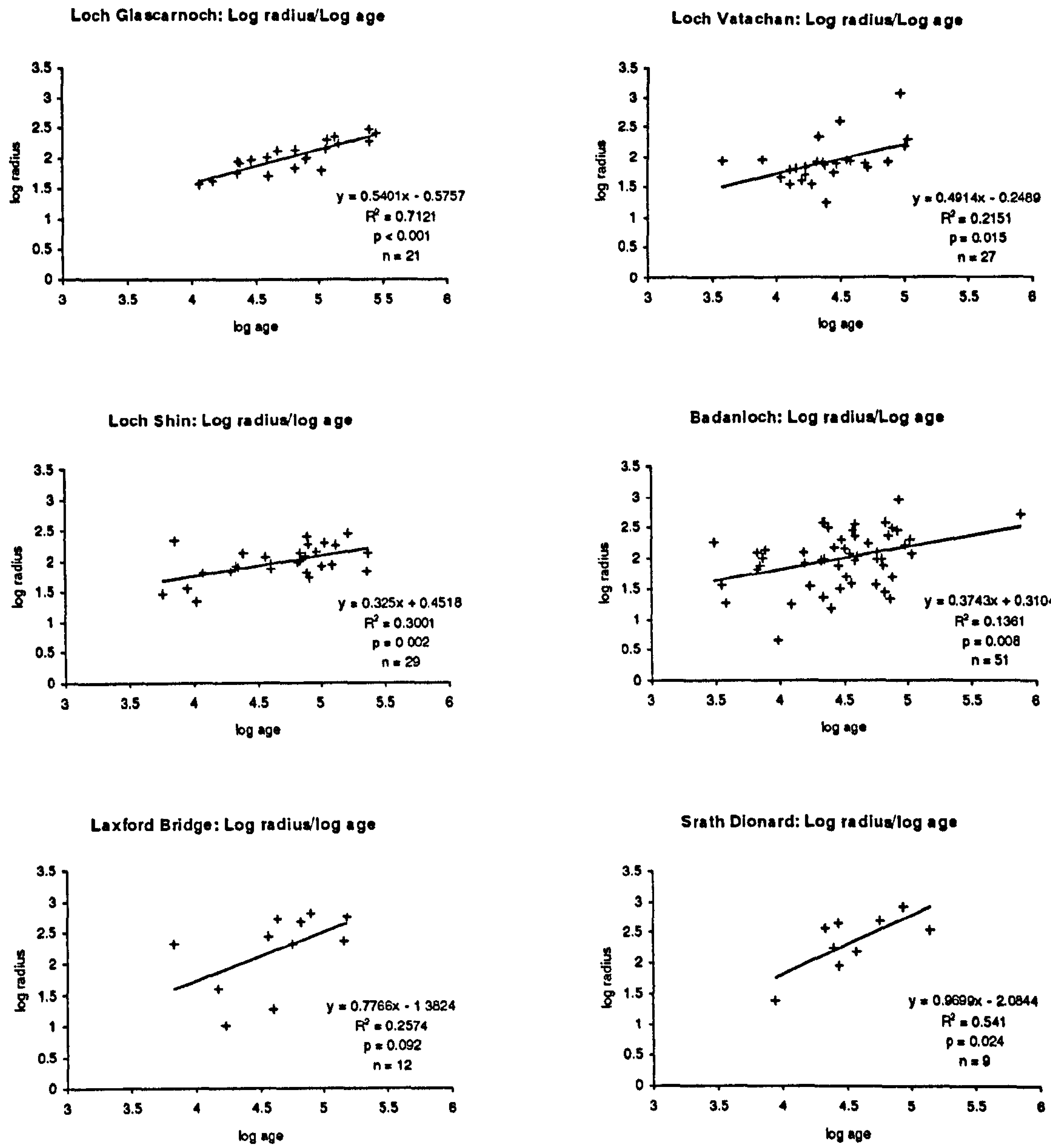
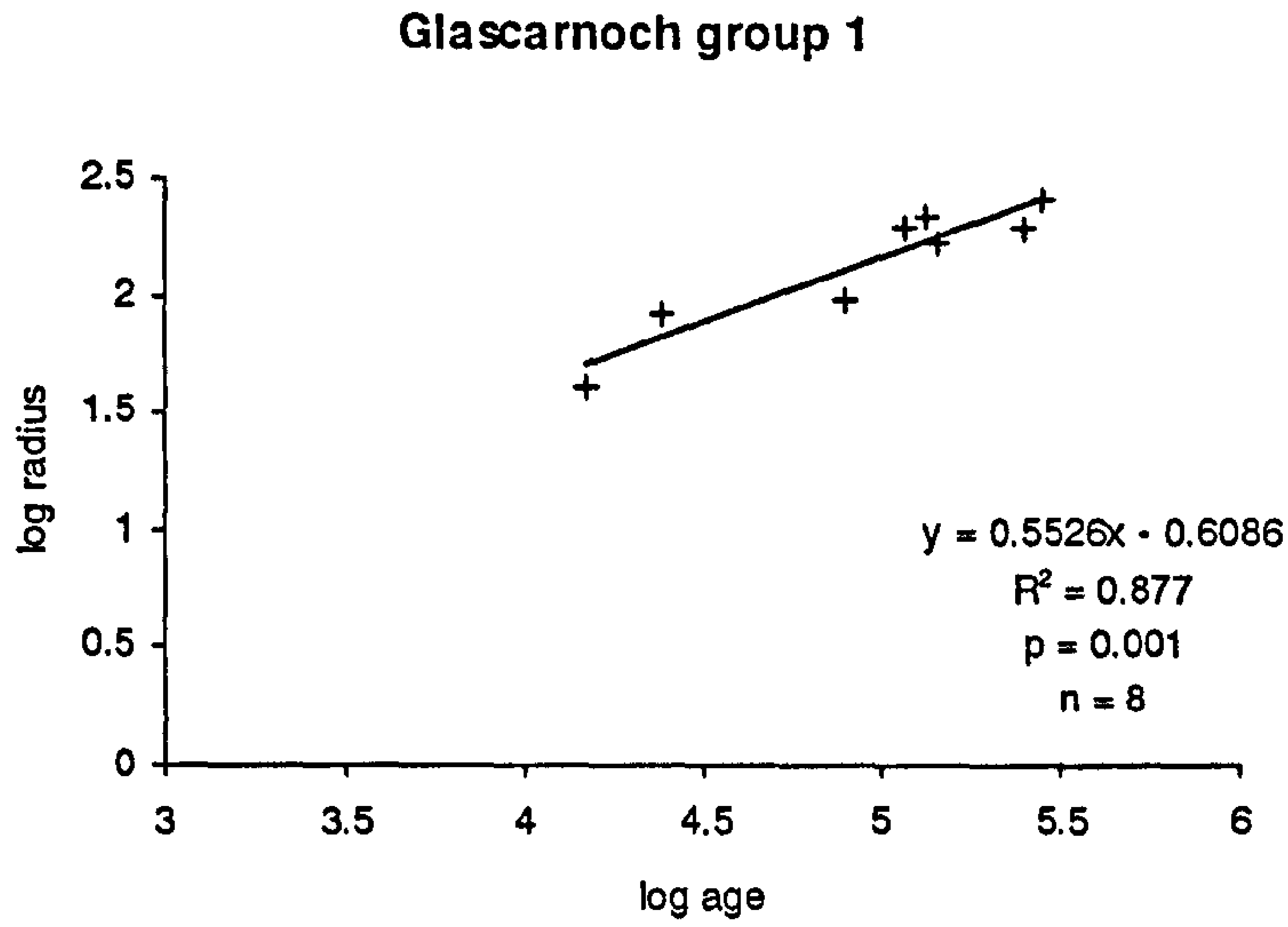


Figure 3.59. Log radius against log tree age for the Northern Scottish study sites.



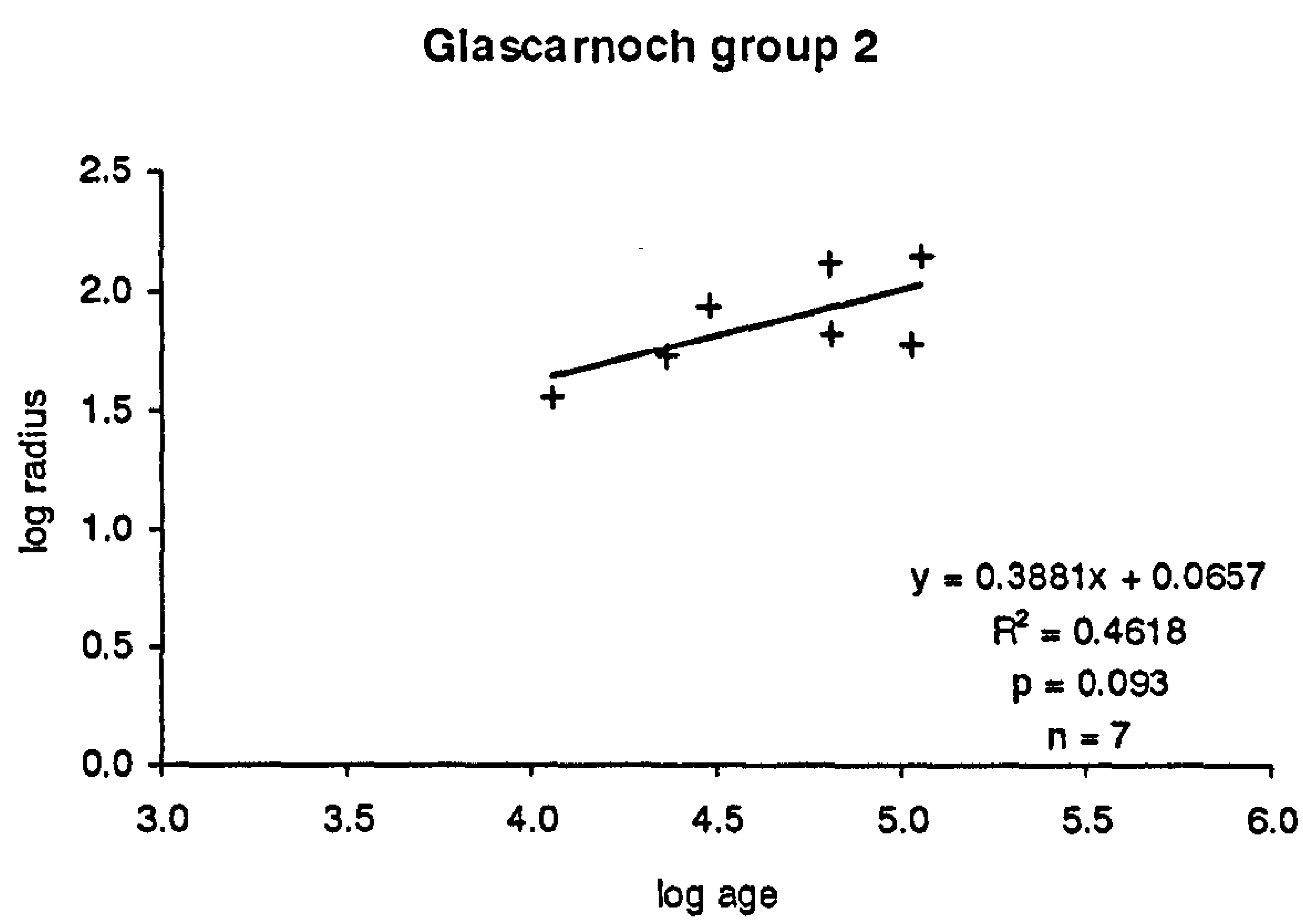


Figure 3.60. Log radius plotted against log age for the two separate crossmatched groups at Loch Glascarnoch.

