A SLICE THROUGH TIME

Dendrochronology and precision dating

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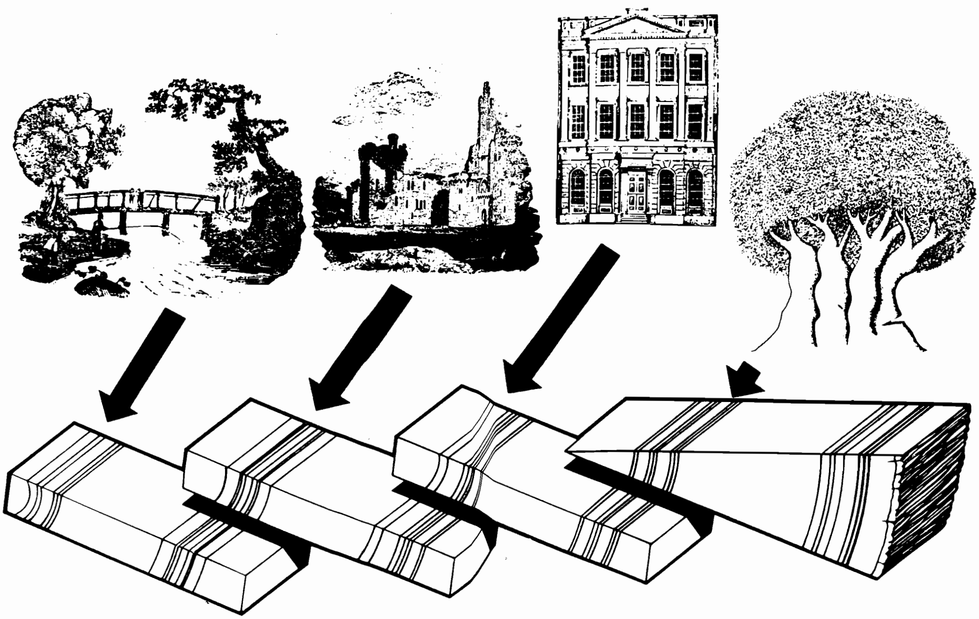
method

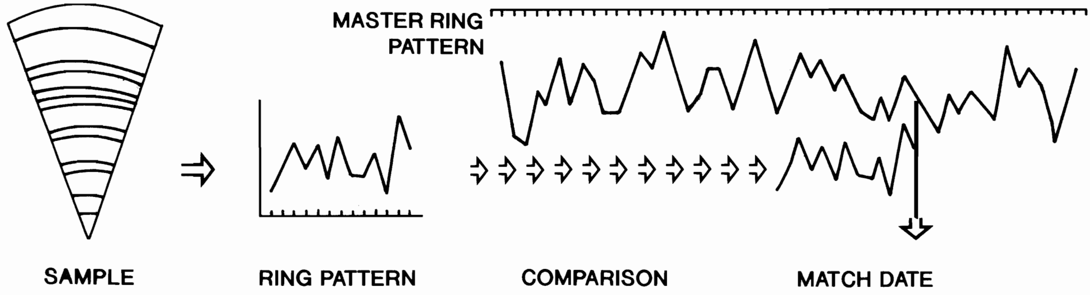
Basic principles

In concept, tree-ring dating is still an extremely simple method. It relies, like most dating methods, on a natural clock; in this case the natural clock provided by the annual growth rings of trees. For the sake of discussion the following descriptions will concentrate on the characteristics of oak, because, in northern Europe, oak underpins the tree-ring method. Many of the comments could be applied in a general way to a number of other species. Most temperate trees put on a single ring of new wood each year. This ring is formed immediately under the bark and, in the case of trees such as oak, forms a visually apparent band on a cut or polished cross-section of the main stem. The annual bands of new wood accumulate over the lifetime of a tree into a year-by-year record of the tree's life – its ring pattern. To some extent this ring pattern must record the conditions under which the tree grew. We might expect, and herein lies the basis of the dating method, all trees of the same species in the same 'climatic area' to record at least some aspects of common growth conditions. If such common records do exist, and clearly they do because the method works repeatably, it becomes possible to compare the pattern of rings from one tree to its neighbour and, as importantly, to overlap patterns back in time. In practice, widespread studies of oak growth patterns have shown that there is a strong common element to the patterns over surprisingly large areas.

Fig. 1.1 illustrates the process of chronology building. The ring pattern of the modern tree is anchored at the present – the date of its last growth ring is known. The pattern of its inner rings are overlapped with the outer rings of an ancient specimen; in this case from an historic building. This process is carried on through the



1.1 Schematic representation of the principle behind dendrochronology



1.2 Schematic representation of the dating process

patterns of successively older timbers from buildings, from archaeological sites and, ultimately, from natural sources such as lake margins, submerged forests, peat bogs and river gravels. As a result, and we will look at this in some detail in Chapter 2, very long master chronologies can be constructed, with lengths of seven–nine millennia. The master chronologies do not of course depend on the patterns from single trees. If we consider oak, many individual ring patterns are cross-dated for every period and the master pattern is therefore a year-by-year record of average oak growth, for a particular region.

