The use of tree-ring analyses in the absolute dating of historic sites and their use in the interpretation of past climatic trends

by

Patricia Anne Leggett
(maiden name: Bond)

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Department of Biology,
Liverpool Polytechnic,
Byrom Street,
Liverpool L3 3AF.

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Dedicated to my parents
Ivy Patricia Bond and
the late Daniel Bond

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Abstract

Absolutely dated, well replicated oak tree-ring chronologies from trees at a maritime site, Maentwrog and at a rainshadow site, Peckforton were constructed. These data were used in a comparative study of tree growth at sites which differ climatically. The site chronologies were compared with other British Isles tree-ring chronologies. Correlation analyses identify periods when annual growth was best correlated, indicating the periods when limiting climatic conditions probably prevailed. There was no correspondence between the Maentwrog and Peckforton chronologies and various European chronologies.

Response functions were used to examine the strength and nature of climatic signals in chronologies at the two sites. The major difference was the response of tree growth to precipitation. At the rain shadow site, low precipitation is limiting to growth during many months of the year; there is a significantly positive response to precipitation during the prior June, August, September and October, and January and March during the current year of growth. In the response functions for the maritime site there is no positive response to precipitation. These differences in response to climate will make a valuable contribution to the determination of climatic anomalies in the British Isles. A positive effect of October temperature and a negative effect of December temperature on growth in the following year was found at both sites. The relationship between climatic variables and tree-ring variations was also examined in high-pass and low-pass filtered data.

For Maentwrog and Peckforton, the estimates 27.21 ± 9.95 and 29.9 ± 18.59 (mean ± 95% confidence limits) were obtained for the number of sapwood rings to be applied to the heartwood/sapwood boundary, in the determination of felling dates. Tree diameter and age were found to be significantly related in trees exceeding 70 years.

The construction of absolutely dated chronologies provides a modern anchor for a north west of England regional tree-ring chronology. Continuous chronologies have only been established for the north of Ireland and for Scotland. Once established, a continuous, absolutely dated regional chronology enables the dating of local oak structures. The north west of England and Wales regional chronology spans the period A.D. 930 - 1976 with breaks from A.D. 1330-1378 and 1595-1710. In producing this chronology, constructional dates for a number of oak structures were proposed. Crossdating tests between these component chronologies and other British Isles chronologies indicated the presence of local variations in tree growth and the need for a regional chronology for the north west of England.

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CHAPTER 1 - INTRODUCTION

1.1 The fundamentals of dendrochronology

The science of dendrochronology can be defined as the systematic study of the chronological sequence of annual growth rings in trees applied to dating past events and evaluating climatic history. One of the principal pioneers of the science was A.E. Douglass although he was not the first to recognise the underlying principle. Eckstein *et al*. (1975) ——— cite a number of European workers who had already recognised "crossdating" in the 18th and 19th centuries. Nevertheless, it was the systematic studies of Douglass which led to the greatest development of the science. A full account of the researches of Douglass are given by Fritts (1976) and Robinson (1976) thus, only major developments and their implications will be outlined. In 1901, in attempting to relate the cyclic activity of sunspots to the behaviour of climate, Douglass's studies led him to examine the growth of trees which he felt may be proxy records of climate. From examinations of the radial sections of trees, the same patterns of wide and narrow rings could be recognised in all the trees which had been growing during the same time period. This sequence was so predictable that it was possible to match it to that of trees growing nearby, at lower elevations. The recognition of recurrent patterns in the annual increment forms the basis of the principle fundamental to dendrochronology that of crossdating. It has been defined as the procedure of matching ring-width variations and other structural characteristics among trees that have grown in nearby areas allowing the identification of the exact year in which each ring was formed (Fritts, 1976).

The technique of crossdating is dependent upon the formation of the growth ring being annual. Although the increments appear as concentric rings encircling previously formed rings when viewed in transverse section, they are actually layers of wood extending the full height of the tree. In conifers, the wood tissue or secondary xylem is composed of tracheids and axial and radial parenchyma. The tracheids perform two functions: the thin-walled cells laid down at the beginning of the growing season are concerned with conduction whilst the thick-walled cells formed later in the season have a strengthening function. The transition from the layer of thin-walled cells, the earlywood, to the layer of thick-walled cells, the latewood may be gradual, as in white pine. In other species it is abrupt for example, in Douglas fir. Hardwoods are far more complex consisting of four or five cell types: vessel elements, libriform fibres, parenchyma cells, tracheids and fibre tracheids. The vessel elements are concerned with water movement through the tree, fibres constitute a strengthening tissue, living parenchyma are concerned with food assimilation and the wood rays of parenchyma cells are concerned with the translocation of assimilates. In general, the vessels formed at the beginning of the growing season are thinner-walled than those formed during the later part of the season. In some species, the decrease in cell size is gradual throughout the annual ring, for example, beech, birch and sycamore. In a few species, there is an abrupt change in size to the cells of the latewood for example, oak, ash and elm. Thus, in conifers and hardwoods the growth rings are apparent because the wood produced at the beginning of the growing season is different in character from that formed later in the season.

Crossdating between sequences of growth increments is possible because the same or similar environmental conditions have limited the ring widths in large numbers of trees. The year-to-year fluctuations in the limiting environmental factors that are similar throughout the region produce synchronous variations in ring structure. Thus, a tree-ring record can be extended back from the present day by matching the tree-ring patterns from successively older material - a process known as chronology building. When the record cannot be extended from the ring patterns of living trees, those from tree stumps, and from trees in old buildings and from archaeological contexts are utilised. Thus, the older part of the sequence from a living tree may be matched with the younger part of the sequence from the tree stump; the older part of this sequence may be matched with the younger section of the sequence from structural timber and so on. The procedure can continue so long as successively older timber is available. In the resultant chronology, a known date for the most recently formed ring allows the assignation of calindrical dates to all the other rings in the sequence. The master chronology is unique in its year-by-year pattern since nowhere throughout time is the sequence repeated since the year-to-year variations are never the same. The synchronous variations in ring width on samples from living trees are shown in Plate 1.1.

The success of the crossdating technique depends on the selection of trees which are limited by climatic variables and which are not greatly affected by competition which may interfere with the climatic response. The selection of the site at which the trees are examined therefore plays a primary role in determining the success of crossdating and the value of the resulting chronology. In North America,

Plate 1.1 The synchronous variations in ring width on samples LP 555B and LP 561B taken from trees at Peckforton Hills. Each pair of arrows indicates the corresponding growth rings in each tree-ring series

dendrochronology has been successfully applied along the arid and semi-arid forest border where low moisture is limiting to growth (Schulman, 1956; McGinnies, 1963; Fritts, 1965; Fritts et al., 1965a; Fritts et al., 1965b; Ferguson, 1969; Fritts, 1974 and LaMarche, 1974a). Similar successes have been achieved in northern latitudes where the limiting climatic variable is usually temperature during the growing season (Giddings, 1947; Anderson, 1955; Høeg, 1956; Mikola, 1962 and LaMarche, 1973).

The tree-ring patterns of trees growing where climatic factors are frequently limiting are termed sensitive. At sites where climate seldom limits growth processes, for instance where soil moisture is adequate, tree-rings show little variation in width from year to year except for a gradual decrease in width associated with an increase in girth with age. Such series are termed complacent. Douglass (1941) identified conditions favourable to crossdating: lower elevations, sandstone and limestone bedrock under shallow soils, steep slopes, high ridges and "shadow" sides of the mountains (away from moist westerly winds); and conditions which decreased crossdating: deep moist soils, higher elevations and running streams.

The reliability of the master chronology constructed through crossdating depends not only on accurate identification of the annual rings but also on the number of tree-ring sequences it contains. The best representation of tree growth and estimate of climate is provided by the average of replicated measurements from a large number of trees since the growth variation associated with climatic variations is retained when these averages are made (Fritts, 1976).

Consequently, chronologies that comprise the tree-ring patterns of a small number of trees have a limited value for dating and climatic reconstruction. In addition, replication within and amongst trees allows statistical comparisons of variability in these two categories (Section 2.6.4).

Not all woody plants are suitable for tree-ring analysis since some plants form more than one growth layer a year, some have ill-defined layers whilst others are not greatly affected by variations in the environment. Douglass (1914) conducted his initial studies on ponderosa pine (*Pinus ponderosa* Laws.) but other major trees used in the south western United States include Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) pinyon pine (*Pinus edulis* Engelm.) and Rocky mountain juniper (*Juniperus scoputorum* Sarg.) More recent studies have examined two species of the upper timberline, bristlecone pine, (*Pinus aristata* Engelm.) and limber pine (*Pinus flexilis* James) (Ferguson, 1970). Of the hardwoods, oak has provided good dat~~e~~able material particularly white oak (*Quercus alba* L.) and black oak (*Quercus velatina* Lam.) in the central Mississippi Valley (Estes, 1970). Other genera include *Araucaria*, *Artemesia*, *Fagus*, *Abies*, *Sequoia*, *Picea* and *Thuja*. In Europe the genera used for dendrochronology and dendroclimatology include *Abies*, *Pinus*, *Picea*, *Larix*, *Quercus* *Fagus*, *Juniperus*, *Betula*, and *Alnus*. The most widely used genera are *Quercus* and *Pinus*. In Australia species of the genera *Athrotaxis* *Libocedrus* and *Callitris* have been used successfully.

Since the systematic studies of Douglass in the early twentieth century intensive dendrochronological and dendroclimatological research has been advanced in many parts of the world. Some of the methods used by early workers have been revised. The development of computer techniques, has facilitated a more detailed analysis of the tree-ring and climatic data. (Julian and Fritts, 1967; Eckstein and Bauch, 1969; Fritts *et al.*, 1969; Fritts *et al.*, 1971; Stockton and Fritts, 1971; Baillie and Pilcher, 1973; Nash *et al.*, 1975 and Wendland, 1975) and data pertinent to tree physiology (Stevens,1975). Nevertheless, the basic principles of site selection, crossdating and chronology building remain just as important.

1.2 Applications of Dendrochronology

The applications of dendrochronology were recognised in the early stages of its development by A.E. Douglass (1914, 1919, 1921) who realised its importance as a chronological tool and a way in which patterns of past environmental conditions could be examined. In the last six decades, many tree-ring chronologies have been established for many parts of the world for these purposes but also with a view to applying the technique to other fields of study. These included radiocarbon analysis, glacier movements, sea level changes, dynamics of river flow, ecology and environmental controls.

Historical dating

To archaeologists, historians and architects the main attraction of dendrochronology is absolute dating since no other method can give such accurate results. In some cases calendar dates cannot be immediately assigned to the structure of interest since a reference chronology covering the same period with which the new sequence can be matched, may not exist. In this undated state, the new chronology is termed "floating". Nevertheless, the relative dating of individual timbers within the site is often as important as calendar dates since it can provide details of the site's constructional history. This is clearly illustrated at the excavation at Novgorod (Russia) in which 32 wooden pavement layers could be chronologically related to one another so that a precise chronological sequence could be established for the different layers. The oldest layer dated from the year A.D. 953 (Kolchin,1972). Dendrochronological analysis of many wood samples from the excavation of the medieval settlement of

Haithabu (Northern Germany) provided an absolute date for the beginning of the settlement, A.D. 800-810 (Eckstein, 1978). In London, waterfronts excavated at Seal House and New Fresh Wharf have been dated to the Roman period whilst further successive waterfronts at Seal House could be identified as medieval using tree-ring analysis (Morgan, 1977a). Hillam (1979a) has been able to construct a chronology for a medieval revetment at Chapel Lane Staithe, Hull, for which the outer year could be dated A.D. 1297. Excavations at sites in Dublin have revealed that they consisted of two phases, one of which was of 10th to 12th century date when the predominant timber was ash. In the second phase, 12th to 14th century, oak predominated. By dendrochronological analysis, the outer year of the oak chronology could be dated precisely to A.D. 1306 and subsequently contributed to the oak chronology for Dublin (Baillie, 1977b). In New Mexico, a chronology constructed for timbers from the large ruin of Pueblo Bonito was initially floating until it was eventually dated to the 11th century (Douglass, 1935). Similarly, from the timbers at Aztec, another ruin in New Mexico, a construction date of between A.D. 1111 and 1120 could be established. Forty prehistoric ruins in the American southwest were eventually dated in terms of the Christian calendar by the overlapping of matching tree-ring patterns and extension of the absolute chronology (Douglass, 1935).

Conventional tree-ring studies on a variety of species of wood excavated from trackways at the Somerset Levels have led to the examination of more unusual aspects of dendrochronology (Morgan et al., 1978). Comparisons have been made of the woodworking techniques employed during different prehistoric periods in addition to an evaluation of the effects of man on the local woodland through extensive felling. The studies also demonstrated the practice of forest management in the fourth millenium B.C. Age determinations of young twigs established the presence of coppice cycles and in which season the trees were felled.

In dating timber structures and thereby the sites in which they were used, dendrochronology can often lead to a greater understanding of the dynamics of past settlements. At the Bronze age settlement at Zug-Sumpf, Switzerland, dendrochronological analysis of oak, ash and alder showed that the site had been occupied for almost 200 years (Huber and Merz, 1962). At Thayngen-Weier, dendrochronological studies showed that the neolithic Swiss lake settlements were inhabited for only a few years or decades (Huber and Merz, 1963).

Dendrochronology has an important role to play in architectural history since the status of a building and its future often depends upon its age. Often, documentary sources are fragmentary or non-existent and dating by radiocarbon analysis covers a span of ages too great for this type of problem. The facility for dating individual years and often the exact date of construction or estimate of it (with smaller limits than radiocarbon analysis) makes dendrochronology an invaluable tool. Using this technique Laxton et al. (1979) dated a timber framed barn at Keyworth, Nottinghamshire, and confirmed the completion date given for the building of A.D.1651. Baillie (1976) has been able to suggest construction dates for some cottages for the 17th and 18th centuries in the north of Ireland. The results from this study have made the first major contribution to the complex study of the chronological sequence of timbering techniques in the north of Ireland. In dating the Trier and Speyer cathedrals by dendrochronology, an exact and differentiated sequence of the different stages of the construction was formed (Hollstein, 1968). In addition to confirming certain constructional dates, tree-ring dating contradicted already existing results. In the church of St. Martins at Landshut, south of Munich, the completion date given to the tympanon was A.D. 1432. In dating the fir foundation poles of the church, Becker and Giertz-Siebenlist(1970) established a date of A.D 1441 which was 9 years later than that given for the completion date of A.D. 1432. Thus, dendrochronology has wider implications in this field of history than purely dating.

In the art world, several techniques are available for dating and examining the authenticity of paintings. When wood panels rather than canvas are used as supports for the paintings, dendrochronology can be added to the list of techniques because the panels contain the annual growth rings of the tree from which they were prepared. At present, most of this work is concentrated on oak. With the absolute dating of the tree-ring series it is possible to determine an exact *terminus post* for the age of felling and for the time when the paintings were created (Bauch and Eckstein, 1970). Many Dutch, Flemish and German paintings of the 14th to the 19th century have been dated using this method (Bauch, 1978). Fletcher (1978a) has measured 200 oak panels used for paintings of late Medieval, Tudor and Jacobean times 80% of which have been dated. Leggett (unpublished data) has provided a terminus post for the creation of several 16th century paintings deposited in the Walker Art Gallery. Dendrochronological analysis of panel paintings can also provide information on preparation methods for the supports. It is often believed that wood for panels was stored for at least twenty years before manufacture. From the analysis of a large number of Wouwerman paintings Bauch and Eckstein (1970) have shown that the period between the felling date of the tree and the creation of the painting was much shorter. On average the figure is 8± 5 years (Bauch *et al.*, 1972). Tree-ring analyses can also provide clues regarding the provenance of the wood used in a painting. Bauch (1978) concluded that some German paintings of the 14th to the 16th century were done on wood from the Netherlands. Thus, dendrochronology can aid in verifying the authenticity of paintings, chronologically place undated paintings and provide additional information on manufacturing techniques.

Dendroclimatology

Through the success of crossdating in his early studies, Douglass realised that the ring-width patterns reflected environmental conditions. The fact that much of the variation was observed in all his trees suggested that this must reflect certain factors occurring over a region. These factors were concluded to be the yearly fluctuations in climate. Thus, the field of dendroclimatology relates to dendrochronological analysis in that it uses the climatic information in dated growth layers to study the variability in present and past climate. Recent research has produced a number of powerful analytical methods for extracting this climatic information (Fritts, 1974; Fritts _et_ _al_., 1971)

LaMarche (1974a) points out that there is a need to know more about past climatic variations since it is felt that man may be having an increasing influence on climate. A greater understanding could possibly lead to the opportunity for anticipating changes resulting from such man made and natural activities. This cannot be achieved from the records of meteorological data since these are relatively short. Tree-ring chronologies of annual growth which extend far into the past and which can be dated provide the source for the palaeoclimatic data required for the reconstruction of past climate. The annual growth increments of trees fulfil this role when they vary as a function of some limiting climatic factor. The most suitable trees are often found at forest margins where climatic factors frequently limit growth processes. In arid and semi-arid regions, trees can provide long rainfall records since moisture stress due mainly to low precipitation results in a narrow ring. In Indiana, the effect of precipitation and temperature on the annual growth of *Quercus alba* L., *Q. montana* Willd., *Q. velutina* Lam. and *Q. borealis* Michx.f. was examined by Kleine, Potzger and Friesner (1936). For the period 1909 to 1933 it was found that precipitation played the primary role of limiting factor in annual ring growth. The optimum condition for growth was found to be a cool temperature with high precipitation during June, July and August. Fritts (1974) using a chronology for Great Basin bristlecone pine, an arid site conifer of Western North America, found that ring-width variations were directly related to precipitation and inversely related to temperature.

In cold arctic regions, narrow rings reflect fluctuations in summer temperature and thereby provide records of past temperature fluctuations. Mikola (1962) has found that in Finland the effect of summer temperature on the radial growth of Scots pine increases from south to north and is most accentuated at the northern timber line. In evaluating the relationship between climate and the growth of spruce in the Tatra mountains in Poland, Feliksik (1972) has shown a strong positive correlation of growth with high temperatures in the vegetation period from June to August. The correlation was negative with precipitation. The chronology constructed for *Pinus longaeva* D.K. Bailey.at the upper elevational limits for the species (LaMarche and Harlan, 1973) was statistically modelled with temperature and precipitation. Narrow rings were found to be correlated with low temperatures (LaMarche, 1974a). It was also found that periods of growth and the advance of mountain glaciers in the Northern Hemisphere showed good agreement with the periods of low temperature inferred from his model. However, rainfall has been shown to have a significant influence on the growth of Scots pine close to the timber line (Kärenlampi, 1972).

In temperate regions, the annual increments are often not as closely correlated with single climatic conditions as those in trees from the more extreme regions. However, on certain limiting sites clear climatic signals can exist (Pilcher, 1976). The complex nature of these climatic relationships in temperate zones is shown by the results of Brett (1978a).. Using an elm chronology derived from trees in London the following relationship was determined: a direct relationship between ring width and precipitation during the previous autumn and early winter, an inverse relationship to rainfall the previous summer; a direct relation with temperature during the previous autumn but an inverse relationship between ring width and temperature during March and April at the commencement of the growing season. Serre (1978) investigated the relations between the annual growth of European larch (*Larix decidua* Mill.) of the French Maritime Alps and climate. The relationship was complex; there was an inverse relationship to temperature and precipitation for the months of June and July. In addition, temperature and rain in the previous autumn and winter and in the March and May of the current years growth affected ring formation.

The expansion of dendroclimatology during the 1970's has led to recommendations of certain procedures for subsequent climatic analyses (Fritts and Shatz, 1975). These procedures assure objectivity in the selection of quality tree-ring data and allow comparisons of the statistics for new chronologies to the established data sets. Methods for the reconstruction of past climate are given in detail by Fritts (1976) and Blasing (1978). It is first necessary to establish the relationships between variations in annual tree growth and climatic variation. The model obtained is used, through transfer functions to produce estimates of climate. The reconstructions are verified by independent data outside the calibration period. The most powerful verification method is the utilisation of actual climatic data outside the calibration interval which is tested against reconstructed data for the same time interval. Only when such verification is obtained is the climatic reconstruction considered to be valid and significant (Fritts, 1976). The climate of Schleswig-Hollstein was reconstructed according to Fritts (1976) by Schmidt (1977) for times when tree-ring records were available but climatic data were not. Schweingruber _et_ _al_., (1978a) used maximum density instead of ring width to reconstruct climate at four meteorological stations in Switzerland using the method described above. Reconstructions of anomolous variations in atmospheric circulation for portions of the Northern Hemisphere back to A.D. 1700 have been made by Fritts (1971). Stockton and Fritts (1971) have presented a method for making probability statements rather than actual reconstructions, about past climatic conditions for the State of Arizona. Probability statements were made about extreme climate from A.D. 1650 to A.D. 1899 based upon the joint occurrence of the statewide average seasonal climate and ring widths during A.D. 1899 to A.D. 1957. LaMarche and Stockton (1974) were able to show a general warming trend between the periods A.D.1901 to A.D.1930 and A.D.1931 to A.D.1960 in the Western United States from a statistical comparison of ring-width variations of Bristlecone pines (*Pinus longaeva* D.K. Bailey and *Pinus aristata* Engelm.) with meteorological data. Climatic reconstructions have been used to investigate the movements of past settlements. The occurrence of droughts at Mesa Verde, Colorado as inferred from several tree-ring chronologies have been used in an attempt to explain the decline in the prehistoric populations in the area (Fritts et al., 1965c).

The width of the annual growth rings can also be affected by the defoliation of the tree. Heavy defoliation by the Douglass fir tussock moth caused growth of the host species to decrease by 75% to 90% in one year (Brubaker, 1978). Normal growth rates returned within three to four years after maximum defoliation. The effect of a moderate attack could not be reliably identified in the chronologies. Varley (1978) found that the summer increment, the latewood, of oaks (*Quercus robur* L.) near Oxford was reduced by damage to the foliage in May caused by many species of caterpillars. It was considered that variations in the latewood increment was better correlated with caterpillar numbers than with climatic factors. Varley (1978) concluded that if the effects of adverse weather and insect damage are similar then correlations between tree growth and weather factors cannot be safely used to infer past changes in the weather. This argument is refuted by Hughes et al., (1979), in reply to criticism given by Varley et al. (1979) regarding the identification and nature of climatic signals in British tree-ring chronologies (Hughes et al., 1978a). They point out that the correct selection and handling of the tree-ring and climatic data invalidates their criticism. In particular, the selection of material which conforms to a common pattern of ring-width variation ensures a pattern which could only have been produced by factors acting similarly and synchronously on all the trees selected. There is no sound evidence for such an effect being produced on British oaks by defoliators (Varley *et al.*, 1979) although studies in Europe on stand samples rather than dendrochronologically selected material have shown defoliation to have an effect on the annual growth ring of oak (Juttner, 1959; Mikhailov, 1972).

The resumé of the researches given above indicates the range of species and the direction of study that can be applied to the investigations of variations in tree growth and climate. It illustrates how dendrochronology forms the basis for the determination of these relationships in addition to providing an important source of palaeoclimatic data.

Radiocarbon Analysis

The growth rings of trees may be used to examine isotope ratios of the past which can reflect the occurrence of geophysical events. In particular, this can be assumed for the carbon isotope ratio $^{14}C/^{12}C$ which forms the basis of the radiocarbon dating method. This method was developed by Libby (1954) and is based on the principle that the radiocarbon isotope ^{14}C is produced by cosmic rays and is mixed with the inactive carbon in the atmosphere. It enters the carbon cycle in nature through its assimilation by plants or its dissolution in water. Since ^{14}C is radioactive, the tree or any other living organism compensates the decay of ^{14}C by assimilation so that an equilibrium is established. With the death of the organism the assimilation process is halted so that only the disintegration process continues. By knowing the half-life of ^{14}C and the ratio between the activity of a standard (a living sample) and that of a dead organism, the time which has elapsed since death and hence its age, may be calculated.

Radiocarbon dates so produced are more useful in correct archaeological interpretations if they are converted to calendar years to which other dating methods directly relate. An accurate and convenient methods of conversion is therefore desirable. The ^{14}C content of dendrochronologically dated wood samples provides the basis for this conversion. Since the atmosphere of the earth is well mixed and of a composition which is essentially independent of geographic location, the growth ring of a tree formed in a particular year should represent the average radiocarbon content of the atmosphere during its growth period (Cain and Suess, 1976). The method of radiocarbon dating is based on the assumption that the radiocarbon level in the atmospheric carbon dioxide has always remained constant. This assumption is not correct and it is now known that the correction for ^{14}C variation in the atmosphere is only one of several which must be applied in relating radiocarbon dating to a calendar time scale (Pearson et al., 1977).

The variations in atmospheric radiocarbon were first noticed by H. De Vries (1958) who compared dendrochronologically determined ages with the carbon -14 ages of wood samples. He found that the radiocarbon content in some of his wood samples was up to two per cent higher than that calculated from their dendrochronologically determined dates. Since the findings of De Vries (1958), the problem has been investigated further by many other workers. Bristlecone pine from North America has been a primary source of wood for the calibration of the radiocarbon time scale attempted by several workers (Damon et al., 1966; Stuiver and Suess, 1966; Ralph and Michael, 1967; Suess, 1967; Damon et al., 1974 and Cain and Suess, 1976). In Europe, Ferguson et al.(1966) and Pearson et al.(1977) have produced calibration curves for radiocarbon dates using oaks. The data resulting from these radiocarbon analyses of dendrochronologically dated wood confirm the results of De Vries (1958) in showing that radiocarbon dates do not completely agree with the conventional solar calendar. Current research is attempting to describe details of the deviations away from the theoretical relationship in assessing the validity of major short-term variations or 'wiggles.' (Suess, 1970; Damon et al., 1974 and Pearson et al., 1977). Dendrochronology has thus made possible the calibration of the radiocarbon time scale for which several curves now exist (Suess, 1970; Wendland and Donley, 1971; Damon et al., 1972; Ralph et al., 1973 and Clark, 1975).

Dendrogeomorphology

Dendrogeomorphology refers to the method by which dendrochronology can facilitate the chronological placement of geomorphological changes (Alestalo, 1971). In south central Europe, Becker (1978) has used the tree-ring analysis of subfossil oaks to provide datings of Holocene valley fillings and details of their mode of formation. These data also provide evidence for the influence of man on the hydrosystem of Central Europe. The occurence of submerged forests around the coasts of the British Isles results from the drowning of coastal woodlands by the post-glacial rise in sea-level (Heyworth, 1978). Heyworth (1978) has shown that from the ring-width patterns of these remnants in a particular locality at different elevations, the rate at which the sea-level rose can be determined. The tree-ring analyses of trees from submerged forests at different localities have enabled the calculation and comparison of the relative vertical increments of the land at these sites (Heyworth, 1978). Litton, Salisbury and Whitley (unpublished data) have measured the ring widths of oak trunks found during the excavations of gravel pits in Nottinghamshire from which two tree-ring chronologies have been established. It is hoped that these analyses will contribute to the understanding of the dynamics of the River Trent in the past.

Ecology and environmental problems

Dendrochronology may be used as a tool for studying past and present environments and for assessing the effects and magnitude of man-induced changes. Fritts et al.(1965a) have examined the tree-ring characteristics of two species of pine and one of fir along a vegetation gradient in northern Arizona. The forest vegetation represented four major forest types from high elevation moist forests grading to lower elevation arid forests. At the lower forest border the tree-rings were narrowest, the variation in ring width from one year to the next was highest and the variance that was common both within and between trees was greatest. At the semi-arid forest border there was a high incidence of partial rings (rings which are discontinuous around the stem), a feature undesirable for successful crossdating. At the more mesic forest interior where arboreal dominance is high, there was little year-to-year variation in ring width and correlations within and between trees was poor. It was concluded that the lower forest border provided the best record of climatic fluctuations. These results show that tree-ring characteristics can be used as a basis for evaluating the growth response of a species to its environment and the ecological differences between sites. Bartholin (1978) has used the difference in growth rates of trees dating from different periods to reconstruct past landscapes in South Sweden.

The potential of tree-ring analysis for monitoring heavy metal pollution patterns has been examined by several workers (Rolfe, 1974; Lepp, 1975; Kardell and Larsson, 1978 and Tan, 1979). Hall et al. (1975) have found that the wood of oak and ash from polluted and unpolluted sites contained slightly higher levels of lead at the polluted site. Vinš and Tesař (1969) and Ashby and Fritts (1972) have shown that the size of tree-rings may be reduced in trees growing near industrial sources of air pollution.

X-ray densitometry

In addition to the widening range of fields to which dendrochronology can be applied, an understanding of the properties of the annual ring itself is also increasing. The width of the annual ring is only one of its properties which reflects changes in the environment of the tree. The density of the annual increment is another and is one which is receiving much attention. Accounts of the principle of x-ray densitometry of wood have been given by Polge (1965), Fletcher and Hughes (1970) and Hughes and Sardinha (1975). One technique involves the exposure of a wood sample and film to low-energy x-radiation. The denser latewood absorbs more radiation than the earlywood so that a negative is produced in which film density is proportional to wood density. The negative is scanned by a densitometer so that a density plot is produced that clearly defines each annual ring. Thus, the year-to-year variation in the annual increment may be assessed in terms of density instead of ring width. Several workers are convinced that the maximum annual density is a better parameter than ring width for chronological and dendroclimatological investigations (Polge, 1978; Schweingruber et al., 1978b). The superiority is a consequence of its high sensitivity to climatic factors but density is also very sensitive to other sources of variation: genotype, soil and position within the stem (Polge, 1978). The use of maximum latewood density also improves the potential for dating specimens that previously have been considered too complacent for dating. Parker and Henoch (1971) found that Englemann Spruce (*Picea engelmannii* Parry) at Peyto Lake, Alberta, contained complacent ring-width records but maximum latewood density chronologies that were sensitive. Schweingruber et al. (1978a) have obtained excellent climatic reconstructions using x-ray density measurements. They have demonstrated the value of density data with traditional ring-width data especially in mesic and high altitude sites. The information given by density can, therefore, be used with that given by ring widths to make the dating of wood and the reconstruction of past climates easier and more reliable.

Densitometric studies on oak from North Wales have been carried out by Milsom (1979) which included the examination of the density of ring-width series from different heights above the ground. Techniques for sample preparation and standardisation were also developed.

1.3 The value of oak for tree-ring research

Many species of both coniferous and broad-leaved trees have been used for dendrochronological research throughout the world. In Europe, these two groups assume different levels of importance to dendrochronology in different regions of the continent. In northern and eastern Europe and in the Alpine region research has been largely based on coniferous species whilst in central and western Europe broadleaved species have a greater application. In the British Isles broadleaved trees assume a greater importance although an intensive programme of research using pine is currently underway (Cartwright, pers. comm.) Whilst ash, alder and hazel have a limited use they have proved useful in examining past techniques in woodland management (Morgan et al., 1978). Elm has been used with success in the south of England (Brett, 1978a and Brett, 1978b). By far the most suitable material for tree-ring research in the British Isles is the broadleaved tree, oak (*Quercus*).

Distribution

Since Boreal times, oak woods have been the most common type of natural and semi-natural deciduous woodland in the British Isles (Tansley, 1968). There are two native British species of oak; sessile oak (*Quercus petraea* (Mattuschka) Liebl.) and pedunculate or common oak (*Quercus robur*.L.). The name of the former derives from the state of its acorn cups which are considered sessile, i.e. they sit directly on the stem. Pedunculate oak by constrast has acorn cups with longstalks. In natural populations the two species hybridise so that many oak trees show a mixture of the characters normally used to distinguish the two species. The occurrence of more than 5% of such hybrids in populations is usually considered unusual (Jones, 1960).

Quercus petraea and *Quercus robur* occur throughout lowland Europe from the western seaboard of Britain and France to the Urals (Jones, 1960). They have a generally similar distribution with the northern limits of *Q.robur* extending further than *Q.petraea*. *Q.robur* grows in northern Scotland in the region of Kildonan, to 63^{O}N in western Norway, 61^{O}N in eastern Norway and southern Sweden, to southern Finland, and extends to Orsk in the Urals where it reaches its eastern limit. *Q.petraea* does not extend far into Russia extending from Poland through Moldavia to Rumania and Bulgaria. The southern limits of both species are uncertain due to confusion with allied species. *Q.robur* occurs in the Mediterranean basin and in coastal regions of northern Portugal and in Italy and parts of the Adriatic coast. *Q.petraea* in general does not extend so far south as *Q.robur* and is more montane; along the Atlantic coast it extends to northern Portugal and is practically absent from Gascony and the western Pyrenees and much of the coast of western Spain and Portugal.

In the British Isles, *Q.robur* is the regular woodland tree of midland, south-eastern and most of southern England and is much commoner than *Q.petraea* in much of eastern Scotland and in Ross and Sutherland. *Q.robur* is the usual standard in the coppice-with-standard woods of the lowlands and is relatively rare in high forest. *Q.petraea* is the major and sometimes only species throughout most of Ireland, Wales, Devon and Cornwall and the west of Scotland. In the hill and mountain regions of the Pennines and Lake District practically all the woods are composed of *Q.petraea* (Tansley, 1968). However, on the plains and valley bottoms in the west and north where the rocks are more easily weathered and the soil is deeper, *Q.robur* is the characteristic tree. *Q.petraea* frequently forms high forest. It is apparent from these distributions that oak in the north west of England is existing towards the limits of its distribution. Any species which grows near its ecological limits is more likely to reflect any change in environmental factors than one which is within its range of optimum. This optimum is not always in the centre of the area in which a species occurs (Cox et al., 1973). On the basis of this argument, oak in the British Isles offers great potential for examining the effects of climate on tree growth.

Longevity

One of the characteristics of oak which makes it attractive to tree-ring research is its relative longevity. In Northern Ireland Baillie (1973b) has found that most trees attain ages between 100 and 250 years. Simpson (unpublished data) has sampled trees in the East Midlands with 130 to 343 growth rings. Baillie (1977c) has found trees in south west Scotland greater than 300 years old. However, ages in excess of these figures have been found, for example in Switzerland a torso of *Quercus robur* was found to be at least 930 years old (Schadelin, 1905) and in Sherwood Forest one large slow growing tree was found to be at least 515 years old (Simpson, unpublished data).

The discovery of many sub-fossil trees has given an indication of the ages reached by trees growing in prehistoric times, trees removed from bogs in Northern Ireland exceeded 400 years in age (Pilcher et al., 1977). Although the variability in the ages reached by oak is attributable in part to differences in site conditions, the longevity of oak is clearly exemplified.

The annual growth ring and its formation

The part of the tree which is basic to dendrochronology is the annual growth layer. The growth layers are secondary xylem which is formed by the activity of the vascular cambium which constitutes a meristematic sheath around stems, roots and branches. The arrangement of the cell types of the secondary xylem, as seen in transverse section, is shown in Plate 1.2. The large thin-walled vessels of the earlywood are arranged in one or two rows. They have an average tangential diameter of 268µ (Jane, 1970). The latewood contains thick-walled latewood fibres, fibre tracheids and small latewood vessels with thin walls. Of the three cell types, the fibres occur most frequently. The vessels in the latewood occupy a smaller proportion of the total volume than those in the earlywood and have a smaller average tangential diameter, 34µ (Jane, 1970). The vessels tend to run in V or Y shaped bands or 'flames' which become wider towards the end of the growing season. These bands alternate with radial bands of fibres and fibre tracheids. Bands of one or two rows of apotracheal parenchyma run tangentially across the bands of latewood tissue. The earlywood and latewood together constitute the annual growth ring. Early in the growing season, immediately after the completion of the earlywood a dense layer of fibre is laid down. This area is the most dense part of the annual ring (Milsom, 1979). The radial wood rays consist of parenchyma cells and in oak the rays are present in two sizes. The smaller rays are uniseriate and numerous; the larger rays are multiseriate and conspicuous ranging from approximately 0.3 to 0.7 mm in width. The large rays appear as broad horizontal sheets on the radial race forming the 'silver grain' of oak. On the tangential surface they appear as dark vertical lines as much as 4cm in length (Jane, 1970).

Plate 1.2 The arrangement of cell types of the secondary xylem in oak, as seen in transverse section.

Key: er - earlywood

f - 'flame' or band of latewood vessels

ar - annual ring

ap - apotracheal parenchyma

ft - fibres and fibre tracheids

mwr - multiseriate wood ray

The arrow indicates a uniseriate wood ray.

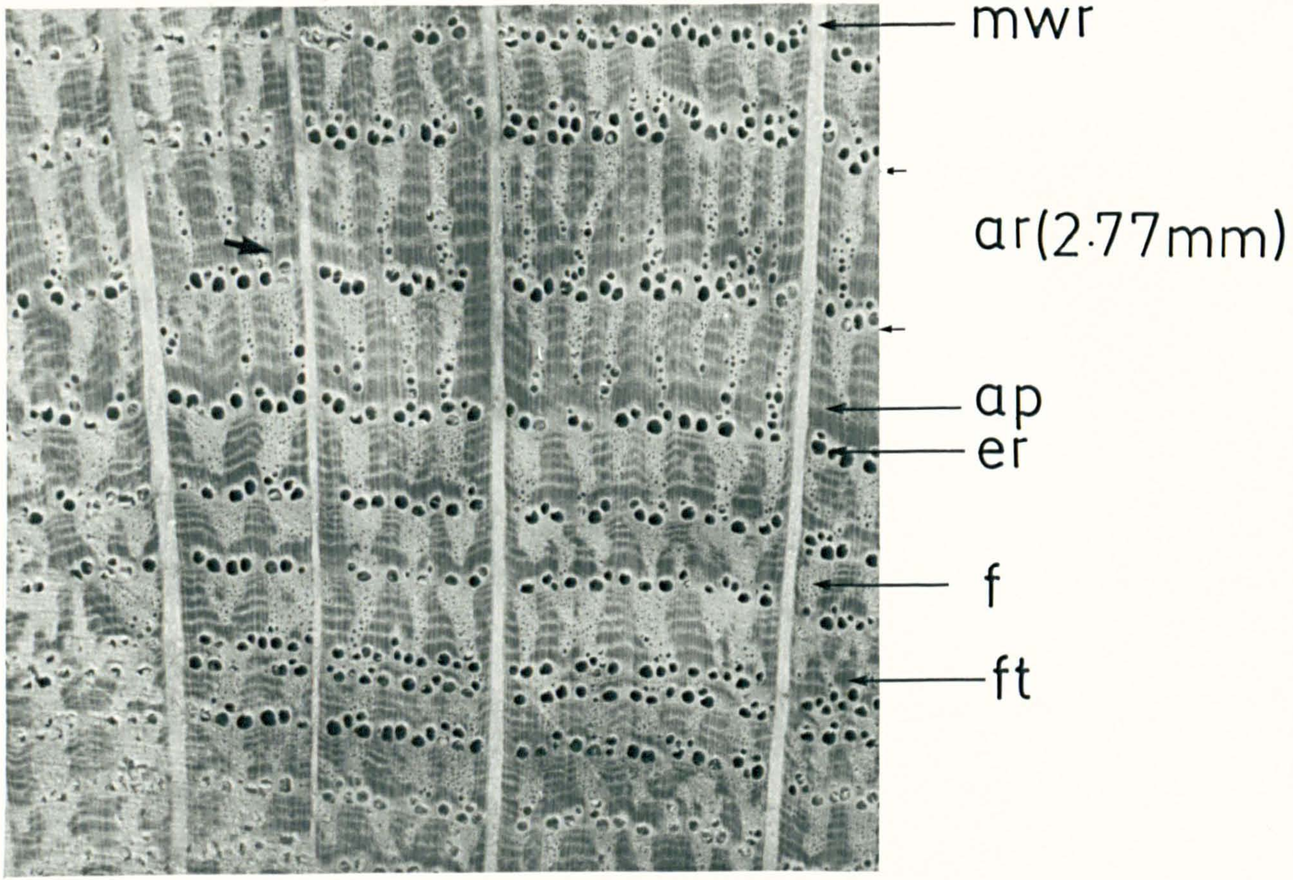
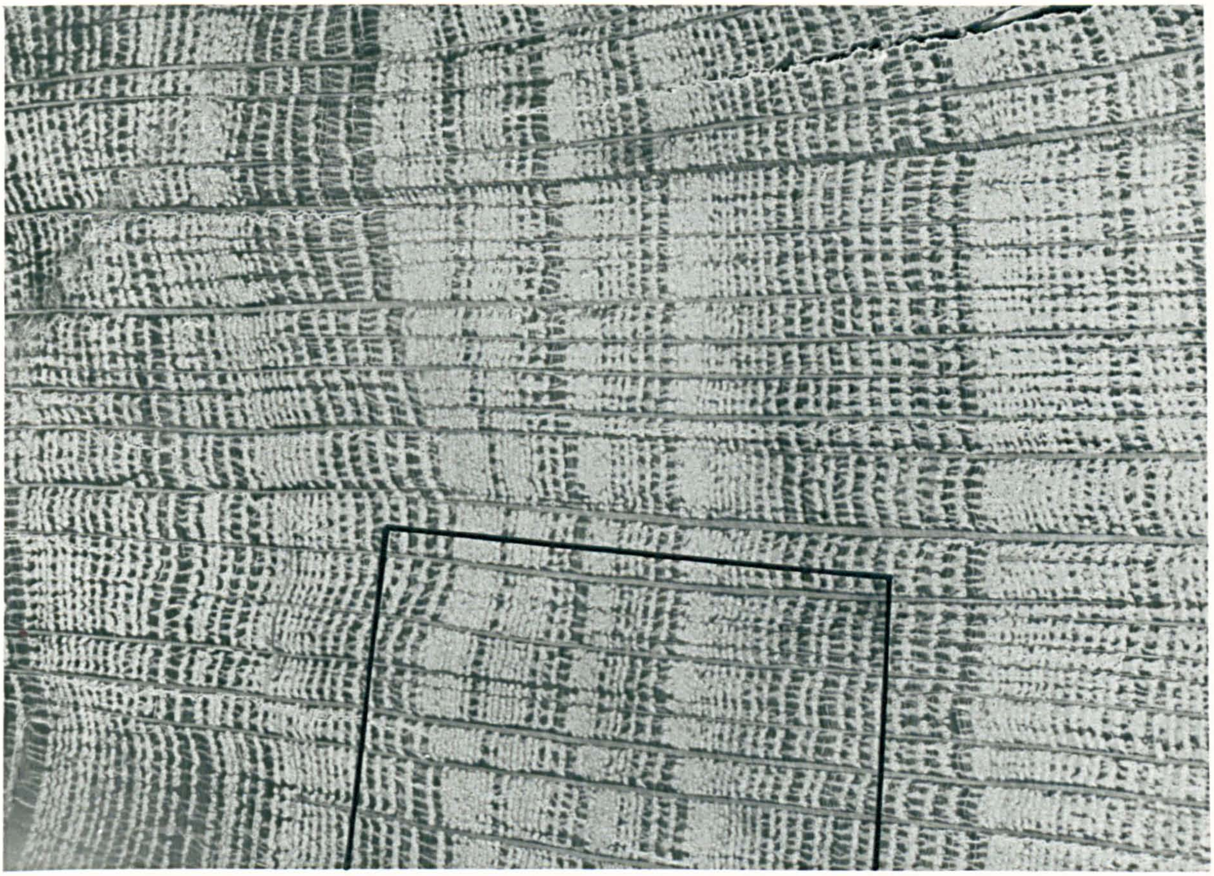

mwr
ar(2·77mm)
ap
er
f
ft

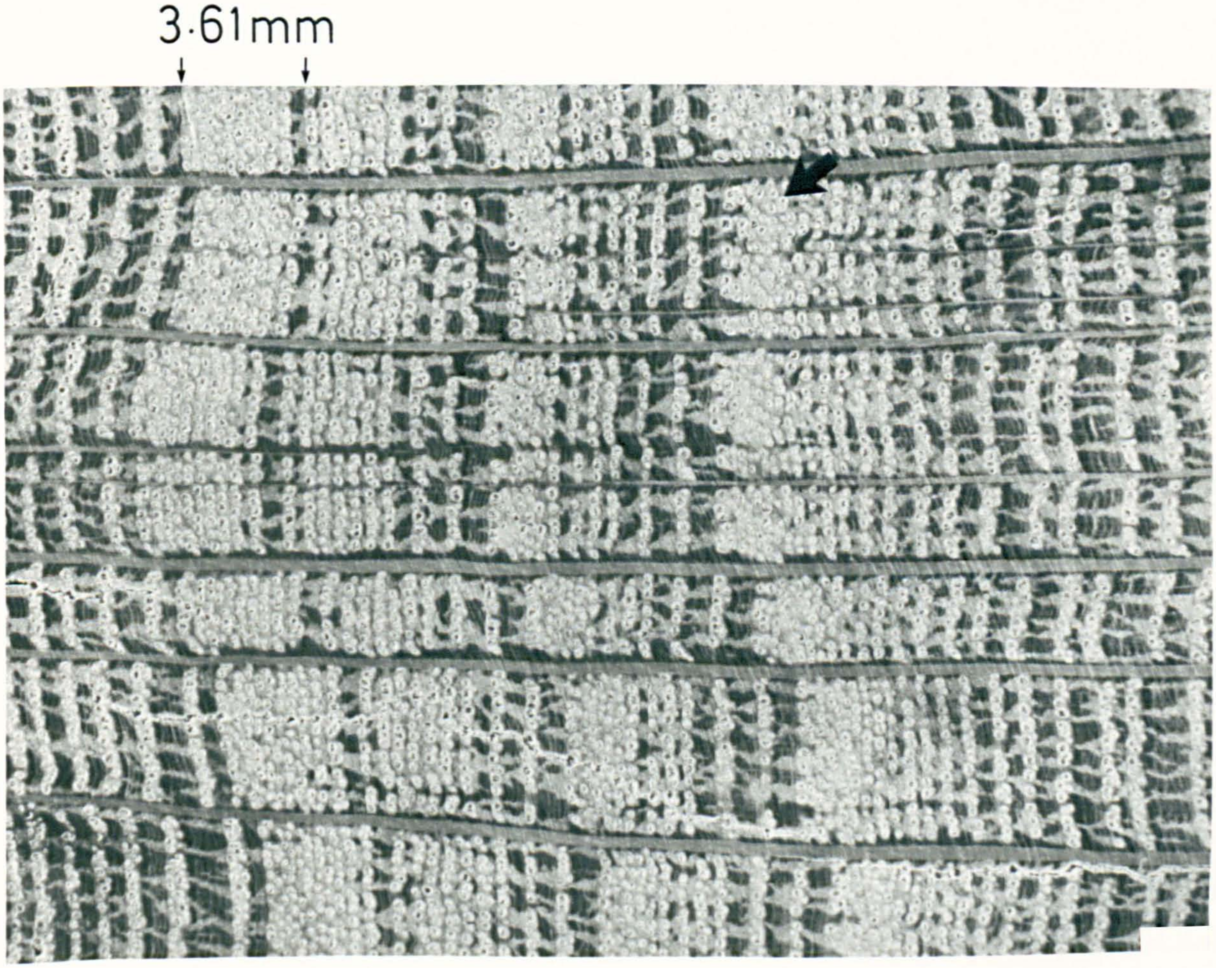
Plate 1.2 clearly illustrates the abrupt change in cell size from the earlywood to the latewood. It can also be seen that a continuous ring is formed by the vessels of the earlywood. When these features are present the wood is termed ring-porous (Desch, 1962). It is the ring-porous nature of oak which it shares with ash and elm and the presence of wood rays of two sizes that makes the wood of oak in cross-section, distinguishable from other trees. Its ring-porous nature is also one of the reasons for the reliable recording of the annual increments.

Although the ring-porous nature of oak facilitates the clear demarcation of the annual growth ring, in some rings the boundaries cannot be positively identified. This usually arises when the formation of the latewood has been reduced to such an extent that it appears non-existent. Consequently, the earlywood of the year of reduced growth and that of the following year appear as one layer of earlywood consisting of two rows of cells. Such rings present problems in measuring the ring-widths; these two rings could be read as one instead of two and so produce a significant error in the tree-ring record. The error can be identified from a comparison with the tree-ring pattern from another radius or with a mean curve for the site since a lack in synchroneity will occur between the curves from the point of error. The problem is made more acute when several narrow rings occur in groups and at numerous points along the ring-width record. Plate 1.3a shows the occurrence of bands of narrow rings in a sample taken from a construction timber. In extreme cases, the distinct ring formed by the earlywood vessels becomes broken up so that the boundary of each year cannot be identified positively. This apparent mixing of earlywood vessels is shown in Plate 1.3b.

Plate 1.3a Bands of narrow rings occurring between years of faster growth

Plate 1.3b In some cases the cells of the earlywood layers become misplaced so that the earlywood layers of different years become intermixed (indicated by arrow).




3·61mm

Any programme of research which examines the growth of trees and variations in growth that are determined by extrinsic factors such as climate must be based on a sound understanding of growth initiated by internal processes. With few exceptions, the major part of the bulk of a mature woody plant is a product of the cambium. In oak and other temperate trees cambial activity is not constant throughout the year since it passes through a period of dormancy from about September through to spring of the following year. The vascular cambium is then reactivated by a stimulus from the unopened buds (Wareing, 1951; Reinders-Gouwentak, 1965 and Zimmermann and Brown, 1971) which is generally accepted to be auxin produced by the dormant buds (Romberger, 1963). This activity initiates the formation of the large vessels of the earlywood to the inside of the cambium, a process associated with the leaf expansion phase of shoot growth (Larson, 1969). At the same time, the cells of the phloem are produced to the outside of the cambium. Since this phase of differentiation occurs before there is any great establishment of the photosynthetic leaf area, most of the energy and raw materials for the formation of the earlywood must come from food stores laid down in the previous year (Varley and Gradwell, 1962). The earlywood vessels are thin walled and are responsible for the upward translocation of water from the roots to the aerial parts of the tree as growth recommences.

In the latter part of June there is an abrupt change to latewood formation with much smaller vessels and thick-walled fibres (Priestly and Scott, 1936; Ladefoged, 1952). This change coincides with the cessation of shoot elongation (Larson, 1969). The change starts in the twigs before reaching the main stem and is delayed in shoots with multiple flushes, so that false rings are not normally formed

(Wight, 1930; Studhalter et al., 1963). The variation in the width of the latewood is dependent on the photosynthetic food supplies available to the tree which in turn are dependent on the foliage canopy, temperature, water supply and the amount of sunlight available for conversion into food.

The time at which cambial activity and hence wood production ceases, varies by a month from season to season (Fraser, 1962) but it is typically long before leaf senescence (Daubenmire and Deters, 1947; Jackson, 1952) and later than the cessation of leaf initiation (Denne, 1976). The causes of cambial dormancy are obscure although it has been found that dormancy can be induced photoperiodically (Wareing, 1956). However, it is considered not to be regulated solely by day length since the onset of dormancy can vary with light intensity within the tree (Denne, 1974). Whatever the regulating factors involved,by September the vascular cambium is dormant (Denne, 1976) and the season's wood production is complete. The tree is then dormant during the winter period until activity is once more induced the following spring by temperature induced hormonal activity.

Double and missing rings

The lack of false or missing rings is another advantage of oak for dendrochronological studies. This feature contrasts with that of species used by other workers in America where Douglas fir, a tree widely used in dendrochronological studies,has a high incidence of locally absent rings. False rings caused by a change in cell structure within the annual ring which resembles the boundary of the true annual ring is a common feature of another widely used tree, ponderosa pine. However, a number of workers have found isolated examples of irregularities in the ring pattern of oak. Huber and

Giertz (1970) observed what appeared to be a double ring in a stake from the neolithic settlement of Auvernier in Switzerland. On enlargement, however, it could be easily identified as being an abnormal ring and was thoughtto have been caused by insect attack. Baillie (1973b) identified a ring in which enlarged latewood vessels gave the appearance of double growth. Barefoot *et al.*(1974) observed a ring in which one short space essentially contained no latewood to separate the two layers of earlywood vessels. The ring was, therefore, discontinuous only in the latewood.

The use of Oak

Another advantage of oak lies in the fact that it has been used extensively in ancient artefacts. Such usage is hardly surprising since oakwoods have been the most common type of natural woodland for many centuries. In Northern Ireland, oak stakes were uncovered during the excavation of Cullyhanna Hunting Lodge (Hodges, 1958) and found to be of Bronze Age origin (Hillam, 1976). In London, a series of excavations exposed Roman and Medieval waterfronts, all of which were constructed using oak timbers (Tatton-Brown, 1974; Schofield, 1975; Schofield and Miller, 1976 and Morgan, 1977a). Oak has also been an important timber in the construction of boats as, for example, in the Saxon Graveney boat (Evans and Fenwick, 1971) and the saxon Sutton Hoo ship burial (Godwin, 1940). Barefoot (1975) studied a number of oak planks from H.M.S. Victory, the insertion of which could be dated to the early nineteenth century. The use of oak as supports for paintings provides a means of dating panel paintings from several periods. The tree-ring analysis of unsigned paintings by Wouwerman enabled a creation date to be assigned to each of them (Bauch and Eckstein, 1970).

The extensive use of oak in the past provides material for the study of the growth patterns of trees which were growing many centuries ago. This feature is fundamental to the present study for the construction of a long regional chronology. The many characteristics of oak discussed: its relative ubiquity and longevity, the rareness of missing and double rings and its extensive use in ancient artefacts make it an ideal material for use in tree-ring studies throughout the British Isles.

1.4 Tree-ring research in the British Isles

The development of dendrochronology has been far slower in the British Isles than in other countries in Europe and in south western America. Although some of the pioneers of the science were Europeans (Švedov, 1892; Kapteyn, 1914) the major advances in Europe were made from 1938 onwards by Huber and his associates in southern Germany (Huber, 1941; Huber and Giertz-Siebenlist, 1969; Huber and Giertz, 1970 and Berger et al., 1971). Since the evolution of dendrochronology in Europe a great deal of research has been carried out for which a number of surveys have been given (Høeg, 1956; Mikola, 1956; Huber et al., 1961; Kolchin, 1965 and Eckstein, 1972).

The application of dendrochronology in the British Isles is indicated by Godwin (1940) from measurements of the ring widths of timber from the Sutton Hoo ship burial. He concluded that the conditions in which trees grow in the British Isles were unfavourable to successful dendrochronological studies. Nevertheless, Lowther (1951) was able to crossdate the ring-width patterns of timbers from the Chilcomb church and from the wreck of the River Hamble. Apart from the efforts of Schove and Lowther (1957) tree-ring research was negligible and it was not until the late 1960's that any systematic research in dendrochronology was undertaken. These studies were largely directed towards constructing chronologies to enable the absolute dating of timber-framed structures and artefacts. Baillie (1973a) constructed a tree-ring chronology from A.D. 1970 back to A.D. 1380 for the dating of Irish medieval and post-medieval timbers, a chronology which has recently been extended back to A.D. 1001 (Baillie, 1977a). An oak chronology from A.D. 1975 back to A.D. 946 has been constructed for South West Scotland (Baillie, 1977c).

Barefoot et al. (1974) produced a chronology for the Winchester area for local dating purposes. An oak chronology constructed for timbers from Wales and the West Midlands (Siebenlist-Kerner, 1978) has been used to date other oak structures (Morgan, 1977b; Laxton et al., 1979). An oak chronology, at present discontinuous, has been constructed for the city of Dublin for A.D. 885 to A.D. 1306 and A.D.1357 to A.D. 1556 (Baillie, 1977b). Fletcher (1977) has produced a number of chronologies all for dating purposes. However, four of them (Refs. 1 to 4) have shown little agreement with other British chronologies possibly since they contain ring-width data from panel paintings and may have a continental origin. Ref. 6 (Fletcher,1977) covers the period A.D. 780 to A.D. 1193 and matches well with other British chronologies of the same period (Baillie, 1978).

The result of this activity is that chronologies now exist for several parts of the British Isles but only two of them, Belfast (Baillie, 1977a) and South West Scotland (Baillie, 1977c) are continuous for longer than 300 years. The remainder are isolated chronologies for discrete periods which are determined by the overall span of years on the timbers under investigation. As far as the north west of England is concerned no chronologies in any form have been published.

Of the other applications for dendrochronology only limited research has been carried out. Its value for the calibration of the radiocarbon time scale is being exploited by one laboratory, Queens University, Belfast, where part of their 2,990 year floating subfossil tree-ring chronology is being utilised (Pearson et al., 1977). In addition to dating, one of the major applications of dendrochronology is in the understanding of the growth response of trees to variations in climate. In areas where tree growth is controlled by an easily identified limiting climatic factor, for example in semi-arid areas or near altitudinal or polar tree lines, the relationship is a clear and simple one (Fritts et al, 1971). In the British Isles, research in this field is minimal because it has been debatable whether the tree-ring chronologies of the British Isles, where the climate is temperate, would contain a definite climatic signal. Also, very few well replicated chronologies have been available for such investigations. Examination of variations in tree growth and climate have been made for oak by Pilcher (1976), Hughes et al. (1978a) and Hughes et al. (1978b) and for elm by Brett (1978a, 1978b). Reconstruction of climate using oak tree-ring chronologies has been attempted by few workers. Pilcher and Baillie (unpub.data) have presented a climate calibration for tree-rings of the historic period using a series of modern oak tree-ring chronologies. In preference to the transfer function methods of Fritts (1976) the authors chose to work with the recorded extremes of certain climatic variables for a relatively small number of years. Milsom (1979) has used ring-width and density series in multiple correlations to predict eigenvectors of temperature, precipitation and climate (temperature and precipitation) and actual values for mean summer temperature and precipitation.

The climatically complex nature of the British Isles was recognised by Berger et al. (1971) who examined the tree-ring patterns of oak timbers from several English buildings. These investigations were made to determine whether there was any internal homogeneity in England and any synchroneity between English and continental curves. They concluded that "England, ..., will require a massive onslaught from many different regional centres of study...."

The state of dendrochronology and dendroclimatology in the British Isles has prompted further study. The objectives of the present investigations are as follows:-

1. It is intended to establish a continuous absolutely dated well-replicated tree-ring chronology for the north west of England which will facilitate, primarily, the dating of oak structures from the area. The chronology will provide additional data for determining the applicability of tree-ring chronologies to areas other than those from which they originate. It will also provide the basis for the long independent localised chronology in England considered so necessary for a greater understanding of patterns of tree growth throughout the British Isles (Baillie, unpublished data).

2. It is intended to provide tree-ring data from modern trees which have been processed in such a way that a clear climatic signal, if one exists, may be detected. It is proposed to establish tree-ring chronologies for two sites which have different climatic regimes; maritime and rainshadow, and to examine the differences in the growth response of these trees to the same climatic variables. It has been shown that there are problems associated with the reconstruction of the climatic signal from the relationship between variations in tree growth and climate from individual sites (Gray, unpublished data). The tree-ring chronologies from maritime and rainshadow sites will form part of a network of regional chronologies to be used in a future multisite climatic analysis of the British Isles.

PART I - MODERN TIMBERS

CHAPTER 2 - MATERIALS AND METHODS

2.1 Description of sites

2.1.1 Maentwrog

The woodland selected to represent a maritime site was at Coedydd Maentwrog (Lat. 52°56'N; Long. 3°55'W) in the county of Gwynedd, North Wales (Figures 2.1 and 2.2). It is one of a number of western oakwoods (Steele, 1974) still in existence in North Wales. The woodland occupies an area of 62 hectares with heights ranging from 15 to 150 metres O.D. Flowing through the woodland are three small streams. Coedydd Maentwrog is in a region of equable moist climate where rainfall is well distributed throughout the year, the average of which is 1,750 mm. Extremes of temperature are rare, the average being 10.5°C and atmospheric humidity is high.

The average daily duration of bright sunshine is thought to be about 4 hours and the annual average percentage of the possible sunshine is about 30% (Coedydd Maentwrog Management Plan, 1967).

The Ffestiniog valley in which the woodland lies is well known for a steep rainfall gradient of from 1,000 mm per annum at the mouth of the estuary to around 2,000 mm per annum 12 to 15 km up the valley.

The average wind speed at 9.60 m in the open is about 25 km/h and the approximate average annual number of gales is 10.

Coedydd Maentwrog lies upon Cambrian sediments. The strike of the strata runs east north-east to west south-west, following the trend of the Vale of Ffestiniog. Information regarding the soils of the woodland are drawn from Halliday (1965) and

Figure 2.1 The location of the woodlands at Maentwrog and Peckforton described in the text

LOCATION OF MODERN SITES

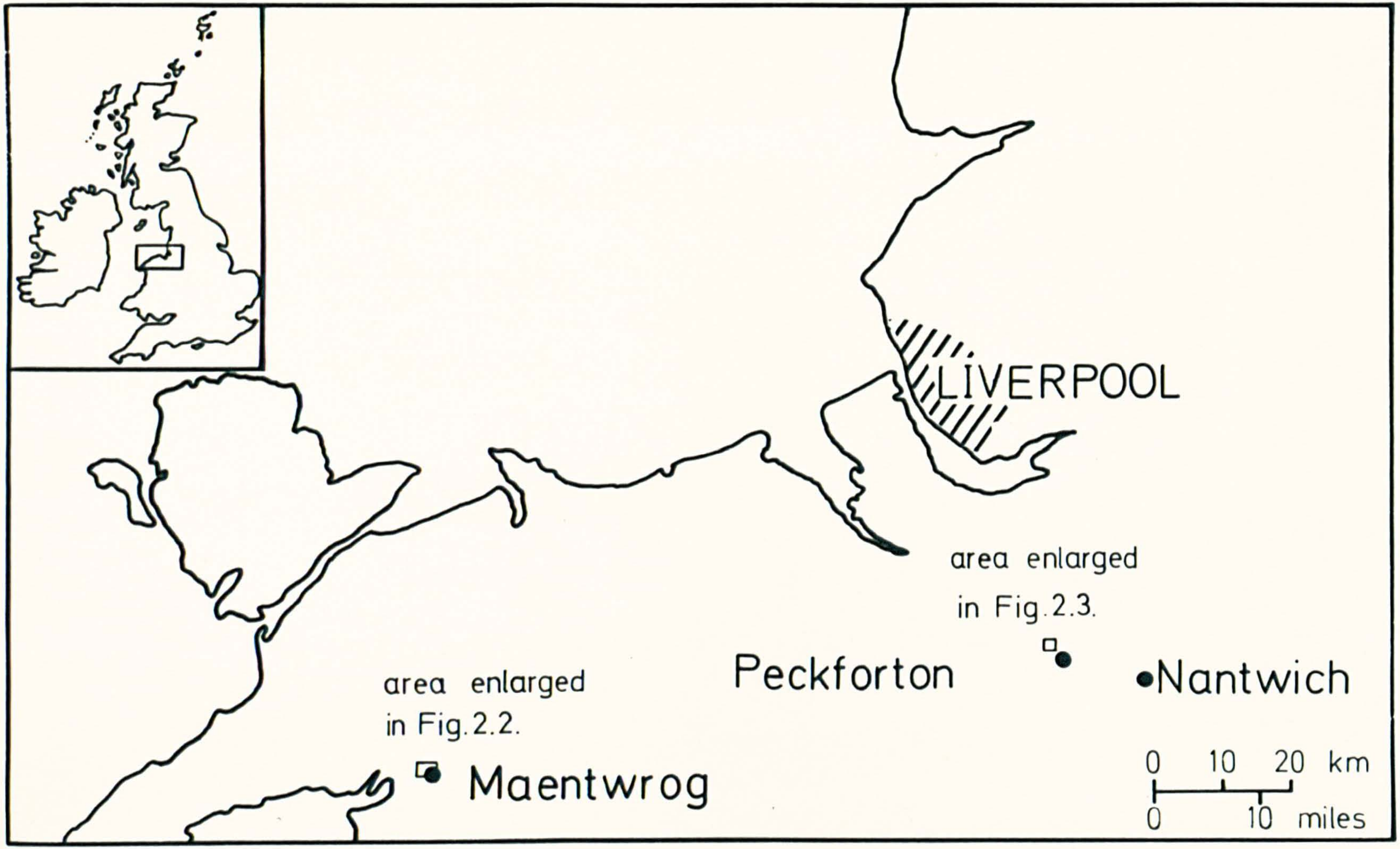
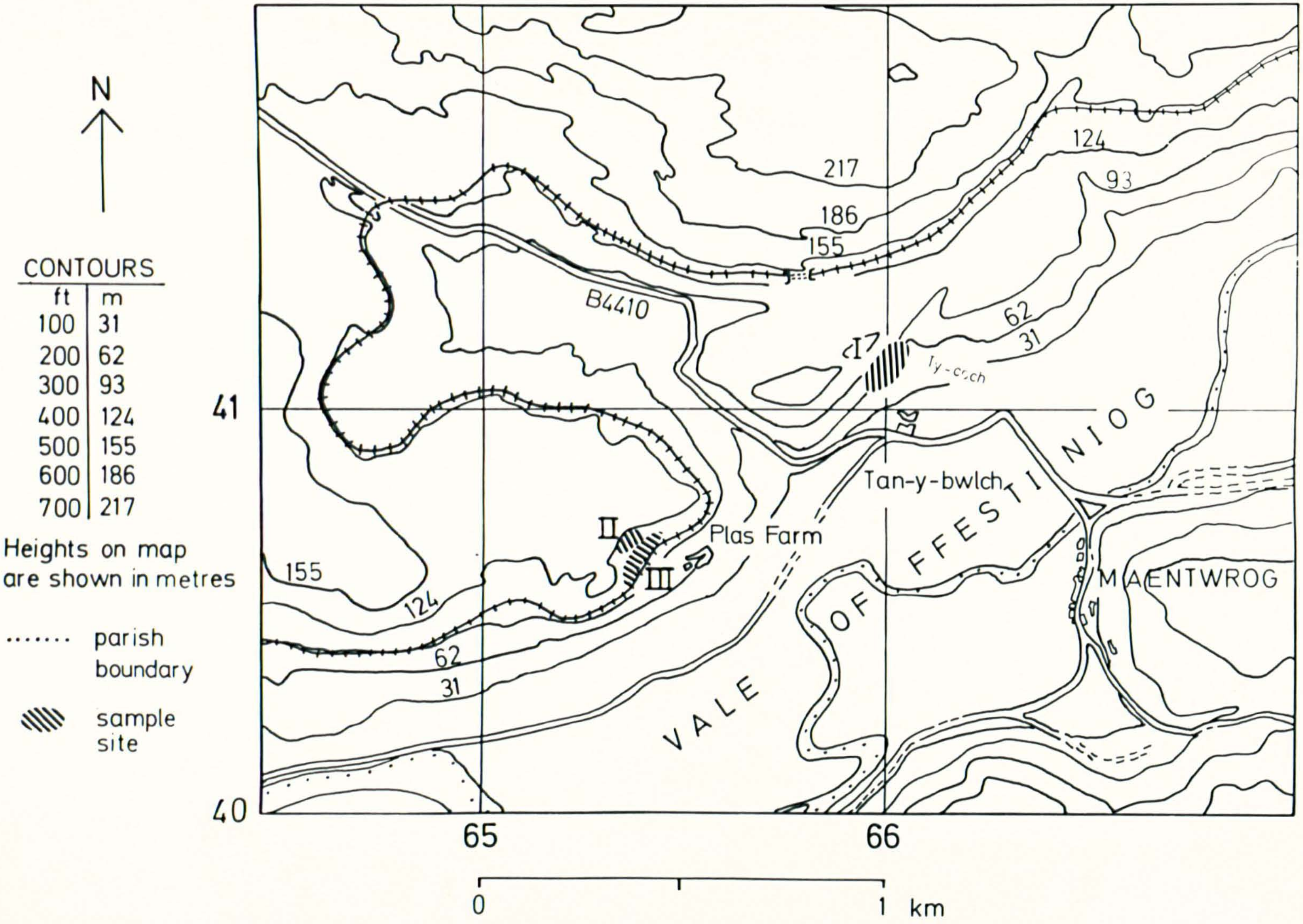


Figure 2.2 Location of sampling sites (I, II and III) at Maentwrog, North Wales.

LOCATION OF SAMPLING SITES AT MAENTWROG



visits by D.F. Ball. The typical soil parent material over much of the woodland is a head deposit derived from frost-shattered shale. Head is a product of frost-shattering under periglacial conditions and consists of angular stones in a loamy matrix. Where such a matrix is absent or insignificant in quantity, the deposit is termed scree and may be seen in a small part of Site I (Plate 2.1).

The dominant soil profile formed over the head is a weakly developed Brown Podzolic soil. A surface horizon of 5-10 cm of organic loam overlies a stony loam to silty loam, reddish brown in colour passing into the very stony parent material. Plate 2.2 shows a soil profile at Site II, Coed Bryn Mawr which is representative of the whole woodland. The pH of the surface horizon is 4.6 while that of the subsurface horizons is 4.3

Two areas within the woodland were studied, the locations of which are shown in Figure 2.2. Site I lies towards the eastern portion of the reserve and is almost bisected in a north-south direction by the boundary of Compartments 1 and 2 designated in the Nature Conservancy Council Management plan for the woodland. To the western side of this boundary is Compartment 1 which is largely covered by relatively dense oakwood, the species of oak being *Quercus petraea* (Mattuschka) Liebl. The Rhododendron shrub layer is dense in the western portion of this compartment excluding all other species from the lower layers. A series of ridges and terraces is present on the upper slopes with oak being denser on the ridges. The ground then slopes fairly evenly down to the southern boundary. Bracken and

Coedydd Maentwrog

Plate 2.1 Scree is present in areas within Site I. View to the north-west.

Plate 2.2 Soil profile at Site II, which is representative of the whole woodland. The dominant soil profile formed over the head deposit derived from frost-shattered shale is a weakly developed Brown Podzolic soil. Further descriptions are given in the text.


1m

Rhododendron dominate the ground flora where the oak is less dense but elsewhere *Anthoxanthum odoratum* and *Deschampsia flexuosa* dominate the ground flora. The dominant mosses are *Polytrichum formosum*, *Dicranum scoparium* and *Leucobryum glaucum*. *Oxalis acetosella* and *Digitalis purpurea* occur occasionally. Ash, Sycamore and Alder occur with oak along the stream which divides Compartments 1 and 2. Plates 2.3 and 2.4 show the nature of the woodland in Compartment 1. Several of the samples taken from stumps are shown in Plate 2.5.

Compartment 2 is less steep than Compartment 1 and the tree cover is less dense. Oak occurs mainly along the steeper slopes and on the rock outcrops (Plates 2.1, 2.6, 2.7). Where the tree cover is sufficiently dense to exclude Bracken the ground flora consists of a mixture of grasses; *Deschampsia flexuosa*, *Anthoxanthum odoratum*, *Agrostis tenuis* and *Poa* sp. A dense Bryophyte carpet is absent in this Compartment and although the species of mosses present are the same as those in Compartment 1, they are short, sparse and dry. The herb, *Endymion non-scripta* occurs within the *Pteridium*-dominated areas where this is less dense.

Site II occupies an area in the eastern part of the Reserve within the woodland Coed Bryn Mawr. The dominant tree species is sessile oak, *Quercus petraea* (Mattuschka) Liebl. with *Betula pubescens* and *Salix caprea* saplings occurring frequently. The shrub layer is dominated by a relatively dense layer of Rhododendron. The ground flora is largely dominated by *Pteridium aquilinum*, *Anthoxanthum odoratum*, *Chamaenerion*

Coedydd Maentwrog

Plate 2.3 The woodland in Compartment 1, Site I, viewing to the south-east.

Plate 2.4 The woodland in Compartment I, Site I, viewing to the north-west.

Coedydd Maentwrog

Plate 2.5 The trees sampled from stumps in Compartment 1, Site I. Viewing to the north-east.

Plate 2.6 The woodland in Compartment 2, Site I, viewing to the north-east.

Coedydd Maentwrog

Plate 2.7 The woodland in Compartment 2, Site I, viewing to the south-east.

Plate 2.8 The woodland at Site II, viewing to the north-east.

angustifolium and *Rubus* sp. *Geranium robertianum*, *Rumex acetosella* and *Uritica dioica* occur occasionally. Some parts of this site support dense Bryophyte carpets, the most important components being *Rhytidiadelphus* sp., *Dicranum* sp. and *Polytrichum* sp. *Brium* sp. was also common. Plate 2.8 shows part of Site II
Throughout the two sites studied, there was present a varied epiphyte flora which was associated with the high atmospheric humidity and clean air characteristic of the site.

The oak trees from which samples were taken at Site I and Site II grew on slopes facing south south-east. At Site I the trees grew at heights between approximately 50 and 100 metres O.D. and at Site II between 100 and 140 metres O.D. These sites were approximately 650 metres apart.

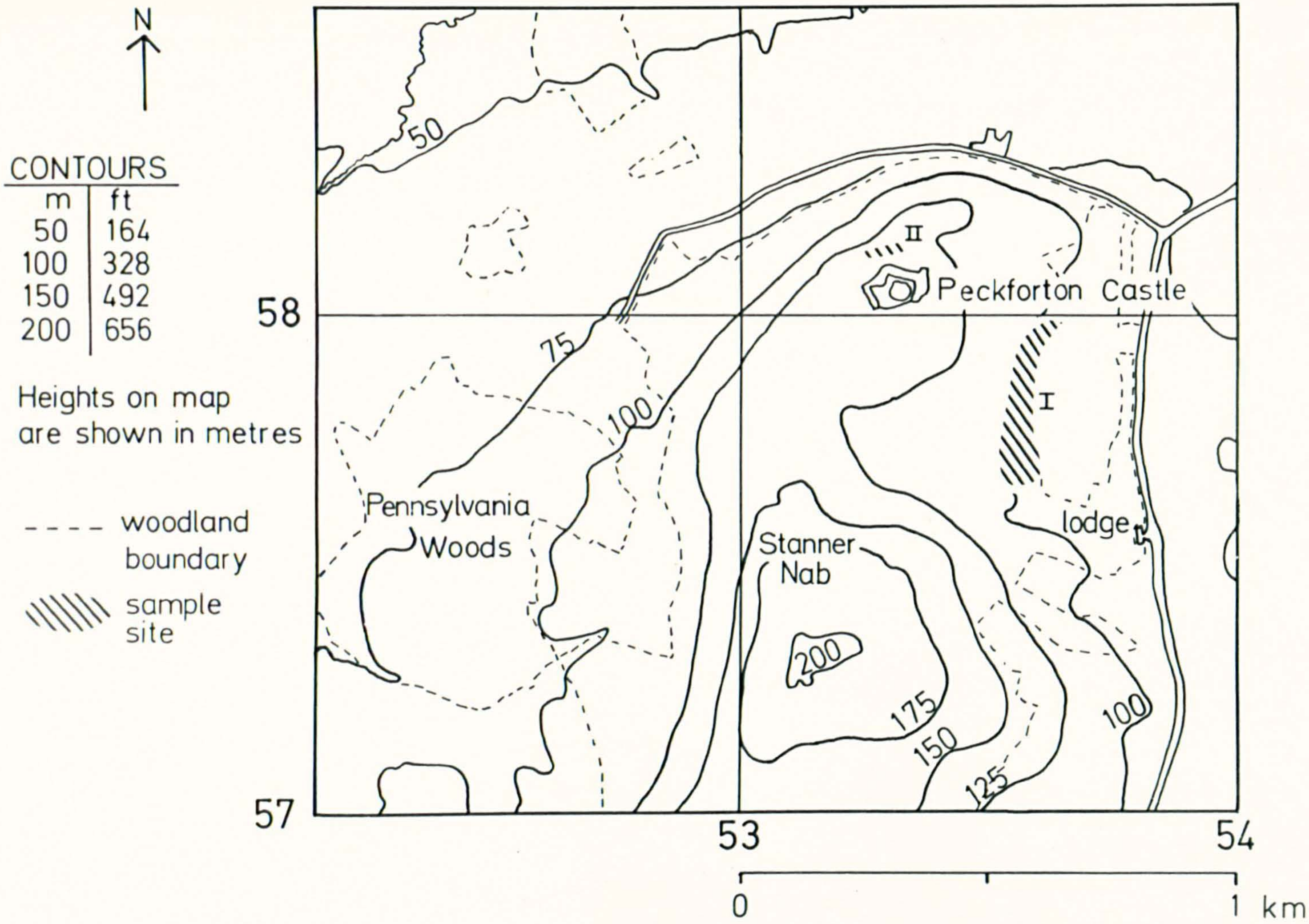
Lower down the slope from Site II is the area (Site III) studied by Mr. S. Milsom. Data obtained from his study were gratefully received and incorporated into the results from Sites I and II (Section 3.1).

2.1.2 Peckforton Hills

The Malpas-Peckforton Hills of Cheshire form the southern part of the Mid-Cheshire ridge and lie in the rain shadow of the mountains of North Wales. The location of Peckforton Hills (Lat 53°7'N, Long 2°42'W) is shown in Figures 2.1 and 2.3. The woodland occupies an area of 283 hectares with heights ranging from 90 to 215 m OD. The average yearly rainfall is 775 mm with the maximum amount of rainfall occurring in late Summer and early Autumn (Furness, 1978). This low rainfall figure is due

Figure 2.3 Location of sampling sites (I and II) at Peckforton, Cheshire.

LOCATION OF SAMPLING SITES AT PECKFORTON



to the rainshadow effect where downslope movements of air from upland regions to the west become warmed causing increased evaporation and moisture deficiencies in Summer. Excess of evaporation over rainfall progressively reduces the soil moisture content to give an average maximum potential soil water deficit of approximately 114 mm (Furness, 1978). The mean annual temperature on the plain is approximately 10°C with this part of Cheshire in which Peckforton lies having a growing season of 7 to 8 months (Gregory, 1964). The average daily duration of bright sunshine at the nearest recording station, Bidston, is approximately 4 hours.