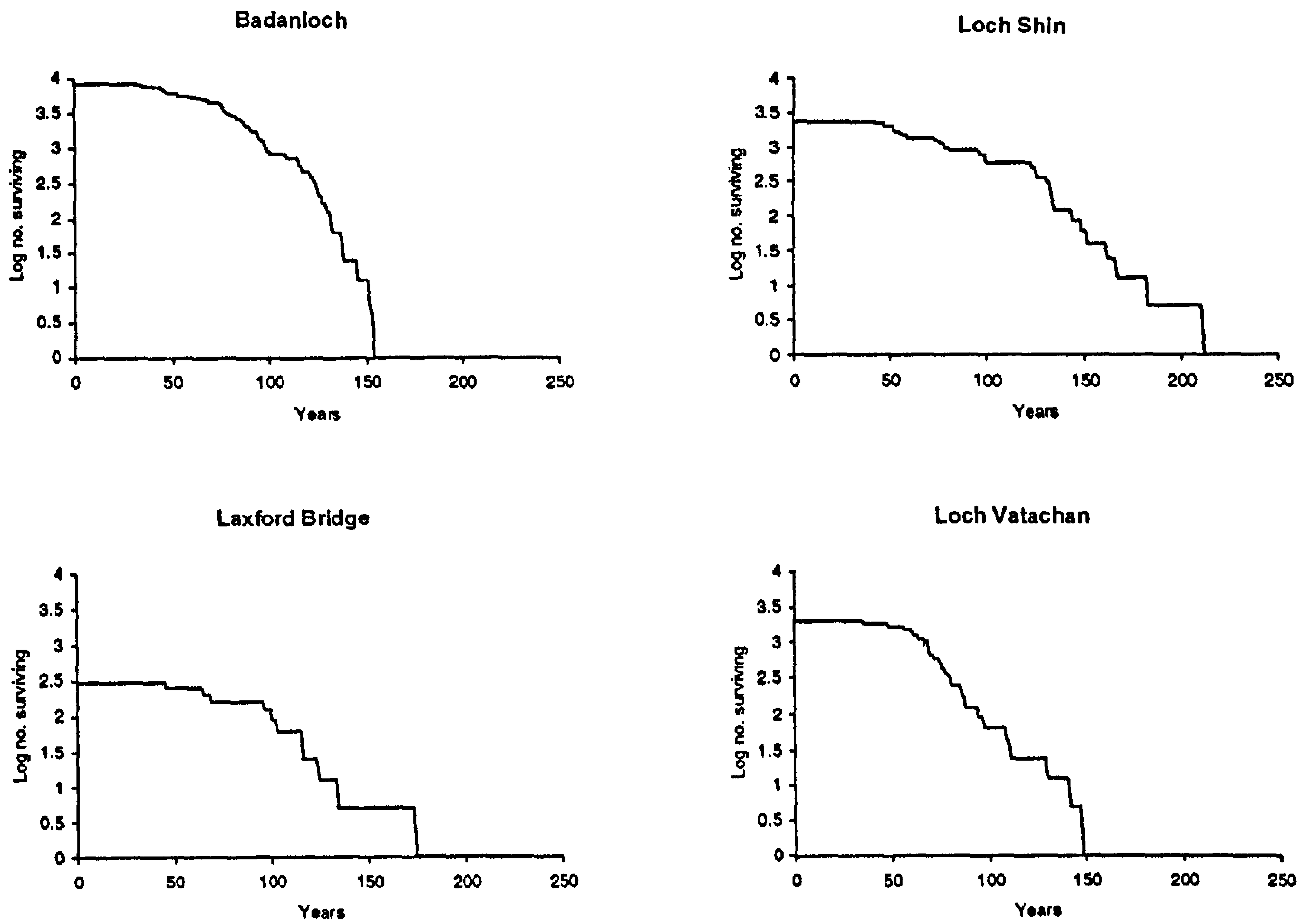


Figure 3.61. Survivorship curves for four sites in Northern Scotland (after Krebs, 1985)

3.10.1.3 Density of trees and recruitment rates

These are shown in Figure 3.62 for those sites where reasonable numbers of successfully crossmatched stumps were available. In this context all the crossmatched trees for each site have been considered including the less secure ones. The different rates of recruitment at the sites are clearly seen, there appearing to be a direct relationship between these rates and the final densities reached, the faster the recruitment the higher the final density. It may be that these maximum densities represent different carrying capacities for the sites, with the different recruitment rates and maxima reflecting differences in site quality, but this interpretation takes no account of either patchy distribution of the original woodland (the areas sampled are of the order of 0.1 - 0.2 ha) or incomplete recovery of samples (either at the collection or processing stages). More data from larger areas of subfossil woodland are required to elucidate this.

The maximum density, 452 trees ha^{-1}, reached at Loch Shin compares well with figures given in other studies of subfossil pine on peat. McNally and Doyle (1984a) give a figure of 500 trees ha^{-1} for their site at Glashabaun, and Bridge, Haggart and Lowe (1990) found densities of 660 trees ha^{-1} and 880 trees ha^{-1} at Gorton and Gleann Fuar respectively on Rannoch Moor. In terms of pine densities found on modern sites the Loch Shin maximum compares well with that of 550 trees ha^{-1} found for trees (above 1.5 m in height) on a modern north Swedish mire by Ågren *et al.* (1983), particularly as those trees crossmatched in the present study must all have exceeded this height (see Section 3.2.2.3). The Loch Shin figure also lies within the range (max. 778 trees ha^{-1}) recorded by Goodier and Bunce (1977) for modern open pine woods in Scotland.

3.10.2 Inter-site crossmatching.

This was carried out between the site chronologies and two Irish pine chronologies as described in Section 2.4.5. Also included were two individual trees from sites where no chronologies were available, but where strong, replicated matches were found. The results are presented in Table 3.21 and Figure 3.63 together with their relation to two Irish pine chronologies, Garry Bog Pine 1 (Brown, 1991) and Sharvogues (both kindly supplied by the Paleoecological Centre of Queen's University, Belfast).

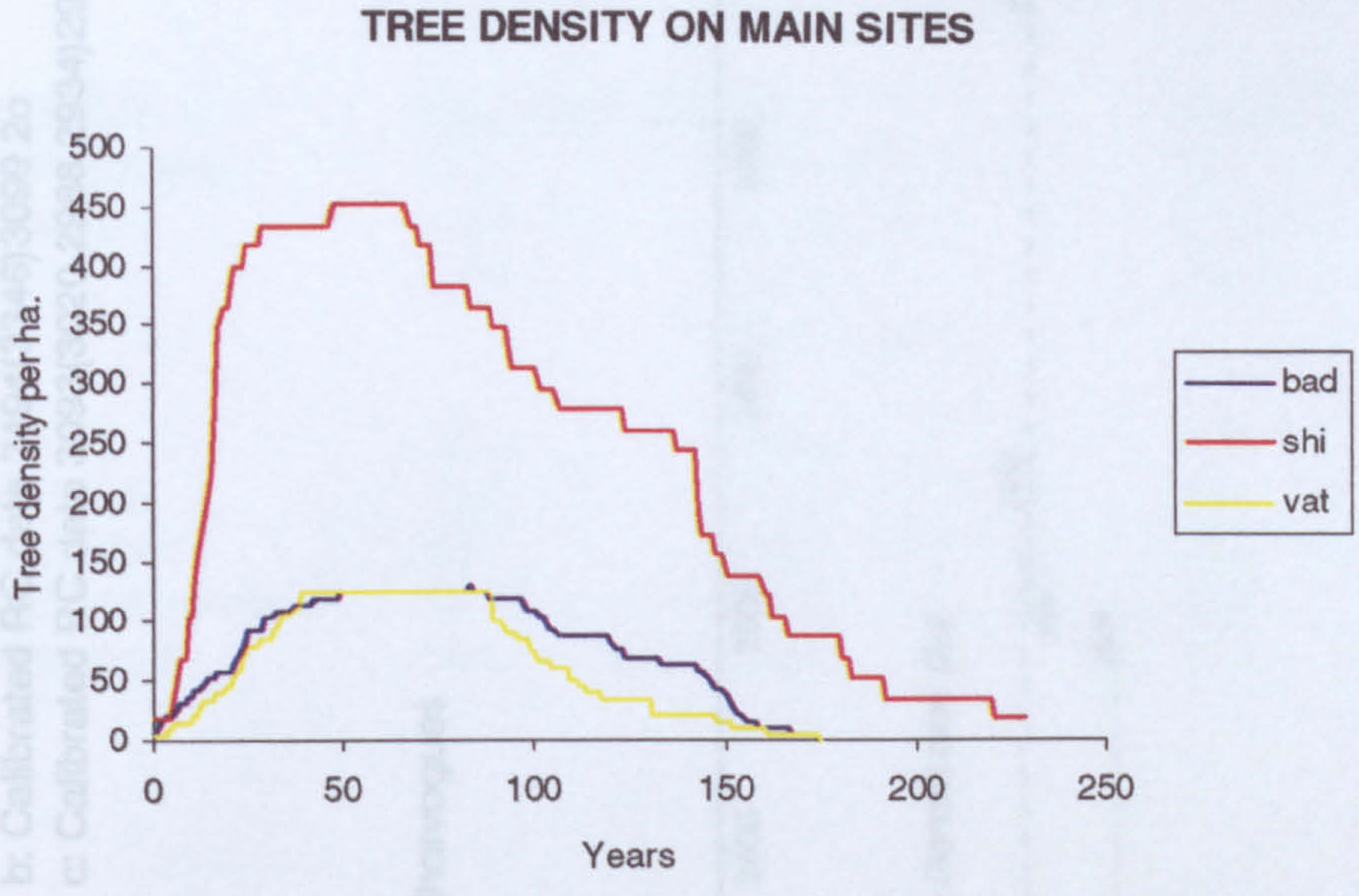


Figure 3.62. Tree density (trees ha^{-1}) at Badanloch, Loch Shin and Loch Vatachan.

Figure 3.63. North of Scotland crossmatching (see Section 3.10.2). The lines above the axis represent chronologies and trees (thin lines) matched dendrochronologically. The dashed lines below the axis indicate the 2σ limits of the positions of chronologies fixed by radiocarbon dating. The dotted line indicates the outer 2σ limits of all the Lochstrathy radiocarbon dates. The figures in italics are the 2σ limits of calibrated radiocarbon dates. The 't' values are for the Baillie and Pilcher filtered values in each case.

Table 3.21. Regional crossmatching as shown in Figure 3.63.

SITE OR INDIVIDUAL SAMPLE	YEAR OF MATCH		END OF SEQUENCE	
	from start of GBP1	Year BC based on GBP1/ Sharvogues.	from start of GBP1	Year BC based on GBP1/ Sharvogues.
FAI006	-27	3446	222	3197
KNO001	-23	3442	68	3351
Loch Shin	-22	3441	196	3223
Loch Vatachan	14	3405	188	3231
Badanloch	264	3155	437	2982

The crossmatches of the Loch Shin, Loch Vatachan and Badanloch chronologies are well supported by their ^{14}C dates, the matched positions for Loch Vatachan and Badanloch being well within the 1σ limits of their corresponding ^{14}C dates and that for Loch Shin being within 5 years of the lower 1σ limit of its wiggle match. The individual samples from Fain and Knockanrock match with each other well and with the Loch Shin chronology. However the ^{14}C dates for other trees from these sites are about 500 and 300 years later respectively than the death dates of the crossmatched samples, although no crossmatching exists between the trees recovered from each site. This either implies spurious crossmatching between FAI006, KNO001 and the Loch Shin chronology, or, given the location of the sites, a much longer occupation of Fain and Knockanrock as discussed in Chapter 4 Section 1.

Figure 3.63 also shows the relationship of the unmatched but ^{14}C dated chronologies from Srath Dionard and Laxford Bridge. These are represented as two extreme positions for the chronologies based on the 2σ limits of their dates. Also shown are the overall (i.e. oldest for the earliest and youngest for the latest) 2σ limits for the five dates for Lochstrathy (see also Figure 3.69).

Figures 3.64 and 3.65 show the raw and Baillie and Pilcher filtered curves for the crossmatched chronologies in their relative positions, together with the relevant portion of the Garry Bog Pine 1 (Brown, 1991) and Sharvogues chronologies from Ireland. Years of particularly low values both in Scotland and Ireland occur in 3411 BC, 3404 BC, 3379 BC, 3368 BC and 3235 BC (Figure 3.64) and in 3111 BC, 3094 BC and 3085 BC (Figure 3.65).

The possibility of these relating to wider scale events, particularly volcanic eruptions, was considered. However, no chronological relationship was found between these dates and any of the Scottish tephra layers (Dugmore *et al.*, 1995), neither does there appear

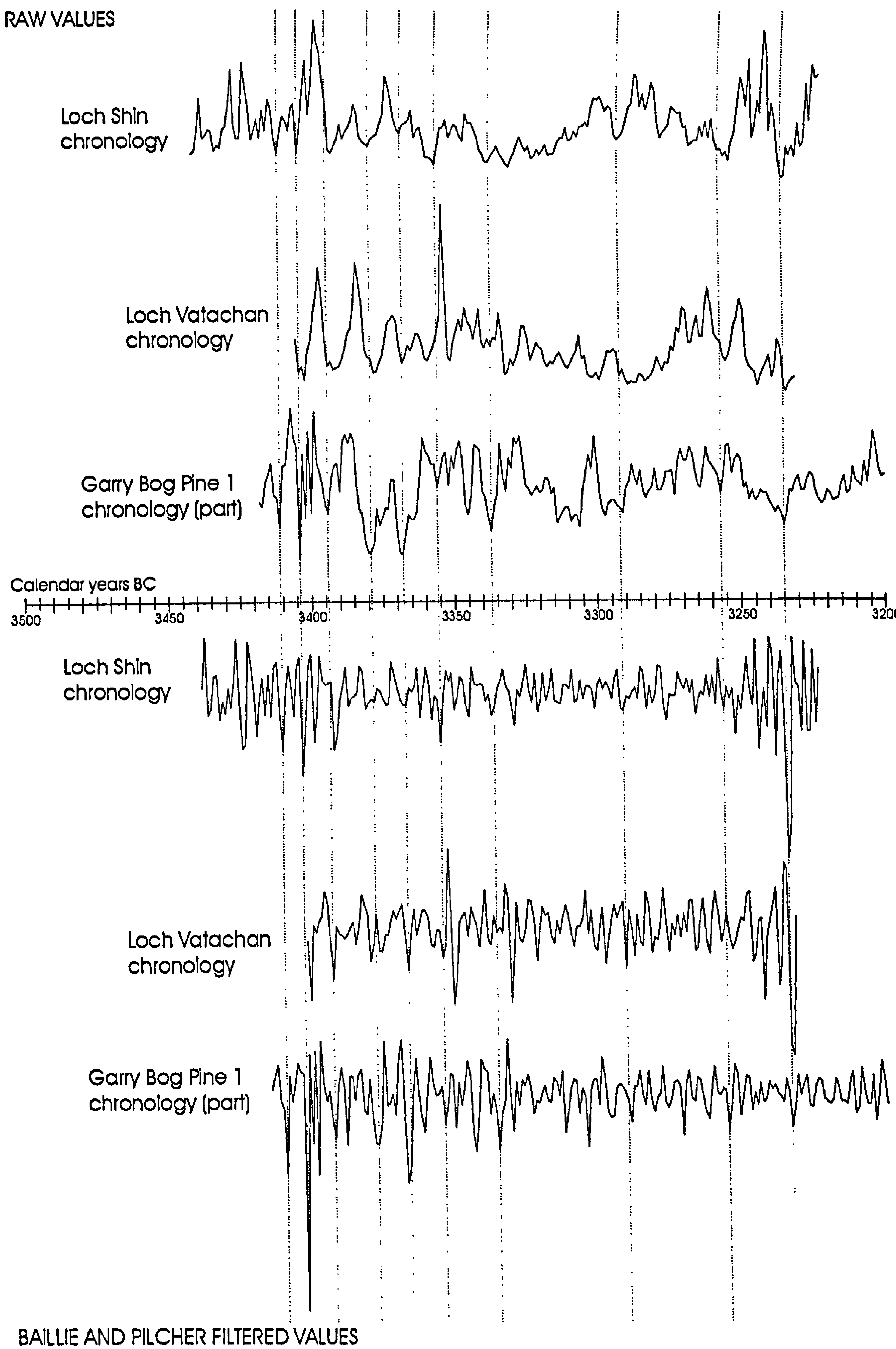


Figure 3.64. Crossmatching between chronologies 1. The curves above the axis are raw values 'simply standardised', the curves below are in Baillie and Pilcher filtered values. The axis scale is based on the Irish chronologies.