From a dating point of view, once a master chronology is available, the next stage is to analyse a timber of unknown age. This involves preparing the transverse surface of the specimen in such a way that the ring pattern is clearly visible. Once prepared, the width of each individual ring, from the centre to the outside of the specimen, is measured using one of a range of measuring devices. The resulting list of consecutive ring widths – the ring pattern of the specimen – can then be compared with the master chronology for the appropriate area and species (**Fig. 1.2**). In concept, there are strong similarities with the fingerprinting of humans. In tree-ring studies the comparisons are made both visually and statistically. Statistical computer packages represent an invaluable aid to the dendrochronologist and are mostly based on the same general principles. A correlation coefficient is calculated at every position of overlap between the specimen ring pattern and the master pattern. If the specimen is of the correct species, if it is from the same area as the master chronology, and, if it is suitably long, then often it will be possible to find a unique matching position, i.e. only one position where the pattern fits the master visually and with a really high correlation value. The correct matching position will be where the year-by-year record of the specimen refers to the same span of years in the master. If the pattern matching is successful, the date of the last ring on the specimen can be read off with exact calendrical precision from the master. To compound the fingerprinting analogy, if enough points of similarity are established between a tree-ring sample and a master pattern, the sample's *time* is identified.

Such a dating method is breathtaking in its elegance and simplicity and, of course, the real joy is that it has been found to work, and work repeatably, in many areas and for a number of species. Different workers have built chronologies and arrived at the same answer when attempting to date test samples. The following chapters will be liberally sprinkled with examples which show the levels of replication which are possible between chronologies and the almost unbelievable accuracy of the results. Many sites yield specimens where the time of felling is restricted to about six months: 'the timbers used in the construction of the Corlea 1 trackway (in Co. Longford, Ireland) last grew in 148 BC and were felled either late in 148 BC or early in 147 BC' or 'the main activity at the Sweet Track was in the winter/spring of 3807/6 BC'. Occasionally it is possible to specify felling in the early part of the summer, i.e. to within about two months. Here then is a tool which can be used to resolve historical and archaeological questions, on the one hand, and which can give information on such diverse topics as river gravel formation, bog growth and past environmental conditions, on the other.

Historical elements

Dendrochronology has come a long way in the last 90 years. The first half of this century was largely monopolized by work in America by A.E. Douglass and his followers. Because of the nature of the method, Douglass' descriptions of his pioneer work are still fresh today (see, for example, Douglass 1919). While there may be differences in detail the basic elements of chronology building never change. Douglass was the first to face up to putting together the main elements of master chronologies, contending with gaps in the record due to sampling deficiencies, ironing out problems – worse for him because his stressed pines from the arid south-west of the United States frequently missed rings – and checking for replication to prove the chronologies. Douglass' completion of the first, great, classic, chronology-building exercise, involving many overlaps through successively older yellow pines, ensures his position as the 'father' of dendrochronology (Robinson 1976; Baillie 1982).

The work initiated by Douglass continued and expanded, mostly at the dedicated Laboratory for Tree-Ring Research in the University of Arizona at Tucson, with eventual chronologies for bristlecone pine running back to beyond 6000 BC (Ferguson and Graybill 1983). In comparison, European work developed slowly from the 1930s onwards with the main European flowering coming only in the last twenty years. From the late 1960s a whole generation of workers dedicated themselves to the construction of long master chronologies. It is undoubtedly the case that these long chronologies form the backbone of the subject. When Ferguson published his bristlecone pine chronology in 1969 the longest published tree-ring chronologies in Europe extended only as far as AD 822 and AD 832 (Hollstein 1965; Huber and Giertz 1969). Now there are continuous records for Ireland back to 5479 BC (Brown and Baillie 1992), for England back to 4989 BC (Baillie and Brown 1988), for south Germany back to 7237 BC (Becker and Schmidt 1990) and for north Germany back to 6200 BC (Leuschner 1992). Leuschner also reports that Becker's south German chronology has now broken the 10,000-year barrier. Overall, dendrochronology is now based on a well-tried and tested methodology. The remainder of this chapter examines the main elements in both the working of the method and chronology construction. This is a necessary section for those not previously familiar with tree-ring dating. Although only an outline, it should be sufficient to give the newcomer a feel for the methodology which underpins the results in the following chapters.

Sampling

As dendrochronology deals with ring patterns, clearly ring patterns have to be acquired for study. The requirements are extremely simple. Sampling is about extracting ring patterns – the widths of all the successive rings from the pith to the bark of a tree. The tree can be standing, felled, cut up and built into a building, buried in an archaeological site or natural deposit. It may be in a secondary position, for example, a jumble of timbers from a demolished building or a pile of tree-trunks recovered from some drainage operation. The optimum method of obtaining the ring pattern of a timber will always be the cutting of a complete cross-section (i.e. transverse to the original direction of growth) and this is straightforward when dealing with timbers out of context.

Sampling problems arise mostly where the dendrochronologist has to be as non-destructive as possible. This is certainly the case with living trees and with timbers in important or occupied buildings. Obviously it is also important when attempting to extract the ring patterns of valuable museum objects, such as panels in furniture or those supporting paintings. Methods include wet and dry coring, X-ray analysis, ultrasonic probes and body scanners on the one hand, through to simple photography and contact 'lifting' on the other. I was introduced to this latter procedure by Hubert Leuschner and it nicely demonstrates the empirical nature of tree-ring studies.

In a word dendrochronologists need ring patterns and it doesn't much matter what sort of Heath Robinson device is used to get them, as long as, at the end of the day, an accurate set of numbers is available from the timber. For example, the 'lifting' procedure involves making a thin strip of a child's moulding clay. The strip is then laid along the ring pattern (the edge of a panel, for instance) and pressed firmly on to the wood. Dust present (or applied in the form of chalk) in the spring vessels of each ring is transferred to the strip and remains as a well-defined image when peeled off. Moreover the material can be rendered permanent by heating in a domestic oven, thus providing a useful record for storage purposes. The procedure works particularly well on oak with its ring-porous structure and large spring vessels. So samples can end up in the laboratory as everything from complete cross-sections of trees, sections of beams, cores, charcoal, X-ray plates and photographs to strips of modelling clay. If the sample is wood, as most inevitably are, it can be wet, dry, solid or decayed. The job of the dendrochronologist is then to extract from the sample that all-important ring pattern.