The hills at Peckforton are composed of faulted Bunter and Keuper sandstones. They are comparatively drift free and provide most of the exposures of Triassic rocks in the district (Poole & Whiteman, 1966). Consequently, the soil cover is thin throughout the woodland having a depth of 8 to 46 cm. The soil profiles formed over these sandstones are of three types; a Brown Earth, a Brown Sand and a Brown Podzol (Furness, 1978).

Tree cover in the woodland is largely a result of successive plantings during the last 200 years; hardwoods were planted in the 1800's and softwoods in the 1900's. Scots pine, *Pinus sylvestris* L. and Corsican pine, *Pinus nigra* var. *maritima* (Ait.) Melville were found to be very successful. Plantings of European larch, *Larix decidua* Mill. were made in 1910.

Studies were made in two areas of the woodland which are in the northern quarter of the hills and approximately 385 m apart.

The locations of these two areas (Sites I and II) are shown in Figure 2.3. The soil type in this region of the hills is a Brown Earth and a soil profile at Site I is shown in Plate 2.9. A litter layer of 4 cm overlies the stony organic horizons which are dark brown in colour and extend to a depth of 24 cm below the ground surface. The underlying mineral horizons progress from dark red brown to yellow dark brown and have a depth of 68 cm (not shown in Plate 2.9) below the organic horizons. The mineral horizons then pass into the underlying sandstone of the area. The pH of the organic horizons is 4.8 while that of the mineral horizons ranges from 3.5 to 3.7.

The dominant tree species at Sites I and II are sessile oak, *Quercus petraea* (Mattuschka) Liebl., pedunculate oak, *Quercus robur* L. and hybrids of these two species. *Betula pubescens*, *Acer pseudoplatanus* and *Castanea sativa* are also present. The ground flora is largely dominated by *Pteridium aquilinum* where the oak is less dense, *Chamaenerion angustifolium*, *Agrostis tenuis* and *Rubus* sp. The bryophyte flora consists of *Dicranella heteromalla* and *Polytrichum formosum*. Appendix II gives a list of plant species found at Sites I and II. A fuller account would have been given had the author been able to assess these areas fully prior to the clearing operations.

At Site I, the oak trees from which samples were taken grew on a slope facing east-south-east at heights between 95 m and 105 m. The trees were sampled during clearing operations, the effects of which are shown in Plates 2.10, 2.11 and 2.12. Trees at Site II grew on the edge of a plateau close to Peckforton

Castle at a height of 135 m.

Peckforton Hills

Plate 2.9 Soil profile at Site I. The soil type is a Brown Earth. Further description given in the text.

Plate 2.10 An area of the woodland sampled, after felling operations had taken place, viewing to the south-east.

Peckforton Hills

Plate 2.11 An area of the woodland sampled, after felling operations had taken place, viewing to the south-west.

Peckforton Hills

Plate 2.12 An area of the woodland sampled, after felling operations had taken place, viewing to the north. Subsequent to felling, branches and foliage were gathered into heaps for burning.

2.2 Sampling techniques

Materials for tree-ring analysis were obtained from Maentwrog and Peckforton both as cores and as discs. The cores were taken with a Swedish incremental borer. This tool is designed to remove pencil-like cores of wood reaching from the pith to the bark without damaging the tree. In conifers, the hole left in the tree by the corer is quickly sealed by sap (Stokes and Smiley, 1968) so that pests and diseases cannot enter and cause damage. This does not happen in oak so that the holes left by the borer were plugged with dowling which had previously been dipped in Arbrex. At both sites, borers with handleshafts of 30 cm and 40 cm long which removed a core with a diameter of 4.5 mm were used. The discs of wood were obtained using a power chain saw fitted with a 55 cm bar and chain.

Ideally, the trees selected for sampling should be those with no obvious injury or disease since such features could affect growth and the tree-ring record. This procedure was followed as far as possible but a number of samples did have obvious fire damage.

2.2.1 Maentwrog

Material for tree-ring measurement was obtained from two types of source at Site I and from one type at Site II. At Site I, two increment cores were taken at breast height from each of eleven living trees. These had first been examined to locate the best places at which to remove the cores. Areas where the tree-ring pattern was likely to be distorted, such as close to branches, or on the uphill or downhill sides of the tree, were avoided. Consequently, cores were, wherever possible, taken in such a manner that the sampled radii were opposite to each other and parallel to the contours of the hillside. Each core was examined for faults such as breaks, fire damage and ring distortion and for the number of growth rings it contained. Had any of the cores shown less than 100 growth rings they would have been discarded. In fact, all the trees sampled as cores were older than 100 years.

The cores were then stored in paper straws which were sealed and labelled with the site name, tree number and radius number. The straws were stored in larger plastic tubes for transportation. If a core was broken during its removal from the tree the fragments were numbered to facilitate its reconstruction in the laboratory.

The identification of tree stumps had to be done using different characteristics than those used for living trees. The wood of oak may easily be distinguished from that of other trees by its ring porosity (which it shares with ash and elm) and the presence of medullary rays of two sizes. The larger rays are multiseriate and conspicuous being between 0.3 mm and 0.7 mm wide whilst the smaller ones are more numerous and uniseriate.

The discs were cut from nine stumps of trees felled at earlier, initially unknown dates. It was believed at the time of sampling, that they had been felled in the last part of the nineteenth or first part of the twentieth century. Each disc was labelled using the same identification system as that used for the cores.

At Site II sections were cut from the stumps of ten trees felled a few days before sampling. The cuts were made so that opposite radii were sampled (Plate 2.13). Fire damage had resulted in distortion in some of these stumps which prevented measurement of the outer sections of the tree-ring record. Plate 2.14 shows were part of the cambium had been destroyed by fire (indicated by the arrow). Cambium not affected was able to give rise to new wood which eventually enclosed the damaged area.

All cores and discs were sampled in the winter of 1976/77. Since the season's wood production has ceased by the end of September (Longman and Coutts, 1974) the growth ring immediately beneath the bark is that formed in 1976.

2.2.2 Peckforton Hills

Materials for tree-ring measurement at Peckforton were also obtained from two types of source. At Site I two increment cores were taken from each of two trees felled several days before sampling, in January 1978. The outermost growth ring would therefore have been formed in 1977. Discs were cut from the bases of twenty-one trees which were believed to have been felled two weeks before sampling. This material was made available as a consequence of a management programme of thinning in the woodland. Since branches and foliage were removed and piled into heaps subsequent to felling (Plate 2.12) it was not possible to determine the species of oak sampled. However, it was at least possible to determine which species

Plate 2.13 One of the trees sampled from stumps at Site II, Coedydd Maentwrog. The cut was made so that opposite radii were sampled.

Plate 2.14 Cross section of an oak stem taken from a stump at Site II, Coedydd Maentwrog, North Wales. Damage by fire which occurred when the tree was 108 years old has caused an interruption in the normal growth pattern.

were present at the site by examining the discarded parts of the tree. Identifications were made using the criteria of presence or absence of the acorn stalk and leaf characteristics (Jones,1960).

The trees from which the discs were cut could not be sampled at breast height as this would have reduced the economic value of the prepared tree for Peckforton Estates. One disc was also cut from what appeared to be an old stump.

At Site II, discs were cut from the basesof three trees which were thought to have been felled in 1976.

2.3 Sample preparation

The materials from Maentwrog and Peckforton were prepared for examination using the methods described below.

The preparation of cores for tree-ring measurement followed the procedure described by Stokes and Smiley (1968). The fragile nature of cores requires them being mounted before any surfacing can be done. The cores were allowed to dry and were then glued and secured with string in mounts grooved to accommodate them. Since the annual rings are more conspicuous when seen in cross section than in radial view the core was positioned in the mount so that the transverse section could be viewed. Following convention, that end of the core with the most recently formed year was placed to the right. When the glue had dried, the string was removed and the core was ready for surface preparation.

Discs were stored for at least ten weeks in an unheated, very well ventilated room, stacked so that air could move freely around them and thus minimize distortion. Sections were cut from the discs so that two opposite radii, analogous to those sampled as cores could be prepared and measured.

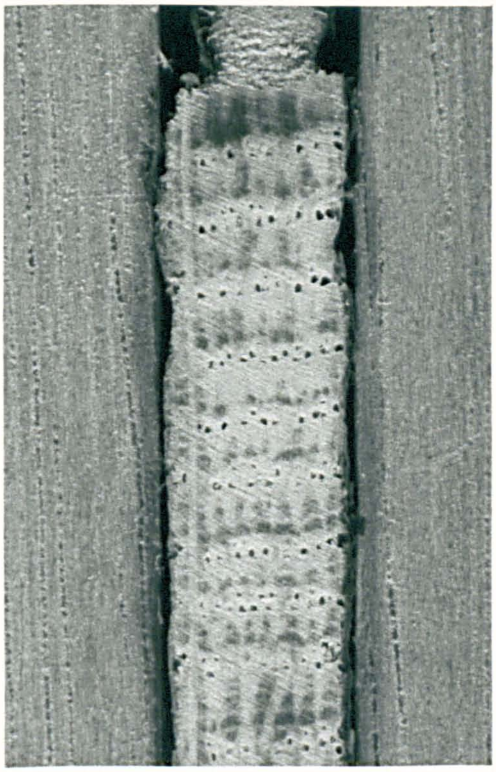
Several techniques have been used for preparing the surfaces of materials prior to tree-ring measurement. Ferguson and Wright (1962) used a belt sander to sand cross-sections of pinyon pine. Initially, this was the method used in the present study on oak but it was found to be very time consuming since the sample had to be constantly lifted from the belt for examination. Sanding with a rotary sander made it possible to view the surface of the sample as it was being prepared. This method of sanding is also favoured by Baillie (1973a).

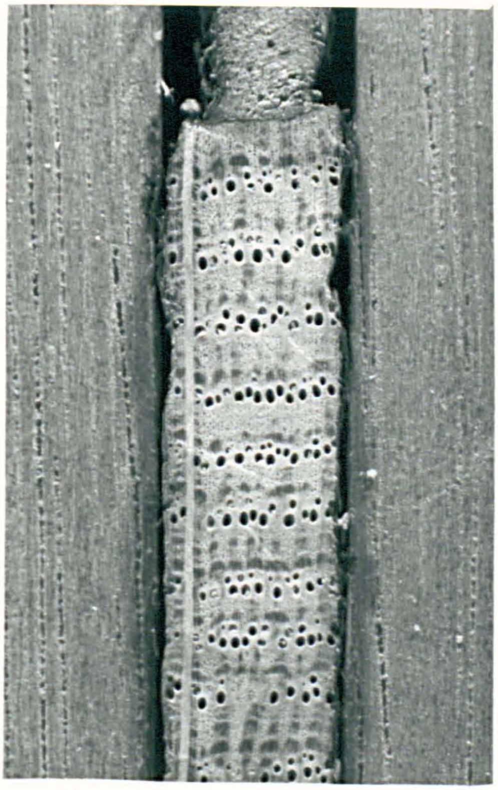
In the present study, the tree-rings on cores and discs were exposed by sanding with a rotary sander using successively finer grades of sandpaper (Grits 80 and 120). However, a clearer surface was often found to be obtained by slicing the core at right angles to the direction of the vessels using a Stanley knife fitted with blade number 5901. In particular, the rings of the sapwood became more distinct by slicing since sanding often caused the large early wood vessels to become filled with wood dust. The resolution of bands of narrow rings was also found to be improved by the slicing method. Surfaces prepared by sanding and by slicing are shown in Plates 2.15 and 2.16.

Preparation techniques

Plate 2.15 The sapwood of oak prepared for measurement by the sanding method.

Plate 2.16 The sapwood of oak prepared for measurement by the slicing method.





2.4 Tree-ring Measurement

Measurements of the tree-ring widths were made on the polished transverse surfaces to 0.01 mm using a Bannister Incremental Measuring Machine (Bannister,1972). Throughout the study, the readings were taken for the entire annual ring, that is from the beginning of the earlywood through the latewood of one year to the boundary of the latewood and the earlywood of the following year. By way of convention, measurements were made from the pith to the bark along radii in regions free of knots, obvious tension wood and other defects. To facilitate a check and future reinvestigation decades were maked by the symbol •, 50 years by •• and centuries by •••. The following information was recorded for each sample; date of sampling, site name, tree number, radius number, tree genus, number of years measured, number of sapwood years, presence of bark, width of each growth ring and any other comments considered important. For instance, any damage by fire as shown in Plate 2.14 would be noted.

2.4.1 Variation in tree-ring measurements

In order to assess the variation in ring-width measurements, a programme of measurement replication was undertaken. A series of 50 rings on sample LP572A which covered a range of widths from 0.48 mm to 3.45 mm was measured along a line on ten separate occasions. The sequence of 50 rings is shown in Plate 2.17 . From the replicated measurements,the mean ring width, standard deviation, standard error and coefficient of variation were calculated for each year of growth. These values with the raw ring-width data are shown in Appendix III.

Plate 2.17 The series of 50 growth rings used in the evaluation of the variation in the ring width measurements. Decades are indicated .

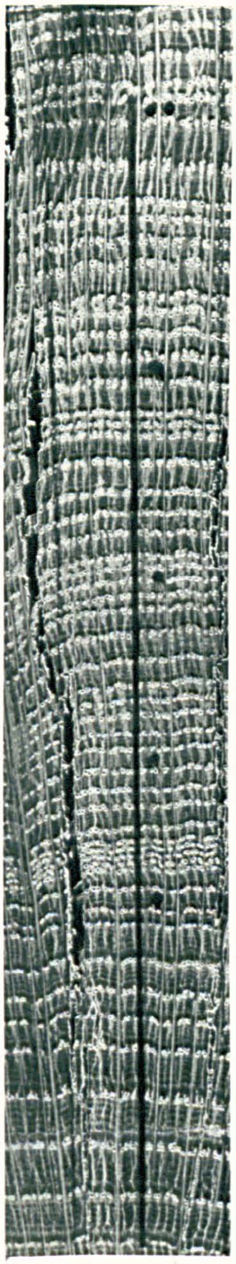
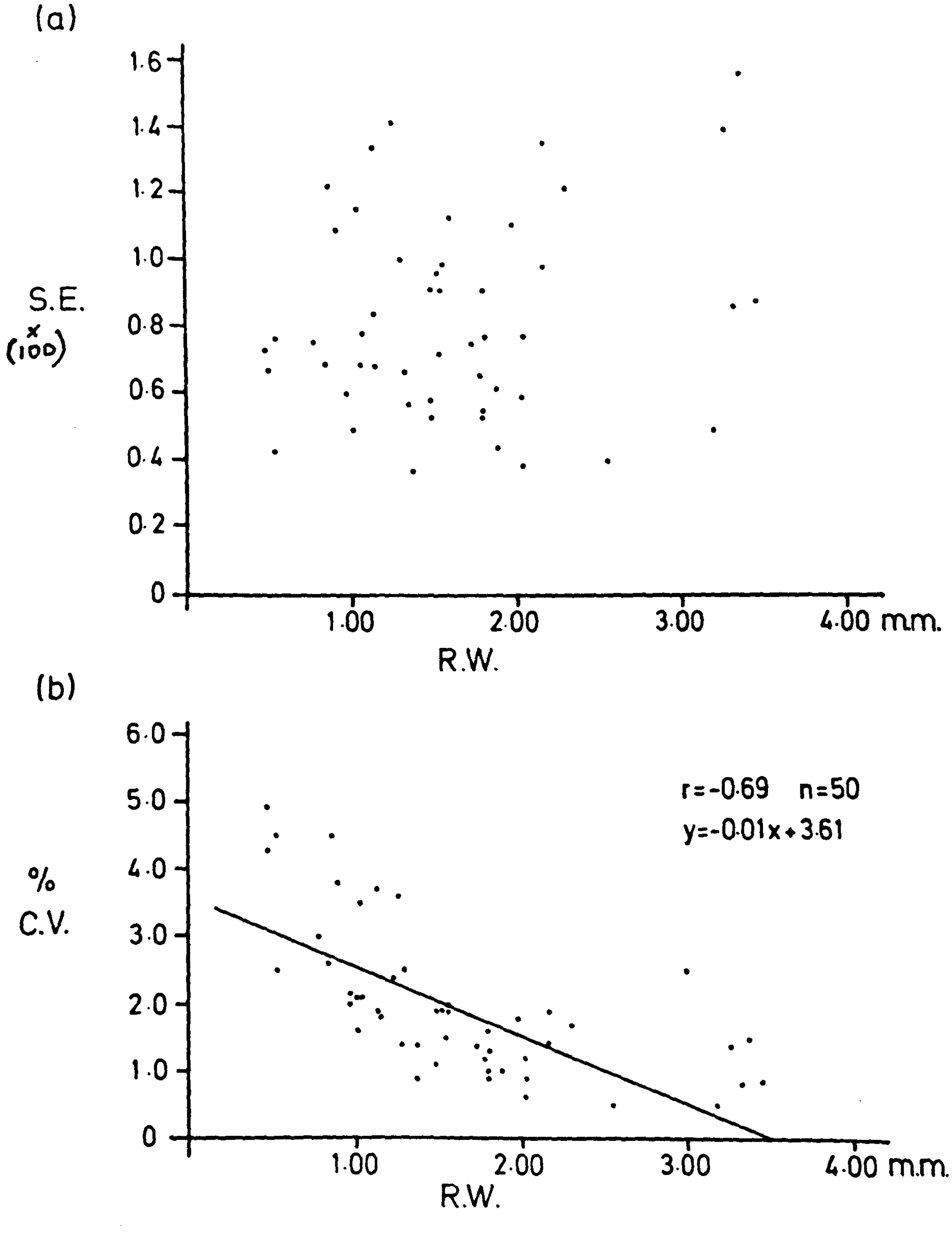


Figure 2.4(a) shows standard error plotted against mean ring widths. Absolute values of standard error are small, ranging from 0.0037-0.0156 mm. No correlation exists between this and mean ring width ($r = -0.1426$, $p > 0.443$ at 0.001) so that errors in absolute measurements are not related to either small or large rings. However, as might be expected a relationship does exist when the error as standard deviation is expressed as a percentage of the ring width. Figure 2.4(b) shows the percentage of coefficient of variation (standard deviation as a percentage of the mean) plotted against mean ring width. The correlation between them is a negative one ($r = -0.6911$, $p < 0.001$). Therefore, although absolute errors may not be greater in narrow rings the percentage error will be. This will not significantly affect the value of the tree-ring sequence for crossdating because it is the occurrence (not the actual width) of a narrow ring or a band of narrow rings between wider rings that provides the characteristic pattern on which crossdating is based. However, resolution will be lost in very narrow-ringed material.

Figure 2.4 Variation in tree-ring measurements

(a) Standard error plotted against mean ring width - no significant correlation exists.

(b) Percentage of coefficient of variation plotted against mean ring width - a significant negative correlation exists.


(a)
S.E.
(x/100)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
1.00
2.00
3.00
4.00 m.m.
R.W.
(b)
%
C.V.
6.0
5.0
4.0
3.0
2.0
1.0
0
r=-0.69 n=50
y=-0.01x+3.61
1.00
2.00
3.00
4.00 m.m.
R.W.

2.5 Data Handling Techniques

2.5.1 Representation of Primary Data

Throughout the studies of tree growth several methods have been used for describing the patterns of the annual increments in forms that can easily be handled for analysis. In North America, many of the trees examined during dendrochronological research have been found to be highly sensitive, exhibiting outstanding sequences of wide and narrow rings (Douglass, 1946; McGinnies, 1963; Estes, 1970). Comparisons and subsequent crossdating between the ring sequences of such trees was found to be greatly facilitated by the skeleton plot technique developed by Douglass (1945) and described in detail by Stokes and Smiley (1968). The plots aid in relating chronologically a group of specimens to each other by pattern matching and in determining dates for the individuals in a group.

Skeleton plots have most often been used for representing the annual growth patterns of trees which have a clear relationship with climate. This is not always the case for trees growing under the temperate conditions experienced in Europe where growth is often limited not by one climatic factor but by the complex interaction of several climatic factors. There is less variation in the ring-widths of such trees so that the whole length of the tree-ring curve is taken into consideration rather than sporadic characteristic years. The basic representative techniques used as aids to dating materials from temperate forest trees are plots of ring widths, plots of logarithms of ring widths and plots of index values. These techniques are also used in tree-ring studies of the sensitive trees discussed above, especially in studies of ring-width variability associated with climate.

Throughout the present study extensive use was made of plots of logarithms of ring widths and of index values. The use of plots of logarithms of ring widths introduced by Huber (1941) has advantages over direct ring-width plots and is considered to be the best method of depicting relative changes in magnitude (Kolchin, 1962). The justification for this is described mathematically by Ruden (1945) and outlined by Høeg (1956) and is based on the fact that the size of the variation is proportional to the mean width of the growth rings. His argument is as follows: if 'a' represents the width of one growth ring and 'a_n' that of another and the ratio between them is $a_n/a = f$ then the difference when represented on a linear scale is described by

$$a_n - a = af - a = a(f - 1).$$

As a consequence, the difference is proportional to 'a'. With the use of logs the relationship is described by

$$\log a_n - \log a = \log(af) - \log a = \log f .$$

The difference is now independent of 'a' and proportional only to 'f'. Thus in a graphic representation of the logarithms of the ring widths, the difference between any two adjacent growth rings depends not on their absolute values but on the proportion between the widths. This representation is achieved by plotting the actual ring widths on transparent semi-logarithmic graph paper. The horizontal scale of years is linear, whilst the vertical scale of ring widths is logarithmic. The same percentage of change in growth results in the same slope and the same length of the curve. In addition, the maxima of the curve are smoothed and the minima accentuated, a feature which greatly facilitates the visual matching of curves (section 2.5.2) since it has been found that the narrow rings are important for determining the position of correct match between tree-ring sequences (Kolchin,1962). The plots were made from left to right, the left hand end representing that nearest the pith and the right hand end that nearest the bark, if present and therefore nearer to the present time. In common with the practice of the Belfast laboratory, ring widths were plotted on a horizontal scale of 4 years to 1 cm rather than the scale of 2 years to 1 cm used by Fletcher (pers. comm.). No information is lost by this reduction and the handling of long curves is made easier.

The use of plots of ring-width indices, values of ring widths corrected for the changing age and geometry of the tree, was less extensive, being employed in the representation of the composite masters of each site studied.

2.5.2 Crossdating techniques

The graphical techniques described in the previous section provide a means for the comparison of the complete tree-ring record. In order to construct chronologies from timbers for a local site, a larger region or from buildings and archaeological excavations,the next stage in the study involves the establishment of cross-correlations between the ring patterns. The assumption that such correlations may exist forms the basis of the concept of dendrochronology,in that trees growing under the same conditions over the same period of time should contain similar growth patterns which manifest themselves in the tree-ring record.

Comparisons of such sequences have been made by visual and statistical means.

(i) Visual Methods

The skeleton plot method (section 2.5.1), one of the most extensively used techniques is based upon a visual estimate of the difference of relative ring widths of successive years in each sample. Narrow rings in each sequence are expressed as vertical lines along a horizontal linear scale of years, with the degree of narrowness represented by the length of the line. Missing rings which are common in some species (for example, *Pseudotsuga taxifolia* - Douglas fir and *Pinus edulis* - pinyon pine) may be identified by comparison of the relative ring pattern with ring patterns from other species in the same area. Such rings are indicated by dotted lines on the skeleton plot. When the individual plots have been matched and lined up with one another a composite skeleton plot for the group can be constructed.

Douglass has also used two other visual methods of crossdating. His 'method of sliding coincidence' (Douglass, 1941) involves sliding the edges of the actual samples past one another so that a comparison of the relative ring widths can be made as successive rings come into contact. The 'memory method' (Douglass, 1941) relies on the memory of the examiner. Initially, signature years such as a group of narrow rings which is common to several samples is selected. This combination is then sought for in other specimens from the site and when identified allows them to be placed in their related chronological positions.

Visual matching may also be done on pairs of semi-logarithmic traces described above. The principles involved are essentially the same as those employed in the 'memory method' used extensively by Douglass (1941). The traces are moved past each other until a good visual fit on the basis of characteristic features and of the general form of the curve is achieved. At the position of best fit the area between the curves is at a minimum. This visual inspection essentially utilizes the high frequency variance in the ring widths (Fritts, 1974).

(ii) Statistical Methods

Since visual matching may not be quantified several statistical methods have been used to measure the significance of matches obtained visually. The objective comparison used by Huber (1943) was the percentage of agreement or that of disagreement (Gegenläufigkeitsprozent). This statistic provided a single number which expressed the strength of agreement in the yearly rises and falls of two tree-ring series. It was an inverse function, so that a greater agreement was given by a smaller number.

For random curves, the percentage of agreement almost equals that of disagreement, approximately 50%. In reality this value varies with the number of years (n) and is given by:

$$\% \text{ agreement} = 50 \pm \frac{50}{\sqrt{n}}$$

where $\frac{50}{\sqrt{n}}$ is one standard deviation (Huber & Giertz,1970). When two curves are mismatched, the percentage agreement will be similar to that for two random curves. A match between two curves is considered significant when a value for percentage agreement greater than three standard deviations from the mean (which occurs once in every thousand random matches) is produced (Baillie, 1973a). Any value occurring outside these limits is considered to be highly significant.

Eckstein and Bauch (1969) have measured the correlation between tree-ring curves by converting Huber's number into a direct function, the number referred to as the Gleichlaufigkeitswert. It is defined as the percentage of parallel intervals in two different curves, not taking into account the absolute tree-ring widths (Eckstein 1972). Their computer programme (Eckstein & Bauch, 1969) calculates the % agreement figures ('W' values) and prints them with their significance levels.

A similar method developed by Schove and Lowther (1957) and used by Elphick (1970) is called the 'sign-agreement test'. It provides a measure of the number of years in which similar increases or decreases in ring widths are exhibited by the two ring curves under comparison.

Several workers have found that significant results could be obtained using the method of Eckstein and Bauch (1969), (Brongers, 1973; Barefoot et al.,1974;Fletcher, 1974a, 1978b) However, both the authors of the method and Barefoot et al.(1974) recognise that total dependence on the 'W' values produced is not possible. Barefoot et al.(1974) quote an instance where the known date of the outer year of a tree-ring curve and that given for it by the highest 'W' value do not agree. On the contrary, it was the lowest of the 'W' values that was associated with the correct match. The use of this value is purely as an aid to finding the correct match between curves and as Eckstein (1972) states 'from a number of equally useful positions reported by computer, the best one has to be selected visually'.

The method described by Eckstein and Bauch (1969) is a nonparametric test whose model does not specify conditions for the parameters of the population from which the sample was drawn. However, certain assumptions are associated with most nonparametric tests but these are fewer than those associated with parametric tests. Those tests which have the strongest or most extensive assumptions about the conditions of a particular statistical model are considered to be the most powerful (Siegel, 1956). The concept of power in statistics is defined as the probability of rejecting the null hypothesis (H_o) when it is in fact false. H_o is a hypothesis of no differences and is usually formulated for the purpose of being rejected. If it is rejected, the alternative hypothesis (H_1) may be accepted. H_1 is the operational statement of the investigator's research hypothesis. The research hypothesis is the prediction derived from the theory under test.

The parametric tests have a variety of strong assumptions underlying their use which when valid, are the most likely tests to reject H_o when H_o is false. The meaningfulness of the results of a parametric test depends on the validity of these assumptions.

Baillie and Pilcher (1973) describe a direct parametric correlation method for assessing the agreement between two tree-ring series which takes into account the magnitudes of the annual variations in ring width. Baillie (1973a) had found a number of drawbacks to Eckstein and Bauch's method and argued that since it is nonparametric it takes no account of the magnitudes of the year-to-year changes in ring width. A long overlap between ring curves and an agreement better than 60 per cent is required for the match to be significant. When curves of only 100 years long, as commonly found in European oaks, are compared the percentages produced by actual agreements are masked by those produced by mismatch agreements.

The computer programme CROS was subsequently written by

Baillie and Pilcher (1973) to calculate the product moment correlation coefficient (r) at each position of overlap. r is defined as

$$r = \frac{\Sigma_i x_i y_i - N\bar{x}\bar{y}}{\sqrt{(\Sigma_i x_i^2 - N\bar{x}^2)(\Sigma_i y_i^2 - N\bar{y}^2)}}$$

where x and y are two series and $\bar{x}$ and $\bar{y}$ are the means of all the x and y values respectively.

The method is based on the assumption that when two trees have been growing under similar conditions over the same span of years, the correlation between the ring patterns should be high. Since the value of 'r' takes no account of the number of variables N (number of years of overlap), the values of 'r' given cannot be immediately interpreted in terms of probability of occurrence. The calculation of Student's t provides a way of relating 'r' values to probabilities. For the values of 't' to be valid the set of values of x and y must be bivariate (Parker,1973). This condition is fulfilled in the programme by a simple standardising technique which removes trends from the basic data. Each ring width is converted to a percentage of the mean of the five rings of which it is the central value. The data although not normally distributed vary about a mean of 100. Normalisation is achieved by taking log to base e of the percentage figures. Probability levels for any value of N can be obtained from tables of Student's t.

Baillie (1973b) found that most of the Irish timbers under investigation contained 100 or more rings. With such data, the 0.1% significance level was slightly less than $t = 3.5$, a value which should arise by chance once in every 1,000 matches. This was equivalent to the three standard deviation level in the percentage agreement method described above. He found that background t values fell between $t = 0.00$ and $t = 3.5$ whilst t values for the correct match of ring patterns fell between $t = 3.5$ and $t = 10.00$.

However, Litton (pers. comm.) holds that the statistical significance of results obtained in the cross-matching of tree-ring sequences using the cross correlation method is extremely misleading. He has found, using simulated data, that when 200 year sequences are cross-matched with a minimum overlap of 100 years, the chance occurrence of a t value greater than 3 is 0.26 and that a value of 4.6 or greater (chance occurrence of 0.001) should be considered highly significant. In this situation a t value of 6 ($p \leqslant 0.00001$) would be considered very good with little doubt about the match.

There appeared to be two methods from which to choose for assessing the degree of similarity between the growth curves of trees growing in the North West of England and North Wales. The length of the tree-ring sequences present on timbers in the initial stages of this project was approximately 100 to 250. These figures are similar to those encountered by Baillie (1973b) and those from which he drew his conclusions regarding the inadequacies of the percentage agreement method. One of its drawbacks concerned the lack of sensitivity when overlaps between curves were short. Although short overlaps were not expected to be a problem in constructing chronologies from trees growing over a common time period, they were considered more likely to be so in the construction of a long regional chronology. The construction of such a chronology requires the establishment of linkages between numerous chronologies spanning many centuries, where the lengths of overlaps between them likely to be encountered is at present unknown.

Programme CROS is considered to provide a greater distinction between true crossdating and random similarity and results on which greater statistical confidence can be placed (Baillie & Pilcher, 1973). Comparisons carried out by the percentage agreement method and that using the product moment correlation coefficient indicate that in the case of the latter, the confidence limits are in general several orders of magnitude higher. On the basis of the discussion presented, the direct parametric correlation method described by Baillie and Pilcher (1973) was chosen as the most powerful statistical test relevant to the present study.

Regardless of the statistical test chosen to test the degree of similarity between tree-ring curves, a visual inspection of the computed match must also be made. The value of using the visual criteria described above alongside statistical comparisons is sometimes questioned (Fleming,1978). Their value is exemplified in the following case: a discrepancy in the ring measurement of only one year in one of the radii from a tree would appear as a distinct lag of one year when the two patterns are superimposed. When the ring patterns are compared using, for example programme CROS, this lag and the error in measurement would not be detected. Thus, in the present study, all tests for crossdating between tree-ring sequences used programme CROS (Baillie & Pilcher,1973) and the visual criteria described above.

2.5.3 The combination of tree-ring series

(i) Within-tree

In order to construct a tree-ring chronology for a given site, it is necessary to determine that crossdating exists within the trees at that site. Once this has been established it is required that the data from the measured radii be combined to represent a set of mean values for that tree. Programme MEAN was written by Dr. M.K. Hughes to calculate the mean ring width for each year of growth from the ring widths of the 2 measured radii. The Programme prints and punches onto cards the set of mean values for each tree. Tree mean curves may then be tested for crossdating using the criteria described above.

(ii) Between-tree

Within a study site, whether it is a woodland or a site yielding used timbers, once crossdating has been established for a group of samples, it is desirable to combine these samples to produce a working master against which the remaining material may be compared. Programme MITTELWERT provides a rapid means of producing this master prior to fuller compilation and analyses using programme INDXA (Fritts *et al*, 1969) (section 2.6). The output of programme MITTELWERT includes listings of the ring widths for each year of growth in the appropriate order for each tree-ring series and of the resulting mean values. Years in which the ring widths either increase or decrease in all samples are indicated. Such years may be used as signatures in subsequent crossdating tests (Becker, pers. comm.).

2.6 Characteristics and statistics of tree-ring series

Series of tree-ring measurements may be regarded as time series. Usually, successive values of such time series are not statistically independent of one another owing to the presence in the series of persistence, cycles, trends or some other non-random component (Mitchell et al., 1966). Any comprehensive study of tree-ring series, especially with regard to relationships with climatic variables, involves the identification of the nature and extent of the randomness and non-randomness in the time series of tree-ring and meteorological data. The properties of such ring-width series including these components may be characterized using the computer programmes described in the following sections.

2.6.1 Data format conversion and filtering techniques

In using Programme CROS (Baillie & Pilcher, 1973) to detect the position of highest correlation between tree-ring patterns, the data must be in a specified format known as Belfast format. The use of programmes RWLST and INDXA (Sections 2.6.2 and 2.6.3) requires that the data be in a different format known as Tucson format in which tree-ring series must be dated. The Programme TRANFILT has been written by Dr. M.K. Hughes to convert data between these two formats. It can also pass the tree-ring data through a digital filter resulting in the output of both the High-pass and Low-pass series. Transformed data, filtered and unfiltered, is printed as output and punched onto cards.

Applying digital filters or moving averages to tree-ring data is a way of studying variance at particular frequencies. Moving averages are ring-width averages for a given number of successive rings with the sequence being moved ahead by one year each time the average is calculated. For example, in a three-year moving average the first is a mean of the widths for years 1, 2 and 3, the second of years 2, 3 and 4 and so on. Each average is assigned to the year of the central ring.

This moving average puts equal weight on all values being averaged which can produce peaks and troughs in locations other than those present in the original sequence. However, if the numbers are weighted with the central value having twice the weight of the value at each end, then the peaks and troughs are located only in the original positions (Fritts, 1976). The number and value of weights may vary depending upon which frequencies of variation are to be retained and which eliminated. The high-pass and low-pass filters referred to above represent such weights. The three-year weighted moving average blocks out the rapidly changing growth variation (high frequencies) and passes the slowly changing variation (low frequencies). When the resulting averaged series retains only the long-term or low-frequency variations, the weights are referred to as a low-pass filter. Such variations in ring widths can arise from changes in tree structure or the environment including long term variations in climate.

A high-pass filter removes the smooth lower frequency fluctuations and emphasizes the year-to-year variations in a tree-ring series. This may be done by first differences which are calculated by subtracting the value of each item in a series from its immediate successor.

The low-pass and high-pass filters used in programme TRANFILT are reciprocal filters designed to pass variance in different areas of the frequency spectrum. The low-pass filter passes low frequencies and blocks the variance with wavelengths less than eight years, while the high-pass filter passes high frequencies and blocks most of the variance with wavelengths greater than eight years. Since they are reciprocal, they can be applied to the same ring-width or index series (section 2.6.3) to separate the variance into its high- and low- frequency components. The number 300 was added to the ring-width values prior to the application of the high-pass filter. This prevented the occurrence of negative values which would not have been acceptable for programme INDXA (Fritts *et al.*,1969). Figure 2.5 shows the effects of filtering on a tree-ring series from sample LP570 from Peckforton.

The equation by Mitchell *et al.* (1966) for the calculation of the filtered value of an observation $\bar{x}_t$ is given by

$$\bar{x}_t = \sum_{i=-n}^{+n} w_i \, x_{t+1}$$

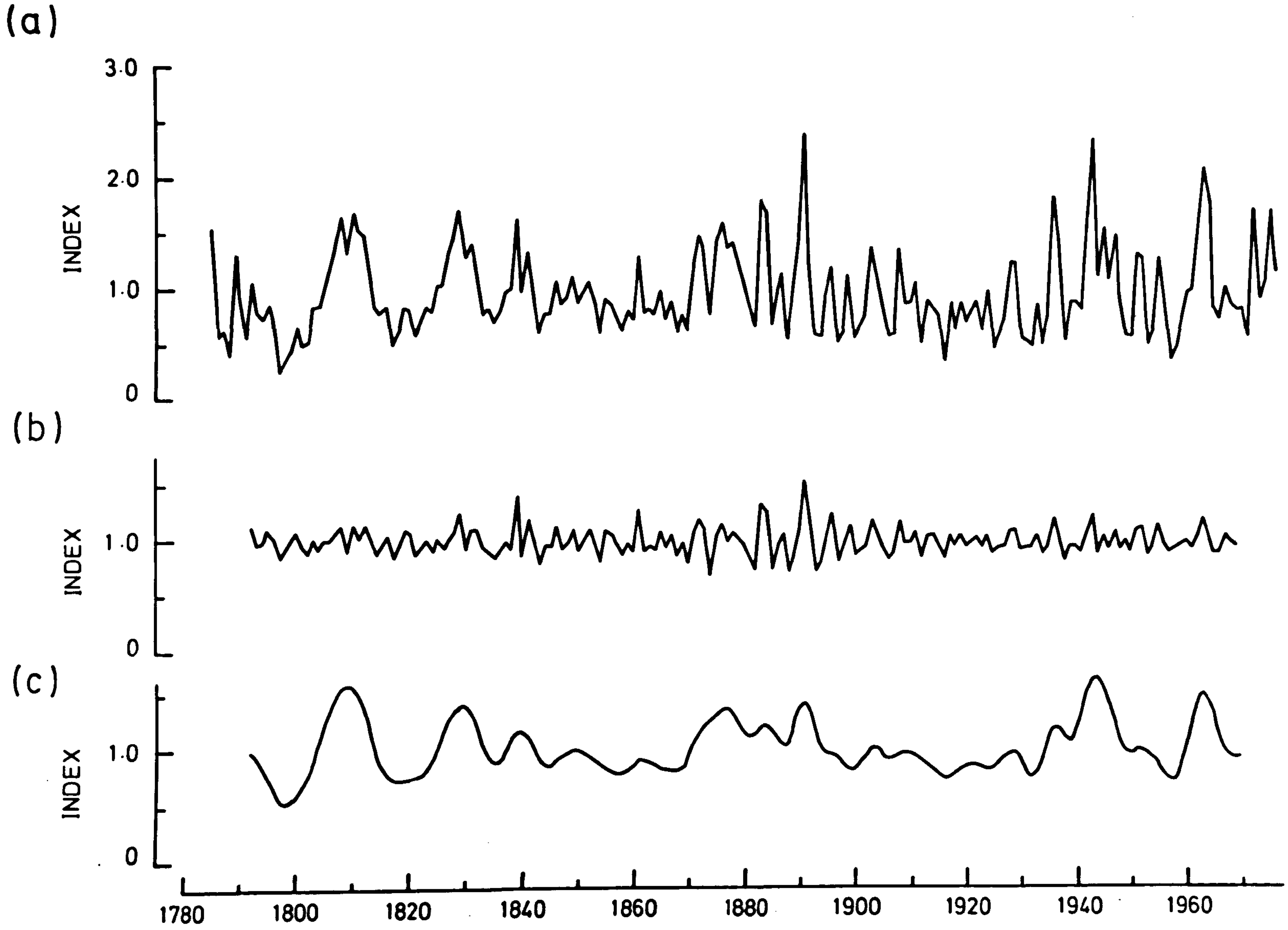
where w_i is the weight by which the value of the series i units removed from t is multiplied. The length of the filter (moving average) defined in this way is 2n + 1 time units. In the equation the weights of the filter are multiplied by the appropriate ring-width values and the products are then summed. Techniques for the selection of filter weights giving a desired frequency response are presented by Craddock (1957) and Holloway

Figure 2.5 The effects of applying a pair of reciprocal digital filters to the index series of sample LP 570A from Peckforton

(a) unfiltered data

(b) high-pass filtered data

(c) low-pass filtered data.


(a)
3·0
2·0
1·0
0
INDEX
(b)
1·0
0
INDEX
(c)
1·0
0
INDEX
1780
1800
1820
1840
1860
1880
1900
1920
1940
1960

(1958).

LaMarche and Fritts (1972) used the reciprocal filters in association with other techniques in an attempt to detect relationships between the annual Wolf sunspot numbers and ring indices. LaMarche (1974b) employed the filters in a study of chronology characteristics from four sites which ranged from the arid lower forest border to the upper tree line in the Snake Range of eastern Nevada. Reciprocal filters were also used in a study designed to assess the quality of a selected set of data for subsequent dendroclimatic analysis (Parker & Henoch, 1971; Fritts & Schatz, 1975).

Another justification for applying filters is based on the assumption that variation at other frequencies is either random error, or is of no significance to the particular type of evaluation being carried out.

A separate edition of TRANFILT exists for the standardisation of data requiring calibration; for example, unstandardised density data.

2.6.2 Mean sensitivity

Once the ring-width series of each core has been tranformed to Tucson format, they must be run through a ring-width listing programme (RWLST) before further analyses can be performed. The output from this programme includes for each core, a listing of all the annual ring widths by decades and a calculation of a 20-year running mean, mean sensitivity at 10-year intervals and the slope for overlapping 20-year periods. The programme also plots the 20-year running means.

The mean sensitivity, referred to above, expresses the relative year-to-year variations in the ring-width values. It is defined as the average ratio of the absolute difference between each two successive widths divided by their mean (Douglass,1919; 1938). The average mean sensitivity is calculated by the following equation:

$$ms_x = \frac{1}{n - 1} \sum_{t=1}^{t=n-1} \frac{2(x_{t+1} - x_t)}{x_{t+1} + x_t}$$

where x is the ring width, t is the year number of the ring and n is the number of years in the series. The ring widths in the series are treated as consecutive and the difference between each pair is divided by the average width. An average is then taken of the sum of all the calculations. Most values of mean sensitivity fall within the range 0 to 0.6. They become relatively greater in sensitive series, falling above 0.3 (Creber,1977). When values fall below 0.3 the record is considered by Creber to be complacent and is typical of trees growing on sites with characteristics favouring optimum growth. According to Creber (1977) a figure of 0.3 would indicate that a tree's water supply was limited and variable from year to year; 0.6 would result from a water supply extremely restricted in average quantity and very variable in the amount of replenishment each year.

Similarly, for trees growing at the arctic timberline, the annual variation in ring widths reaches the maximum, the limiting growth factor being summer temperature (Mikola, 1962).

Mean sensitivity can be considered to act as a high-pass filter (section 2.6.1) since it measures the absolute value of high-frequency variations observable in the differences between adjacent widths or indices (Fritts, 1976). The ring-width series of a Douglas fir (*Pseudotsuga menziesii*) with a large value for mean sensitivity of 0.64 was shown to have considerable high-frequency variance.

The value of the mean sensitivity statistic is a criterion of the usefulness or otherwise of the data from a tree or a group of trees for high quality crossdating and as an index of the limiting effects of climate on tree growth (Schulman, 1956).

A much better indicator of dating quality is the relationship between the mean sensitivity of cores and that of the mean curve discussed by Fürst (1963). The calculation of the quotient S_m:S_E (average fluctuation of the mean curve in relation to the individual curves and called R) is an indication of the agreement between the individual curves and the mean curve. Fürst (1963) found that the fluctuation was less in mean curves. The greater the value of R, the greater the agreement and the quality of the mean curve for dating and use in climatic studies.

Thus, in addition to providing information regarding the potential 'usefulness' of the ring-width series, programme RWLST is also used to check ring widths for errors and to plot the 20-year means which helps the investigator to choose the curve-fitting option for programme CORE (section 2.6.3).

2.6.3 Standardisation

"Many factors, both intrinsic and extrinsic, influence the width of an annual ring as measured on a radius at a given height up a tree. Intrinsic factors such as cambial age and distance from the canopy may produce effects continuous along the axis of the tree whilst others, such as branching and branch abscission may produce more abrupt changes. Factors external to the tree but intrinsic to the stand interact with these; the nature of branching and timing of their abscission will be affected by the state of the forest stand as a whole. This in turn will be influenced by the complex processes of tree population dynamics. Even in a uniform physical environment and with a genetically homogeneous population of trees great between-tree variations in growth rate and growth curve form are to be expected. These will be particularly apparent in the annual radial increment in the lower bole of those tree species with a mainly horizontal branching system such as *Quercus petraea*" (Hughes et al, 1978b).

Such variability in the growth rates present complications in studies of dendrochronology and dendroclimatology in which the aim is to correlate changes in growth with changes in climatic conditions. It is therefore necessary to separate that variability in ring widths common to all the trees at a site from those derived from conditions special to individual trees.

The changes associated with the ageing of trees, the growth function, may be removed by a procedure called standardisation. This involves converting the ring widths to ring indices by dividing each ring-width measurement by the estimated value of the growth function for that year (Fritts,1965). The mean value of the indices is one and since they are a stationary series (Matalas,1962) they are relatively independent of tree age.

Consequently, the larger variability in ring width in the younger fast-growing portions of the tree is made comparable to the lesser variability in the older slow-growing portions of the tree (Fritts,1974). However, as in any indexing procedure, the long-term trends will be removed.

A number of methods have been used to remove the growth function:

(1) One of the earliest methods of standardising is that proposed by Douglass(1919). The ring-width measurements or means are plotted on graph paper, a standardising line following the general trend of the curve is drawn and the width of a growth ring is expressed as the departure from the standardising line. Høeg (1956) considered this method worked well for trees growing in Norwegian forests since the growth of these trees often showed the effects of environmental changes, features which would be wholly or partly eliminated in this form of standardisation. In addition, he considered that for Norwegian forests it was much better than any strictly mathematical method (Aandstad,1938; Ording,1941; Ruden,1945; Eidem,1953) although he does not state which criteria he used to test this.

(2) In recent years, to aid in placing eye-fitted trend lines more accurately, long-period means have been plotted on the curve to be fitted. For example, Bitvinskas (1968) favoured the use of 20-year running means with a 5-year step. Schulman (1956) also made extensive use of this semi-graphical method.

(3) Fritts (1976) gives a comprehensive account of the type of curves that may be fitted to ring-width data to describe the growth function of tree growth series. Fritts *et al.* (1969) have developed a computer programme which performs ring-width standardisation through a choice of these several curve-fit options. The negative exponential function is commonly used for conifers growing on drought subjected sites because it resembles the declining rate in the conifer biological growth function. The form of the curve is as follows:

$$y_t = a\,e^{-bt} + k$$

where the values of a, b and k vary from series to series depending on the slope of the curve required to fit the data, e is the base of natural logarithms and y_t is the expected growth at a given year t.

(4) When trees do not exhibit the exponential growth trend seen in conifers another curve-fitting option must be used. Pilcher (1976) and Baillie (unpublished data) found this to be the case with their tree-ring sequences for oak at Rostrevor and Raehills respectively. Consequently, they chose to use a method known as the polynomial function

which uses the method of least squares producing coefficients at higher and higher powers. However, the flexibility of this curve-fitting option introduces the risk of removing some climatic variation. A test is subsequently made because of this risk whereby the procedure is terminated if the addition of another coefficient reduces 5% or less of the variance. In this way the curve is not allowed to become too flexible. The polynomial curve-fitting option is an extremely flexible one which allows for a situation in which each radius measured may have a different growth trend.

(5) Barefoot et al. (1974) also considered the model used for conifers to be unsuitable for describing the growth trend of English oak. They found that an exponential weighted smoothing technique proposed by Brown (1959), which is in its simplest form a variation of a weighted moving average, provided a reasonable alternative to the negative exponential function. The technique was used to estimate and remove the underlying growth trend found in the ring-width series of oaks growing near Winchester. Standardised curves were subsequently produced by subtracting the estimated ring width from the observed ring width and plotting the resultant series of differences.

After the appropriate curve-fitting option has been chosen and the curve has been fitted to the ring-width data, the equation for the expected yearly growth (z_i) is solved. The measured ring widths (y_i) are then converted to ring indices (w_i) by dividing each width for year i by the expected growth (z_i) as follows:

$$w_i = \frac{y_i}{z_i} \quad .$$

The resulting time series is referred to as ring-width indices or a standardised ring-width chronology. Fritts (1976) compares the statistical properties of ring widths and indices in three data sets. Differences in the standard deviations in indices are less than those for ring widths and most of the autocorrelation (section 2.6.5) due to trend is eliminated. However, mean sensitivity estimates are similar in the two forms of data.

Figure 2.6 shows the ring-width series from two radii from tree LP570 at Peckforton which were fitted by polynomial curves and the standardised index series derived from them. Radius LP570A is described only by a polynomial equation with 4 coefficients. Figure 2.6 illustrates the more complex nature of radius LP570B which is described by an equation with a greater number of coefficients, in this case 6. The effect of removing the long-term variations in growth is shown by the standardised index series below each radius.

The output from programme CORE described above provides the basic tree-ring data for the subsequent analyses discussed in this text.

The combination of standardised index series

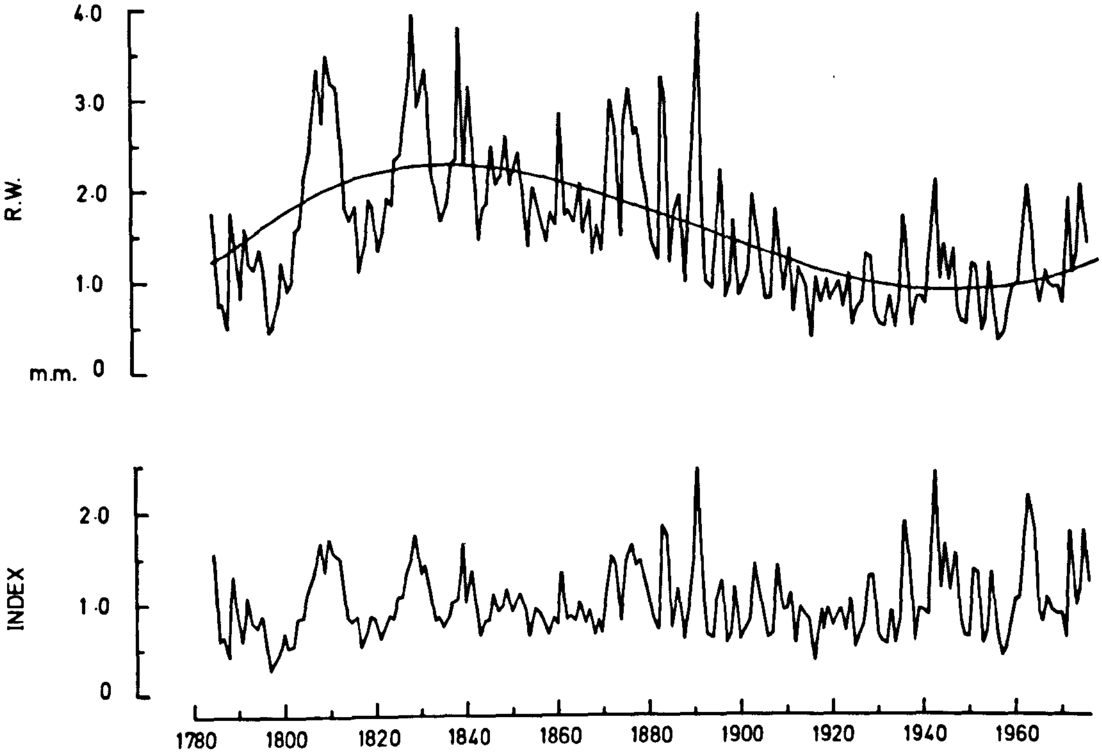
The value of the mean chronology which comprises indexed individual curves rather than ring-width curves is explained by

Figure 2.6 The two ring-width series from tree LP 570 from Peckforton

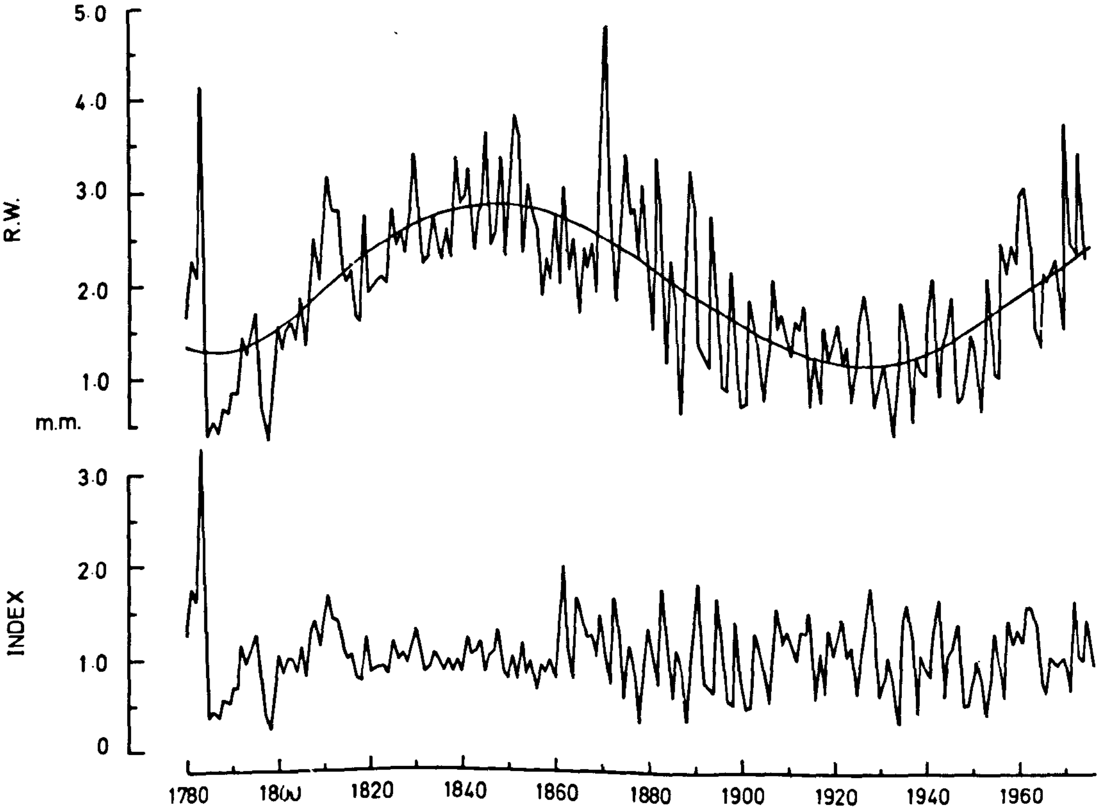
The ring-width series from two radii from tree LP 570 at Peckforton were fitted by polynomial curves (upper plots for each radius). The index series derived from them are shown below the ring-width series.

LP 570A is described by a polynomial equation with 4 coefficients. LP 570B is described by a polynomial equation with 6 coefficients.

LP 570A



LP 570B



Douglass(1936); 'Standardisation brings all ring-width curves to a uniform mean value so that one tree-ring record with a large average growth will not dominate other records of small average growth when the two series are combined into a mean chronology.'

Programme SUMMARY averages standardised ring-width indices to produce mean chronologies of several types: it will average index values for the cores of each tree, for types of radii, for example, north and south cores and finally all the cores to produce a master chronology for the site. The output of this programme includes a compact listing of all trees and all cores to provide a succinct reference to the master chronology and its basic statistical properties.

2.6.4 Analysis of variance

Programme ANOVA performs an analysis of variance. This is a powerful technique which sorts out and measures the sources in the tree-climate system which govern the variance of the master chronology. The sources of such ring-width variation within a woodland have already been described in section 2.6.3 and these have been shown to be considerable. The analysis of variance has been developed specifically for indices derived from tree-ring data which have been collected in such a way that several of these sources of error may be represented (Fritts,1976). The mean indices and sums of squares of indices for the individual core series calculated by programme CORE serve as input for the analysis of variance programme. The printed output of ANOVA is the estimated mean squares and percent of estimated mean squares for the core chronology, the tree chronology and the group chronology. The estimated mean squares provide an estimate of the variance component for each chronology. The percent of estimated mean squares measures the percentage of variability due to differences in chronologies several radii, differences in chronologies among the several trees as compared to the remaining variability in the chronology for the group. The analysis of variance aids in assessing the relative similarities and differences in the growth response of trees to their total environment.

Fritts (1976) gives a detailed description of the analysis of variance technique and the implications of the results using ring-width data collected from a stand of *Pinus longaeva* in California.

2.6.5 Cross correlation and serial correlation

Whilst it is desirable to use the analysis of variance, it is often not possible to obtain the replication required for its use. In such cases, an important statistic, the correlation coefficient may be used which provides a relative measure of variability in common between two sets of data. Unlike analysis of variance, however, correlations cannot partition the variance into separate components. The correlation coefficient is important since it may be used to measure the association, if any, between series of ring widths and climatic factors, such as precipitation and temperature. It is defined as

$$rxy = \frac{\sum_{t=1}^{t=n} (x_t - m_x)(y_t - m_y)}{(n - 1)sx\,sy} \qquad \text{(Fritts, 1976)}$$

where x_t and y_t are two data sets, t represents time, mx, my, sx, sy are the means and standard deviations of the sets of data, n is the sample size. Correlation statistics are derived after the ring widths of individual radii have been standardised (section 2.6.3). Values may be calculated for the correlations between (i) cores within a tree, (ii) trees and (iii) chronologies from different sites. Correlation analyses may be run for a number of time intervals such as 10- or 20-year periods lagged every 5 years. A comparison of the results for different time periods allows an assessment of periods when ring widths were best correlated and hence most limited by climatic conditions as opposed to those of the site (Fritts,1976).

The use of analyses of variance and correlations provide a quantitative means by which the quality of the material sampled may be assessed.

Serial correlation

Programme CROSS also calculates another type of statistic, the autocorrelation or serial correlation coefficient. This is defined as 'the correlation between successive values in a time series or lagged correlation between two time series (Fritts, 1976). Thus, the ring index of a particular year may be correlated with that of the previous or following year or correlated with ring widths at lags greater than 1. The serial correlation coefficient is a measure of the importance of persistent trends or fluctuations in the record (LaMarche and Stockton, 1974).

Serial correlation may be calculated from the equation above by calculating the correlation coefficient for the terms x_t and

$x_t + L$ where L is the lag in years of the second ring behind the first and n is reduced in number by the length of the lag L. When L = 1 the serial correlation is of the first-order, when L = 2 it is of the second order and so on. If the items in a series are completely random with respect to their positions within the time series, the values of the computed serial correlations at all lags will be small and will vary in a random fashion about a mean value of zero (Fritts,1976). Fritts (1976) gives further details of serial correlation analyses.

In general, there is an inverse relationship between serial correlation and mean sensitivity (section 2.6.2) since the former measures the proportion of low-frequency variance while the latter measures the proportion of high-frequency variance. Mean sensitivity and the correlation coefficients described above are useful in the selection of chronologies for dendroclimatic analysis.

The Tucson programmes, RWLST and INDXA described in the preceding sections, have been modified by Mrs. Barbara Duncan to allow implementation in Extended Fortran on the Liverpool Polytechnic ICL 1903A computer under George 2 operating system.

2.7 Construction of modern chronologies

The construction of tree-ring chronologies requires firstly the establishment of correlations between the ring patterns of individual radii within the tree. For oak, the sampling of 2 radii per tree is sufficient to confirm the growth pattern of that tree. Although computer programmes are available which indicate the positions of the best matches between tree-ring series (section 2.5.2), all matches must still be checked visually. The reasons for choosing programme CROS (Baillie & Pilcher,1973) as the statistical test are given in section 2.5.2. In the present study, crossdating between tree-ring curves was considered to exist only when both the visual and statistical criteria had been satisfied. In the event of both criteria not being satisfied it was often possible, using the visual criterion to identify an area of doubt, for example, a group of very narrow rings consisting largely of earlywood. In such cases, a careful re-examination and remeasurement of the two radii was made utilising the marking system described in section 2.4 in the hope of detecting errors.

The crossdating method described above was found to be a valuable one and was used in establishing the reliability of ring identification and ring-width measurement.

Between-tree crossdating

In those trees where crossdating was established between the two radii, mean curves were prepared. Initially, this was done manually by summing the widths for a given year from the two radii and dividing by two. Subsequently, the time required to perform this operation was greatly reduced by the introduction of programme MEAN which was written by Dr. M.K. Hughes.

The same procedure of crossdating, based on both statistical and visual criteria was then applied to pairs of mean curves. For this purpose any measurements which came from only one of the two radii were omitted from the mean curve for that tree.

In order to be as reliable as possible, trees whose mean curves crossdated visually and were given by high't'values were initially combined into a working master against which the other materials could be tested. The production of this working master was done using the computer programme INDXA (Fritts et al, 1969) (section 2.6) as follows:

The unfiltered ring widths for each radius were converted to indices using the polynomial curve-fit option. This option was chosen after examination of the plots of the 20-year means for each core. Only a limited number of cores exhibited the exponential growth trend seen in conifers; the majority showed patterns of a more complex nature to which a negative exponential curve or straight line could not be fitted. In using the polynomial curve-fit option, a line of more or less close fit to the actual data can be produced. The level of 5% as the criterion for the addition of another coefficient was found to be an adequate one in the curve-fitting procedure. Figure 2.6 shows the polynomial curves fitted to the tree-ring series of cores LP570A and LP570B from Peckforton. Had the curves exhibited the same slope in all cores, this may have indicated that certain information was being removed.

The derived index values for all radii to be included in the working master were then combined to produce that master.

The materials not already included in the working master were tested for crossdating against it using the procedures described above. Where both within-tree and tree-working master crossdating was shown to exist, the two measured radii for that tree were included in the final chronology for the site. A flow chart of the procedures followed in the construction of a master site chronology is shown in Figure 2.7.

The ring widths of the cores included in the final Maentwrog chronology were passed through a high-pass and low-pass filter (section 2.6.1). These filtered ring widths were converted to indices using the polynomial curve-fit option and filtered site chronologies were constructed using the method described above. The characteristics of the three forms of the final site master were examined to determine the properties of the data.

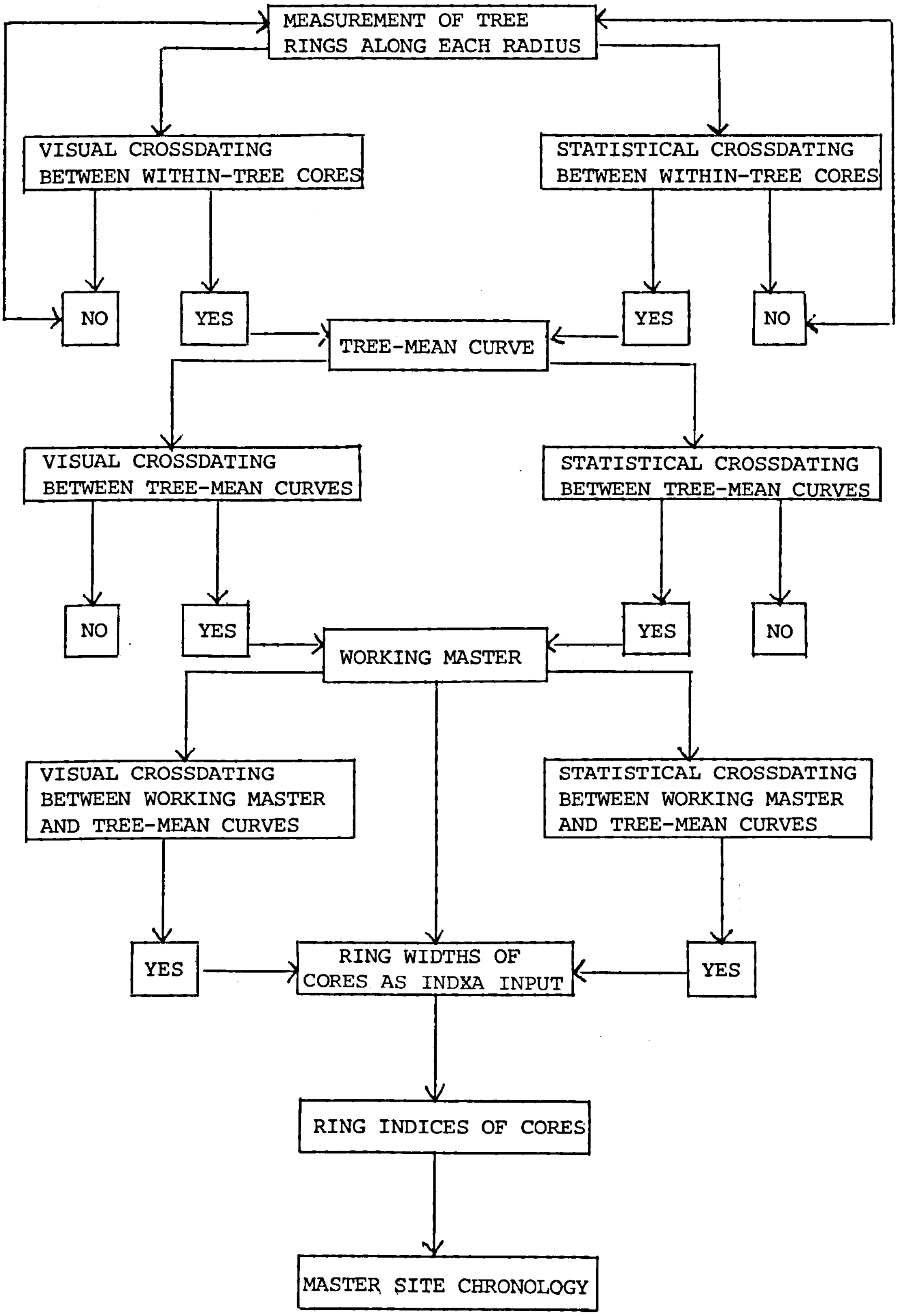


Figure 2.7 Flow chart for construction of a master site chronology

CHAPTER 3 - RESULTS

3.1 Maentwrog

- 3.1.1 Working master and the standard chronology
- 3.1.2 Chronology statistics

3.2 Peckforton

- 3.2.1 Working master and the standard chronology
- 3.2.2 Chronology statistics

3.3 Comparisons of modern standard chronologies

- 3.3.1 Maentwrog and Peckforton chronologies
- 3.3.2 Maentwrog, Peckforton and British Isles chronologies
- 3.3.3 Maentwrog, Peckforton and European chronologies

3.1 Maentwrog

3.1.1 Working master and the standard chronology

Within-tree crossdating was established in 38 of the 40 trees sampled which included 10 provided by Mr. S.J. Milsom. The two trees which failed to crossdate internally had been sampled as cores and contained groups of very narrow rings that could not be resolved. Had these trees been sampled as discs a clearer pattern of growth may have been found along other radii. There was no evidence of either missing rings or apparent double rings in any of the radii measured. 'T' values obtained for matches within the tree were high ranging from 7.30 to 24.05. The mean ring width of cores ranged from 0.56 mm to 2.63 mm.

Thirteen of the 38 trees which exhibited within-tree crossdating were combined into a working master against which the remaining 25 were tested. Figure 3.1 shows the working master in an indexed form and the mean curves from which it was constructed which are shown in ring-width form. The working master spans the period 1710-1974 in which a number of characteristic years are marked by vertical lines, namely 1839, 1882, 1906 and 1966. The output of programme CROS (Baillie & Pilcher, 1973) for trees comprising the working master is shown in Table 3.1 as probabilities for each pair of tree-mean curves. The probability of 'r' (the correlation coefficient) occurring by chance is less than 0.0001 in 60% of the pairs.

A further 24 mean curves crossdated with the working master. 35 of this total of 37 were then combined using the method

Figure 3.1 Maentwrog working master and its components.

The upper thirteen curves are of mean ring width for each tree,plotted on a semi-logarithmic scale.

The lower curve is the thirteen-tree working master, produced by merging indices as described in the text.

MAENTWROG: WORKING MASTER AND ITS COMPONENTS

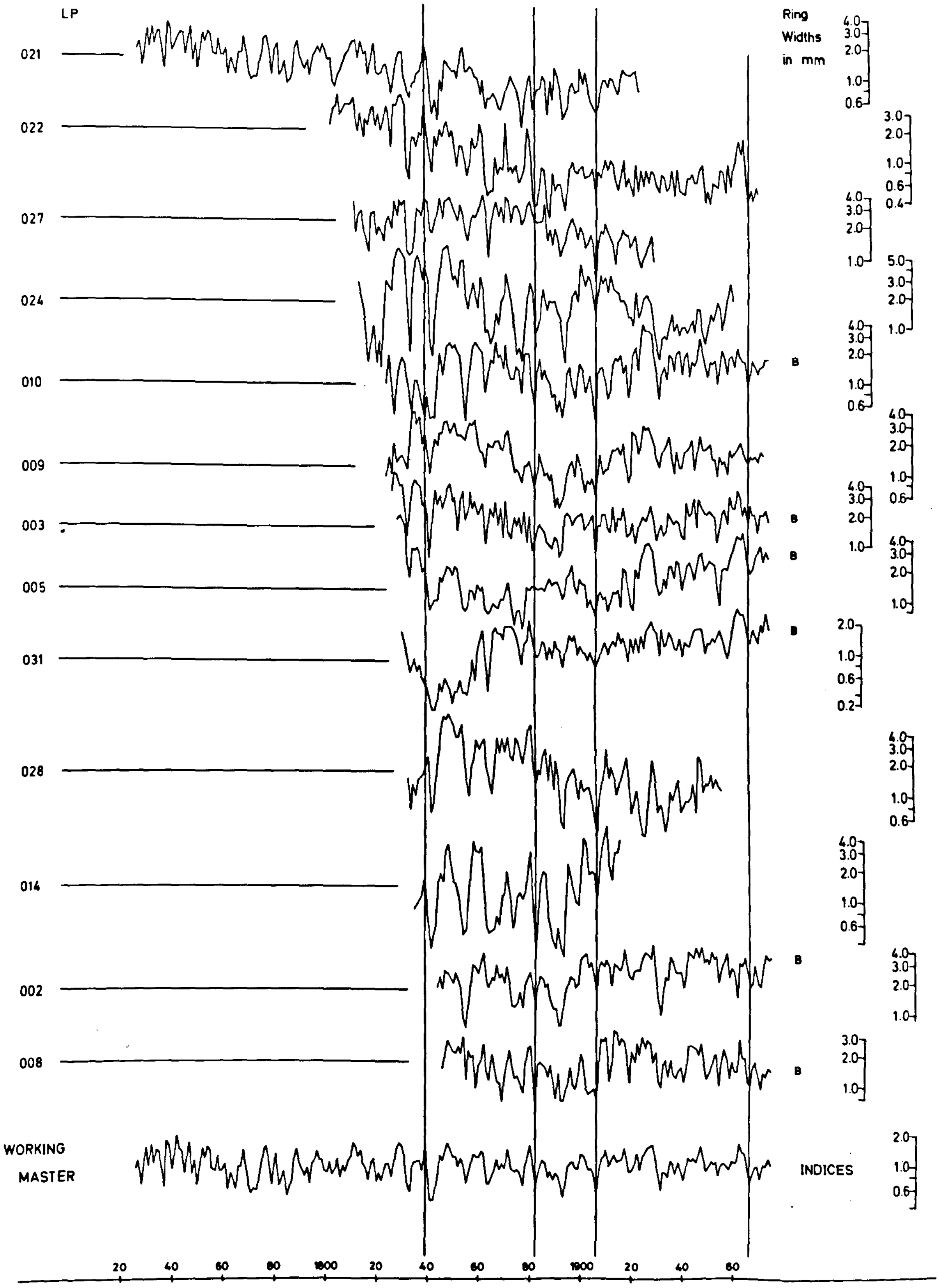


TABLE 3.1

Probabilities of observed values of 'r' between components of the working master arising by chance.

LP No.	003	005	008	009	010	014	021	022	024	027	028	031
002	xxx	xxx	xxx	xxx	xxx	xxx	x	xx	xx	xx	xx	xx
003		xx	xxx	xxx	xxx	xx	xxx	xxx	xx	xxx	xxx	xx
005			xxx	xxx	xxx	xxx	x	xxx	xxx	xxx	xx	xx
008				xxx	xxx	xxx	xxx	xx	xx	xx	xx	xxx
009					xxx	xx	xx	xxx	xxx	x	xx	x
010						xxx	xx	xx	xx	xx	xx	xxx
014							xx	xxx	xxx	xx	xxx	xxx
021								xxx	xxx	xxx	xxx	xx
022									xxx	xxx	xx	xxx
024										xxx	xxx	xxx
027											xxx	xxx
028												xxx

x $\leqslant$ 0.02

xx $\leqslant$ 0.001

xxx $\leqslant$ 0.0001

described in Section 2.7 to produce a standard Maentwrog chronology for the period 1710-1974. The temporal distribution of the components of the chronology is shown in Figure 3.2. Where bark was present at the time of sampling the notation 'B' is used. The number of sapwood rings is shown by a hatched area at the distal end of the record. Where the two radii measured for an individual tree had differing numbers of sapwood rings, the earlier sapwood boundary is shown by a vertical bar. The position of the later boundary is indicated by a broken vertical line. It can be seen that as most of the trees sampled by increment corer or recently felled have a complete record up to and including the bark, the materials present an opportunity to produce a chronology anchored at a known felling date.

Two trees (LP 016 and LP 017) which did crossdate with the working master were not included in the standard Maentwrog chronology because of a limit on the number of series the Liverpool version of the INDXA package can summarise.