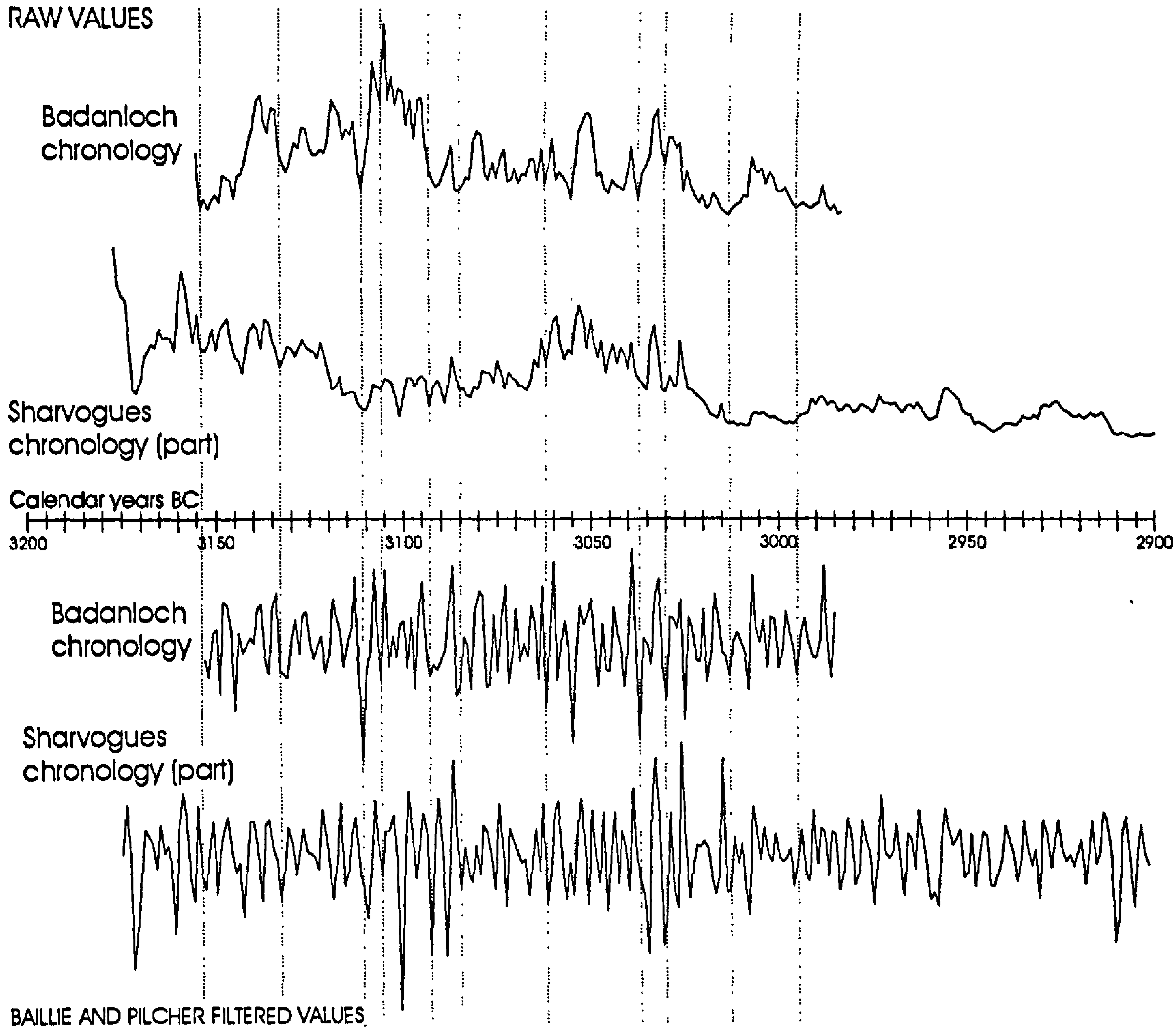
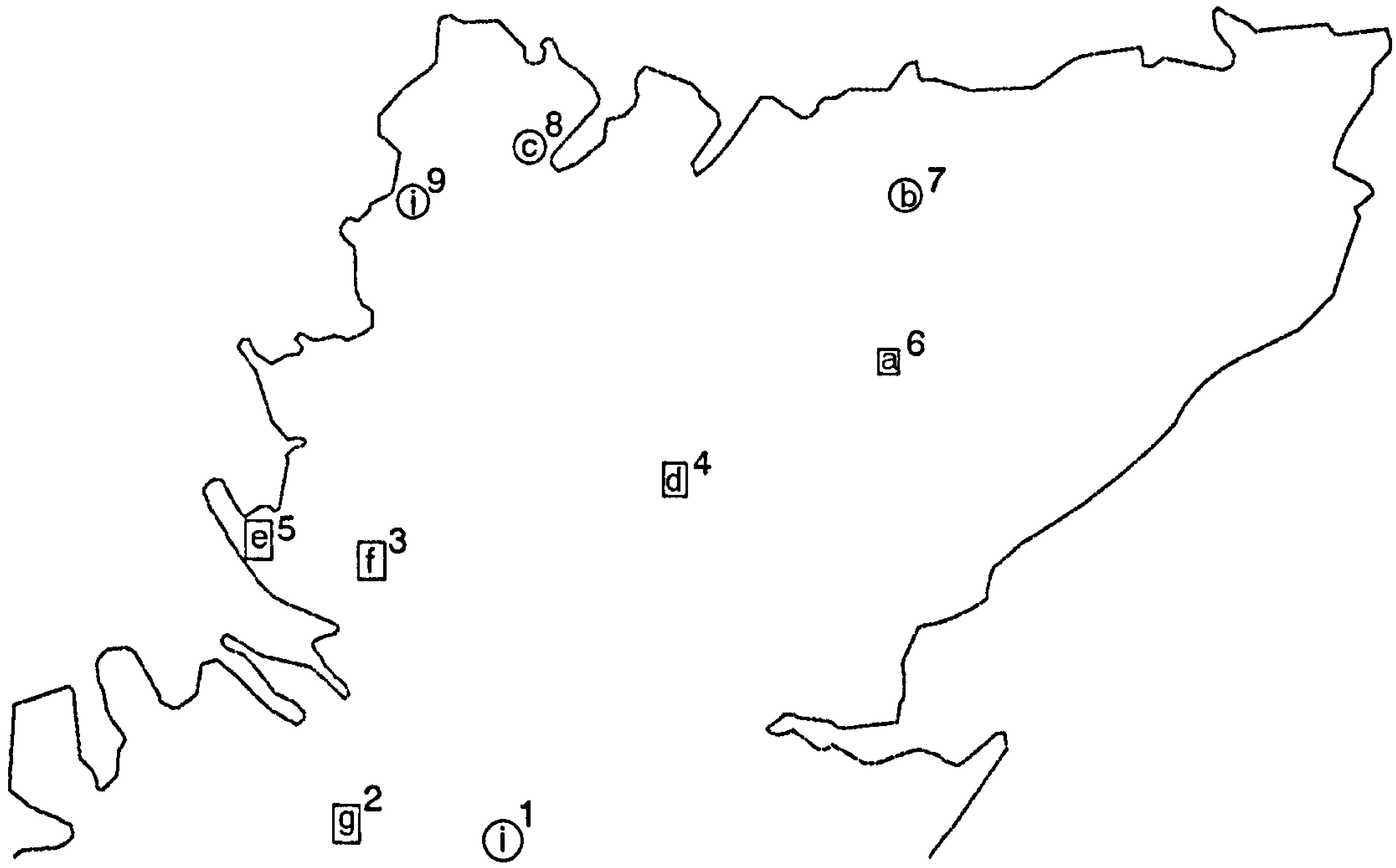


Figure 3.65. Crossmatching between chronologies 2. The curves above the axis are raw values 'simply standardised', the curves below are in Baillie and Pilcher filtered values. The axis scale is based on the Irish chronologies.

to be any narrow ring event in the Belfast oak chronology related to them (Baillie and Munro, 1988). Similarly, there are no acidity peaks recorded from the Camp Century ice core that relate to these dates (Hammer *et al.*, 1980), although one acidity peak from this core, not attributed to any particular eruption is dated as either 3150 ± 90 BC or 3250 ± 80 BC. Whichever date is the correct one, then one of the Scottish narrow ring sequences at 3235 BC could be related to this acidity peak. However Baillie and Munro (1988) associate the same acidity peak with narrow rings in the Belfast oak chronology around 3199 BC. The Scottish narrow ring sequences are discussed further in Section 4.3.

Figure 3.63 also suggests a sequence of colonisation starting in the south-west of the region, which is demonstrated in more detail in Figure 3.66. This figure shows the sequence of appearance of the first dated trees on each site, based on crossmatching and ^{14}C dating. In the case of the latter there is sufficient separation even allowing for the 2σ limits of the dates to indicate a clear progression northwards and eastwards, with the exception of the Lochstrathy dates which are widely spread and not linked by any crossmatching.

Figure 3.67 attempts to assess the spread of pine across the region in terms of suggested migration rates from the literature. Figure 3.67a shows the separations both in time and distance between the locations indicated in Table 3.21 and Figure 3.63, based on the timings for the first appearance of crossmatched trees at the various sites (see also Figure 3.66). Figure 3.67b shows the range of times that would be required for the spread of pine across the distances indicated in Figure 3.67a at the migration rates suggested in Huntley and Birks (1983) and Gear and Huntley (1991). Those times in Figure 3.67a (Group 2) which are compatible with these rates are indicated by shading, and are the migration times from Fain to Loch Vatachan, and those from Knockanrock and Loch Shin to Loch Vatachan. These are consistent with a spread of pine from the south-west from the direction of Fain, or westwards along Strath Oykel via Knockanrock. The actual rates of migration thus implied for this spread are given in Figure 3.75c, and cover a range of 405 - 1278 m yr^{-1}, lying below the maximum (1500 m yr^{-1}) given by Huntley and Birks (1983) based on pollen mapping across Europe, and around the range (350 - 800 m yr^{-1}) given by Gear and Huntley (1991) based on ^{14}C dating for the spread of pine across northern Scotland to the north coast. The apparent time to reach Badanloch is much greater, and it should be noted that constant migration rates do not reflect threshold effects caused topographically, such as the time required to surmount a barrier of high ground. Overall the time differences between the sites are consistent with a spread of pine from the south and west of the region.



The letters in squares indicate sites matched to other sites dendrochronologically, those in circles indicate sites placed in the sequence by ^{14}C dating.

a - Badanloch b - Lochstrathy c - Srath Dionard d - Loch Shin e - Loch Vatachan
f - Knockanrock g - Fain h - Laxford Bridge i - Loch Glascarnoch

Figure 3.66. Order of appearance of the first matched tree on each site. Where this is based on radiocarbon dating it is very approximate and the order takes no account of the overlap of 2σ limits (see text).

a) Distance in km between sites

FAI	36	31	54	83
41	VAT	15	46	80
4	37	KNO	33	66
5	36	1	SHI	35
291	250	287	286	BAD

Separation in years between sites from crossmatching results (see text).