Preparation and measurement

Since the principal aim is to extract an optimum ring pattern from the sample, it is important that the individual growth rings be rendered clearly visible. Different workers favour different methods when dealing with wood samples, depending on whether the sample is wet or dry. With wet samples paring or planing is the preferred technique and certainly paring renders the structure of the wood visible down to the level of individual cells. With dry samples, sanding often produces optimum results and the surface can be rendered highly visible by the application of successively finer grades of abrasive. Normally pared or sanded specimens are treated with chalk dust or some other agent, which highlights the spring vessels and ring boundaries.

Since the most useful dates produced by dendrochronologists will be those which specify the felling year of the timber, it is important, whenever possible, to take samples which run out to the bark surface (see also under 'sapwood', below). In oak the stem is made up of an inner cylinder of robust, consolidated, heartwood and an outer, unconsolidated, layer of sapwood. So, since the sapwood runs out to the underbark surface, complete sapwood is vital for really precise dating. Unfortunately the unconsolidated sapwood readily suffers damage due to insect attack (in buildings) or rot (in buried specimens). As a result, difficulties can be experienced with both dry samples from buildings and wet samples from archaeological contexts. When coring building timbers it is important to extract subsidiary samples of complete sapwood so that the ring patterns can be reconstructed out to the felling surface. With wet archaeological samples the sapwood is often so de-natured that it can be damaged simply by the weight of the sample itself. In this latter case it is wise to measure the ring pattern in the sapwood as soon as possible to guard against either physical damage or damage due to differential drying.

So procedures for dealing with particular sample conditions are largely a matter of common sense and experience. The same can be said for measurement. In essence the idea is to measure the width of each ring in the sample from as close to the centre (pith) as possible, to as close to the felling surface (bark) as possible. Although the individual rings should be measured radially, there is no rule which dictates measurement along a single radius. The governing factors are:

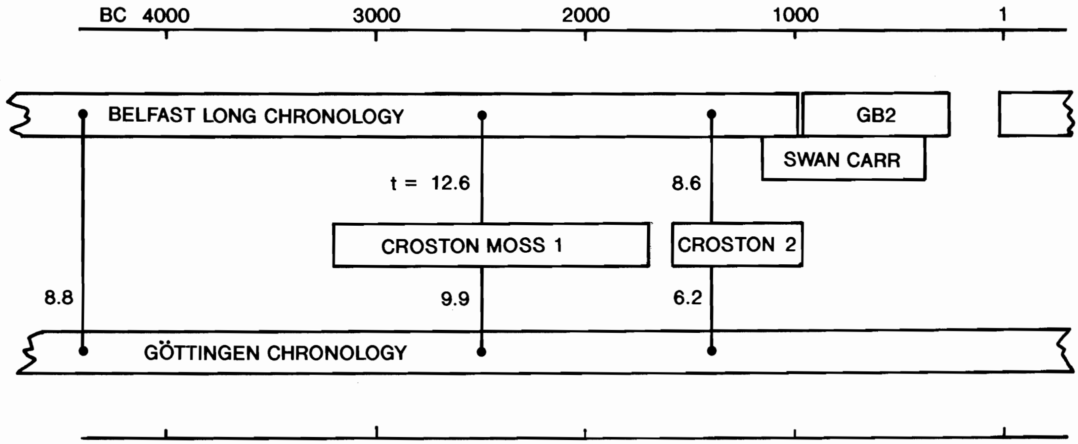
(i) that the measurement of the individual ring should clearly reflect the relative width of the ring being measured to the width of the previous ring;
(ii) that the overall pattern should reflect measurement where the rings are most 'regular'.

These factors arise out of experience and represent an optimizing of the ring pattern. An alternative procedure would be always to measure in an exact radial line and take the mean of three such radial measurements. In the course of measurement it is essential to mark the pattern at regular intervals – normally every tenth ring, with additional marks to highlight each fiftieth and hundredth ring – to facilitate subsequent checking of the sample and to guard against losing one's place during measurement.

Once an optimum ring pattern has been produced for a sample, the ring widths are plotted against a scale in years. Different procedures are used depending on preference, some workers using raw ring widths while others employ semi-log plots. The end result is a graph for the individual tree with a scale in years which can subsequently be converted to calendar dates once the sample is precisely dated. The graph will also carry annotations on such things as problem rings, anomalous rings, the position of the heartwood/sapwood boundary and the condition of the felling surface (if it exists). Having sampled and prepared the timber and having measured the ring pattern, the original wood sample is converted to a graph and a set of numbers. The sample itself can then be stored for future reference. This is where dry samples, photographs and even modelling clay do prove an advantage as they can be stored indefinitely. Wet samples tend to take on a life of their own! Even if frozen, they remain dependent on someone supplying money for electricity; wet they play host to a wealth of organisms bent on recycling the cellulose.