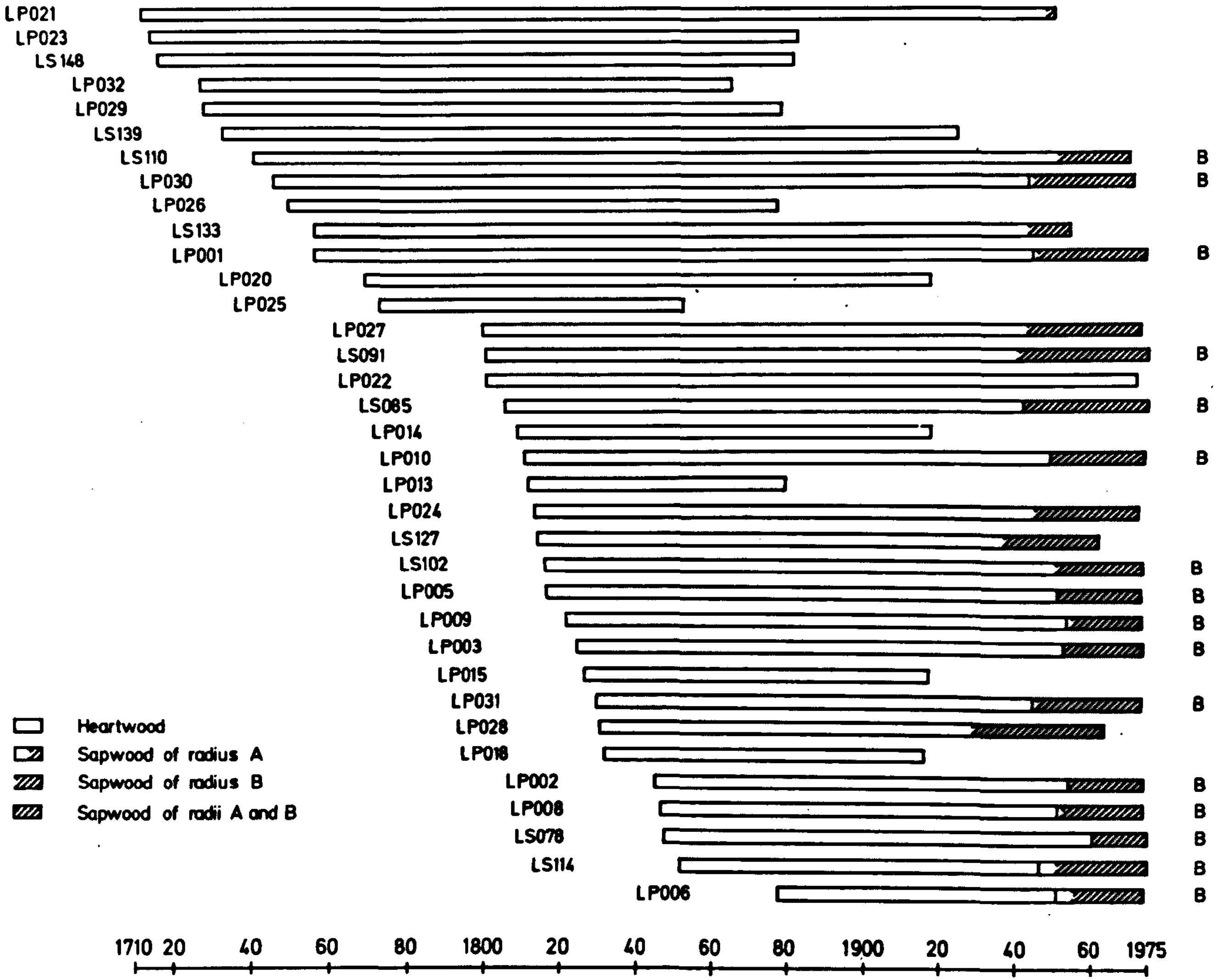
3.1.2 Chronology statistics

The Maentwrog Index chronology is shown in Figure 3.3 and the indices of this chronology series comprising 35 trees are given in Appendix IV. The chronology statistics for the period spanned by the standard Maentwrog chronology (1710-1974) are shown in Table 3.2. Of the 35 trees comprising this chronology, 14 were selected that covered the longest common period and a statistical analysis was carried out for the period 1875-1952. Such a series is called the Anova series (Section 2.6.4) and is

Figure 3.2 Temporal distribution of components of Maentwrog chronology

Figure 3.3 Maentwrog Index chronology

COMPONENTS OF MAENTWROG CHRONOLOGY



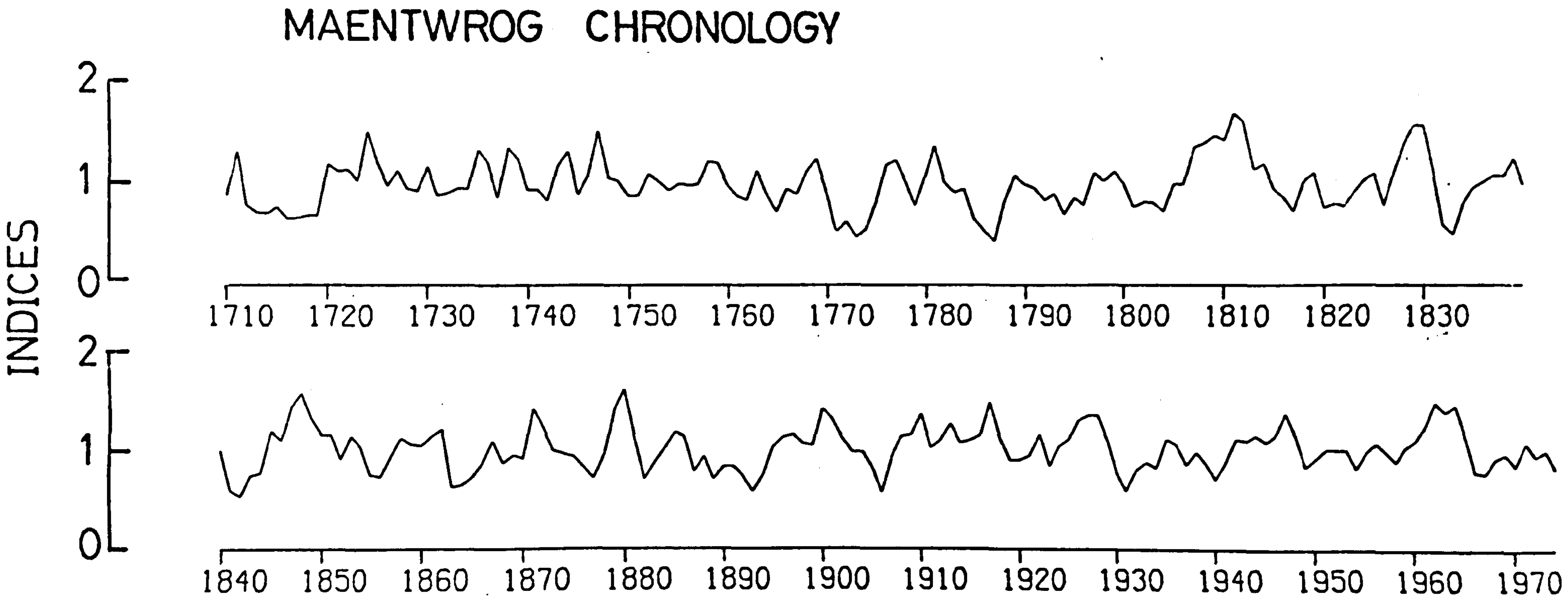

MAENTWROG CHRONOLOGY
INDICES
2
1
0
1710
1720
1730
1740
1750
1760
1770
1780
1790
1800
1810
1820
1830
2
1
0
1840
1850
1860
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970

TABLE 3.2

General statistics for Maentwrog oaks

Chronology series

Number of trees - 35

Number of radii - 70

Mean ring width - 1.59 mm

Method of standardisation	Polynomial curve-fit	High-pass filter	Low-pass filter
Years analysed	265	251	251
Interval	1710-1974	1717-1967	1717-1967
Mean index	0.9949	0.9991	0.9998
Serial correlation	0.6231	0.0845	0.9026
Mean sensitivity	0.1844	0.0905	0.0503
Standard deviation	0.2519	0.0858	0.1419

Anova series

Number of trees - 14

Number of radii - 28

Years analysed - 78

Interval - 1875-1952

Method of standardisation	Polynomial curve-fit	High-pass filter	Low-pass filter
Mean index	0.9887	0.9993	0.9973
Serial correlation	0.5300	-0.0350	0.9381
Mean sensitivity	0.2521	0.1133	0.0583
Standard deviation	0.3340	0.0955	0.1873

Analysis of variance Results

	Polynomial curve-fit	High-pass filter	Low-pass filter
Per cent variance, Years	25.5317	30.4721	14.2647
Per cent variance, Years x Trees	41.7048	40.7021	39.1465
Per cent variance, Years x Radii x Trees	32.7635	28.8258	46.5888
Error of y	0.0777	0.0232	0.0494

Cross-correlation Results

	Polynomial curve-fit	High-pass filter	Low-pass filter
mean correlation of cores			
within trees: r =	0.652	0.697	0.500
between trees: r =	0.264	0.334	0.165
mean correlation between trees, r =	0.310	0.386	0.204

the series used for analysis of variance and correlation analyses. The general statistics of the Anova series are also shown in Table 3.2.

To illustrate temporal variation in the Maentwrog chronology, the general statistics of the Anova series are plotted for 10-year periods lagged every 5 years (Figure 3.4).

Mean sensitivity (Figure 3.4(c)) shows little variation during the period analysed with the lowest values appearing during the periods 1895-1904 and 1935-1944. Greater variation was found in the mean index and correlation among trees which in general changed in opposition to one another (Figures 3.4(a) and (b)). The correlation coefficients are plotted on an inverse scale to illustrate this feature. The values of mean index ranged from 0.841 to 1.131 and those of correlation among trees from 0.213 to 0.543. The periods of highest correlation were 1900 to 1914 and 1925 to 1934. Figure 3.4(a) indicates a relationship between mean index and correlation among trees; high mean index values appear to be associated with low coefficients of correlation. This association is best illustrated for the periods 1895-1904 and 1910-1919.

Examination of Figures 3.4(c) and (b) indicates a relationship between mean sensitivity and correlation among trees. For example, during the period 1895 to 1904 correlation among trees is low and mean sensitivity is low. During 1900 to 1909 the correlation coefficient is high as is mean sensitivity. However, this hypothesis does not appear valid for all periods.

Figure 3.4 Chronology statistics for Maentwrog oaks

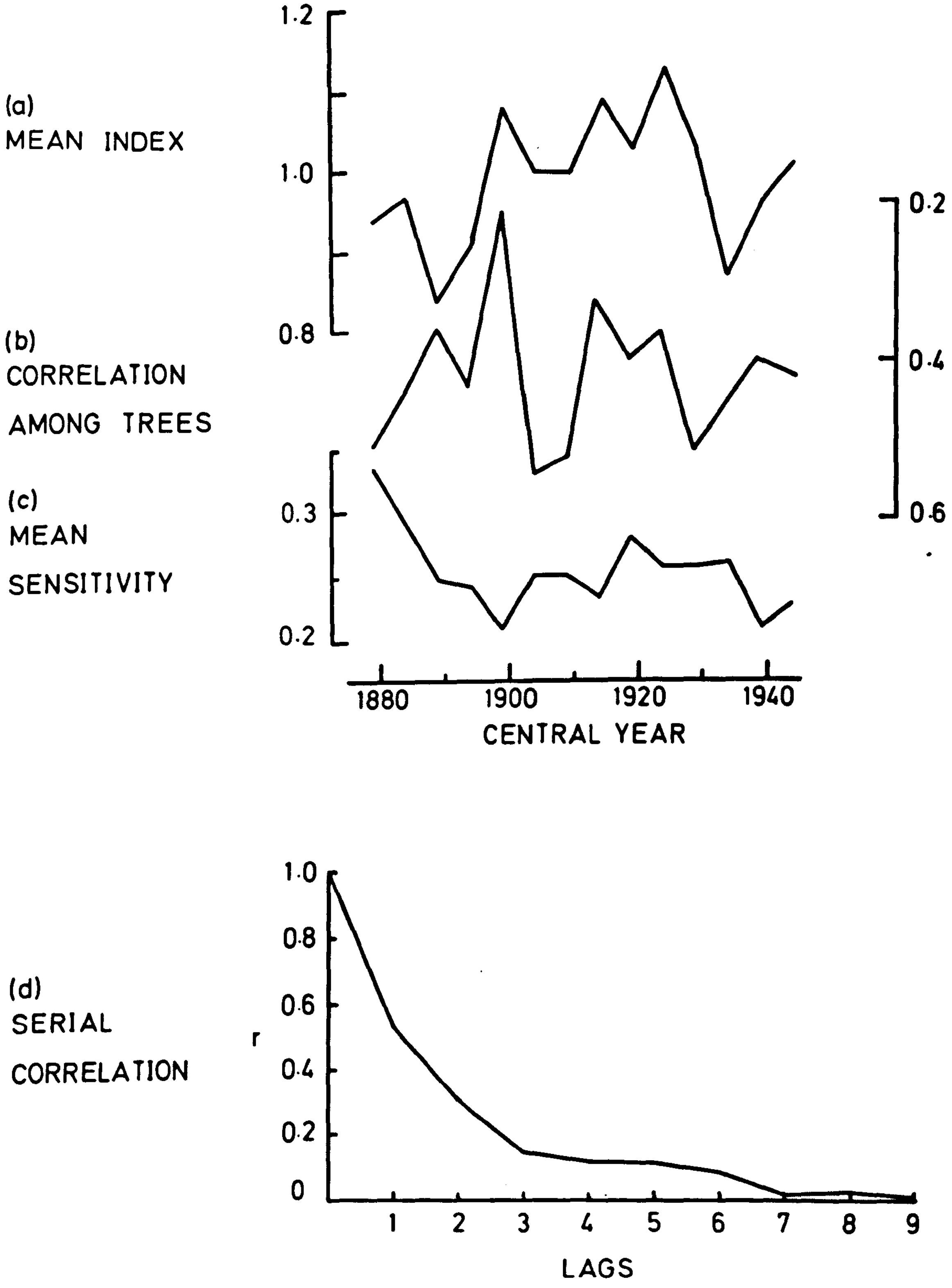
(a) Mean index for 10-year periods lagged every 5 years

(b) Correlation among trees for 10-year periods lagged every five years

(c) Mean sensitivity for 10-year periods lagged every 5 years

(d) Serial correlation: lags 1 through 9.

MAENTWROG


(a)
MEAN INDEX
(b)
CORRELATION
AMONG TREES
(c)
MEAN
SENSITIVITY
1.2
1.0
0.8
0.2
0.4
0.6
0.3
0.2
1880
1900
1920
1940
CENTRAL YEAR
(d)
SERIAL
CORRELATION
r
1.0
0.8
0.6
0.4
0.2
0
1
2
3
4
5
6
7
8
9
LAGS

Regression analyses were used to test for the existence of any association between the following chronology statistics:

1. mean index and correlation among trees
2. mean sensitivity and correlation among trees.

The data used in the computations are shown in scatter diagrams (Figures 3.5 (a) and (b)) together with the estimated regression lines. Student's t was used to determine whether the observed regression coefficient was significantly different from the hypothetical value, zero.

The statistics examined above are data which are not randomly distributed through time. Fritts (1976) considers that when such data are being handled, the number of degrees of freedom will be fewer than the number of observations. Ring-width indices are not randomly distributed through time since they are ordered chronologically according to the year of formation. This is also true for the mean index values calculated for 10-year periods lagged every 5 years. The effective sample size of a time series of ring-width indices is inversely related to the amount of significant autocorrelation or persistence that is present (Fritts, 1976). This reduction in sample size may be approximated by using the first-order autocorrelation (Section 2.6.5) in the equation proposed by Mitchell _et al._ (1966):

$$n' = n \frac{1 - r^1}{1 + r^1}$$

where n' is the effective sample size, n is the number of observations and r^1 is the first-order autocorrelation.

Since mean sensitivity is calculated for 10-year periods lagged every 5 years, consecutive values will be derived from 50% common data and will consequently be correlated with one another to some degree. The effective sample size was therefore calculated using the equation described above.

Table 3.3 shows the results of the regression analyses, sample size before and after correction, Student's t and significance at the 5 per cent level. For the period 1875 to 1952 no significant association exists between mean index and correlation among trees or between mean sensitivity and correlation among trees.

It has been proposed that mean sensitivity is a good indicator of the quality of a chronology for dating (Fürst, 1963). The quality of the Maentwrog chronology was assessed by using the equation described by Fürst (1963) outlined in Section 2.6.2. For the period 1875 to 1952 the average mean sensitivity of 28 cores was 0.2512 and the mean sensitivity of the mean chronology was 0.1689. Thus R,

$$\frac{S_m}{S_E} = \frac{0.1689}{0.2512} = 0.6724$$

Figure 3.6(a) shows the minimum, maximum and average mean sensitivity of the individual curves and the mean sensitivity of the mean curve for different periods.

The serial correlation of the Maentwrog chronology (Anova series) is plotted in Figure 3.4(d) for lags 1 through 9. It shows an expected decline similar to that of a first-order

Figure 3.5 Relationship between

Maentwrog:

(a) Mean index and correlation among trees

(b) Mean sensitivity and correlation among trees

Peckforton:

(c) Mean index and correlation among trees

(d) Mean sensitivity and correlation among trees

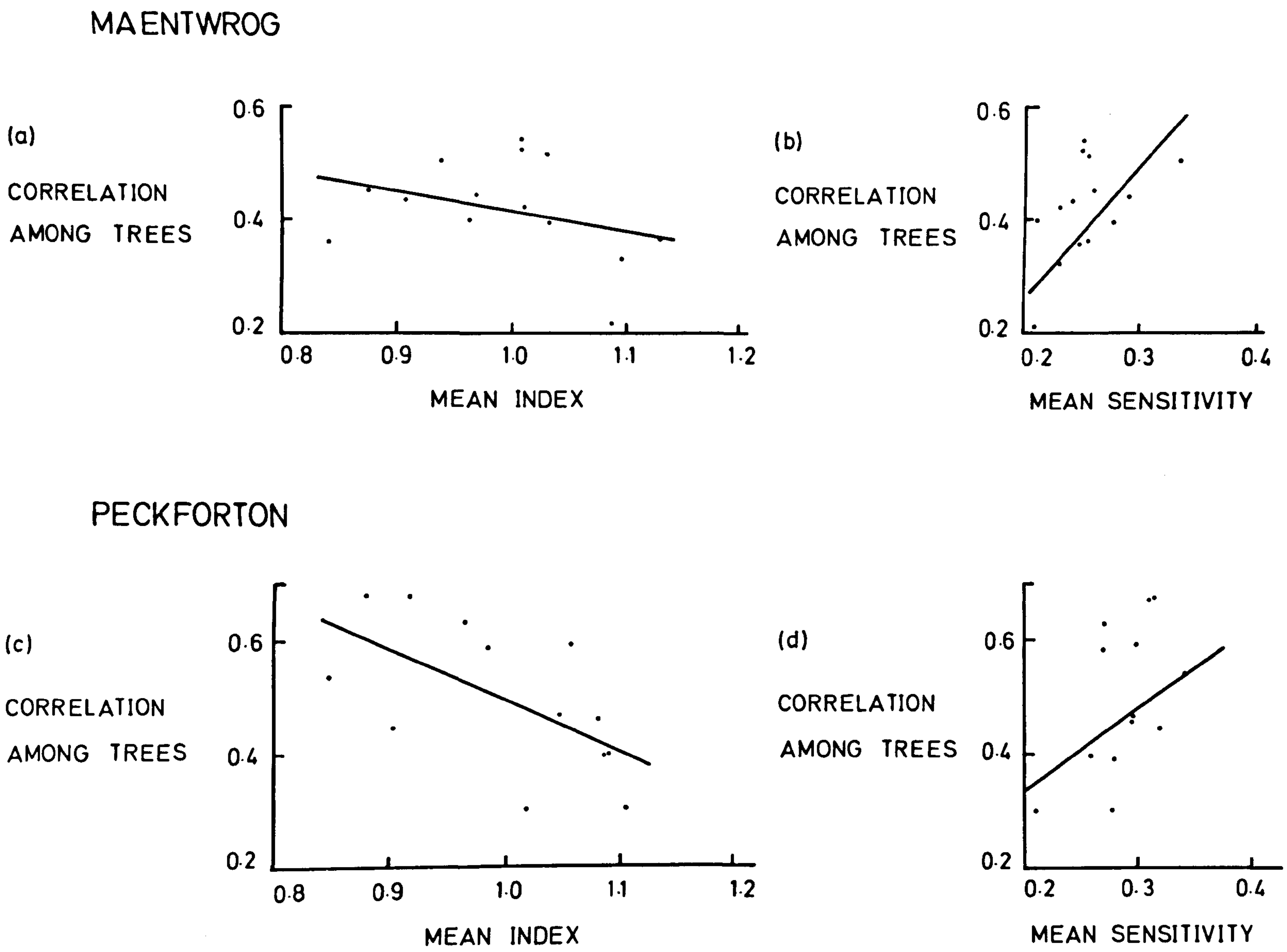

MAENTWROG
(a)
CORRELATION AMONG TREES
0·6
0·4
0·2
0·8
0·9
1·0
1·1
1·2
MEAN INDEX
(b)
CORRELATION AMONG TREES
0·6
0·4
0·2
0·2
0·3
0·4
MEAN SENSITIVITY
PECKFORTON
(c)
CORRELATION AMONG TREES
0·6
0·4
0·2
0·8
0·9
1·0
1·1
1·2
MEAN INDEX
(d)
CORRELATION AMONG TREES
0·6
0·4
0·2
0·2
0·3
0·4
MEAN SENSITIVITY

Table 3.3 Statistical analysis of relationship between certain chronology statistics for two oak chronologies

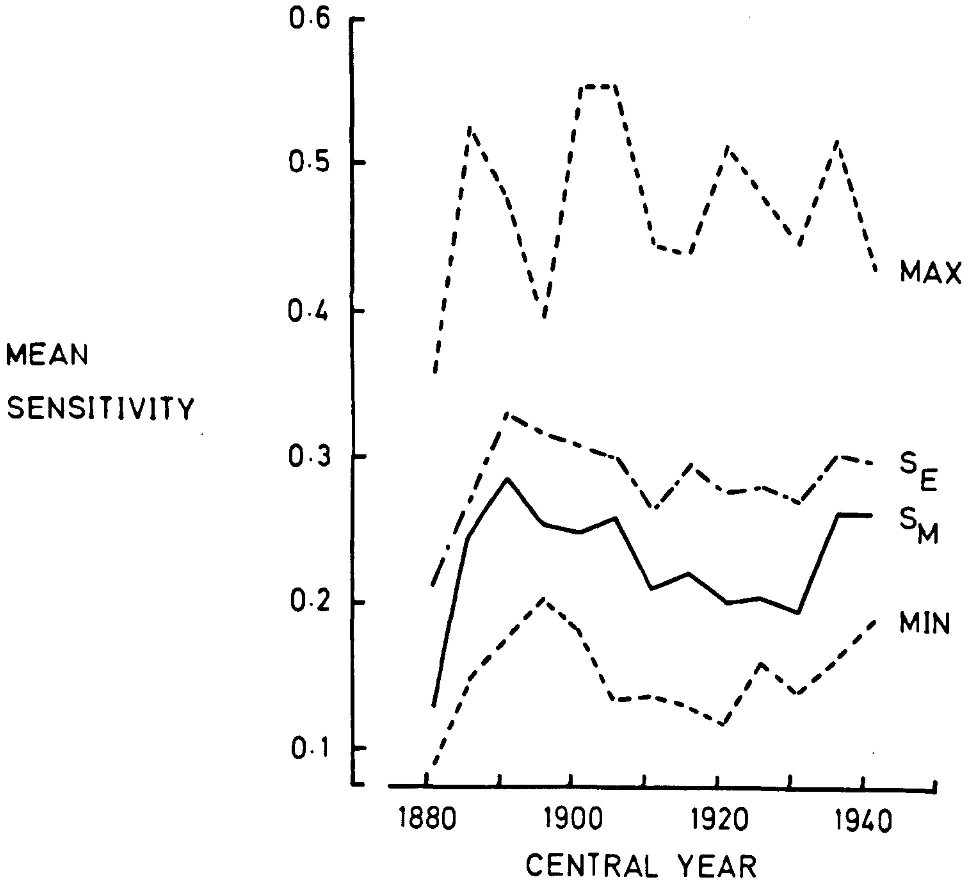
parameters	regression equation	t	actual sample size	serial correlation	effective sample size	significance at 5 per cent
<u>Maentwrog</u>						
(a) Mean index and correlation among trees	$y = -0.350x + 0.768$	-1.197	14	-0.330	8	None
(b) Mean sensitivity and correlation among trees	$y = 1.475x + 0.047$	2.026	14	0.423	6	None
<u>Peckforton</u>						
(c) Mean index and correlation among trees	$y = -0.096x + 1.410$	6.444	13	0.596	3	None
(d) Mean sensitivity and correlation among trees	$y = 0.624x + 0.320$	2.231	13	0.345	6	None

Figure 3.6 Fluctuation in mean sensitivity for the mean chronology and individual tree-ring curves

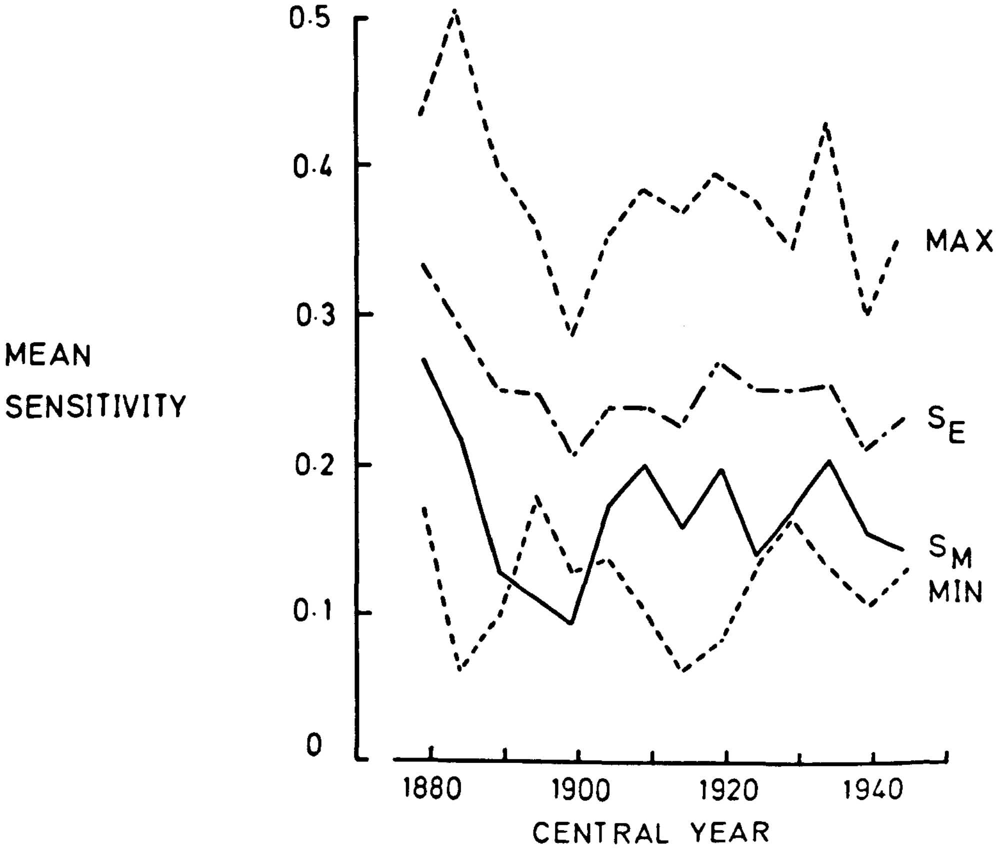
(a) Maentwrog

(b) Peckforton.

(a) MAENTWROG



(b) PECKFORTON



correlation model in which a linkage of each value in a time series with only the condition of the item immediately preceeding it is represented (Fritts, 1976).

The analysis of variance (Table 3.2) performed by INDXA (Fritts et al., 1969) permits the calculation of the signal to noise ratio in a tree-ring series. This ratio indicates the amount of ring-width variation that is due to climatic factors, the signal, and that due to nonclimatic factors such as stand development, management, ontogeny, the noise. Those chronologies of most value in the determination of climatic relationships and climatic reconstruction are those with the highest signal to noise ratio. The ratio is calculated by

$$\mathrm{VC(Y)} : \frac{\mathrm{VC(YT)}}{\text{no. trees}} + \frac{\mathrm{VC(YCT)}}{\text{no. cores x trees}}$$

where the number of trees was 14 and the number of cores was 2 per tree. The signal to noise ratio was 6:1. For the full chronology of 35 trees and 2 cores per tree the ratio was 12:1.

A study of the variation of the tree-ring data was made through the application of digital filters. The statistics of the Maentwrog chronology, after filtering with both the high-pass filter which blocks variance with wavelengths greater than eight years and the low-pass filter which blocks variance with wavelengths less than eight years are shown in Table 3.2. Of the three, the high-pass filtered series has the lowest first-order serial correlation whilst the low-pass filtered series has the lowest mean sensitivity. This series has the highest first-order serial correlation. Analysis of variance shows that the variance retained by the common chronology is higher in the high-pass series than in the unfiltered series. This variance is much lower in the low-pass series. The value of such filtered series is examined in Chapter 6.

3.2 Peckforton Hills

3.2.1 Working master and the standard chronology

Of the 27 trees sampled, 21 proved suitable for inclusion in a chronology, as 6 were found to be too short-lived. Crossdating was established within the tree in 20 of the suitable 21 trees. The one tree (LP 569) which did not crossdate internally contained several bands of very narrow rings which could not be adequately resolved to allow precise measurement. The Student's t values obtained for the internal matches were high ranging from 4.29 to 21.42 with values greater than 10.0 being given by more than half of the pairs. The mean ring width of cores ranged from 0.88 mm to 2.45 mm.

In several cases it was not possible to measure the complete tree-ring sequence from the pith to the bark. For instance, measurements could only be made to the heartwood/sapwood boundary on tree LP 564 because the entire sapwood had become rotten. Consequently, the measured ring record was too short for inclusion in the chronology. Similarly, distorted heartwood rings immediately inside the sapwood in tree LP 610 reduced the usefulness of the measured tree-ring sequence. Distorted rings in the outer portion of the sapwood in tree LP 609 prevented measurement to the bark and hence the final year of growth.

Eleven of the 20 trees which exhibited within-tree crossdating were combined into a working master against which the remaining 9 were tested. The working master covers 196 years spanning the period 1780 to 1976 and is shown in Figure 3.7 in its indexed form together with the tree-mean curves from which it was constructed. The ring widths of the tree-mean curves are shown in millimetres. A number of characteristic years are marked by vertical lines namely 1844, 1888, 1947 and 1957. The Student's t values obtained between the components of the working master ranged from 3.90 to 19.71 so that the probabilities of observed values of 'r' (correlation coefficient) arising by chance were less than 0.0001 in all cases.

The effectiveness of the methods used in programme CROS which transform tree-ring sequences into bivariate normal data was investigated in terms of their autocorrelation. Since any data which are not randomly distributed through time have fewer degrees of freedom than the number of observations (Fritts, 1976), the original sample size or the number of years of overlap, in programme CROS, may be effectively reduced. It is therefore important to know how much, if any, autocorrelation remains in the transformed data.

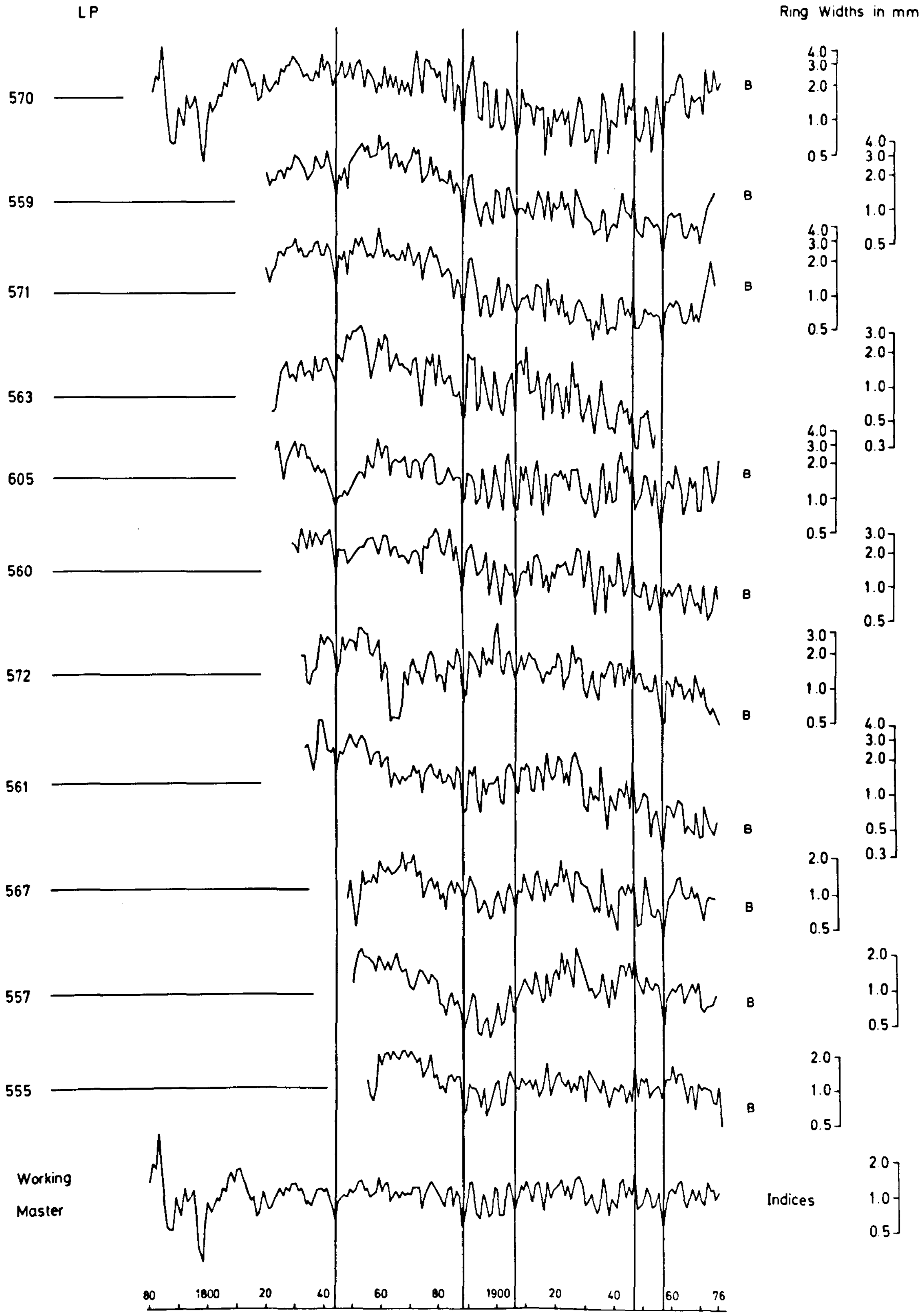
At Peckforton, trees LP 551 and LP 572 crossdated with a Student's t value of 5.45 with 116 years overlap ($p \leqslant 0.0001$). The autocorrelation present in the original ring widths of LP 551 and LP 572 were calculated for the 116 year common period and found to be 0.516 and 0.499 respectively. The autocorrelation values of the transformed series between which the values of 'r' were calculated were 0.029 and -0.123. From these autocorrelation values the effective sample sizes of the transformed series of LP 551 and LP 572 were found to be 106 years and 87 years respectively and 37 years and 39 years

Figure 3.7 Peckforton Working Master and its components

The upper eleven curves are of mean ring width for each tree, plotted on a semi-logarithmic scale.

The lower curve is the eleven-tree working master produced by merging indices as described in the text.

PECKFORTON : WORKING MASTER AND ITS COMPONENTS



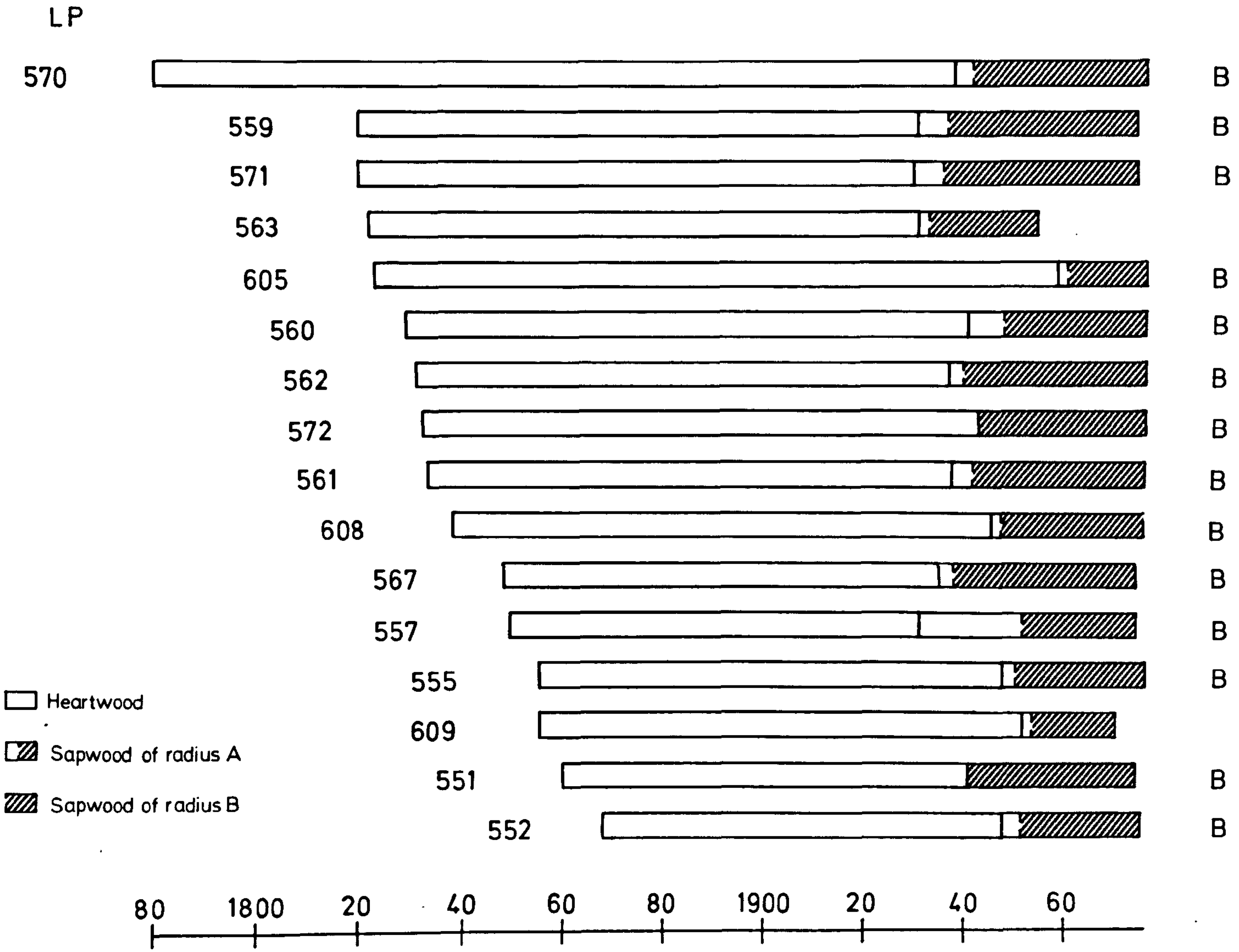
respectively for the raw ring-width series. Although these results show that programme CROS removes persistence effectively from the original tree-ring series, in this example the low values of 37 years and 39 years did not cause any increase in the level of probability obtained for the transformed data ($p \leqslant 0.0001$). However, for other pairs the original autocorrelations for the period of overlap may have been sufficiently high to affect the sample size and hence the statistical significance of the results of programme CROS.

In the final stage of the Peckforton chronology, a further 7 tree-mean series were found to cross-date with the working master. This total of 18 trees was combined using the method described in Section 2.7 to produce a standard Peckforton chronology for the period 1780 to 1976. Examination of the correlations between trees given in the output of the INDXA package (Fritts et al. 1969) revealed that two trees (LP 554 and LP 556) were negatively correlated with several other trees comprising the standard chronology. Since such relationships are undesirable, these trees were removed so that the standard Peckforton chronology comprised only those trees which represented a strongly correlated group. The temporal distribution of the components of the revised chronology is shown in Figure 3.8. The notations used in this figure are described in conjunction with Figure 3.2.

It can be seen that the majority of trees included in the standard Peckforton chronology have a complete ring record up to and including the bark. The ring pattern which terminates

Figure 3.8 Temporal distribution of components of Peckforton chronology. Explanation in text.

COMPONENTS OF PECKFORTON CHRONOLOGY



in 1955 is that exhibited by tree LP 563, the tree sampled as a weathered stump. The ring record of tree LP 609 terminates prematurely due to the distorted sapwood rings which prevented measurement up to the bark. The standard Peckforton index chronology is shown in Figure 3.9 and the indices of this chronology comprising 16 trees are given in Appendix V.

3.2.2 Chronology Statistics

The chronology statistics for the period spanned by the standard chronology (1780-1976) are shown in Table 3.4. Unlike the trees comprising the Maentwrog chronology, those comprising the Peckforton chronology covered a very similar time span. It was therefore possible to carry out further statistical analysis on all the trees in the standard chronology for the period 1877-1946. This is the Anova series.

The general statistics for this series are also shown in Table 3.4. The temporal variation of the Peckforton chronology was examined from plots of a number of the statistics calculated for the Anova period (Figure 3.10). Figure 3.10(c) shows mean sensitivity plotted for 10-year periods lagged every 5 years and illustrates the small variation in values. Values varied within the range 0.209 to 0.343. Figures 3.10(a) and (b) show mean index and an inverse plot of correlation among trees plotted for 10-year periods lagged every 5 years. Values of mean index ranged from 0.848 to 1.106 and those of correlation among trees from 0.300 to 0.678. Figures 3.10(a) and (b) illustrate the relationship between these two statistics which appear to vary in opposition to one another. The general downward trend followed

Figure 3.9 Peckforton Index Chronology

PECKFORTON CHRONOLOGY

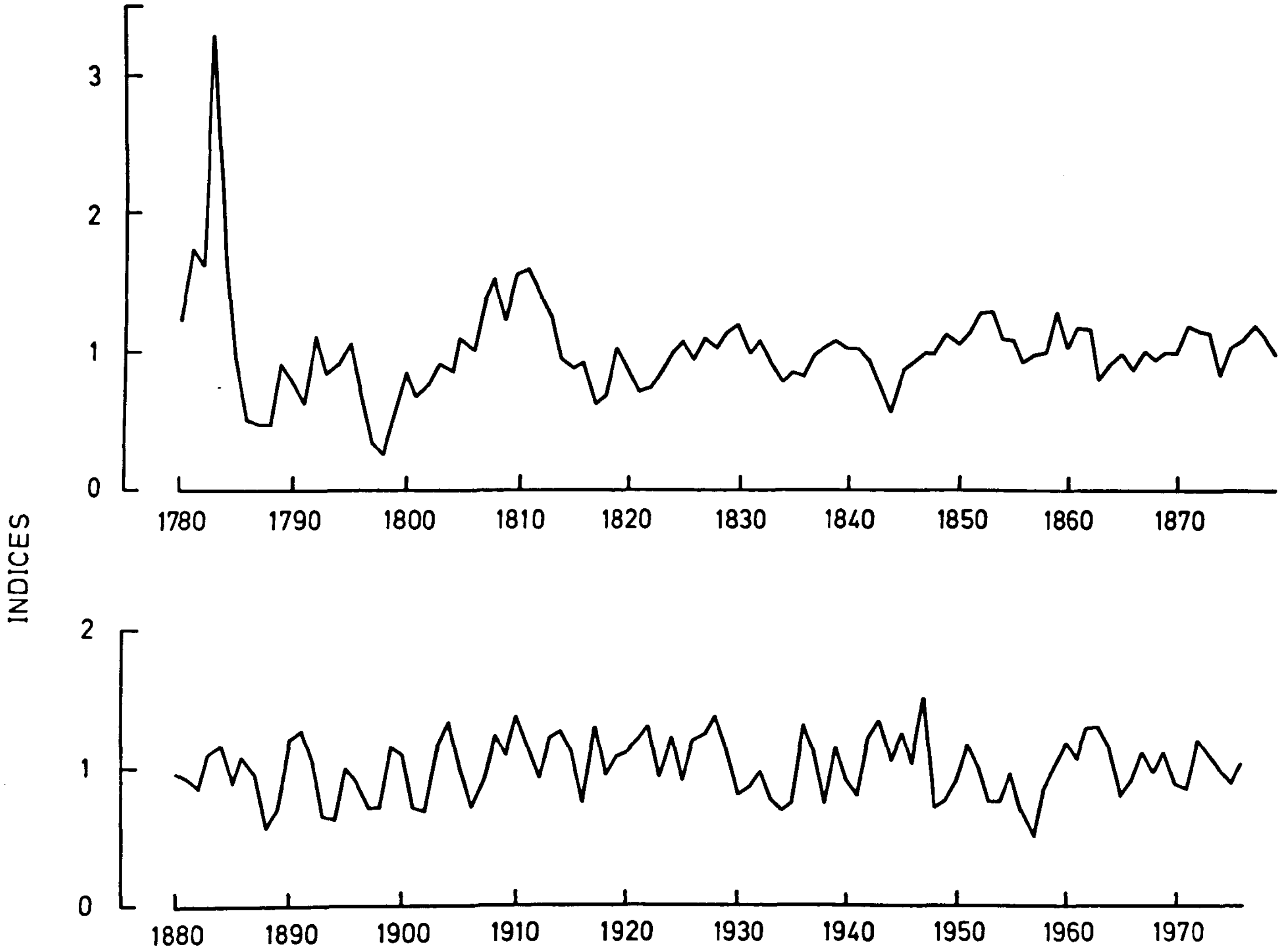


Figure 3.10 Chronology statistics for Peckforton oaks.

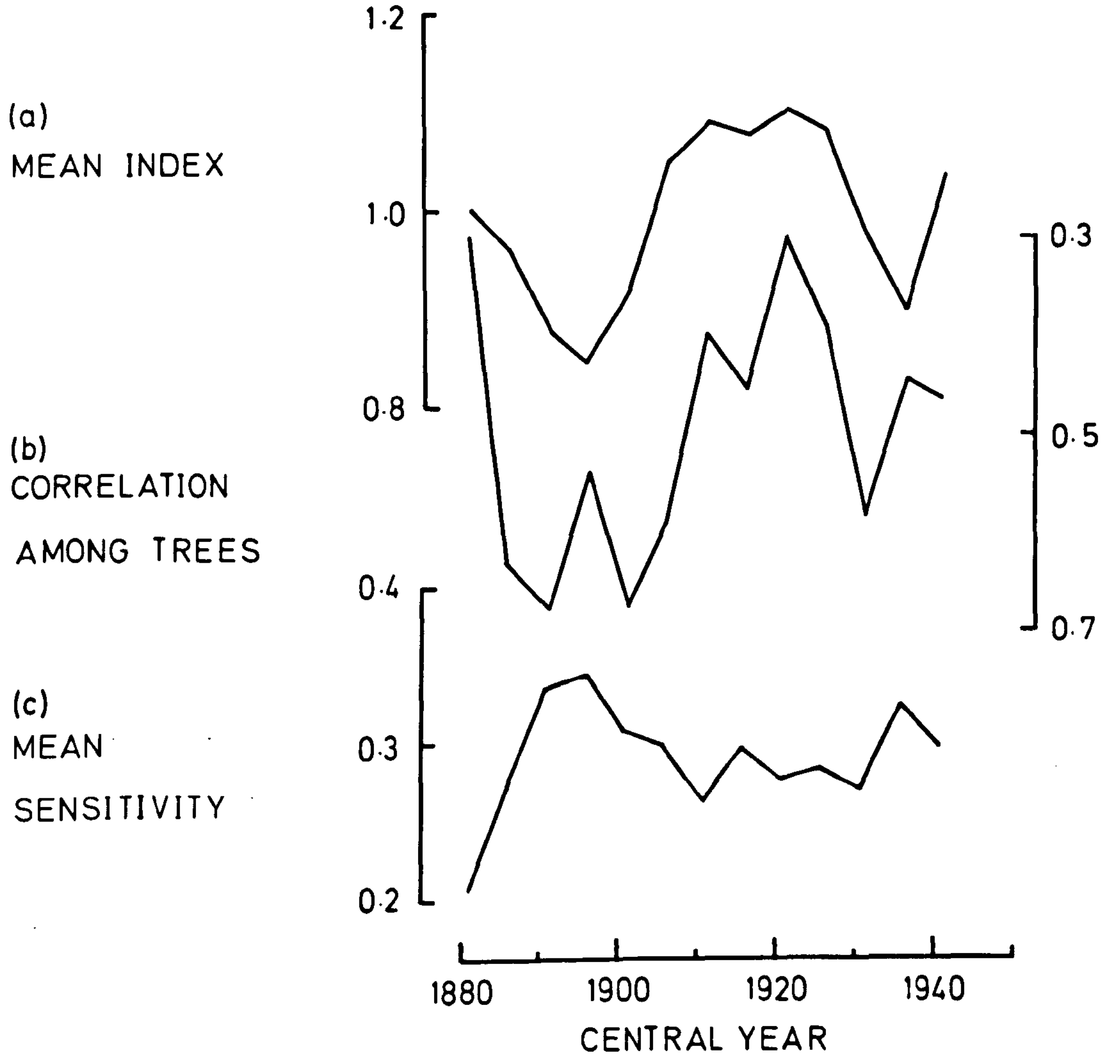
(a) Mean index for 10-year periods lagged every 5 years

(b) Correlation among trees for 10-year periods lagged every 5 years

(c) Mean sensitivity for 10-year periods lagged every 5 years

(d) Serial correlation: lags 1 through 9.

PECKFORTON


(a)
MEAN INDEX
(b)
CORRELATION
AMONG TREES
(c)
MEAN
SENSITIVITY
1·2
1·0
0·8
0·4
0·3
0·2
0·3
0·5
0·7
1880
1900
1920
1940
CENTRAL YEAR

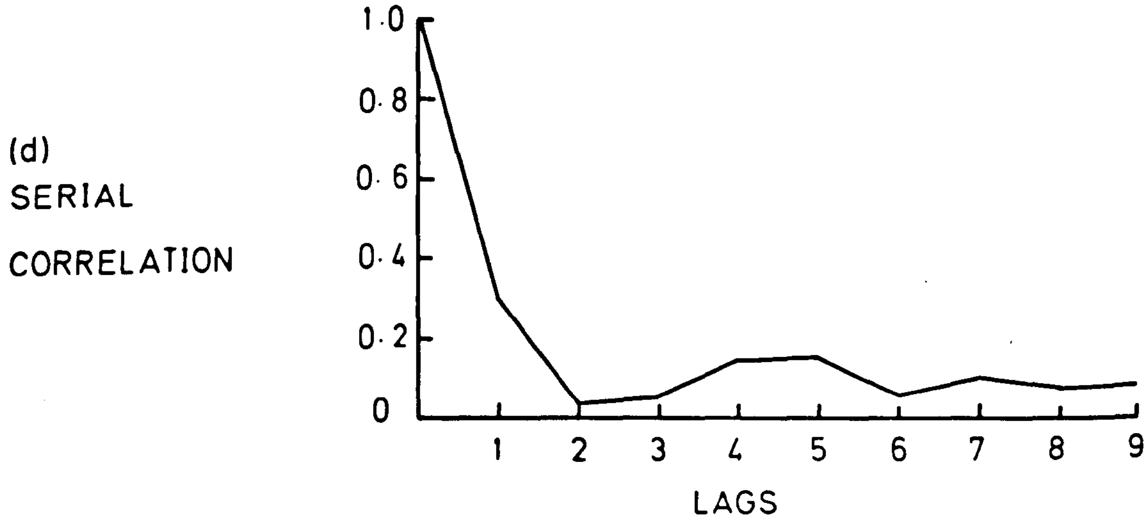

(d)
SERIAL
CORRELATION
1·0
0·8
0·6
0·4
0·2
0
1
2
3
4
5
6
7
8
9
LAGS

Table 3.4

General Statistics for Peckforton Oaks

Chronology Series

Mean ring width - 1.5248

Method of standardisation	Polynomial curve-fit	High-pass filter	Low-pass filter
Number of trees	16	15	15
Number of radii	32	30	30
Years analysed	197	183	183
Interval	1780-1976	1787-1969	1787-1969
Mean index	1.0065	0.9990	0.9937
Serial correlation	0.5257	-0.0550	0.9351
Mean sensitivity	0.1980	0.0834	0.0390
Standard deviation	0.2912	0.0704	0.1357

Anova Series

Method of standardisation	Polynomial curve-fit	High-pass filter	Low-pass filter
Number of trees	16	15	15
Number of radii	32	30	30
Years analysed	70	62	62
Interval	1877-1946	1885-1946	1885-1946
Mean index	1.0045	0.9967	1.0110
Serial correlation	0.2970	-0.1060	0.9180
Mean sensitivity	0.2851	0.1273	0.0412
Standard deviation	0.3140	0.1136	0.1318

Analysis of variance Results

	Polynomial curve-fit	High-pass filter	Low-pass filter
Per cent variance, Years	32.7165	32.2009	16.9614
Per cent variance, Years x Trees	24.4681	20.8331	5.9730
Per cent variance, Years X Radii x Trees	42.8155	46.9700	77.0600
Error of y	0.0505	0.0212	0.0226

Cross-correlation Results

	Polynomial curve-fit	High-pass filter	Low-pass filter
Mean correlation of cores,			
within trees: r =	0.577	0.633	0.330
between trees: r =	0.344	0.398	0.234
Mean correlation between trees: r =	0.351	0.487	0.257

by an upward trend in mean index appears to correspond with the upward and downward trends exhibited by the coefficients of correlation.

Regression analyses were carried out to test for the existence of any association between the following pairs of parameters:

1. mean index and correlation among trees
2. mean sensitivity and correlation among trees.

The results of the analyses are shown in Table 3.3 and the data used are shown in the scatter diagrams with the estimated regression lines (Figures 3.5(c) and (d)). For the period 1877 to 1946 there was no significant association between either mean index and correlation among trees or mean sensitivity and correlation among trees.

However, the mean sensitivity values of both the cores and the mean chronology may be used to examine the dating quality of the master chronology (Fürst, 1963; and Section 2.6.2). For the period 1877 to 1946, the average mean sensitivity of 32 cores was 0.2851 and the mean sensitivity of the mean chronology was 0.2192. Thus

$$R = \frac{S_m}{S_E} = \frac{0.2192}{0.2851} = 0.7689$$

Figure 3.6(b) shows the minimum, maximum and average mean sensitivity of the individual curves and the mean sensitivity of the mean curve for different periods.

Figure 3.10(d) shows the serial correlation of the Peckforton chronology (Anova series) for lags 1 through 9.

The amount of ring-width variation due to climatic and non-climatic factors was calculated using the equation described in Section 3.1.2. For 16 trees and 32 cores (2 cores per tree) the signal:noise ratio was 11.2:1.

The statistics discussed above apply to the unfiltered Peckforton index series. Digital filters were applied to the Peckforton tree-ring data to study the variance at certain frequencies. Table 3.4 shows the statistics of the Peckforton chronology after filtering with both high-pass and low-pass filters (Section 2.6.1). First-order serial correlation is lowest in the high-pass filtered series and greatest in that passed through a low-pass filter. Mean sensitivity is lowest in this latter series. Analysis of variance shows that the variance retained by the common chronology is different in the filtered chronologies. The variance for the high-pass series is higher than that in the unfiltered series but in the low-pass series this variance is greatly reduced. The high-pass series shows the greatest correlation between cores within trees.

3.3 Comparisons of modern standard chronologies

Previous to and during the course of the present study, several workers have been attempting to construct modern, absolutely dated tree-ring chronologies for a number of regions in the British Isles. In Sections 3.1 and 3.2 the construction of chronologies for the north west of England and North Wales has been described. The oak chronologies constructed for other British Isles sites are given in Tables 3.5 and 3.6. The Belfast regional chronology (Baillie, 1977a) is an extension of the Belfast regional chronology reported by Baillie (1973b) for A.D. 1380 back to A.D. 1001. Figure 3.11 shows the locations of the British Isles chronologies. The existence of these chronologies allowed a comparison of tree-ring patterns from different parts of the British Isles to determine the area in which a similar pattern of tree growth occurs.

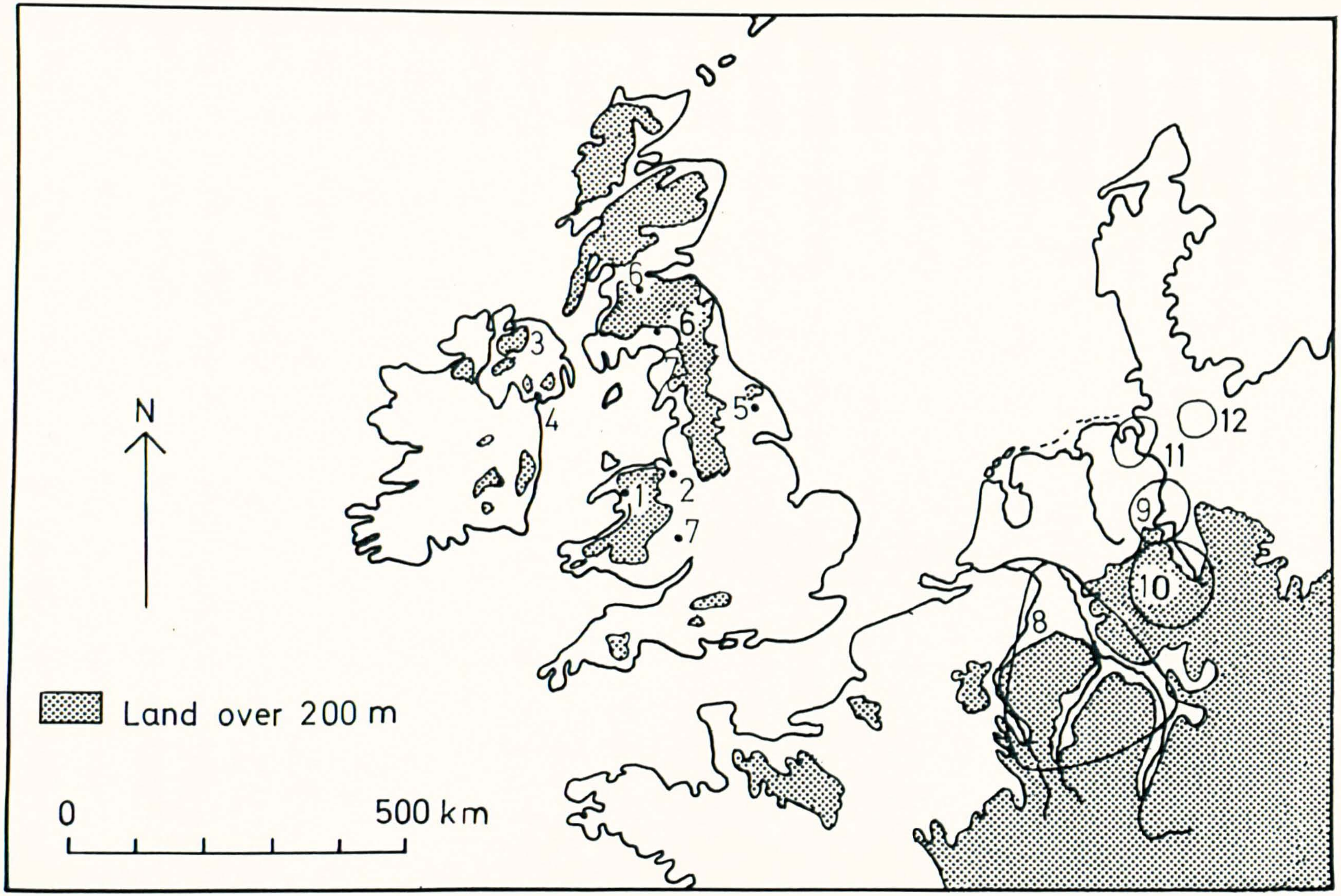
The comparisons were made using two computer programmes. The existence of crossdating between the chronologies was tested using programme CROS (Baillie & Pilcher, 1973) which is described in Section 2.5.2. Visual crossdating checks were made using the criteria described in Section 2.5.2. Programme CROSS, one of the programmes in the INDXA package (Fritts et al., 1969) which is described in Section 2.6 was used to calculate the cross-correlations for a common period spanned by all the chronologies. This period was 1800 to 1965 and is hereafter referred to as the full period. In order to assess when the indices were best correlated, correlations were also calculated for 10-year periods lagged every 5 years.

Figure 3.11 Location of European oak chronologies

<u>Key</u>

1. Maentwrog
2. Peckforton
3. Belfast
4. Rostrevor
5. Yorkshire
6. South West Scotland
7. Cumberland/Herefordshire
8. West German
9. Weser and Leine Uplands
10. South German
11. Lower Saxony Coastal Plain
12. Hamburg

LOCATION OF OAK CHRONOLOGIES



3.3.1 Maentwrog and Peckforton chronologies

The value of Student's t between the Maentwrog and Peckforton chronologies at the known position of match was 3.84 ($p \leqslant 0.00005$). The curves were also matched by programme CROS (Baillie & Pilcher, 1973) at four wrong positions as given by significant 't' values which ranged from 3.54 to 3.99 with overlaps longer than 100 years. However, these matches could be discounted since the position of the correct match was the best in terms of visual crossdating and was already known from the independently dated curves. This result gave an indication of the problems that were likely to arise in comparing undated series, the type of series usually encountered in archaeological dating.

The correlation coefficient obtained from the INDXA output for the full period was 0.510. After correcting for autocorrelation within the series (Section 3.1.2) this value was found to be significant at the 1% level. The correlations between the unfiltered data of the Maentwrog and Peckforton chronologies for different periods are shown in Figure 3.14 and 3.15. There are a number of periods where correlation coefficients are high, for example 1800 to 1834, 1855 to 1874, 1905 to 1914, 1925 to 1934 and 1945 to 1954. During these periods the ring widths of the two chronologies were best correlated and therefore more limited by common climatic conditions rather than site factors. The plot also shows that negative correlations existed for 1845 to 1854, 1875 to 1884 and 1895 to 1904 when at such times the ring widths of each chronology changed in opposition to each other.

Table 3.5

Comparison of the Maentwrog chronology with some European oak chronologies; Student's t values, the probabilities of 'r' arising by chance and the correlation coefficient between British Isles chronologies for the period 1800-1965.

Chronology	Years spanned	no. of years overlap	t	'r'	r (1800-1965)
Peckforton	1710-1974	195	3.84	$p \leqslant 0.00005$	0.510
Belfast[a]	1001-1970	261	3.35	$p \leqslant 0.00023$	0.181
Rostrevor[b]	1750-1975	225	5.09	$p \leqslant 0.00001$	0.276
Yorkshire[c]	1800-1972	173	1.16	$p \leqslant 0.12507$	0.181
South West Scotland[d]	946-1975	265	3.30	$p \leqslant 0.00048$	0.217
Cumberland/Herefordshire[e]	1731-1969	230	5.66	$p \leqslant 0.00001$	0.309
West German[f]	822-1964	255	1.36	$p \leqslant 0.08851$	-
Weser Upland[g]	1004-1970	261	2.03	$p \leqslant 0.02275$	-
South German[h]	832-1960	251	1.63	$p \leqslant 0.05480$	-
Lower Saxony Coastal Plain[i]	1740-1972	233	2.78	$p \leqslant 0.00347$	-
Hamburg Marshland[j]	1338-1967	258	0.32	$p \leqslant 0.38209$	-
Vallø[k]	1840-1949	110	1.60	$p \leqslant 0.05620$	

[a] Baillie,(1977a); [b] Pilcher (1976); [c] Morgan (pers. comm.); [d] Baillie (1977c); [e] Siebenlist-Kerner (1978); [f] Hollstein (1965); [g] Delorme (1972); [h] Huber and Giertz-Siebenlist (1969); [i] Schwab (1975); [j] Eckstein, Mathieu & Bauch (1972); [k] Holmsgaard (1955).

Table 3.6

Comparison of the Peckforton chronology with some European oak chronologies; Student's t values, the probabilities of 'r' arising by chance and the correlation coefficients between British Isles chronologies for the period 1800-1965.

Chronology	Years spanned	no. of years overlap	t	'r'	r (1800-1965)
Maentwrog	1710-1974	195	3.84	$p \leqslant 0.00005$	0.510
Belfast[a]	1001-1970	191	4.29	$p \leqslant 0.00003$	0.293
Rostrevor[b]	1750-1975	196	2.84	$p \leqslant 0.00256$	0.337
Yorkshire[c]	1800-1972	173	5.93	$p \leqslant 0.00001$	0.311
South West Scotland[d]	946-1975	196	3.94	$p \leqslant 0.00005$	0.165
Cumberland/Herefordshire[e]	1731-1969	190	5.93	$p \leqslant 0.00001$	0.267
West German[f]	822-1964	185	1.71	$p \leqslant 0.04457$	-
Weser Upland[g]	1004-1970	191	1.54	$p \leqslant 0.06681$	-
South German[h]	832-1960	181	2.63	$p \leqslant 0.00466$	-
Lower Saxony Coastal Plain[i]	1740-1972	193	3.03	$p \leqslant 0.00135$	-
Hamburg Marshland[j]	1338-1967	188	0.03	$p \leqslant 0.50000$	-
Vallø[k]	1840-1949	110	2.10	$p \leqslant 0.01900$	-

[a] Baillie (1977a); [b] Pilcher (1976); [c] Morgan (pers. comm.); [d] Baillie (1977c); [e] Siebenlist-Kerner (1978); Hollstein (1965); [g] Delorme (1972); [h] Huber & Giertz-Siebenlist (1969); [i] Schwab (1975); [j] Eckstein, Mathieu & Bauch (1972); [k] Holmsgaard (1955)

Although these results show that crossdating is present, filtering techniques may be used to separate the long-term and short-term variations so that the relationships among the series at different frequency ranges of variation can be studied. The general statistics of the filtered Maentwrog and Peckforton chronologies have been shown in Tables 3.2 and 3.4. Plots of the two site chronologies after filtering are shown in Figure 3.12. The correlation coefficient between the high-pass filtered chronologies was +0.302 which after correction for autocorrelation was significant even at the 0.1% level. The similarity between the short-term or high-frequency variations in the site chronologies is shown in Figure 3.12(a). Figure 3.12(b) shows the similarity between the long-term or low-frequency fluctuation in the two site chronologies. These smoothed series were positively correlated with a correlation coefficient of +0.615. However, low-pass filtered series by definition have much more autocorrelation than the high-pass filtered or unfiltered series. After correction for this autocorrelation the correlation coefficient of +0.615 was found not to be significant at any level.

Chronology variance

Table 3.7 shows the variances of the unfiltered indices and the filtered series of the two modern chronologies. The variances of the filtered sets are also shown as percentages of the variance of the unfiltered series. These results indicate that the filters used in this study are not perfect filters (there is some ambiguity in handling the variances at wavelengths near eight years (Fritts, 1976)) since the total variance of the filtered series (0.063 at Maentwrog and 0.046 at Peckforton)

Figure 3.12 Maentwrog and Peckforton high-pass and low-pass filtered chronologies

(a) High-pass series

(b) Low-pass series

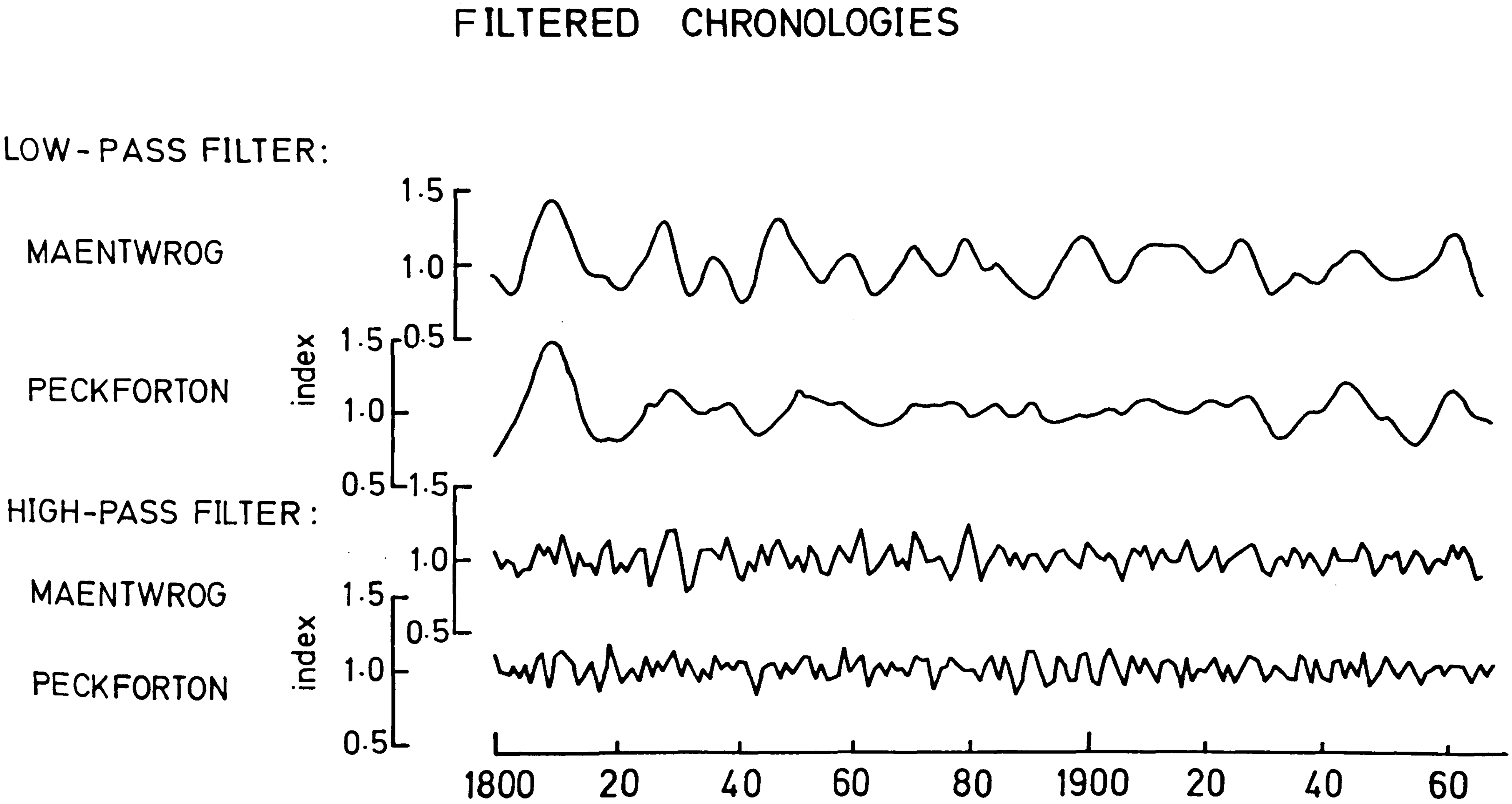

FILTERED CHRONOLOGIES
LOW-PASS FILTER:
MAENTWROG
PECKFORTON
HIGH-PASS FILTER:
MAENTWROG
PECKFORTON
index
index
1.5
1.0
0.5
1.5
1.0
0.5
1.5
1.0
0.5
1.5
1.0
0.5
1800
20
40
60
80
1900
20
40
60

Table 3.7

Variance retained by the common chronology in the Maentwrog and Peckforton chronologies; unfiltered, high-pass and low-pass filtered.

	Maentwrog	Peckforton
Unfiltered data		
variance	0.139	0.132
high-pass filter		
variance	0.012	0.016
% of unfiltered variance	8.627	11.730
low-pass filter		
variance	0.051	0.030
% of unfiltered variance	36.880	22.588
Total amount of variance passed by filters	0.063	0.046
Amount of variance not accounted for	0.076	0.086

does not equal that of the unfiltered series (0.139 at Maentwrog and 0.132 at Peckforton).

Why was this so? The filters used were reciprocal in the sense that the filtered series add together to give the unfiltered series. However, it does not follow from this that the variances of the filtered series add together to give that of the unfiltered series. Given the filters used, i.e. the high-passed data are essentially the raw data minus the low-passed data, the variance should not be conserved (Kelly, pers. comm.). There are two ways of showing this:

1. The variance is determined by the sums of the squares of the data. Let the unfiltered data be z_i, high-passed data x_i; low-passed data be y_i; where

$$x_i = z_i - y_i$$

(a) $\mathrm{Var}\ (z_i) \propto \sum_{i=1}^{n} z_i^2$

(b) $\mathrm{Var}\ (y_i) \propto \sum_{i=1}^{n} y_i^2$

(c) $\mathrm{Var}\ (x_i) \propto \sum_{i=1}^{n} x_i^2 = \sum_{i=1}^{n} (z_i - y_i)^2$

$$= \sum_{i=1}^{n} (z_i^2 - 2y_i z_i + y_i^2)$$

i.e. $\mathrm{Var}\ (x_i) \neq \mathrm{Var}\ (z_i) - \mathrm{Var}\ (y_i)$

i.e. (c) $\neq$ (a) - (b) even if $x_i = z_i - y_i$

This is a general mathematical result.

2. The second argument is based on the filter weights and the associated response function (i.e. the way the variance is passed with frequency) (Kelly, pers. comm.). The frequency response curve is an important characteristic of any filtering function and the response is defined by

$$M(f) = \sum_{=1}^{k} \omega_j \sin 2\pi f_j \qquad \text{(Craddock, 1968)}$$

where ω_j is the coefficient of a symmetric filter (Craddock, 1968) of the j^{th} harmonic, and f_j is the frequency of the j^{th} harmonic.

The filters used in the present study are the high-pass and low A-pass filters used by LaMarche and Fritts (1972) which remove most of the variation at frequencies lower than $1/8$ cpy and at frequencies higher than $1/8$ cpy respectively. The weights of these two digital filters are given in Table 3.8 and their frequency response curves are shown in Figure 3.13. Although the weights of the high-pass filter have the same values but opposite sign to those of the low-pass filter weights, this does not mean that the response function is the "mirror image". At $1/8$ cpy which is the frequency at which attempts are being made to partition the variance, each filter passes variance in the domain of the other.

Power spectrum analysis

A technique which allows the examination of the effect of high-pass and low-pass filters on the original unfiltered series is power spectrum analysis. It is designed for the study of rhythmic behaviour in a time series and is one which presupposes nothing as to the nature of the non-randomness in a series.

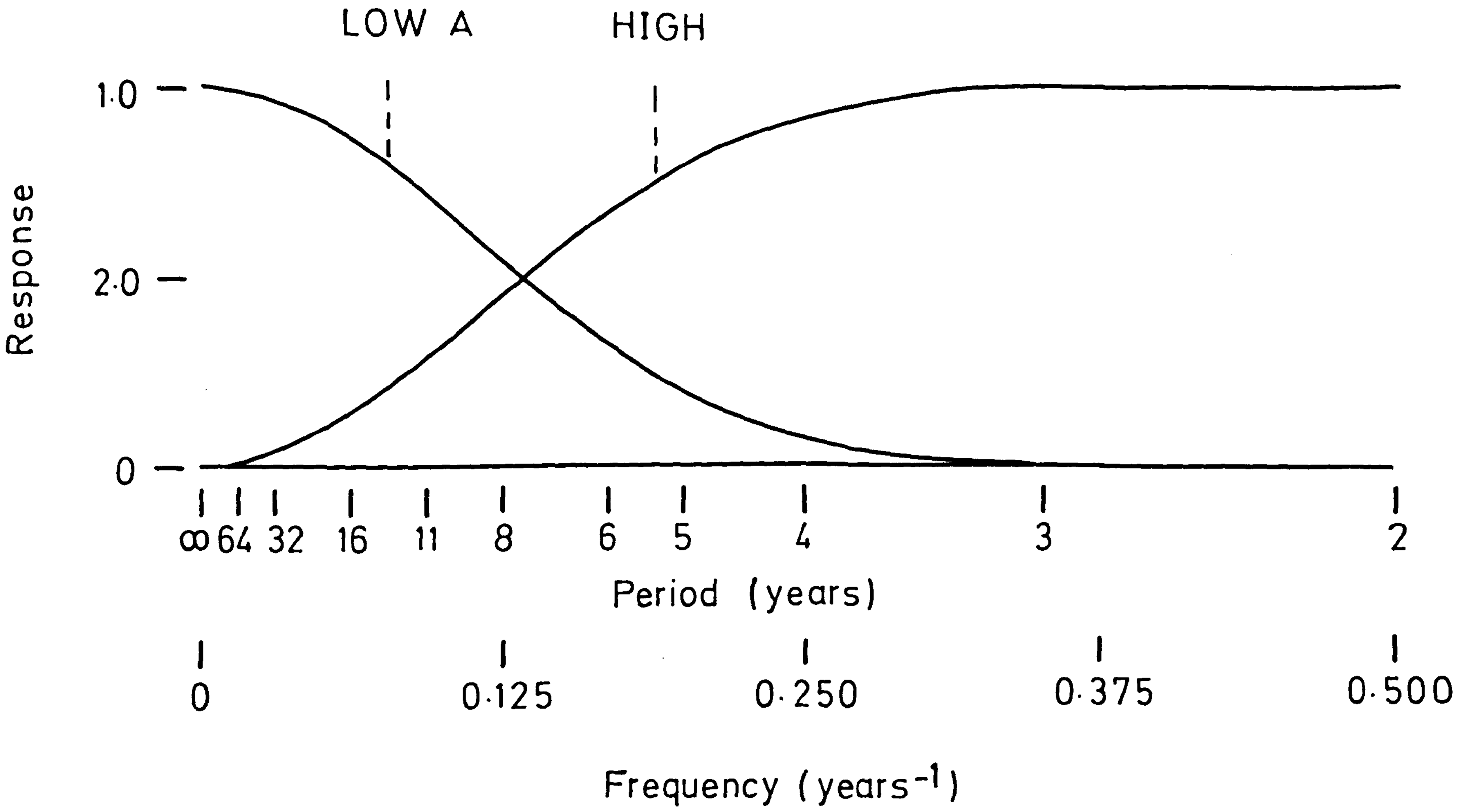
Power spectrum analysis is derived from principles stated by Wiener (1930,1949) and is based on the assumption that time series consist of virtually infinite numbers of small oscillations spanning a continuous distribution of wavelengths

Table 3.8

Weights for two digital filters

m	High-pass	Low-pass
0	0.7744	0.2256
±1	-0.1933	0.1933
2	-0.1208	0.1208
3	-0.0537	0.0537
4	-0.0161	0.0161
5	-0.0030	0.0030
6	-0.0003	0.0003

Figure 3.13 Frequency response curve for the high-pass and low-pass filters (taken from LaMarche and Fritts, 1972).



FREQUENCY RESPONSE CURVES

rather than being composed of a finite number of oscillations, each with a discrete wavelength (Mitchell et al, 1966). The spectrum therefore gives a measure of the distribution of variance in a time series over a continuous domain of all wavelengths, ranging from the shortest wavelength that can be resolved by the annual values (a half cycle per year or one cycle every two years) to infinite wavelength (linear trend) (Mitchell et al., 1966).

The procedures for computing power spectra use the method developed by Tu~~y~~key (1950) and Blackman and Tu~~y~~key (1958). A summary of the method is given by Mitchell et al. (1966) and Fritts (1976). The power spectrum for an annual time series is obtained by calculating the autocorrelation function for a lag of one year, two years and so forth up to a predetermined number of lags. The autocorrelation coefficients plotted against lag constitutes the autocorrelation function. Estimates of the relative spectral density at each of a number of frequencies are then obtained by an harmonic analysis of the autocorrelation function. These spectral estimates, regarded as "raw" at this stage, are then smoothed using a moving average filter. A plot of these smoothed values produces a spectrum containing peaks and humps the former of which correspond to exact periodicities in the original tree-ring series and the latter to less regular variations (LaMarche and Fritts, 1972).

Each power spectrum produced is therefore a means of showing the relative importance of the power, or variance of oscillations in different wavebands (Craddock, 1968). The use of filters allows an examination of these oscillations with different frequencies separately. This is accomplished by designing a filter which has a magnification function approximating unity within the narrow range of frequencies of interest and approximating zero for all other frequencies, so that the amplitudes of oscillations are reduced to something near zero outside the main band. Thus, power spectrum analysis was applied to the filtered series to test that the filters were doing what they were supposed to do i.e. to pass only the variance with wavelengths less than eight years in the case of the high-pass filter and to pa ss only the variance with wavelengths greater than eight years in the case ofthe low-pass filter.

Power spectrum analysis was applied to the filtered and unfiltered forms of the Maentwrog and Peckforton chronologies by Dr. P.M. Kelly of the Climatic Research Unit at the University of East Anglia. The power spectra of these series are described and discussed below. The percent variance accounted for (x-coordinate) is plotted against the harmonics of the fundamental period, the true period or the frequency of the harmonic oscillations (y-coordinate). The dashed line gives the 95% confidence limits for spectral estimates from a Markov process having a first-order autocorrelation coefficient equal to that observed for the time series (Mitchell et al., 1966). As LaMarche and Fritts (1972) stress, a peak in the power spectrum does not prove that an underlying periodicity exists unless it can be shown that this result is unlikely to have been obtained by chance alone. Only when the peaks of the power spectrum lie outside the confidence limits which parallel the calculated null continuum are they considered to be statistically significant.