Group 1 — below range indicated in b)
Group 2 — within range indicated in b)
Group 3 — above range indicated in b)

b)

FAI				
24,45,103	VAT			
21,39,89	10,19,43	KNO		
36,68,154	30,58,131	22,41,94	SHI	
55,104,237	53,100,229	44,83,189	23,44,100	BAD

Range of required migration times in years (a, b, c)
a - Huntley & Birks (1983)
b,c - Gear & Huntley (1991)

c) Migration rate (m/yr)

FAI | 878 | VAT
VAT | 405 | KNO
 | 1278 | SHI

Figure 3.67. a) Top right - distances in km between sites in this study.
Bottom left - time in years between the appearance of the first crossmatched trees at each site.
The shading in the bottom left section indicates whether these times fall within the ranges shown in b)

b) Times required for trees to migrate between sites at 1500 m yr^{-1}, 800 m yr^{-1} and 350 m yr^{-1}.
These times are based on rates estimated by Huntley & Birks (1983) and Gear & Huntley (1991).

c) Calculated migration rates between sites in Group 2

3.10.3 ^{14}C dating

Figure 3.68 shows the calibration results for the ^{14}C dates obtained in this study plus those from Badanloch and Lochstrathy. The ten dates for Loch Shin are indicated by the span of their wiggle matched sequence and the rather earlier date for Loch Glascarnoch (see Section 3.2.3) is not included. The dates shown are in broad agreement with dates from earlier studies for subfossil stumps from the region, and where applicable are consistent with the dating obtained from the crossmatching.

Table 3.22 gives all the ^{14}C dates on subfossil pine obtained in this study together with others obtained from the region by previous workers. The dates are listed in order of ^{14}C age, with their calibrated dates and the distance east and north from the origin of the Ordnance Survey National Grid of the locations at which the samples were found. Figure 3.69 shows the spatial distribution graphically in two plots. The vertical lines in these represent the 2σ span of the calibrated dates arranged in one plot by the eastings from Table 3.22 and in the other by their northings. Where more than one date is available from a location the overall 2σ limit for all the dates from that location is shown. Thus for example the span at Loch Shin runs from the earliest 2σ limit of the earliest of the calibrated dates from the site to the latest 2σ limit of the latest date.

Figure 3.69 confirms that with the exception of Loch Glascarnoch, the dates obtained in this study lie in the same broad range as those given by previous workers. More importantly there is an indication that the earliest dates occur towards the west and south of the region, and that the latest tend to occur in the north and east. This supports the suggestion of a spread up the west coast occurring at the same time as a north-easterly expansion inland. It also appears that the period covered by the dates is longer in the west, but there are too few dates available from the east of the region to confirm this impression and further study is required to establish it.

3.10.4 Pollen and tephra

The results of this portion of the study are summarised in Figure 3.70. This shows the pine pollen curves for the three monoliths plotted on the same vertical scale. The curves are aligned vertically on the horizon where shards of volcanic glass were found. The three curves from the present study show peaks indicating the probable local presence of pine at about 20-25 cm below this tephra horizon. As described earlier in this chapter, this tephra has been tentatively identified as from the Hekla 4 eruption in 2310 ± 20 BC, an identification further supported by Hekla 4 being the only tephra layer so far found across the north Scottish mainland other than the Glen Garry layer some 1700 radiocarbon years later (Dugmore *et al.*, 1995). On this basis, if similar rates of

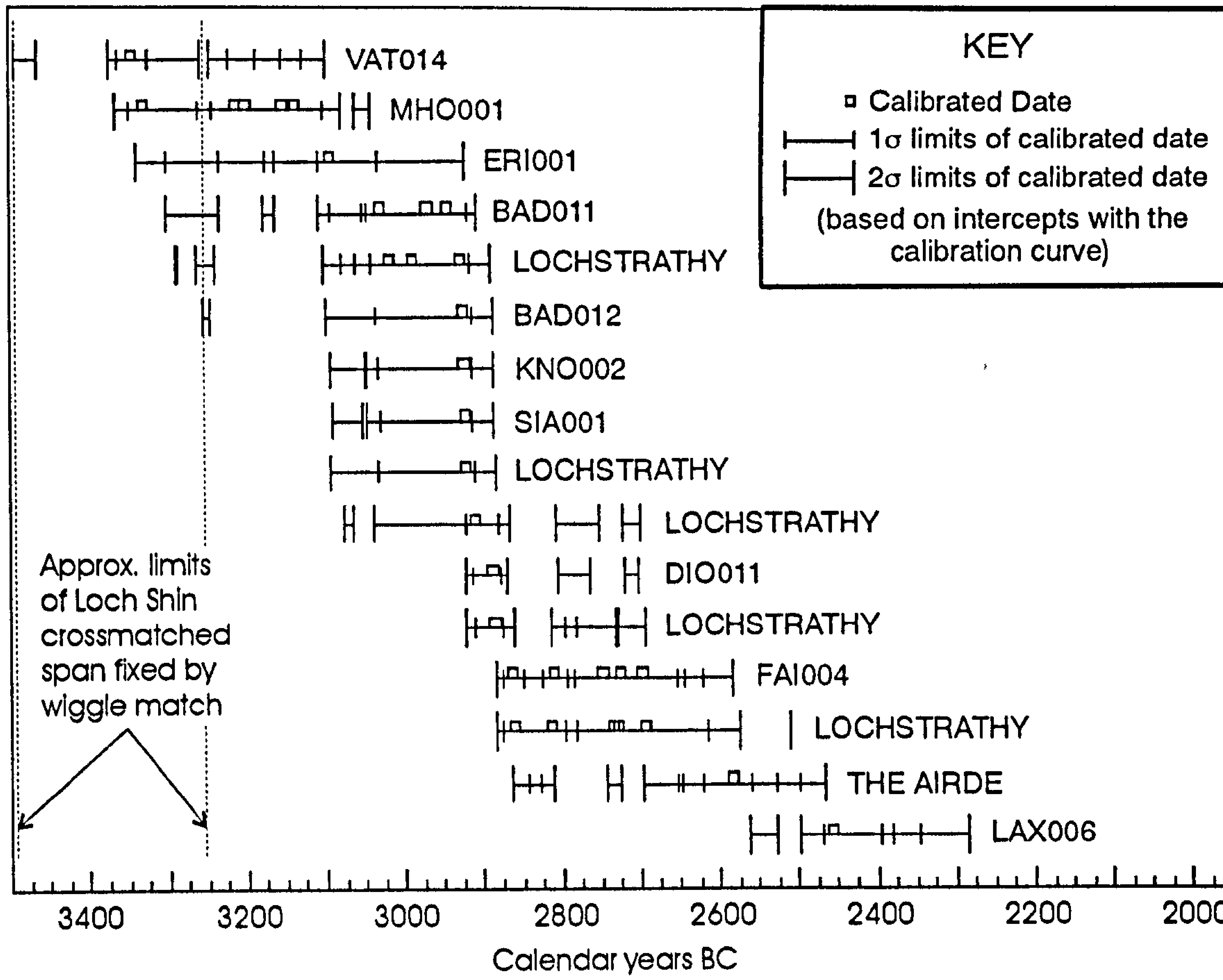


Figure 3.68. 1 and 2σ limits of calibrated ¹⁴C dates for sites covered in this study (excluding Loch Glascarnoch and Loch Shin, but showing the wiggle match range for the latter site - a minimum error of + 17 - 40 years at the 1σ level should be attached to this).

Diagram based on the output from CALIB rev. 3
(Stuiver and Reimer 1993: Stuiver and Pearson, 1993)

Table 3.22. Northern Scotland: ^{14}C dates and Grid locations for subfossil pine

Km from Nat. Grid origin		^{14}C date	Calibrated date (Cal yr BC)			LAB NO
East	North	(years BP)	max. 2σ	Date	min. 2σ	
228.8	874	5975	4940	4896, 4882, 4845	4778	SRR-5799
247.6	919.7	4895	3776	3690, 3666	3548	SRR-5803
247.6	919.7	4710	3632	3506, 3408, 3385	3362	SRR-5810
247.6	919.7	4685	3624	3500, 3452, 3438, 3428, 3380	3354	SRR-5811
247.6	919.7	4680	3623	3498, 3455, 3379	3352	SRR-5804
212.7	914.6	4674	3630	3500, 3460, 3380	3340	Q-1031
247.6	919.7	4665	3618	3495, 3464, 3376	3347	SRR-5809
247.6	919.7	4595	3500	3355	3107	SRR-5808
202	909.8	4570	3494	3346	3099	SRR-5814
247.6	919.7	4570	3494	3346	3099	SRR-5812
247.6	919.7	4560	3491	3343	3096	SRR-5805
254.5	960	4530	3365	3332, 3214, 3201, 3154, 3139	3042	SRR-5802
239.4	954.1	4460	3340	3094	2923	SRR-5797
201.3	910.1	4420	3365	3040	2787	NPL-13
247.6	919.7	4415	3302	3034	2913	SRR-5806
278.6	933	4405	3302	3031, 2970, 2946	2908	SRR-3566
246.3	922.9	4395	3296	3025, 2980, 2929	2899	SRR-3573
248.7	960.5	4393	3295	3024, 2982, 2928	2897	Q-1121
260	944.2	4390	3311	3020, 2990, 2930	2885	SRR-3559
279.6	949.1	4385	3291	3018, 2990, 2927	2891	SRR-3574
247.6	919.7	4380	3255	3015, 2998, 2926	2895	SRR-5807
278.6	933	4370	3255	2924	2887	SRR-3567
217.7	906.7	4365	3094	2923	2888	SRR-5800
244.1	963.5	4360	3092	2921	2887	SRR-5813
279.6	949.1	4360	3095	2921	2885	SRR-3577
282.9	943.3	4335	3083	2916	2880	SRR-3562
225.7	877.4	4320	3261	2910	2696	Q-1153
279.6	949.1	4300	3077	2910	2699	SRR-3578
261	954.4	4295	3072	2900	2698	SRR-3557
221.4	960.3	4275	3014	2889	2701	SRR-3568
233.8	958.6	4270	2922	2888	2702	SRR-5796
279.6	949.1	4255	2921	2885	2694	SRR-3575
279.6	949.1	4225	2918	2880	2615	SRR-3501
201.3	910.1	4220	3076	2880, 2790	2492	NPL-14
260	944.2	4220	2921	2880, 2790	2502	SRR-3560
216	876.7	4165	2885	2864, 2810, 2748, 2725, 2698	2583	SRR-5798
224.6	921.2	4163	2914	2860, 2810, 2750, 2730, 2700	2489	Q-1155
279.6	949.1	4155	2885	2861, 2813, 2735, 2782,2695	2509	SRR-3576
252.2	913.9	4070	2863	2582	2467	SRR-5795
277.2	963.2	4050	2866	2570, 2510	2456	SRR-3569
257.9	964.3	4045	2867	2570, 2520, 2510	2406	SRR-3556
292	940.8	3985	2610	2469	2340	SRR-3564
273.5	906.8	3976	2867	2470	2146	Q-1156
282.9	943.3	3955	2580	2460	2286	SRR-3561
261	954.4	3945	2575	2460	2281	SRR-3558
222.7	946.8	3935	2561	2458	2285	SRR-5801
308.3	950	3865	2465	2321	2143	SRR-3571
257.9	964.3	3825	2456	2279, 2217, 2209	2049	SRR-3555
292	940.8	3815	2454	2274, 2243, 2205	2046	SRR-3565

NPL dates: Lamb (1964) Q dates: Birks (1975) SRR-3... dates: Gear and Huntley (1991)
SRR-5... dates from the current study