Cross-dating

Cross-dating is the art of dendrochronology. The sample has been fingerprinted: its ring pattern has been taken. Now the dendrochronologist must identify that ring pattern against other individual ring patterns or against a master chronology. The course of action will depend on particular circumstances. If one is dealing with a group of timbers from a single context, it will often be possible to cross-match the individual ring patterns visually by examining the graphs superimposed over a light box. Often an internally consistent site chronology can be constructed purely by visual matching. A site master chronology can then be constructed by meaning the individual ring patterns together at their correct relative positions. A site master has the advantage of ironing out a lot of the 'noise' associated with individual samples and concentrating the matching 'signal'. Indeed, experience shows that site masters have a higher dating success rate than individual timbers. In practice extensive use is made of cross-correlation computer programs which calculate some sort of correlation coefficient on the high-frequency (year-to-year) component of the ring patterns. Statistics such as the German 'coefficient of parallel variation' (*w*) values (Eckstein and Bauch 1969) or *t* values obtained from programs such as CROS (Baillie and Pilcher 1973) or Cross-84 (Munro 1984) are still in widespread use. Attempts have even been made to combine these two measures of correlation to assist with the identification of a single position of strongest correlation (Schmidt 1987). It is almost certain that this latter approach has little validity to a statistician – combining two statistics which are not themselves independent. However, this in itself helps to highlight an aspect of dendrochronology which is widely misunderstood. When a dendrochronologist uses a computer-based



1.3 Completely integrated correlations between independent chronologies. The long sections of English chronology from Croston Moss, Lancashire, match at exactly the same date against both the Irish and German master chronologies, with highly significant correlations

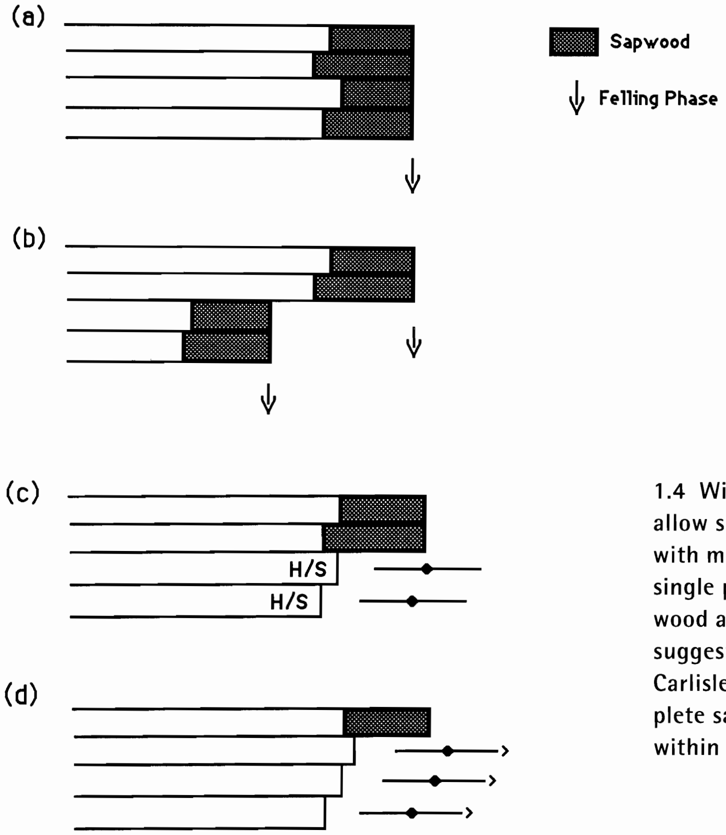
correlation program 'to pick out possible matches' he or she is using the correlation coefficients as a *guide*. Matches between ring patterns, whether between individual trees or between master chronologies, are not perfect 100% matches. The practised dendrochronologist is looking for matches which he/she is willing to accept, based on experience, as correct matches between long ring patterns (see also below).

Misunderstandings between statisticians and dendrochronologists have always centred on this cardinal point: the statisticians are talking about 'statistical tolerances and significance levels', while the dendrochronologists are talking about 'guides' as to where to look for significant matches (Orton 1983). Of course it is nice, when a computer match between a 200-year ring pattern and a master chronology is $t = 8.5$ with a statistical tolerance of $p = 0.0000000002$; however, it is not necessary for the dendrochronologist to have this level of correlation in order to establish an absolutely correct match. The secret is that the dendrochronologist has relevant experience and a repertoire of multi-match back-up, in the form of *replication*. The dendrochronologist is seldom looking at a single match and a single correlation value. Most of the time there are multiple correlations, all of which have to be self-consistent to make the match acceptable. So, for example, when the English Croston Moss chronology matches with both the independent German and Irish master chronologies at self-consistent positions with significant t values (**Fig. 1.3**), it is no longer a case of statistical tolerances, it is a case of absolute certainty. Purists would argue that, since the probabilities are multiplicative, the probability of such a self-consistent set of correlations being wrong becomes vanishingly small.

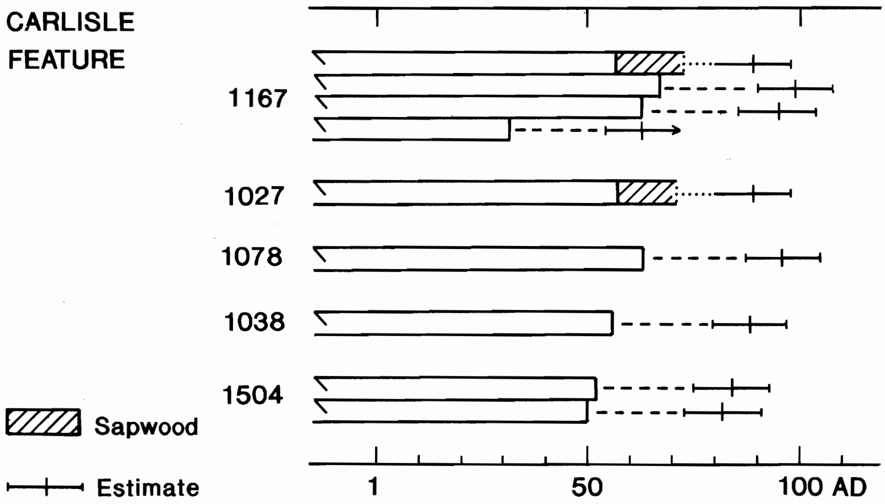
So, correlation programs are extremely useful and this is particularly the case with some of the reference chronologies which are thousands of years in length. In such cases it would not be practical to search for matching positions by eye. High-correlation positions are checked visually and, where appropriate, backed up by replicative matches. It should be pointed out that other approaches to the problem of cross-dating have been suggested (see, for example, Wigley *et al.* 1987 and Yamaguchi and Allen 1992, among others). Unfortunately, in none of these cases have working programs gone into general usage. This is a direct reflection of the fact that the method works repeatably, and to the satisfaction of the peer group, using variants of the existing *w* and *t* programs, in combination with visual matching and replication. (Anyone wanting to perfect a computer program which will give absolutely certain matches is presumably working towards a black box system which will automatically measure and cross-date samples and eliminate the subjective human element in dendrochronology. I wish them luck!)