1. Maentwrog power spectra

Power spectrum analysis was initially applied to the unfiltered series. It shows that the variance is spread throughout the full frequency range with a greater concentration at the beginning of the spectrum, corresponding to more long-period variation in the series than short-period variation. Statistically significant peaks occur at $^1/_{10}$ cpy and $^1/_{9.7}$ cpy and also at $^1/_{4.6}$ the latter of which appears to correspond to a higher harmonic of its basic wavelength. Other significant values occur at $^1/_{4.2}$ cpy and $^1/_{2.8}$ cpy.

In using the filters described above and by LaMarche and Fritts (1972) an attempt to split the total variance at $^1/_8$ cpy is being made. The remaining plots in the analyses show the effectiveness of this exercise. These analyses show the power spectrum for the high-pass series. At the frequencies $^1/_{4.6}$ cpy and $^1/_{4.5}$ cpy a statistically significant amplified peak occurs which corresponds to the significant peak at $^1/_{4.6}$ cpy in the power spectrum for the unfiltered series. Other significant values occur at the frequencies $^1/_{6.1}$ cpy, $^1/_{4.3}$ cpy and $^1/_{4.2}$ cpy. This power spectrum also shows that most of the variation at frequencies less than $^1/_8$ cpy is removed. Compare the variance at $^1/_{16}$ cpy (4.4%) in the power spectrum for the unfiltered series with that in the power spectrum for the high-pass series (0.5%). However, a considerable amount is not removed as shown by the variance to the left-hand side of the 22nd harmonic with peaks at 1/9.7 and 1/9.2 cpy, frequencies in the domain of the low-pass filter. These peaks are also statistically significant.

Apart from this failure to remove all the variation at frequencies lower than 1/8 cpy, the high-pass filter is essentially accomplishing its task in that it is amplifying the variations under investigation while reducing variations which have different characteristic time scales.

Additional spectrum analyses show the power spectrum for the low-pass filtered series. Most of the variance is concentrated at frequencies less than 1/9.5 cpy with peaks at 1/17.2 cpy and 1/10.1 cpy. This is a good filter since most of the variation at frequencies higher than 1/8 cpy is removed.

2. Peckforton power spectra

The analyses initially calculated the power spectrum of the unfiltered series. Although a number of peaks occur none are statistically significant indicating that no underlying periodicity exists in this series.

Subsequent spectrum analyses show the power spectrum for the high-pass series. At frequencies greater than 1/8 cpy the amplified peaks correspond to those in the unfiltered series. Statistically significant peaks occur at 1/4.5, 1/4.3 and 1/3.7 cpy. The power spectrum also shows that this high-pass filter is not removing all the variation at frequencies less than $1/8$ cpy. In the power spectra from both the Maentwrog and Peckforton high-pass series there is a statistically significant peak at $1/4.5$ cpy and around $1/4$ cpy.

The power spectrum of the low-pass filtered series has also been constructed. It shows that most of the variance is concentrated in the frequency range $1/31.5$ to $1/14$. The variance at frequencies greater than $1/8$ cpy has been fully removed by the filter.

Power spectrum analysis of the unfiltered and filtered series at Maentwrog and Peckforton has thus shown how the high-pass and low-pass filters affect the original unfiltered series. The low-pass filter is behaving as it should by removing the variation at frequencies greater than $1/8$ cpy. The high-pass filter while passing the variation at frequencies greater than $1/8$ cpy is also passing i.e. not removing, some of the variance less than $1/8$ cpy.

3.3.2 Maentwrog, Peckforton and British Isles chronologies

Table 3.5 shows the values of Student's t obtained from programme CROS (Baillie & Pilcher, 1973) between the Maentwrog chronology and the standard chronologies listed. The probabilities of observed values of 'r' arising by chance is also given, as are the correlation coefficients obtained for the period 1800 to 1965. The best matches were obtained between Maentwrog and the Rostrevor (t = 5.09) and Cumberland/ Herefordshire (t = 5.66) chronologies. The Maentwrog and

Yorkshire chronologies did not crossdate (t = 1.16). Crossdating results of Peckforton with the Belfast and Rostrevor chronologies gave 't' values of 4.42 and 3.96 respectively for the date of the outer year of the Peckforton chronology of 1904.

Table 3.6 shows for Peckforton, values of 'Student's t obtained from programme CROS (Baillie & Pilcher, 1973), probabilities of observed values of 'r' and correlation coefficients for the period 1800 to 1965. The highest 't' values were obtained with the Yorkshire chronology (t = 5.93) and with the Cumberland/Herefordshire chronology (t = 5.93). Crossdating with the Rostrev or chronology was poor (t = 2.84).

Figures 3.14 and 3.15 show the correlations between the Maentwrog and the Peckforton chronologies respectively for 10-year periods lagged every 5 years for the period 1800 to 1965. In the 1800's correlations were high for the first decades for Maentwrog/Rostrevor and Peckforton/Rostrevor. For the earlier part of this period, correlations were high and positive for 1810 to 1829 and 1810 to 1819 between the Yorkshire chronology and the Maentwrog and Peckforton chronologies respectively. In addition, high positive correlation values were obtained for the period 1805 to 1819 between the Cumberland/Herefordshire curve and Maentwrog and Peckforton.

A common period of high positive correlation shown between the Maentwrog, Peckforton and Rostrevor chronologies is 1860 to 1869 although high values occur between Maentwrog and Peckforton during the longer period of 1855 to 1874. However, during the period

1850 to 1869 growth patterns at Maentwrog and Peckforton were negatively correlated with that for Cumberland/Herefordshire, the chronology which showed very good crossdating with both chronologies (Tables 3.5 and 3.6). High negative correlations occurred between the Yorkshire and the Maentwrog and Peckforton chronologies for the period 1860 to 1869. For the period 1875 to 1889, high negative correlations also occurred between the Maentwrog and Belfast and Rostrevor chronologies and for 1875 to 1884 between Maentwrog and the Yorkshire chronologies. The comparison of Peckforton and Rostrevor showed only one 10-year period in which a negative correlation occurred, this being only -0.11.

3.3.3 Maentwrog, Peckforton and some European chronologies

The Maentwrog and Peckforton chronologies were also tested for crossdating with five German oak chronologies and one Danish oak chronology, the locations of which are shown in Figure 3.11. They include chronologies for west of the Rhine (the West German chronology) (Hollstein, 1965), the Weser and Leine Uplands (Delorme, 1972), east of the Rhine (the South Germany chronology) (Huber & Giertz-Siebenlist, 1969), the Lower Saxony Coastal Plain (Schwab, 1975) and for the marshland area of Hamburg (Eckstein, Mathieu & Bauch, 1972). The Danish oak chronology was constructed for trees growing at Vallø (Holmsgaard, 1955). The existence of crossdating was tested using programme, CROS (Baillie & Pilcher, 1973).

Tables 3.5 and 3.6 show the Student's t value obtained at the known position of match for each pair of chronologies compared with the probability of the observed value of 'r' arising by chance (assuming no autocorrelation). There appeared to be little crossdating between the Maentwrog and Peckforton chronologies and the German curves described. The highest 't' values were obtained for the matches between the Lower Saxony Coastal Plain chronology (Schwab, 1975) and both the Maentwrog and Peckforton chronologies (t = 2.78 and 3.03 respectively). Visually these matches were not good although for the period 1908 to 1926 between Peckforton and the Lower Saxony Coastal Plain, it was very good. Similarly, the distinctive narrow rings in 1786 and 1787 are present in both the Maentwrog and Lower Saxony Coastal Plain chronologies. The Student's t between the South German chronology and the Peckforton chronology was 2.63, a match which was also poor visually. A 't' value of 3.54 was obtained between the Peckforton and the Weser Upland chronologies at a wrong position of match, the outer year of the Peckforton chronology being given as 1915. The chronology for Vallø did not crossdate with either the Maentwrog or the Peckforton chronology.

Figure 3.14 Cross-correlations for different periods between Maentwrog chronology and some British Isles oak chronologies. for the period 1800 -1965.

Each point is a 10-year mean calculated at 5-year steps

MAENTWROG CORRELATIONS

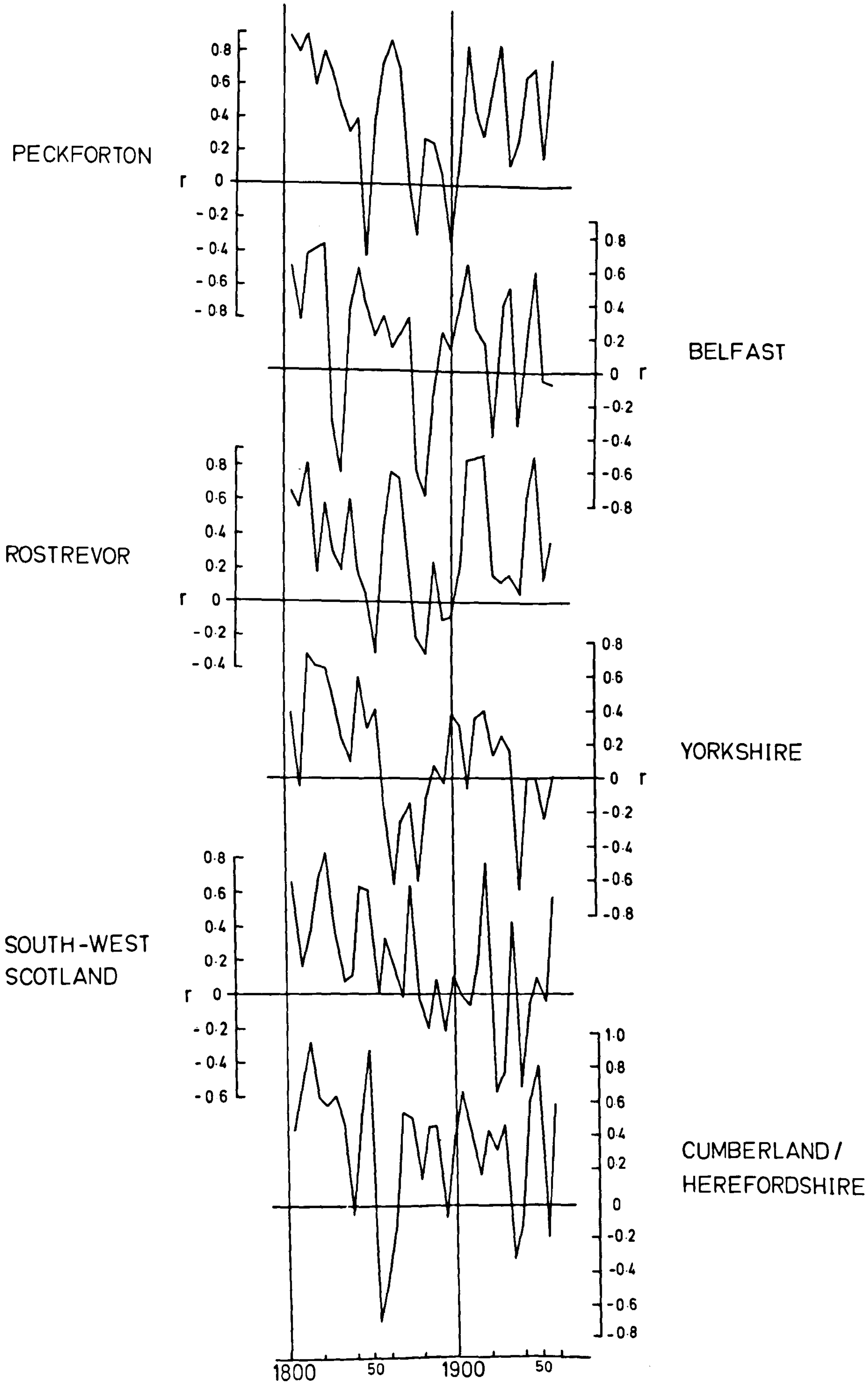
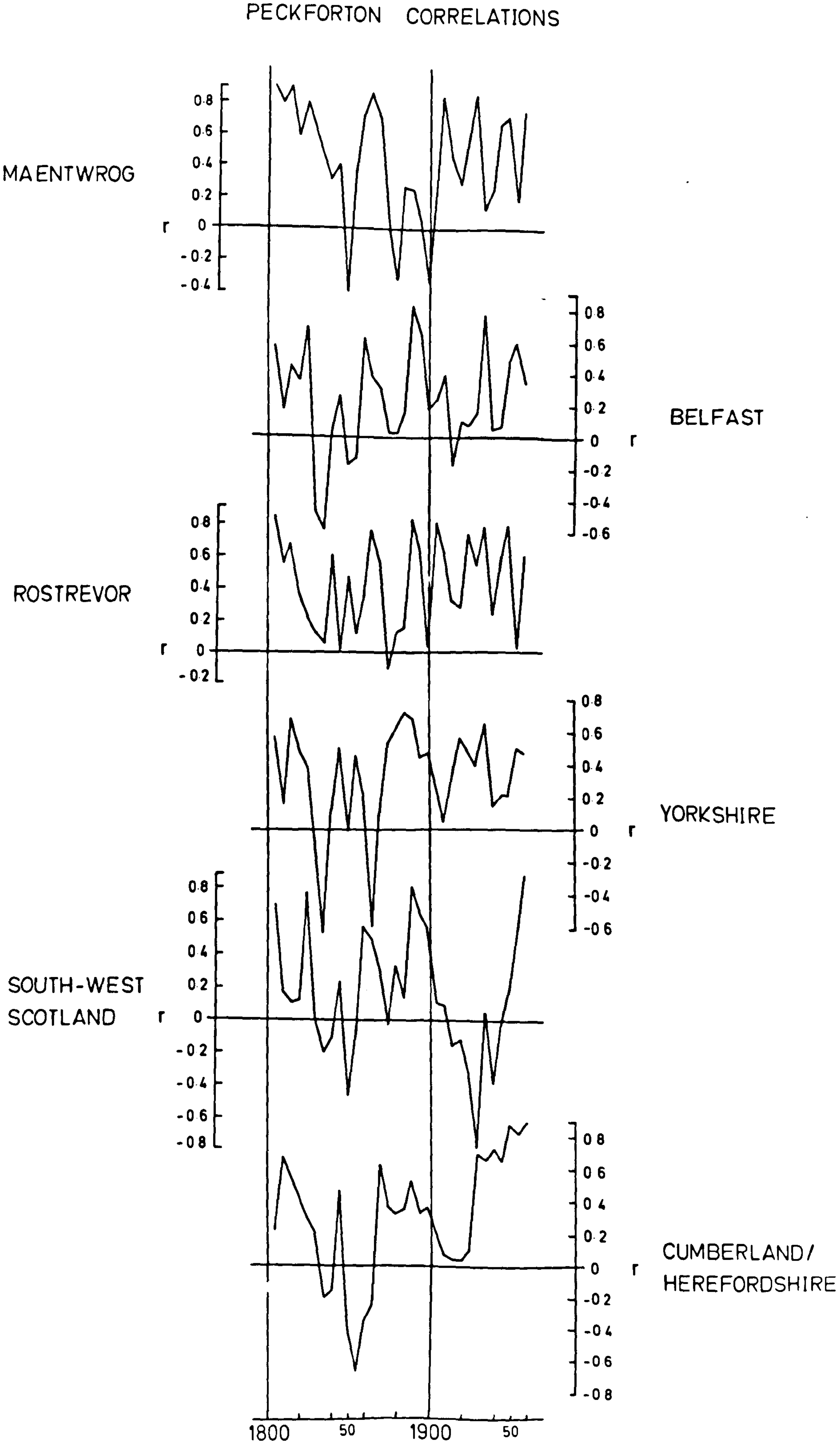


Figure 3.15 Cross-correlations for different periods between Peckforton chronology and some British Isles oak chronologies for the period 1800+1965

Each point is a 10-year mean calculated at 5-year steps.


PECKFORTON CORRELATIONS
MAENTWROG
0·8
0·6
0·4
0·2
r 0
-0·2
-0·4
BELFAST
0·8
0·6
0·4
0·2
0 r
-0·2
-0·4
-0·6
ROSTREVOR
0·8
0·6
0·4
0·2
r 0
-0·2
YORKSHIRE
0·8
0·6
0·4
0·2
0 r
-0·2
-0·4
-0·6
SOUTH-WEST SCOTLAND
0·8
0·6
0·4
0·2
r 0
-0·2
-0·4
-0·6
-0·8
CUMBERLAND/ HEREFORDSHIRE
0·8
0·6
0·4
0·2
0 r
-0·2
-0·4
-0·6
-0·8
1800
50
1900
50

CHAPTER 4 - DISCUSSION

Whilst systematic research in dendrochronology was initiated in America in the early twentieth century by A.E. Douglass, the slow development of the science in England and the rest of Europe has been attributed to two factors. Firstly, trees do not reach the great ages of those in America (except in the Alps or near the northern tree-line) and secondly, climatic relationships are much more complex (Kolchin, 1965). In this last respect it has often been assumed that the factors affecting tree growth are so numerous and variable that similarities between trees even in the same woodland would be uncommon (Fletcher, 1974a). The temperate English climate was usually considered responsible for this situation. According to Fletcher (1974a) this assumption soon became a doctrine and was responsible for the lack of systematic dendrochronological studies in England. In Ireland, this belief was encouraged to some extent by the results of a tree-ring dating study (Harrington, 1943) on timbers from Ballinderry Crannog excavated by Hencken in the 1930's. However, while her results were poor she did state that ".... dating from tree-rings in Ireland can be done ....".

When tree-ring studies are undertaken in a 'new' region, the prerequisites for success include known dates of felling of the trees to provide an anchor point for subsequent chronologies and adequate replication. The indications of the feasibility of constructing tree-ring chronologies in North west England and North Wales were first provided by the excellent within-tree crossdating at both Maentwrog and Peckforton. This, coupled with good crossdating between trees within each site and sufficient replication demonstrate the practicability of establishing adequately replicated, absolutely dated chronologies in these areas.

In addition to providing a modern anchor point, the studies at Maentwrog and Peckforton provide materials to investigate the properties of growth rings of trees growing under different climatic conditions. The woodland at Maentwrog is considered to experience a maritime climate whilst that at Peckforton exists in the rain shadow of the mountains of North Wales.

Table 4.1 shows a comparison of the general statistics for oak at Maentwrog and Peckforton. For the chronology series which at Maentwrog covers a greater period, mean ring width, mean index, first-order serial correlation, mean sensitivity and standard deviation of the unfiltered data are very similar. In selecting the period for the Anova series, the aim was to find the longest period covered by as many trees as possible whilst keeping the periods comparable. Therefore, the Anova period for Maentwrog and Peckforton are 1875 to 1952 and 1877 to 1946 comprising 14 and 16 trees respectively. For the Anova series mean sensitivity is low at both sites whilst being higher than in the chronology series. Mean ring width is also similar at both sites. The first-order serial correlation at Maentwrog is similar to that in the chronology series but at Peckforton first-order serial correlation has changed from 0.53 to 0.30. Clearly, the years outside the period 1877 to 1946 must make a substantial contribution to the first-order serial correlation. For the Anova period first-order serial correlation is higher at Maentwrog. One reason for high auto-correlation is given by Pilcher (1976) who explains that high autocorrelation values in oak are due to the production of reserve food storage during the previous summer which are utilised in the spring in the formation of the earlywood vessels. In addition, since in oaks grown under stress the earlywood represents a significant proportion of the annual ring, higher serial correlations might be expected. The standard deviation is slightly lower at Maentwrog.

The analysis of variance of the Anova series shows that the percent variance years or variance retained by the common chronology is 25.5 per cent at Maentwrog and 32.7 per cent at Peckforton. Per cent variance years x trees or the between-tree variance is higher at Maentwrog, 41.7 per cent compared with 24.5 per cent at Peckforton. Per cent variance years x radii x trees or variance for the core chronologies is 32.8 per cent at Maentwrog and 42.8 per cent at Peckforton. The high value of 41.7 per cent for the tree components indicates that Maentwrog is a relatively heterogeneous site where varying factors affect the growth of individual trees in different ways. The nature of this heterogeneity is examined in Chapter 6. The analysis of variance results suggest that Peckforton is the better site in terms of its value in the determination of climatic relationships and reconstruction of climate.

Initial examination of a number of statistics for the two chronologies indicated the existence of relationships between them. Subsequent analyses revealed that mean sensitivity, mean index and cross-correlation coefficients are not significantly related at either site.

The values for R (the agreement between the individual and mean curves) at Maentwrog and Peckforton of 0.67 and 0.77 are comparable to those of Fürst (1963). He obtained values for R between 0.65 and 0.72 for oak at several locations in central Europe. Values for some conifers have been found to have higher values; Schulman (1956) often obtained values of 0.96 and 0.98 for *Pinus ponderosa* and *Sequoia gigantea* and gave average values of 0.81 for Douglas fir.

In addition tothe comparison of the chronologies' statistics, the actual form of the curves may also be compared. Although a significant Student's t value of 3.84 was obtained at the position of correct match, a visual comparison showed that there were several periods when years of poor growth at one site were not present in the other. The use of programme CROSS (Fritts et al, 1969) permitted a more detailed examination of the correlations for different periods (Figure 3.14). The correlation coefficients ranged from -0.4 to +0.8. Although values were high for a number of periods, the value of 0.51 for the full period (1800 to 1965) resulted from the combined effects of several negative and low positive values together with the high positive values.

Further examination of the similarities between the chronologies was made through the use of a pair of reciprocal digital filters. The use of filtering techniques as described by LaMarche and Fritts (1972) can be used to separate the long-term and short-term variations and to study the relationships among the series at different frequency ranges of variation. An analysis of variance of the tree-ring data before and after filtering with the low-pass and high-pass filters allows an estimation of the variance accounted for in these different frequency ranges.

The initial examination of the correlation analyses between Maentwrog and Peckforton (unfiltered and filtered series) indicates that both chronologies exhibit more low-frequency variance than high-frequency variance. However, the fact that the high-pass variance added to the low-pass variance did not equal that of the unfiltered series appeared surprising at first sight. Consideration of a simple mathematical model and the frequency response of the filters used showed that the situation above (i.e. high-pass variance + low-pass variance = unfiltered variance) does not necessarily exist (Section 3.3). The results indicate that the estimate of the low-pass variance (Table 3.7) is a reasonable one.

Correlation analysis of the low-pass chronologies showed that there was a high positive correlation between them ($r = +0.615$). After correction for autocorrelation,this figure was found not to be significant at any significance level. LaMarche (1974b) has also used these digital filters to separate and study the variances at different frequencies. In studying four bristlecone pine chronologies from four different elevations in east-central Nevada, he obtained, as in the present study, high correlation values between the low-pass portions of three of the chronologies. However, no indication is given as to the consideration of autocorrelation in each series. As a consequence, these results may also indicate the existence of significant relationships which do not exist since the autocorrelation in the bristle cone pine chronologies analysed was high (LaMarche, 1974b). It is therefore important to consider the autocorrelation present in all time series especially those treated with low-pass filters. For the high-pass series in the present study, the results indicated a high degree of similarity between the short-term variations in the Maentwrog and Peckforton chronologies.

Further utilisation of digital filters must include an evaluation of their behaviour. In particular, the filters need to be totally reciprocal in terms of the actual data and variance. Craddock (1968) goes through the derivation of a set of filters which do conserve the total variance. Further research involving the use of digital filters must include a consideration of this work.

Comparisons with British Isles chronologies

The extent to which trees in the British Isles respond to a common signal may be examined from comparisons of the tree-ring curves from a number of sites. Such comparisons show that, in general, the Maentwrog and Peckforton chronologies crossdate with the chronologies for Belfast (Baillie, 1977a), Rostrevor (Pilcher, 1976), South West Scotland (Baillie, 1977c) and Cumberland/Herefordshire (Siebenlist-Kerner, 1978) although the Peckforton and Rostrevor chronologies show much reduced agreement. The greatest amounts of cross agreement within this group occur between the chronologies for Maentwrog and Rostrevor (t = 5.09), Maentwrog and Cumberland/Herefordshire (t = 5.66) and Peckforton and Cumberland/Herefordshire (t = 5.93). It appears that trees from these sites are responding to a common signal, the nature of which may be partly due to similarities in site conditions. Maentwrog and Rostrevor are on acidic soils providing free drainage and on steep south south-east facing and south-west facing slopes respectively, features which give them the status of stressed sites. As such, they show a greater response to variations in climatic conditions when these become limiting.

The modern chronology constructed by Siebenlist-Kerner (1978) comprises trees from two woodlands in climatically different areas. One is in a wet western region of England (Cumberland) and the other is in a rain shadow area (Herefordshire). This combination presents a likely explanation for the high cross-agreement between this chronology and the Maentwrog and Peckforton chronologies which are constructed from trees from a wet western upland area and from a rain shadow area respectively. These results might provide an argument for the formation of large scale chronologies suggested by Fletcher (1978b). However, a consideration of the results of the present study (e.g. lack of crossdating between Maentwrog and Yorkshire) indicates that such mixing could confuse the signals.

Excellent crossdating was also obtained between the chronologies for Peckforton and Yorkshire (t = 5.93) constructed for woodlands approximately 160 km apart. This good cross agreement may be explained in terms of similarities in soil type and the fact that both sites exist in climatically similar regions. These are rain-shadow areas where downslope movements of air from upland regions to the west involve warming, increased evaporation and periodic moisture deficiencies in summer.

Baillie (1977c) has also determined the existence of crossdating over considerable distances. He found that excellent crossdating exists between the South West Scotland chronology and that for Belfast, the latter of which comprised trees obtained from several types of source.

Comparisonswith European chronologies

Different results were obtained for the Maentwrog and Peckforton chronologies in their comparisons with the European oak chronologies. In general, crossdating was found not to exist between these British curves and the European curves either visually or statistically although some agreement (probably chance) was indicated between some of them. Other workers have obtained more positive results. The Bewdley chronology from the England-Wales border showed good crossdating with the South German master chronology giving W = 61.1% for 231 years overlap (Berger, Giertz and Horn, 1971). For the period 1359 to 1591, good crossdating also existed between the chronology for Bishop's House in Sheffield and the chronology for South Germany (t = 3.26 with 233 years overlap) (Morgan, 1977b). For more recent periods, Siebenlist-Kerner (1978) found that good crossdating (t = 4.67) existed between the chronology from 4 oaks from Cumberland and 5 oaks from Herefordshire and the southern German chronology for 1731 to 1969. Results obtained by Fletcher (1974a) indicated the existence of good crossdating between chronologies from the south east of England and the South German curve from the early nineteenth century to the late twentieth century (W = 58% to 67%).

As in the present study, Baillie (1978) also found a lack of crossdating with German chronologies. He found that although the Belfast chronology crossdated well with the Bewdley chronology and the

Bewdley chronology crossdated well with the West German curve (Charles, 1971), no significant agreement existed between the Belfast and West German chronologies. The results in Tables 3.4 and 3.5 show that a similar situation exists for the period 1780 to 1960. Good crossdating exists between the Cumberland/Herefordshire chronology and the Maentwrog and Peckforton chronology and between the Cumberland/ Herefordshire and the South German chronologies. However, no significant agreement exists between the South German chronology and the Maentwrog and Peckforton chronologies. Thus, adjacent areas seem to contain similar patterns of tree growth but not so the areas on either side.

The results presented here, in common with those of Baillie (1978) suggest that the Irish Sea Basin represents an area with common but not exclusive tree-ring growth patterns. In addition, subsequent analyses by Baillie (1978) which incorporated oak chronologies from southern and eastern England have led to the suggestion that the British Isles as a whole "....constitutes a single tree-ring area within which master chronologies can be crossdated with considerable certainty". The results of the present study support this view to some extent in that many tree-ring chronologies from the British Isles do crossdate with one another. However, some qualification is required since chronologies from sites in lowland rainshadow areas show the best crossdating between themselves and similarly for chronologies from sites in mountainous regions. The crossdating between chronologies from these different areas is not good and in some cases does not exist at all, for example, the Student's t for the Maentwrog and Yorkshire match was

1.16. Thus, the British Isles appears to constitute a single tree-ring area if the climatically different areas are considered separately, such areas being different from the point of view of precipitation.

10-year period correlations

From an examination of the cross-correlations for 10-year periods between the two modern chronologies presented in this study and between them and a number of standard chronologies, it appears that there are several periods when the correlation coefficients are high. It has been suggested that the period 1875 to 1900 was one of greater climatic variability than 1905 to 1930 since the latter period had a high frequency of days with westerly winds (Lamb, 1966). Hughes et al. (1978b) have shown that for Maentwrog the percentage variance held by the common chronology is slightly greater in 1875 to 1900 than 1905 to 1930. This led them to suggest "......that in such a period of greater climatic variability, limiting conditions more commonly occur, bringing ring-width variation between trees into unison and so increase the variance held by the common chronology". This reasoning may also account for the existence of high correlation coefficients between (as well as within) chronologies during the later decades of the nineteenth century. However, such high correlations only occur for comparisons of the standard chronologies with the Peckforton chronology; comparisons with the Maentwrog chronology show low positive or negative correlations for this period. An analysis of variance of the periods 1875 to 1900 and 1905 to 1930 for the Peckforton chronology also showed that the % variance held by the common chronology was greater for the earlier period (38%) than for the later less variable period (27%).

The presence of high correlation coefficients identifies periods of similar growth responses in chronologies in the twentieth century during which time the glacier retreat was continuous. The early decades of the twentieth century, the years considered less variable than those discussed above (Lamb, 1966) are characterised by high correlation values in five chronology pairs. Similarly, the period 1945 to 1954 is distinctive in that the ring-widths of chronology pairs Maentwrog/Peckforton, Maentwrog/Belfast, Maentwrog/Rostrevor, Maentwrog/(Cumberland.Herefordshire), Peckforton/Rostrevor and Peckforton/(Cumberland.Herefordshire) are well correlated. The plot of the number of westerly type days over the British Isles from 1861 to 1969 (Lamb, 1970) indicates that from 1950 the frequency of such days began a steady decline indicating an increase in climatic variability and the likelihood of a more common occurrence of limiting conditions. The absence of high correlations during the early 1900's in comparisons of the Maentwrog chronology and the other chronologies, while being present in all the Peckforton comparisons, suggests that variations in tree growth at Maentwrog differed from all the other sites during this period.

Correlation analyses have served to identify periods when the ring widths of the Maentwrog, Peckforton and the other standard chronologies were best correlated thus identifying periods when limiting climatic conditions are most likely to have prevailed. These studies and the use of programme CROS (Baillie and Pilcher, 1973) have indicated the area over which chronologies crossdate and hence when similar variations in tree growth occur. The areas having similar tree-ring patterns are shown in Fig. 4.1.

Similarities in the properties of chronologies may also be illustrated in a comparison study of chronology statistics. Table 4.1 shows a comparison of the Maentwrog and Peckforton chronologies with the Rostrevor chronology, one of the few oak chronologies similarly analysed and reported in the literature. Mean ring-width, first-order serial correlation, mean sensitivity and standard deviation are similar in all three chronologies. Between-tree variance is higher at Maentwrog than at the other two sites and also exhibits the smallest amount of variance retained by the common chronology. Although the correlation coefficients in the three correlation classes examined are consistently higher at Rostrevor, the results for the three chronologies are comparable. In general, the statistical properties of the Maentwrog and Peckforton chronologies are broadly similar to those of Rostrevor. The statistical properties of the chronology for Schleswig (Eckstein and Schmidt, 1974) which has been similarly analysed, also compare with those of Maentwrog and Peckforton.

The general conclusion that dendrochronology is feasible even under those conditions that might appear to be unfavourable (Godwin, 1940) reinforces the findings of the Belfast group (Baillie, 1973b; Pilcher, 1976) and of Milsom (1979). The validity of this conclusion is further underlined by the existence of crossdating between the Maentwrog and

Peckforton chronologies and those from a number of woodlands in other parts of the British Isles.

Figure 4.1 Areas exhibiting similar tree-ring patterns

Key

1. Maentwrog
2. Peckforton
3. Belfast
4. Rostrevor
5. Yorkshire
6. South West Scotland
7. Cumberland/Herefordshire
8. West German
9. Weser and Leine Uplands
10. South German
11. Lower Saxony Coastal Plain
12. Hamburg

———— relates to the results of crossdating tests for Maentwrog

- - - - - relates to the results of crossdating tests for Peckforton

-·-·-·-·- crossdating between the German curve and some British chronologies

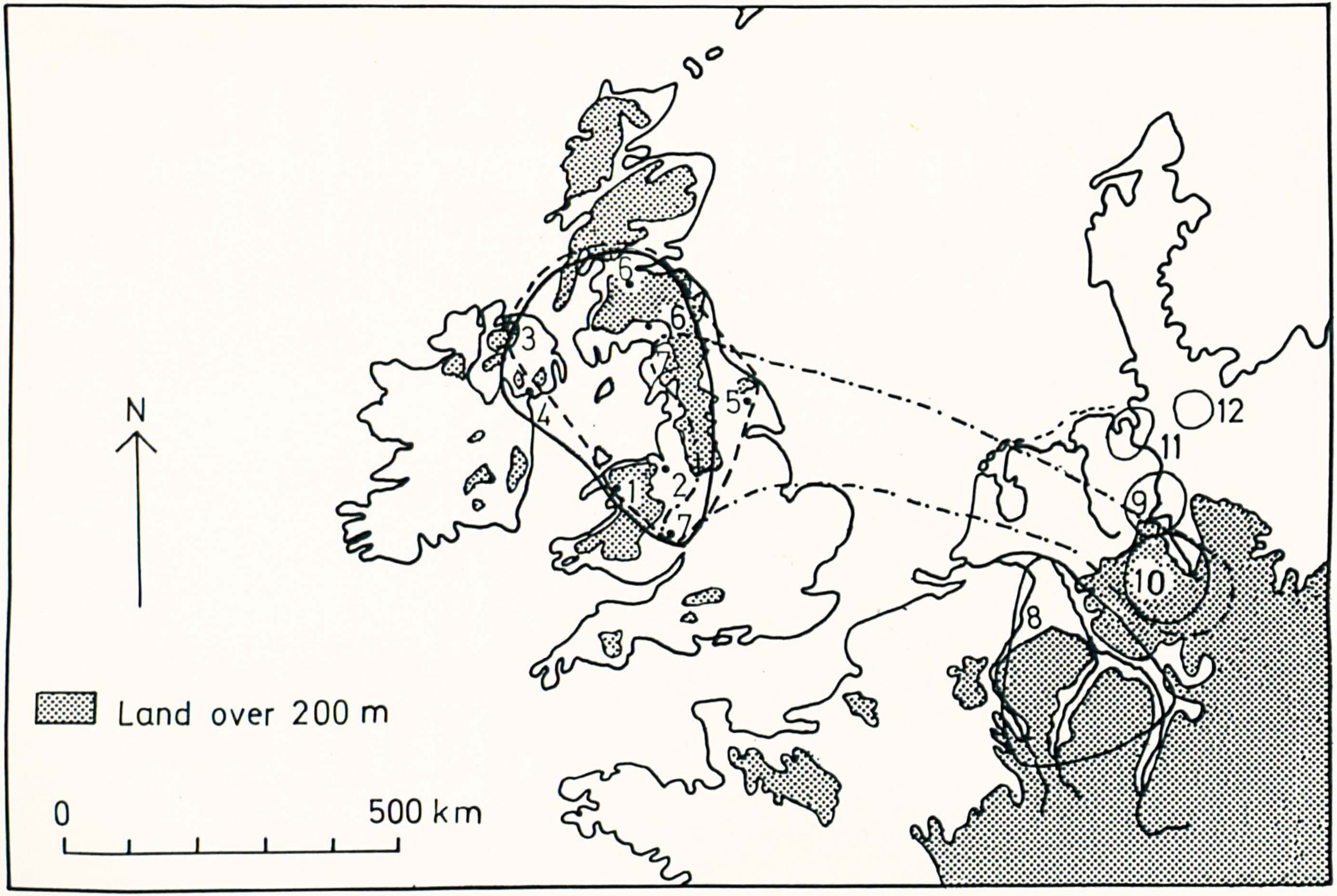

N
1
2
3
4
5
6
6
7
7
8
9
10
11
12
Land over 200 m
0
500 km

Table 4.1

Comparison of general statistics for oak at three sites

	Maentwrog	Peckforton	Rostrevor
Chronology series			
Number of trees	35	16	18
Number of radii	70	32	36
Years analysed	265	197	226
Interval	1710-1974	1780-1976	1750-1975
Mean ring width	1.59 mm	1.52 mm	1.00 mm
Mean index	1.00	1.00	1.00
Serial correlation	0.62	0.53	0.56
Mean sensitivity	0.18	0.20	0.22
Standard deviation	0.65	0.29	0.30
Anova series			
Number of trees	14	16	10
Number of radii	28	32	20
Years analysed	78	70	100
Interval	1875-1952	1877-1946	1780-1879
Mean ring width	1.40 mm	1.33 mm	1.10 mm
Mean index	0.99	1.00	1.00
Serial correlation	0.53	0.30	0.62
Mean sensitivity	0.25	0.29	0.24
Standard deviation	0.33	0.31	0.35

Analysis of variance results			
Percent variance, Years	26	33	42
Percent variance, Years x Trees	42	25	28
Percent variance, Years x Radii x Trees	33	43	30
Error of y	0.08	0.05	0.10
Cross-correlation results			
Mean correlation of cores within trees	0.65	0.58	0.70
between trees	0.26	0.34	0.44
Mean correlation between trees	0.31	0.35	0.53

CHAPTER 5 - SAPWOOD IN OAK

5.1 Introduction

5.2 Sapwood estimation

5.3 Results

  5.3.1 Maentwrog

  5.3.2 Peckforton

5.4 Discussion

5.1 Introduction

Oak has been one of the most widely used timbers in the construction of many structures, the variety of which is described in section 1.3. This extensive use provides the historic and prehistoric timbers required for the construction of absolutely dated continuous tree-ring chronologies . Such chronologies may then be used to determine the age of undated material. This study requires that the felling dates of the timbers under investigation are accurately assessed (Baillie, 1973a). It is only when the bark and hence the most recently formed year of growth is present on the timber that the year in which the tree was felled can be identified. The oak timbers that are found in historic and archaeological structures have usually lost their bark during construction in the shaping processes. However, a distinctive feature of oak has been found to aid in the estimation of felling dates when bark is missing. This is the sapwood.

Sapwood is secondary xylem comprising vessels, fibres and parenchyma cells. It is the only part of the secondary xylem which contains live parenchyma cells concerned with the translocation of food substances and where the outermost growth rings of which are concerned with the conduction of water (Longman & Coutts, 1974). Many of the differences between the sapwood and heartwood are chemical. With increasing age the wood loses water and stored food substances and becomes infiltrated with various organic compounds such as oils, resins, tannins and colouring materials. The development of the colour in the heartwood is a slow process dependent on the oxidation of phenols which, in turn, follows the disappearance of starch and an apparent breakdown in the enzymatic control over the activities of living cells (Frey-Wyssling & Bosshard,1959). Tyloses may also form in the vessels in association with the ageing process. They are formed by the enlargement of the pit membranes of the half-bordered pit pairs between wood parenchyma or wood ray cells and vessels. The delicate membrane is expanded and grows apparently by invagination, pushing out of the pit cavity and protruding far into the lumen of the non-living cell. Part of the cytoplasm and even the nucleus pass into the bladderlike extensions of the parenchyma cells. Thus the transition from sapwood to heartwood involves the loss of living protoplasts from the parenchyma cells and the cessation of the conductive function of the vessels. These chemical changes make the heartwood more durable and less attractive to wood boring pests.

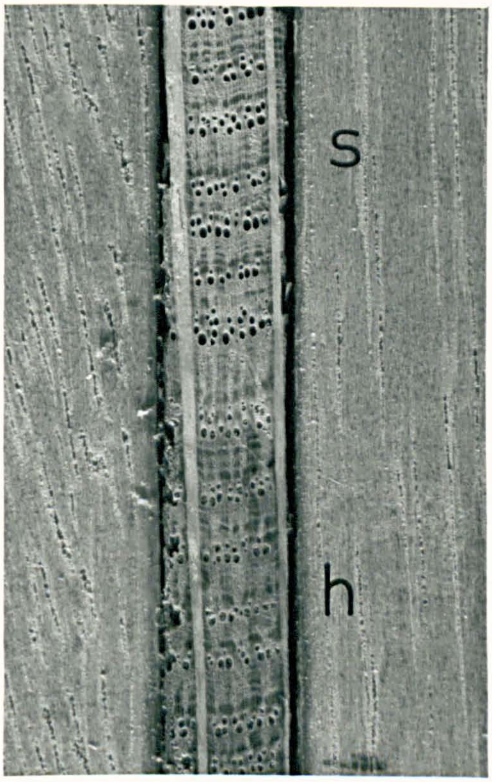
Sapwood in oak may be easily distinguished from the inactive heartwood by the hollow appearance of the earlywood vessels and by its paler colour. Plate 5.1 shows the transition from the empty earlywood vessels of the sapwood to the blocked vessels of the heartwood.

The sapwood in oak is a valuable feature from a dendrochronological standpoint because the number of growth rings it contains is considered to be somewhat predictable. Baillie (1973a) details two cases where the presence of the outermost growth ring may be determined when bark is absent. The first of these is when a beam retains the original curved surface of its sapwood, the outer ring should be continuous over a significant arc of the

Plate 5.1 Heartwood, sapwood and heartwood/sapwood transition in oak

h - heartwood

s - sapwood


s
h

circumference. Also, if the outer ring is present the ribbed cambial surface (or waney edge) which would have been beneath the bark would be observable. Plate 5.2a shows the ribbed surface of the cambium and Plate 5.2b shows this surface from a transverse view. In the second case, when a group of timbers from a structure contain sapwood, in which the outer year on all samples is the same year, then this date is assumed to be the date of felling.

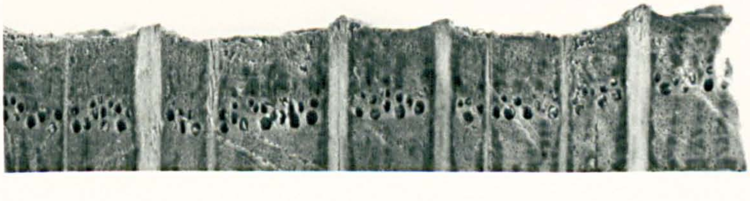
When the bark and part of the sapwood are missing, either by removal due to woodworking or through attack by decay or wood boring organisms, the assumed predictability of the number of sapwood rings is utilised to estimate the date of felling. Sapwood is considered to occupy a fixed proportion of the radius of a tree so that a mean value may be calculated for the number of sapwood rings from measurements taken from trees which contain complete sapwood. This estimate is then added to the date of the youngest heartwood ring to provide a felling date with specified confidence limits. Several estimates have been made for sapwood in oak; for German oaks Hollstein (1965) obtained an estimate of 20 ± 6 from measurements on approximately 200 trees in an age group of 100 to 200 years; Gürsu and Bernhart (1964) obtained a similar value to Hollstein for oaks growing in Anatolia (Turkey). Huber (1967) obtained a figure of 25 years. For Irish oaks, Baillie (1973a) established a mean value of 32 ± 9 where ± 9 represents one standard deviation on the mean, from measurements on 37 modern and post-medieval timbers. These estimates may also be applied when the bark and the total sapwood are missing if the heartwood/sapwood transition can be identified. When timbers have lost all the sapwood and part of the heartwood it is impossible to estimate how many heartwood rings were present up to the heartwood/sapwood boundary and hence the date of felling. However, Baillie (1973a) describes a method for estimating the felling date under these circumstances and where a large population of samples is available from a single building. The method is based on the supposition that where oak beams are produced either by radial splitting or by sawing, a large proportion of the timbers originally retained some trace of the outside of the parent tree.

A defect in the sapwood of oak, included sapwood, has given workers the opportunity of studying long-term cycles of climatic fluctuations. Included sapwood is visible in cross-section as annual rings of light colour surrounded by the darker heartwood. According to Bolychevtsev (1970) most investigators attribute this defect to severe frost. In particular, Bolychevtsev (1970) found that for oak (*Quercus robur* var. *praecox*) growing in the southern part of the conifer/hardwood subzone of European Russia, included sapwood occurred only in those periods when a very cold winter with prolonged frosts was preceded by two successive dry summers. In addition, such damage occurred approximately once in 50 years. It is these findings which provide the basis for using the defect of included sapwood as an indicator of abrupt weather anomalies in studying cycles of climatic fluctuations. In the present study on British oaks no examples of included sapwood were found in the samples from either Maentwrog or Peckforton Hills.

Ribbed surface of cambium in oak

Plate 5.2a Longitudinal view

Plate 5.2b Transverse view showing waney edge



5.2 Sapwood estimation

Although estimates have been made in other countries no estimates have been made of the average number of sapwood rings in oak trees in northern England and Wales. The reasons for such an investigation being undertaken in the present study were two-fold:

(i) to compare sapwood estimates with others from Ireland and Europe.

(ii) to provide an estimate which could be applied to timbers without bark occurring in historic and archaeological structures in the north west of England.

A series of measurements was made on 38 radii (19 trees) and 44 radii (23 trees) from Maentwrog and Peckforton respectively. In order to obtain an estimate of the mean number of sapwood rings, it was necessary to use samples where bark was present or where the absolute date of felling and sapwood boundary were known. The sapwood boundary was identified using the criteria of colour change and earlywood cell characteristics. For each radius, measurement was made of the number of sapwood rings, width of sapwood zone, length of radius and the age of the tree. The number of sapwood rings and sapwood width were each plotted against mean radius, diameter and age of the tree. The number of sapwood rings was also plotted against the number of rings per cm. The relationships, if any, between these parameters were investigated. In addition, the mean number of sapwood years and variance were calculated for each site.

5.3 Results

5.3.1 Maentwrog

The arithmetic mean of the number of sapwood rings in 38 radii was 27.21. The estimated standard deviation of this sample mean (the standard error) is

$$S(\bar{x}) = \frac{S(x)}{\sqrt{n}}$$

where S(x) is the standard deviation of the observations and n is the number of observations. Thus

$$S(\bar{x}) = \frac{4.83}{\sqrt{38}} = 0.78 \ .$$

This estimate has 37 (n - 1) degrees of freedom. From this estimate of the scatter about the mean and the assumption that x (and therefore $\bar{x}$) is normally distributed, limits can be calculated within which the mean of the population from which the observations were drawn is likely to lie. The limits must be based on Student's t distribution because only the estimated standard deviation is available. Reference to Student's t tables shows that with 37 degrees of freedom (n - 1) 95% of values of 't' will fall between -2.03 and +2.03.

The Gaussian confidence limits for the population mean (given an estimate of it, $\bar{x}$, the sample mean) are

$$\bar{x} \pm t\sqrt{\left(\frac{S^2(x)}{n}\right)}$$

where $S^2(x)$ is the variance of the observations.

$$= 27.21 \pm 2.03\sqrt{\left(\frac{S^2(x)}{n}\right)} = 27.21 \pm 1.58 \ .$$

$$P = 0.05$$

The standard error has been used in the calculations in preference to the standard deviation of the observations since the aim is to estimate the accuracy of the sample mean $\bar{x}$. It is used when the object of making the observations is to estimate the population mean rather than to estimate the inherent variability of the population.

If limits are required within which a new observation from the same population is expected to lie the result is somewhat different from that above. The calculation of such limits may be described by

$$\bar{x} \pm t \sqrt{\left(s^2(x).\left(\frac{1}{n} + \frac{1}{m}\right)\right)}$$

where m is the number of new observations (Colquhoun, 1971).

Thus the limits within which a single new observation would be expected to lie are

$$27.21 \pm t\sqrt{23.32\left(\frac{1}{38} + \frac{1}{1}\right)}$$

$$= 27.21 \pm 2.03 \sqrt{24.02}$$

$$= 27.21 \pm 9.95$$

It was not possible to examine the relationships between the sapwood and other tree parameters because only a small number of trees exhibited complete ring sequences from the pith to the bark. Many of those samples as cores failed to reach the pith while those sampled as discs were either rotten in the centre or had been damaged by fire sometime in the past.

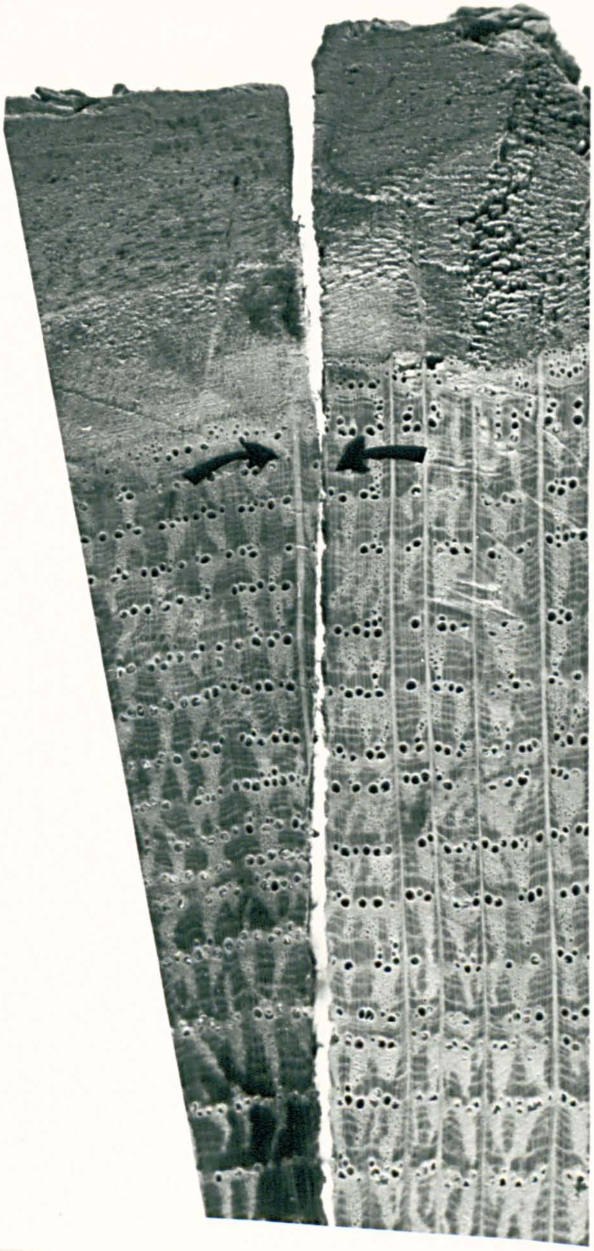
Other tree parameters have been measured by John Good (unpublished data), namely tree diameter and tree age. Analysis of these data for trees greater than 124 years old indicates that there is no relationship between tree diameter and tree age.

5.3.2 Peckforton

The concept of missing and double rings in oak was discussed in Section 1.3 and their absence was considered to be important in the choice of oak for dendrochronological studies. Evidence of a locally absent ring was found in tree LP 611 from Site I. This feature was found in the sapwood when it was observed that the tree-ring patterns of the two radii measured crossdated except that one curve extended beyond the other by one year at the bark end. This was puzzling because as bark was present on both radii the final ring on each should have been formed in the same year. After comparing the curve of each radius with the working master it became apparent that the ring of 1977 was missing from radius LP 611B. Plate 5.3 shows where the tree-ring patterns of the two radii correspond. The arrows identify the 1975 ring. The ring formed in 1977 is present in LP 611A (right hand side) but absent in LP 611B (left hand side). The 1976 ring in LP 611A has earlywood vessels of a different arrangement from those in the rest of the tree. They are arranged in single files which extend almost to the earlywood of the 1977 ring. There was no evidence of apparent double rings in any of the radii measured.

Plate 5.3 Locally absent ring in oak sample LP 611 at Peckforton

Arrows indentify the ring formed in 1975.



The arithmetic mean of the number of sapwood rings in the 44 radii examined was 29.9 with standard error of 1.36. The 95% confidence limits for the population mean are

$$29.9 \pm t\sqrt{\frac{83.72}{n}}$$

$$= 29.9 \pm 2.77$$

Using the equation described in section 5.3.1, the limits for a single new observation are

$$29.9 \pm t\sqrt{83.72\left(\frac{1}{44} + \frac{1}{1}\right)}$$

$$= 29.9 \pm 18.59$$

In the following results each value for the number of sapwood rings and for the width of sapwood is the mean of two radii from a tree, unless otherwise stated. The width of sapwood varied from 1.9 cm to 6.4 cm. On the basis of the measurements described in Section 5.2 the presence of associations was examined between the following parameters:

1. mean number of sapwood rings and tree age
    - (a) all trees
    - (b) trees greater than 100 years old
2. mean sapwood width and tree age
3. number of sapwood rings and the radius of which it is part
4. sapwood width and the radius of which it is a part
5. mean number of sapwood rings and mean number of rings per cm.

The measurements made in this investigation of sapwood relationships provided data for the following examination:

6. tree diameter and tree age
    - (a) all trees
    - (b) trees greater than 100 years old.

The results of these analyses including the correlation coefficients'r'and the regression equations where appropriate, are shown in Table 5.1. The plots of the parameter pairs (1) to (6) are shown in Figure 5.1. None of the 5 pairs of parameters regarding the sapwood were significantly associated at the 5% significance level. However, the results show that for the population of trees sampled at Peckforton Hills, the diameter and the age of a tree are significantly related at the 5% level in all the trees examined (i.e. trees of 70 years of age or more).

Table 5.1

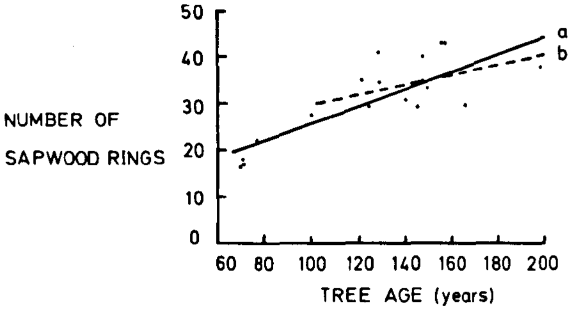
Sapwood relationships in Peckforton oaks (parameters described in text)

parameters	R	regression equation	Student's t	n	significance at 5%
1 (a)	0.80	$y = 0.18x + 7.22$	0.0001	19	-
(b)	0.45	$y = 0.10x + 19.58$	1.00	15	-
2	0.28	—	—	—	—
3	0.35	—	—	—	—
4	0.39	—	—	—	—
5	0.41	$y = 1.66x + 19.96$	1.88	19	-
6 (a)	0.51	$y = 0.17x + 17.83$	2.37	19	+
(b)	0.60	$y = 0.32x - 4.95$	2.57	15	+

Figure 5.1 Sapwood relationships in Peckforton oaks

1. Number of sapwood rings and tree age
2. Sapwood width and tree age
3. Number of sapwood rings and tree radius
4. Sapwood width and tree radius
5. Number of sapwood rings and mean number of rings per cm
6. Tree diameter and tree age

(1)


NUMBER OF SAPWOOD RINGS
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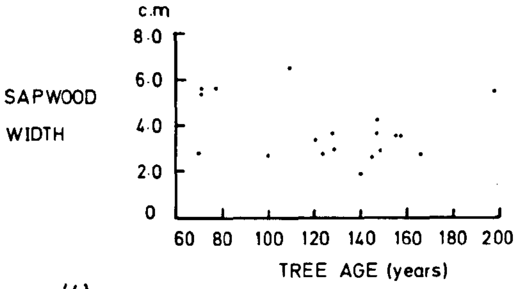
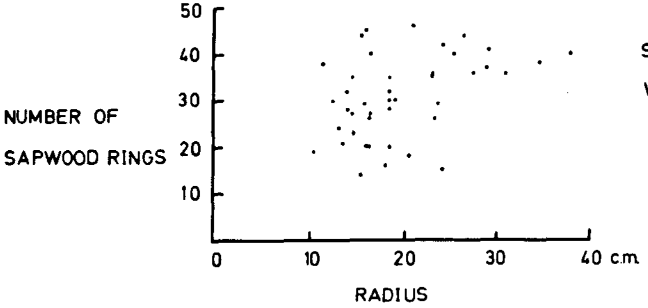
10
20
30
40
50
a
b
60 80 100 120 140 160 180 200
TREE AGE (years)

(2)


c.m
SAPWOOD WIDTH
0
2·0
4·0
6·0
8·0
60 80 100 120 140 160 180 200
TREE AGE (years)

(3)


NUMBER OF SAPWOOD RINGS
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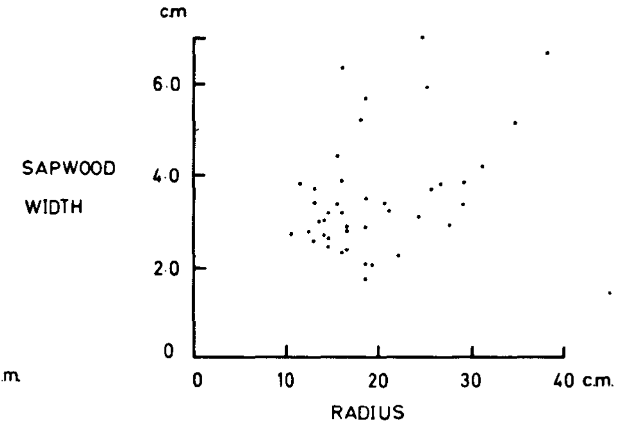
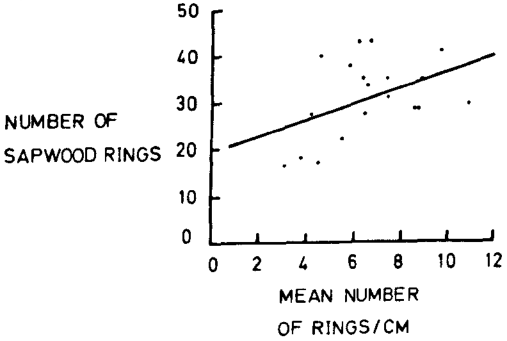
20
30
40
50
0 10 20 30 40 c.m.
RADIUS

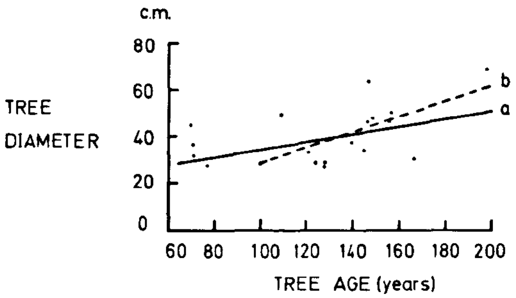
(4)


cm
SAPWOOD WIDTH
0
2·0
4·0
6·0
0 10 20 30 40 c.m.
RADIUS

(5)


NUMBER OF SAPWOOD RINGS
0
10
20
30
40
50
0 2 4 6 8 10 12
MEAN NUMBER OF RINGS/CM

(6)


c.m.
TREE DIAMETER
0
20
40
60
80
b
a
60 80 100 120 140 160 180 200
TREE AGE (years)

5.4 Discussion

One of the recognised advantages in using oak for the construction of tree-ring chronologies is the lack of missing and double rings. It is interesting to note that the recognition of such features by other workers has always involved the observation of supposed double rings. In the present study, a locally absent ring was detected in the sapwood in one tree out of the 23 trees examined. Unfortunately, this tree had been moved subsequent to felling so that the occurrence of this irregularity in relation to compass direction or slope of the hillside could not be examined. Nevertheless, it appears that during the formation of the 1976 ring, growth was terminated on one side of the tree.

As previously described, the sapwood is an important feature of oak because it helps in determining the exact felling date of the tree. This is of value when timbers which require dating have lost the bark but retain a portion of sapwood. The figure 20 ± 5 obtained for German oaks is used by many workers as the number of sapwood rings to be added to the date of the heartwood ring at the heartwood/sapwood boundary. Bauch and Eckstein (1970), Bauch, Esckstein and Meier-Siem (1972) and Fletcher (1974b) used this figure to determine the cutting date of oak panels used for paintings. Other workers have used the estimate of 25 sapwood rings (Barefoot, 1975; Morgan, 1975,1977a,1977b). Baillie (1973a) found the arithmetic mean of the number of sapwood rings from 37 Irish samples to be 31.8 ± 9 where ±9 represents one standard deviation. The estimate 32 ± 9 was used to estimate the felling date of any Irish oak material which exhibited a heartwood/

sapwood transition.

All the estimates for the number of sapwood rings in oak listed above are derived from measurements on either German or Irish oaks. Previous to the estimation of the Irish value, the only statistical estimates published ~~were~~ those for German and Turkish trees. Consequently, this was the value used by many workers for the determination of felling dates for British timbers since no other existed.

The programmes of sampling at Maentwrog and Peckforton permitted the calculation of sapwood estimates for northern England and North Wales which were 30 ± 18 and 27 ± 10 respectively. The wider limits at Peckforton are a reflection of the greater variability in the number of sapwood rings, not only between trees but also within trees. The estimates for Maentwrog and Peckforton both have much wider confidence limits than those of Hollstein's (20 ± 6) or Baillie's (32 ± 9) because allowance is made for a new sample not present in the population from which the estimate was made. These estimates become 20 ± 12 and 32 ± 19 respectively when allowance is made for a new additional sample.

Throughout the remainder of this study the value 30 ± 18 is used to estimate the felling date of any timbers that exhibit a heartwood/sapwood transition. The figure for Peckforton is used in preference to that for Maentwrog because the wider limits of the former will automatically encompass the Maentwrog figure. Strictly speaking, the values obtained for the mean number of sapwood rings in any study will only be valid for the estimation of felling dates of trees from the populations from which the estimates were made. However, in many situations where oak has been used in the past, for example, as building timber or in panel paintings, it is not common to find a complete record of sapwood. In consequence, the absolute felling date will not be known. It is more common to find timbers or panels with partial sapwood. However requests for building dates from architects, archaeologists and others have demanded that what information is known in other situations (i.e. sapwood estimates from living trees) be utilised here.

Apart from allowing an estimation of the mean number of sapwood rings, the presence of complete sapwood on many of the trees sampled at both sites has permitted a study of sapwood width. Fletcher (1974b,1978a) has stated that for mature oaks the width of the sapwood is relatively constant, about an inch. Results from the present study have shown this to be incorrect, at least for trees from North Wales and northern England. In mature oak trees the width of the sapwood was found to have a range of 1.6 to 6.5 cm (approximately ½ to 2½ inches) at Maentwrog and 1.8 to 7.0 cm (approximately ¾ to 2¾ inches) at Peckforton. Thus, from the variation shown in these results it would be quite wrong to quote that the width of sapwood will be "about an inch".

Sampling sufficient trees for the construction of dated well replicated chronologies provides material for the examination of associations between tree parameters in addition to direct sapwood estimations. The lack of a significant relationship between the mean number of sapwood rings and tree age agrees with the findings of Baillie (1973a) for Irish oaks. The figures 25-45 years for the lifetime of the parenchyma cells in oaks greater than 100 years old are also comparable (Baillie, 1973a).

The lack of any significant relationship between both the number of sapwood rings and radius and the sapwood width and radius indicates that the sapwood cannot be used to estimate the size of a complete radius when, for example, the primary interests are woodland mensuration.

There also appears to be no significant relationship between the mean number of sapwood rings and the number of rings per cm so that the former is independent of the widths of the annual growth rings. Trees at Peckforton exhibited values for the number of rings per cm, somewhat larger than the figure of 5.2 ± 1.1 quoted by Baillie (1973a) for modern Irish trees grown in open conditions. 19 trees at Peckforton had a mean of 6.60 rings per cm, standard error 0.45. For the 15 of the 19 trees which contained 100 or more growth rings themean number of rings per cm was 7.21, standard error 0.44.

A belief held by many people is that the size of a tree, in terms of its diameter or girth, is an indication of its age. Several workers, however, have found this not to be the case. For Irish oaks Baillie (1974) found that in trees containing more than 100 growth rings, size was largely unrelated to age. Jones (1960), from numerous measurements made on oak in England also concluded that size is an imperfect guide to the age of the tree. The measurements from oaks at Peckforton appear to contradict these conclusions. Statistical analyses indicate that a significant relationship exists between tree age and diameter growth in trees greater than 70 years old. Estimates based on measurements of girth would be unduly high due to the inclusion of bark in the initial measurement.

The establishment of modern chronologies from North Wales and the north west of England provides chronologies which are absolutely dated and so serve as modern anchors for subsequent analyses of undated material. Measurements from living and recently felled trees have provided data relevant to the investigation of relationships between certain tree parameters, parameters which are pertinent to tree growth and the estimation of felling dates.

CHAPTER 6 - CLIMATIC STUDIES

6.1 Introduction

The construction of absolutely dated well replicated tree-ring chronologies from an area on the wet western flank of Great Britain and from a drier inland site reinforces the results of other workers (Pilcher, 1976; Baillie, 1977a and Baillie, 1977b). They have detailed the potential of dendrochronology in Great Britain, a region with conditions that might appear to be unfavourable (Godwin, 1940). Tree-ring chronologies constructed from trees on limiting sites in western North America have been successfully used to examine the relationships between variations in ring width and climatic variables (Fritts, 1974). The detection of this relationship is made difficult since factors other than climate influence the growth of the tree. These factors are usually regarded as "noise" which may derive from ontogeny, stand development, stand management and growing conditions at the site (Section 3.1.2).

The most fruitful dendrochronological investigations have been made where changes in ring width associated with tree age are separated from changes associated with climate variation (Fritts, 1971). This is accomplished through the process of standardisation (Section 2.6.2). Ring-width variability due to factors other than climatic variability is minimised by the careful section of sites. At the best sites the ratio between the signal (ring-width variation due to climatic factors) and the noise (ring-width variation due to non-climatic factors) is large (Hughes <u>et al.</u>, 1978a). Selection of the sites at

Maentwrog and Peckforton was made with these considerations in mind. Analysis of variance results suggest that there is sufficient common signal in the tree-ring chronologies from Maentwrog and Peckforton for them to be considered for the subsequent climatic studies.

There are a number of aims to this climatic study:

1. The intention is to determine whether and to what extent the annual signal in two modern chronologies is climatic. The chronologies for Maentwrog and Peckforton are derived from trees growing in woodlands with very different climatic regimes. Maentwrog is a wet maritime site with 1,750 mm rainfall per annum, whilst Peckforton, being in the rain-shadow of the Welsh mountains, is much drier with only 750 mm per annum. The aim is to determine how trees at these sites respond to variations in climate and whether the nature of the site should be considered when applying models of tree growth and climate to historic timbers.
2. It is proposed to examine the extent of the homogeneity at the Maentwrog site. An analysis of the properties of the Maentwrog chronology provides results which suggest that the site is not homogeneous. The response function approach is applied to the component chronologies to identify any differences between them in their response to variations in climate.
3. Filtering techniques (Section 2.6.1) have been used by several

workers to create new time series with most of the chronology variance in a particular frequency range (Stockton and Fritts, 1971; LaMarche and Fritts, 1972; LaMarche, 1974b; Fritts and Shatz, 1975 and Hughes et al., 1978b). The justification for doing this is that many processes in nature including tree growth are complex and feedback mechanisms are usually found. In the relationship between tree growth and climate for example, "an unfavourable year in a favourable period does not have the same effect as when situated in an unfavourable period" (Guiot, Berger and Munaut, in press). It therefore becomes important to distinguish between long-term climatic variations and short-term climatic changes, the interannual variability. Digital filtering is a technique which allows an analysis of these effects. LaMarche (1974b) and Fritts and Shatz (1975) have compared filtered chronologies by cross-correlation analysis to examine the similarities between sites in different frequency ranges. Stockton and Fritts (1971) have used the technique to identify periods of heterogeneity in several chronologies. In this study, the application of the response function approach will be used to identify and examine the nature of the relationship between climatic variables and tree-ring variations which lie in particular frequency ranges.

6.2 Quality of climatic records and tree-ring data

(a) Climatic data

The utilisation of climatic data in the investigation of relationships between ring-width variation and climatic variables requires a thorough evaluation of the available climatic records. Mitchell et al. (1966) have recognised the problem of inhomogeneity of climatic data and its implications for local and world-wide studies of climatic change. The diversification and sophistication in the uses of meteorological data have led to changes in data requirements. Consequently, this has led to changes in station locations, instrumentation and observing routines. As a result, inconsistencies are introduced into the climatic record. In addition, Mitchell et al. (1966) recognise the fact that the longest available climatic series usually come from expanding urban areas. In such areas, local conditions may no longer represent those of outlying rural areas. These more gradual changes can introduce inhomogeneities as trend.

The problem of inhomogeneity of climatic data is accompanied by the problems of missing data. Missing data reduce the quality of the climatic record and affect a shortening of the calibration period.

Several graphical and statistical methods have been used for the identification and adjustment of the inhomogeneities of climatic series. For temperature, a number of procedures have been described (Mitchell et al., 1966) of which the most useful has been to compute the year-to-year differences between the series to be examined and each of the other series. The resulting series of differences are plotted together on linear graph paper. Any sizable errors present in the temperature values in the series being examined will be shown as "spikes" at the same date in all or most of the plotted series. LaMarche (see Fritts, 1976) has also developed a method to test for homogeneity in temperature records. For precipitation, methods have been described by Kohler (1949) and Mitchell et al. (1966). The double-mass analysis technique first described by Merriam (1937) and later by Kohler (1949) provides a means not only of determining the consistency of observations collected over a long period of time but also of adjusting the early records to conform to those of an existing site of a station which has been moved. The annual or seasonal precipitation totals for the station under test and those for the comparative station or stations are plotted against each other in the form of cumulative sums starting with the most recent year. If the data for the stations being compared are relatively homogeneous the plotted totals will fall closely either side of a diagonal straight line. If only one of the records is homogeneous, for example if one station has been moved, then the plotted totals will tend to lie along two line segments of different slope. If both stations have been moved then several variations in slope appear in the plot. For the case where only one record is considered homogeneous, the adjustment factor for the early records of the other station will be equal to the ratio of the slopes of the two line segments (Mitchell et al., 1966). It is realised by Mitchell et al. (1966) that this type of plot will not show which of the two records contains inconsistencies. This drawback may be overcome by plotting each of the station records under test in a similar manner against a base derived from records from a large number of stations in the surrounding area. Mitchell et al. (1966) consider that an evaluation of the absolute homogeneity of a record may only be obtained by making the comparisons with such an average series.

Statistical evaluation of homogeneity has largely involved the evaluation of relative homogeneity between two or more series which are considered one pair at a time. Tests of homogeneity are made by testing for the presence of non-randomness in derived series of values from the two stations under test (Conrad and Pollak, 1950).

Maentwrog

Weather data used in this study are taken from meteorological records at Aberyswyth (Lat. 52°25'N; Long 4°05'W) and Bont Newydd (Lat. 52°57'; Long. 3°55'W). Earlier climatic studies at Maentwrog (Hughes et al., 1978b) suggest that the association between ring-width variation and climatic variables might be improved by using climatic records from a nearer meteorological station than Aberyswyth. This was particularly so with respect to rainfall since rainfall is so much more dependent upon local details of exposure, aspect and surface heating than temperature. The meteorological station at Bont Newydd is thus better placed since it is only 5½ km from Maentwrog and it is in the same valley. Although the rainfall record is much shorter here than at Aberyswyth it was considered a reasonable alternative. The locations of the two meteorological stations are shown in Figure 6.1.

Double-mass analysis was carried out on the rainfall data from Aberyswyth and Bont Newydd to determine whether these records were homogeneous. The analysis of precipitation utilises cumulative totals for January through December. The totals for one station are plotted as a function of the totals for the other station starting with the most recent record, for the period 1921 to 1966 (Figure 6.2(a)). Homogeneity is indicated in both records by the straight diagonal line. Had inhomogeneity been indicated further comparisons with other records would have been necessary to determine if the record of interest was homogeneous. Average values for temperature at Aberyswyth for the period 1906 to 1966 and for precipitation at Bont Newydd for 1921 to 1966 are shown in Figure 6.3(a) and (b).

Peckforton

The location of Peckforton Hills in the Cheshire Plain seemed initially to be well situated in terms of the numerous

Figure 6.1 Location of tree-ring sites and meteorological stations

M - Maentwrog
P - Peckforton Hills

A - Aberyswyth
Pt - Pont (Bont) Newydd

E - Eaton Hall
R - Reaseheath Hall
Md - Macclesfield

L - Liverpool

LOCATION OF TREE-RING SITES AND METEOROLOGICAL STATIONS

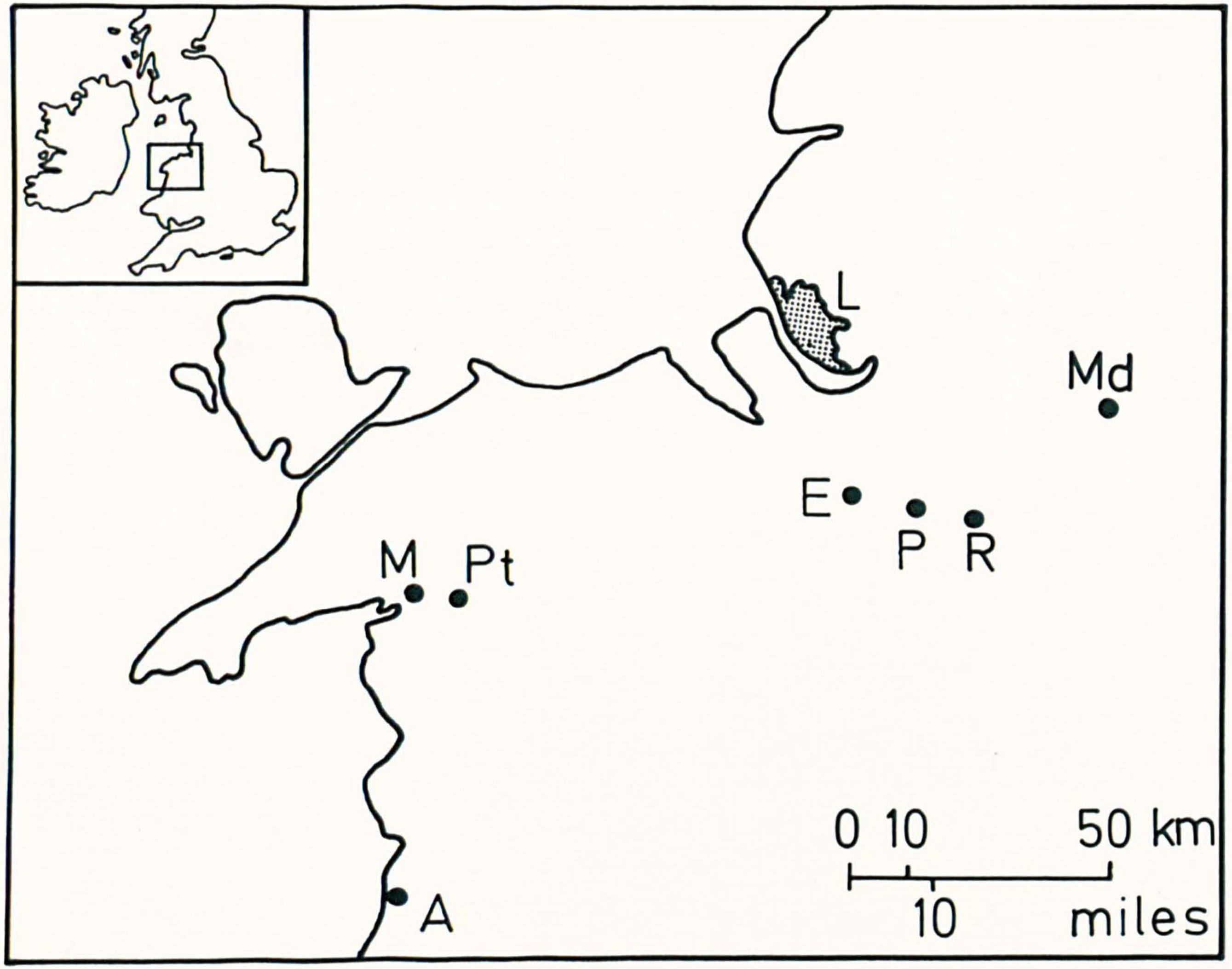


Figure 6.2 Tests for homogeneity in precipitation records using double-mass analysis.

(a) Bont Newydd and Aberyswyth for the period 1921-1966.

(b) Eaton Hall and Reaseheath Hall for the period 1903-1975.

CUMULATIVE PRECIPITATION (Jan.-Dec.)