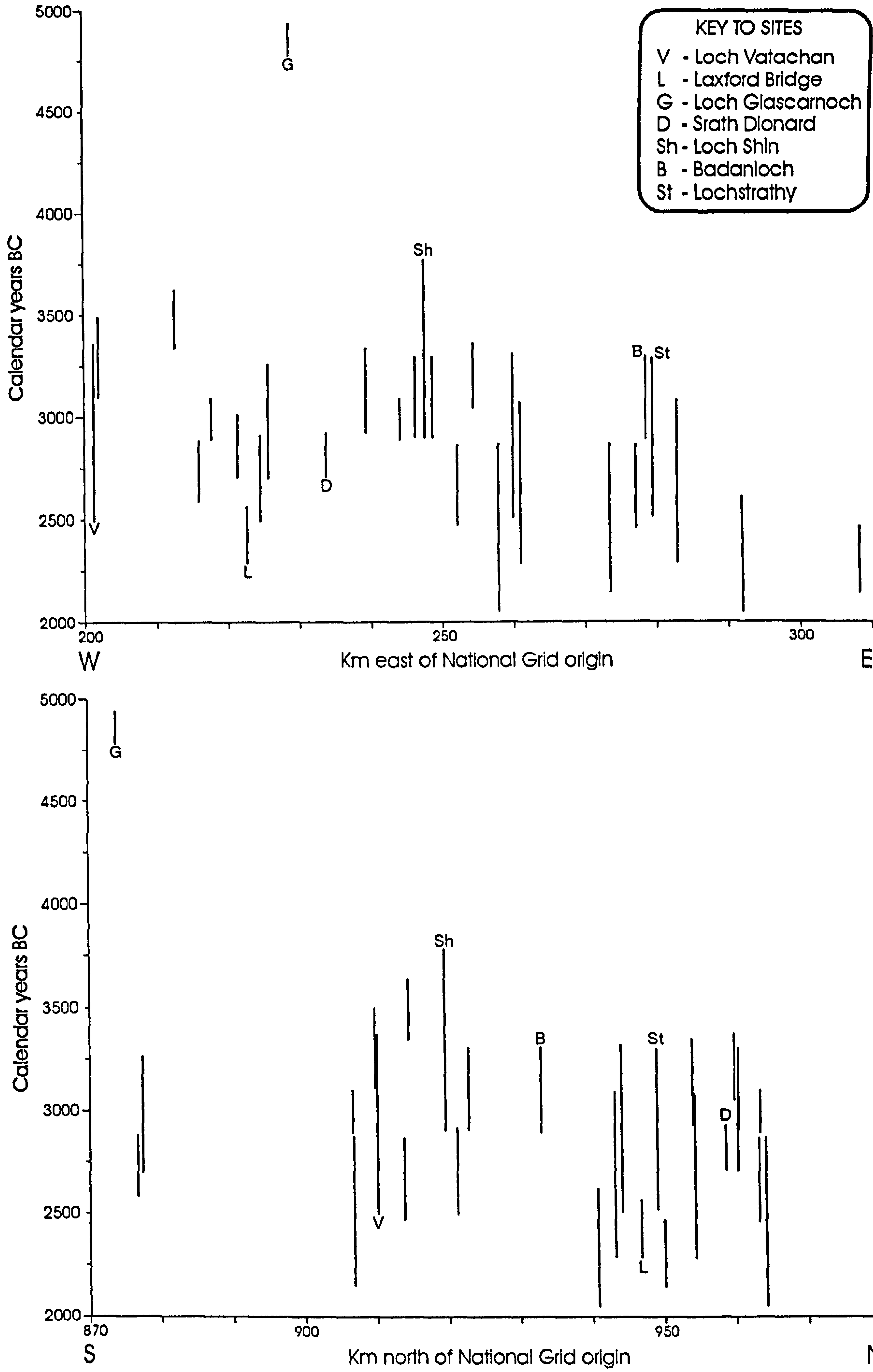
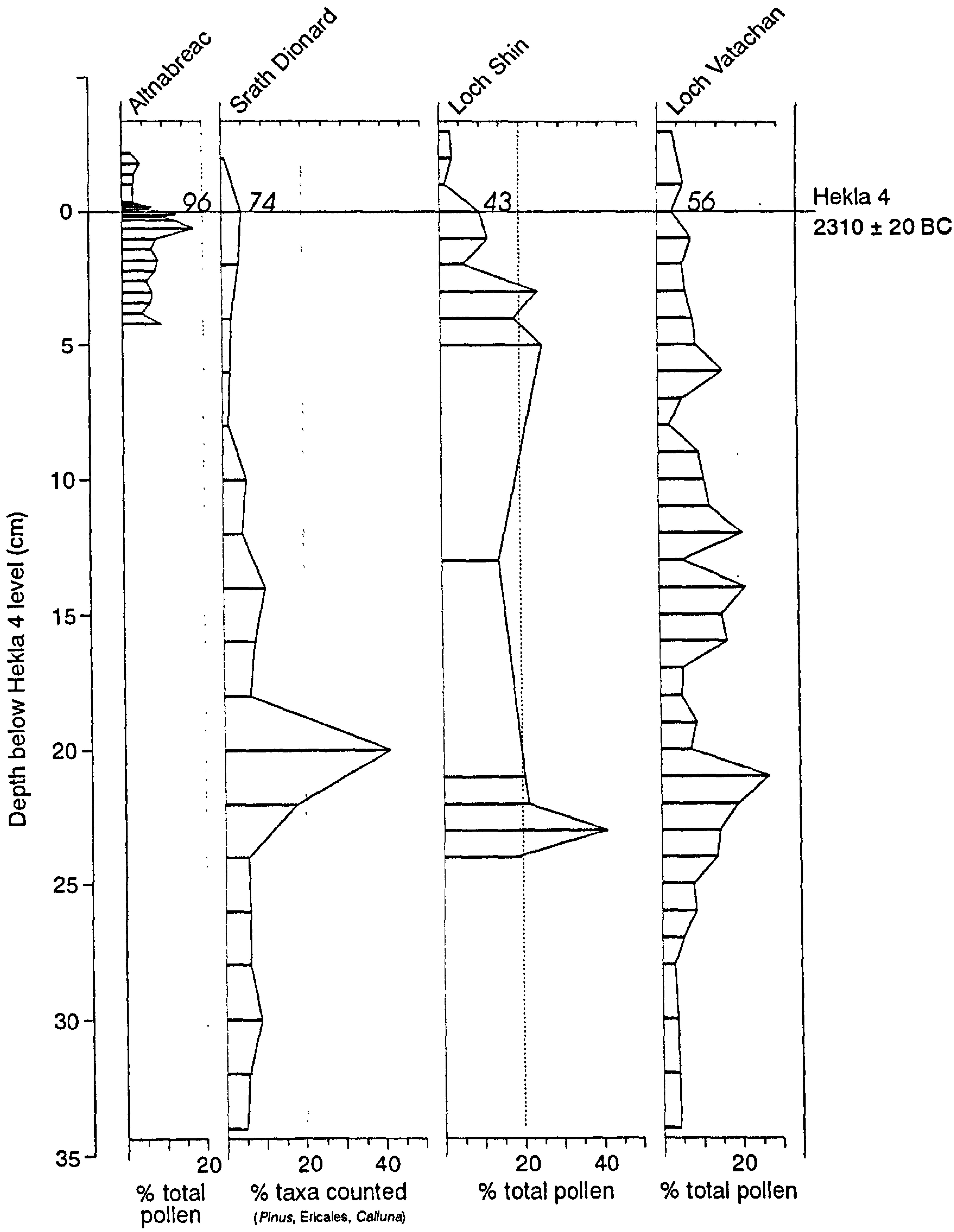


Figure 3.69. 2σ limits of calibrated ^{14}C dates for sub-fossil pine in Northern Scotland, arranged by Grid Easting and Grid Northing (NB oldest dates at top).



The figures initalics are the depth in cm of the tephra layer down that particular profile. The curve from Altnabreac, included for comparison, is reproduced from Blackford *et al.* 1992.

Figure 3.70. Percentage pine pollen curves for different sites across the region. These are aligned on the tentatively identified Hekla 4 tephra layer.

deposition are assumed for the three sites, then the positions of the peaks in each profile are consistent with a more or less simultaneous occupation of the sites by Scots pine. Furthermore, identifying these peaks with the colonisation of these sites, the macrofossils from which have been dated as described earlier (Figures 3.63, 3.69), a rate of deposition of about 0.02 cm yr^{-1} is implied, comfortably within the range 0.0133 - 0.04 cm yr^{-1} found by Gear (1989) for similar peats during this period at Lochstrathy. Also shown in Figure 3.70 is a pine curve reproduced from a pollen diagram published by Blackford *et al.* (1992) for Altnabreac in Caithness (see Section 1.2). This curve is aligned on the same horizon as the others, but only extends some 4 cm below it, and the peaks shown do not seem high enough to confirm the immediate local presence of pine. This suggests that Blackford *et al.*'s (1992) hypothesis that the eruption of Hekla 4 caused the demise of the pines growing on the peat surface cannot be applied to the sites in the present study, and that it is rather unlikely to apply to the pines at Altnabreac. However all the pine curves show a decline in pine pollen at this time which may well indicate a climatic deterioration brought about by the Hekla 4 eruption.

Chapter 4 - DISCUSSION AND CONCLUSION

In discussing the results of this study, the comments on the dendrochronological results made at the beginning of Chapter 3 should be borne in mind, together with the following two points.

The first is that all the subfossil samples were from trees that had been growing on, and were preserved in, peat deposits. No direct information is available about the growth and distribution of pine on the mineral soils of the region apart from what might be inferred from pollen studies, although an assessment of the possible rôle of these soils in the spreading of pine across the region is made below.

The second point is that in interpreting the results it is necessary to reconcile evidence of widely differing temporal scale and resolution. Dendrochronological investigation has given a precise picture of relationships within and between particular groups of trees across the region with a resolution of single years and across a time span of 600 years or so. This is fixed by the crossmatching with the Irish pine chronologies against a background of information from individual ^{14}C-dated subfossils across the region scattered in time over a period of nearly 3000 years. The individual dates have 1σ limits of as much as $\pm$ 100 years in their uncalibrated form, and after calibration span a 2σ range of at least 200 years (with the exception of SRR-5799 at Loch Glascarnoch), the average being around 350 years (see Table 3.22). The two sets of evidence are linked by the ^{14}C dates for the crossmatched trees which correspond closely with the calendrical dates from the Irish sequences.

The results of the present study are discussed under three main headings:

Tree growth on the dendrochronological sites
The spread of pine across the region
Climate change

though obviously these overlap to some degree.

4.1 Tree growth on the dendrochronological sites

The growth characteristics of the trees at all the sites studied on blanket peat are strikingly constant and similar to those found elsewhere in Scotland, Ireland and Scandinavia on mire surfaces today and in the past (see Section 3.10). Where available, figures for 1st order autocorrelation are again similar, and as an indicator of the dependency of any year's growth upon reserves from the previous year, perhaps represent a constant for *Pinus sylvestris* on blanket peat. Figures for the mean sensitivity of the Scottish trees are similar for all the sites but seem rather higher than those given by Pilcher *et al.* (1995) for northern Ireland. This could indicate a higher degree of stress in the Scottish pines caused by growth in marginal situations, but may also be caused by distortion in ring patterns sampled in the root collar rather than higher up in the trunk.

Unfortunately there is little information about the form of the trees when alive as virtually all the samples recovered were from the root buttresses of the pines. However there is some evidence available in the form of two trunks found at Badanloch and Loch Glascarnoch, from some remains found during the wider survey, and also from other studies. The trunk from Loch Glascarnoch is described fully in Section 3.2.2.3. That found at Badanloch is similar (see Plate 7), but straight for all its length (about 5 m) although it is not clear how much is missing from either end. The diameter (about 8 cm) of the trunk recovered suggests that probably most of the trunk is present. Remains found at Meall a' Gruididh above Glen Oykel (Table 3.2) during the distribution survey were of a straight trunk, with two branches, about 2.1 m long. Again it was not clear how much of the rest of the trunk might have been missing from the top of the tree although the base was clearly present. The trunk was about 7 cm thick at its mid-point. Manley (1945) describes the trunk recovered at Loch Vatachan and subsequently dated by Lamb (1964), as being 'well grown' and about 17 feet (approx. 5m) long, 7.5 inches (19 cm) in diameter and with about 78 rings. The trunks from Badanloch and Loch Glascarnoch appear to have had branches of ascending habit for most of their length, but as explained in Section 3.2.2.3 it is not clear whether the external surface of the trunk had been clean. Overall then, the impression gained is of straight trees, possibly of the habit types no. 1 (*Pinus sylvestris* L. var. *horizontalis* Don) or no. 3 (*P. sylvestris* L. f. *ascensa*) described by Steven and Carlisle (1959), but not reaching a height of much above 7-8 m.

This is further supported by modern examples of *Pinus sylvestris* growing on peat surfaces. Ågren and Zackrisson (1990), at eight different peatland sites in Sweden, found few pines with a height above 10 m. McVean (1963a) describes mature trees growing on bogs in Scotland as 'small and short lived, although often straight and of good form'. An example from the present study is the stand in Glen Cassley (Section 1.3.5). Here the trees on the bog are much smaller than the trees on the adjacent mineral soil (Plate 11), with a maximum height and girth of 9 m and 60 cm respectively, as opposed to the 20 m and 180 cm of their more vigorous neighbours (heights estimated with a clinometer). The girth of 60 cm is equivalent to a radius of 9.5 cm, which corresponds well with the mean of 8.6 cm for the subfossil trees in this study. The paler green of the foliage suggests that the trees on the bog are growing much less vigorously, perhaps lacking nitrogen amongst other nutrients (Carlisle and Brown, 1968). Unfortunately details of

Plate 11. Glen Cassley. The poorly growing pines in the foreground are on the bog, while the healthier-looking trees in the background are on well drained mineral soil.

the history of this site are not available (although Steven and Carlisle (1959) suggest that pine was growing in Glen Cassley in the eighteenth century) so the relative ages of the trees are not known, although the constant size of the those growing on the bog suggests they are a single generation.

The apparent lack of vigour in trees growing on bog surfaces is attributable to the poor nutrient status of peat and to the effect of water-logging. Water-logging can affect the ability of pine roots to extract what nutrients there are from the substrate (Carlisle and Brown, 1968), either directly or through inhibition of the formation of mycorrhizal associations. These associations are crucial to the successful establishment of pines, and without them the trees rapidly go into check, complete water-logging killing the trees outright (McVean 1963b). In the case of the subfossil stumps and their root systems it is clear that only a limited depth of peat above the water table was available to the trees as a source of nutrients. As a result the roots form shallow wide-spreading 'plates' with little or no tap root development. Given the nutrient-poor status of the peats and the height of the water table within them, this horizontal structure suggests that intensive root competition must have taken place between the trees, a situation similar to that found by Ågren *et al.* (1983) on a modern mire site in northern Sweden. As these authors suggested, this would have inhibited the establishment of any seedlings and would have been another factor affecting the relative growth of the trees. The most striking northern Scottish example of these root patterns is found at Badanloch, where the root systems are clearly visible (see Plate 5) and their intertwining gives visual emphasis to this idea of root competition. By contrast at Loch Glascarnoch, where some at least of the trees were growing about 1500 years earlier than those further north, there is a suggestion of more vertically developed root systems with the occasional tap root penetrating to the mineral substrate beneath.

This limited depth of peat above the water table must have made the trees extremely sensitive to fluctuations in its level, and there is evidence from some of the ring sequences that trees were going into check from time to time with these fluctuations as a probable cause, either directly or through breakdown of mycorrhizal associations. The examples of SHI006 (Figure 3.26), with extremely narrow rings for the last 55 years of its span, and VAT020 (Figure 3.14), with similar very narrow rings for the last 75 years or so of its life are particularly striking.