Sapwood and interpretation

Let us imagine that the dendrochronologist has successfully sampled, measured and cross-dated either one timber or a group of timbers. In an ideal world each timber would be complete to its felling year and interpretation would be straightforward. In **Fig. 1.4a** we see examples of this ideal situation. Each sample last grew in the same year and any interpretation devolves to discussions of possible storage or seasoning – or the relationship of the timbers to the building in which they occurred. All such arguments are secondary to the dating: we know the exact felling dates. In **Fig. 1.4b** there are two clear felling phases and any interpretation falls to the archaeologist or building historian. The tree-ring evidence is unequivocal. In these complete sapwood cases interpretation is essentially trivial. Indeed, it is in these cases that one is drawn into the minutiae of the *season* of felling. In oaks, the large spring vessels at the beginning of a ring are normally the product of growth in April–May. So a timber felled in the early summer will show a ring pattern truncated immediately after the spring vessels of its last ring. On the other hand, if its summer wood appears complete, then it could have been felled at any time between roughly September of its final growth year and March of the following year. Hence there is a fine distinction between the 'last year of growth' and the 'felling year' of a tree. As such examples accumulate, dendrochronologists become more punctilious in their language. Note how the Sweet Track timbers 'last grew' in 3807 BC and



1.4 With complete sapwood (a) and (b) allow straightforward interpretation, (c) with missing sapwood no longer defines a single phase, while (d), with missing sapwood and some missing heartwood, suggests only a terminus post quem. The Carlisle example (e) illustrates how incomplete sapwood can prohibit any phasing within the features from a single site



were felled late in 3807 BC or early in 3806 BC (Hillam *et al.* 1990). It often seems laughable that dendrochronologists are worried about a semantic nicety which, at most, might make a difference of about four months. However, tree-rings are about absolute precision. In a case like the Sweet Track it is wrong to say that the timbers were felled in 3807 BC because they might, in fact, have been felled in 3806 BC! Perhaps this tendency to exactitude is brought about by the summer-felled trees where one is no longer talking about years but about 'felling in May or June' of a particular year (Baillie 1982: 162).

Unfortunately, given the friable nature of sapwood, the felling date of many archaeological samples cannot be specified to the year; there are a whole series of retreats from the precise dating scenario. Sapwood can be partially present or totally absent. These are several possibilities:

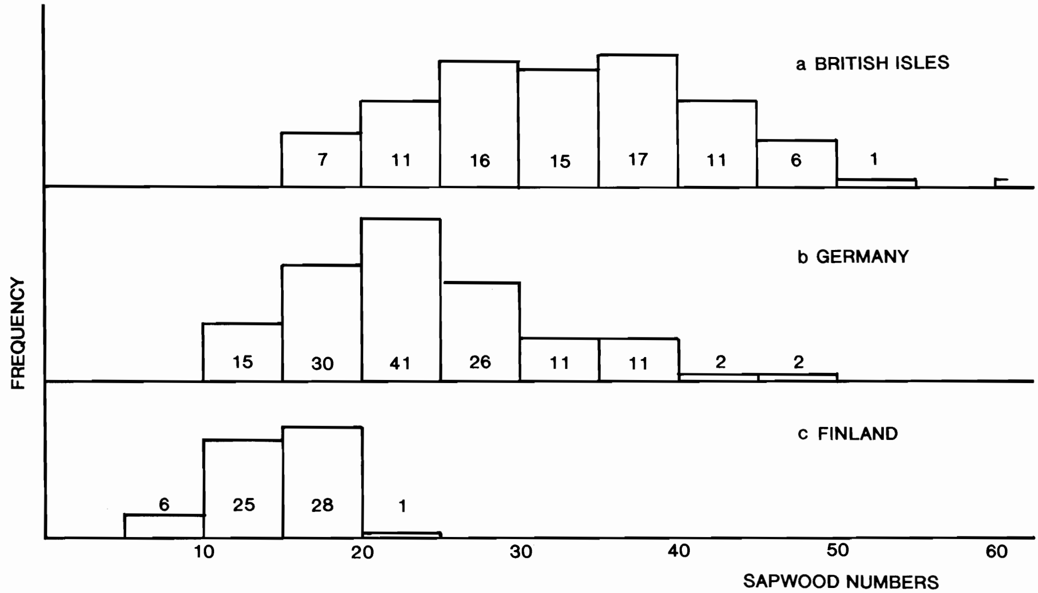
i) where a small amount of the sapwood is damaged or missing;
ii) where most of the sapwood is missing but one or two definite sapwood rings remain;
iii) where all the sapwood is missing but other evidence suggests that *only* the sapwood is missing and the heartwood is complete;
iv) where all the sapwood plus an unknown quantity of heartwood is missing.