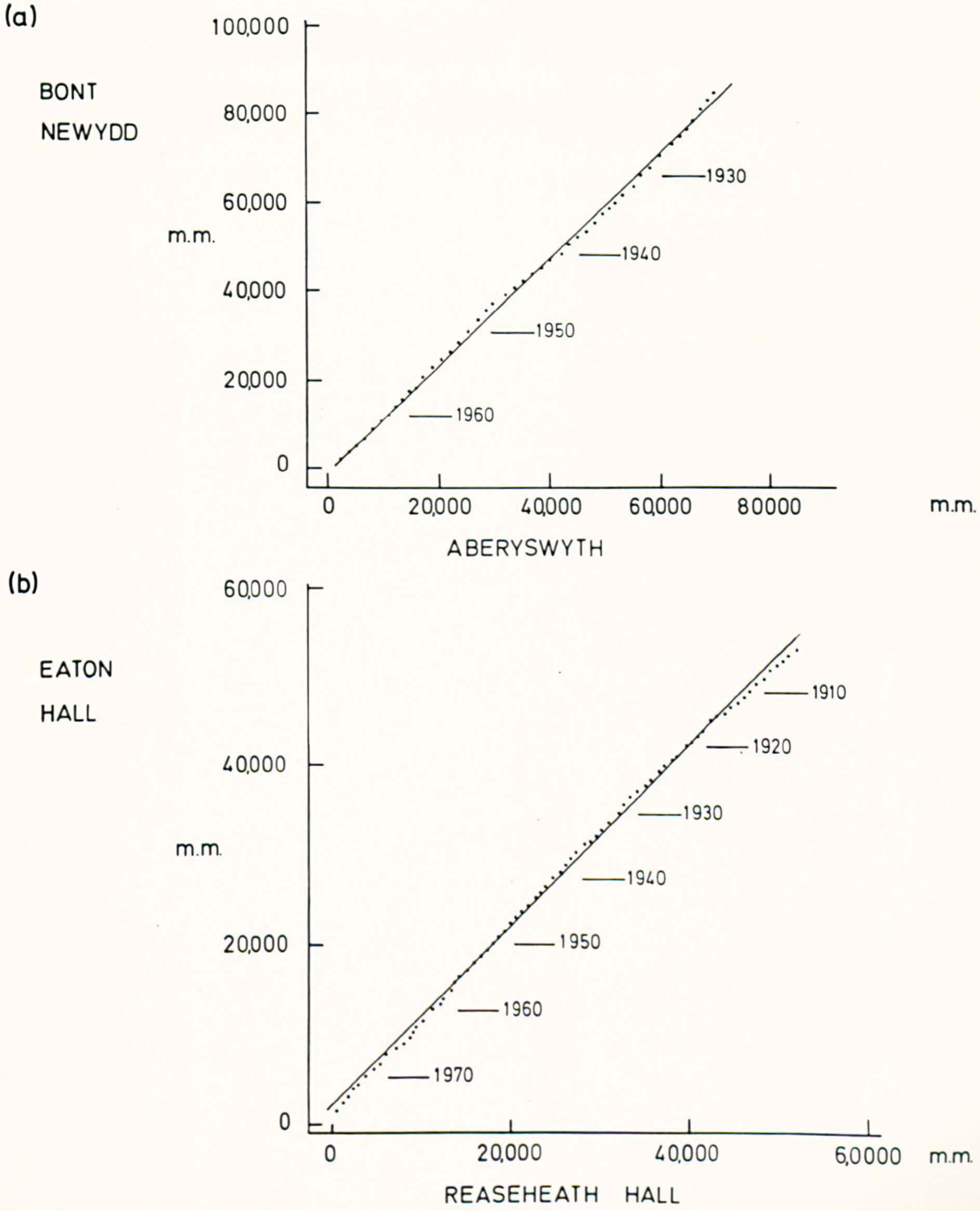


Figure 6.3(a) Mean Monthly Temperature

at Aberyswyth for the period 1906-1966

and at Macclesfield for the period 1895-1975.

Values for the period 1921-1966 follow very closely those for 1895-1975.

Vertical lines show 95% confidence limits.

(a) MEAN MONTHLY TEMPERATURE

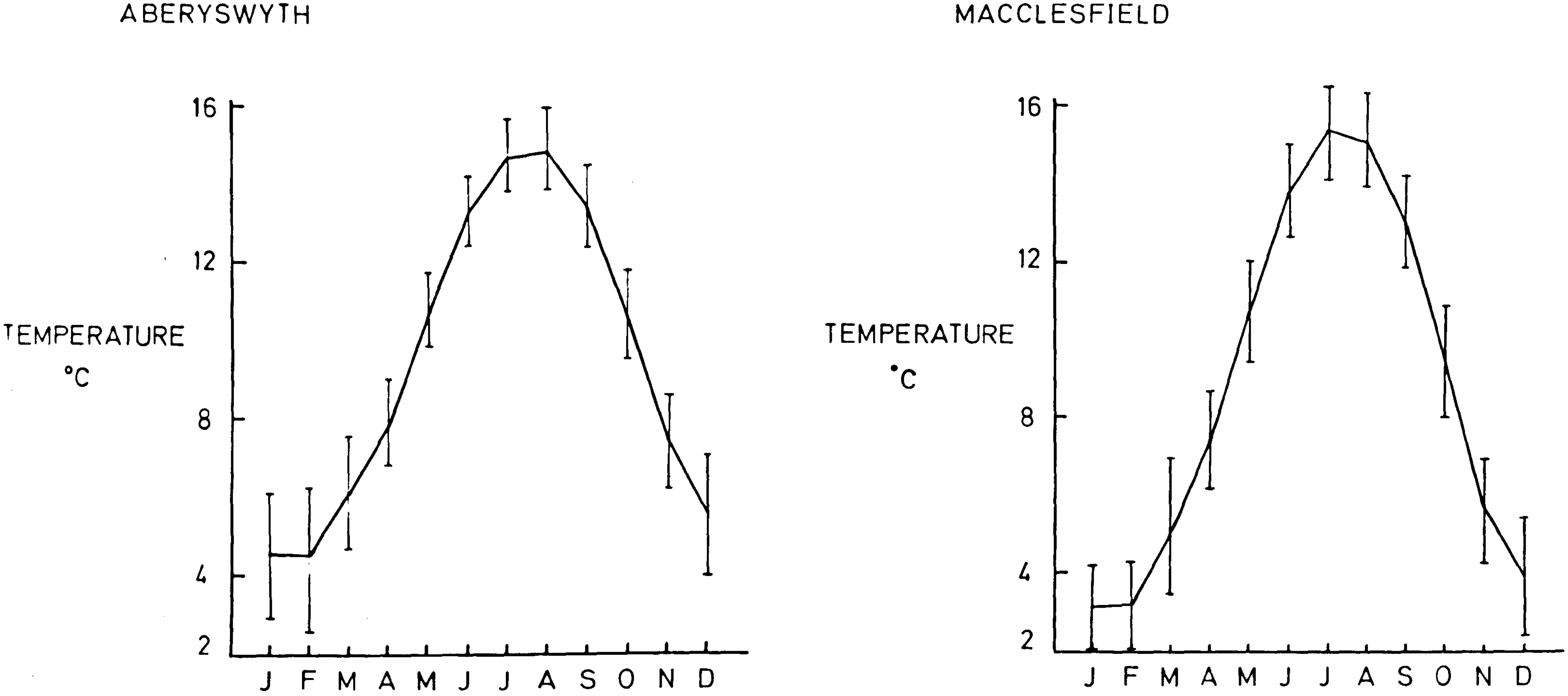


Figure 6.3(b) Total Monthly Precipitation

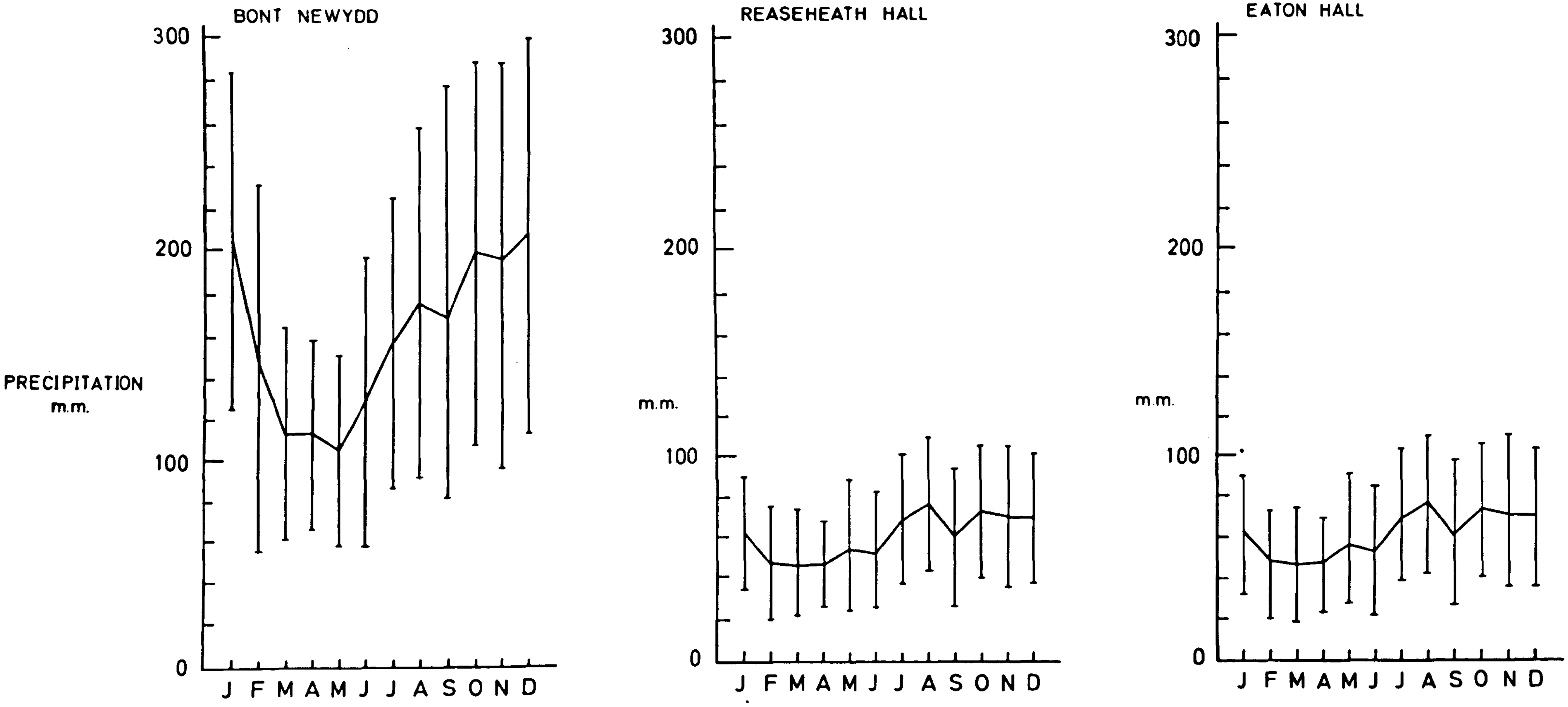
at Bont Newydd for the period 1921-1966.

at Reaseheath Hall for the period 1895-1975. Values for the period 1921-1966 are very similar to those for 1895-1975.

at Eaton Hall for the period 1903-1969. Values for the period 1921-1966 are very similar to those for 1895-1975.

Vertical lines indicate 95% confidence limits.

TOTAL MONTHLY PRECIPITATION



surrounding meteorological stations. However, the majority of these stations held records with small amounts of data i.e. 20 or 30 years.. For temperature, there was only one station with a record sufficiently long and complete to be considered. This station was at Macclesfield (Lat. 53°15'N, Long. 2°7'W) which is 41 km north east of Peckforton Hills. Temperature records began in 1881. For rainfall, records were available at Peckforton pumping station but these only began during 1955. Longer records were available from 1886 at Eaton Hall (Lat. 53°9'N, Long. 2°53'W) 12 km to the north west of Peckforton Hills and from 1895 at Reaseheath Hall (Lat. 53°5'N, Long. 2°31'W) 11.5 km to the south east of Peckforton Hills. Figure 6.1 shows the location of all these recording stations.

Since there were no comparable temperature records available in the area, tests for homogeneity in the Macclesfield records could not be made. It was therefore necessary to accept this record as being homogeneous. The existence of three precipitation records within the Cheshire Plain allowed an evaluation of homogeneity in all the data. Double-mass analysis was carried out on the following pairs of stations:

1. Reaseheath Hall and Eaton Hall
2. Reaseheath Hall and Peckforton
3. Eaton Hall and Peckforton.

Figure 6.2(b) is a plot of cumulative annual totals from Reaseheath Hall against those from Eaton Hall for the period 1903 to 1975. Figure 6.4(a) and 6.4(b) show the plots of cumulative annual totals for Reaseheath Hall and Peckforton and Eaton Hall and Peckforton for the periods 1956 to 1975 and 1956 to 1976 respectively. Homogeneity is indicated in all plots.

Although the precipitation records at Peckforton are the most likely records to reflect the precipitation at the woodland, their length limits their value for studies of ring-width variation and climate relationships. Thus, the records from Reaseheath Hall and Eaton Hall appear to have more value in spite of their distance from the woodland. Yearly totals of precipitation for Reaseheath Hall and Eaton Hall were plotted against those for Peckforton to examine the similarity or dissimilarity in the records (Figure 6.4(c) and (d)). Precipitation at both stations appears to be very similar to that at the Peckforton station. Thus, the precipitation records for Reaseheath Hall and Eaton Hall were considered homogeneous and consequently both sets of data were used in subsequent analyses. Mean monthly temperature at Macclesfield for the period 1895 to 1975 and 1921 to 1966 is shown in Figure 6.3(a). Total monthly precipitation at Reaseheath Hall for the periods 1895 to 1975 and 1921 to 1966 and at Eaton Hall for the period 1903 to 1969 is shown in Figure 6.3(b).

(b) Tree-ring data

Quality in climatic data must be accompanied by quality in the tree-ring data. To obtain this it is necessary to use a tree-ring series which is representative of tree growth within

Figure 6.4 Tests for homogeneity in precipitation records using double-mass analysis:

(a) Peckforton and Reaseheath Hall for the period 1956-1975.

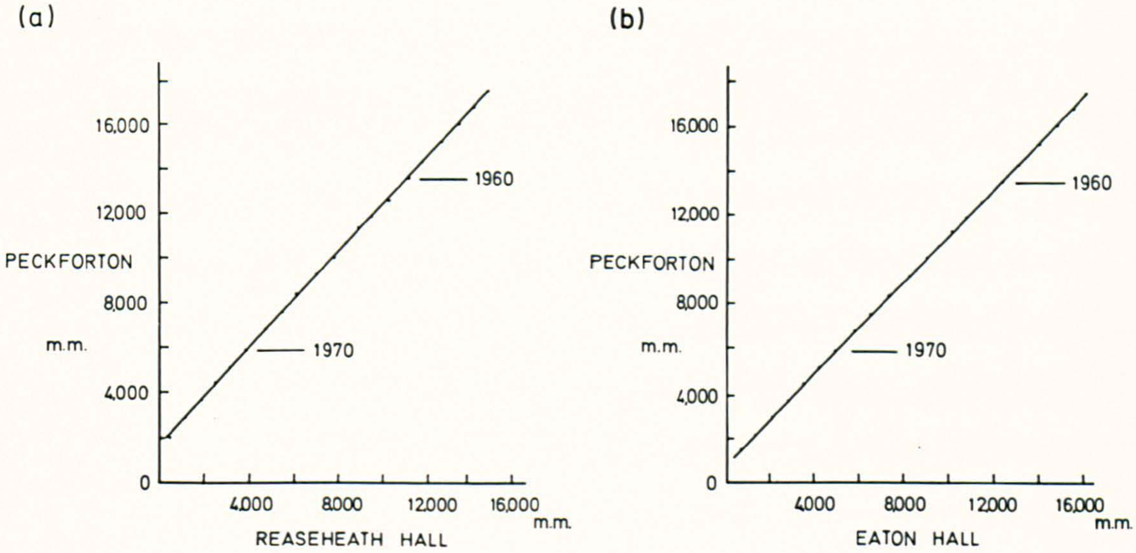
(b) Peckforton and Eaton Hall for the period 1956-1976.

Yearly precipitation totals:

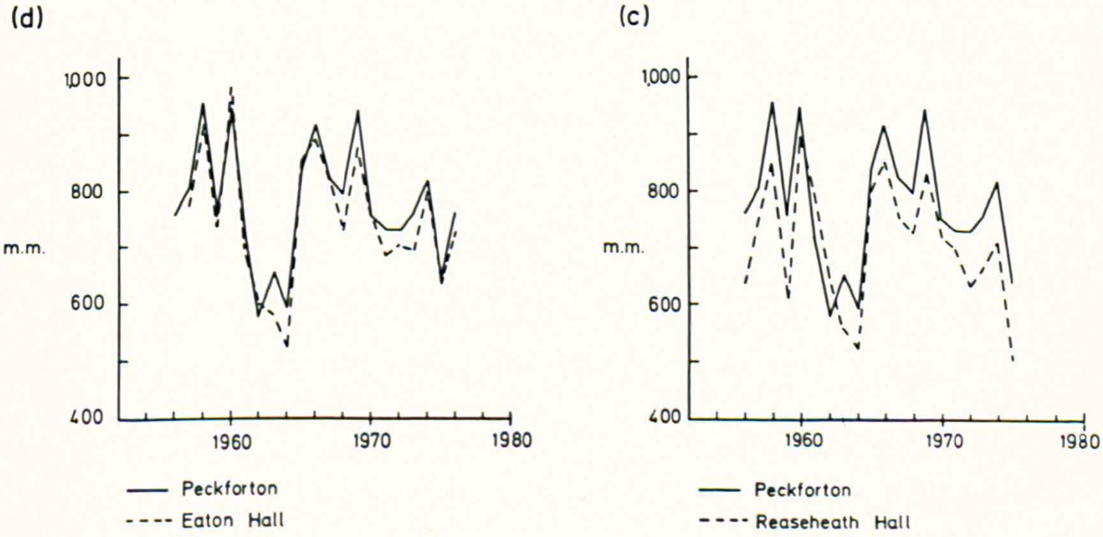
(c) Peckforton and Reaseheath Hall

(d) Peckforton and Eaton Hall.

CUMULATIVE PRECIPITATION (Jan-Dec)



YEARLY PRECIPITATION TOTALS



the woodland under study. Such representativeness may only be achieved by using a tree-ring series which comprises many individual trees from the site. The analysis of variance programme in the Indxa package (Fritts et al, 1969) then provides a means of assessing the quality of this tree-ring series for climatic studies.

For the Maentwrog chronology, the analysis of variance of the Anova series showed that 25.5% of the annual variance was in common. This figure is not as high as those for other oak woodlands; Rostrevor 42% (Pilcher, 1976) and Schleswig 38% (Eckstein and Schmidt, 1974). Nevertheless, it does indicate that there is sufficient common signal for the Maentwrog chronology to be used in a climatic study. At Peckforton, the annual variance in common was higher, 32.7% indicating that sufficient common signal was also present in this chronology.

A reappraisal of the nature of the site at Maentwrog suggested that the low value for variance retained by the common chronology (25.5%) may be explained by the consideration that this site is really two. It may be that the trees at these two sites are subject to some differences in the growth controlling processes whilst containing sufficient common signal to facilitate good crossdating between them. To examine this hypothesis the trees comprising the standard Maentwrog chronology were positioned as they had originally been sampled i.e. those from Site I and those from Site II. Figure 2.2 shows that the two sites are in different parts of the woodland. Tree-ring series were subsequently constructed for site I and II from 12 and 13 trees respectively. Analysis of variance was carried out on these chronologies for the periods 1875 to 1961 and 1875 to 1952 respectively. It was proposed to examine the response of trees to variations in climate at these two sites (Section 6.4 (i)).

Reciprocal filters were applied to the data of the site I and site II chronologies to examine the response of trees to climate in different frequency ranges. Analysis of variance was carried out on the filtered chronologies for the periods 1875 to 1961 (Site I) and 1875 to 1952 (Site II). The calibration period for the response of trees to climate is 1921 to 1966. Analysis of variance was therefore carried out for this period on the unfiltered Maentwrog and Peckforton chronologies when the chronology components allowed this. This was also the case in the filtered series.

6.3 Calibration Methods

A variety of methods have been described in the literature for the calibration and measurement of the association between ring widths and climate. A comprehensive account and review of these methods are given by Fritts (1976). The statistical technique, multiple regression and correlation is preferred to techniques involving simple correlations since the tree growth and climate relationship is such a multiple variable system (Fritts, 1976). Simple correlation cannot deal with the situation where variables of the climatic system are highly correlated with each other as well as with tree growth, which is usually the case. Multiple regression and correlation can deal with this situation by using statistical procedures to determine variable intercorrelation so that the relative effect of each variable upon the amount of growth is described in one equation. This technique has been used successfully by a number of workers (Tryon et al., 1957; Eklund, 1957 and Serre et al, 1966). The disadvantage of using stepwise multiple regression analysis is that it cannot handle all the intercorrelations between the independent variables. An approach which may overcome this difficulty is one which uses principal components combined with regression. This is the Response Function described by Fritts et al. (1971).

The Response Function

In the response function approach the predictor values are transformed into a new set of uncorrelated variables. The uncorrelated variables are called eigenvectors which are then used in a stepwise multiple regression analysis. Once the regression coefficients for the selected set of uncorrelated variables have been calculated, a new set of coefficients may be transformed which correspond to the original set of correlated values.

The elements of the tree-ring chronology are estimated by

$$ {}_1\hat{P}_n = {}_1R_p\,{}_pE'_m\,{}_mF_n $$

where ${}_1\hat{P}_n$ is a row vector of estimates of ring-width indices, ${}_mE'_p$ the transpose of the eigenvector matrix of climatic data, ${}_mF_n$ the original climatic data for m variables and n years and ${}_1R_p$ a row vector of p significant multiple regression coefficients between ring-width indices and the eigenvectors of climatic data. The regression coefficients associated with the eigenvector amplitude can be converted into a new set of coefficients, ${}_1T_m$, which express the same relationships but in terms of the original variables rather than the eigenvector amplitudes. ${}_1T_m$ may be derived thus:

$$ {}_1T_m = {}_1R_p\,{}_pE'_m \,. $$

Subsequently, each element of the response function can be interpreted in terms of an anomaly in monthly temperature or monthly precipitation, the climatic variables used in the analysis.

The response function in this form does not take account of the autocorrelation found in tree-ring chronologies (Section 2.6.5) which can affect the tests of significance. Therefore, the ring-width indices for the three previous years are included as three additional variables in the regression analysis.

On the basis of the discussion given by Fritts (1976) the response function approach (Fritts et al., 1971) was used to examine the strength and nature of the climatic signal in the Maentwrog and Peckforton chronologies. The response functions for these oak chronologies are based on a 14-month year for mean monthly temperature and monthly precipitation which commences in June of the year before growth and finishes in July of the current year of growth. Longman and Coutts (1974) suggest that this period contains the periods of latewood formation in both years. The extension to a 16-month period ending in September of the current year's growth for an oak chronology from Northern Ireland (Pilcher, 1976) increased the variance accounted for by the response function by only 1.5% (Hughes et al., 1978a).

Calibrations for modern sites

At Maentwrog the response function approach has been used to examine the strength and nature of the climatic signal in the chronologies listed below. Each chronology was examined in relation to mean monthly temperature at Aberyswyth and monthly precipitation at Bont Newydd for the period 1921 to 1966.

Standard Maentwrog chronology:

unfiltered

high-pass

low-pass

Site I chronology:

- unfiltered
- high-pass
- low-pass

Site II chronology:

- unfiltered
- high-pass
- low-pass.

For Peckforton, the unfiltered chronology only was examined in relation to mean monthly temperature at Macclesfield and monthly precipitation at Eaton Hall for the period 1903-1969. The analysis was repeated replacing the precipitation records from Eaton Hall by those from Reaseheath Hall for the period 1895-1975. On the basis of the amount of chronology variance related to climate and the number of significant elements, one of these precipitation records was selected for use in further analyses. These further analyses examined the relationship between ring-width variation in unfiltered chronologies and variables of climate.

The longer climatic records at these recording stations made possible the examination of a longer calibration period than that used at Maentwrog. In order to make the results at Maentwrog and Peckforton directly comparable, the calibration period used for Peckforton was shortened to equal that used for Maentwrog, namely 1921 to 1966. Thus the Peckforton chronologies used in the calibrations were:

Standard Peckforton chronology (1895-1975):

unfiltered	
high-pass	(1895-1969)
low-pass	(1895-1969)

Standard Peckforton chronology (1921-1966):

unfiltered

high-pass

low-pass

6.4 Results

The response functions of the unfiltered and filtered chronologies for Maentwrog and Peckforton listed in Section 6.3 are shown in Figures 6.5 to 6.8. The vertical lines through each response function element show the 95% confidence limits. Where the lower limit is above the zero line, there is a signficantly positive response function element. Where the upper limit is below the zero line, there is a significantly negative response function element. If each element of the response function is divided by the standard deviation of the climatic variable it represents then the absolute effect of climate (as measured at the climatic station) upon ring width may be calculated (Fritts et al., 1971). In the response functions presented the elements are thus transformed to relative measures of the effect upon ring-width index of a one degree Centigrade rise in temperature and a 2.5 centimetre increase in precipitation for separate months of the year. To obtain the effects of decreases in temperature and precipitation the signs are reversed. The significant elements for variables of temperature and precipitation in the response functions are compared in Tables 6.1, 6.2 and 6.6.

The chronology variance accounted for by each response function is shown in Tables 6.3 and 6.4. For each chronology, the variance held by the common chronology for the calibration periods is shown in Table 6.5.

Maentwrog

Table 6.3 shows the percentage chronology variance accounted for by the Maentwrog response functions. A greater percentage of variance related to climate is shown by the standard chronology (45.5%) and site II (47.5%) than by site I (35.8%). The total amount of chronology variance accounted for by the response function is also greater at these two sites.

Figure 6.5 shows that the nature of the climatic signal differs in the three chronologies. Their response functions all contain a significantly negative element for temperature in the December prior to growth. Only site II and the standard chronology show a significantly positive temperature element in the October prior to growth. This element in the current May is shown only by site I and the standard chronology. The most important difference between the response functions for the component chronologies (sites I and II) is the response to precipitation. Three significantly positive elements are shown by site I; for September prior to growth and for the current March and April. No significantly positive elements are shown for site II or for the whole site chronology. The response functions for the three unfiltered Maentwrog chronologies all show prior growth to be a significant element at a lag of one year. Further differences between these response functions are shown in Table 6.1(a) and Figure 6.5. Differences between any response functions are meaningless if they are not statistically significant. In the response functions for site I and site II there are differences in the actual significance of the elements and where their

Figure 6.5 Maentwrog Response Functions

unfiltered data, period 1921-1966.

(a) Standard chronology; contains

temperature - 6 significant elements
precipitation - 3 significant elements
prior growth - 2 significant elements.

(b) Site I chronology; contains

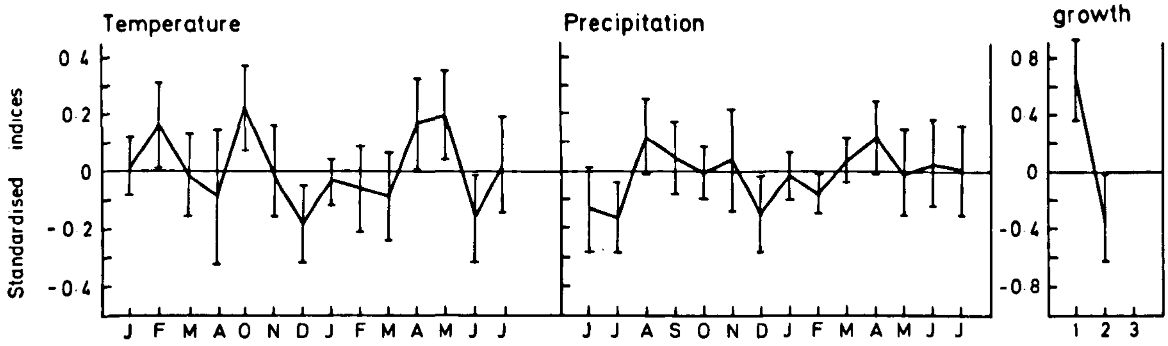
temperature - 3 significant elements
precipitation - 4 significant elements
prior growth - 1 significant element.

(c) Site II chronology; contains

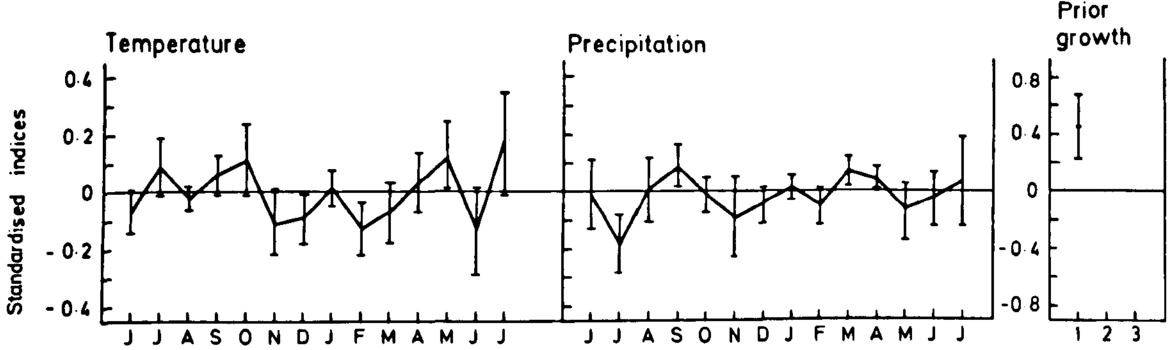
temperature - 5 significant elements
precipitation - 3 signficant elements
prior growth - 2 significant elements.

MAENTWROG RESPONSE FUNCTIONS
UNFILTERED DATA

(a) STANDARD CHRONOLOGY



(b) SITE I CHRONOLOGY



(c) SITE II CHRONOLOGY

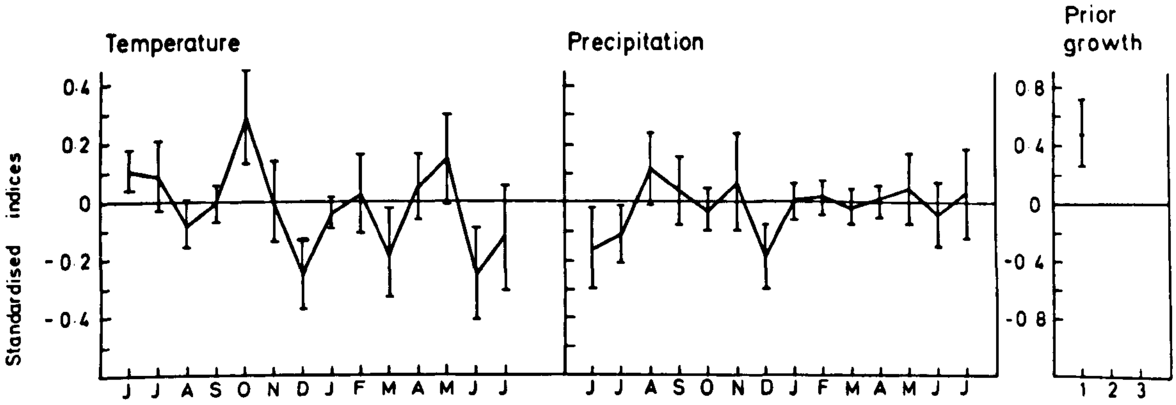


Table 6.1 Significant elements in the Maentwrog response functions

	TEMPERATURE														PRECIPITATION														PRIOR GROWTH (LAGS.YRS)		
	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	1	2	3
Period 1921-1966																															
(a) unfiltered chronologies																															
Standard chronology		+			+		-				+	+	-		-						-		-						+	-	
Site I chronology							-		-			+				-		+						+	+				+		
Site II chronology	+				+		-			-			-		-	-					-								+		
(b) high-pass filtered chronologies																															
Standard chronology	-	+		+	+	-	+		-	+			-	-	+	-	+	+	-	-	-	+	-	+			+			-	
Site I chronology	-	+	-	+					-	+					+	-	+	+				+		-	+					-	
Site II chronology				+		+		-	-	-			-	-		-	+				-	+					+			-	

limits of confidence overlap one another the differences become insignificant.

A comparison of the variance related to climate in the filtered data is shown in Table 6.3. The proportion of chronology variance related to climate is very similar in all cases; 39.2%, 40.4% and 42.3% for the whole site, site I and site II respectively. These values lie close to those for the unfiltered chronologies. The variance related to prior growth is lower in all the high-pass chronologies since long-term variations have been blocked in the filtering process.

Table 6.1(b) and Figure 6.6 show the changes in the nature of the climatic response after the application of the high-pass filter. At site I, the number of significantly positive temperature elements increases from 1 to 3 and the significantly negative elements increase from 2 to 3. For precipitation, the number of significantly positive elements increases from 3 to 5 and the significantly negative elements from 1 to 3. Similarly at site II, the number of significant temperature and precipitation elements is increased in the high-pass filtered data. In particular, the response function now contains 3 significantly positive precipitation elements whilst that for the unfiltered data contained none at all. The response function of the total complement of trees (the standard chronology) showed a similar change. The introduction of 6 significantly positive precipitation elements in the prior June, August and September and the current January, March and July was the most drastic

Figure 6.6 Maentwrog Response Functions

high-pass filtered data, period 1921-1966.

(a) Standard chronology; contains

temperature - 9 significant elements

precipitation - 11 significant elements

prior growth - 1 significant element

(b) Site I chronology; contains

temperature - 6 significant elements

precipitation - 7 significant elements

prior growth - 1 significant element.

(c) Site II chronology; contains

temperature - 7 significant elements

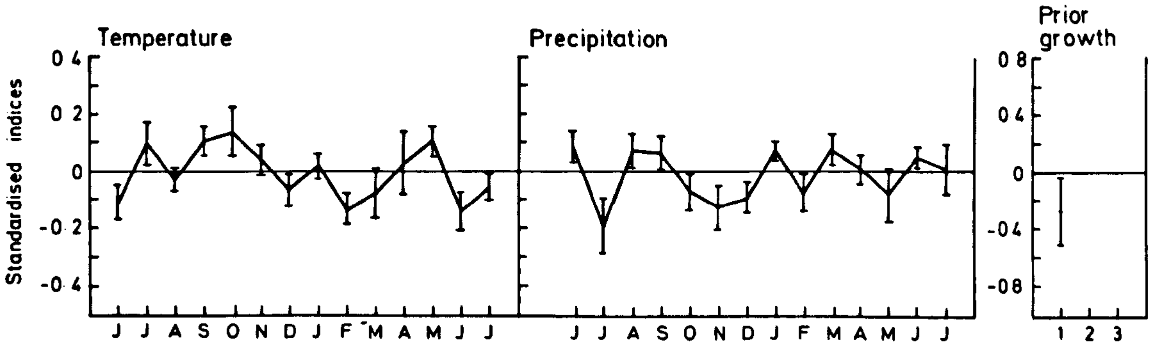
precipitation - 5 significant elements

prior growth - 1 significant element

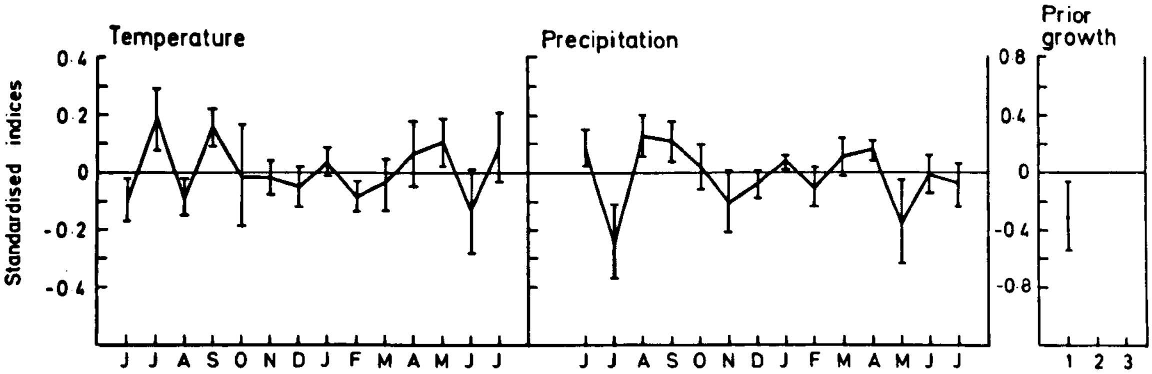
MAENTWROG RESPONSE FUNCTIONS

HIGH-PASS FILTERED DATA

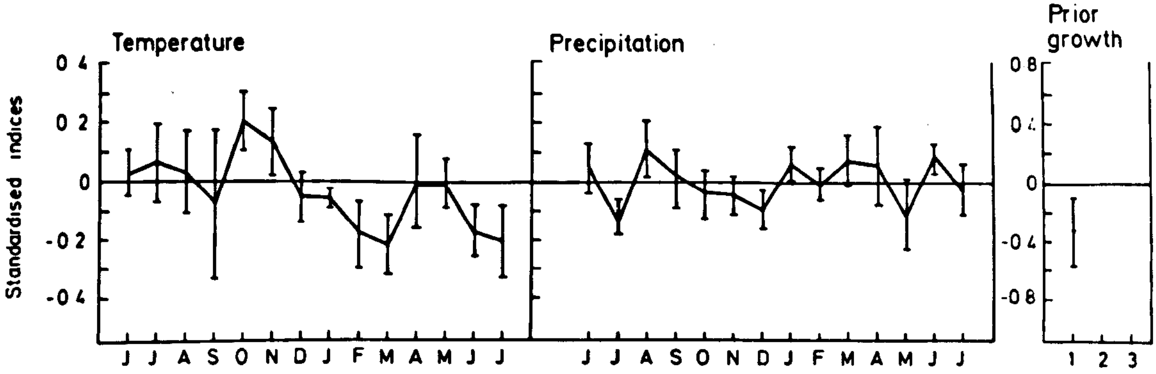
(a) STANDARD CHRONOLOGY



(b) SITE I CHRONOLOGY



(c) SITE II CHRONOLOGY



change. The response function for the unfiltered chronology had contained no significantly positive elements for precipitation. The response functions of all three high-pass filtered chronologies showed prior growth at a lag of two years to be negative and significant.

Peckforton

Table 6.2(a) shows the presence of significant elements in the Peckforton response functions. The first uses Reaseheath Hall precipitation data and the second, precipitation at Eaton Hall. A greater proportion of chronology variance is accounted for by climate (39%) when the records from Reaseheath Hall are used in the calibration rather than those from Eaton Hall (28%). In addition, the number of significant elements is higher at Reaseheath Hall (14 against 12). Thus, temperature at Macclesfield and precipitation at Reaseheath Hall present the better model for describing the relationship between ring-width variation at Peckforton and variations in climate. On the basis of these results the Reaseheath Hall precipitation records were used in subsequent response functions.

In the response function for the calibration period 1895 to 1975 the amount of chronology variance accounted for by climate is 39.3%. The nature of the climatic signal for this period is shown in Figure 6.7(a). The most obvious feature of this response function is the positive effect of precipitation on the width of the annual ring. Significant elements occur for the prior June, August, September and October and for the current January

Figure 6.7 Peckforton Response Functions

unfiltered data.

(a) calibration period 1895-1975; contains

temperature - 7 significant elements

precipitation - 7 significant elements

prior growth - 2 significant elements

(b) calibration period 1921-1966; contains

temperature - 5 significant elements

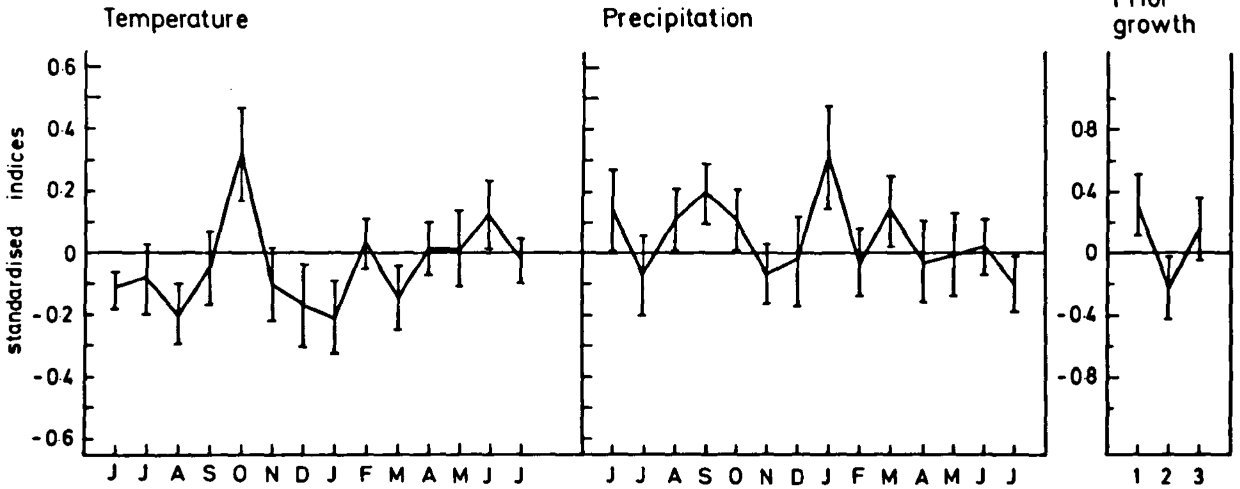
precipitation - 7 significant elements

prior growth - 0 significant elements

PECKFORTON RESPONSE FUNCTIONS

UNFILTERED DATA

(a) 1895 - 1975



(b) 1921 - 1966

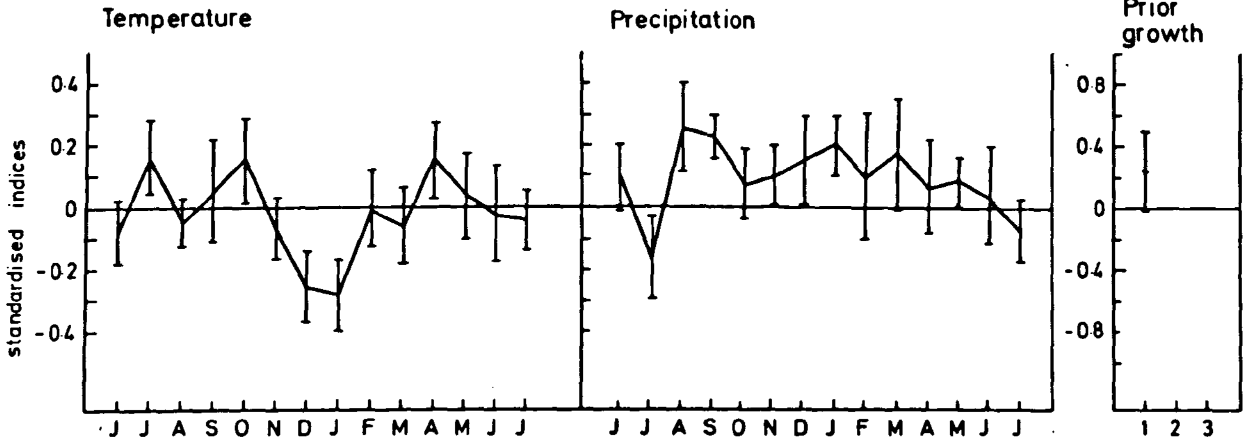


Table 6.2 Significant elements in the Peckforton response functions

	TEMPERATURE														PRECIPITATION														PRIOR GROWTH (LAGS.YRS)		
	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	1	2	3
(a) Unfiltered chronology																															
Period 1895-1975 (Reaseheath Hall precipitation)	-		-		+		-	-		-			+		+		+	+	+			+		+				-	+	-	
Period 1895-1969 (Eaton Hall precipitation)	-	-			+	-	-	-		-			+	+		-								+			+		+		
Period 1921-1966 (Reaseheath Hall precipitation)		+			+		-	-			+				+	-	+	+			+	+				+					
(b) High-pass filtered chronology																															
Period 1895-1969	-		-		+			-		-	-		+		+			+				+	-	+		+				-	-
Period 1921-1966	-	+					-					+	-		+	-				+	+	+		+					-	-	

and March. Significantly positive elements for temperature occur in the prior October and current June. Significantly negative temperature elements occur during the prior and current year of growth. Prior growth is significant at lags of one and two years.

In the response function for the shorter calibration period (1921 to 1966) the amount of chronology variance accounted for by climate is 52%. Table 6.2(a) and Figure 6.7(b) show the nature of the climatic response. The main features are the same as those for the longer calibration period but some differences are apparent. Although the element for October temperature is still significantly positive it becomes less important to growth. The significantly positive temperature element for the current June is absent but occurs for the prior July and the current April. Prior growth was not significant at lags of one, two or three years.

The strength and nature of the climatic response was also found to differ in the high-pass filtered data (Figure 6.8 and Tables 6.2(b) and 6.4). In the response functions for both calibration periods climate accounted for less of the chronology variance. For 1895 to 1969 this figure was reduced by only 2.6% but for 1921 to 1966 the reduction was 14.5%. The chronology variance accounted for by prior growth became increased; for 1895 to 1969 by 10.2% and for 1921 to 1966 by 17.1%.

Although the nature of the climatic signal in the high-pass filtered data is very similar to that of the unfiltered data, several differences arise. For the calibration period 1895 to 1975, precipitation in the autumn prior to growth becomes less important. Similarly, precipitation in the current January is less important. On the other hand, precipitation in the March of the year of growth becomes more important in the high-pass filtered data. Table 6.4 also shows that the nature of the response to prior growth also differs.

The response function for the period 1921 to 1966 also shows the reduced importance of precipitation in the autumn prior to growth. In addition, a somewhat different response is also shown to winter and spring temperature. For the unfiltered data, lower than average temperatures in December and January are beneficial to growth. For the high-pass filtered data a general response of this nature extends from December to April although four of these five elements are not significant. The nature of the response to prior growth also differs. In the unfiltered data it is not significant at any number of lags (one to three); in the filtered data it is significantly negative at a lag of one and two years.

After the application of the low-pass filter to the Maentwrog and Peckforton chronologies very little of the chronology variance is related to climate (Tables 6.3 and 6.4). The proportion of chronology variance related to prior growth accounts for almost the total amount of variance accounted for

Figure 6.8 Peckforton Response Functions

high-pass filtered data

(a) calibration period 1895-1975; contains

temperature - 7 significant elements

precipitation - 7 significant elements

prior growth - 2 significant elements

(b) calibration period 1921-1966; contains

temperature - 6 significant elements

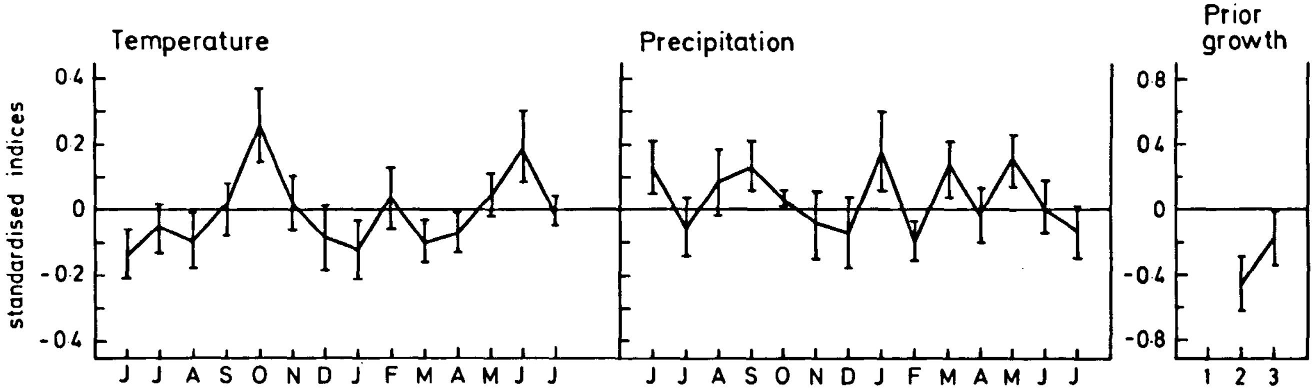
precipitation - 6 significant elements

prior growth - 2 significant elements

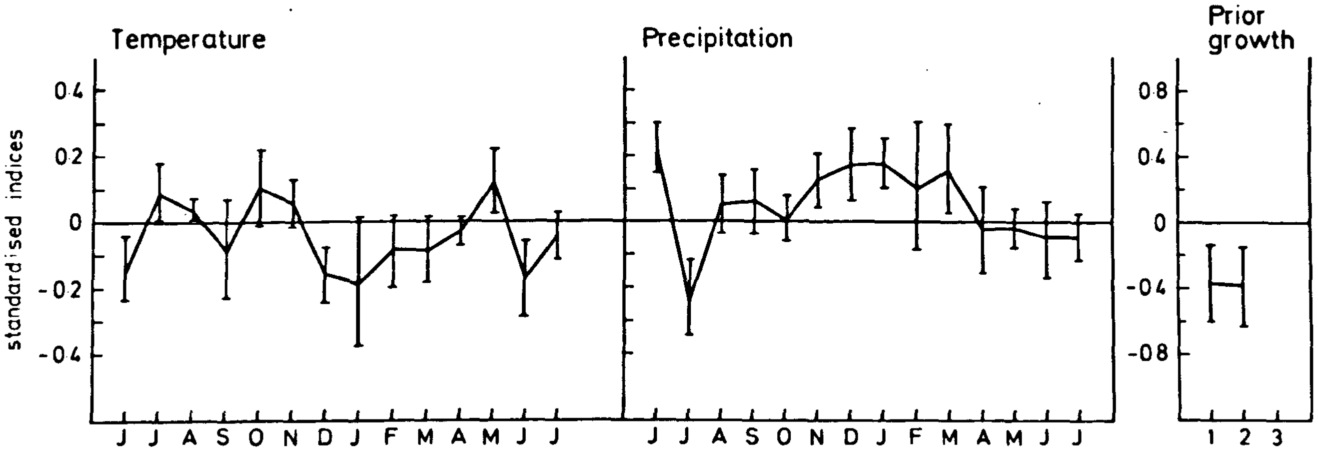
PECKFORTON RESPONSE FUNCTIONS

HIGH-PASS FILTERED DATA

(a) 1895-1969



(b) 1921-1966



by the whole response function. The figure for prior growth is greater than 90% in all cases. These results indicate that the low-pass filter (Section 2.6.1) is accomplishing the task it was designed to do.

Table 6.3

Maentwrog: % chronology variance accounted for by response functions for the period 1921-1966

	Climate	Prior Growth	Total
Whole site			
unfiltered data	45.5	25.0	70.5
high-pass filtered data	39.2	7.9	47.1
low-pass filtered data	1.00	97.9	98.9
Site I			
unfiltered data	35.8	20.8	56.6
high-pass filtered data	40.4	9.3	49.7
low-pass filtered data	2.0	96.6	98.6
Site II			
unfiltered data	47.5	22.6	70.1
high-pass filtered data	42.3	10.6	52.9
low-pass filtered data	3.6	91.8	95.4

Table 6.4

Peckforton: % chronology variance accounted for by response functions

	Climate	Prior Growth	Total
1921-1966			
unfiltered data	52.0	6.0	58.0
high-pass filtered data	37.5	23.1	60.6
low-pass filtered data	-0.04	98.50	98.46
1895-1975			
unfiltered data	39.3	11.8	51.1
high-pass filtered data (-1969)	36.7	22.0	58.7
low-pass filtered data (-1969)	0.38	97.03	97.41

Table 6.5

Analysis of variance results for the Maentwrog and Peckforton chronologies

Maentwrog

Whole site

	Unfiltered	High-pass
Number of trees	15	10
Number of cores	30	15
Period	1921-1966	1921-1966
Number of years	46	46
% variance, years	29.9	34.7
% variance, years x trees	33.0	37.3
% variance, years x radii x trees	33.9	27.9
Error of y	0.07	0.03

Site I

	Unfiltered	High-pass
Number of trees	8	7
Number of cores	16	14
Period	1921-1961	1921-1961
Number of years	41	41
% variance, years	35.9	37.7
% variance, years x trees	41.5	33.1
% variance, years x radii x trees	22.6	29.7
Error of y	0.09	0.03

Site II

	Unfiltered	High-pass
Number of trees	6	3
Number of cores	12	6
Period	1921-1961	1921-1961
Number of years	41	41
% variance, years	50.6	34.9
% variance, years x trees	9.7	28.2
% variance, years x radii x trees	39.8	36.8
Error of y	0.10	0.02

Peckforton

1921-1966 calibration period

	Unfiltered	High-pass
Number of trees	16	15
Number of cores	32	30
Period	1922-1959	1922-1959
Number of years	38	38
% variance, years	31.0	35.3
% variance, years x trees	33.1	39.9
% variance, years x radii x trees	35.8	24.8
Error of y	0.06	0.02

1895-1975 calibration period

	Unfiltered	High-pass
Number of trees	16	15
Number of cores	32	30
Period	1877-1946	1885-1946
Number of years	70	62
% variance, years	32.7	32.2
% variance, years x trees	24.5	20.8
% variance, years x radii x trees	42.8	47.0
Error of y	0.05	0.02

Maentwrog (periods not used in response function analyses)

Whole site

	Unfiltered	High-pass
Number of trees	14	14
Number of cores	28	28
Period	1875-1952	1875-1952
Number of years	78	78
% variance, years	25.5	30.5
% variance, years x trees	41.7	40.7
% variance, years x radii x trees	32.8	28.8
Error of Y	0.08	0.02

Site I

	Unfiltered	High-pass
Number of trees	7	7
Number of cores	14	14
Period	1875-1961	1875-1961
Number of years	87	87
% variance, years	29.7	37.7
% variance, years x trees	37.2	33.1
% variance, years x radii x trees	33.1	29.2
Error of Y	0.11	0.03

Site II

	Unfiltered	High-pass
Number of trees	5	4
Number of cores	10	8
Period	1875-1952	1875-1952
Number of years	78	78
% variance, years	34.8	38.1
% variance, years x trees	36.2	41.3
% variance, years x radii x trees	28.9	20.6
Error of Y	0.13	0.03

Table 6.6 Significant elements in the unfiltered Maentwrog and Peckforton response functions

	TEMPERATURE														PRECIPITATION														PRIOR GROWTH (LAGS.YRS)		
	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	1	2	3
Maentwrog chronology (1921 - 1966)		+			+		-				+	+	-			-					-		-						+	-	
Peckforton chronology (1921 - 1966)		+			+		-	-			+				+	-	+	+			+	+				+					
Peckforton chronology (1895 - 1975)	-		-		+		-	-		-			+		+		+	+	+			+		+				-	+	-	

6.5 Discussion

The construction of tree-ring chronologies from sites which differ in their climatic regimes, as well as in other ways and which show a clear climatic signal, allows a comparison of the response of trees to different climatic variables. The woodlands at Maentwrog and Peckforton are known to be maritime and rain-shadow sites respectively. Rainfall in the former is high (1,760 mm per annum) and well distributed throughout the year and considerably lower in the latter (750 mm per annum) (Figure 6.3(b)). The response functions (Figures 6.5 to 6.8) show important differences in the response of trees to climate at these climatically different sites.

At Maentwrog it may be inferred from the response function (Figure 6.5(a)) that tree-rings will be wider than average when temperatures are

1. higher than average in the July and October prior to growth and in the April and May of the year of growth and
2. lower than average in the December prior to growth and the June of the year of growth.

Wider than average rings will also be formed when precipitation is lower than average in the prior July and December and the February of the year of growth. Figure 6.7(a) shows the response function for Peckforton for the period 1895 to 1975. It may be inferred from this response function that wider than average rings are formed when temperatures are

1. higher than average in the October prior to growth and in the

June concurrent with growth and

2. lower than average in June, August and December prior to growth and the January and March of the year of growth.

Wider than average rings will also be formed when precipitation is

1. higher than average in the June, August, September and October prior to growth and the January and March of the current year of growth and
2. lower than average in the July of the year of growth.

However, Fritts (1976) stresses the need for caution in interpreting the elements for prior and current summer climate if prior growth at a lag of one year is significant. As he describes "the regression portions out the growth and climatic effects as it attempts statistically to reconcile their intercorrelations. If climate and growth are highly correlated with one another, their individual weights in the response function may be diminished or be of opposite sign."

It is clear that the major difference between tree growth at these two sites is the response to precipitation. Maentwrog shows no positive response to precipitation whatsoever. Peckforton shows six significant positive precipitation elements, the element for January of the year of growth being the most important. Maentwrog shows three significantly negative precipitation elements. Peckforton shows only one and this is for a different month from any of those at Maentwrog. For temperature, Maentwrog shows four significantly positive elements and Peckforton two, with the element for October being included in both. Similarly, December is included in the significantly negative elements for both sites. In June of the year of growth the element for temperature is significantly negative at Maentwrog but significantly positive at Peckforton.

These differences in the response functions indicate that the trees at each site have a characteristic response to climate. The particular combination of ecological, physiological and genetic factors which determine the interaction between tree growth and site conditions are elements which give rise to this (Fritts, 1974). The site conditions at Peckforton are much drier than those at Maentwrog as described by the amount of rainfall recorded there. The nature of the soil and the slope, factors which determine the amount of water retention, are similar at both sites.

The fact that six precipitation elements are significantly positive indicates that precipitation is limiting to tree growth at Peckforton for many months of the year. The increase in precipitation towards the end of the growing season favours prior growth conditions. At this time the tree is more physiologically active and produces more food for storage for utilisation in earlywood production in the following growing season. High October temperatures also appear beneficial to growth (Figure 6.7) and may operate in conjunction with high October precipitation. Evidence for activity in October in the form of shoot elongation and leaf expansion is given by Longman and Coutts (1974). It is possible that the beneficial effect of high

October temperature and precipitation may be much more complex; for example, it may be related to the survival of leaf primordia. An indication of the utilisation of food produced late in the growing season may be inferred from the relationship between cambial activity and photosynthetic activity. According to Daubenmire and Deters (1947), Jackson (1952) and Ladefoged (1952) the cessation of this cambial activity occurs long before leaf senescence. Food produced after cambial activity stops cannot be used in the production of the latewood vessels of that year's growth. Instead, that part not utilised in respiration will be stored for the following year's growth when the cambium is reactivated.

Higher than average precipitation in the January of the year of growth is indicated as an important element. It is important possibly through the effect of high precipitation on soil moisture recharge. At Maentwrog the response to winter precipitation is a negative one. Higher than average precipitation at Peckforton in the current March is important to growth. At an arid site in Lakeview, Oregon, higher than average precipitation in the current March is thought to be important to growth through the maintenance of favourable water balances within the tree (Fritts, 1976). At Peckforton, although March is a time when precipitation is at its lowest (Figure 6.3(b)), soil moisture may not be. Studies in a Danish woodland with a poor sandy soil and total precipitation for November through March which is very similar to that at Peckforton have shown that the water content in March at a 0-6 cm depth has the second highest value (Overgaard Nielsen unpub. data). At a depth of 3-6 cm soil moisture is lower but still much higher than most of the remaining months. Thus, it seems that even when soil moisture is high, precipitation can be limiting to growth. It may be that a superabundance of water is required during the renewed physiological activity.

A study of the climatic response of oak trees at Rostrevor using the response function approach (Hughes et al., 1978a) and a simple linear regression of the tree-ring indices with climatic variables (Pilcher, 1976) both showed that trees at this site were also drought sensitive. This appeared at first to be a somewhat surprising result when the rainfall in Northern Ireland was considered, some 1,125 mm per year (Pilcher, 1976). However, the oak wood at Rostrevor is located on a steep slope which would afford good drainage, greater run-off and percolation. Such features are likely to contribute to a depletion in moisture and thereby relate tree growth to an increase in precipitation.

One of the most striking features shared by the Maentwrog and Peckforton response functions is the importance of higher than average temperatures in the October prior to growth. Oak has been found to show this response at other European sites also, viz Raehills in south west Scotland, Rostrevor on the east coast of Northern Ireland (Hughes et al., 1978a) and an oak stand in Schleswig-Hollstein (Eckstein and Schmidt, 1974). At Vallø Denmark higher than average temperatures in August and September have been found to be important for growth (Holmsgaard, 1955).

Higher than average temperatures in October may favour an increase in leaf expansion, a process which is still active in October (Longman and Coutts, 1974). Conditions therefore become favourable for an increase in photosynthetic activity by increasing the area over which it may occur in addition to extending the length of the growing season itself.

Another common response indicated by the Maentwrog and Peckforton response functions is that to December temperature in the year prior to growth. Growth in the following year is increased when temperatures are lower than average in December. The response functions for oak chronologies at Rostrevor (Hughes et al., 1978a) and Schleswig-Hollstein (Eckstein and Schmidt, 1974) all contain a significantly negative temperature element for December. In addition, the significantly negative element for temperature in January in both the Peckforton response functions is also found in that for Raehills. This indicates that below average winter temperatures are beneficial to tree growth in both these woodlands. The element for April temperature is significantly positive at Maentwrog, Peckforton (1921 to 1966 calibration period) and Rostrevor. This is the period during which bud break occurs, cambial activity is reactivated, the earlywood vessels are formed and the roots begin to elongate. Increased temperatures promote bud break and leaf expansion leading to earlier photosynthesis. The promotion of root elongation leads to the availability of sufficient water allowing these higher rates of photosynthesis to continue. For precipitation, Peckforton (1895 to 1975 calibration period) shares the significantly positive precipitation element for October with Raehills and Rostrevor. The way in which higher than average October precipitation may operate to increase growth is discussed above. However, the response functions for almost all the published modern oak chronologies do show the same response to temperatures in October and December. This indicates that higher than average temperatures in the prior October and lower than average temperatures in the prior December are highly significant to the radial growth of oak growing inthe temperate climate of Europe.

The fact that the chronologies for Maentwrog and Peckforton respond in different ways to the same conditions of climate makes them important for the determination of climatic anomalies. Fritts (1976) points out that the results obtained from the response function for a single chronology only provide a broad estimate of past climatic variations. This is because the response is intergrated over one or more years. He has recognised that it is not easy to determine in which season a particular climatic anomaly associated with growth variations occurs and whether the anomaly is associated with high temperatures, low precipitation or both. When chronologies from two or more sites have different growth responses to the same climatic conditions more detailed inferences may be made.

LaMarche (1974a) has applied this principle by using two chronologies for *Pinus longaeva* which responded in different ways to temperature and precipitation. These responses were used to infer past climatic anomalies. The response functions for

Maentwrog and Peckforton provide similar information which will be available for use in a future multisite climatic analysis for the British Isles.

The two response functions for Peckforton are shown in Figure 6.7 and Table 6.2. The shorter calibration period was used to make the response function comparable to that for Maentwrog. A comparison of the shorter response function with that for the longer period at Peckforton shows significant differences. The main features in both are the same but some differences are apparent. For temperature, there is a difference in the number and distribution of significant positive and negative elements. The number of significant positive precipitation elements is unchanged at seven but the months for which they appear are different. Prior growth is not significant in the shorter period but is significantly positive at a lag of 1 year and significantly negative at a lag of 2 years. Clearly, these results demonstrate that response functions produced from short calibrations may not be representative of the true response.

As far as the standard Maentwrog oak chronology is concerned, it was suggested in Chapter 4 that the high value of 41.7% for between-tree variance may be accounted for by the lack of homogeneity within the site. Such heterogeneity is likely to result from varying factors affecting the growth of individual trees in different ways. The response functions for the whole site and the components of the whole site (sites I and II) show how the trees respond to climatic variables. These results allow an assessment of the similarity of dissimilarity of the component sites. The most fundamental difference between the response functions for sites I and II is the response to precipitation. At site I the trees respond to an increase in precipitation in the September prior to growth and in the March and April in the year of growth. March and April comprise the period of cambial reactivation, commencement of earlywood vessel formation and the first bud break (Longman and Coutts, 1974). No significant positive precipitation elements are shown for site II whatsoever. Thus, the elements for precipitation indicate that above average precipitation in the prior September and the current March and April are beneficial to growth most probably since they affect the water balance of the trees. There is thus a direct relationship between tree growth at site I and precipitation. Precipitation is not limiting to tree growth at site II during any month of the year. Therefore, the indications are that site I is a drier site than site II.

These results show that at least some of the heterogeneity at Maentwrog may be partly explained by climatic variables having different effects on the trees at the component sites. The drawback to this approach of splitting the whole site is that by taking chronologies constructed from fewer trees the confidence limits of the results will be larger and the uncertainty greater. Nevertheless, there appears to be no alternative to this split if attempts are to be made to explain the properties of the whole from its components.

The application of digital filters allowed the differentiation between the climatic factors which have an immediate effect on growth and those which have an effect lasting several years to several decades. The response functions for the filtered Maentwrog and Peckforton chronologies pick up different components of the climatic response. The relationship is stronger in the data passed through the high-pass filter. When the data is passed through a low-pass filter, prior growth becomes an important variable which is itself related to climate.

Summary

This climatic study has shown, through the utilisation of the response function approach that differences do exist in the climatic response of trees at Maentwrog and Peckforton. The major difference is the response to precipitation. In the rainshadow site low precipitation is limiting to growth during many months whilst at the maritime site it has no positive effect on growth. The study also reinforces the positive effect of October temperature and the negative effect of December temperature on growth in the following year found by workers for a number of oak woodlands in Europe.

The availability of long climatic records for Peckforton allowed an evaluation of the quality of long and short calibration periods. This work demonstrates that response functions produced from short calibration periods may not be representative of the true response. The results therefore exemplify the dangers of using short calibration periods when examining the relationships of variations in ring-width index and climate.

The present study demonstrates that the response function approach may be used to examine the heterogeneity of a site. The indications are that the heterogeneity at Maentwrog is explained by the trees at the component sites having different responses to climate. The differences however were not significantly different.

The present work has also examined in detail the climatic response of trees at different frequencies and found it to be different. At Maentwrog the nature of the relationship is greater in the data passed through the high-pass filter. However, in all the tree-ring chronologies except that for Site I at Maentwrog, climate accounted for less of the chronology variance in the high-pass filtered data.

PART II - HISTORIC TIMBERS

CHAPTER 7 - HISTORIC TIMBERS

7.1 Introduction

The positive results of the dendrochronological study of modern timbers from North Wales and Cheshire reinforce the findings of the Belfast group (Baillie, 1973b; Pilcher, 1976 and Baillie, 1977c). Such success inevitably prompts a similar examination of older timbers to facilitate the extension of the chronologies obtained from the modern timbers. The extended chronology will provide a record of past environmental conditions spanning many centuries for the north west of England. The intention is to use this chronology for dating oak timbers from the region and possibly elsewhere.

The sources of older timbers are most commonly found in timber-framed buildings for which large quantities of wood were obviously required. Apart from elm and pine which have a local usage, oak was the most widely used timber through all historic periods. Its "success" was due to its widespread occurrence throughout the country and its quality in terms of strength and durability. The value of oak timbers for tree-ring analyses have been reported by several authors. Huber and Merz (1963) have found oak pilings in one of the settlements of the Swiss Lake Dwellers, the neolithic settlement at Thayngen (Michelsberger Kultur). Oak timbers were found during excavations at the Viking settlement at Haithabu and have provided data for the construction of a tree-ring chronology spanning the 9th and 10th centuries (Eckstein, 1978). Morgan (1977b) has constructed a chronology for the period A.D. 1359 to A.D. 1591 using timbers from Bishop's House, Sheffield and from building timbers in Wales and West Midlands, Siebenlist-Kerner (1978) has constructed a chronology for the period A.D. 1341 to A.D. 1636. Similarly, Laxton _et al_.(1979) have used timbers from a barn in Nottinghamshire to construct a chronology for the period A.D.1453 to A.D.1628. In Dublin, timbers from excavated buildings provided material for a chronology spanning the period A.D. 855 to A.D. 1306 whilst 16th century timbers provided data for the 14th, 15th and 16th centuries (Baillie, 1977b).

Apart from being used in buildings, oak has played an important role in structures for industrial processes, for example, as brine conduits in the Nantwich (Cheshire) salt industry (Hill, unpublished data). Oak is also used in several other types of structure (Section 1.2) but in the north west of England its dendrochronological importance has developed from its use as a building timber.

Throughout the region halls can be found which were once the homes of Lords of the Manor and other wealthy families. These buildings usually have timber framing which is infilled with brick. Unfortunately, many of them have either been demolished during the present and last century or they have been left to decay. The houses of the village contained within each manor also would have contained oak timbers but their lack of significance in the area has not ensured the survival of many to the present time. Nevertheless, it is this demolition and dereliction which has provided much of the material for tree-ring analysis. Its acquisition depends largely on co-operation from the planning department of councils and local architects.

The following sections describe the sites that were examined and found to contain sufficient timbers of a quality suitable for a dendrochronological study. The results form the framework for an absolutely dated regional tree-ring chronology for the north west of England.

7.2 Methods

At the sites where oak timbers were available for tree-ring analysis, samples were taken with a power saw unless stated otherwise. The samples were prepared and the ring widths measured using the techniques described in Sections 2.3 and 2.4. The only exception was the Nantwich excavation material which because of its water-logged condition required different preparation methods. These methods are described in the account of the site. The analysis of the tree-ring data employed the techniques described in Sections 2.5 and 2.6 and are outlined below:

1. The tree-ring measurements of each sample were plotted on semi-logarithmic graph paper.
2. The ring-width patterns of individual samples were compared statistically using programme CROS (Baillie and Pilcher, 1973) and visually to determine the presence or absence of cross-dating.
3. The ring-width patterns which crossdated with one another were initially combined using programme MASTER MITTELWERT (Becker, pers. comm.) to produce a working master for the site. The chronology so produced is in ring-width format.
4. The probabilities of observed values of 'r' between the components of the working master arising by change (output of programme CROS) are tabulated.
5. The tree-ring series not included in the working master were tested for crossdating against it using the visual and statistical criteria.
6. The components of the working master and those which crossdated with it were combined using programme INDXA (Fritts *et al.*, 1969) to produce an index site chronology.

7. The temporal distribution of the components of the index site chronology is shown.
8. The index values of the site chronology are given (Appendix)
9. The site chronology was compared with standard reference chronologies so that it could be assigned calendrical dates. These reference chronologies and their authors are given in Table 7.1.

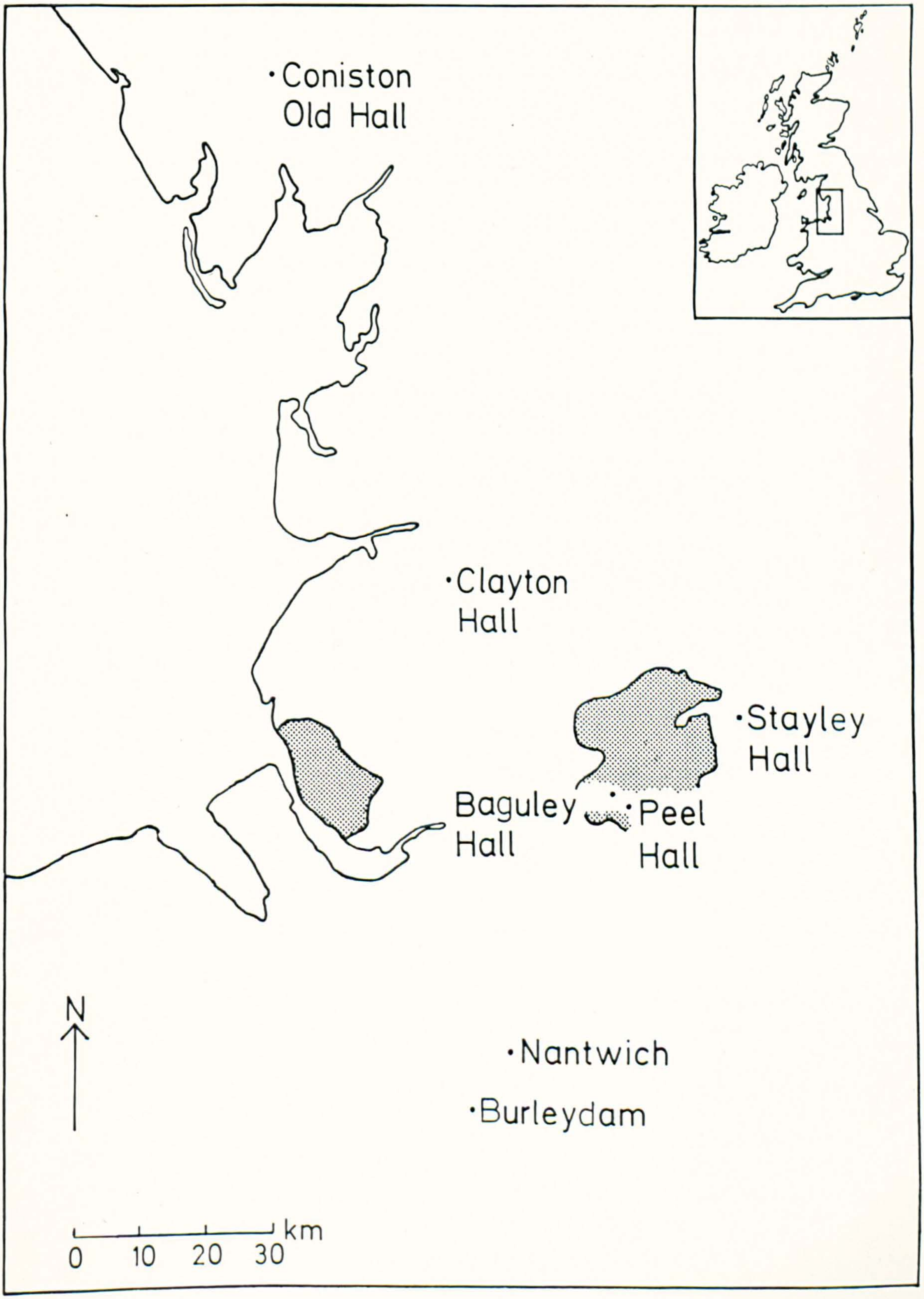
Table 7.1

The oak tree-ring chronologies listed in the subsequent tables

Chronology	Period spanned	Author
Belfast	1001-1970	Baillie, 1977a
Dublin (1)	0855-1306	Baillie, 1977b
Dublin (2)	1357-1556	Baillie, 1977b
South West Scotland	946-1975	Baillie, 1977c
Bishop's House	1359-1591	Morgan, 1977b
Wales/West Midlands	1341-1636	Siebenlist-Kerner, 1978
Seal House	950-1192	Morgan, 1977a
REF.1	1210-1588	Fletcher, 1977
REF.2	1280-1571	Fletcher, 1977
REF.3	1340-1609	Fletcher, 1977
REF.4	1120-1399	Fletcher, 1977
REF.6	780-1193	Fletcher, 1977
Yorkshire building timber	1370-1623	Hillam, unpublished data
Coppergate	1057-1245	Hillam, unpublished data
Hull	1126-1297	Hillam, 1979a
Glastonbury Barn	1102-1313	Bridge, unpublished data
Exeter	811-1216	Hillam, 1979c
West German Curve	822-1964	Hollstein, 1965

Figure 7.1 Location of historic sampling sites

HISTORIC SITES



7.3 Clayton Hall

The Site

Clayton Hall (SD564221)was situated 7 kilometres south south east of Preston, Lancashire (Figure 7.1). It was a 17th century brick building of two stories on a high stone plinth with low mullioned windows and a stone slated roof (Plate 7.1). The front of the hall which was 150 metres long, faced east and had a wide gable at the north end projecting 1.72 metres. The south end of the building seemed to have been rebuilt since the windows were modern with wood frames and brick heads(Farrer and Brownbill, 1911). In 1976 the hall was considered to be in a very dangerous state and as a consequence, it was demolished.

The timbers

As Clayton Hall had been demolished prior to the author being notified, the original locations of the timbers could not be determined. The selection of timbers was made by searching in the remaining rubble (Plate 7.2). Many timbers were long and straight and appeared initially to be of value for tree-ring dating. Further examination revealed that the timbers had been prepared from young trees some of which had fairly sensitive growth patterns whilst others had patterns that were complacent. The timbers were mainly trunks that had been hewn into halves and quarters and some were younger trees from which the whole trunk was used. A number of the larger beams contained mouldings found in many Lancashire vernacular buildings. From this wealth of material only 22 timbers were considered suitable for dendrochronological analysis. Even these timbers were not ideal since they contained only 70 to 100 growth rings, the absolute minimum from which significant results can be obtained (Hillam, 1979b). Nevertheless, it was felt that

Plate 7.1 Clayton Hall before dereliction

Plate 7.2 The timbers of Clayton Hall after demolition

further examination was justified if the timbers formed a strongly related contemporary group.

Results

From the comparisons of tree-ring patterns of 22 timbers, the series from 5 were combined into a working master of 110 years of growth (Figure 7.2). A number of characteristic years namely, arbitary year 19, 45, 47 and 82 are marked by vertical lines. The probabilities of observed values of 'r' between the components of the working master arising by chance are shown in Table 7.2. A further 8 tree-ring series crossdated with the working master and were combined with it to produce an index chronology for Clayton Hall spanning 110 years. The temporal distribution of the chronology components is shown in Figure 7.3. The index values of the site chronology are given in Appendix VI.

As Clayton Hall is recorded as having been a 17th century building (Farrer and Brownbill, 1911) the "floating" site chronology was initially compared with dated chronologies that spanned the 16th, 17th and 18th centuries. This would ensure an adequate overlap if the 17th century date was correct. Only two chronologies spanned these periods: Belfast (Baillie, 1977a) and South West Scotland (Baillie, 1977c). Using visual and statistical criteria it was concluded that neither chronology dated the Clayton Hall master series (Table 7.3). Reference chronologies which spanned periods other than the 17th century were also compared with the Clayton Hall chronology (Table 7.3). Although significant 't' values were obtained with some of these chronologies, no consistent significant match was obtained. Visual comparisons confirmed these results.

Six of the timbers used for the Clayton Hall chronology still retained some sapwood (Figure 7.3). In two of these the structure

Figure 7.2 Clayton Hall working master and its components. The curves are plotted on a semi-logarithmic scale.