It is also possible that these periods of very low annual increment are the effect of attack by various pests. There is no direct evidence of damage caused to the wood itself in any of the samples recovered, apart from one stump at Badanloch (Daniell, 1992) which showed signs of attack by a wood boring beetle, possibly *Criocephalus rusticus* L. The principal habitat of this particular species is damp wood, particularly pine stumps, which suggests attack by the beetle after the death of this particular tree, confirmed by the ring patterns which show no growth response to the damage. Indeed the damage may be modern, occurring after re-exposure of the stump to the air. Narrow rings could also be caused by damage from defoliating pests such as the pine looper, *Bupalus piniaria* L.; for example, Filion and Quinty (1993) present narrow ring sequences from subfossil eastern hemlock (*Tsuga canadensis* (L.) Carr.) from Québec, which they suggest are possibly caused by insect defoliators.

However, Filion and Quinty (1993) point out the great difficulty in distinguishing between biotic and abiotic causes for these patterns, and although they are similar in appearance to the narrow ring sequences found in the present study, it seems on balance that in the Scottish trees pests are not a serious influence. This view is supported by the generally low incidence of pest damage found in present day native pine woods, attributable both to the natural resistance of the Scottish trees and the absence from Scotland of any species with the capacity to inflict widespread damage (Steven and Carlisle, 1959).

From the dendrochronological results it seems likely that the drying peat surfaces, at least those at Loch Vatachan and Loch Shin, were colonised by a single generation of Scots pine. The peat profiles at all the sites, and pollen diagrams from Loch Vatachan and Loch Shin, suggest that this pine was growing either with or just after birch. At Loch Vatachan pine appears after a rapid fall in birch pollen (pollen percentage and concentration diagrams - Figures 3.19 and 3.20), whereas at Loch Shin birch seems to persist through the pine peak (Figures 3.33 and 3.34). Further evidence for this latter case is given in Plate 12, which shows pine and birch stumps at the same level. Generally however birch seems to have appeared at Loch Shin before pine. The competitive relationship between Scots pine and birch is complicated. In terms of climate birch seems to prefer more oceanic conditions, milder and wetter, while pine does better under a more continental régime, the native pinewoods tending to occupy north facing slopes (Steven and Carlisle, 1959). However this distinction is modified by the substrate, with birch outcompeting pine on calcareous soils and brown forest soils of higher nutrient status (Carlisle and Brown, 1968). The interaction of these climatic and edaphic factors gives rise to different combinations, for instance with birch forming the tree-line above pine in some locations (e.g. Glen Affric) though *vice versa* in most others. Mixed woodlands of pine and birch exist, particularly in the west of the highlands where more oceanic conditions allow the birch to compete (Steven and Carlisle, 1959; see also McNally and Doyle, 1984b). Thus the dramatic decline of birch before the appearance of pine at Loch Vatachan (Figures 3.19, 3.20) on the west coast is surprising, as birch might have been expected to co-exist with pine at this site. As this decline covers 4 cm of the profile it is unlikely to be the result of a sudden catastrophe such as fire (nor is

Plate 12. Loch Shin shoreline. Subfossil pine stump in foreground, with birch stump behind it at the same level.

there a charcoal layer to support this). However there is a peak in *Sphagnum* spore values just above the birch decline suggesting rapid paludification, with a simultaneous rise in *Alnus* pollen, possibly related to a rise in level of the loch itself, and the consequent demise of the birch. Subsequent drying of the bog surface then led to the establishment of *Calluna*, followed by pine on the nutrient-poor peat.

The maximum tree density reached at the dendrochronologically studied sites varied considerably (Section 3.10.1.3). However, it is not possible to say whether the systematically higher densities found at the reservoir shore-line sites were attributable to the nature of exposure of the stumps at these sites leading to a bias in the sampling. In contrast such a bias could not have occurred at the peat-cutting site at Loch Vatachan where the distribution of stumps was not readily apparent. This may in part explain the low density of trees found at Loch Vatachan, but its coastal location in the extreme west could have made it a less hospitable site for pine, with the low density reflecting this. The possibility of wind stress at this site has already been raised, though it is probable that the climate was less windy than at present, as discussed in Section 4.3.

That only a single generation of trees appeared on some of the peat sites suggests that the drier climatic phase producing suitable germination conditions was brief. However, the establishment and maturation of trees on the bog surface would tend to lower the water table in the peat through evapotranspiration, buffering the effects of any short term increases in wetness of the bog surface, and thus extending the effect of any climate-induced drying. Also, though the potential germination period might be extended by this buffering, increasing root competition or shading from the established trees, as described above, would tend to make it harder for any further young trees to establish themselves. This might fix the rate of recruitment and effectively set a carrying capacity as suggested in Section 3.10.1.3. By the time the first generation trees began dying conditions on the bog surfaces were no longer suitable for germination.

Overall then, an impression is gained of open woodlands on peat, looking much like the trees on the bog in Glen Cassley (see Plate 11). The individual trees here are of the likely size and appearance of the subfossil trees, and the tree density on this modern site is comparable with that found at Loch Shin, the most densely populated of the subfossil sites.

If this description of the subfossil woods is accepted, then it becomes clear that competition between individuals was taking place at root level, as with the spacing and sparse narrow crowns suggested by Plate 11, the shading produced was unlikely to have played a significant rôle. That this competition was intense is borne out by the sensitive ring sequences found at each site, the variation between even successfully crossmatched trees being very high. It is probable that the bulk of the noise in the within-site matching is attributable to this cause, only the major site-wide events being apparent (e.g. the strikingly wide rings around site year 52 at Loch Vatachan - Figures 3.14 and 3.15).

Another possible source of variation between the ring patterns of the trees on a year by year basis could have been relative variations in the drainage of the sites on a local scale, one small patch becoming wetter whilst another dried. Certainly there were considerable differences in wetness from place to place depending on the structure of the bogs (hummocks, hollows etc.), and an illustration is given by Steven and Carlisle (1959) of pine growing on a deep peat bog at Ballochbuie on the River Dee. Here the trees are growing on hummocks surrounded by standing water, the slight elevation of these hummocks providing just enough clearance above the water table for the tree roots, the variations in drainage across the bog being at intervals of a few metres. However, the fact that pine can grow to any size at all in such situations suggests that the hummock and hollow features are fairly permanent. In terms of the subfossil sites then, it seems that at the scale of the areas sampled relative variations in drainage year by year are unlikely to have been very great, and would have contributed little to the tree-ring signal.

Thus it is most likely that variations in water table were on a site-wide scale, driven by changes in annual precipitation, and that these changes, coupled with variations in summer temperature sums, were responsible for the site-wide tree-ring signal that permitted crossmatching of the trees within each site. Because these trees were highly sensitive, growing in poor conditions at the edge of their range, the within-site and across-site influences dominate the tree-ring signal, producing, as suggested in Section 3.10.2, sufficient noise in the site chronologies to mask some of the regional information. So, although the site chronologies did produce some significant crossmatches across the region, the lower quality of these, as compared for instance with similar work in Ireland (Pilcher *et al.*, 1995), may well reflect this effect.

4.2 The spread of pine across the region

In this section dates based on dendrochronological links to the Irish pine chronologies are quoted as 'BC'. Dates based on individual calibrated ^{14}C dates will be quoted as a 'cal BC' range, this range being their 2σ limits.

4.2.1 Timing and direction

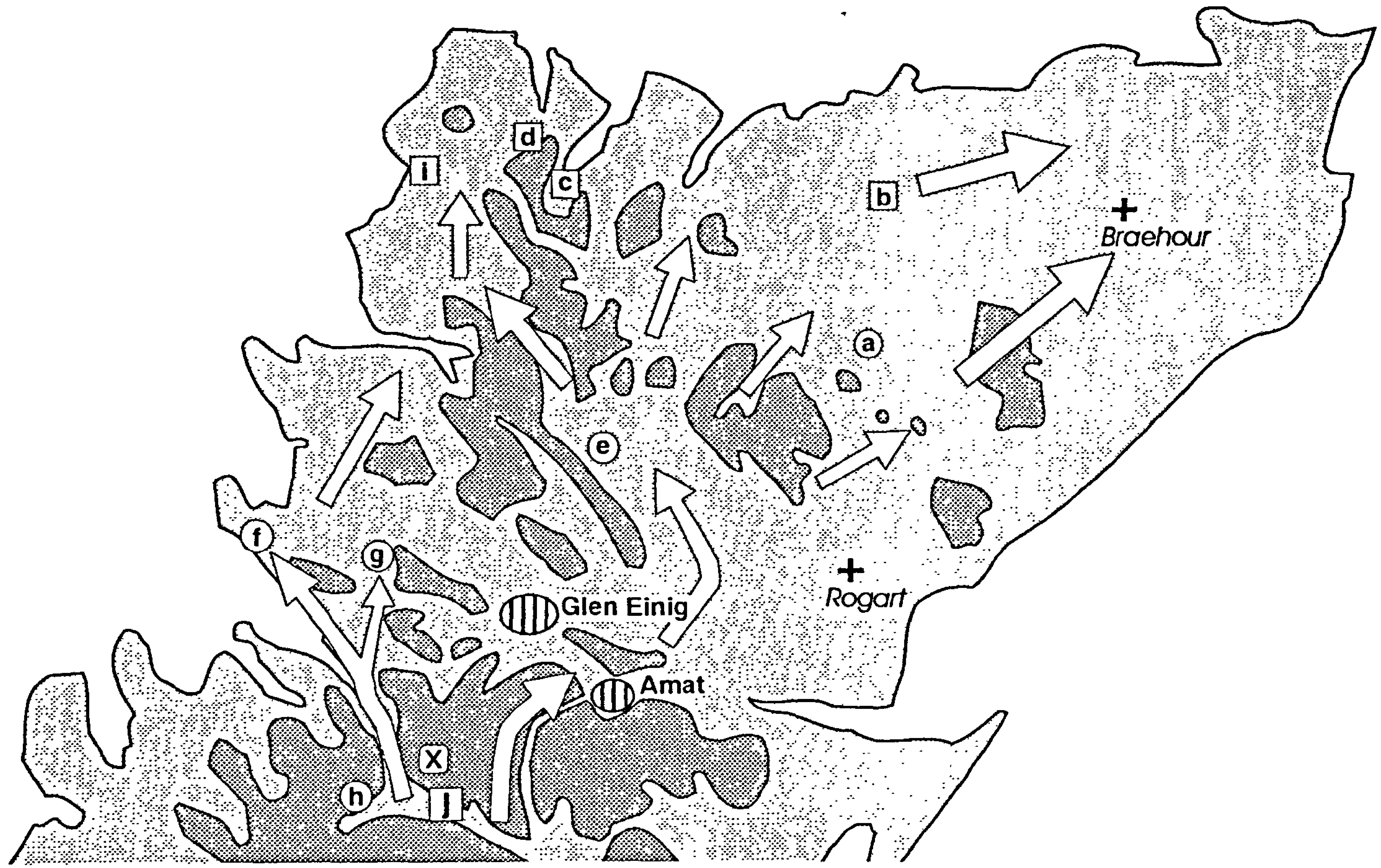
As stated in the previous chapter the earliest evidence of *Pinus sylvestris* in northern Scotland was found in the south and west of the study area. This was at Loch Glascarnoch, where one crossmatched set of stumps was ^{14}C dated to between 4853-4691 Cal yr BC, about 1500 Calendar years earlier than elsewhere. The next earliest date is for the establishment of FAI006 at Fain (slightly to the north and west of Loch

Glascarnoch), fixed by dendrochronology at 3446 BC. On the basis of this and the ^{14}C date for FAI004, 2885-2583 cal BC, the Fain site could have been occupied by pines for up to 800 years. From the time of the appearance of this first tree at Fain, expansion seems to have occurred rapidly up the west coast reaching Loch Vatachan in 40 years (3405 BC). At the same time pine was spreading inland north-east via Glen Oykel, including the present day native woodland sites at Glen Einig and Amat, and was established at Loch Shin by 3418 BC, reaching Badanloch rather later by 3155 BC, and possibly Lochtrathy at around the same time.

This sequence is confirmed by the spatial distribution of ^{14}C dates shown in Figure 3.69. This figure also indicates that pine had reached north-west Sutherland (Srath Dionard) by 2922-2702 cal BC and the eastward limit of its distribution in Caithness (Braehour - see Figure 4.1) by 2465-2143 cal BC. However, these are ^{14}C dates on single stumps and as such give no precise indication of the first appearance or final demise of pine at that particular site. Subject to these limitations, and those stated at the beginning of this chapter, Figure 3.69 also suggests that the pines growing on blanket peat declined across the entire north of the region more or less simultaneously. However few dates are available from the east and more work is required to clarify this.

Nevertheless the dendrochronological and pollen studies at the individual sites suggest a rapid expansion on to the peat of a single generation of trees, albeit with a possible scattering of isolated individuals both before and after this expansion phase. This, taken in conjunction with the dating, would confirm a rapid spread and similarly rapid decline. It is worth noting that this single colonisation phase is most marked on the west coast site at Loch Vatachan, with the inland sites further to the east showing more evidence of precursors and successors to this recruitment phase.