In each of these cases attempts to rescue dating accuracy involve the use of some estimate of the expected number of sapwood rings. However, with sapwood there is good news and bad news. An estimate of the number of sapwood rings on an oak can be made by measuring a lot of examples with complete sapwood. Unfortunately it transpires that the sapwood estimates are very variable both within an area and between areas. In Ireland the 68% confidence limits on oak sapwood are 23–41 years (95% confidence 14–50 years) (Baillie 1973, 1982) while in England Hillam *et al.* (1984, 1987) propose a 95% range of 15–50 years. While these estimates are consistent they have to be viewed against average sapwood numbers around 20 years in Germany (Hollstein 1980) and as low as 14±3 in Finland (Baillie *et al.* 1985).

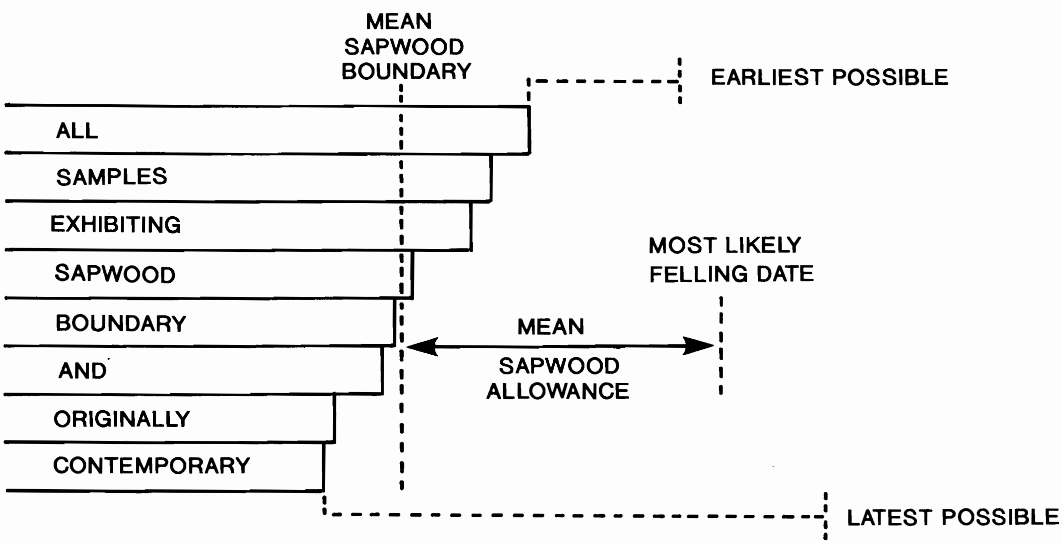
So, with the loss of sapwood there is an immediate and serious step-down in dendrochronological accuracy from those marvellously precise examples where the sapwood was complete. Fig. 1.4 illustrates the problem. In **Fig. 1.4c** we see two timbers with complete sapwood and two with definite heartwood/sapwood boundaries. In this case the estimated felling dates are 'not inconsistent with' all the timbers having been felled in the same year. However, that is quite different from being able to say that they *were* all felled in the same year, the case with Fig. 1.4a. In **Fig. 1.4d** we have several timbers without any trace of sapwood and in each case felling could be within the range of the sapwood estimate *or later*, i.e. the estimated felling range is only a *terminus post quem*. In this case sensible interpretation rapidly breaks down: the timbers without sapwood could easily have been felled later than the sample with complete sapwood. Such problems can be accommodated where the timbers are all from a single structure and/or where archaeological information would infer simultaneous use. However, when timbers from different structures all have missing sapwood it can become impossible to assign any kind of relative dating.

An example of this is shown in **Fig. 1.4e** where the felling dates of timbers, from an early analysis of different Roman structures at Carlisle, could not be separated by tree-ring analysis (Eckstein *et al.* 1984). Interestingly, a later detailed analysis of a large sample of timbers from Carlisle, by Cathy Groves at Sheffield, did allow the isolation of detailed Roman building phases at Carlisle, starting in AD 72/73 and earlier than the traditional historical date of AD 79 based on Tacitus (Hillam 1992). From the point of view of this discussion, the building phases in AD 72/3–85 and AD 93–7 could only be separated with timbers with complete sapwood.

Such are the problems with incomplete samples, and other examples will be encountered below. The important point is that these interpretive difficulties are not in any way semantic. There are many quite genuine examples where potentially serious dating errors could occur if the concept of missing heartwood rings is ignored. In an early example from Hillsborough Fort in Co. Down, two timbers cut from the same parent tree, felled around AD 1660, had final heartwood rings at 1585 and 1488. Failure to recognize that truncation was a significant factor



1.5 Sapwood numbers for oaks from different areas within Europe showing an apparently systematic decrease with distance from the Atlantic (Baillie et al.1985)



1.6 Hollstein's proposed method for assessing the closest felling date from a group of timbers with missing sapwood (Hollstein 1980)

in this case could have led to estimated felling ranges of 1617±9 and 1520±9 respectively; dates too early by two and seven human generations. In such cases, where no evidence for sapwood exists, it is essential to state the uncertainty by adding 'or later' to any felling estimate, i.e. provide a *terminus post quem*.

Additional information on the effects of wood-working practice on sample completeness is given below (see Island MacHugh in Chapter 4). The subject of sapwood can become even more difficult when account is taken of factors such as importation. When making sapwood allowances it is obviously quite important to know the area of origin of the timbers involved (**Fig. 1.5** and Chapter 3).