CLAYTON HALL : WORKING MASTER AND ITS COMPONENTS

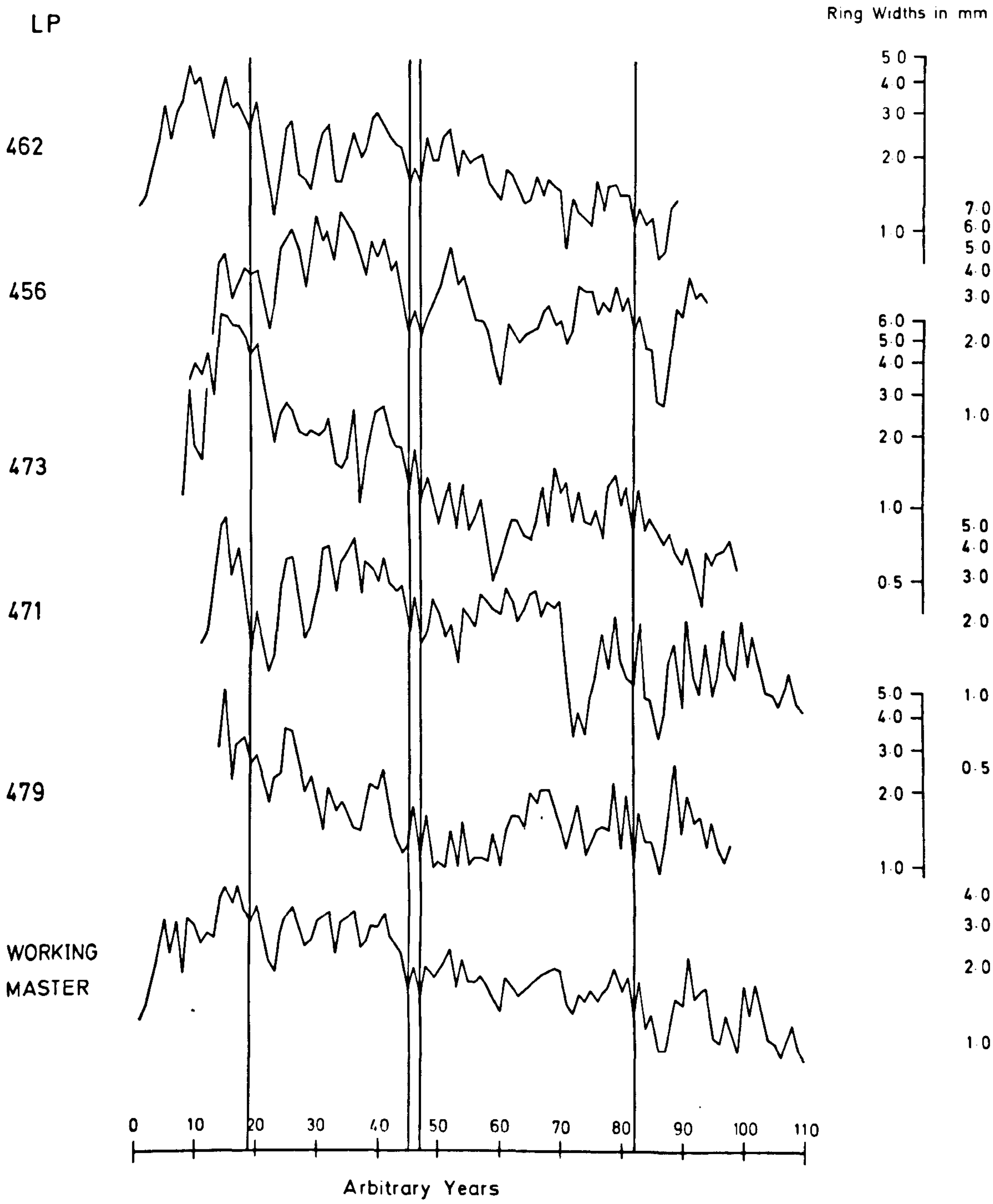


TABLE 7.2

Clayton Hall: probabilities of observed values of 'r' between components of the working master arising by chance.

LP No.	462	471	473	479
456	xx	xxx	xx	xxx
462		xxx	xxx	xxx
471			xxx	xx
473				x

Key

x ≤ 0.00024

xx ≤ 0.00009

xxx ≤ 0.00001

Figure 7.3 The temporal distribution of the components of the Clayton Hall chronology

COMPONENTS OF CLAYTON HALL CHRONOLOGY

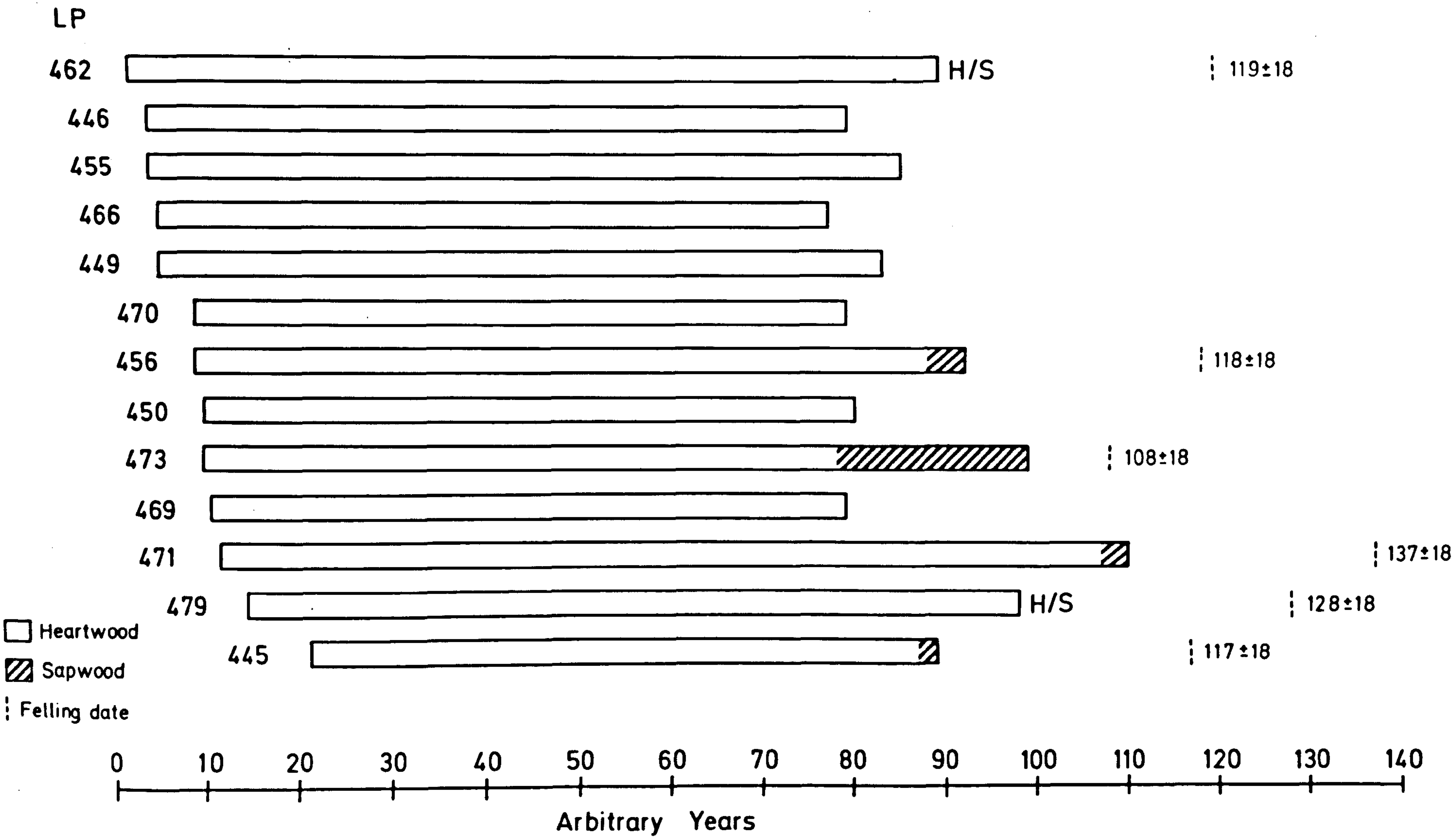


TABLE 7.3

Comparison between the Clayton Hall chronology and various oak chronologies; Student's t-values and the probabilities of 'r' arising by chance.

Chronology	date of outer year	't'	no.years overlap	'r' (p≤)
Belfast	1095	3.59	95	0.00032
	1949	3.60	110	0.00032
South West Scotland	-	-	-	-
Dublin (2)	-	-	-	-
Bishop's House	1580	3.88	110	0.00012
	1644	3.69	56	0.00033
Wales/West Midlands	-	-	-	-
Stayley Hall	1580	3.60	84	0.00032
(Section 7.4)				
Peel Hall I	-	-	-	-
(Section 7.5)				
Peel Hall II	115 year overlap	3.83	110	0.00017
(Section 7.5)	147 " "	6.30	110	0.00001
West German curve	1783	3.74	110	0.00024
	1869	3.52	110	0.00044

References for chronologies are given in Table 7.1

of the sapwood was so degraded as to render its rings unmeasurable. Measurements were, therefore, made up to the heartwood/sapwood boundary. The application of 30 ± 18, the estimate for the mean number of sapwood rings obtained for Peckforton oaks (Section 5.3.2) allowed the calculation of relative felling dates for the timbers with sapwood. These dates are 108 ± 18, 117 ± 18, 118 ± 18, 119 ± 18, 128 ± 18 and 137 ± 18. Since the Clayton Hall chronology is "floating" these dates are arbitary.

Discussion

The lack of crossdating between the Clayton Hall chronology and the standard chronologies prompts the question, why? It must be inferred that during the period spanned by this chronology the response of the Clayton Hall timbers to conditions of climate was different to that shown by the trees comprising the other chronologies. It has been suggested that in periods of greater climatic variability, limiting climatic conditions more commonly occur bringing variations in ring width into agreement (Hughes *et al.*, 1978b). The period spanned by the Clayton Hall chronology may have been one in which limiting climatic conditions were not common and therefore, lack of agreement in ring-width variation. Whilst agreement between certain chronologies has been found to be excellent in the 19th century, agreement is much reduced for the 17th and 18th centuries (Baillie, 1977c). The results from Clayton Hall recorded as 17th century (Farrer and Browbill, 1911) appear to follow this pattern to the extreme.

The failure in dating the Clayton Hall chronology at present means that it cannot be incorporated in a north west of England chronology. Nor can the results be used to make inferences regarding the date of the hall's construction. Nevertheless, this study has allowed the relative dating of some of the timbers used in the structure for which young trees of approximately 100 years had been felled. Maps of the County of Lancaster for 1645 (Blaeu, 1645) and 1714 (Jansson, 1714) show the existence of woodlands close to the site of the hall. These woodlands occur on the Salop soil association which is extensive in the county (Hall and Folland, 1970). This association is formed on medium to fine textured, slightly calcareous till and occupies gentle slopes or flat ground. Poor drainage is widespread since with 750-1000mm rainfall, run off is negligible and percolation through the subsoil is slow. If the source of the timber for the hall was a local one, these characteristics would explain the reduced sensitivity of the tree-ring patterns. It is hoped that when other chronologies which span the 17th century are available, either from the author or from other workers, that absolute dating of this Clayton Hall chronology will be achieved.

7.4 Stayley Hall

The Site

Stayley Hall (SJ975997) is located on a spur overlooking the Tame Valley and Millbrook in Greater Manchester on a mound offering natural defence (Figure 7.1). A detailed structural description of Stayley Hall is given in the Stayley Hall Report (1976) prepared by the County Planning Officer of the Greater Manchester Council and Poole, Dick and Partners, Chartered Quantity Surveyors. The following account gives details of the hall that are pertinent to the present study.

Much of the existing fabric of the hall is the result of Tudor reconstruction which occurred after A.D. 1580 but the medieval manor house was constructed about A.D. 1340 and it has been suggested that the central section contains timbers from the first construction. The Tudor reconstruction involved replacing and extending the framework of the hall to a formal plan with a symmetrical south elevation approximating to the Elizabethan 'E' shaped layout.

The main part of the hall is symmetrical with elevations facing the four points of the compass. The finest elevation faces south overlooking the courtyard and consists of a three storey,five bay layout, to a formal design (Plate 7.3). This elevation consists of:

1. a three storey east wing, with a large south facing gable.
2. a central portion enclosing the original Great Hall. This is subdivided into three bays with a recessed three storey centre section.
3. a three storey west wing, matching the east wing.

The other three sides of the main hall, facing north (Plate 7.4), east and west are gaunt and without embellishment. The 'informal'

Plate 7.3 Stayley Hall, south elevation

Plate 7.4 Stayley Hall, north elevation

part of the layout adjoins the main building to the west. It consists of kitchen (Plate 7.4) and ancillary rooms of one or two storeys. The ground floor plan is shown in Figure 7.4.

The timbers

The timbers sampled at Stayley Hall were located in several parts of the house. The collapse of the roof and upper floors of the east wing afforded the opportunity of taking 7 samples suitable for tree-ring analysis. A further sample was taken from the ground sill beam which separated the east wing from the original Great Hall. One sample was taken from a beam at the first floor level in the Great Hall. Eight slices were taken from the timbers in the kitchen which adjoins the west wing. Two further samples were taken from timbers which were lying in an ancillary room which adjoins the west wing and lies to the south of the kitchen. In total, 19 timbers were found to be suitable for tree-ring analysis.

Results

The Stayley Hall timbers contained tree-ring series ranging from 88 to 182 growth rings which varied greatly in width. The tree-ring sequences from 5 timbers were combined into a working master of 151 years. The Student's 't' values between these timbers ranged from 3.75 to 6.44. This output of programme (Baillie and Pilcher, 1973) (probabilities of 'r' occurring by chance) is shown in Table 7.4. The positions of best match given by this programme were also checked visually and found to be very good. Figure 7.5 shows the working master and its components where characteristic years namely, arbitrary years 46,50 and 106 (later dated as A.D. 1442, 1446 and 1502) are indicated by vertical lines.

Figure 7.4 Ground floor plan of Stayley Hall

gs - ground sill beam

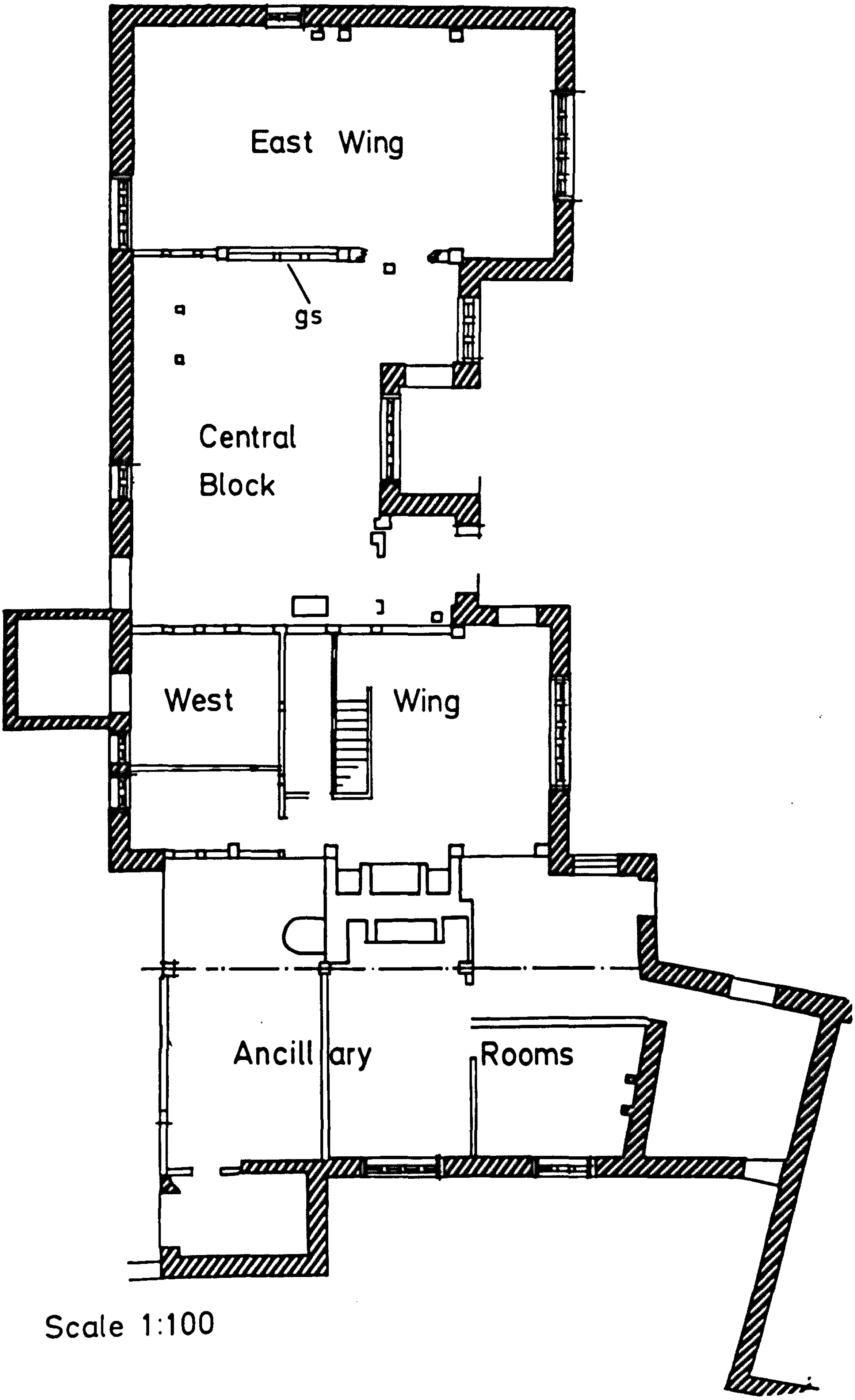


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TABLE 7.4

Stayley Hall: probabilities of observed values of 'r' between components of the working master arising by chance.

LP No.	490	492	525	530
489	x	xx	xx	xx
490		xx	xxx	xxx
492			xx	xx
525				xxx

Key

$x \leqslant 0.00016$

$xx \leqslant 0.00009$

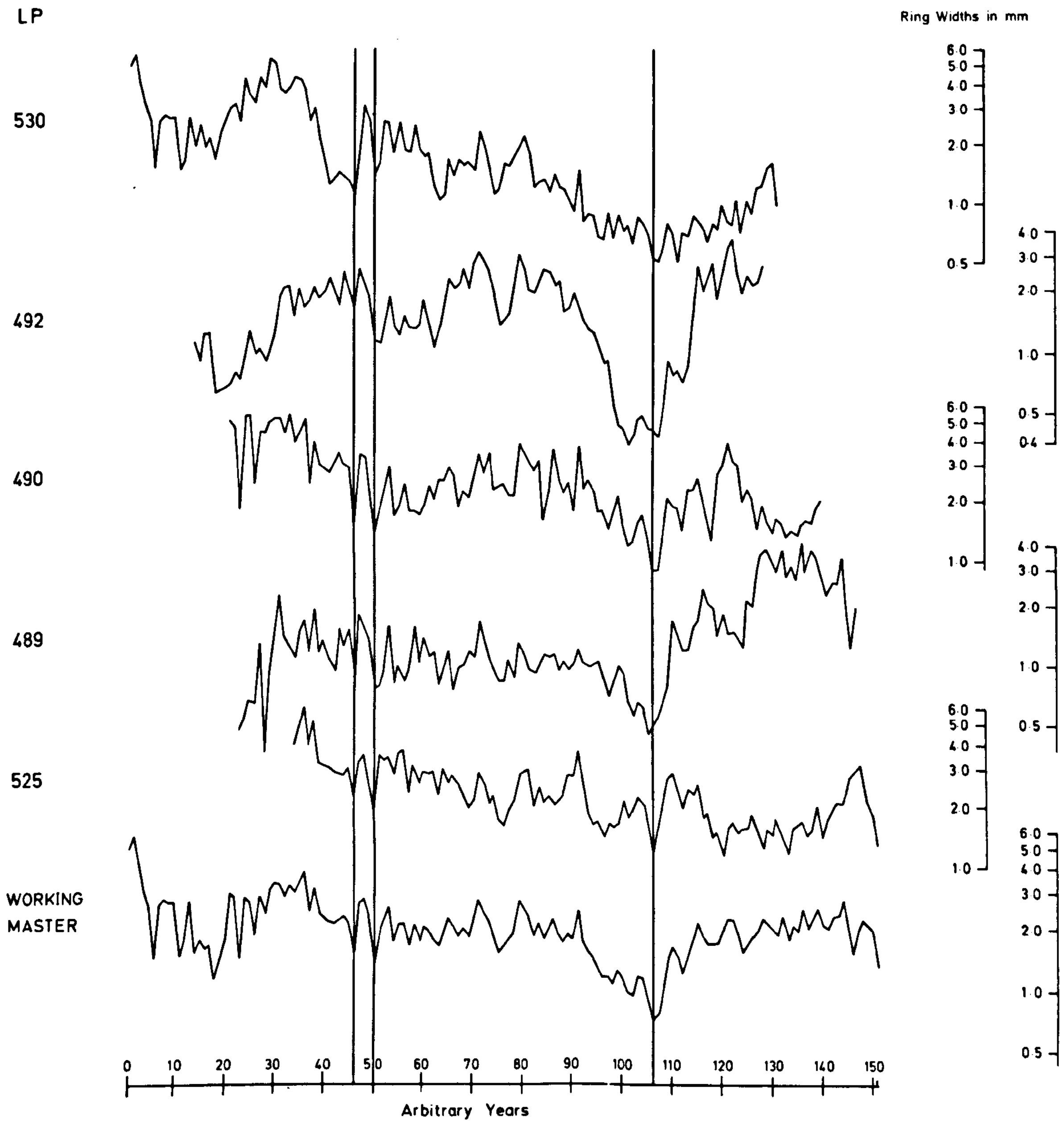
$xxx \leqslant 0.00001$

Figure 7.5 Stayley Hall working master and its components.

The curves are plotted on a semi-logarithmic scale.

Characteristic years, namely arbitrary years 46, 50 and 106 are marked by vertical lines.

STAYLEY HALL : WORKING MASTER AND ITS COMPONENTS



The tree-ring curves of 8 timbers crossdated with the working master and were combined with it to form a 190 year index series for Stayley Hall. The temporal distribution of the components of the Stayley Hall chronology are shown in Figure 7.6. The index values of the Stayley Hall chronology are given in Appendix VII.

In order to assign calendar years to this "floating" chronology and to the relatively dated timbers it was necessary to compare the chronology with absolutely dated reference chronologies (Table 7.5). The obvious choice for such comparisons was the chronology for timbers from English and Welsh buildings (Siebenlist-Kerner, 1978) and that for Bishop's House in Sheffield (Morgan, 1977b) since they were constructed for buildings in the same region of the British Isles. These chronologies also cover the period from which many of the timbers at Stayley Hall were thought to span. The outer year of the Stayley Hall chronology was dated to A.D. 1554 by the chronology of Siebenlist-Kerner (t = 10.34, 190years overlap) but A.D. 1410 by Bishop's House (t = 3.55, 50 years overlap). The 't' value, 2.83 is given with Bishop's House for outer year of Stayley Hall, A.D. 1554. The date of A.D. 1554 was also given by the chronologies for the Belfast region (Baillie, 1977a), South West Scotland (Baillie, 1977c) and Dublin (Baillie, 1977b). The 't' values for these matches were 6.72, 4.87 and 5.28 respectively. Thus the Stayley Hall chronology spanned the period A.D. 1365 to A.D. 1554, a total of 190 years. The chronologies for Stayley Hall, Wales/West Midlands and Bishop's House are shown at the matched position in Figure 7.7.

The reference curves, REF 1, REF 2 and REF 3 described by Fletcher (1977) spanned the period of the Stayley Hall chronology and were also tested for crossdating with it. The statistical and visual checks showed that there was no significant match between Fletcher's reference curves and the series for Stayley Hall.

Figure 7.6 The temporal distribution of the components of the Stayley Hall chronology.

The locations of the timbers within the hall and estimated felling dates are given.

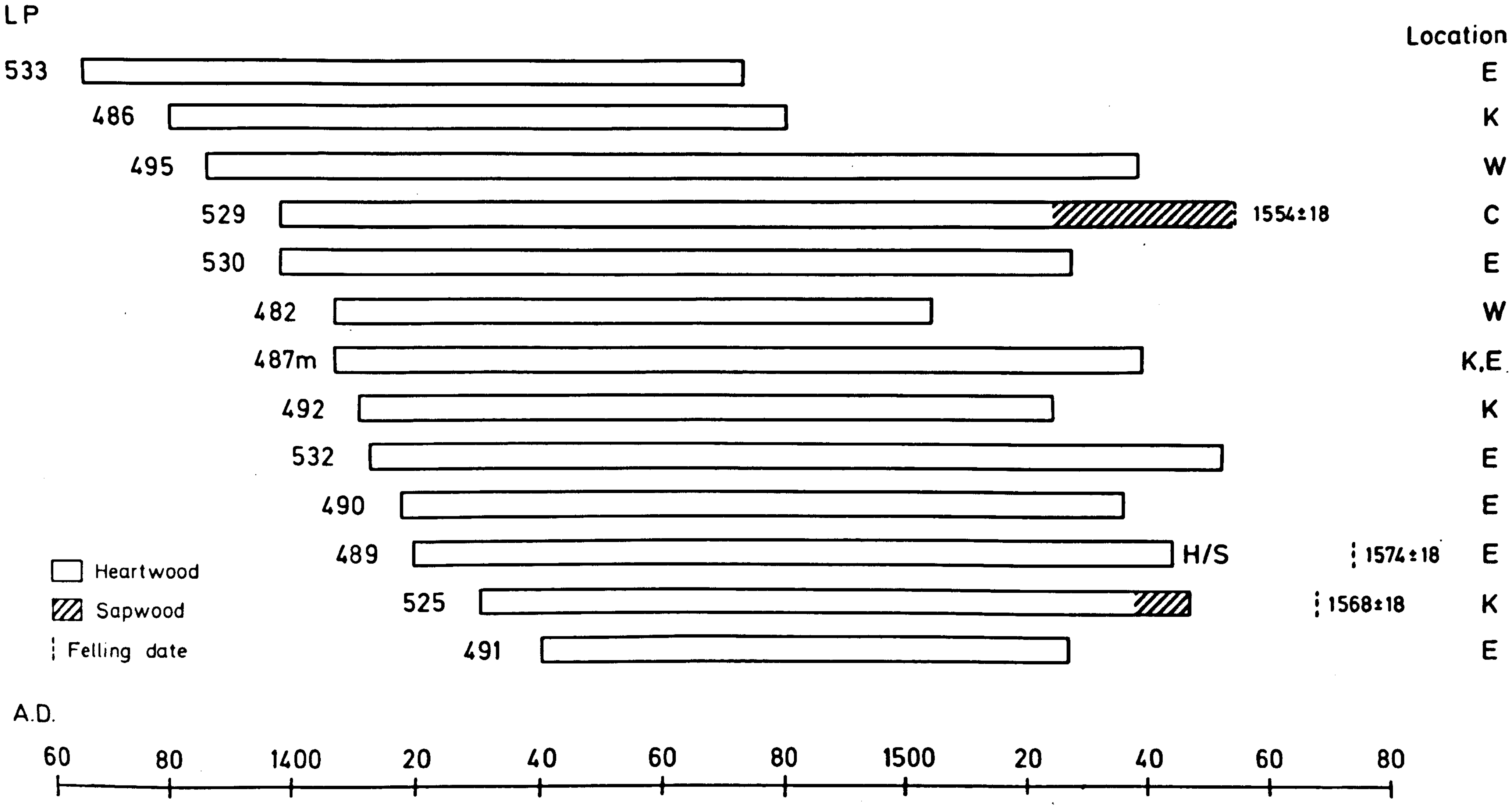
C - Central block

E - East wing

K - Kitchen

W - West wing

H/S - heartwood/sapwood boundary



COMPONENTS OF STAYLEY HALL CHRONOLOGY

TABLE 7.5

Comparison between the Stayley Hall chronology and various oak chronologies; Student's t-values and the probabilities of 'r' arising by chance.

Chronology	date of outer year	't'	no. years overlap	'r' ($p \leqslant$)
Belfast	1059	3.51	59	0.00044
	1554	6.72	190	0.00001
South West Scotland	1316	4.96	190	0.00003
	1554	4.87	190	0.00003
Dublin (2)	1554	5.28	190	0.00001
Wales/West Midlands	1530	3.66	190	0.00023
	1554	10.34	190	0.00001
Bishop's House	1410	3.55	50	0.00058
	(1554)	(2.83)	(190)	(0.00256)

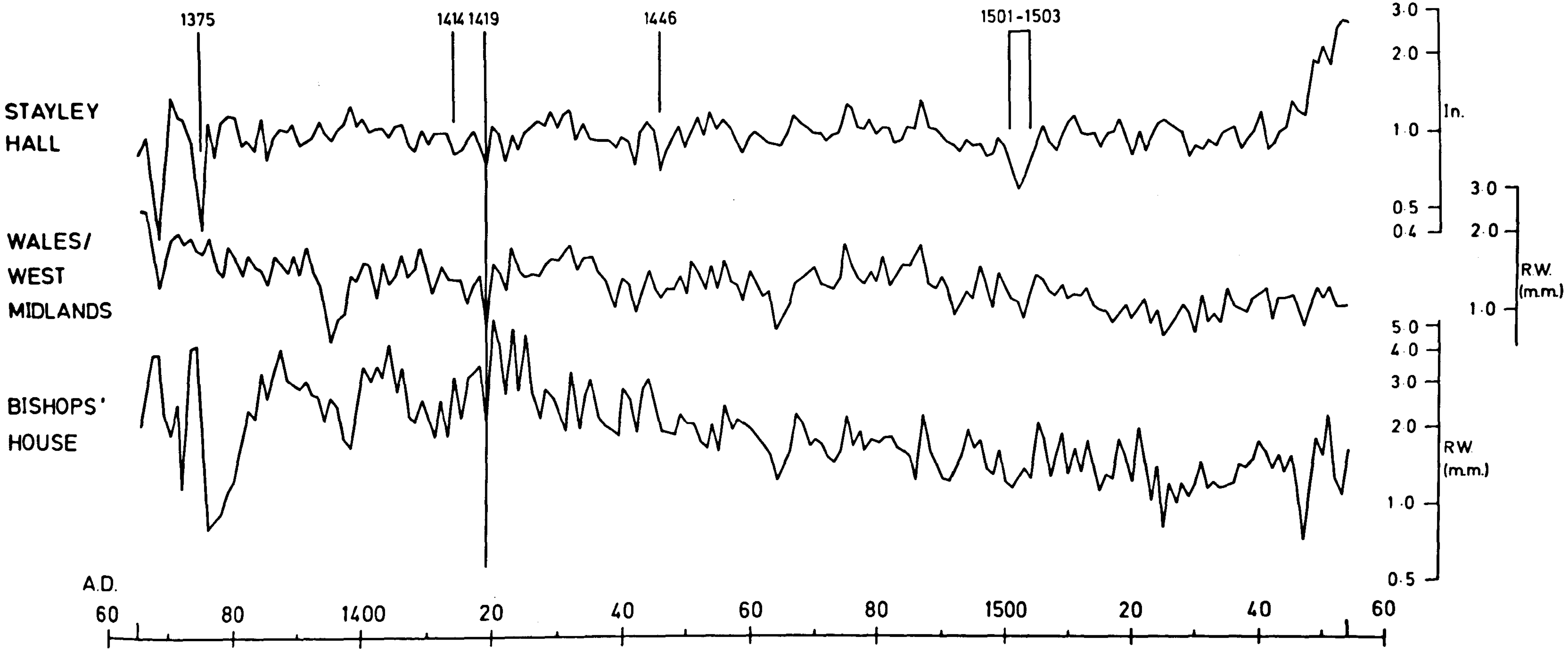
References for chronologies are given in Table 7.1

The feature from which an estimate of felling dates can be made, the sapwood was present on only three of the timbers contained in the Stayley Hall chronology (Figure 7.6) and in one of these (LP 489) it was so degraded that no measurements could be made. Nevertheless, the position of the heartwood/sapwood boundary and hence one year of sapwood could be identified on this timber. The three timbers containing sapwood had been taken from different rooms in the hall and, therefore, provided estimates of felling dates for at least one timber in these locations. In the east wing, the timber having the most recent growth ring was that with a heartwood/sapwood boundary only (LP489). Applying the figure for the mean number of sapwood rings obtained for Peckforton oaks (Section 5.3.2) of 30 ± 18 gave an estimated felling date between A.D. 1556 and A.D. 1592 inclusive. The timber from the kitchen area with some sapwood was estimated, using the figure above,to have been felled between A.D. 1550 and A.D. 1586 whilst that for the timber in the ceiling of the Great Hall was between A.D. 1536 and A.D. 1572. None of the timbers from the collapsed south west corner contained sapwood.

During the tests for crossdating between the timbers it was noticed that two timbers appeared to be very similar. They were similar in terms of the actual ring-width values and the appearance of the tree-ring pattern on the wood samples themselves. It seemed evident that these two timbers had been cut from the same tree and there were sufficient grounds for combining the two series (LP 487 and LP 534) of 120 and 122 years to produce a mean series (LP 487m) of 134 years.

Figure 7.7 The chronologies for Stayley Hall, Wales/West Midlands (Siebenlist-Kerner, 1978) and Bishop's House (Morgan, 1977b) at the position of match.

The Stayley Hall chronology is given in index format, the others in ring-width format.


1375
1414 1419
1446
1501-1503
STAYLEY HALL
WALES/ WEST MIDLANDS
BISHOPS' HOUSE
3.0
2.0
In.
1.0
0.5
0.4
3.0
2.0
R.W. (m.m.)
1.0
5.0
4.0
3.0
2.0
R.W. (m.m.)
1.0
0.5
A.D.
60
80
1400
20
40
60
80
1500
20
40
60

Discussion

The sampling procedure followed at Stayley Hall viz the partition of timbers according to their locations within the hall, was done with the view to determining construction dates for each of the sections. Figure 7.6 shows that the timbers comprising the index chronology all cover a similar time span. This suggests that they form part of structures of a similar date. This hypothesis cannot be taken any further since the majority of timbers showed no sapwood and could possibly have lost many heartwood rings also. The six timbers from the east wing that showed no sapwood could have had another 50 or 100 heartwood rings before the sapwood was reached, thereby, giving a much later construction date.

The timber with sapwood said to be from the east wing is really one of the timbers which separates the Great Hall from the east wing. The fact that this timber is the ground sill beam on which the frame of the east wall of the Great Hall is supported should give an indication of its date of erection providing no subsequent reassembly has taken place. With this in mind it was, therefore, surprising to find that the felling date of the ground sill beam was estimated to be 1574 ± 18 years. From this result, it would appear that the construction of the east frame occurred during the period when the post A.D. 1580 extensions were made. It seems, therefore, that the framework of the hall on the east wall was rebuilt when the wings were added after replacing the ground sill beam, perhaps because of decay,with fresh timber of the period. It is impossible to determine how many more timbers have been replaced in this central block without acquiring more samples from this section. This has not been possible in the present study as the timbers not previously sampled were sound and stable within the framework, properties which do not lend the timbers readily available for sectioning.

The sampling of one other timber in the Great Hall did provide some information regarding the insertion of the first floor level. This timber contained 31 sapwood rings and showed no features consistent with a previous constructional function (Smith, pers. comm.). The estimated felling date of A.D. 1555 ± 18 gives an indication of when this beam was inserted. Since the date of the most recently formed sapwood ring, A.D. 1554, post dates part of the estimated range (A.D. 1536 to 1572) part of the range may be discounted showing that this timber could not have been used before A.D. 1554. It does not form part of the original structure which in any case would have been open to the roof,nor is it a timber with a new function from the A.D. 1340 construction. Thus, the insertion of this timber,if not the ceiling,took place just prior to the Tudor extensions of post A.D. 1580. Again,a greater number of samples would have reinforced or disproved the date of the ceiling insertion.

Of the 4 timbers sampled from the kitchen area, that with the most recently formed ring was the only timber with sapwood. The estimated range of felling dates of A.D. 1550 to A.D. 1586 for this timber is very similar to that for the ceiling timber in the Great Hall. Since the other timbers from the kitchen did not contain any sapwood it is possible that they are from a later date.

None of the timbers from the collapsed corner by the west wing contained sapwood. Therefore, no realistic estimate of their felling dates can be made. However, even if the most recently formed ring of each sample is the ring at the heartwood/sapwood boundary then the estimated felling date of each would be A.D. 1534 ± 18 and A.D. 1566 ± 18 and the timbers are not likely to have been inserted before A.D. 1516 and A.D. 1548 respectively.

The conclusion that several sections of the Hall viz the east wing and the kitchen were constructed at about the same time is reinforced by the timbers LP487 and LP534. The tree-ring patterns of these timbers were so much alike that they appear to have been cut from the same tree. However, these timbers were not found in the same part of the hall as might have been expected but from the east wing and the kitchen. There have been several instances reported in the literature of tree-ring patterns being combined because the timbers were assumed to be from one tree. In many of these cases the criteria used for assuming their common origin are not given. One reason given by Morgan et al. (1978) was the excellent agreement shown by two-ring patterns (Student's t = 13). Results from the study of Peckforton oaks (Section 3.2) show that this is not a criterion to be relied upon since excellent agreement was found between samples from different trees with Student's t values of up to 19. Thus, this criterion should not be used in isolation, tree-ring series only being combined when there is a very close similarity between the absolute ring widths and between their patterns on the wood itself. However, the converse of this is not true, i.e. the lack of a strong similarity means a different origin. The studies on modern timbers illustrate this point where at Peckforton, cores from one tree crossdated with a 't' value of 4.00.

The excellent crossdating between the Stayley Hall chronology and the chronologies for Wales/West Midlands and the similarity with that for Bishop's House poses the question of the origin of the timbers used in the construction of Stayley Hall. It has been suggested that the Wales/West Midlands chronology may have been derived from trees growing in the WyreForest whilst the source of the Bishop's House timbers "remains enigmatic" (Morgan, 1977b). The major rebuilding that took place at Stayley Hall after A.D.1580 largely resulted from the appointment of Sir William Booth as the High Sheriff of Chester in A.D. 1571, an event which was a high point in the family's fortunes (Stayley Hall Report, 1976). This work used timbers which were mostly long and straight with a slow and sensitive growth rate, the type of timber which would be cut from mature straight oak trees. According to Morgan (1977b) trees of this nature were becoming increasingly scarce at this time and it may have been that the increased wealth of the Booth family allowed them to be more selective in their choice of oak, using timber from other areas. However, an examination of the historical descriptions of the nature of the land around Stayley Hall leads to the suggestion that the source of timber was a local one. In Baines (1868) the neighbouring hills of Stayley Hall are described in the time of the Staveleighs and "for several ages afterwards" to have been clothed in stately oaks. In Hill (1907) the Vale of Stayley is described as "the native place of the prime oak, towering on high; the stately monarch of the forest, lofty as the taper pine... These stately monarchs overspread this part of the Country." With this good supply of apparently good timber there would seem to be no reason for looking elsewhere. The land, which is described above, would also exhibit the type of conditions (steep hills, good drainage) under which trees with a slow and sensitive growth rate would be found. Such conditions are also to be found at the sites from which the South West Scotland chronology was derived and the Wales/West Midlands chronology if the component trees of the latter were taken from the Wyre Forest.

The Stayley Hall chronology may be compared with the dated chronologies in terms of their signature years (years in which rings are characteristically wide or narrow). Such comparisons provide information on regional variations in growth, part of which is related to climate. Of the well known signatures which occur in England, viz, A.D. 1419 and A.D. 1422 (Morgan, 1977b) the former is present in all the 5 chronologies that crossdated with the Stayley Hall master and in the latter (Figure 7.7). It was less pronounced in the Belfast chronology probably because of the regional nature of the series. The A.D. 1422 signature is only found in the chronologies for Dublin and Bishop's House. In the Stayley Hall chronology other narrow rings occur in A.D. 1375, A.D. 1414, A.D. 1446 and A.D. 1501 to A.D. 1503 (Figure 7.7).

The tree ring studies at Stayley Hall presented,have provided additional information about its constructional history. Whilst the estimated construction dates of the extensions are not inconsistent with that of post A.D. 1580 given by documentary evidence the results have shown that at least one wall of the Great Hall was dismantled during this work and that part of the first floor timbers must post date A.D. 1554. These studies have also provided the material from which a dated tree-ring chronology spanning the period A.D. 1365 to A.D. 1554 could be constructed and one which provides a further section of the regional chronology for the north west of England. The contribution made by the Stayley Hall chronology to the regional chronology is shown in Figure 7.24..

7.5 Peel Hall

The Site

Peel Hall (SJ 833 873) was situated approximately 13 kilometres south of Manchester city centre in a modern estate known as Wythenshawe (Figure 7.1). Originally, the farm and the land covered approximately 120 hectares but today this figure is in the region of 3 hectares. The history of Peel Hall derives from the 13th or 14th centuries and it seems that the old manor house for the Manor of Etchells was on this site (Riley and Hall, 1974). It later became a dower house to the Tatton family of Wythenshawe Hall and was restored in A.D. 1578 (Riley and Hall, 1974) (Plates 7.5 and 7.6).

Peel Hall was surveyed in 1975 by Mr. Eric Mercer (National Monuments Record) who recognised 4 main building periods:

1. "A late 16th - early 17th century timber-framed building, of two storeys throughout, the upper one being open to the roof. This had a hall, heated by a big side fire place, and another room at each end, with nothing now to show what their functions were nor where the staircase was...."
2. "Addition of a parlour wing in the late 17th century and in brick."
3. "Addition of kitchen and staircase probably soon after the addition of the parlour. It may well have been at this time (late 17th or early 18th century) that the old timberwork was largely re-faced in brick."
4. Early 19th century alterations.

Thus, the building as it stood in 1975 contained building phases of the late 16th/early 17th century, the late 17th/early 18th century and the early 19th century. In their "History of Peel Hall," Riley and Hall (1974) state that the late 16th century building was pulled

Plate 7.5 Peel Hall, north elevation

Plate 7.6 Peel Hall, east elevation

down and replaced by a brick-built farmhouse in the early 19th century. In addition, part of the farmhouse was supposed to contain an 'original' staircase "from wall to wall leading to what was the old chapel at the top of the house." By 1976 Peel Hall had deteriorated to such an extent that it was considered dangerous and was consequently demolished.

The timbers

The demolition of Peel Hall presented the opportunity of examining a number of timbers for tree-ring analysis. The rapid demolition and subsequent removal of all the wood to a timber yard prevented the recording of timbers according to their locations within the hall. A total of 29 timbers were sampled and thought to be suitable for tree-ring analysis. The majority of these timbers were square, quartered trunks and rectangular, halfed trunks. Several of the halfed trunks appeared to be from joists of a type of floor construction known as a "beam and board floor" (Wright, pers. comm.) Other samples were cut from upright posts. Eleven timbers contained sapwood.

Results

The Peel Hall timbers contained tree-ring series which were very sensitive and which ranged from 67 to 142 growth years. Cross-dating tests indicated that some of these series fell into two groups. In the first group,6 timbers crossdated with one another with high 't' values ranging from 4.27 to 11.98 (Table 7.6). The 6 series were combined to form a working master of 96 years of growth. Figure 7.8 shows the working master and its components. Characteristic years namely, arbitary years 17, 34 and 61 (lated dated as A.D. 1402, 1419 and 1446) are indicated by vertical lines. The tree-ring series of 10 samples crossdated with the working master with 't' values ranging from 3.54 to 5.24.

TABLE 7.6

Peel Hall I: Probabilities of observed values of 'r' between components of the working master arising by chance.

LP No.	408	422	424	426	439
375	xx	xx	xx	xx	xx
408		xx	xx	xx	xx
422			x	xx	xx
424				xx	xx
426					xx

Key

x $\leqslant$ 0.00009

xx $\leqslant$ 0.00001

TABLE 7.7

Peel Hall II: Probabilities of observed values of 'r' between components of the working master arising by chance.

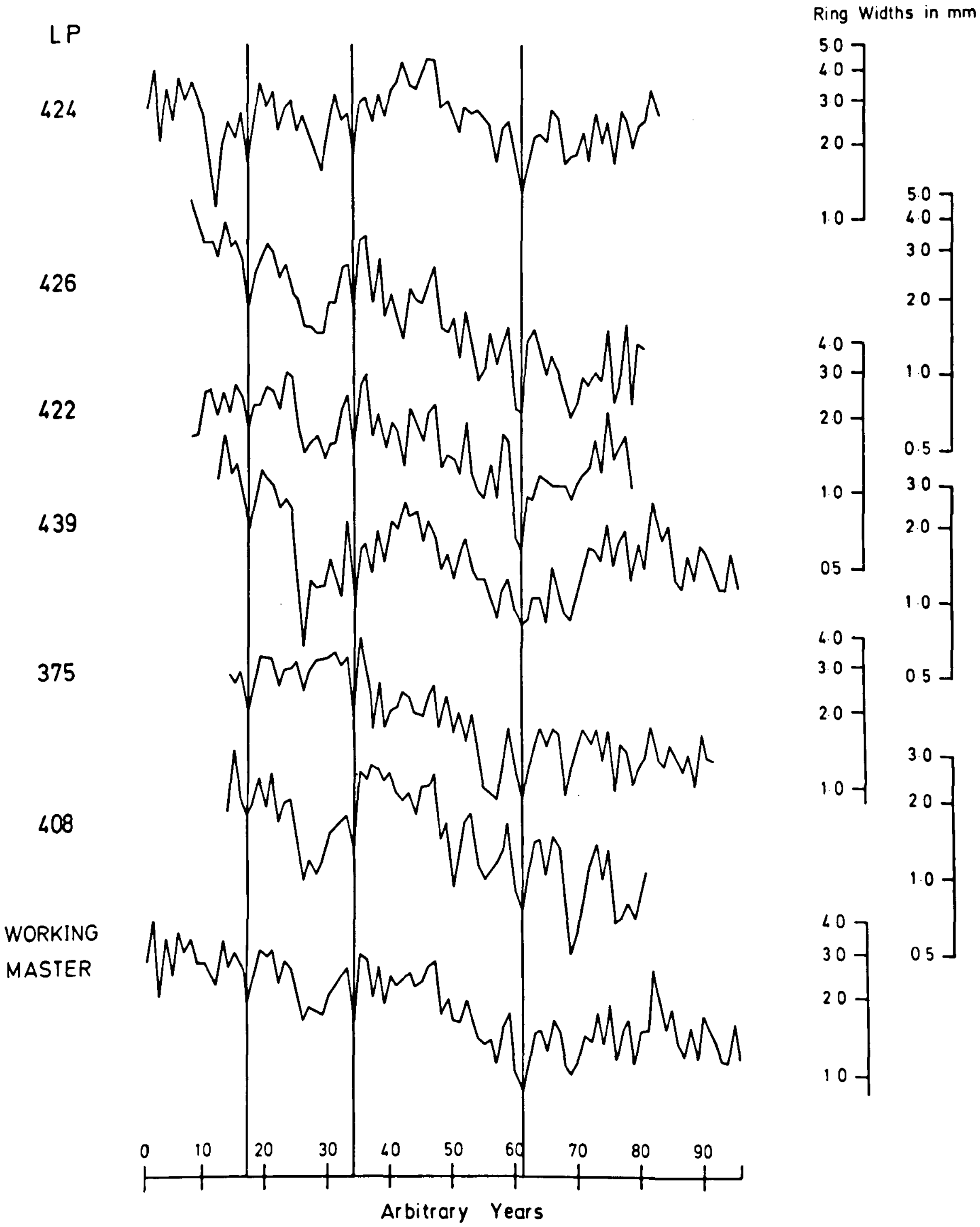
LP No.	387	391	394
383	x	xx	x
387		x	xx
391			x

Key

x $\leqslant$ 0.00009

xx $\leqslant$ 0.00001

Figure 7.8 Peel Hall I working master and its components. The curves are plotted on a semi-logarithmic scale. Characteristic years, namely arbitrary years 17, 34 and 61 are marked by vertical lines.



PEEL HALL I: WORKING MASTER AND ITS COMPONENTS

Two of these 10 samples exhibited extremely similar ring-width values with the pattern of growth looking almost identical on the wood itself. In addition to this, there was a similar span of years on each sample. It was concluded that these features suggested that the samples were cut from one tree. The two tree-ring series were combined to form a mean series, LP609M.

A master chronology, Peel Hall I, was constructed from the series comprising the working master and those which crossdated with it. This made a total of 15 samples. The temporal distribution of the components of the 104 year master series is shown in Fig.7.9. The index values of the Peel Hall I chronology are given in Appendix VIII.

To obtain absolute dating of the Peel Hall I master chronology, the series was compared with a number of standard chronologies (Table 7.8). These results show that the Peel Hall I chronology was dated by many of the standard chronologies: Belfast, South West Scotland, Dublin, Bishop's House and Wales/West Midlands, all of which, suggested the youngest ring to be A.D. 1481. Visual crossdating confirmed these matches, thus dating the Peel Hall chronology which spanned the period A.D. 1378 to A.D. 1481. The chronologies for Wales/West Midlands, Stayley Hall and Peel Hall I for this period are shown in Figure 7.10. The signature years given for England viz A.D. 1419 and A.D. 1422 (Morgan, 1977b) are not present in the Peel Hall I master index chronology shown in Figure 7.10. The narrow rings described for the Bishop's House chronology, A.D. 1442 and A.D. 1464 (Morgan, 1977b) can be seen in each series. During the ten-year period A.D. 1415 to A.D. 1424 a series of alternating wide and narrow rings occurs.

Figure 7.9 The temporal distribution of the components of the Peel Hall I chronology.

Estimated felling dates are given for timbers with sapwood.

H/S - heartwood/sapwood boundary.

COMPONENTS OF PEEL HALL I CHRONOLOGY

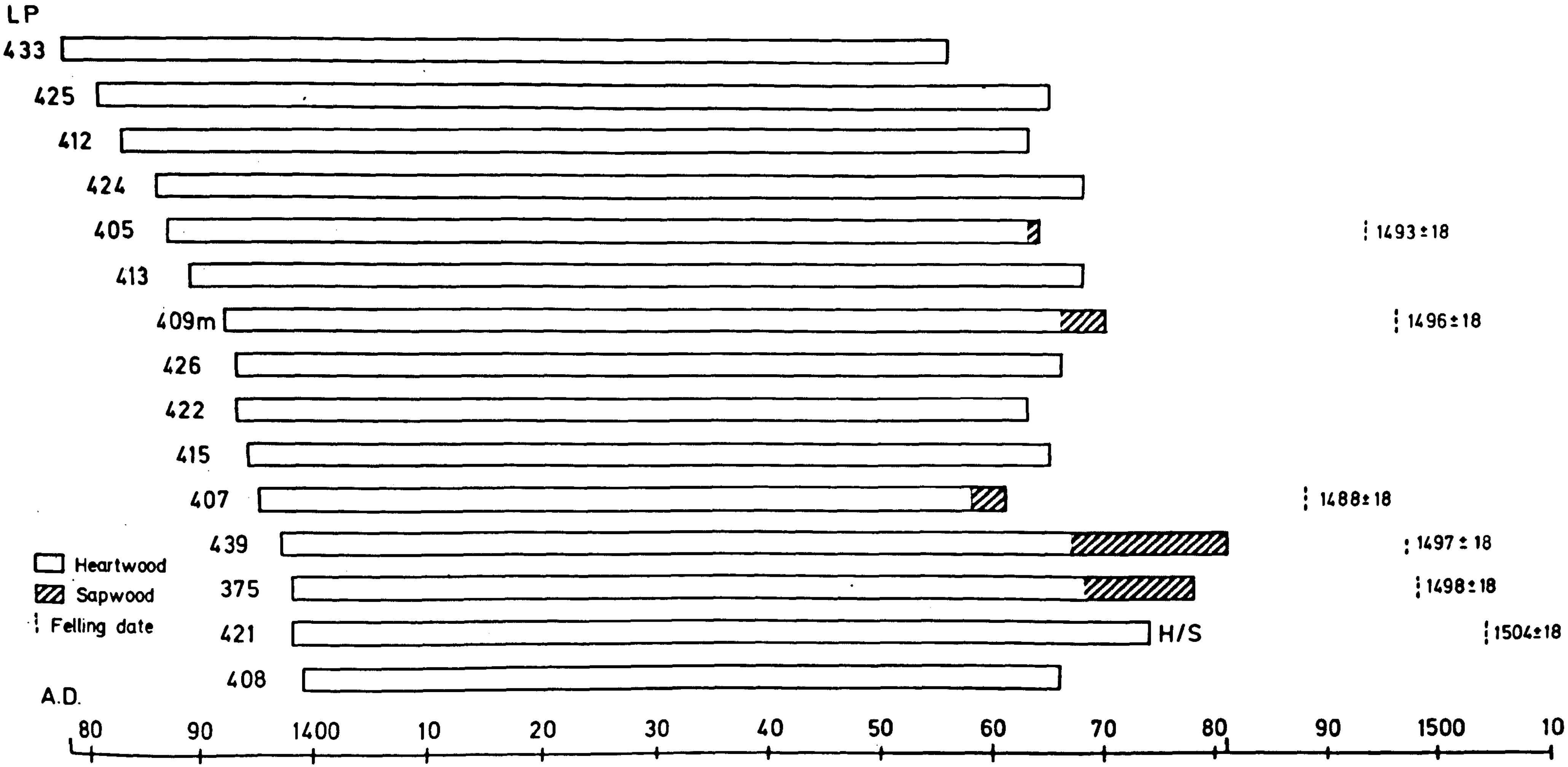


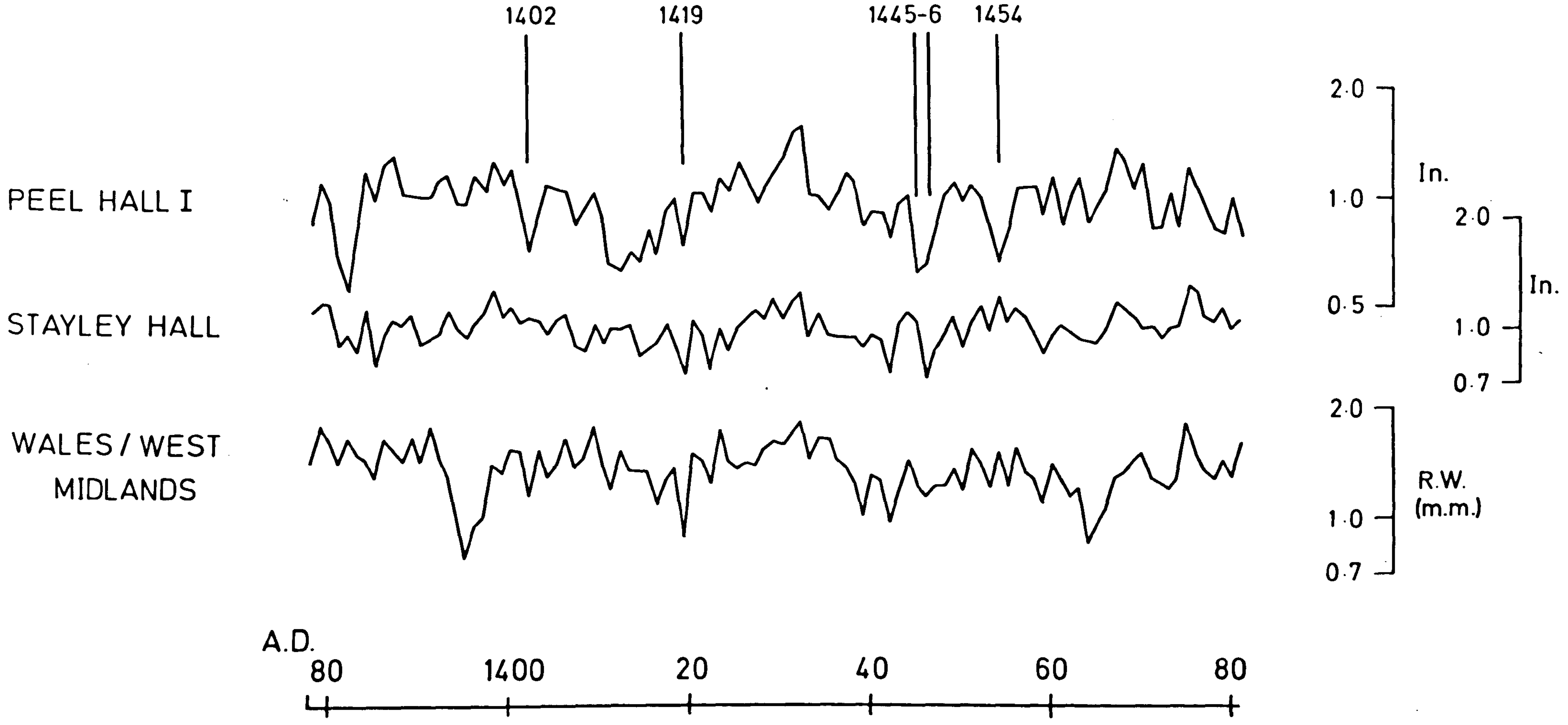
TABLE 7.8

Comparison between the Peel Hall I chronology and various oak chronologies; Student's t-values and the probabilities of 'r' arising by chance.

Chronology	Date of outer year	't'	no. years overlap	'r' (p≤)
Belfast	1481	3.60	104	0.00032
	1731	3.70	104	0.00024
South West Scotland	1481	4.34	104	0.00009
	1678	3.58	104	0.00032
Dublin (2)	1481	4.12	104	0.00009
Bishop's House	1481	4.37	104	0.00009
Wales/West Midlands	1481	6.85	104	0.00001
Stayley Hall	1481	6.96	104	0.00001

References for chronologies are given in Table 7.1

Figure 7.10 The chronologies for Peel Hall I, Stayley Hall and Wales/West Midlands (Siebenlist-Kerner, 1978) (at the position of match). The chronologies for Peel Hall I and Stayley Hall are given in index format whilst that for Wales/West Midlands is given in ring-width format.


1402
1419
1445-6
1454
PEEL HALL I
STAYLEY HALL
WALES / WEST MIDLANDS
A.D.
80
1400
20
40
60
80
2·0
1·0
0·5
In.
2·0
1·0
0·7
In.
2·0
1·0
0·7
R.W. (m.m.)

Sapwood was present on five of the samples comprising the Peel Hall I chronology. The sapwood on one other sample, whilst being recognisable,was far too rotten for an assessment of the number of rings to be made. Nevertheless, the identification of sapwood on this sample did allow the determination of the heartwood/sapwood boundary. The figure of 30 ± 18 for the mean number of sapwood rings estimated for Peckforton oaks was attached to the youngest heartwood ring on each timber with sapwood. This gave estimated felling dates for those timbers of A.D. 1493 ± 18, A.D. 1496 ± 18, A.D. 1488 ± 18, A.D. 1497 ± 18, A.D. 1498 ± 18 and A.D. 1504 ± 18, (Figure 7.9).

A second master chronology,Peel Hall II,was constructed for timbers, which showed no crossdating with Peel Hall I either as a group or as individuals. The components of this group form the second of the two groups of timbers indicated by the crossdating tests. The Peel Hall II chronology comprises the tree-ring measurements of 4 timbers although it seems likely that two were cut from the same tree. Figure 7.11 shows this chronology with its components where characteristic years, namely arbitary years 54, 92 and 109 are indicated by vertical lines. The probabilities of 'r' between the components occurring by chance are shown in Table 7.7. This chronology, Peel Hall II,is listed in index format in Appendix IX. One timber,LP394 contained 26 sapwood years (Figure 7.11).

The Peel Hall II chronology was compared with many standard chronologies which covered a variety of centuries but no consistent significant match was obtained. This chronology was also compared with undated chronologies to obtain some relative if not absolute dating. The result was that it crossdated with the floating Clayton Hall chronology (t = 6.30, 147 years overlap). This statistically significant match was also good visually (Figure 7.12).

Figure 7.11 The Peel Hall II working master and its components. The curves are plotted on a semi-logarithmic scale. Characteristic years, namely arbitrary years 54, 92 and 109 are indicated by vertical lines.

PEEL HALL II: WORKING MASTER AND ITS COMPONENTS

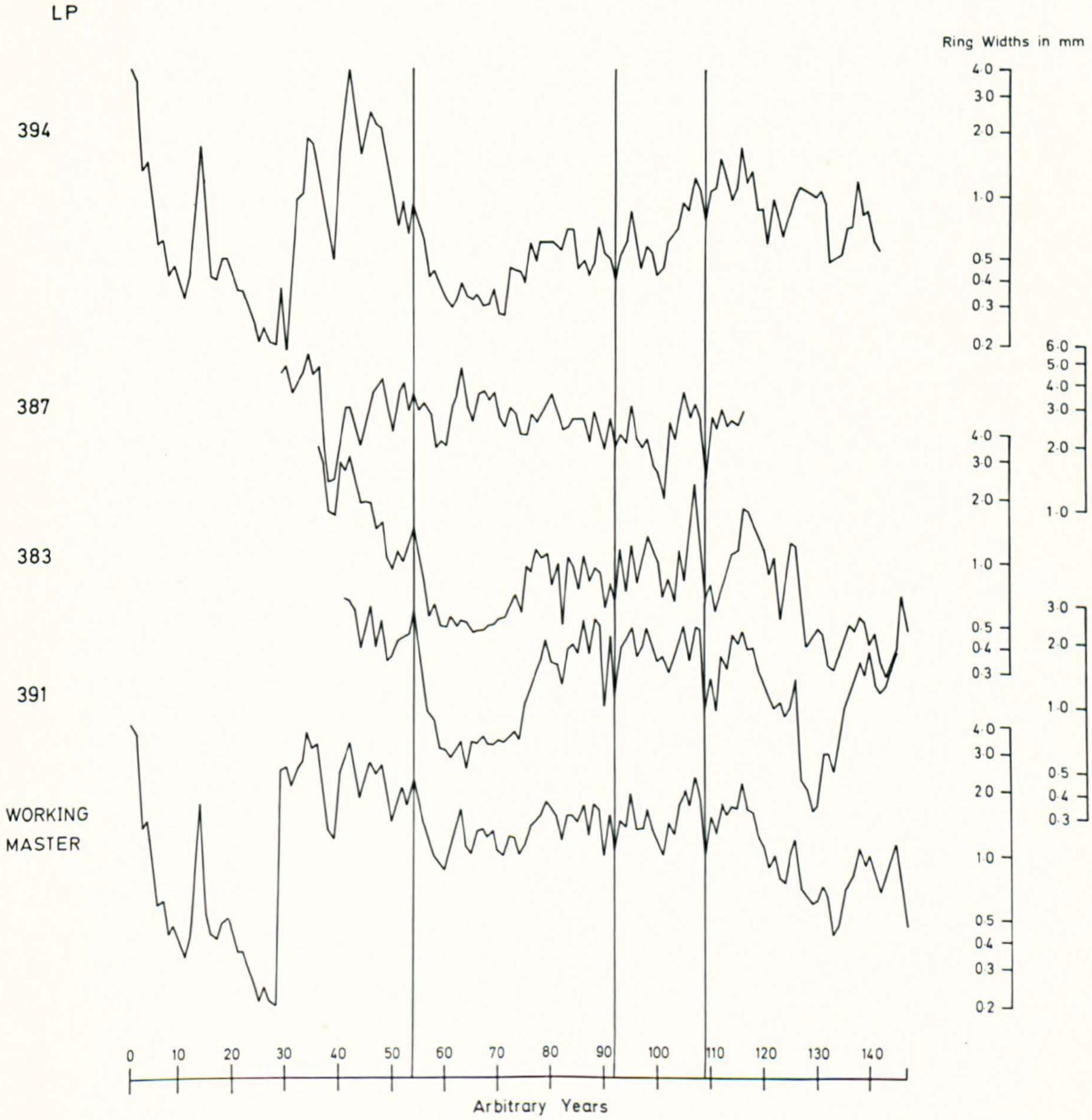
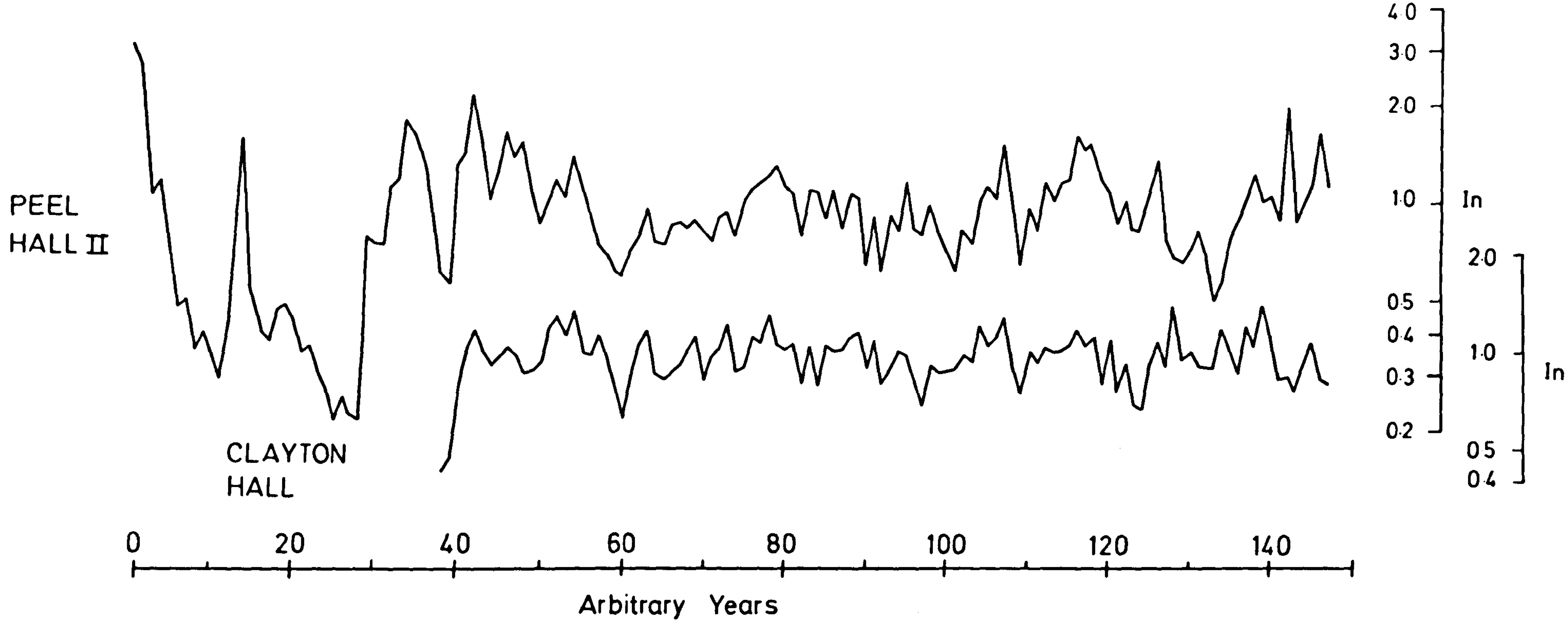


Figure 7.12 The chronologies for Peel Hall II and Clayton Hall shown at the position of match.

Both curves are shown in index format.


PEEL
HALL II
CLAYTON
HALL
0
20
40
60
80
100
120
140
Arbitrary Years
4·0
3·0
2·0
1·0
0·5
0·4
0·3
0·2
In
2·0
1·0
0·5
0·4
In

The chronologies for Peel Hall II and Clayton Hall are shown at the position of match in Figure 7.12.

Since these two chronologies crossdated with one another but could not be absolutely dated as individual series, they were combined into a mean series, Clay/Peel. Local variations present in each chronology are reduced in the mean series which is more representative of growth conditions in the region. The mean chronology was compared with many standard chronologies but still no consistent significant match was obtained.

Discussion

The dating of the Peel Hall I chronology and consequently the individual timbers leads to an indication of the number of older timbers re-used in the 19th century hall. The presence of sapwood allows a more accurate assessment of the felling dates and subsequent insertion of these timbers. Although sapwood was not present on all the timbers it is tempting to suggest that they were cut from trees of approximately the same age and at the same time. Most of the samples show the position of the pith to be within 20 years and in those with sapwood, the transition from heartwood to sapwood occurs within a range of 10 years (Figure 7.9). These timbers were estimated to have been felled in the late 15th or early 16th century.

Timber of this date does not appear to be contemporary with any of the building phases outlined by Mercer above. The staircase described as original by Riley and Hall (1974) may have been associated with the restoration work carried out in A.D. 1578. Even if this staircase had survived to the 20th century it would still not account for the presence of timbers felled in the late 15th or early 16th century; the seasoning and storage time is not likely to have been 50 years. The shape of the samples taken from the Peel Hall I timbers suggests that they did not form part of a staircase but were structural members of a "beam and board floor." This type of floor was laid down up to A.D. 1527 (Wright, pers. comm.). Had the precise locations of the timbers been known, the relationship between them and timbers from the dated building phases could have been determined. The rapid demolition of the hall prevented such a survey and one examining the possible re-use of timber from an earlier building being made. The insertion of this group of timbers must represent a phase of building not previously documented in the history of the hall.

The lack of such documentation provides no information as to the source of the timber. Even for the documented phase of building in the 13th or 14th century, there is no suggestion as to the source of the timber (Riley and Hall, 1974). The answer must be left to conjecture. One possible source of good oak timber could have been the Vale of Stayley which was known to be clothed in oak in the sixteenth century and later (Hill, 1907). The carriage of the timber, an important consideration would not have posed a problem since the Vale of Stayley is only approximately 20 kilometres from the site of Peel Hall.

The absolute dating of the Peel Hall II chronology remains a problem even though it crossdates with the chronology for Clayton Hall. The samples from which the Peel Hall II chronology was constructed appear to derive from floorboards of a design dating from the 17th or early 18th century (Wright,pers. comm.). Even with this clue,it has not been possible to date the chronology precisely. In addition to providing more data for the regional chronology, dating the Peel Hall II chronology will provide more details of the constructional history of the hall. It is interesting that the floor from which the Peel Hall II timbers originate and Clayton Hall are both attributed to the 17th century building activities and the fact that they crossdate indicates that the eventual dating of one will allow the assignation of calendrical dates to the other. Until more timber becomes available this will not be possible.

The study of the Peel Hall timbers has shown that yet another chronology from one area of the British Isles has shown excellent crossdating with chronologies from sites in Scotland, Ireland and the Midlands. In particular, this common growth pattern was shown by the Stayley Hall chronology (Section 7.4) and the Wales/West Midlands chronologies (Siebenlist-Kerner, 1978), which gave 't' values of 6.96 and 6.85 respectively with the chronology for Peel Hall I (Table 7.8). Morgan (1977b) has stated that A.D. 1419 and A.D. 1422 are signature years for the British Isles, being characteristically narrow. Whilst in the Peel Hall I chronology the rings for these years are narrower than those adjacent to them, they could not be described as "characteristically narrow." Narrow signatures do occur in the years: A.D. 1402, A.D. 1445, A.D. 1446 and A.D. 1454 (Figure 7.10). The narrow ring in A.D. 1446 is also present in the chronologies for Stayley Hall and Belfast (Baillie, 1977a).

This study has provided additional data for the north west of England regional chronology as well as posing new questions about the history of Peel Hall. The results show that the Peel Hall I chronology spans the period A.D. 1378 to A.D. 1481 and in doing so spans the period already represented by the Stayley Hall chronology (Figure 7.24). The Peel Hall I chronology does consolidate the chronology for Stayley Hall where it is at its weakest. It, therefore, reinforces the validity of that tree-ring series for the period A.D. 1378 to A.D. 1481 and makes the regional chronology for A.D. 1365 to A.D. 1554 more representative.

7.6 Bucknell Barn

The Site

The barn originally stood in the small village of Bucknell near Craven Arms in Shropshire until 1978 when it was dismantled. It was transported to Cheshire and re-erected in 1979 at Burleydam (SJ 608 434) (Figure 7.1). The building is a typical 3 bay barn thought to date from the 16th, 17th or 18th century (Blacklay, pers. comm.) (Plates 7.7 and 7.8). This spread of dates results from the fact that in this area, people were very conservative in their building. Nevertheless, any one of these dates was likely to render the barn of use in the construction of the regional chronology for the north west of England.

The timbers

Due to the fact that the barn was to be reassembled using its original timbers the removal of samples was seriously limited. A total of 6 samples, mostly from quarter hewn timbers, were taken for tree-ring analysis. Sapwood was not present on any of these samples.

Results

The 6 timbers yielded tree-ring sequences which ranged from 140 to 240 growth years. Four of these series were found to crossdate with one another with 't' values ranging from 3.93 to 10.49. Table 7.9 shows the probabilities of 'r' for each pair of curves arising by chance. The four series were combined to produce a working master chronology for the Bucknell barn for 182 years of growth (Figure 7.13). Characteristic years namely,46, 79 and 83 are marked by vertical lines. Since neither of the remaining tree-ring series crossdated with the working master, the index chronology for Bucknell Barn also comprised 4 tree-ring series. The temporal distribution of the components of the site chronology is, therefore, also shown in Figure 7.13. The index values of the Bucknell Barn chronology are

Plate 7.7 Bucknell Barn, re-erected in Cheshire

Plate 7.8 Bucknell Barn, end wall, re-erected in Cheshire.

TABLE 7.9

Bucknell Barn: probabilities of observed values of 'r' between components of the working master arising by chance.

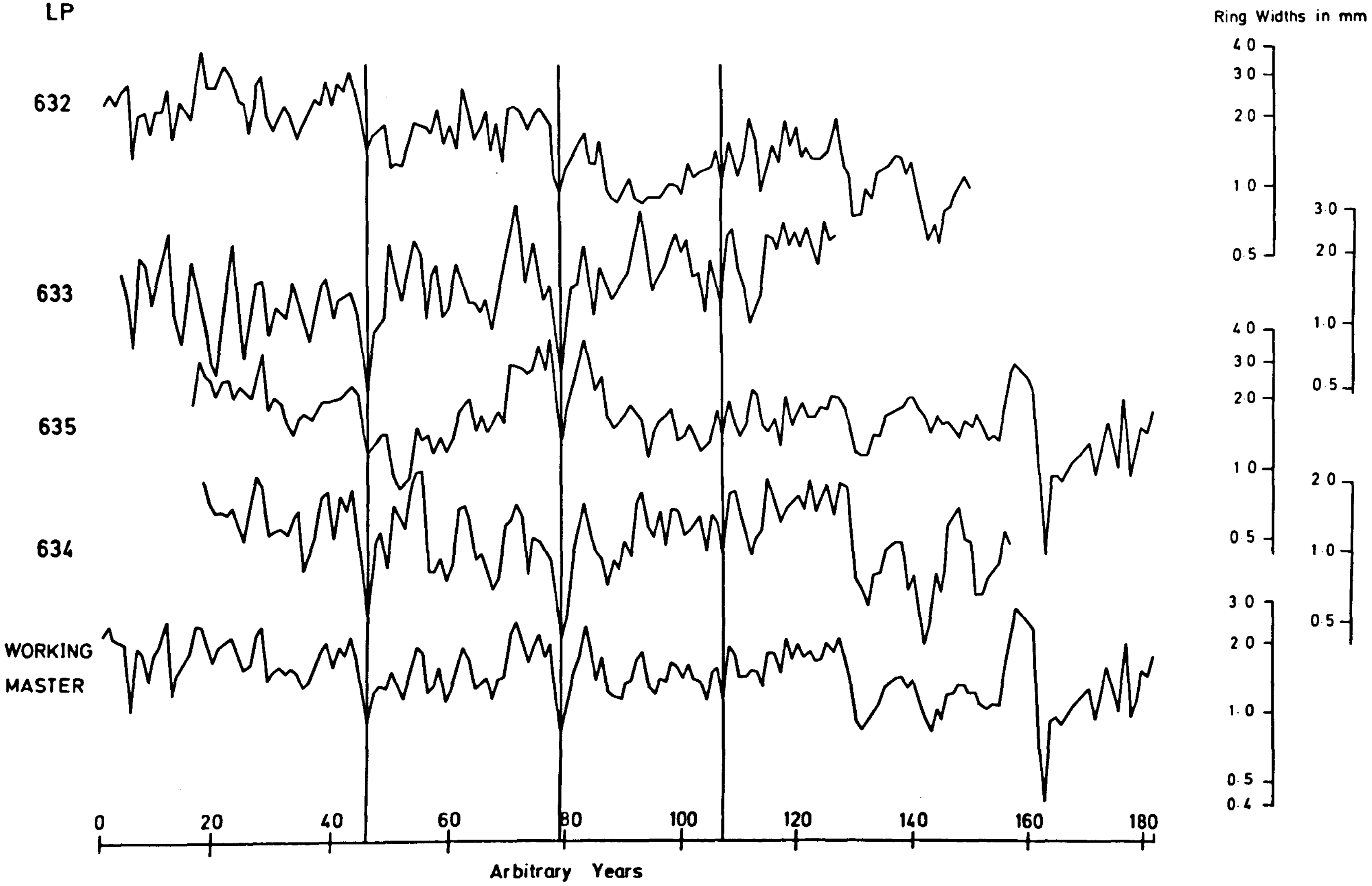
LP No.	633	634	635
632	XX	XX	XXX
633		XXX	X
634			XXX

Key

X $\leqslant$ 0.00009
XX $\leqslant$ 0.00005
XXX $\leqslant$ 0.00001

Figure 7.13 Bucknell Barn working master and its components. The curves are plotted on a semi-logarithmic scale. Characteristic years, namely 46, 79 and 83 are indicated by vertical lines.

BUCKNELL BARN : WORKING MASTER AND ITS COMPONENTS



given in Appendix X.

In the comparisons with standard chronologies the Bucknell Barn chronology matched well with those for Bishop's House (Morgan, 1977b), Wales/West Midlands (Siebenlist-Kerner, 1978), Stayley Hall (Section 7.4) and Yorkshire building timber (Hillam, unpublished data) (Table 7.10). The period spanned by the Bucknell Barn chronology was dated by these chronologies to A.D. 1414 to A.D. 1595 (Figure 7.14). The English signature year of A.D. 1419 (Morgan, 1977b) is more apparent in this site chronology than in the chronologies for Stayley Hall and Peel Hall I. There was no significant match with the chronologies for Belfast (Baillie, 1977a), Dublin (Baillie, 1977b) and South West Scotland (Baillie, 1977c).