Figure 4.1 illustrates the directions of the spread of pine suggested above. These are based on the considerations of timing described here and at the end of the last chapter coupled with the topography of the region. The 300 m contour was selected as this altitude represents about the highest at which subfossil pine was found, either in this study (Tables 3.1 and 3.2) or that of Gear (1989). This suggests that land much above this height might have formed a barrier, at least initially, to the spread of the trees through the region. However at a rather later date it appears that in the south at least the tree-line was higher. The point 'x' in Figure 4.1 marks the location where Birks (1975) found subfossil pine at an altitude of 519 m on the slopes of Beinn Dearg to the north of Loch Glascarnoch. This pine was ^{14}C dated (Q-1153) to 3261 - 2696 cal BC, around the same date as the trees at Badanloch (Figure 3.63). This suggests the possibility that the expansion of pine may have occurred in two phases, the second, later one being both a spread north-eastward from the area of Loch Shin and also an upward movement of



Land over 300 m

Present day native pinewoods

(X) Pine at 519 m, dated 4320 BP (Q-1153 - see text)

Letters in circles are sites that are dendrochronologically linked, those in squares are ^{14}C dated.

a - Badanloch b - Lochstrathy c - Loch Eriboll
d - Srath Dionard e - Loch Shin f - Loch Vatachan
g - Knockanrock h - Fain i - Laxford Bridge j - Loch Glascarnoch

Figure 4.1. Possible directions of spread of pine into northern Scotland from about 3500 Cal BC.

the tree-line across the region. Certainly by this time pine was widespread across the landscape in the south of the region and it seems that it persisted (as at Fain for example) on the peat for rather longer than the apparent occupation of the sites further north. There is also a date for subfossil pine from Rogart (see Figure 4.1) in the south east of the region, 2867-2146 cal BC (Q-1156: see Table 3.22 and Figure 3.69), which supports this hypothesis. It was probably the fragmentation of this pine forest with deteriorating climate that left the native pinewoods at Glen Einig and Amat isolated, although subsequent human activity could have had much to do with this.

Finally, it is possible that pine reached the far north western sites either via the valley connecting Loch Shin to the sea at Laxford Bridge ('i' in Figure 4.1) or up the west coast from the direction of Loch Vatachan. At the moment there is no evidence to favour either route, and indeed it is possible that both occurred. However in any spread up the west coast the rôle of pine growing on mineral soils should be considered.

4.2.2 Spread of pine on mineral soils

The general direction of the pine expansion across the region suggested by Figure 4.1 is of course based on evidence from stumps growing on, and subsequently preserved in blanket peat. The spread of pine onto mineral soils in the region, potentially more important in the west where blanket peat is more fragmented, is harder to assess in the absence of any subfossil remains preserved in these soils.

The main options for a spread on mineral soils are:

a) Pine spread faster and/or earlier on the mineral soils than the peat.

b) Pine spread across the region at the same rate and time on both substrates.

c) Pine did not grow at all on the mineral soils.

Considering option a), if this was so, then pine would be already occupying mineral soils across the region and so would have been a seed source from which expansion onto the bog surfaces could have occurred later as these dried. This expansion might thus be expected to have been more or less simultaneous, regardless of the northing or easting of the site. There would have been variations in the timing of colonisation of the bogs due to differences in conditions (local hydrology etc.) at the different sites, but regionally these would tend to be randomly distributed. There is a possibility that an apparent directional expansion as in Figure 4.1 could occur, if for example the blanket peat surfaces in the north east became drier later than those in the west, but given the topography and the present day rainfall patterns which it creates, it is difficult to envisage a mechanism to cause this.

Under option b) a directional expansion would be expected as reservoirs of seed would not be available even if the bogs dried simultaneously across the region. All the evidence from this and previous studies indicates that such a directional expansion did take place, in the form of the clear trend northwards and eastwards of the pine expansion onto peat summarised in Figure 4.1.

Given this northward and eastward spread across the blanket peat, there remains the possibility raised by option c). This situation could have occurred if the mineral soils were already occupied by other species such as birch or hazel, or alder. As the blanket peat to the east of the Moine Thrust is effectively continuous, evidence of competitive exclusion cannot be obtained from the spread pattern of pine here. Also competitive exclusion from better soils would not preclude the spread of pine via the fragmented blanket peat and shallower peaty soils on the west coast, so patterns of spread in the west also tell us little. The Loch Vatachan pollen diagram does suggest the sharp decline of birch on that part of the west coast and it may be that here pine replaced or co-existed with birch even on mineral soils, aided by an increase in continentality of climate which would give the pine a competitive advantage (Steven and Carlisle, 1959). Overall however there is little evidence for either the presence or absence of pine on mineral soils, the low background pine count from other pollen diagrams across the region rather suggesting its absence.

On this basis, it seems that pine did spread northwards on blanket peats across the region in the directions indicated above. It is possible that pine colonised mineral soils in some places and could have persisted on these rather longer than on the peatland sites as Pilcher *et al.* (1995) found in Ireland, and there is also the possibility that it survived in sheltered coastal valleys into historic times (see Section 1.1).

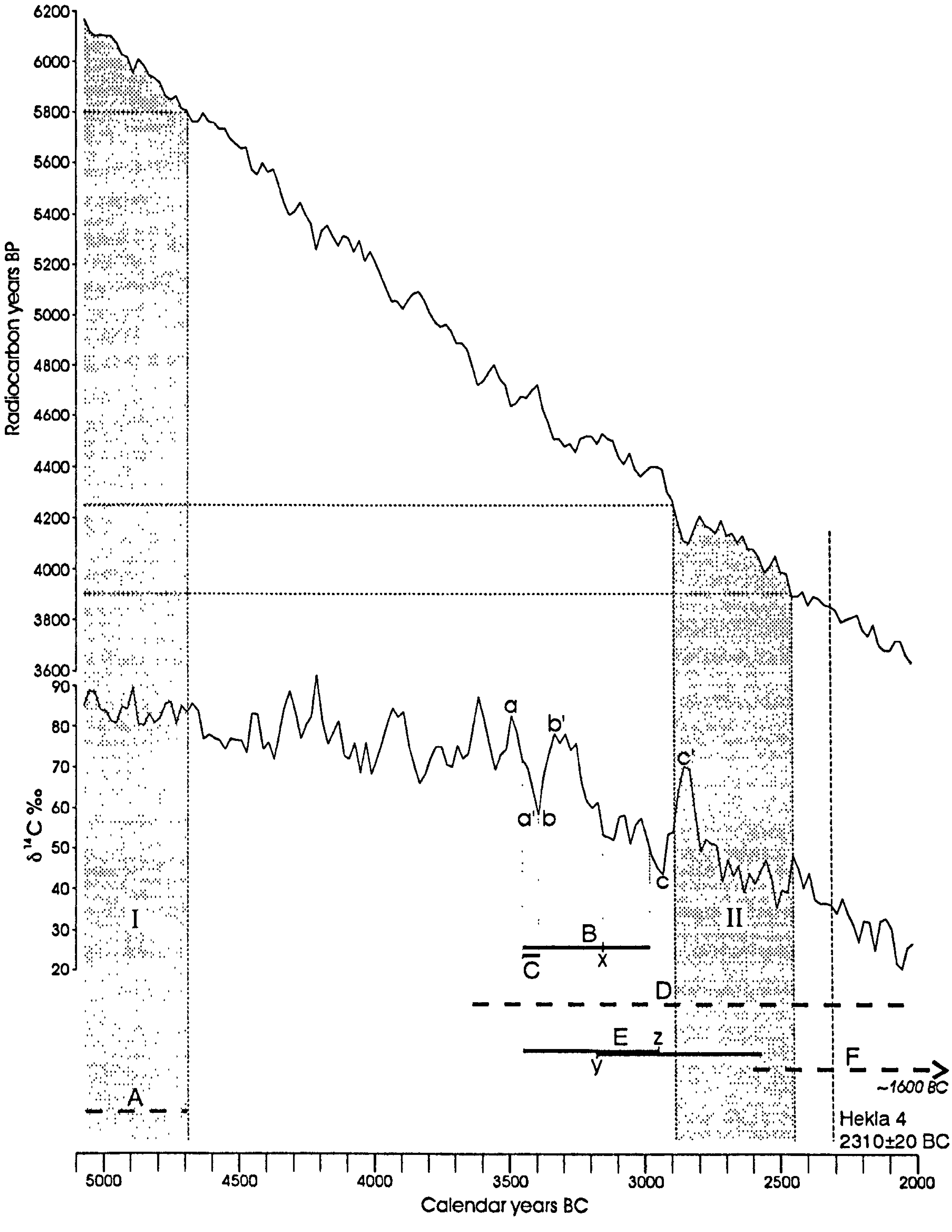
4.3 Climate Change

Generally it is accepted that the distribution of Scots pine is determined by temperature; in particular it has been suggested that while pine will tolerate extremely low winter temperatures, it needs at least four summer months with a mean temperature greater than 10.5°C to produce ripe seed and four months with a mean temperature above 8.5° for vegetative growth (Carlisle and Brown, 1968), However, in trying to establish the environmental changes that controlled the presence of pine on the peat bogs in the far north of Scotland it is clear that wetness is the limiting factor, though changes in windiness may have affected growth on the exposed sites. That wind was generally not a major factor is indicated by the small number of preserved trunks recovered, suggesting that the trees decayed standing after death as seen frequently on mires today (Ågren and Zackrisson: 1990) and were not blown over (Plate 13).

Plate 13. Native pine woods at Loch Maree, showing trees decaying while standing, and two different growth forms. The soil is mineral based. Note also the birch growing with the pine at this western site.

The surface wetness of blanket peat depends on changes in the dynamic balance between incoming precipitation and outflow (drainage and evapotranspiration), and from the initial growth and subsequent preservation of the subfossil pines it is apparent that changes in this were quite marked during the period of the pine expansion. This, coupled with the rapidity of spread discussed in the previous section, suggests a regional climatic change as the probable cause. Gear and Huntley (1991) point to a simultaneous expansion and subsequent retreat of the limits of pine in Fennoscandia, controlled in this case by summer temperatures (cf. Briffa's (1994) climate reconstruction for northern Fennoscandia in the mid to late Holocene), and suggest that the most appropriate climatic mechanism to explain these changes is a movement north, or expansion north-eastwards, of the Azores summer high pressure zone which would in turn cause a northwards shift of the jet stream. This would result in a more continental climate for Fennoscandia and north Britain, with warmer summers in Fennoscandia and generally reduced rainfall in the north of Scotland. It would also tend to produce less windy conditions in the west of the region.

There is further evidence to suggest that changes in climate may have occurred on a global scale at this time. Van Geel *et al.* (1996) suggest that a rapid change to a cooler, wetter climate in north-west Europe around 850-760 BC can be identified with simultaneous changes in climate in both hemispheres. They show that this change is paralleled by a rapid increase in atmospheric $\delta^{14}C$ of the order of 20 ‰. Changes of similar magnitude in the $\delta^{14}C$ curve occur earlier in the Holocene and Figure 4.2 shows the relationship of three of these (a - a', b - b' and c - c' in Figure 4.2) to the various dates from the present study and studies of pine in Ireland. Also shown as two shaded bands are two of the 'pluvials', or periods of increased precipitation, of Dubois and Ferguson (1985 - cited in Bridge *et al.*, 1990) which are based on analysis of deuterium:hydrogen ratios in ^{14}C dated pine stumps from the Cairngorms. The beginning of the earlier of these is beyond the left end of the horizontal axis, at about 5200 BC and coincides approximately with a $\delta^{14}C$ rise of around 20 ‰. An earlier pluvial, also not shown in the figure, is roughly aligned with a similar rapid rise in $\delta^{14}C$ at about 6500 BC. In terms of the present study a rapid decrease (a - a' in Figure 4.2) in $\delta^{14}C$ coincides with the beginning of the recruitment phase of pine at Loch Shin and Loch Vatachan (C in Figure 4.2), possibly indicating increasing dryness and warmth, and a large increase (b - b') of $\delta^{14}C$ coincides with the end of this recruitment phase and may represent the onset of cooler, wetter conditions bringing this to a close. Similarly the later beginning of the Badanloch sequence (x in Figure 4.2) occurs at the end of a large decrease in $\delta^{14}C$ values.



A - 2σ limits of Loch Glascarnoch span based on calibrated ^{14}C dating.

B - Span of trees crossdated in this study (dated from Irish pine chronologies)

C - Overall duration of recruitment phase at Loch Shin and Loch Vatachan.

D - Span of 2σ limits of calibrated dates in Table 3.21 and Figure 3.77 (less Loch Glascarnoch).

E - Span of Garry Bog/Sharvogues pine chronologies (Brown, 1991; Pilcher *et al.*, 1995)

F - 2σ limits of Glashabaun floating chronology (McNally and Doyle, 1984)

I, II - Dubois and Ferguson pluvials (as quoted by Bridge *et al.*:1990)

x - beginning of Badanloch chronology. y - beginning of Sharvogues chronology,

z - end of Garry Bog pine 1 chronology. a, b. c, - see text.

Figure 4.2. Outline dates from northern Scottish subfossil pine with the ^{14}C calibration curve and $\delta^{14}C$ fluctuation curve for the same period. The curves are based on data from Dataset 1 of CALIB 3.0 (Stuiver and Reimer, 1993).