Finally, on the subject of sapwood allowances, it is sometimes possible to rescue dating accuracy where a number of samples from a single phase all have clear heartwood/sapwood boundaries (**Fig. 1.6**). With the provision that only the sapwood is missing, and assuming that the timbers were originally felled at the same time, then the outermost heartwood years should be at distances from the felling date governed by the sapwood estimate and standard deviation (range). This approach essentially involves finding the *mean* sapwood boundary and adding on the *mean* sapwood allowance. Although this approach seems eminently sensible, the fact that sapwood estimates are mostly skewed distributions complicates the issue somewhat (Fig. 1.5).

Building a chronology

Having outlined the ways in which the dendrochronological method works, we can, by way of an example, trace the development of chronology construction in the British Isles during the 1970s. What follows is essentially a précis of *Tree-Ring Dating and Archaeology* (Baillie 1982, from here on referred to as '*TRDA*'). This serves two functions. It acts as an extended introduction for those not familiar with dendrochronology and it sets the scene for several aspects of the remainder of the volume.

The first stage in building an indigenous tree-ring chronology is to choose a suitable species. The requirements are stringent:

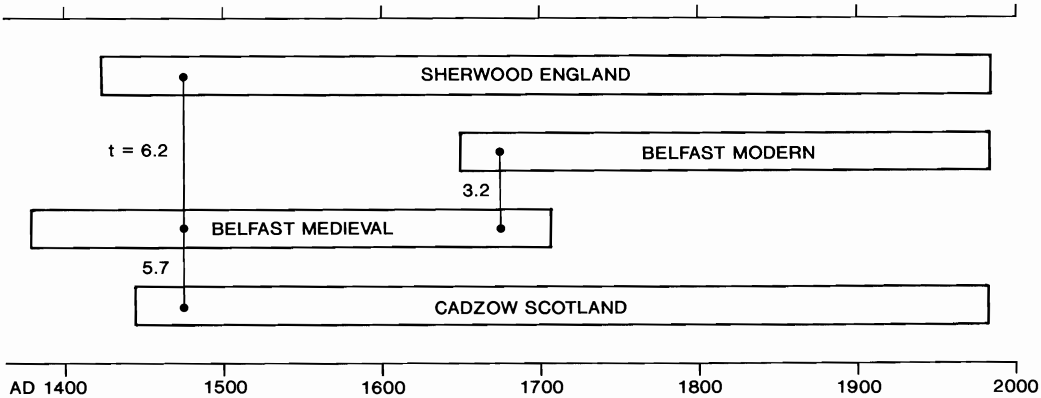
1) The species has to be long lived – or it will never be possible to significantly extend the chronology, all the overlaps being taken up in the matching process.
2) The species has to be available from all periods – otherwise a continuous chronology will be impossible.
3) The species has to be a good subject for dendrochronology – it has to exhibit cross-dating.

These three criteria have so far restricted most north European dendrochronology, and the really long chronologies, to oak. However, other species have received attention in Germany, Scandinavia and Switzerland where extensive use has been made of conifers (Schweingruber 1983). One recent climate reconstruction has been based on a Fennoscandinavian pine chronology which extends back to AD 500 (Briffa *et al.* 1990) and it is reported that a 7000-year chronology has been outlined in the area with only one or two gaps (Keith Briffa and Pentti Zetterberg pers. comm.).

Modern trees

Having selected a species for chronology building, modern samples are acquired to form the anchor in time. These modern samples of known felling or sampling dates also allow the cross-matching properties of the species to be investigated (a variety of corers exist which allow non-destructive sampling of living trees). Clearly, if the method is not capable of cross-dating known-age test samples there would be little hope of building a long chronology. In most European studies the modern samples have also supplied some information on tree-age, measurement difficulties, missing or absent rings and, in the case of oak, sapwood properties.

The choice of study area is potentially critical. For example, having chosen to build a long chronology in Ireland, in part because of the large numbers of prehistoric bog oaks, it turned out that Ireland, for complex reasons, has no really long-lived modern oak trees. The oldest Irish oak, so far discovered, ran back only to 1649. In Scotland, living trees were found with ring patterns which stretched back to 1444 (from Cadzow near Hamilton), while in England Sherwood Forest specimens ran back to 1425. However, while it might have proved easier to build a medieval chronology in Scotland, it would have been next to impossible to extend that chronology into the prehistoric period. So, while the medieval section may have been more