Discussion

This study had been undertaken to determine the date of construction of the Bucknell Barn. By dating the master chronology, the individual timbers comprising it also became dated. However, a precise estimate of a construction date has not been possible since none of the timbers sampled contained any sapwood or an indication of the heartwood/sapwood boundary. As a consequence, it is not possible to give a precise estimate for the felling dates of the trees from which the timbers were cut. Nevertheless, the termination of the tree-ring series of these timbers, largely during the latter part of the 16th century indicates that the construction of the barn was unlikely to have taken place before the beginning of the 17th century.

The results of the crossdating tests indicated an interesting pattern. Table 7.11 shows that the Bucknell Barn chronology crossdates with several local chronologies, all of which match with the Irish and Scottish chronologies. However, the chronology for Bucknell Barn does not crossdate with the Irish and Scottish chronologies. It would appear, therefore, that the local variations present in this

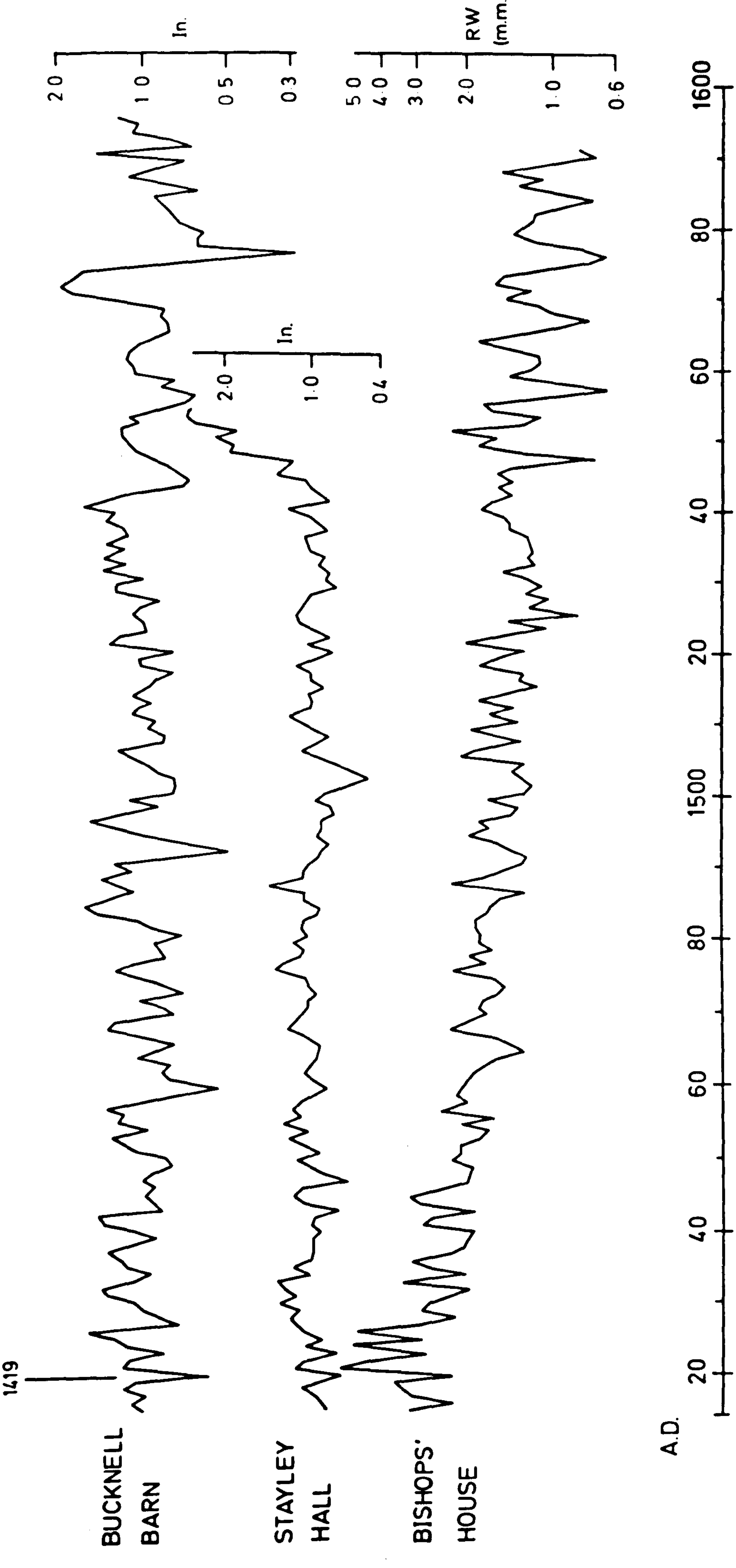
TABLE 7.10

Comparison between the Bucknell Barn chronology and various oak chronologies', Student's t-values and the probabilities of 'r' arising by chance.

Chronology	date of outer year	't'	no. years overlap	'r' ($p \leq$)
Belfast	-	-	-	-
South West Scotland	-	-	-	-
Dublin (2)	-	-	-	-
Bishop's House	1595	5.38	178	0.00001
Wales/West Midlands	1595	3.86	182	0.00007
	1634	3.78	182	0.00007
	1728	3.89	90	0.00017
Stayley Hall	1595	5.23	141	0.00001
Yorkshire building timber	1595	4.40	182	0.00003
Peel Hall I	(1595)	(3.38)	(68)	(0.00082)

References for chronologies are given in Table 7.1

Figure 7.14 The chronologies for Bucknell Barn, Stayley Hall and Bishop's House (Morgan, 1977b) at the position of match. The chronologies for Bucknell Barn and Stayley Hall are given in index format and that for Bishop's House in ring-width format.


BUCKNELL BARN
STAYLEY HALL
BISHOPS' HOUSE
1419
A.D.
20
40
60
80
1500
20
40
60
80
1600
In.
2.0
1.0
0.5
0.3
In.
2.0
1.0
0.4
RW (m.m.)
5.0
4.0
3.0
2.0
1.0
0.6

chronology are also strongly represented in those from the same region, and those with which it crossdates.

The overlap for Bucknell Barn and Peel Hall I is very short being only 68 years (t = 3.35). There is, therefore, no justification at present for combining these chronologies even though they both crossdate with the chronology for Stayley Hall (Tables 7.8 and 7.10).

The dating of the chronology for the Bucknell barn has, therefore, provided additional information regarding regional patterns of tree growth and has facilitated the extension of the North West of England chronology under construction (Figure 7.24). Although much of the period A.D. 1414 to A.D. 1595 is already represented by the chronologies for Peel Hall and Stayley Hall, the chronology does extend this post-medieval section forwards in time by 51 years.

Table 7.11

Crossdating results for various oak chronologies.

Chronology	Stayley Hall	Bishop's House	Wales/ West Midlands	Belfast	South West Scotland	Dublin
Bucknell Barn	+	+	+	-	-	-
Stayley Hall	+	+	+	+	+	+
Bishop's House			+	+	+	+
Wales/West Midlands				+	+	+

Key

+ Chronologies crossdate

\- Chronologies do not crossdate

7.7 Nantwich

The Site

During 1974 and 1976 excavations were carried out in Nantwich on behalf of the Department of the Environment and Cheshire County Council. The site (SJ 650 523) was a proposed car park for the National Westminster Bank. The location of Nantwich is shown in Figure 7.1. The 1976 excavation was undertaken by Dr. D.H. Hill and Mr. J. Parkhouse (Manchester University).

The principal features on the site represented the mediëval brine industry and its associated activities (Plate 7.9). A complex series of channels with a post and plank construction in clay-lined trenches running North - South represented several phases of brine conduits. The conduits had been mutilated for the most part by post-mediëval building activity on the site. The conduits were interpreted as collection and control ponds for a brine supply feeding a salt-works which must have been situated further down the hill. During the 1976 excavation a number of fragments of wattle fence were found associated with the channels. A wattle and daub-lined well was also found. This excavation also revealed part of a substantial tanning pit which was lined with timber planking and contained a well preserved deposit of organic material. Small finds included pottery sherds, leather shoes, a leather decorated knife sheath and part of a wooden lathe-turned bowl.

The timbers

The timbers revealed in these excavations were in a very water-logged condition. During the 1976 excavation many well-preserved timbers were lifted and stored in polythene bags to prevent them from drying out. Forty timbers were examined to determine their suitability for tree-ring analysis; thirty seemed promising. The timber structures uncovered in the main 1974 excavation were not raised but were re-

Plate 7.9 A section of the 1976 Nantwich excavation.

covered with clean material. However, those found in the excavation of a trial trench in 1974, 7 metres to the east, had been lifted and stored in polythene bags. Eight timbers were available in 1976 and were examined in conjunction with those from the second excavation. Four timbers from this trial trench were found to be suitable for subsequent tree-ring studies making a total of 34 in all. Unsuitable timbers contained few tree-rings and were usually small and rectangular in section. All but two of the suitable 34 timbers had been prepared as planks. They varied from 9cm to 33cm in width and from 1cm to 8cm in thickness (Plate 7.10).

Methods

The waterlogged condition of the timbers demanded different sampling and preparation techniques from those required by timbers of sound wood. The use of a power saw to cut the wood would have been unwieldy and likely to shatter the sample. Instead, a hand saw was found to be efficient in tackling this relatively soft material. Wherever possible, the sample was cut from each timber at a position where the number of tree-rings appeared to be greatest. Since the majority of timbers had been radially split, the number was greatest at the widest point of the plank. Knots were carefully avoided. This selective sampling was not always possible especially when a timber contained important archaeological features. In these cases the cut was made approximately 4-5cm from the end containing the greatest number of rings.

The preparation of the cut sample could not be done by sanding as had previously been the case on dry wood. Instead, each sample was stored in a sealed polythene bag in the deep freeze until it was frozen. When it was required for measurement it was removed and exposed to the air until the surface had begun to thaw. In this state the sample was soft enough to cut whilst retaining sufficient rigidity to remain entire and to allow a clean cut. The annual rings were exposed by

Plate 7.10 Oak timbers in the Nantwich excavation (located by white tickets).


cms
2

slicing across the transverse surface of the sample with a Stanley Knife with blade 5901 which has a 34mm cutting edge. When sapwood was present on the sample, slicing was begun from the sapwood towards the inner rings. This minimised the possibility of ripping the sapwood which tends to occur more easily when slicing into it from the other direction.

An examination of the cut surface revealed that the colour difference between the layers of earlywood and latewood which usually aids in their identification, was absent in these preserved timbers. These timbers were entirely black or dark brown. Nevertheless, the different cell layers could be clearly distinguished by the change in cell size from the earlywood to the latewood. There was also no difficulty in identifying the sapwood since this was much lighter in colour than the heartwood (Plate 7.11).

Before each sample was measured it was allowed to thaw completely to ensure that the cell size was stable. Each decade was identified with a straight pin as a reference point should reinvestigation be necessary. On most samples only one radius could be measured because each of these timbers had been split radially.

Results

The timbers from the Nantwich excavations exhibited patterns of tree growth which were sensitive and which contained from 93 to 299 years of growth. These long narrow-ringed series indicated that the radially split timbers had been taken from mature trees of slow growth. Some must have been much older than was indicated by the number of rings on the sample since all the sapwood and some of the heartwood had been removed. Furthermore, the wood rays which radiate from the centre of the tree were still running parallel on the inner and older edge of the sample. It may be inferred from these features that timber from the inner part of the tree had also been lost. The mean

Plate 7.11 A sample from the Nantwich excavation showing the colour difference between the darker heartwood and the lighter sapwood.


Inch = 25·4 millimetres
Foot = 30·48 centimetres
Centimetre = 0·3937 inch
MM
8THS

ring width of these series was approximately 1.00mm. From a comparison of the tree-ring patterns of 32 timbers, crossdating (both criteria being satisfied) was initially established between the curves of 5 timbers. The 5 series were combined to produce a working master of 337 years. The Student's t values obtained for these matches ranged from 4.45 to 8.22. The probabilities of 'r' foı each pair of tree-ring curves arising by chance are shown in Table 7.12. The working master and its components are shown in Figure 7.15. The time scale is in arbitary years since the chronology is still "floating" at this stage. A number of signature years namely, 42, 72, 96, 159 and 185 are indicated by vertical lines. These timbers represent a strongly crossdated group on both statistical and visual grounds.

The tree-ring series of 11 timbers crossdated with the working master. The series from 16 timbers were, therefore, combined to produce an index chronology spanning 401 years for the excavated Nantwich site. Of the remaining 14 curves, a number of them could be matched with the index chronology at several positions along the curve. Definite crossdating was, therefore, considered not to exist which justified the omission of these curves from the final chronology. The temporal distribution of the components of the index chronology is shown in Figure 7.16. The Nantwich chronology is listed in index format in Appendix XI. Apart from the beginning and the end of the chronology, each 20 year period is well replicated. Five timbers retained a number of their sapwood rings which ranged from 12 to 27.

The greater length of the Nantwich chronology allowed a more detailed analysis of the data than was possible at the other sites. The chronology statistics are shown in Table 7.13. The mean ring width is small (1.07mm) with much autocorrelation as shown by the high figure for serial correlation (0.60). Mean sensitivity is low and just below

TABLE 7.12

Nantwich: probabilities of 'r' between the components of the working master occuring by chance.

LP No.	346	354	368	369
333	xxx	x	xxx	xxx
346		xx	xxx	xxx
354			xx	xxx
368				xx

Key

x $\leqslant$ 0.00048

xx $\leqslant$ 0.00003

xxx $\leqslant$ 0.00001

TABLE 7.13

Chronology Statistics for oak at Nantwich

Mean ring width (mm)	1.07
Serial correlation	0.60
Mean sensitivity	0.15
Standard deviation	0.23
Years of analysis	401
Period of analysis	A.D. 930 - 1330

Figure 7.15 Nantwich working master and its components.

The component curves are in ring-width format; the working master is shown in index format.

Characteristic years, namely arbitrary years 42, 72, 96, 159 and 185 are indicated by vertical lines.

NANTWICH: WORKING MASTER AND ITS COMPONENTS

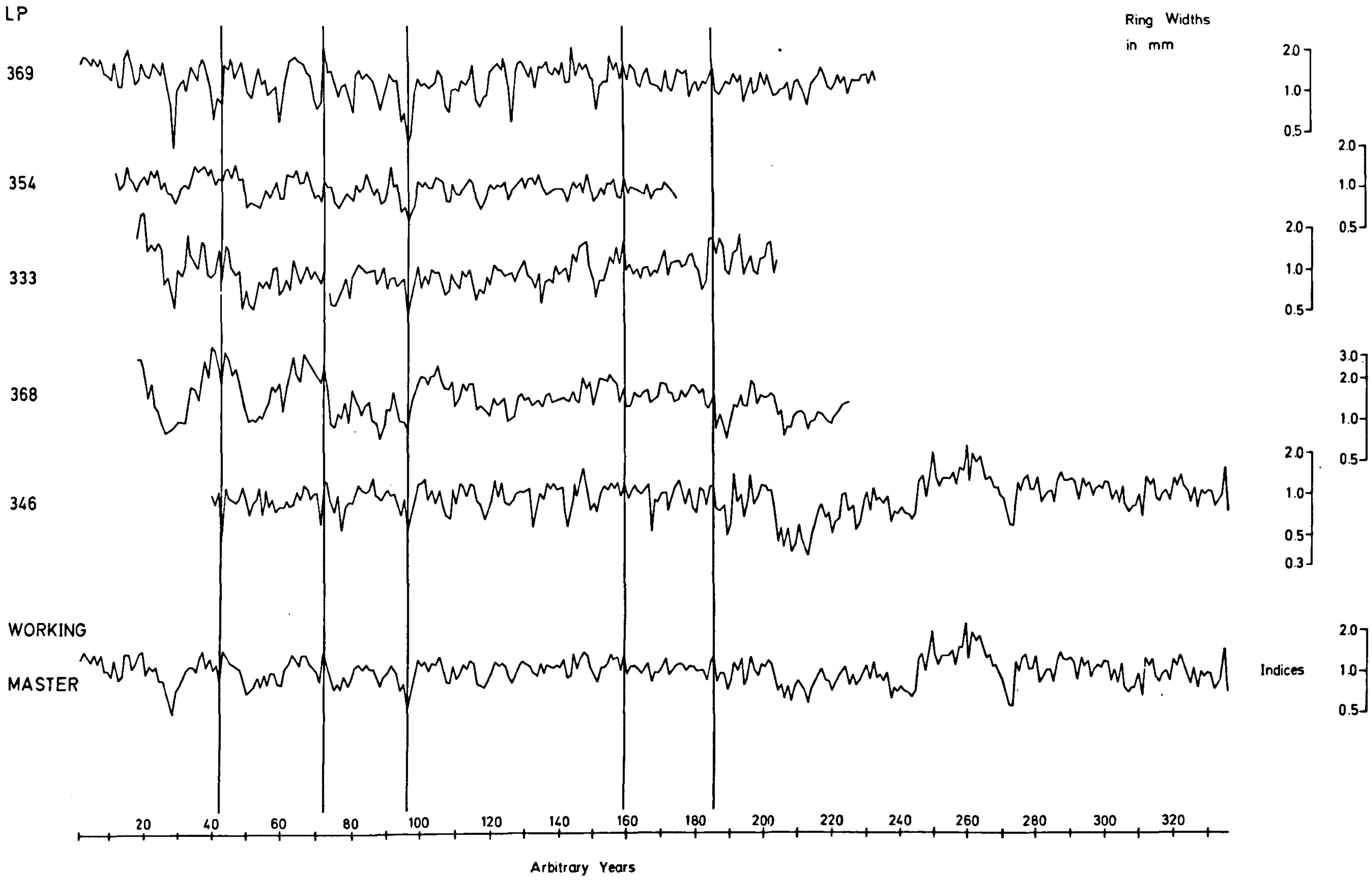
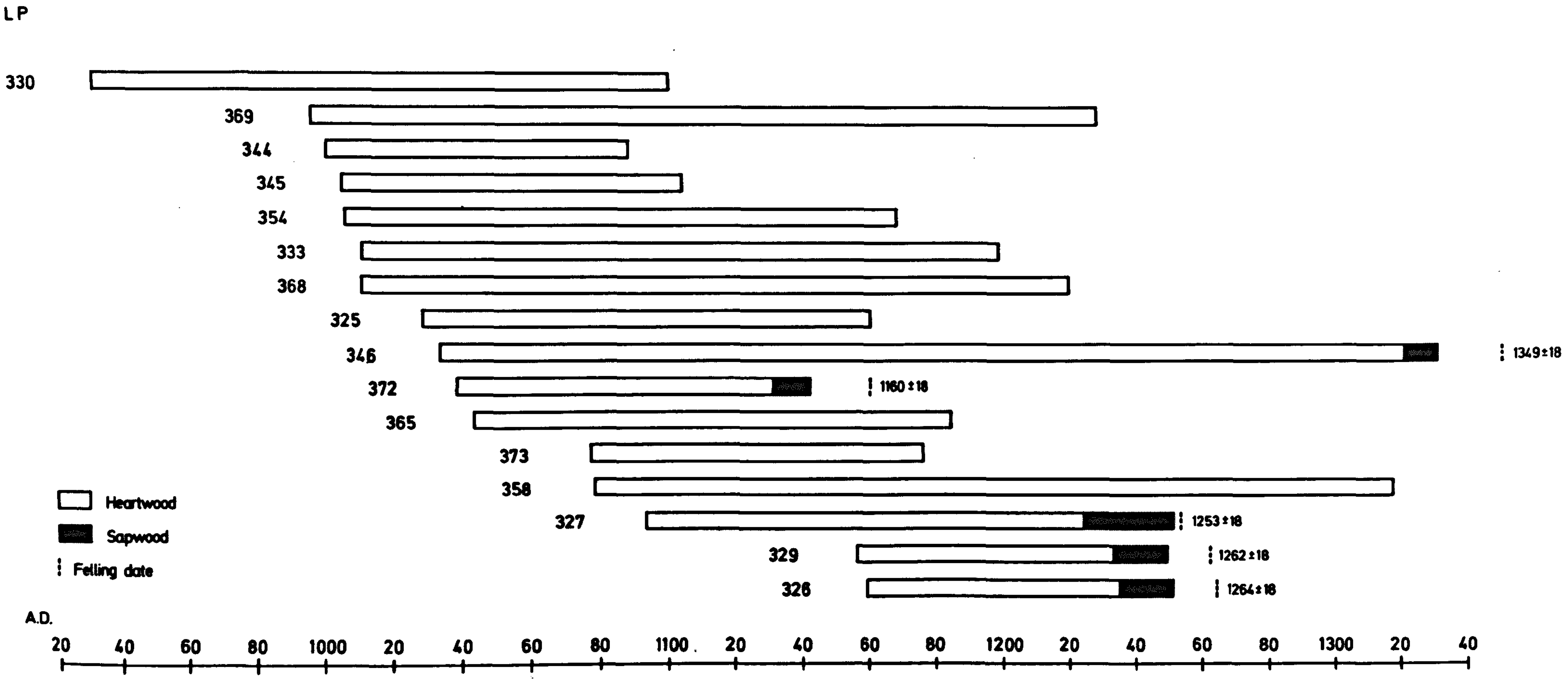


Figure 7.16 The temporal distribution of the components of the Nantwich chronology.

Estimated felling dates are given for timbers with sapwood.

COMPONENTS OF NANTWICH CHRONOLOGY



the range of values found for oak at other sites in the British Isles (Table 4.1).

A clue to the period represented by the Nantwich chronology was given by archaeological evidence in the form of pottery taken from the excavations. The sherds led to the suggestion by Mr. R. Williams (pers. comm.) that this site had been in use during the 12th and 13th centuries. Dated reference chronologies which spanned these periods were tested for crossdating against the Nantwich chronology in an attempt to date the latter (Table 7.14). The best match was obtained with the Dublin chronology (Baillie, 1977b) which gave a 't' value of 5.68 ($p \leqslant 0.00001$), this dated the most recent ring as A.D. 1330 so that the Nantwich chronology spanned the period A.D.930 to A.D. 1330. This chronology was likewise dated by Reference curve 6 (Fletcher, 1977) and by the Seal House chronology constructed for timbers at a London waterfront (Morgan, 1977a). The Nantwich chronology also matched that for Hull (Hillam, 1979a). The Dublin and Nantwich chronologies are shown at the matched position in Figure 7.17.

The correlations between the Nantwich chronology and the chronologies for Dublin, REF 6 and Seal House for 10-year periods lagged every 5 years for the period A.D. 950 to A.D. 1190 are shown in Figure 7.18. The Nantwich/Dublin plot (Figure 7.18a) shows one period when the agreement between the chronologies was outstanding, A.D. 1085 to A.D. 1109. For the remainder of the analysis period values for 'r' were mostly positive and there were no large negative values. The Nantwich/REF 6 plot (Figure 7.18b) shows more periods of high correlation with the outstanding period in Figure 7.18a being less important. In addition, there were fewer negative correlation values. Although REF 6 incorporates the Seal House chronology the Nantwich/Seal House plot (Figure 7.18c) exhibits a different set of

TABLE 7.14

Comparison between the Nantwich chronology and various oak chronologies; Students t-values and the probabilities of 'r' arising by chance.

Chronology	date of outer year	't'	no.years overlap	'r' (p≤)
Belfast	1101	3.74	101	0.00024
	1330	4.03	230	0.00003
South West Scotland	1330	3.68	385	0.00016
	1406	3.80	401	0.00003
Dublin (1)	1330	5.68	306	0.00001
Seal House	1330	4.93	244	0.00001
REF. 6	1330	5.26	264	0.00001
REF. 1	-	-	-	-
REF. 2	-	-	-	-
REF. 3	-	-	-	-
REF. 4	1199	3.55	80	0.00044
	1222	3.81	103	0.00017
Hull	1330	3.78	172	0.00011

References for chronologies are given in Table 7.1

Figure 7.17 The chronologies for Nantwich and Dublin (Baillie, 1977b) shown at the position of match.

Both chronologies are shown in index format.

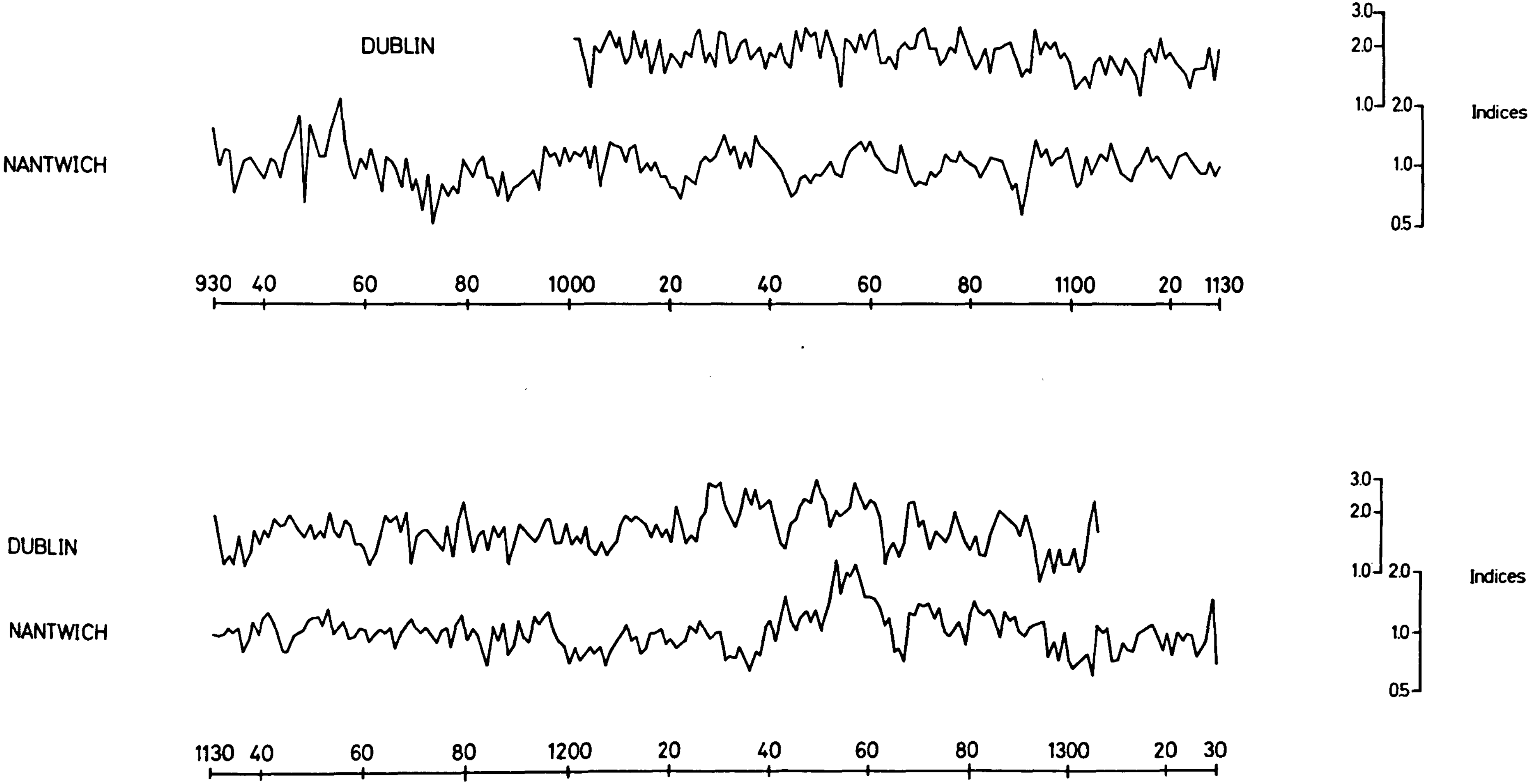

DUBLIN
NANTWICH
930
40
60
80
1000
20
40
60
80
1100
20
1130
3.0
2.0
1.0
2.0
1.0
0.5
Indices
DUBLIN
NANTWICH
1130
40
60
80
1200
20
40
60
80
1300
20
30
3.0
2.0
1.0
2.0
1.0
0.5
Indices

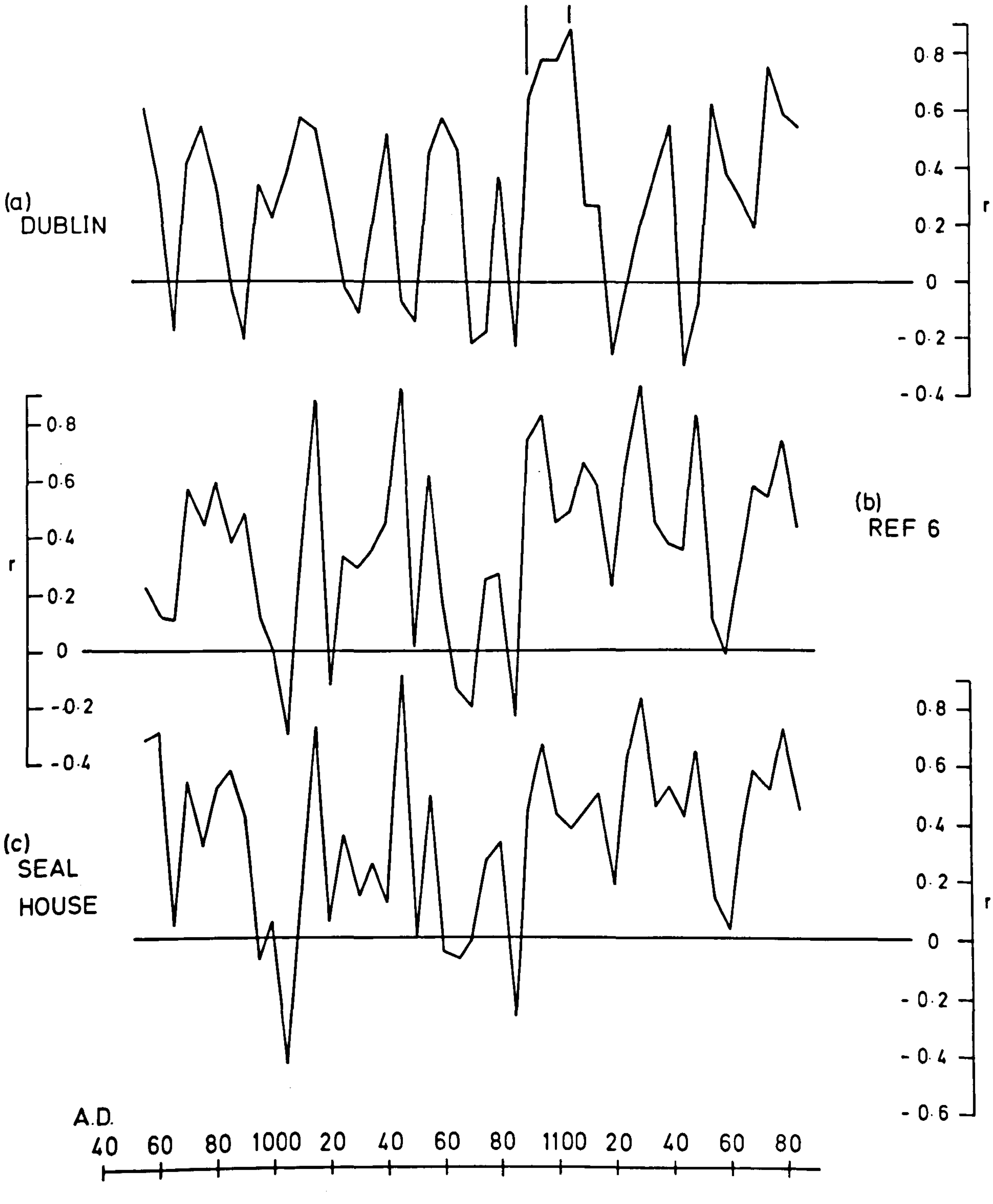
Figure 7.18 Correlation between the Nantwich chronology and some other oak tree-ring chronologies for the period A.D. 950–A.D. 1190. Each point is a 10-year mean, calculated at 5-year steps.

(a) Nantwich and Dublin (Baillie, 1977b) chronologies

(b) Nantwich and REF. 6 (Fletcher, 1977) chronologies

(c) Nantwich and Seal House (Morgan, 1977a) chronologies.

NANTWICH CORRELATIONS



periods when the correlation between the chronologies was extremely high. Clearly, the characteristics of the other chronologies comprising REF 6 are masking those of the Seal House chronology.

In order to determine the time of felling of the trees from which the Nantwich timbers were hewn, the number of sapwood rings was examined. Sapwood was present on 12 of the timbers considered suitable for tree-ring analysis although only 5 of these formed part of the Nantwich chronology. The absolute dating of the chronology meant that each year on each timber (hitherto relatively dated) could also be assigned calendrical dates. The identification and allocation of a date to the heartwood/sapwood boundary allowed an estimation of the felling dates of the timbers with sapwood. The estimate 30 ± 18 for the mean number of sapwood rings for Peckforton oaks (Section 5.3.2) was applied to the date of the most recently formed heartwood ring. The estimated felling dates were A.D. 1160, 1253, 1262, 1264 and 1349 all with attached limits of ± 18 years.

Discussion

Tree-ring analysis of the timbers from the Nantwich excavations was initiated with the intention of producing another portion of a continuous absolutely dated chronology for the north west of England. The results of these investigations have shown that these attempts have been successful in producing a tree-ring series which spans 401 years. In addition, as is shown here, such studies can also provide important information for the relative dating of timbers in the site. The absolutely dated timbers may be examined in conjunction with the stratigraphic details recorded by archaeologists during the excavation, to determine the relationship between the various timber structures exposed.

Sapwood provides additional information since it allows a realistic estimate of the felling dates of the timbers containing it. In the Nantwich chronology,the timbers with sapwood fall into three groups but two of these contain only one timber. In the first group, some felling occurred in the middle of the 12th century, in the second group felling occurred in the middle of the 13th century and in the third group it took place about the middle of the 14th century. In some cases part of the range given for the felling date has to be discounted when these years are already present on the timber. If this does occur it will relate to the earlier part of the range. This situation arises for the timbers in the second group; Samples LP327, LP329 and LP326 have estimated felling dates with ranges of A.D. 1235 to A.D. 1271, A.D. 1244 to A.D. 1280 and A.D. 1246 to A.D. 1282 respectively. An examination of the years already present on these samples shows that in real terms these ranges are A.D. 1251 to A.D. 1271, A.D. 1249 to A.D. 1280 and A.D. 1251 to A.D. 1282.

The spread of timbers with sapwood indicates there has been three phases of timber insertion spanning 200 years. However, these results do not undeniably identify three construction phases; timbers from another structure could have been re-used at this Nantwich site. These interpretations must be made by archaeologists familiar with the site.

With regard to the estimates used to determine the felling dates, ideally they should be calculated using trees growing in a similar period and environment to those under investigation. It is most unlikely that a large number of trees complete with sapwood and bark of medieval date will become available. In addition, the environment in which the excavated timbers were growing is not known. However, the slow growth of the Nantwich timber indicated by the narrow rings, does indicate that the trees were growing in close competition in closed stands known to be common in the early medieval period (Jones, 1960). Therefore, in this case, the estimate for Peckforton would seem to be a pertinent one.

The good crossdating between the Nantwich chronology and the chronologies for Dublin, Seal House and REF 6 leads to the question of provenance. During the early middle ages timber supplies in Cheshire were abundant. In addition to the three large forests of Delamere, Wirral and Macclesfield there were extensive woodlands in several parts of the county (Hewitt, 1967). The drift geology of Cheshire is largely represented by boulder clay and glacial sand and gravel (Sylvester and Nulty, 1958). It is likely that the forests and woodlands on the sandy, freely draining soils would have contained trees with sensitive growth patterns of the kind lifted at Nantwich. Growth patterns of great sensitivity have been found in trees growing at Delamere Forest on slopes that were sandy and with fairly shallow gradients (Bennett, pers. comm.). The salt making processes at Nantwich would have required fuel to effect the evaporation of brine in lead pans. The neighbouring woodlands could also have provided this fuel in the form of branches, twigs and deadwood. In the fifteenth and sixteenth centuries timber was regularly supplied from Delamere Forest for the repair of religious and secular buildings alike (Driver, 1971). A consideration of the above facts points to the likelihood of the source of the Nantwich timbers being a local one. Whatever the source, it was one in which slow grown mature trees provided long straight timbers.

For the Dublin chronology, the tree-ring patterns are almost certainly from locally grown oaks (Baillie, 1977b). The Seal House chronology is thought to be constructed from the tree-ring patterns of oaks growing in south east England. No indication is given for the source of timbers used to construct REF 6 (Fletcher, 1977) although some will originate from central, south and south east England. While the conditions of growth appear to have been very similar in Nantwich, Dublin and the south of England during these centuries, some differences are apparent (Figure 7.17). For the period A.D. 1066 to A.D. 1075 a trough in the Nantwich chronology is shown as a period of increasing growth by the Dublin curve. Furthermore, the deep troughs shown for A.D. 1242, 1243 and 1244 by the Dublin chronology are shown as years of increased growth in the curve for Nantwich. In the late 13th and early 14th centuries when the Nantwich chronology comprises only 2 timbers the similarity with the Dublin curve is less, illustrating the necessity for well replicated chronologies throughout all periods. In some parts of the curves, the index values are almost identical, for example, A.D. 1093 to A.D. 1110. Some differences also occur between the Nantwich chronology and the other dated chronologies; for example in the Seal House curve the ring for A.D. 1057 is narrow but this is seen only as an average ring in the chronology for Nantwich.

The absolute dating of the Nantwich chronology and its component timbers has provided important data for both the author and the archaeologists. It has indicated the period during which the site was in use, in addition to identifying periods of timber insertion or replacement. More importantly for the present study, the site has provided material from which a 401 year absolutely dated continuous chronology could be constructed. Its position within the regional chronology is shown in Figure 7.24.

7.8 Baguley Hall

The site

Baguley Hall is located about 90 kilometres south of Manchester (SJ817887) (Figure 7.1). Originally a manor house, Baguley Hall was later used as a farmhouse until the tenancy expired when it was used as a corporation timber store.

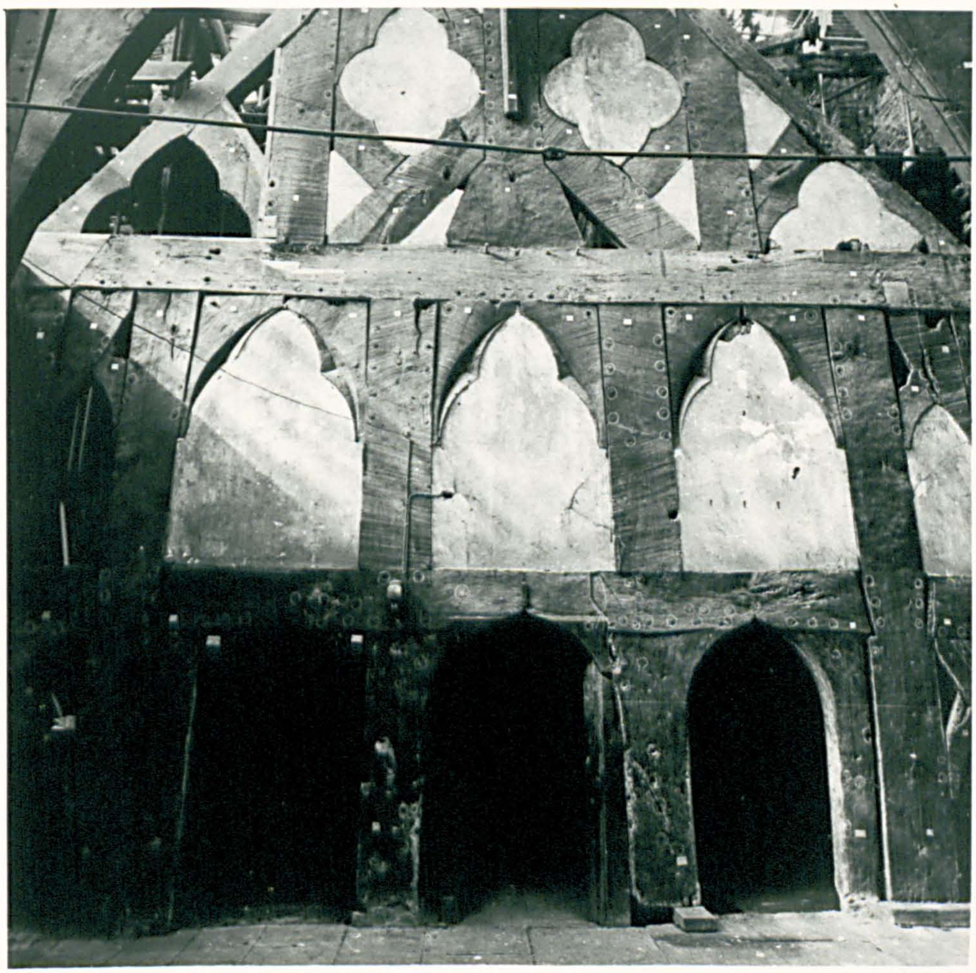
The hall as it now stands has an open timber-framed hall thought to date from the middle of the 14th century with repairs of probable 19th century date (Plate 7.12). It is aligned approximately north and south with brick wings at each end. The north wing which contained the 'service' quarters, is of medieval date and is either an addition of that date or a complete reconstruction of whatever stood their before (Smith and Stell, 1960). The hall is entered on the west through a porch which was added in the late 16th century.

Inside the building a screens passage is divided from the main body of the hall apparently in the manner typical of Lancashire houses, by a spere-truss.

The hall itself is of two bays not quite equal in size. The internal widths at Baguley Hall are 8.38 metres at the north wall (Plate 7.13) and the spere truss, 8.92m at the open truss and 8.61m at the south end (Smith and Stell, 1960). These measurements show that the south end of the hall does not diminish to the same width as the spere truss. Within the side walls, the windows at the south end are very close to the south wall which has led to the suggestion that the hall has been truncated at this end (Smith and Stell, 1960). Recent excavations in the south wing which revealed a continuation of the foundations of the east wall have also led to this conclusion (Startin, pers. comm.).

Plate 7.12 Baguley Hall, east elevation

Plate 7.13 Baguley Hall interior, north wall



The timbers

The most noticeable feature of the hall is the massiveness of the timber work; the main post is 78.54cm wide and inside, the attached shaft for the open truss has been carved in the solid, giving a maximum thickness of 35.56cm. Even the intermediate posts are 53.34cm wide by 17.78cm thick which according to Smith and Stell (1960) would be sufficient to make two principal posts for an early 15th century hall in the south of England. The width of 17.78cm is constant for nearly all the timbers. The wall plates are 50.80cm deep and the cornice which serves no structural purpose is 25.40cm by 15.42cm. This large size is not confined to the outer walls; the timbers of the north wall with its screens passage is uniformly 17.78cm thick (Plate 7.13). The king post is 121.92cm at the bottom of its splayed base and the common rafters which are relatively slight are 30.48cm by 17.78cm. The timbers at Baguley Hall thus have a plank rather than a beam appearance varying in length and width but having a uniform thickness of 17.78cm.

Sampling programme

The restoration of Baguley Hall by the Department of the Environment provided an opportunity to sample timbers which, it was hoped would extend the regional chronology back from the 14th century. An examination of the sawn and tenoned ends of the timbers revealed that they had been cut in a variety of ways. The cornices and the rafters were timbers consisting of approximately one quarter of the tree trunk although no sapwood was present. The measured principal and intermediate posts from the north and west walls were quarter sawn timbers. Those timbers which were available for analysis but not suitable were mostly flat sawn planks in which the rings ran parallel to the thickness of the plank. With such a cut,the number of rings is limited to the thickness of the plank and in all cases was duplicated with no more than 50 or 60 rings. Many of the spere trusses were also flat sawn planks and, therefore, were not suitable for analysis. Those that were suitable were the timbers that had been quarter sawn. However, some quarter sawn timbers had growth rings that were so wide that, again, approximately 60 rings was the maximum.

During the restoration work the ends of some timbers had been sawn off to allow for the grafting on of a new timber. The sawn ends were removed and prepared in the laboratory. Other timbers were either to remain within the framing or were to be replaced into it in their original form. Consequently, the timbers in the former group had to be measured <u>in situ</u> whilst those in the latter were measured on site. These measurements could not be made with the Bannister Machine used for the other sites since many of the timbers were 5 metres above the ground and the support for the operator consisted of planks and scaffolding. There was also no means of fastening the machine to the ends of the timbers. This situation called for a much smaller device which could be handled with ease in awkward circumstances. Modifications were made to a travelling microscope that enabled it to be used in such restricted conditions (Plate 7.14). This device consists of a monocular eye piece mounted on a secondary base plate which is adjustable for angular and longitudinal displacement on a primary base plate. The primary base plate is fixed to the wood sample. The eyepiece has coarse, longitudinal positional adjustment on the secondary base plate with fine adjustment measured by a clock gauge calibrated to 0.01mm. The overall magnification is 20X. The results so obtained are directly comparable to those obtained in the laboratory using the Bannister machine (Section 2.4).

A total of 20 timbers were measured from Baguley Hall which were as follows:-

6 rafters

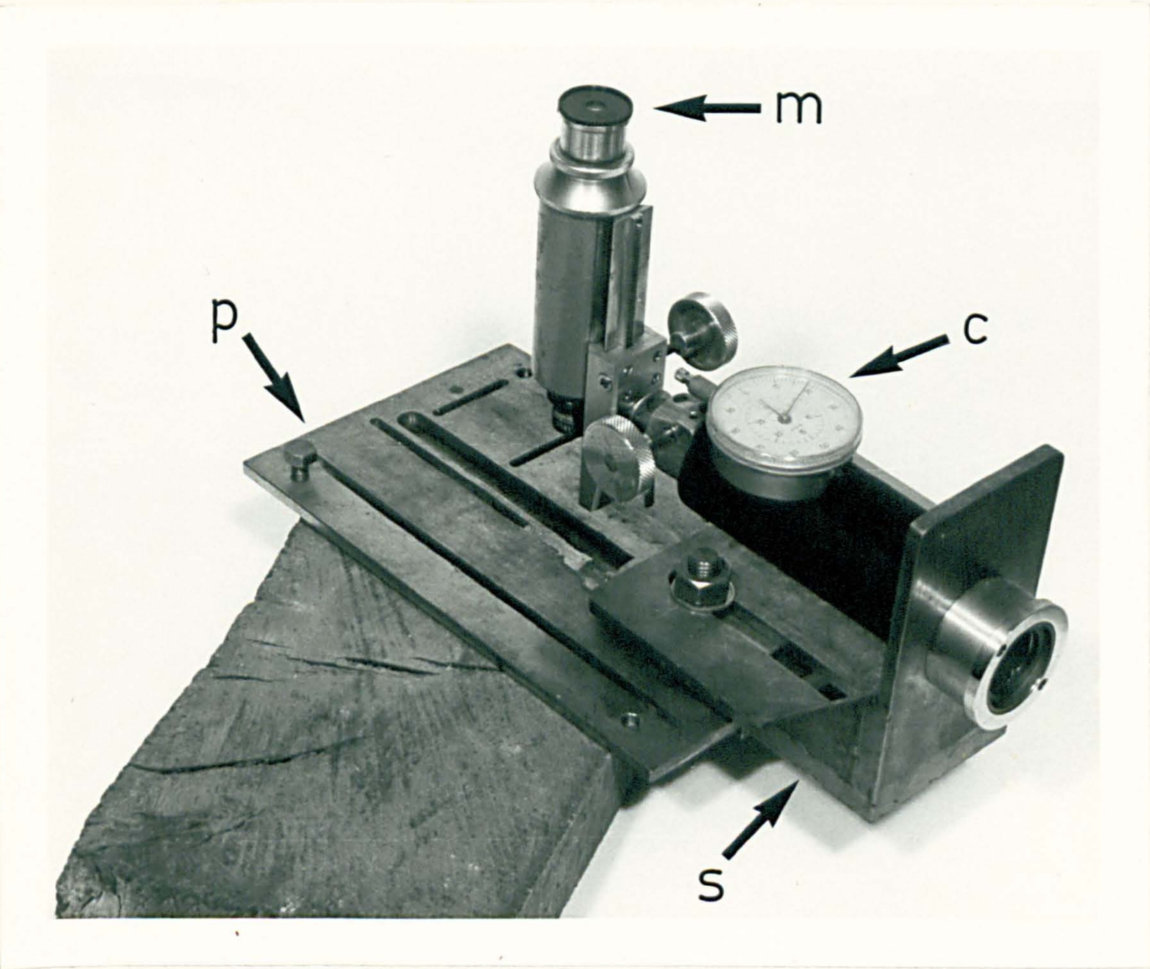
6 pieces of cornice

2 spere trusses

Plate 7.14 Portable measuring machine

m - monocular eyepiece
p - primary baseplate
s - secondary baseplate
c - clock gauge.

Wood screws are used for fixing the primary base plate to the transverse surface of a timber. Plate 7.14 shows wood screws replaced by jacking screws which are used for levelling the plate when fixation is not required.


m
p
c
s

3 uprights from the north wall

3 uprights from the west wall

the wall plate from the east wall

Results

The 20 timbers from Baguley Hall contained tree-ring series with 93 to 209 years of growth. Sapwood was present on only one timber which contained 21 sapwood rings. This was the east wall plate which is thought to have been inserted during the 19th century.

The results of crossdating tests for 20 tree-ring series suggested that there were two distinct groups of tree-ring series. For the first series consisting of 4 timbers, the probabilities of 'r' arising by chance are shown in Table 7.15. The 't' values ranged from 3.50 to 4.93. These tree-ring series were combined to form a working master of 151 years of growth. Figure 7.19 shows the working master and its components characteristic years namely, arbitary years 43,66 and 77 are indicated by vertical lines. The tree-ring series for one other sample crossdated with the working master. A total of 5 tree-ring series, all from rafters were, therefore, combined to produce a chronology of 151 years, designated BAG I. The temporal distribution of the components of the BAG I chronology is shown in Figure 7.20. The BAG I chronology is listed in index format in Appendix XII.

The second group comprised the tree-ring series for 3 timbers which crossdated with 't' values ranging from 5.88 to 7.97 (probabilities of 'r' arising by chance, Table 7.16). A working master of 254 years was constructed for these timbers and is shown with its components in Figure 7.21. Vertical lines indicate some characteristic years namely, 62, 109 and 130 (later dated as A.D. 1098, 1145 and 1166 respectively). The tree-ring series of this group were derived from 2 pieces of cornice and from the east screen spere truss. None of the remaining tree-ring series crossdated with the working master. The tree-ring series of the

TABLE 7.15

Baguley Hall I: probabilities of observed values for 'r' between components of the working master arising by chance

LP No.	580	581	584
578	xxx	xx	xx
580		xx	x
581			xx

TABLE 7.16

Baguley Hall II: probabilities of observed values for 'r' between components of the working master arising by chance.

LP. No.	549	577
538	xxx	xxx
549		xxx

Key (for both tables)

x $\leqslant$ 0.00044

xx $\leqslant$ 0.00009

xxx $\leqslant$ 0.00001

Figure 7.19 Baguley Hall I working master and its components. The curves are plotted on a semi-logarithmic scale. Characteristic years, namely arbitrary years 43, 66 and 77 are indicated by vertical lines.

BAGULEY HALL I: WORKING MASTER AND ITS COMPONENTS

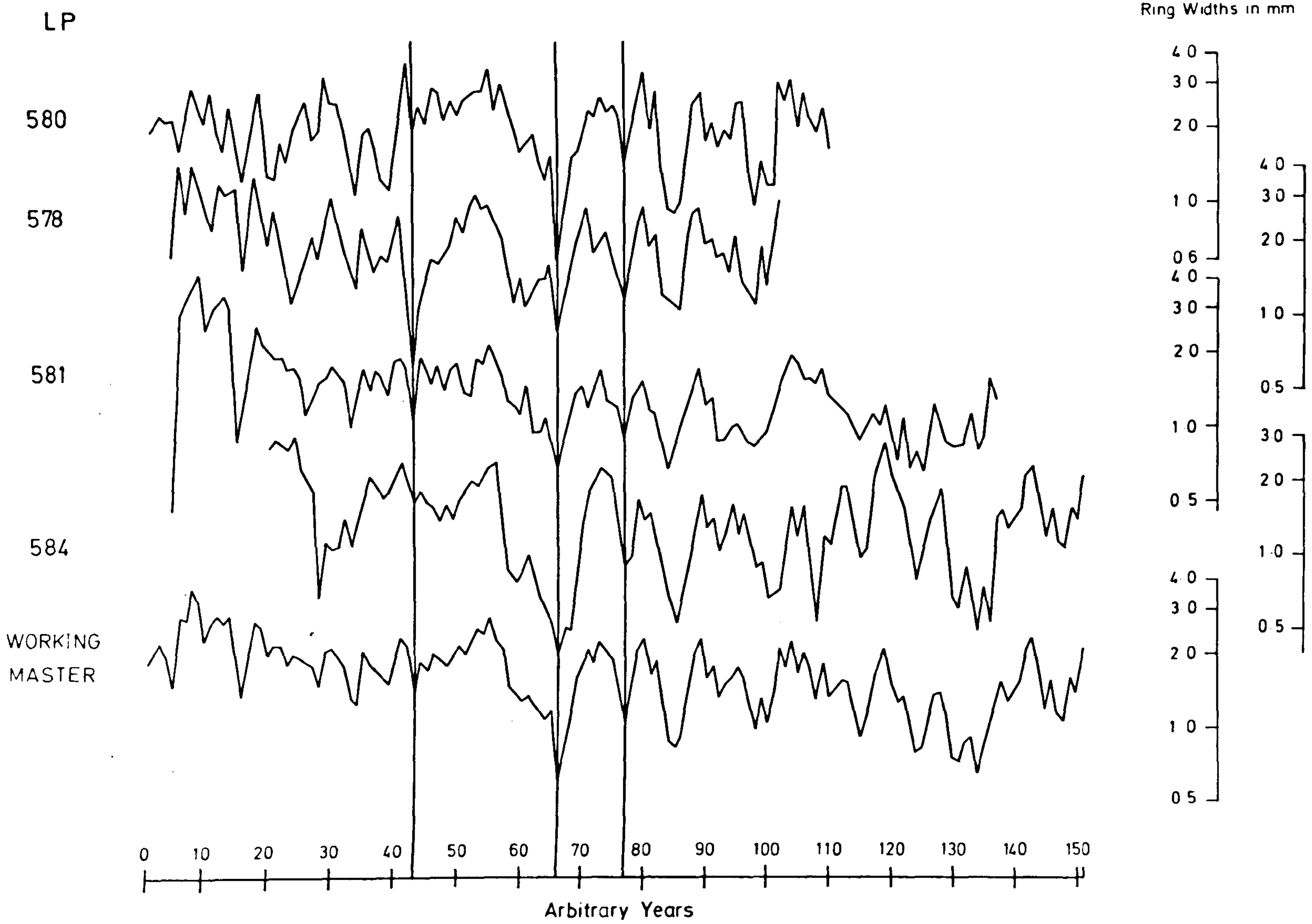


Figure 7.20 The temporal distribution of the components of the Baguley Hall I chronology.

COMPONENTS OF BAGULEY HALL I CHRONOLOGY

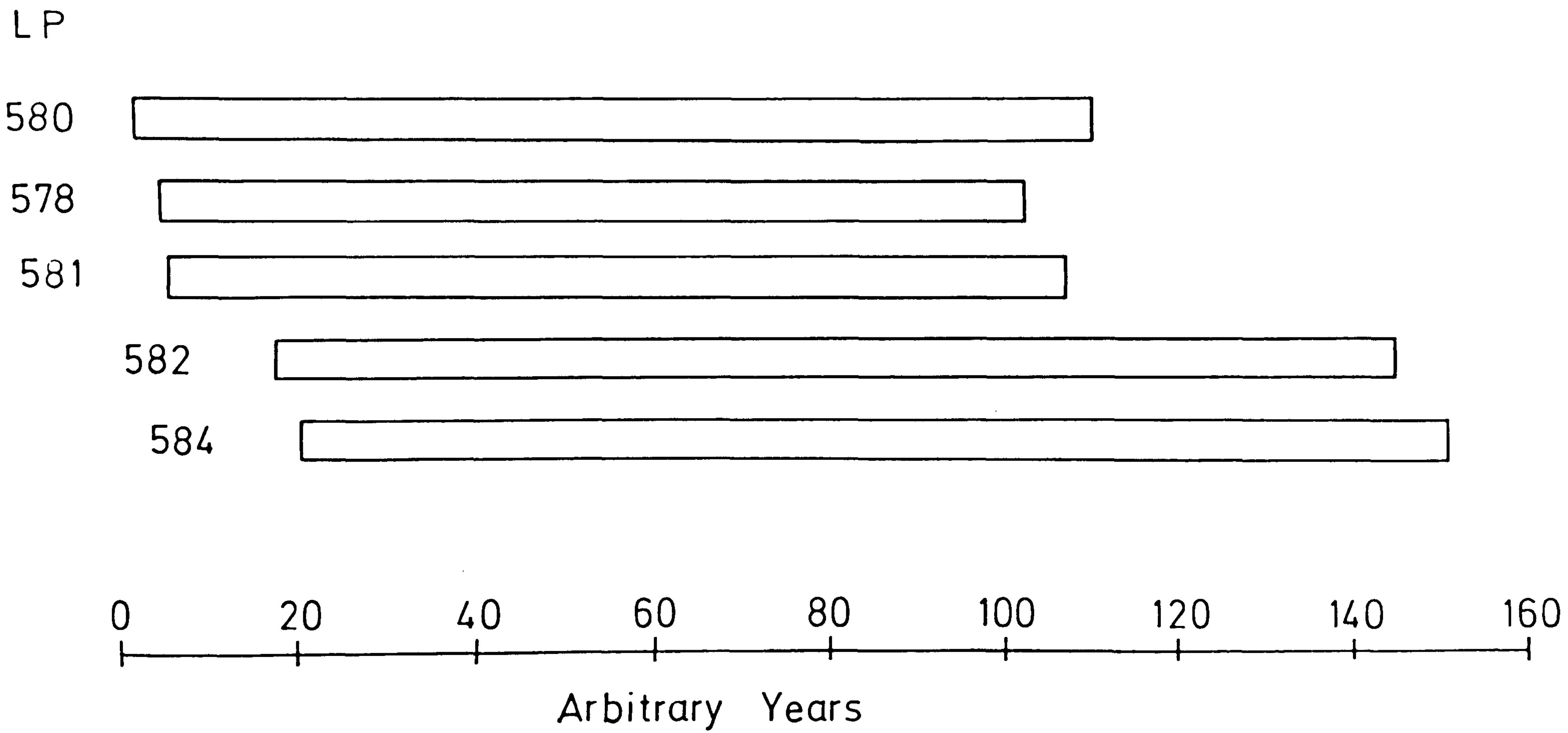
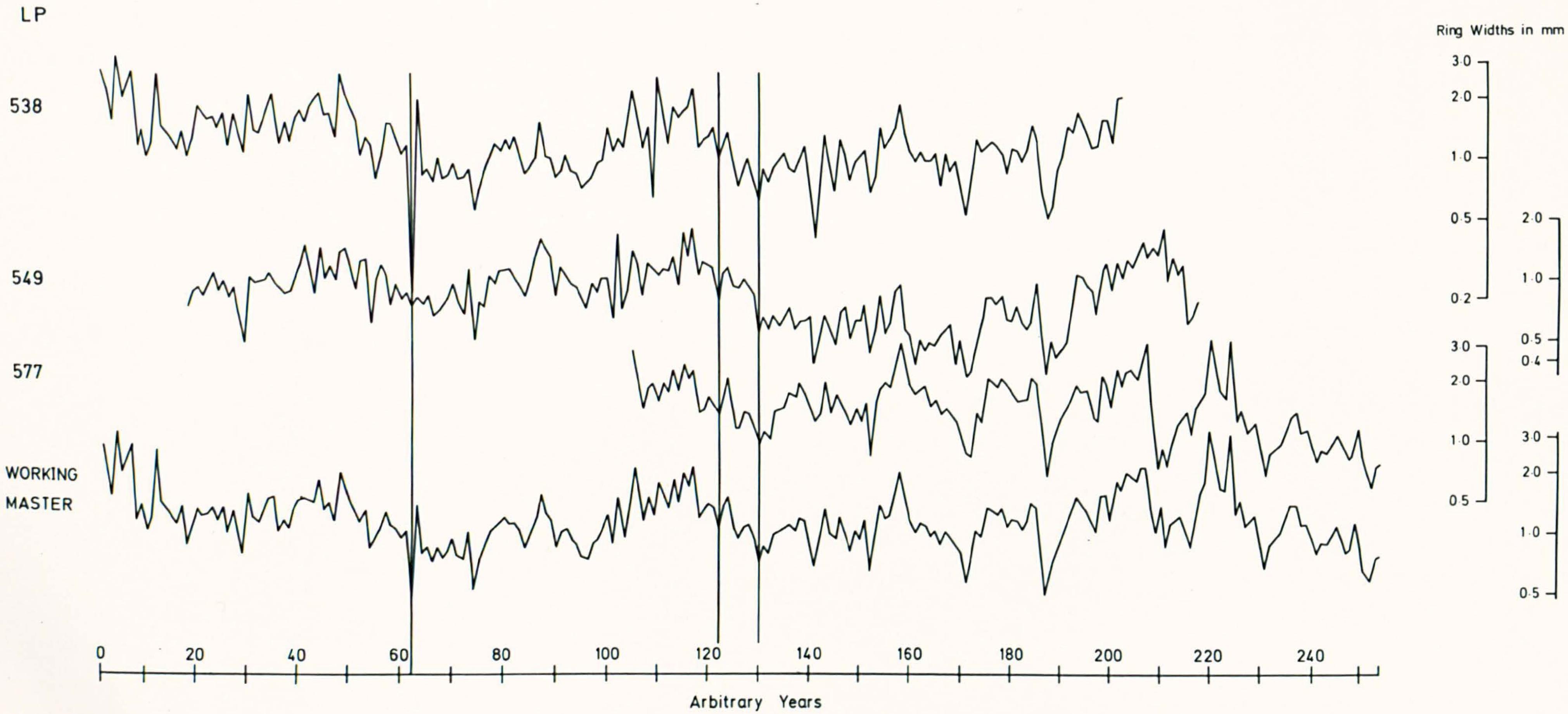


Figure 7.21 Baguley Hall II working master and its components. The curves are plotted on a semi-logarithmic scale. Characteristic years, namely arbitrary years 62, 109 and 130, are indicated by vertical lines.

BAGULEY HALL II: WORKING MASTER AND ITS COMPONENTS



3 timbers were combined to produce an index chronology of 254 years of growth and designated BAG II. The index values of the BAG II chronology are listed in Appendix XIII. Visual and statistical crossdating tests indicated that the chronologies, BAG I and BAG II did not crossdate with one another.

The absolute dating of the floating chronologies, BAG I and BAG II was attempted by comparing them with established dated chronologies which spanned the appropriate centuries. The estimated construction date of Baguley Hall was some time during the 14th century. These chronologies are listed in Table 7.17 with the output of programme CROS (Baillie and Pilcher,1973),showing 't' values of 3.50 or greater. The results show that the date of the most recently formed ring of the BAG I chronology given by the standard chronologies was not consistent. Visual checks of the matches suggested by significant 't' values indicated that the matches were not real. The BAG I chronology was also compared to reference chronologies of a later date, these being for Maentwrog, Peckforton and Rostrevor. No match was obtained with any of these chronologies.

Table 7.17 shows that significant 't' values were obtained for the matches between the BAG II chronology and various standard reference chronologies. With the most recently formed ring consistently dated to A.D. 1290, the BAG II chronology spans the period A.D. 1037 to A.D. 1290. These matches were also good visually. The chronologies for BAG II, Nantwich and REF 6 are shown at the matched position in Figure 7.22.

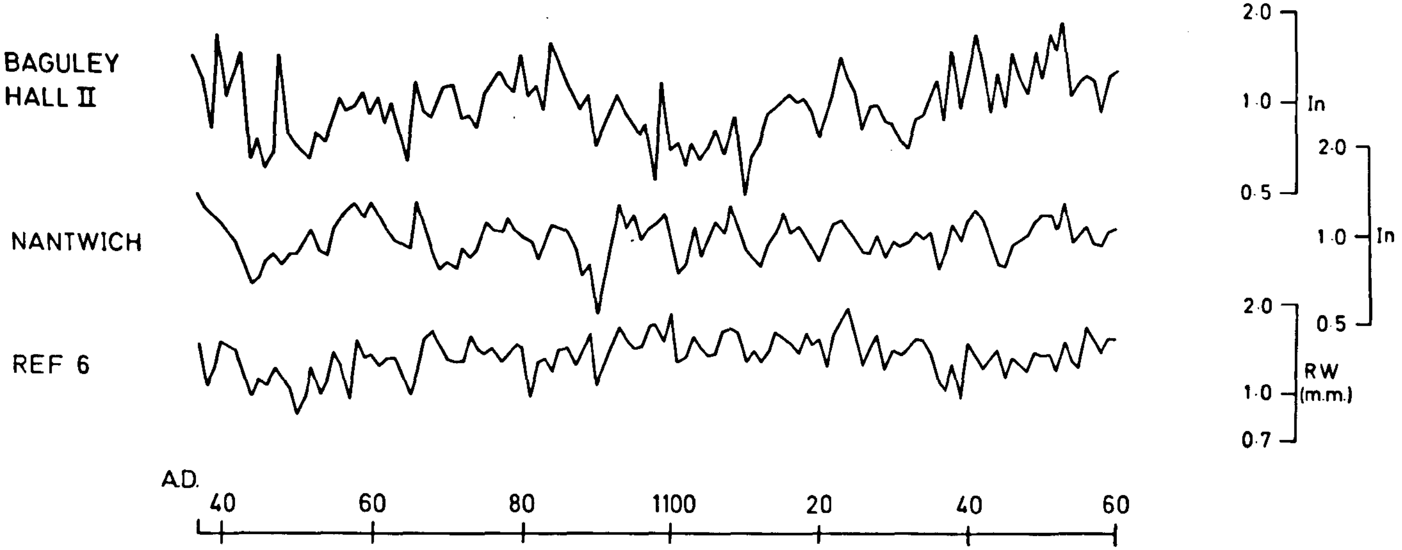
LP545, the timber thought to be a replacement of the 19th century was also compared to dated reference chronologies that spanned a variety of centuries. No consistent significant date was given by any of these chronologies.

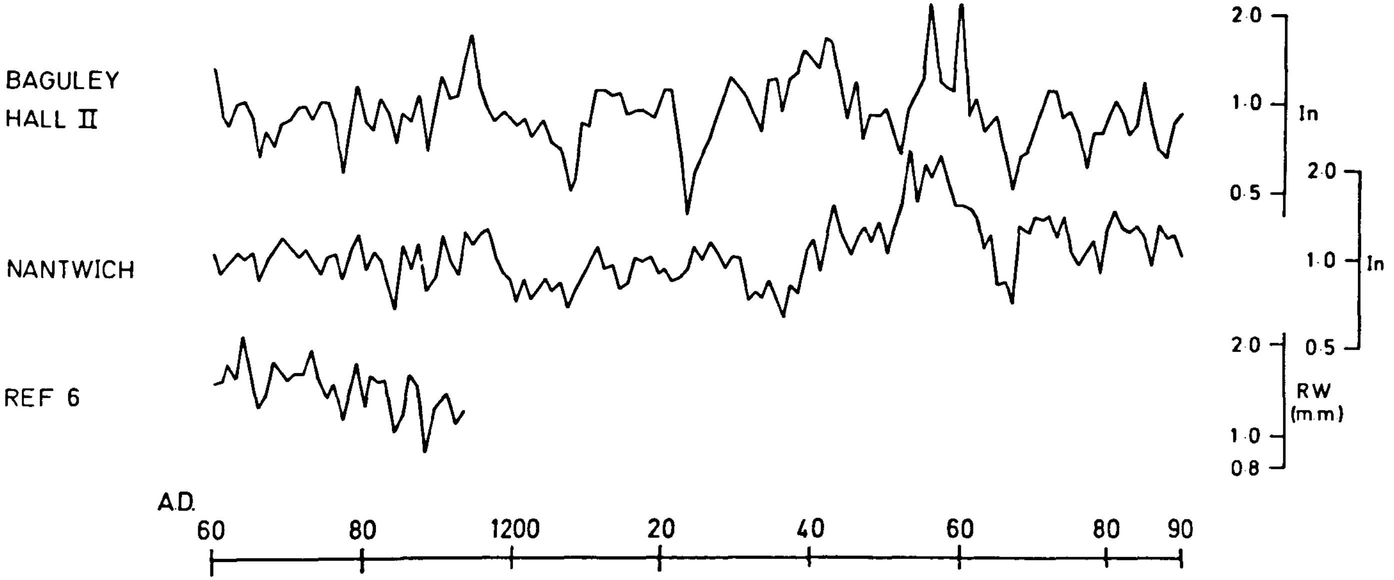
TABLE 7.17: Comparisons between the Baguley Hall chronologies and various oak chronologies; Students t-values and the probabilities of 'r' arising by chance.

	BAG I				BAG II			
Chronology	date of outer year	't'	no. years overlap	'r' (p≤)	date of outer year	't'	no. years overlap	'r' (p≤)
Belfast	-	-	-	-	1290	4.71	254	0.00003
South West Scotland	1141	4.66	151	0.00003	1133	3.55	188	0.00023
					1290	3.48	254	0.00034
					1934	5.22	254	0.00001
Dublin (1)	-	-	-	-	1204	3.94	254	0.00005
					1290	4.30	254	0.00003
Dublin (2)	1374	4.13	18	0.00042	-	-	-	-
	1398	4.10	42	0.00013	-	-	-	-
Bishop's House	1583	3.75	151	0.00011	-	-	-	-
REF. 1	1260	3.57	51	0.00058	-	-	-	-
REF. 2	1474	3.67	151	0.00016	-	-	-	-
REF. 3	1686	4.06	151	0.00003	-	-	-	-
REF. 4	1389	3.60	151	0.00016	-	-	-	-
REF. 6	0805	3.67	26	0.00072	1290	4.74	157	0.00003
	1142	3.80	151	0.00016				
Nantwich	-	-	-	-	980	3.58	51	0.00058
					1290	5.82	254	0.00001
					1308	3.90	254	0.00005
Wales/West Midlands	1411	3.96	71	0.00009	-	-	-	-
Seal House	-	-	-	-	1137	3.62	188	0.00016
Stayley Hall	-	-	-	-	-	-	-	-
Yorkshire building timbers	-	-	-	-	1827	3.88	50	0.00024
Coppergate	-	-	-	-	1220	3.64	164	0.00016
Hull	-	-	-	-	1290	3.70	165	0.00011
Glastonbury Barn	-	-	-	-	1290	4.32	188	0.00003
Exeter	0904	3.91	94	0.00012	1290	3.66	178	0.00016
					1380	3.93	90	0.00012

References for chronologies are given in Table 7.1

Figure 7.22 The chronologies for Baguley Hall II, Nantwich and REF 6 (Fletcher, 1977) shown at the position of match. The chronologies for Baguley Hall II and Nantwich are in index format and REF 6 in ring-width format.


BAGULEY HALL II
NANTWICH
REF 6
2.0
1.0
0.5
In
2.0
1.0
0.5
In
2.0
1.0
0.7
RW (m.m.)
A.D.
40
60
80
1100
20
40
60


BAGULEY HALL II
NANTWICH
REF 6
2.0
1.0
0.5
In
2.0
1.0
0.5
In
2.0
1.0
0.8
RW (m.m.)
A.D.
60
80
1200
20
40
60
80
90

Discussion

Tree-ring analysis of the timbers from Baguley Hall has allowed the construction of two oak chronologies of 151 and 254 years of growth. The chronologies do not crossdate with each other. The fact that there are two chronologies which are derived from timbers which appeared to be original and hence of a similar date was an unexpected result. One possible reason for this may lie in the nature of the growing site. Consideration of the types of timbers in Baguley Hall initially suggested that their sources would account for the existence of two chronologies; the rafters were taken from tall straight timbers whilst other large curved members were thought to have come from parkland (Startin, pers. comm.). However, this hypothesis is only partly correct since the nature of the growth rings of several sections of spere truss indicated that these timbers were taken from trees whose growth had been slow and sensitive. It is from a timber with this type of growth pattern that is included in the BAG II chronology and one which is not characteristic of parkland grown timber. All the tree-ring series included in the Baguley Hall chronologies are of the sensitive growth type. The fact that the timbers used in the formation of the two chronologies are major timbers and appear to be an integral part of the original construction makes the probability of utilising two sources unlikely. It is possible that local conditions within the woodland exploited were so greatly different as to lead to these differences in the patterns of tree growth. Nevertheless, the chronologies do not crossdate.

From the lack of consistent significant crossdating between BAG I and various standard reference chronologies (Table 7.17), it must be concluded that these trees had a different growth response from those of the reference chronologies. The dating of the BAG II chronology which includes the patterns from major structural timbers of the

Great Hall indicates that this section was built after A.D. 1300. The lack of sapwood on the component timbers has prevented a more precise estimation of their felling dates and a likely date of construction. Nevertheless, the terminus post given by the date of the BAG II chronology does correspond with the construction date given for the Great Hall by Smith and Stell (1960).

The contribution made by the BAG II chronology to the regional chronology is shown in Figure 7.24. Rather than extend the Nantwich chronology forward or back in time, the BAG II series spans the period already represented by that for Nantwich. This chronology for Baguley Hall, therefore, consolidates the Nantwich chronology and reinforces the validity of the regional chronology over the period A.D. 1037 to A.D. 1290.

7.9 Coniston Old Hall

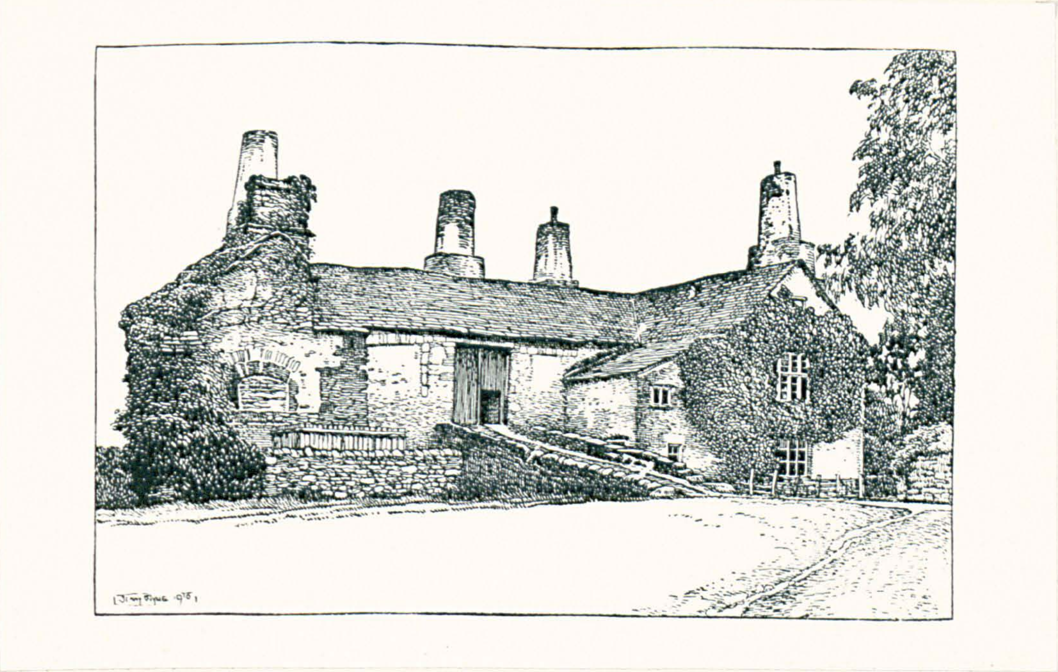
The site

Coniston Old Hall (SD 303 964) stands near the western edge of Coniston Water, about 1.2 kilometres south east of Coniston Village (Plate 7.15). It has been suggested that the house was built by William Fleming in the reign of Elizabeth and, therefore, of 16th century date (Farrer and Brownbill, 1908). The plan of the hall is an adaptation of the central halled house with east and west wings but the building was never H-shaped (Farrer and Brownbill, 1908). The east wing was very short and on the north side only attached to the main building at its north east corner. The hall, possibly due to the low and damp nature of the site, was on the first floor. The walls were constructed of the hard Silurian stone of the district with a thin covering of rough cast and the old windows were of oak. In A.D. 1720 it became derelict and remained unused until it was patched up in 1815 and used as a farmhouse. Only the north east wing was untouched and an inclined way was built up to the level of the hall floor which was turned into a barn.

The complete restoration of the building during 1976 led to the removal of a vast quantity of oak timber providing a wealth of material for tree-ring analysis (Plate 7.16). Since there seems to be no record of another phase of building activity since the patching up operation in 1815 it would seem that these timbers represent a building phase prior to this date, although Farrer and Brownbill (1908) record the removal of all the 'old' oak in the building. Thus the lack of documentation and the amount of timber removed in the 1976 restoration tends to indicate that they represent an earlier building phase and that not all the oak had been removed earlier. The absolute dating of the Coniston Hall timbers would, therefore, settle this question in addition to providing data for the north west of England regional chronology.

Plate 7.15 Coniston Old Hall, north elevation

Plate 7.16 Some of the oak timbers removed from Coniston Old Hall



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The timbers

The timbers removed from Coniston Old Hall fell into three categories; those that were hewn as quarters, those that were almost complete trunks with chamfered edges and those that were small and rectangular. These smaller timbers were rafters and mostly contained less than 100 growth rings. Those in the other two groups contained more growth rings although those with pith were from younger trees. A total of 21 timbers contained more than 100 growth rings and were considered suitable for tree-ring analysis.

Results

The Coniston Old Hall timbers contained tree-ring series with 100 to 251 years of growth. The series were sensitive containing bands of very narrow rings of only 0.2mm to 0.3mm width (Figure 7.23). The results of the comparisons of 21 tree-ring patterns showed that none of them crossdated with each other. The data were then passed through a high-pass digital filter to eliminate any long-term trends which may have been masking the year-to-year fluctuations. Visual and statistical comparisons were made between the high-pass filtered series but the results were negative.