This increase in $\delta^{14}C$ (b - b') may also be related to the episodes of regionally narrow rings at 3411, 3404, 3379 and 3368 BC (Section 3.10.2, Figure 3.64) and the period of reduced growth and slow recovery prominent at Loch Shin and Badanloch that followed it. This is supported by the sharp dips in pollen influx at 73 cm and 64 cm in the peat profiles from Loch Vatachan and Loch Shin respectively, the identification of these with b - b' being consistent with the dates and deposition rates suggested in Section 3.10.4. A still more prominent $\delta^{14}C$ increase (c - c') occurs at the beginning of the later of the two pluvial episodes shown in the diagram (II) and this may indicate the onset of the increasingly oceanic climate conditions and associated waterlogging that ended the pine expansion onto the bog surfaces and led to the continuation of peat growth. This $\delta^{14}C$ increase is consistent with the reduced overall pollen influx and increase in *Sphagnum* spores found at Loch Vatachan (around 69 cm in the profile), and with similar events at Loch Shin (above 52 cm).

This combination of separate strands of evidence reinforces the hypothesis that regional change led to a more continental climate that permitted the colonisation by pine of the peat surfaces in northern Scotland, possibly in two phases, the first starting at around 3500 BC in the south and west of the region and the second about 300 years later, at about 3200 BC, into the north and east. A subsequent increase in oceanicity, initially perhaps quite rapid, at around 2900 BC, brought about the end of the pine expansion and the subsequent preservation of its remains.

This hypothesis, however, is by no means proven and it should be noted that at the moment mechanisms linking changes in atmospheric $\delta^{14}C$ values and climate are still being postulated. ^{14}C is produced in the upper atmosphere by cosmic radiation, and it is known that changes in the solar wind affect the rate of this. What is not clearly known is how these changes are linked to changes in climate, and there has been a certain amount of controversy surrounding this (Wigley and Kelly, 1990: Stuiver and Braziunas, 1991: Magny, 1993). However recent work has suggested a direct link been between cosmic rays and cloud formation (Svensmark and Friis-Christensen, 1997), and the circumstantial evidence for a connection between $\delta^{14}C$ and climate is impressive (see also Van Geel *et al.*, 1996).

4.4 Conclusion

From this study it is clear that *Pinus sylvestris* L. expanded from its previous northern limits in Scotland (which it had reached at the latest by about 5000 BC) from around 3500 BC to reach the north coast about 300 years later. This expansion was both northwards and eastwards from Glen Oykel onto the drying surfaces of the blanket peats across the region. The expansion seems to have been fairly rapid (at rates approaching the maximum found for this species: Huntley and Birks, 1983; Gear and Huntley 1991) as far as the centre of the region studied, but much slower from there northwards to the coast. After about 300-400 years the peat surfaces became wetter again and peat growth recommenced, preserving the remains of the pines. There is some evidence of the onset of increasing wetness after only about 100 years which prevented the pine from reproducing on the bog surfaces, but the original trees survived in some cases for at least 300 years. The spatial and temporal scale of this expansion and subsequent contraction in the range of pine, and its parallels in Fennoscandia and Ireland suggest a climatic cause for the event, and the hypothesis of Gear and Huntley (1991), describing changes in the weather systems of the north east Atlantic, seems the most likely explanation.

However more work is required to determine the origin of the pines that grew on the peats of northern Scotland. It is known that the Wester Ross populations of pines are genetically distinct from the other Scottish populations (Kinloch *et al.*, 1986: Ennos, 1991) but it is not clear from this study whether the trees spreading northwards (or at least those on the west coast) were derived from this group or the northern group, surviving till the present day at Amat and Glen Einig. The latter seems more likely, but genetic study of the subfossil pine could settle the question and reveal much about its origins.

Another question arises as to the presence or absence of pine on mineral soils and the possibility of the survival of isolated groups of pines into historic times. More work is required in the east of the region, and on the west coast to resolve this. Also the relationship of the pines found in outer Hebridean peats to those on the west coast of the mainland should be established dendrochronologically and genetically; this would throw more light on the origins of pine in the region as a whole.

It is also important to develop more reliable chronologies for the region and more samples are needed for this. These should preferably be from trunks, if they can be found, which might give a clearer regional signal than the somewhat distorted ring sequences from stumps. Such chronologies would help confirm the link with the Irish pine chronologies (particularly Garry Bog and Sharvogues) and might fix the events in the north of the region absolutely in time. Combined with this is the possibility of stable isotope studies along the lines of those of Dubois and Ferguson (1985) to identify pluvial episodes which could then be accurately placed within this framework.

In all this there is some urgency as the trees currently being exposed at the sides of reservoirs, in peat cuttings etc. are decaying fast as they dry, and a huge potential source of palaeoecological information is being lost.

The scale and speed of the climatic changes described in this study indicate the importance of the influence of rapid changes in the north Atlantic on the weather systems of north-west Europe. The sensitivity of these systems gives us warning of the potential effects on our present climate of anthropogenically induced changes in our environment.

These results also indicate the rate at which vegetation can respond to such changes, and although this is rapid, it may not be rapid enough to cope with the predicted climate changes for the near future. Indeed, with the present dry phase we are currently undergoing, it may well be that, in the absence of human or animal interference, we will see again a spread of pine onto the blanket peats of the north of Scotland within a few tens of years.

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Appendix 1. List of programs used in this project

(all written by author in Microsoft QuickBasic v. 4.5 except where stated).

CONVERT2
Converts files in eyepiece graticule units to integer files in microns (μ).

TREERING
Calculates number of rings, mean and SD of ring-width of up to three radii from each of two trees. Plots two selected radii as raw or simply standardised values or skeleton plots. Calculates best and second best match between these with multiple probability and IF. Also displays individual probability, t, Fisher's z,and Gleichläufigkeit for any match position.

TREEMEAN
Calculates robust means from up to 3 radii (integer files in μ) of a tree.

TREESTAT
Calculates number of rings, sum, mean and SD of ring-widths, average mean sensitivity and 1st-order autocorrelation.

RINGWID7 by Brian Huntley (Fortran)
Calculates (amongst other values) Baillie and Pilcher, Fritts and Munro values from raw tree-ring data for use as input for CROSDAT5.

CROSDAT5 by Brian Huntley (Fortran)
Performs crossmatching between individual radii from RINGWID7 output, calculates best and second best match for these with individual and multiple probability and IF, for all three filters.

MULTCROS by Brian Huntley (Fortran)
Combines RINGWID7 and CROSDAT5, performing crossmatching between all combinations of trees in the input, listing output as for CROSDAT5 for all these combinations.

MULTCROS-T by Brian Huntley (Fortran)
As MULTCROS, but produces 't' values as output.

BPLOG2
Calculates Baillie and Pilcher's (1973) 5 point filtered normalised values.

FRITTS2
Calculates Fritts' (1976) 13-term 8 year cut-off high-pass filtered log widths.

MUNRO2
Calculates Munro's (1984) 23-term 10 year cut-off high-pass filtered log widths.

ROBCRON

Produces robust mean chronologies, plus year by year number of trees present in the mean.

Appendix 2. Identification characters distinguished in subfossil pine

Output from computer program GUESS v 1.1 by C.A. LaPasha using the identification key of Wheeler *et al.* (1986) based on Phillips (1948).

unknown # 1 - Pinetest
number of misses allowed = 0
search of SOFTWOODS =**-> 3 possible IDs found

definition of this unknown :

3 Latewood conspicuous * present *
4 Distinct odor * present *
16 Ray tracheids * present *
18 Ray trach. dentate (aver.) * present *
20 Horizontal walls thin * present *
21 Horizontal walls unpitted * present *
28 1-3 large X-field pits * present *
33 Normal Vertical ducts * present *

....

possible IDs follow:

PIN PINUS NIGRA(AUSTRIAN PINE)

2 Heartwood colored
3 Latewood conspicuous
4 Distinct odor
16 Ray tracheids
17 Ray trach. minutely dentate - VARIABLE -
18 Ray trach. dentate (aver.) - VARIABLE -
20 Horizontal walls thin
21 Horizontal walls unpitted
23 Indentures - VARIABLE -
28 1-3 large X-field pits
32 1-6 Pinoid X-field pits
33 Normal Vertical ducts
35 Horizontal ducts
39 Europe, etc.
43 Australia - VARIABLE -
44 New Zealand - VARIABLE -

PIN PINUS RESINOSA(RED PINE)

2 Heartwood colored
3 Latewood conspicuous
4 Distinct odor
16 Ray tracheids
17 Ray trach. minutely dentate - VARIABLE -
18 Ray trach. dentate (aver.) - VARIABLE -
20 Horizontal walls thin
21 Horizontal walls unpitted
23 Indentures - VARIABLE -
28 1-3 large X-field pits
33 Normal Vertical ducts
35 Horizontal ducts
45 North America

PIN PINUS SYLVESTRIS(SCOTCH PINE)

2 Heartwood colored
3 Latewood conspicuous
4 Distinct odor
16 Ray tracheids
18 Ray trach. dentate (aver.) - VARIABLE -
19 Ray tracheids reticulate - VARIABLE -
20 Horizontal walls thin
21 Horizontal walls unpitted
23 Indentures - VARIABLE -
28 1-3 large X-field pits
32 1-6 Pinoid X-field pits - VARIABLE -
33 Normal Vertical ducts
35 Horizontal ducts
39 Europe, etc.

Appendix 3. Weights for the Fritts (1976) and Munro (1984) filters.

Fritts' (1976) 13-term 8 year cut-off high-pass filter weights:

-0.0003
-0.0030
-0.0161
-0.0537
-0.1208
-0.1933
0.7744
-0.1933
-0.1208
-0.0537
-0.0161
-0.0030
-0.0003

Munro's (1984) 23-term 10 year cut-off high-pass filter weights

0.000340
0.000000
-0.002515
-0.007808
-0.013569
-0.013667
0.000000
0.032927
0.083054
0.138929
0.183152
0.200000
0.183152
0.138929
0.083054
0.032927
0.000000
-0.013667
-0.013569
-0.007808
-0.002515
0.000000
0.000340

Filters: Matching - tree b on tree a at:		BAILLIE & PILCHER			FRITTS			MUNRO		
		Ring	Mult. Prob. (P)	IF	Ring	Mult. Prob. (P)	IF	Ring	Mult. Prob. (P)	IF
Tree a	Tree b									
shi001	shi003	5	0.00002	944.84	5	0.00007	360.19	5	0.00023	483.91
shi001	shi004	4	0.00000	68461.73	4	0.00000	119570.16	4	0.00002	422.05
shi001	shi005	12	0.00001	1664.89	12	0.00001	1680.32	12	0.00001	4859.43
shi001	shi006	3	0.00002	5765.91	3	0.00001	5550.97	3	0.00006	62.83
shi001	shi007	7	0.00108	599.48	7	0.01096	4.31		-999999.00000	1.00
shi001	shi009	-2	0.00001	11894.18	-2	0.00001	22560.42	-2	0.00006	1835.73
shi001	shi010	9	0.00007	38.41	9	0.00024	46.98	9	0.00030	14.42
shi001	shi011	32	0.00717	15.22	32	0.03232	14.49	51	0.19445	3.57
shi001	shi013	-1	0.00001	75990.69	-1	0.00000	172749.26		-999999.00000	1.00
shi001	shi014	20	0.00157	1.04	20	0.00600	2.05	20	0.00374	19.49
shi001	shi015	8	0.00005	19272.43	8	0.00020	1999.39		-999999.00000	1.00
shi001	shi016	-7	0.00003	2071.81	-7	0.00012	492.43	-7	0.00330	2.26
shi001	shi017	5	0.00004	4779.20	5	0.00041	292.28	5	0.00228	55.12
shi001	shi018	1	0.00016	3586.42	1	0.00009	1988.51	1	0.00040	41.92
shi001	shi019	9	0.00001	23757.91	9	0.00001	17802.63	9	0.00001	15910.36
shi001	shi020	10	0.00004	1291.08	10	0.00006	383.84	10	0.00006	302.00
shi001	shi021	8	0.00013	157.50	8	0.00047	116.22	8	0.00129	27.63
shi001	shi026	69	0.00598	120.27	69	0.01093	69.81		-999999.00000	1.00

Appendix 4. Sample of output from program MULTCROS (B. Huntley).
The -999999.00000 and 1.00 output for the Munro filter indicates no match as the ring sequences were too short for the filter.
(Headings added for clarity)

Appendix 5. Results of original microprobe analysis of tephra from 74 cm level at Strath Dionard done by J.J. Blackford.

STRATH DIONARD

INITIAL EMP TEPHRA ANALYSES: 74 CM
29/3/94 Oulu

	1	2	3	4	5	Mean
Na_2O	1.677	1.855	4.038	3.307	3.583	2.892
MgO	0.02	0	0.005	0	0.1	0.025
Al_2O_3	12.918	13.346	13.061	12.433	13.185	12.9886
SiO_2	72.255	74.306	73.394	69.916	64.945	70.9632
K_2O	2.749	2.71	2.358	2.688	2.264	2.5538
CaO	0.996	1.148	1.152	1.107	1.813	1.2432
TiO_2	0.068	0.1	0.07	0.145	0.187	0.114
MnO	0.182	0.045	0.68	0.068	0.166	0.2282
FeO	1.96	2.008	1.979	1.86	3.012	2.1638
Total oxides	92.825	95.517	96.126	91.523	89.166	
Beam	5	5	5	5	5	
Na time	10	10	10	10	10	
Current nA	10.67	10.68	10.67	10.68	10.68	

Several other readings fell short of 90% total oxides
Machine used: JEOL Superprobe 733, ZAF Correction programme
Analysis: J.J. Blackford and O. Taikina-aho

File U:\jjb\tphsd70