A number of the longer unfiltered Coniston Old Hall series were compared with standard reference chronologies in an attempt to date some of them,as a starting point for further investigation. The standard chronologies used were Belfast (Baillie, 1977a), South West Scotland (Baillie, 1977c), Dublin (Baillie, 1977b), Bishop's House (Morgan, 1977b), Wales/West Midlands (Siebenlist-Kerner, 1978), Stayley Hall and Peel Hall (I and II). None of the single series significantly matched any of the standard chronologies. The ring-width values of the measured Coniston Old Hall samples are listed in Appendix XIV.

Sapwood was present on three samples with a range of 20 to 30 growth rings.

Figure 7.23 The ring-width series for a sample from Coniston Old Hall showing periods of growth release (trees in competition felled) and periods where there is an abrupt change from wide rings to extremely narrow rings (characteristic of trunks of pollarded trees).

TREE-RING PATTERN OF A TIMBER FROM CONISTON OLD HALL

Discussion

At first sight the Coniston Old Hall timbers appeared to have great potential for tree-ring analysis. Many timbers had in excess of 100 growth rings which were extremely sensitive. There were many periods of very slow growth which occurred between periods of faster growth, a pattern which appeared to be represented on many timbers. Only after further examination did it become apparent that these patterns of fast and slow growth were not at all synchronous.

One explanation for this may be that the Coniston Old Hall timbers were hewn from a woodland which was undergoing a continuous programme of thinning and felling. The width of a tree-ring may be seen to alter abruptly from year to year as a result of various management practices within the woodland. An abrupt change from narrow to wide rings is likely to be caused by the felling of standards (trees grown for timber) or coppice poles, close to and in competition with the tree in question. A change to extremely narrow rings followed by a series of increasingly wider rings is a pattern characteristic of the tree-ring series of the trunks of pollarded trees (Rackham, 1976). These trunks are permanent and are known as bollings. The sudden decrease in ring width occurs as a result of the removal of the timber poles which have grown from the cut bolling. Recovery from this harvesting is shown by the increasing ring widths of subsequent years. This pattern will be repeated as the tree is again pollarded. This cycle in ring-width variation may also be seen in coppice stools. The effects of these fellings will be superimposed on the effects of other factors extrinsic to the tree.

The two types of cycle described above are exhibited by the timbers from Coniston Old Hall and they can be seen in part of a polished section (Plate 7.17) and in the ring-width series of another sample (Figure 7.23) In the first type of pattern the growth release seen at the beginning of each period of fast growth occurs in different years in all the timbers.

Plate 7.17 A polished section of a timber from Coniston Old Hall showing periods of growth release and periods where there is an abrupt change from wide rings to extremely narrow rings.


12·7mm

This suggests that trees in competition with those used in the construction of Coniston Old Hall were felled or cut from different parts of the woodland during different years. Such a practice would provide a continuous supply of wood of different ages and is one which is characteristic of woodland management during the Middle Ages and several centuries after.

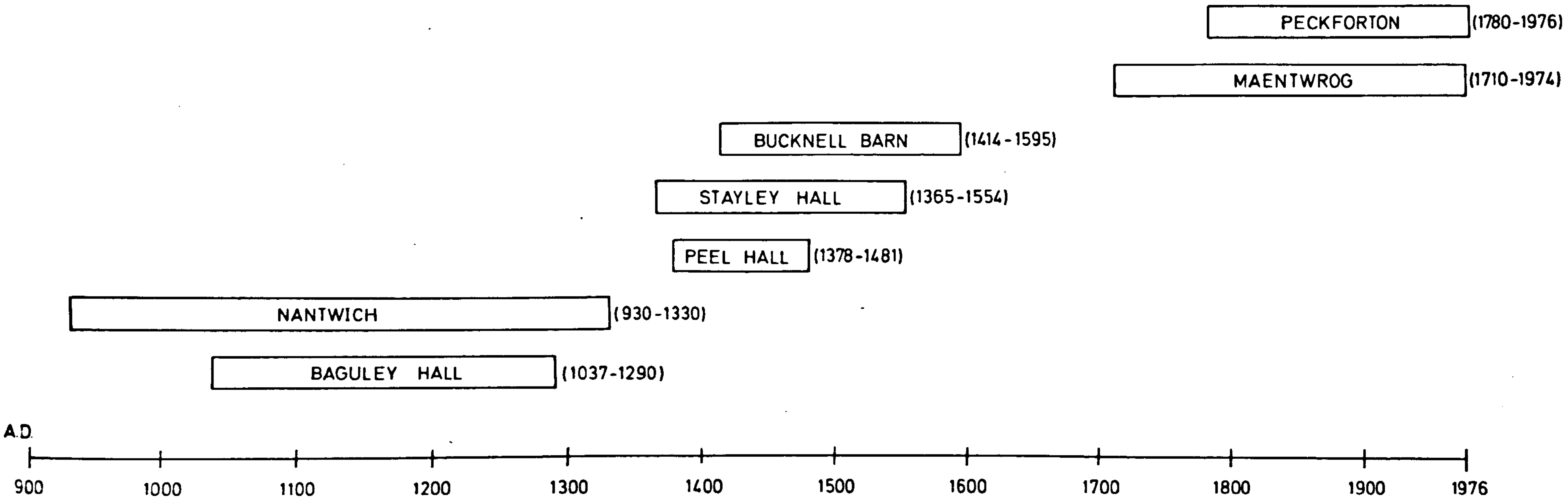
The abrupt change to narrow rings followed by a series of increasingly wider rings also occurs in different years in all the timbers. The period between each cycle varies between 12 and 30 years. If these tree-ring patterns represent those of pollarded trees then it would seem that pollarded trees were being used for the supply of timber! Timber for beams and planks was usually derived from trees grown specifically for this use and known as standards. Perhaps the circumstances were such that the carpenters who were employed to build the hall had no choice but to use the bollings of pollarded trees.

The height that pollarding takes place is usually between 1.8 and 4.5 metres above ground. If these trunks were used in Coniston Old Hall the timbers cut from them could be no longer than approximately 5 metres. An examination of the stockpile of timber outside the hall indicated that the timbers were not of this size. It was difficult to assess if any of these beams and posts represented broken sections of the same timber. In fact the upright posts within the central hall need not have been much longer than 3.66 metres since this was the height above ground of the wall plate. Therefore, in theory the bollings of pollarded trees could have been used in the construction of Coniston Old Hall but in an efficiently managed woodland this practice would have been unlikely.

Although the study of the Coniston Old Hall timbers has not contributed to the construction of the regional tree-ring chronology or to the dating of the hall itself,it is presented here as an example of the problems that can be encountered. One of the criteria used in selecting timbers for tree-ring analysis is the sensitivity of growth. In the Coniston Old Hall timbers there is great sensitivity and yet the growth pattern cannot be synchronised because the effects of climate are masked by changes in site conditions.

Figure 7.24 The site components of the north west of England regional tree-ring chronology.

COMPONENTS OF THE NORTH WEST OF ENGLAND REGIONAL CHRONOLOGY



7.10 Discussion

In studying the tree-ring patterns of historic timbers the primary objective was to construct a continuous absolutely dated tree-ring chronology for the north west of England. The site components of this chronology discussed in the previous sections are shown in Figure 7.24.

Clearly, the regional chronology has several gaps, the most frustrating of which is that of the 14th century. The abundance of timber in the Nantwich excavation (Section 7.7) provided the means for constructing a large section of the chronology and which terminated in A.D. 1330. The oldest ring of the subsequent section of the chronology was that of A.D. 1378 thereby effecting an unrepresented period of 48 years. In dendrochronological terms this gap is larger since an overlap of at least 100 years is required to facilitate a significant bridge. The termination of 15th, 16th and 17th timbers during the late 14th century is a feature first noted by Baillie (1977a; 1977b) for timbers in the north of Ireland and in Dublin. Two other English chronologies terminate in the 14th century; the Wales/West Midlands chronology (Siebenlist-Kerner, 1978) and Bishop's House (Morgan, 1977b).

The hypothesis presented by Baillie (1977a) to explain the preponderance of trees beginning life in the late 14th century and not before, concerns Norman expansion in the north of Ireland. The greatest expansion took place in the 12th and 13th centuries and was a process which required the exploitation of natural resources. Oak was one of them. It is suggested, therefore, that this large scale use of timber and an increased population which would have put heavy pressure on marginal land, could have contributed to the forest decline. If this "development" applies to the north west of England it is more likely to do so in Cheshire than in Lancashire. Cheshire was part of the Norman realm and its most north-westerly county (Sylvester and

Nulty,1958). Although Chester was one of the last important English towns to hold out against the Norman rulers, the county was comparatively remote with extensively forested countryside. On the establishment of Norman rule many woods and wastelands were brought by the Norman earls under forest law to provide royal grounds primarily for hunting. The forests of Mara and Mondrem which came to be known as Delamere came under this law. This practice "saved" the timber in these areas since, whilst the local inhabitants were allowed pannage and to take firewood, they were not allowed to fell any trees without permission. It, therefore, seems unlikely that these rulers cleared such an extent of forest as to produce total obliteration throughout the region although on a local scale the effects could have been substantial. In Lancashire half the county between the River Mersey and Lonsdale was taken as Royal Forest. Unlike the situation in Northern Ireland (Baillie, 1977a) locating buildings which predated A.D. 1600 was not a problem as the previous sections show. Nevertheless, the gap in the 14th century still remains.

The second gap in the regional chronology is larger, extending from A.D. 1595 to A.D. 1710. This gap is one which separates the modern chronologies from those constructed for historic timbers. Bridging this gap has been equally problematic. The termination of the modern chronologies during the 18th century demands the search for structures dating from the 18th century to extend the chronology to at least the middle of the 16th century. From the middle of the 16th century, dated tree-ring series have already been established. The lack of 18th century buildings built from oak probably results from the combination of several factors. There was a great expansion of the Navy in the 18th century through an increase in power and the development of greater accuracy in ships' instruments. This expansion required an increase in the number of ships and led to a depletion in oak timber. At the same time, the importation of 'softwood' timber aided by the opening up of the Russian markets increased in importance. This timber could be widely distributed cheaply by the expanding canal system. The scarcity and resulting costliness of oak timber drastically reduced its role as structural timber so that its use became restricted to the making of fine furniture and panelling.

As the search for 18th century structures lacked success,the answer was to find living or felled trees in the region of 400 years old. Although trees of this age have been found in Scotland (Baillie, 1977c) such specimens were not to be found in the north west of England. The most likely site was Maentwrog in North Wales but extensive sampling in the woodland revealed that none of the trees or stumps exceeded 241 years of growth. This 17th century gap, therefore, still remains with its elimination being unlikely until structures with 18th century timbers become available. These results compare with the problems encountered by Baillie (1977b) in constructing a continuous chronology for Dublin.

The lack of available timber has also prevented the extension of the regional chronology back in time from A.D. 930. The north west of England and Cheshire, in particular has a long history of occupation dating from before Roman settlement. In Cheshire the construction and locations of various towns and fortresses in the 9th century is documented (White and Co., 1860) but such buildings or their remains are no longer in evidence. It seems unlikely at the present time that timbers predating the 11th century will become available.

Many of the structures examined in this regional study have contained timbers with the characteristics required for successful tree-ring analysis. Most of the material has been obtained from timber-framed halls and has mostly been slow-grown timber with a sensitive growth pattern. Where exceptions occur it has largely been in Cheshire. A number of potentially useful sources such as the 15th century Tatton

Old Hall and the 13th century Vale Royal Abbey have contained timbers with wide rings with a complacent growth pattern. These features are characteristic of trees grown under conditions without stress such as in parklands and in valley sites.

It has been suggested by Mr. B. Startin (pers. comm.) that wide-ringed timber was selected when its role in a building required it to have strength. The reasoning for this is the summer or latewood of the annual rings consists largely of fibres, the smaller vessels occupying a smaller proportion of the total volume than in the earlywood.

The spring or earlywood is made up of large thin-walled vessels. The latewood is, therefore, more dense than the earlywood. As the amount of earlywood is fairly constant in each growth ring, a wide ring contains a greater proportion of latewood and is, therefore, more dense and has greater strength. Baguley Hall in Cheshire (Section 7.8) whilst containing timbers with very narrow rings also had timbers with very wide rings. It might be expected from the foregoing argument that such timbers would have different roles within the building but this was not the case. The spere-trusses were constructed from timbers with both types of growth as were the upright posts which supported the wall plates of the east and west walls. The use of the two types of timber was also found in one hall in Lancashire, at Speke Hall. So little timber suitable for tree-ring analysis has so far been available from Speke Hall that no systematic study has been carried out. Since this building has a long history of alterations and additions of many periods which have not yet been identified the two growth types cannot be considered to be contemporary.

On reflection, it is hardly surprising that timber with wide rings with little variation is common in Cheshire buildings as a great proportion of the county is contained in the Cheshire Plain. This area is in the nature of a shallow trough with the first foothills of the Pennines on the east and a low ridge from Bickerton to Helsby on the west. The plain is a large bed of Keuper Marl overlaid by a thick layer of glacial clay, sand and gravel and its rich soil is well watered by the rains of North West England. Where a clay soil predominates on the plain, the existence of trees with a steady, uniform rate of growth seems likely.

It is interesting that the site that has contributed mostly to the regional chronology, having the longest sequences of rings and rings that were very narrow was also in Cheshire at Nantwich. This site is also on the Cheshire Plain but it is clear that this timber had a different source from that in the halls mentioned above. The Nantwich timbers were hewn from trees that had been growing under highly stressful conditions. Areas providing such conditions do exist in the county alongside those fertile complacent sites, for example, on the sandy upland soils of Delamere Forest.

The occurrence of wide growth rings leads to the consideration of the number of rings in a sample. For any size of timber, the smaller the growth rings the greater will be the number of rings present. Many of the timbers examined were found to contain less than 50 growth rings and were, therefore, not suitable for further analysis. On the other hand, many were found to have more than 100 growth rings and some between 200 and 300. Such findings contradict the statement made by Jones (1960) that "...... most trees (for buildings) were felled at - by modern standards - the very early age of 70-100 years." In fact, much older trees were felled for building timber in Lancashire and in Cheshire.

In addition to the problem of complacency in tree growth, problems also arise in material with sensitive growth patterns. The timbers of Coniston Old Hall are a prime example of this. Initially, the extreme sensitivity of all these timbers appeared to give them great potential for tree-ring analysis. Only after comparing all the growth patterns did it become apparent that none of them were synchronous. Without relative dating between the timbers or precise documentary evidence,it is not possible to determine if the timbers used in its construction are contemporary. Although documentary sources indicate one or two phases of alteration, from the vast quantity of timber taken from the hall it seems likely that some must be contemporary. Even under extremely stressful conditions it is unlikely that the tree-ring patterns from so many timbers would not be synchronous. The lack of crossdating is most likely the result of differential thinning and felling within the woodland during the years prior to the construction of the hall. The use of the bollings of pollarded trees in which the tree-ring patterns reflect the effects of pollarding is also a possibility. These studies have shown that even when timbers contain long sensitive patterns of growth, crossdating between them is not ensured even if they are contemporary.

The fact that strong internal dating exists does not ensure that the mean chronology will be dated. Such a situation arises for timbers from Clayton Hall (Section 7.3), Peel Hall (II) (Section 7.5) and Baguley Hall (BAG I) (Section 7.8). Whilst the internal dating is good for each chronology,absolute dating by comparisons with reference chronologies was not accomplished. Had the internal dating not been so good, errors would have been suspected in the initial measurements. In these cases this seems highly unlikely. The positive dating between the floating chronologies for Peel Hall (II) and Clayton Hall indicates that similar variations in growth conditions prevailed at their timber sources. There is no documentary evidence to suggest that the source of timber for each building was a common one. Thus, it appears that during the period spanned by these chronologies there was a growth response, possibly in different parts of the region,that is not represented in any of the tree-ring chronologies so far published.

The secondary objective in this historic timbers study was to identify and date phases of construction of the buildings examined. The determination of the precise date of felling of the tree from which a timber is cut requires the presence of bark on the wood. The presence of bark almost certainly ensures the presence of the growth ring formed in the year the tree was felled. Throughout the study none of the timbers examined was found to have retained any bark. This was not entirely unexpected as the bark was usually removed during shaping processes. It has occasionally been found intact, for example, on a roof beam in a 17th century cottage in Formby, Lancashire. Several remnants of oak timbers, mainly planks from the excavated site at Haithabu, contained well preserved sapwood and bark (Eckstein, 1978).

Sapwood without bark was found on timbers from several of the structures examined in the present study. Although a precise felling date cannot be determined in this case, it does allow an estimate of it to be made. This can often lead to the identification of different phases of building activity or timber replacement, where the estimated dates occur in groups along the span of years represented by the structure's timbers. This was the case for the excavated site at Nantwich (Section 7.7) where three phases of building activity could be recognised, separated by approximately 100 year periods. It was hoped that this approach could be used to determine periods of construction at Stayley Hall where certain sections were thought to derive from post A.D. 1580. It was also hoped to ascertain how much, if any, of the original timbers dating from circa A.D. 1340 still survived. The lack of sapwood on the majority of the timbers examined prevented this comparative study. Those timbers which did contain sapwood have prompted new questions regarding the chronological relationships between certain sections of the hall. In other buildings examined, for example, at Peel Hall (Section 7.5) the spread of the entire complement of estimated felling dates cluster within a period of twenty years. On the basis of those timbers sampled it would appear that the construction of Peel Hall was of one phase. For German trees, Hollstein (1965) describes a number of conditions which, if fulfilled,indicate a uniform felling year for the timbers under investigation. A range of probabilities is also shown for the number of sapwood years, given different quantities of samples from the same object. The boundaries of the period in which the estimated felling year lies are, therefore, determined by the frequency distribution of the sapwood years and by the quantity of dated samples.

When no sapwood is present at all, comments on the date of construction may still be made since the absolute dating of the site chronology gives a terminus post for each timber and hence for the building. Baillie (1973a) has described a method for estimating the felling date of a group of timbers from one building which have no sapwood or trace of the heartwood/sapwood boundary. The estimation requires that the distribution of the outer rings of the existing samples be linear.

The fact that a number of chronologies of the regional chronology crossdate with several reference curves,reinforces the thesis of Baillie (1978) that the Irish Sea Basin represents a single but not exclusive tree-ring area. It is not exclusive since chronologies from the south of England are very similar to those surrounding the Irish Sea. Nevertheless, the fact that there are chronologies with strong internal crossdating which cannot be dated points to the consideration that its application is not total. These anomalies which may be more common than the present study suggests, must surely indicate the necessity of having chronologies which reflect the local variations in growth. Modern studies have shown similar results (Section 3.3.2); there was only a low correlation between the

Maentwrog and Yorkshire (Morgan, unpublished data) chronologies and between the chronologies for Peckforton and Rostrevor (Pilcher, 1976). There are areas, therefore, for which there is no correspondence between tree-ring series.

The eventual dating of the floating historical chronologies will represent patterns of tree growth hitherto unidentified for the north west of England or elsewhere, at the present time. It is hoped that these uncommon local series will subsequently date others that are likely to arise. Hillam (pers. comm.) has recognised this problem for Yorkshire timbers which either prove difficult to date or match various reference curves. Her comment "much more needs to be learnt about regional chronologies before any sweeping statements on their application can be made" (Hillam pers. comm.) has particular relevance in the north west of England.

PART III - GENERAL DISCUSSION

CHAPTER 8 - GENERAL DISCUSSION

GENERAL DISCUSSION

The construction of oak tree-ring chronologies from a maritime and rainshadow area has facilitated a comparative study of tree growth and the response to selected variables of climate. Whilst the general form and properties of the chronologies are similar, the response to these climatic variables is very different. The period of calibration for the climatic study is identical at each site (1921 to 1966) so that the results obtained can be directly comparable. Using the response function approach it can be shown that at the rainshadow site, low precipitation is limiting to tree growth during many months of the year. In addition, an increase in precipitation at the end of the growing season favours prior growth conditions. At the maritime site an increase in precipitation does not relate to an increase in radial growth at any time of the year. These results indicate and describe how the climatic status of a woodland influences the growth response to changing levels of climatic variables. This investigation has, therefore, shown that at climatically different sites, there are significant differences in the way tree growth responds to the same variables of climate. Gray (unpublished data) has indicated the problems in using single-site chronologies in reconstructing past climates. The differences in the response to climate at two sites will, therefore, make an important contribution to the determination of climatic anomalies in the British Isles as a whole and will be used in a future multisite climatic analysis for the British Isles.

Response functions have been prepared for several sites in Europe (Hughes *et al.*, 1978a) and the present study has provided an increase in the understanding of the extent of the growth responses which are common to many sites. For instance, higher than average temperatures in the October prior to growth have been found to be beneficial to radial growth in the following year, at Rostrevor in Northern Ireland (Hughes et al., 1978a), at Raehills in Scotland (Hughes et al., 1978a), in Schleswig-Hollstein (Eckstein and Schmidt, 1974) and at Maentwrog and Peckforton. Similarly, there is a positive growth response to lower than average December temperature in the year prior to growth at Rostrevor, Schleswig-Hollstein, Maentwrog and Peckforton. These conditions of October and December temperature are highly significant to the radial growth of oak growing in the temperature conditions of Europe, whatever the climatic status of the site.

The use of a reciprocal pair of digital filters has facilitated the partitioning of the original time series or chronologies into new sets of series. The filters are used to emphasise certain variations in a series that lie in the frequency range of interest (Mitchell et al., 1966). The application of a high-pass filter which blocks most of the wavelengths greater than eight years, to the index chronology effects the additional standardisation of an already standardised series. The effect of factors which have a gradual and long term influence on growth, such as an expanding canopy, are removed so that the variations in the resultant series are essentially related only to climate. By applying the response function technique (Fritts et al., 1971) to the filtered series, the climatic response of the short-term and long-term components of the original series can be examined. At Maentwrog and Peckforton there are significant differences in the response functions of the unfiltered and high-pass filtered data (Tables 6.1 and 6.2). In the low-pass filtered series in which only slowly changing growth variations remain, almost all the variance accounted for by the response function is related to prior growth. Only a small proportion of the chronology variance is related to climate.

The response function approach also highlights the dangers of using short calibration periods and the importance of using the longest calibration period available. The availability of long records for temperature and precipitation relevant to the woodland at Peckforton, allows a comparative study of short and long calibration periods to be made. The shorter period was also used in a comparative study with Maentwrog for the same period. In the short/long calibration period study the importance of increased precipitation was maintained but the months in which it appeared were different. The status of the prior growth variable became completely altered from being significant at lags of 1 and 2 years to being insignificant at all lags. Thus, it has been shown that response functions produced from short calibration periods may not be representative of the true response. Nevertheless, when the climatic records are short, undoubtedly, a short period is better than none at all.

Regional chronologies have now been established for Northern Ireland (Baillie, 1977a) and South West Scotland (Baillie, 1977c). The applicability of such chronologies to other areas has often been considered (Baillie, 1978; Hillam, unpublished data) and assumed that the establishment of such chronologies for England would not be feasible (Fletcher, 1974a). No continuous regional oak tree-ring chronology had been attempted for any part of England until the present investigation was undertaken. The construction of the oak chronologies for Maentwog and Peckforton has fulfilled two other functions; that of providing the facility for assessing the exclusiveness of a suggested Irish Sea Basin tree-ring area (Baillie, 1978) and providing a modern anchor for a regional tree-ring chronology for the north west of England. The comparisons between the Maentwog and Peckforton chronologies and those for Belfast, South West Scotland, Rostrevor, Yorkshire and Cumberland/Herefordshire have shown the area over which crossdating exists. In general, there is good crossdating with most of the standard chronologies but there are exceptions; Maentwog with Yorkshire and Peckforton with Rostrevor, the former being exceptionally poor (t = 1.18). These exceptions suggest that the Irish Sea Basin cannot be considered to be an exclusive single tree-ring area. This conclusion is reinforced by the comparisons made in the historic timber study (Part II). Here,chronologies were constructed whose components crossdated well but which could not be dated by any of the available standard chronologies. The chronologies used covered periods that were inside and outside those suggested for the construction dates of the buildings concerned. Whilst these timbers could have been brought into Lancashire,it is most likely that the source was a local one.

Where chronologies could be dated, crossdating did not exist with all the standard chronologies within the Irish Sea Basin area. For example, the chronology for Bucknell Barn showed no match with the chronologies for Belfast (Baillie, 1977a), South West Scotland (Baillie, 1977c) or Dublin (Baillie, 1977b) but showed excellent crossdating with the chronologies for Bishop's House (Morgan, 1977b) Wales/West Midlands (Siebenlist-Kerner, 1978) ,Yorkshire building timber (Hillam, unpub. data) and Stayley Hall. The 't' values for these matches were 5.38, 3.86, 4.40 and 5.23 respectively. Although Morgan (1977b) has found that the chronologies for Bishop's House and Belfast are well matched, it is clear that within the designated area distinct local variations do exist. The conclusion is that for modern and historic timbers, crossdating in the Irish Sea Basin area is not total and that regional chronologies, therefore, do have a role to play. The eventual dating of the floating historic chronologies will, therefore, identify patterns of tree growth as yet unidentified in the north west region.

Those historic chronologies which could be dated have provided the data for the extension, although not continuous, of the modern chronologies. Since the historic chronologies have been dated by standard chronologies from other areas, the patterns of tree growth cannot be exclusive to the north west region but they are representative during these periods. If the undated chronologies reflect growth responses exclusive to the north west region,then the only way in which they can be dated is by the overlapping and extension of the modern chronologies back in time until sections of the patterns can be recognised. To do this requires the bridging of the A.D.1595 - 1710 gap which is not possible at present since material with tree-ring patterns of these periods has not yet been identified. The remaining break in the regional chronology occurs between A.D. 1330 and A.D. 1378. Thus, the regional chronology spans the period A.D. 930 to A.D. 1976 with the gaps outlined above. The regional chronology presented, therefore, cannot be considered totally regional and independent until the modern chronologies are extended with local material. It is important that the chronologies so far established be retained as distinct units so that the calendrical dates of each can be verified when the modern chronologies are extended. The data have been treated in this way in the present investigation.

The number of tree-ring chronologies required to adequately grid the British Isles has been examined by Baillie (1978). Although the results were different for certain periods, from the limited data available, four or less basic tree-ring regions were postulated. A long localised tree-ring chronology for the north west of England will provide additional information for testing this hypothesis.

Future Research

The feasibility of using oak tree-ring chronologies as proxy records of temporal and spatial climatic change in the north west of England and North Wales (Chapter 6) and in other parts of the British Isles (Hughes *et al*., 1978a) has been demonstrated. A greater range of climatic variables is reconstructable when chronologies are used which record different elements of climate. Whilst climatic studies have been started, a comprehensive reconstruction of variations in past climate in the British Isles requires the utilisation of many more chronologies which show such differences. Such research is currently underway.

Future work must also include an active search for more historical sites to provide data for the absolute dating of the floating chronologies established in the north west region. Additional material from this region is also required to facilitate the bridging of the gaps in the regional chronology, in particular that of the 18th century. The dates given by reference chronologies to those for the individual sites can then be verified. The establishment of continuity throughout the total period spanned by the site chronologies will ensure a totally independent regional chronology for the north west of England.

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APPENDICES

Appendix 1

List of plant species at Coedydd Maentwrog

	Site I		Site II
	1	2	
Tree layer			
Quercus petraea (Mattuschka) Liebl.	+	+	+
Acer pseudoplatanus L.	+		+
Betula pubescens E.	+		+
Corylus avellana L.	+	+	
Fagus sylvatica L.			+
Fraxinus excelsior L.	+		
Larix europeaus D.C.		+	
Shrub layer			
Crataegus monogyna Jacq.		+	
Rhododendron sp. L.	+		+
Salix caprea			+
Field layer			
Agrostis tenuis Sibth.	+		
Anthoxanthum odoratum L.	+	+	+
Deschampsia flexuosa (L.) Trin	+	+	
Nardus stricta L.	+		
Poa sp. L.		+	
Calluna vulgaris (L.) Hull		+	+
Carex binervis Sm.		+	
Carex flacca Schreb.	+		+
Carex pilulifera L.		+	
Carex ovalis Schreb.			+
Cardimine pratensis L.	+		

	Site 1		Site II
	1	2	
Digitalis purpurea L.	+	+	+
Chamaenerion angustifolium (L.) Scop.			+
Epilobium montanum L.			+
Endymion non-scriptus (L.) Garcke	+	+	+
Frageria vesca L.			+
Galium mollugo L.	+	+	+
Glechoma hederacea L.			+
Geranium robertianum L.			+
Hedera helix L.			+
Juncus effusus L.	+	+	+
Luzula pilosa (L.) Willd	+	+	
Lysimachia nemorum L.		+	+
Oxalis acetosella L.	+		+
Polygala vulgaris L.	+		
Potentilla erecta (L.) Räusch	+	+	
Primula vulgaris Huds			+
Ranunculus repens L.			+
Rubus sp. L.			+
Rumex acetosella L.	+		+
Sedum anglicum Huds	+	+	
Stellaria alsine Grimm.			+
Taraxacum officinale Weber			+
Teucrium scorodonia	+		+
Trifolium repens L.			+
Umbilicus rupestris (Salisb.) Dandy	+		
Urtica dioica L.			+
Vaccinium myrtilus L.	+	+	

	Site I		Site II
	1	2	
Veronica chamaedrys L.		+	
Veronica officinalis L.	+	+	
Vicia sativa L.			+
Viola sp. L.			+
Asplenium sp. L.			+
Blechnum spicant (L.) Roth	+		
Dryopteris dilatata (Hoffm.) A. Gray	+		+
Dryopteris filix-mas (L.) Schott		+	+
Polypodium vulgare L.			+
Pteridium aquilinium (L.) Kuhn	+	+	+
Bryum capillare Hedw.	+	+	+
Dicranum scoparium Hedw.	+	+	+
Hylocomium splendens (Hedw.) B., S. and G.	+		
Hypnum cupressiforme Hedw.	+		+
Leucobryum glaucum (Hedw.) Schp.	+	+	+
Plagiothecium undulatum (Hedw.) B, S. and G	+	+	
Pleurozium schreberi (Brid) mitt (*Hypnum schreberi* Brid.)	+	+	+
Polytrichum formosum Hedw.	+	+	+
Rhacomitrium kanufinosum Hedw. Brid.			+
Rhyridiadelphus loreus (Hedw.) Warnst (*Hylocomium loreum* (Hedw.) B. and S.)		+	
Rhytidiadelphus squarrosus (Hedw.) Warnst (*Hylocomium squarrosum* (Hedw.) B. and S	+		+
Sphagnum rubellum Wils. (*Sphagnum acutifolium* Ehrh. var. rubellum (Wils.) Russ.			+

	Site I		Site II
	1	2	
Thuidium tamariscinum (Hedw.) B., S. and G.	+	+	
Bazzania trilobata (L.) Gray	+		
Conocephalum conicum (L.) Underw.			+
Plagiochila asplenoides (L.) Dum	+		
Cladonia pyxidata (L.) Hoffm.			+
Parmelia trichotera Hue	+	+	+
Exidia glandulosa			+

Appendix II

List of plant species at Peckforton Hills

Tree layer

Acer pseudoplatanus L.

Betula pubescens Ehrhart

Castanea sativa Mill.

Ilex aquifolium L.

Quercus petraea (Mattuschka) Liebl.

Quercus robur L.

Shrub layer

Rhododendron sp. L.

Field layer

Agrostis tenuis Sibth.

Holcus mollis L.

Phleum pratense L.

Chamaenerion angustifolium (L.) Scop.

Digitalis purpurea L.

Endymion non-scriptus (L.) Garcke

Juncus effusus L.

Lonicera periclymenum L.

Rubus Sp. L.

Rumex acetosella L.

Vaccinium myrtillus L.

Dryopteris dilatata (Hoffm.) A. Gray

Pteridium aquilinum (L.) Kuhn

Dicranella heteromalla (Hedw.) Schp.

Polytrichum formosum Hedw.

Appendix III

Raw ring widths in 10 replicate measurements (mm x 100) and associated statistics

Ring no.	Replicates									
	1	2	3	4	5	6	7	8	9	10
1	321	318	323	319	318	318	319	320	319	320
2	331	337	327	335	335	334	332	334	334	333
3	346	348	351	347	343	343	346	345	343	342
4	333	333	330	330	333	340	338	340	343	342
5	208	205	205	204	208	203	203	203	203	200
6	177	181	179	183	185	183	184	180	181	183
7	222	219	223	218	218	215	215	216	215	214
8	255	258	257	256	255	254	255	255	256	254
9	97	102	99	100	96	96	97	97	95	98
10	154	150	153	152	159	150	155	149	155	151
11	130	132	132	133	129	130	122	133	129	131
12	47	50	49	49	43	51	47	46	50	48
13	55	53	53	55	52	52	56	55	54	54
14	51	51	52	54	59	52	52	55	53	54
15	51	53	51	46	50	51	50	47	51	48
16	86	82	83	87	86	81	85	84	81	85
17	147	150	145	148	148	151	155	150	153	150
18	118	118	119	114	120	117	115	115	114	116
19	128	129	130	131	130	125	127	127	130	129
20	154	154	157	157	150	161	156	157	153	159
21	118	115	111	114	115	110	113	116	112	110

Appendix III (continued)

Ring no.	Replicates									
	1	2	3	4	5	6	7	8	9	10
22	131	133	135	137	132	135	135	132	134	133
23	103	100	102	101	104	99	100	103	101	102
24	115	118	115	112	111	114	116	112	116	115
25	182	179	181	180	181	181	180	183	179	177
26	186	189	185	189	191	188	189	187	188	191
27	176	180	182	180	177	178	179	179	178	175
28	111	107	106	102	104	104	105	107	108	106
29	102	101	103	104	107	101	103	107	103	105
30	103	95	106	105	99	105	105	103	107	105
31	81	77	75	78	83	79	78	80	77	81
32	155	162	158	155	153	155	152	154	156	153
33	138	137	139	138	138	140	139	137	137	136
34	149	152	150	149	148	146	148	150	148	147
35	204	205	203	203	203	202	204	205	201	203
36	205	203	204	204	202	202	201	199	205	202
37	84	84	82	81	86	87	94	87	88	90
38	89	92	88	90	93	92	83	96	92	91
39	205	200	205	202	197	197	198	197	196	196
40	188	190	190	190	189	188	187	186	188	187
41	182	178	181	178	173	179	183	182	181	180
42	156	156	151	158	152	152	152	155	155	155
43	108	110	117	107	118	117	117	118	115	113
44	226	224	218	220	214	215	213	220	213	216
45	177	180	180	183	182	178	181	180	181	180

Appendix III (continued)

Ring no.	Replicates									
	1	2	3	4	5	6	7	8	9	10
46	172	169	174	172	172	174	177	170	174	175
47	115	128	128	130	128	128	126	131	128	124
48	241	229	232	230	230	227	230	228	230	230
49	317	329	322	321	328	330	328	328	329	329
50	168	159	161	168	160	160	159	160	162	158

Appendix III (continued)

Ring no.	mean ring width (x100)	standard deviation (x100)	standard error (x100)	coefficient of variation
1	319.5	1.58	0.49	0.5
2	333.2	2.74	0.86	0.8
3	345.4	2.79	0.88	0.8
4	336.2	4.93	1.56	1.5
5	204.2	2.44	0.77	1.2
6	181.6	2.45	0.77	1.3
7	217.5	3.10	0.98	1.4
8	255.5	1.26	0.40	0.5
9	97.7	2.11	0.60	2.2
10	152.8	3.04	0.96	1.9
11	130.0	3.19	1.01	2.5
12	48.0	2.35	0.74	4.9
13	53.9	1.37	0.43	2.5
14	53.3	2.40	0.76	4.5
15	49.8	2.14	0.67	4.3
16	84.0	2.16	0.68	2.6
17	149.7	2.90	0.91	1.9
18	116.6	2.11	0.66	1.8
19	128.6	1.83	0.58	1.4
20	155.8	3.15	0.99	2.0
21	113.4	2.67	0.84	2.4
22	133.7	1.82	0.57	1.4
23	101.5	1.58	0.49	1.6
24	114.4	2.17	0.68	1.9
25	180.3	1.70	0.53	0.9

Appendix III (continued)

Ring no.	mean ring width (x100)	standard deviation	standard error	coefficient of variation
26	188.3	1.94	0.61	1.2
27	178.4	2.06	0.65	1.2
28	106.0	2.49	0.78	2.1
29	103.6	2.17	0.68	2.1
30	103.3	3.65	1.15	3.5
31	78.9	2.37	0.75	3.0
32	155.3	2.90	0.91	1.9
33	137.9	1.19	0.37	0.9
34	148.7	1.70	0.53	1.1
35	203.3	1.25	0.39	0.6
36	202.7	1.88	0.59	0.9
37	86.3	3.86	1.22	4.5
38	90.6	3.47	1.09	3.8
39	199.3	3.52	1.11	1.8
40	188.3	1.41	0.44	0.8
41	179.7	2.90	0.91	1.6
42	154.2	2.29	0.72	1.5
43	114.0	4.24	1.34	3.7
44	217.9	4.32	1.36	1.9
45	180.2	1.75	0.55	1.0
46	172.9	2.37	0.75	1.4
47	126.6	4.50	1.42	3.6
48	230.7	3.86	1.22	1.7
49	326.1	4.43	1.40	1.4
50	161.5	3.59	1.13	2.2

Appendix IV

Maentwrog Master Chronology

Tree ring indices (x 100)

Date	0	1	2	3	4	5	6	7	8	9
1710	90	133	79	72	71	78	66	67	70	69
1720	126	113	155	104	152	121	99	113	96	93
1730	117	89	92	97	96	134	122	87	137	125
1740	94	95	84	119	134	90	110	154	107	104
1750	89	90	110	103	95	102	100	102	124	122
1760	100	89	85	114	91	74	97	91	114	127
1770	94	52	64	48	57	83	121	126	105	80
1780	109	139	103	93	97	66	53	43	83	109
1790	101	97	85	92	71	87	80	111	104	113
1800	101	78	83	82	73	101	101	137	142	149
1810	144	171	162	115	120	96	87	73	104	112
1820	77	81	78	93	105	111	79	113	140	159
1830	159	114	59	50	81	97	103	109	108	126
1840	97	58	52	73	76	117	107	142	155	129
1850	113	113	89	112	100	73	71	92	110	103
1860	101	112	119	62	63	71	85	107	85	93
1870	89	139	120	97	94	91	81	70	94	139
1880	159	107	69	86	100	115	111	77	92	69
1890	82	81	72	57	73	100	111	114	104	102
1900	139	128	109	95	96	80	56	91	112	114
1910	134	100	108	124	105	108	113	146	109	87
1920	88	93	114	82	102	109	128	133	134	107
1930	75	58	79	86	80	109	103	83	96	84
1940	69	86	109	107	113	106	113	135	112	81
1950	90	99	98	98	80	96	104	96	86	101
1960	108	123	146	136	143	112	76	73	89	94
1970	81	104	91	97	79					

Number of radii

0	1	2	3	4	5	6	7	8	9
1	1	2	2	3	4	4	4	4	4
4	4	4	4	4	7	9	9	9	9
9	10	10	10	10	10	10	10	10	10
12	12	12	12	13	13	13	13	14	14
14	14	14	14	14	17	17	17	17	17
17	17	18	19	19	19	19	19	20	20
20	20	22	22	22	22	23	23	23	23
23	23	23	24	24	24	24	24	24	25
25	25	25	25	25	25	25	25	25	26
28	29	30	30	30	31	22	33	34	34
36	37	37	39	40	40	42	43	43	43
43	44	45	46	47	48	50	50	51	51
54	56	56	56	57	58	58	59	59	59
59	59	59	59	60	60	60	61	62	62
62	63	62	62	62	62	62	63	63	63
63	63	62	62	61	61	61	62	62	62
62	62	62	62	62	62	62	60	58	56
56	55	54	54	54	54	54	54	54	54
53	53	53	53	54	54	54	54	54	54
54	54	54	54	54	54	54	53	53	53
53	53	52	52	52	51	50	46	46	46
46	46	46	45	45	44	44	44	44	43
43	42	42	41	41	41	41	41	40	40
40	40	40	40	40	40	40	40	40	40
39	39	39	39	38	37	37	37	37	37
36	36	36	35	34	34	34	33	33	32
29	26	25	22	7					

Appendix V

Peckforton Master Chronology

Tree Ring Indices (x 100)

Date	0	1	2	3	4	5	6	7	8	9
1780	124	174	162	328	172	094	051	048	048	091
1790	078	063	111	86	90	106	74	34	25	55
1800	85	68	75	91	85	110	101	137	153	123
1810	157	161	146	129	95	88	93	63	68	104
1820	89	72	74	84	101	107	95	109	104	115
1830	120	100	109	92	78	86	78	99	104	109
1840	103	103	94	78	59	87	94	101	100	114
1850	108	116	129	130	111	109	94	98	100	129
1860	104	117	117	82	92	98	87	101	96	100
1870	98	119	116	115	84	104	110	121	113	98
1880	95	90	84	108	116	87	106	94	56	69
1890	120	124	105	63	61	98	89	71	71	113
1900	108	69	67	114	131	100	71	92	123	108
1910	135	113	90	121	124	111	72	129	93	108
1920	110	121	128	91	120	89	118	122	136	116
1930	82	84	96	75	68	72	129	109	72	113
1940	88	78	121	133	104	124	101	150	70	74
1950	87	117	100	76	75	95	68	50	82	100
1960	116	106	128	127	116	81	91	111	97	111
1970	87	84	119	113	99	90	104			

Number of radii

0	1	2	3	4	5	6	7	8	9
1	1	1	1	1	2	2	2	2	2
2	2	2	2	2	2	2	2	2	2
2	2	2	2	2	2	2	2	2	2
2	2	2	2	2	2	2	2	2	2
5	5	6	7	7	7	8	8	8	9
10	11	13	16	17	17	17	18	19	19
19	19	19	19	20	20	20	20	21	20
23	23	23	24	24	27	27	28	28	28
29	29	30	30	30	30	30	30	31	31
31	31	31	31	31	31	31	32	32	32
32	32	32	32	32	32	32	32	32	32
32	32	32	32	32	32	32	32	32	32
32	32	32	32	32	32	32	32	32	32
32	32	32	32	32	32	32	32	32	32
32	32	32	32	32	32	32	32	32	32
32	32	32	32	32	32	32	32	32	32
32	32	32	32	32	32	31	31	31	31
31	31	31	31	31	30	30	30	30	30
30	30	30	30	30	30	30	30	29	29
29	28	28	28	28	20	15			

Appendix VI

Clayton Hall Master Chronology

Tree-ring indices (x 100)

Date	0	1	2	3	4	5	6	7	8	9
1		44	48	83	103	117	100	93	98	104
10	99	89	90	94	120	134	115	139	101	99
20	115	99	82	65	86	107	117	87	84	88
30	92	102	114	84	97	106	123	89	92	113
40	109	132	108	105	108	82	105	80	109	103
50	102	112	117	92	111	82	90	100	98	79
60	70	92	88	89	91	99	96	121	110	115
70	130	90	77	101	95	104	102	103	107	119
80	107	113	81	111	76	94	70	67	93	109
90	91	141	97	101	91	91	92	118	105	88
100	121	105	141	115	86	85	77	91	110	84
110	81									

Number of samples

0	1	2	3	4	5	6	7	8	9
	1	1	3	5	5	5	5	7	9
10	11	11	11	12	12	12	12	12	12
12	13	13	13	13	13	13	13	13	13
13	13	13	13	13	13	13	13	13	13
13	13	13	13	13	13	13	13	13	13
13	13	13	13	13	13	13	13	13	13
13	13	13	13	13	13	13	13	13	13
13	13	13	13	13	13	13	13	12	12
9	8	8	8	7	7	6	6	6	6
4	4	4	4	4	3	3	3	3	3
2	1	1	1	1	1	1	1	1	1
1									

Appendix VII

Stayley Hall Master Chronology

Tree-ring indices (x 100)

Date	0	1	2	3	4	5	6	7	8	9
1365						84	97	67	40	68
1370	147	120	116	102	80	42	111	83	109	117
1380	116	92	95	86	115	79	96	103	105	110
1390	90	94	96	113	101	95	104	108	129	109
1400	115	105	106	105	98	109	110	91	85	104
1410	90	101	101	104	85	87	91	100	95	75
1420	109	102	78	101	88	102	106	114	106	124
1430	106	117	128	95	112	96	94	95	95	89
1440	97	94	75	103	113	104	72	86	94	110
1450	88	104	115	98	122	108	113	107	99	85
1460	97	101	97	93	92	92	100	119	114	107
1470	103	102	95	99	102	132	130	106	105	115
1480	100	105	106	94	93	103	103	139	107	105
1490	101	93	91	85	94	92	90	81	83	95
1500	91	74	61	66	77	98	108	91	86	96
1510	111	117	97	98	100	90	98	101	112	95
1520	82	102	86	97	109	112	109	105	101	80
1530	87	86	93	90	98	102	106	86	94	100
1540	122	86	90	100	105	132	122	116	191	188
1550	220	184	251	272	269					

Number of samples

0	1	2	3	4	5	6	7	8	9
					1	1	1	1	1
1	1	1	1	1	1	1	1	1	2
2	2	2	2	2	3	3	3	3	3
3	3	3	3	3	3	3	5	5	5
5	5	5	5	5	5	7	7	7	7
8	8	9	9	9	9	9	10	10	11
11	11	11	11	11	11	11	11	11	11
12	12	12	12	12	12	12	12	12	12
13	13	13	13	13	13	13	13	13	13
13	13	13	13	13	13	13	13	13	13
13	13	13	13	13	13	13	13	13	13
13	13	13	13	12	12	12	12	12	12
12	11	11	11	11	11	11	11	11	11
11	11	11	11	11	11	11	11	11	11
11	11	11	11	11	10	10	10	10	10
10	10	10	10	10	10	10	10	10	10
10	10	10	10	10	9	9	9	7	7
7	7	7	6	6	6	6	5	5	4
3	3	3	3	3	2	2	2	1	1
1	1	1	1	1					

Appendix VIII

Peel Hall I Master Chronology

Tree-ring indices (x 100)

Date	0	1	2	3	4	5	6	7	8	9
1378									85	114
1380	101	64	56	83	121	102	129	134	106	102
1390	103	102	114	118	99	98	117	108	130	113
1400	120	86	73	92	111	110	107	88	95	106
1410	84	65	64	72	68	84	71	94	101	75
1420	108	107	90	116	105	129	116	99	112	116
1430	130	154	162	107	101	95	102	121	112	86
1440	93	91	78	99	105	65	68	83	108	113
1450	99	111	103	80	67	80	108	110	112	92
1460	120	85	104	116	86	98	110	137	128	108
1470	127	88	84	103	83	123	109	98	81	79
1480	110	80								

Number of samples

Date	0	1	2	3	4	5	6	7	8	9
1378									1	1
1380	1	2	2	3	3	3	4	5	5	6
1390	6	6	7	9	10	11	11	12	14	15
1400	15	15	15	15	15	15	15	15	15	15
1410	15	15	15	15	15	15	15	15	15	15
1420	15	15	15	15	15	15	15	15	15	15
1430	15	15	15	15	15	15	15	15	15	15
1440	15	15	15	15	15	15	15	15	15	15
1450	15	15	15	15	15	15	15	14	14	14
1460	14	14	13	13	12	10	8	6	6	4
1470	4	3	3	3	3	2	2	2	1	1
1480	1	1								

Appendix IX

Peel Hall II Chronology

	Tree-ring indices (x 100)										Number of samples									
Date	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
1		313	276	107	118	86	49	51	36	40		1	1	1	1	1	1	1	1	1
10	35	30	37	89	160	57	40	39	48	50	1	1	1	1	1	1	1	1	1	1
20	44	36	37	30	27	22	26	23	22	80	1	1	1	1	1	1	1	1	1	2
30	76	75	109	120	185	168	145	105	63	57	2	2	2	2	2	2	3	3	3	3
40	133	146	214	160	108	128	166	147	159	105	3	4	4	4	4	4	4	4	4	4
50	89	105	117	107	143	116	92	75	71	63	4	4	4	4	4	4	4	4	4	4
60	61	73	79	97	76	76	87	89	86	90	4	4	4	4	4	4	4	4	4	4
70	80	78	93	95	81	100	113	119	122	133	4	4	4	4	4	4	4	4	4	4
80	114	110	82	114	111	92	113	84	107	105	4	4	4	4	4	4	4	4	4	4
90	65	92	61	92	83	117	84	81	99	82	4	4	4	4	4	4	4	4	4	4
100	71	62	82	76	102	114	107	153	113	67	4	4	4	4	4	4	4	4	4	4
110	97	84	118	107	115	119	159	150	152	119	4	4	4	4	4	4	4	3	3	3
120	113	88	105	82	82	114	135	76	70	68	3	3	3	3	3	3	3	3	3	3
130	71	81	72	52	57	79	90	95	121	104	3	3	3	3	3	3	3	3	3	3
140	106	86	212	89	100	114	166	113			3	3	3	2	2	2	1	1		

Appendix X

Bucknell Barn Master Chronology

Tree-ring indices (x 100)

Date	0	1	2	3	4	5	6	7	8	9
1414					94	104	92	111	103	56
1420	111	107	79	105	117	146	70	81	92	101
1430	126	130	102	91	107	114	127	103	86	95
1440	129	137	82	89	92	88	94	89	76	79
1450	96	112	122	93	115	112	128	103	71	52
1460	76	82	78	99	85	74	101	128	121	77
1470	83	99	71	80	105	121	106	80	85	87
1480	72	87	92	140	155	132	102	121	135	108
1490	121	69	49	72	96	106	147	112	87	107
1500	77	74	74	86	89	109	119	84	80	92
1510	88	107	103	90	103	92	91	77	100	102
1520	76	130	119	95	97	105	101	86	120	121
1530	99	136	114	131	116	132	112	116	132	123
1540	159	133	114	71	67	71	80	90	104	109
1550	116	117	102	109	89	73	66	84	75	102
1560	105	113	111	102	89	81	81	85	85	116
1570	168	191	179	166	154	40	29	63	65	62
1580	67	77	79	83	91	66	89	112	95	72
1590	144	68	79	107	104	123				

Number of samples

Date	0	1	2	3	4	5	6	7	8	9
1414					1	1	1	2	2	2
1420	2	2	2	2	2	2	2	2	2	3
1430	3	4	4	4	4	4	4	4	4	4
1440	4	4	4	4	4	4	4	4	4	4
1450	4	4	4	4	4	4	4	4	4	4
1460	4	4	4	4	4	4	4	4	4	4
1470	4	4	4	4	4	4	4	4	4	4
1480	4	4	4	4	4	4	4	4	4	4
1490	4	4	4	4	4	4	4	4	4	4
1500	4	4	4	4	4	4	4	4	4	4
1510	4	4	4	4	4	4	4	4	4	4
1520	4	4	4	4	4	4	4	4	4	4
1530	4	4	4	4	4	4	4	4	4	4
1540	3	3	3	3	3	3	3	3	3	3
1550	3	3	3	3	3	3	3	3	3	3
1560	3	3	3	2	2	2	2	2	2	2
1570	1	1	1	1	1	1	1	1	1	1
1580	1	1	1	1	1	1	1	1	1	1
1590	1	1	1	1	1	1				

Appendix XI

Nantwich Master Chronology

Tree-ring indices (x 100)

Date	0	1	2	3	4	5	6	7	8	9
930	149	96	116	116	70	85	105	107	99	90
940	83	105	100	84	105	127	143	176	63	157
950	134	109	107	144	165	207	147	96	83	108
960	96	121	103	72	109	102	98	75	109	73
970	84	58	89	49	65	78	69	76	71	105
980	98	86	100	107	85	86	68	93	65	76
990	78	83	85	94	72	122	111	113	97	123
1000	103	115	111	122	93	123	76	99	127	125
1010	124	101	117	126	90	100	92	102	87	87
1020	76	76	66	86	84	80	99	107	105	107
1030	122	137	112	124	94	116	94	137	129	115
1040	110	106	97	79	69	71	84	87	79	87
1050	87	96	102	90	86	105	115	122	127	116
1060	133	113	103	96	93	90	130	102	89	78
1070	83	79	92	87	89	112	106	104	116	103
1080	101	97	85	98	111	111	104	92	75	81
1090	54	76	102	127	111	118	99	107	110	120
1100	100	77	80	111	89	101	115	105	130	112
1110	90	86	82	96	103	123	106	110	101	91
1120	84	100	113	115	105	99	91	90	106	87
1130	97	96	96	104	102	104	79	91	113	97

Number of samples

Date	0	1	2	3	4	5	6	7	8	9
930	1	1	1	1	1	1	1	1	1	1
940	1	1	1	1	1	1	1	1	1	1
950	1	1	1	1	1	1	1	1	1	1
960	1	1	1	1	1	1	1	1	1	1
970	1	1	1	1	1	1	1	1	1	1
980	1	1	1	1	1	1	1	1	1	1
990	1	1	1	1	1	2	2	2	2	3
1000	3	3	3	3	4	5	5	5	5	5
1010	5	7	7	7	7	7	7	7	7	7
1020	7	7	7	7	7	7	7	7	8	8
1030	8	8	8	9	9	9	9	9	10	10
1040	10	10	10	11	11	11	11	11	11	11
1050	11	11	11	11	11	11	11	11	11	11
1060	11	11	11	11	11	11	11	11	11	11
1070	11	11	11	11	11	11	11	12	13	13
1080	13	13	13	13	13	13	13	13	12	12
1090	12	12	12	13	13	13	13	13	13	13
1100	12	12	12	12	11	11	11	11	11	11
1110	11	11	11	11	11	11	11	11	11	11
1120	11	11	11	11	11	11	11	11	11	11
1130	11	11	11	11	11	11	11	11	11	11

Appendix XI (Continued)

Tree-ring indices (x 100)

Date	0	1	2	3	4	5	6	7	8	9
1140	116	123	117	96	81	80	98	99	101	115
1150	119	120	108	132	100	104	112	96	95	105
1160	105	90	98	103	98	106	84	100	104	115
1170	107	103	105	101	89	101	103	85	107	119
1180	90	106	98	77	67	108	92	110	76	86
1190	118	95	90	120	111	120	126	99	89	85
1200	69	84	73	77	83	78	82	67	79	88
1210	97	109	92	93	79	82	97	98	101	88
1220	92	83	85	92	108	99	112	106	93	101
1230	99	73	76	74	83	75	63	80	76	108
1240	115	90	115	150	116	102	118	126	112	132
1250	101	129	145	230	152	202	189	220	184	149
1260	149	147	134	107	119	81	82	70	126	122
1270	140	138	139	115	139	100	96	104	115	87
1280	127	145	128	124	129	115	95	128	116	119
1290	101	98	107	109	110	113	75	91	70	102
1300	74	67	69	73	79	60	112	103	107	72
1310	73	88	83	82	105	105	107	112	103	82
1320	105	77	100	95	98	98	77	83	91	148
1330	72									

Number of samples

0	1	2	3	4	5	6	7	8	9
11	11	10	10	10	10	10	10	10	10
10	10	10	10	10	10	11	11	11	12
11	11	11	11	11	11	11	11	10	10
10	10	10	10	10	10	9	9	9	9
9	9	9	9	8	8	8	8	8	8
8	8	8	8	8	8	8	8	7	7
7	7	7	7	7	7	7	7	7	7
7	7	7	7	7	7	7	7	7	6
6	6	6	6	6	6	6	5	5	5
5	5	5	5	5	5	5	5	5	5
5	5	5	5	5	5	5	5	5	4
4	2	2	2	2	2	2	2	2	2
2	2	2	2	2	2	2	2	2	2
2	2	2	2	2	2	2	2	2	2
2	2	2	2	2	2	2	2	2	2
2	2	2	2	2	2	2	2	2	2
2	2	2	2	2	2	2	2	2	2
2	2	2	2	2	2	2	1	1	1
1	1	1	1	1	1	1	1	1	1
1									

Appendix XII

Baquley Hall I Master Chronology

Tree-ring indices (x100)

Date	0	1	2	3	4	5	6	7	8	9
1		87	99	105	84	61	110	113	148	149
10	97	114	120	115	124	79	60	83	117	116
20	94	105	105	95	100	93	93	94	76	102
30	104	92	94	72	70	109	97	97	90	87
40	104	131	113	81	105	102	104	100	100	102
50	114	109	123	136	136	158	137	121	89	71
60	71	83	70	64	60	66	38	47	66	89
70	102	125	119	138	134	127	93	76	103	147
80	148	106	108	68	51	51	57	89	121	146
90	105	143	92	117	110	109	101	86	62	80
100	65	77	98	113	145	121	135	105	87	118
110	104	141	170	142	99	86	88	122	141	176
120	139	118	109	81	63	65	82	102	110	85
130	59	56	65	68	48	68	106	100	122	99
140	111	94	129	155	122	80	103	75	71	104
150	90	135								

Number of samples

Date	0	1	2	3	4	5	6	7	8	9
1		1	1	1	2	3	3	3	3	3
10	3	3	3	3	3	3	3	4	4	4
20	5	5	5	5	5	5	5	5	5	5
30	5	5	5	5	5	5	5	5	5	5
40	5	5	5	5	5	5	5	5	5	5
50	5	5	5	5	5	5	5	5	5	5
60	5	5	5	5	5	5	5	5	5	5
70	5	5	5	5	5	5	5	5	5	5
80	5	5	5	5	5	5	5	5	5	5
90	5	5	5	5	5	5	5	5	5	5
100	5	5	4	4	4	4	4	4	4	4
110	3	3	3	3	3	3	3	3	3	3
120	3	3	3	3	3	3	3	3	3	3
130	3	3	3	3	3	3	3	2	2	2
140	2	2	2	2	2	1	1	1	1	1
150	1	1								

Appendix XIII

Baguley Hall II Master Chronology

Tree-ring indices (x 100)

Date	0	1	2	3	4	5	6	7	8	9
1037								140	115	81
1040	168	107	123	148	64	75	58	65	146	80
1050	76	71	64	79	73	87	106	96	99	109
1060	91	105	81	100	77	60	122	96	92	101
1070	116	116	83	91	85	104	117	123	119	111
1080	145	109	116	93	160	146	117	100	97	108
1090	72	78	92	107	94	92	81	87	45	117
1100	70	74	63	73	68	71	84	70	66	92
1110	48	67	72	92	98	103	110	105	106	96
1120	80	90	110	147	120	113	81	98	101	90
1130	88	76	73	89	93	101	122	89	153	94
1140	129	170	133	95	126	100	151	124	113	153
1150	123	171	150	187	109	117	124	122	93	121
1160	133	95	86	99	100	88	64	80	72	88
1170	88	95	98	89	101	102	85	58	81	116
1180	87	81	106	96	73	90	87	106	60	83
1190	123	102	106	133	170	114	96	84	94	90
1200	84	88	76	88	82	72	69	49	54	85
1210	83	111	112	105	110	90	94	97	87	88
1220	110	113	58	42	56	65	71	86	97	121
1230	113	103	91	80	121	122	91	140	124	148
1240	142	131	165	161	107	90	117	72	91	90
1250	96	74	65	95	106	121	218	124	113	110
1260	215	88	102	79	83	90	67	51	66	68
1270	76	91	108	111	90	93	73	69	78	80
1280	84	100	92	79	83	117	88	68	65	87
1290	93									

Number of samples

0	1	2	3	4	5	6	7	8	9
							1	1	1
1	1	1	1	1	1	1	1	1	1
1	1	1	1	2	2	2	2	2	2
2	2	2	2	2	2	2	2	2	2
2	2	2	2	2	2	2	2	2	2
2	2	2	2	2	2	2	2	2	2
2	2	2	2	2	2	2	2	2	2
2	2	2	2	2	2	2	2	2	2
2	2	2	2	2	2	2	2	2	2
2	2	2	2	2	2	2	2	2	2
2	2	2	2	2	2	2	2	2	2
2	3	3	3	3	3	3	3	3	3
3	3	3	3	3	3	3	3	3	3
3	3	3	3	3	3	3	3	3	3
3	3	3	3	3	3	3	3	3	3
3	3	3	3	3	3	3	3	3	3
3	3	3	3	3	3	3	3	3	3
3	3	3	3	3	3	3	3	3	3
3	3	3	3	3	3	3	3	3	3
3	3	3	3	3	3	3	3	3	3
3	3	3	3	3	3	3	3	3	3
3	2	2	2	2	2	2	2	2	2
2	2	2	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1
1									

Appendix XIV

Ring-width values of samples from Coniston Old Hall (mm x 100)

LP 266

Date	0	1	2	3	4	5	6	7	8	9
1		94	144	88	201	162	155	194	231	161
10	265	208	257	268	337	346	353	250	261	190
20	253	171	371	372	285	429	392	342	382	411
30	485	575	418	130	75	77	260	308	318	414
40	424	344	618	785	758	478	397	324	37	51
50	51	61	47	40	50	93	159	120	104	319
60	272	517	409	406	575	108	89	58	59	84
70	117	124	132	89	123	112	160	75	30	35
80	47	41	64	115	163	190	174	159	193	150
90	241	185	272	201	369	172	191	204	174	228
100	142	244	506	610	352	268	205	194	104	195
110	201	216								

LP 267

Date	0	1	2	3	4	5	6	7	8	9
1		321	313	279	461	285	208	225	195	69
10	53	39	31	44	104	139	214	140	185	427
20	516	743	409	597	438	374	309	112	41	67
30	95	94	103	111	70	133	168	275	217	55
40	42	51	82	106	98	94	162	187	184	148
50	238	139	218	305	483	298	505	466	494	450
60	206	320	438	514	232	191	167	153	106	156
70	140	179	234	323	183	620	383	351	325	448
80	256	113	168	201	181	175	130	265	184	190

Appendix XIV (continued)

LP 267 (continued)

Date	0	1	2	3	4	5	6	7	8	9
90	325	288	297	300	171	230	223	289	235	272
100	187	160	176	347	293	165	285	358	155	154
110	168									

LP 273

Date	0	1	2	3	4	5	6	7	8	9
1		552	319	333	399	363	398	317	90	66
10	84	79	140	128	112	260	211	274	294	100
20	71	65	47	85	104	131	104	198	177	135
30	240	162	324	121	43	53	80	120	137	164
40	187	178	152	84	97	58	57	101	152	155
50	113	104	108	99	128	119	93	58	88	105
60	127	136	60	58	41	64	83	53	59	105
70	104	143	143	124	126	122	123	187	69	84
80	70	66	119	56	89	116	104	126	56	140
90	173	188	113	97	120	119	89	142	99	151
100	105	137	267							

LP 276

Date	0	1	2	3	4	5	6	7	8	9
1		326	209	538	447	235	283	261	363	329
10	166	208	255	207	128	174	163	223	193	71
20	77	81	74	125	145	208	282	211	193	229
30	212	261	96	73	42	49	67	88	70	111
40	152	187	196	54	58	59	52	75	62	98
50	87	113	91	69	36	34	38	72	91	151

Appendix XIV (continued)

LP 276 (continued)

Date	0	1	2	3	4	5	6	7	8	9
60	185	112	148	199	101	74	43	44	67	118
70	162	304	156	134	204	295	328	49	40	88
80	49	69	110	101	108	138	230	193	259	42
90	71	85	55	49	56	73	80	118	163	175
100	184									

LP 278

Date	0	1	2	3	4	5	6	7	8	9
1		131	183	131	118	172	121	169	156	154
10	152	159	163	199	186	153	174	138	112	178
20	147	125	141	154	202	197	136	181	147	132
30	159	157	158	176	95	132	100	108	106	88
40	112	151	194	277	246	202	149	136	179	123
50	198	148	183	204	186	206	207	202	169	203
60	154	143	227	172	188	221	131	70	73	68
70	82	86	113	91	45	45	35	29	45	39
80	40	45	38	50	58	79	100	61	72	81
90	92	71	80	79	107	137	90	74	64	60
100	71	72	99	115	114	122	99	82	108	115
110	116	117	115	124	139	135	111	72	63	58
120	69	88	77	78	96	90	95	84	88	96
130	100	140	136	110	215	258	188	182	203	

Appendix XIV (continued)

LP 281

Date	0	1	2	3	4	5	6	7	8	9
1		155	154	283	152	182	188	266	174	209
10	228	161	159	153	180	131	107	101	90	65
20	105	109	127	102	108	122	74	50	59	58
30	74	90	86	68	67	50	70	59	60	93
40	118	124	135	132	94	77	79	127	87	123
50	98	109	111	99	117	115	120	89	135	123
60	90	94	71	64	62	90	71	64	75	65
70	49	63	41	55	69	42	42	56	64	56
80	51	52	70	88	59	49	49	41	37	44
90	43	38	49	61	59	44	40	40	29	42
100	55	42	50	54	51	39	57	66	68	61
110	60	67	63	56	56	64				

LP 284

Date	0	1	2	3	4	5	6	7	8	9
1		148	203	135	151	145	175	215	159	146
10	200	155	97	123	118	112	96	120	139	109
20	93	147	153	136	170	113	99	88	75	77
30	77	122	104	92	78	105	110	95	61	46
40	59	49	47	63	36	37	32	35	25	51
50	46	56	53	65	49	47	41	50	62	56
60	81	66	86	74	70	56	84	57	96	52
70	53	62	57	65	85	62	59	69	84	115
80	125	90	111	98	97	46	38	32	42	49
90	48	54	66	76	81	60	57	38	33	91

Appendix XIV (continued)

LP 284 (continued)

Date	0	1	2	3	4	5	6	7	8	9
100	67	116	115	112	136	135	122	135	132	139
110	96	150	175	208	130	108	90	51	51	55
120	79	82	124	121	96	130	139	141	123	138
130	98	88	109	107	100	123	144	109	93	73
140	96	104	109	95	108	152	159	101	133	133
150	94	91	125	141	116	105	102	128	109	103
160	81	96	106	123	73	58	65	35	51	42
170	52	50	38	39						

LP 286

Date	0	1	2	3	4	5	6	7	8	9
1		245	313	263	195	173	188	200	321	163
10	160	280	292	210	459	449	503	368	306	117
20	52	51	67	90	86	163	153	138	197	178
30	194	190	189	162	231	105	36	31	43	52
40	95	73	117	130	194	196	123	109	48	66
50	66	112	89	116	156	103	96	51	56	52
60	61	73	67	84	91	97	115	167	132	93
70	38	40	61	49	58	60	74	94	123	65
80	88	108	127	133	125	123	191	191	207	209
90	181	154	131	163	130	184	152	152	201	155
100	113	111								

Appendix XIV (continued)

LP 288

Date	0	1	2	3	4	5	6	7	8	9
1		157	151	138	165	145	136	152	104	132
10	102	102	113	193	192	158	170	111	57	82
20	82	53	88	111	123	106	245	209	151	150
30	203	185	193	199	183	60	56	41	45	60
40	79	71	101	105	143	114	121	136	142	133
50	70	29	29	40	49	73	91	39	62	101
60	121	139	94	114	218	290	122	95	86	106
70	56	71	120	191	158	147	108	154	189	167
80	41	55	36	52	47	37	50	78	45	31
90	39	57	55	56	43	53	92	95	91	95
100	94									

LP 295

Date	0	1	2	3	4	5	6	7	8	9
1		396	458	347	516	547	496	481	553	500
10	39	78	54	49	60	74	110	138	139	115
20	78	129	91	94	131	139	241	63	47	48
30	65	86	92	108	117	82	45	51	64	70
40	93	187	176	195	119	69	45	48	60	80
50	84	119	120	167	168	254	110	171	109	215
60	84	54	45	62	54	74	71	54	57	91
70	88	95	109	170	60	53	118	89	89	111
80	84	113	59	38	46	44	65	50	57	89
90	58	97	50	92	84	115	100	116	102	113
100	85	72	103	163						

Appendix XIV (continued)

LP 297

Date	0	1	2	3	4	5	6	7	8	9
1		92	177	134	120	224	271	169	204	379
10	371	378	239	43	72	78	77	100	106	160
20	136	102	120	130	94	90	105	99	162	172
30	178	53	47	38	63	47	55	50	89	81
40	91	93	112	155	77	61	44	60	69	66
50	112	98	111	60	76	67	76	67	124	120
60	190	237	174	218	35	39	36	61	35	45
70	44	75	91	191	91	109	165	154	180	114
80	106	169	238	156	151	120	64	61	98	131
90	179	192	168	119	230	157	140	100	130	141
100	139	142								

LP 299

Date	0	1	2	3	4	5	6	7	8	9
1		280	340	387	331	339	189	123	243	259
10	232	272	332	320	268	329	272	292	200	207
20	312	248	370	97	65	80	110	104	141	125
30	101	188	180	180	177	178	217	217	133	240
40	407	307	271	185	238	198	199	164	95	77
50	66	40	41	57	49	74	53	67	93	86
60	103	94	59	46	47	33	52	40	36	34
70	35	42	40	66	47	48	65	59	37	46
80	45	68	79	78	52	75	78	55	54	70
90	69	74	70	61	76	76	75	74	74	68
100	52	63	66	70	79	62	67	55	55	53
110	55	115	63	46	57	41				

Appendix XIV (continued)

LP 303

Date	0	1	2	3	4	5	6	7	8	9
1		367	278	262	290	68	88	76	117	130
10	117	323	181	161	224	79	52	74	52	85
20	131	191	149	290	207	255	294	180	226	74
30	50	66	69	101	125	208	186	140	130	49
40	64	47	57	84	160	220	146	90	84	114
50	100	85	85	84	133	146	176	77	65	54
60	74	124	105	85	126	107	157	223	167	172
70	207	219	279	67	32	45	88	119	187	64
80	95	131	108	143	84	115	265	316	189	90
90	110	113	105	78	139	176	253	203	217	140
100	243	233	200	188	247					

LP 304

Date	0	1	2	3	4	5	6	7	8	9
1		166	72	105	174	231	176	199	212	141
10	245	132	226	231	199	157	195	114	88	135
20	162	165	195	178	140	155	162	167	118	142
30	120	150	189	107	104	122	203	157	153	172
40	140	166	140	139	164	182	218	123	151	195
50	190	188	132	124	136	121	185	161	173	156
60	108	48	45	56	56	61	61	62	91	81
70	75	77	75	90	100	84	101	103	138	107
80	133	168	145	44	45	33	47	44	35	46
90	50	53	48	57	59	81	111	127	140	125
100	49	45	49	38	33	60	66	56	53	80
110	75	93	152	72	49	34	32	30	30	34

Appendix XIV (continued)

LP 304 (continued)

Date	0	1	2	3	4	5	6	7	8	9
120	45	49	37	49	54	60	70	54	130	111
130	80	214	132	125	184	201	40	50	64	43
140	38	45	45	58	86	88	98	83	75	76
150	56	37	28	24	27	41	43	58	45	37
160	40	48	65	58	63	51	62	90	50	50
170	42	36	35	51	52	71	79	59	87	104
180	45	44	38	41	33	37	35	33	62	59
190	49	79	58	61	48	85	87	74	88	

LP 307

Date	0	1	2	3	4	5	6	7	8	9
1		366	466	432	282	240	228	247	223	236
10	240	283	289	361	306	300	369	379	340	301
20	497	406	397	359	77	120	122	89	120	116
30	184	205	347	337	467	312	175	372	258	50
40	90	66	95	144	129	78	102	112	143	261
50	64	39	51	53	93	113	102	76	84	100
60	102	90	81	102	84	105	162	118	141	135
70	79	40	50	49	45	67	78	95	84	116
80	110	86	58	35	40	38	27	35	38	48
90	74	71	93	103	36	23	35	31	58	55
100	54	69	99	125	126	52	44	36	51	43
110	37	38	59	137	80	94	112	60	82	73
120	135	88	43	45	52	60	62	71	78	60
130	93	156	161	146						

Appendix XIV (continued)

LP 310

Date	0	1	2	3	4	5	6	7	8	9
1		413	299	246	342	270	368	349	403	338
10	491	273	168	332	350	97	121	118	127	177
20	128	172	209	178	228	287	247	395	406	100
30	49	65	48	60	70	89	115	147	177	168
40	145	159	152	98	47	43	64	59	64	98
50	97	100	75	135	82	73	75	63	70	70
60	62	42	54	66	76	50	49	45	52	47
70	44	46	49	69	94	104	193	89	85	65
80	52	34	36	45	53	45	37	46	57	66
90	63	48	50	43	38	31	35	41	34	41
100	22	28	42	42	62	98	90	73	70	60
110	55	53	66	51	44	54	47	54	89	76
120	86	44	43	46	46	38	38	45	49	45
130	51	41	57	79						

LP 316

Date	0	1	2	3	4	5	6	7	8	9
1		420	346	375	279	452	317	396	306	272
10	223	454	344	394	476	397	247	240	268	205
20	202	136	241	170	96	180	46	40	49	68
30	69	56	60	69	88	126	100	115	131	147
40	155	108	116	143	128	101	82	100	80	88
50	119	77	33	35	32	35	35	37	49	68
60	92	59	92	85	81	86	136	63	47	31
70	28	36	40	42	40	45	52	60	64	99

Appendix XIV (continued)

LP 316 (continued)

Date	0	1	2	3	4	5	6	7	8	9
80	93	139	180	54	30	56	46	43	58	64
90	70	83	105	55	74	75	84	109	60	84
100	112	112	86	53	53	55	66	56	68	86
110	104	127	53	70	94	84	87	84	71	63
120	54	45	39	37	32	33	30	35	35	

LP 318

Date	0	1	2	3	4	5	6	7	8	9
1		278	270	140	159	151	82	128	202	280
10	312	289	451	491	379	286	431	299	279	140
20	103	100	86	88	110	103	125	178	70	55
30	56	94	102	178	152	175	226	310	118	95
40	89	115	121	170	177	189	172	54	39	97
50	112	103	82	144	145	160	58	49	37	47
60	51	57	70	112	119	138	102	99	127	159
70	254	237	92	86	61	57	75	84	73	66
80	59	63	75	102	95	39	57	55	73	44
90	41	66	119	159	134	161	131	124	130	181
100	189	226	224	245	206	237	202	97	74	78
110	62	65	84	82	88	62	89	77	51	49
120	58	64	74	88	100	110	121	104	60	196
130	143	204								

Appendix XIV (continued)

LP 319

Date	0	1	2	3	4	5	6	7	8	9
1		199	208	250	324	308	350	355	343	236
10	134	398	430	564	396	552	625	593	554	530
20	122	161	148	168	182	244	317	399	417	421
30	437	196	74	87	96	115	138	125	269	164
40	266	231	310	272	314	294	434	210	214	236
50	182	244	270	213	245	288	210	158	166	167
60	106	115	148	203	110	304	232	254	280	215
70	207	243	181	122	156	184	184	207	196	194
80	155	185	144	217	191	136	121	139	170	232
90	173	154	148	131	170	197	167	137	154	160
100	128	79	92							

LP 321

Date	0	1	2	3	4	5	6	7	8	9
1		252	293	231	310	380	274	288	225	222
10	178	180	117	223	258	213	185	132	143	192
20	161	136	143	72	45	52	75	66	58	64
30	79	96	84	124	122	149	150	94	45	95
40	92	91	64	55	34	37	32	32	41	56
50	64	72	102	99	104	120	150	146	58	50
60	30	28	40	35	28	41	60	70	70	48
70	58	63	75	80	106	117	195	50	43	33
80	44	42	54	74	69	72	158	194	188	42
90	34	53	44	45	43	74	74	73	82	76
100	81	93	119	98	154	227	180	278	286	271

Appendix XIV (continued)

LP 321 (continued)

Date	0	1	2	3	4	5	6	7	8	9
110	150	177	192	171	72	55	43	57	55	51
120	52	76	55	81	73	90	96	185	203	118
130	141	194	210	211	190	154	174	69	44	48
140	40	65	46	66	55	62	44	92	95	104
150	74	109	169	130	108	90	208	158	158	144
160	117	52	54	66	85	109	123	193	138	114
170	86	72	53	43	52	56	109	92	55	34
180	49	48	64	73	51	91	92	71	51	54
190	73	79	107	88	50	36	33	29	26	29
200	23	28	24	28	23	24	32	34	27	29
210	32	35	32	31	34	38	31	27	32	35
220	37	48	110	62	57	61	81	138	111	107
230	151	130	134	83	86	100	55	99	66	76
240	106	88	62	72	50	44	53	96	88	112
250	172	192								

LP 322

Date	0	1	2	3	4	5	6	7	8	9
1		146	178	260	173	193	207	155	179	100
10	109	124	126	135	84	106	155	112	208	189
20	197	171	112	145	121	131	148	198	156	220
30	170	200	170	246	182	157	157	241	215	277
40	192	194	125	103	140	211	263	286	184	271
50	368	332	219	157	158	215	208	258	204	275
60	174	238	310	307	280	217	159	138	147	163

Appendix XIV (continued)

LP 322 (continued)

Date	0	1	2	3	4	5	6	7	8	9
70	145	246	268	251	370	291	324	329	333	291
80	374	332	374	344	307	393	376	118	89	103
90	146	98	151	136	105	161	179	148	175	187
100	233	178	131	127	114	145	218	223	181	349
110	208	192	427	174	156	123	117	90	67	71
120	58	59	104	96	136	97	116	53	44	50
130	54	59	56	63	73	69	117	105	45	30
140	34	34	33	35	48	62	66	55	95	76
150	87	55	46	36	69	74	56	96	82	85
160	49	79	39	27	40	40	51	110	113	94
170	111	133	111	151	128	158	154	145	129	159
180	112	120	205	185	137	89	41	59	53	50
190	50	55	52	74	75	72	66	64	108	