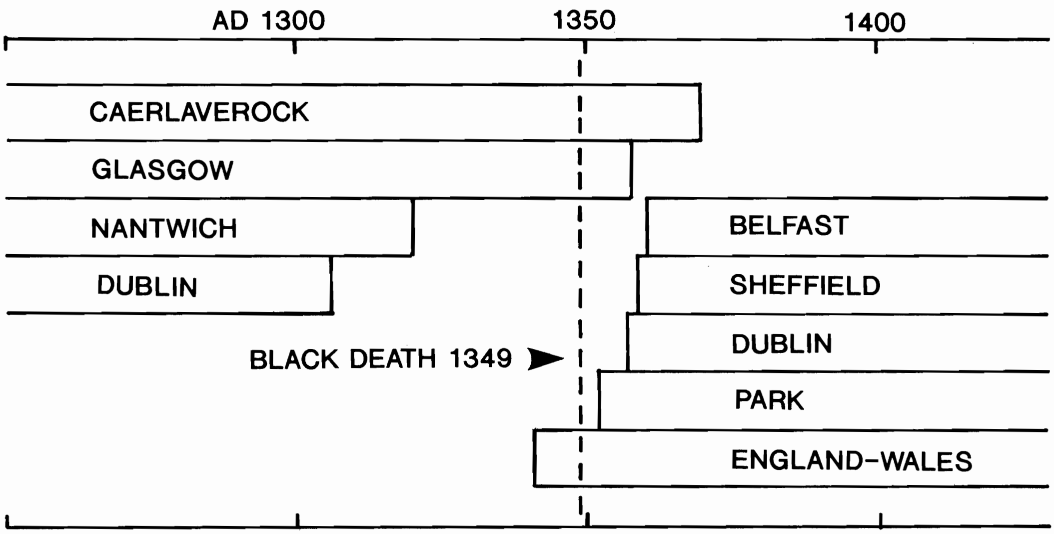


1.7 Placement of the original Belfast medieval chronology was based on a 68-year overlap with a t value of only 3.2. This was later confirmed to be correct by consistent links to two living-tree chronologies from Britain

difficult in Ireland, it was a necessary precursor to the long bog-oak chronology. In retrospect, the difficulties experienced with medieval overlaps in Ireland forced us to face all the questions associated with cross-matching at an early stage (Baillie 1973). Constructing a chronology back to 1380 required the linking of ring patterns from living trees to historic timbers, a link which could subsequently be tested by direct cross-dating to the English and Scottish living-tree chronologies (**Fig. 1.7**). This is a classic example of how extensive replication can confer *absolute certainty* on the dating of a section of ring pattern.

The Middle Ages

By the mid-1970s, with an Irish chronology successfully extended back to the fourteenth century, another problem was encountered. Chronologies existed for both the north of



1.8 Oak chronologies from the British Isles show clear evidence for a major regeneration phase, just at the time of the Black Death, in the mid-fourteenth century

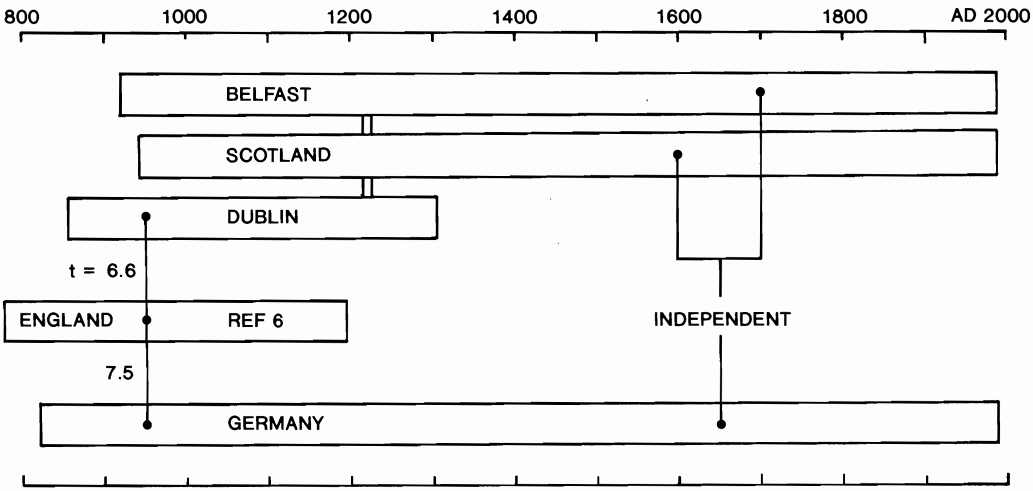
Ireland and the Dublin area covering the tenth–fourteenth centuries. It proved extremely difficult to bridge back across the fourteenth century to link with these earlier chronologies. It became apparent that there was a 'depletion/regeneration' phase *c.* 1350 (**Fig. 1.8**). The same problem had shown up elsewhere, in both England and northern Germany, and it was possible to suggest that this tree-ring hiatus was due to the effects of the Black Death which swept through Europe just at that time. The difficulties associated with attempting to build chronologies across both the seventeenth and the fourteenth centuries in Ireland were the first clues that tree-ring studies could give information of a 'socio-economic' character (see Chapter 8).

Although it took a considerable time, timbers were eventually found in Ireland which allowed the chronology to be extended across the fourteenth century. By 1977 the Belfast chronology ran back to AD 1001 (Baillie 1977a), while the Dublin medieval chronology ran back to AD 855 (Baillie 1977b). This Dublin section was dated not only against the Belfast chronology but also against a parallel chronology from Scotland, which spanned AD 946 to the present (Baillie 1977c). (This Scottish chronology was the source of some considerable irony. While work had gone on from 1968 to 1977 to construct a Belfast chronology back to AD 1001, all the timbers required to construct a similar chronology in Scotland were acquired in a matter of a few months!) So, by 1977 chronologies had been produced in Ireland of an equivalent length to the pre-existing German chronologies of Hollstein and Huber-Giertz.

Replication

One highly significant finding, involving the Dublin chronology, related to the ultimate proof of the whole chronology system. It was discovered that there was a strong cross-correlation between the Dublin chronology and an English medieval chronology, Ref. 6 (Fletcher 1977), which had previously been dated against the German oak chronologies. This observation showed that a section of English chronology could be dated to the same end-year, 1193, against both Irish and German chronologies. QED: both chronologies must be in precise synchronization (**Fig. 1.9** shows the correlation values involved).

So it was possible to check the correctness of a chronology by replication against an independent chronology. This is termed *tertiary* replication. It was to become increasingly obvious that replication was the secret to successful chronology building. It occurs at three levels:



1.9 An early example of tertiary replication between independent chronologies. The English Ref 6 chronology dates to AD 1193 against both Irish and German chronologies

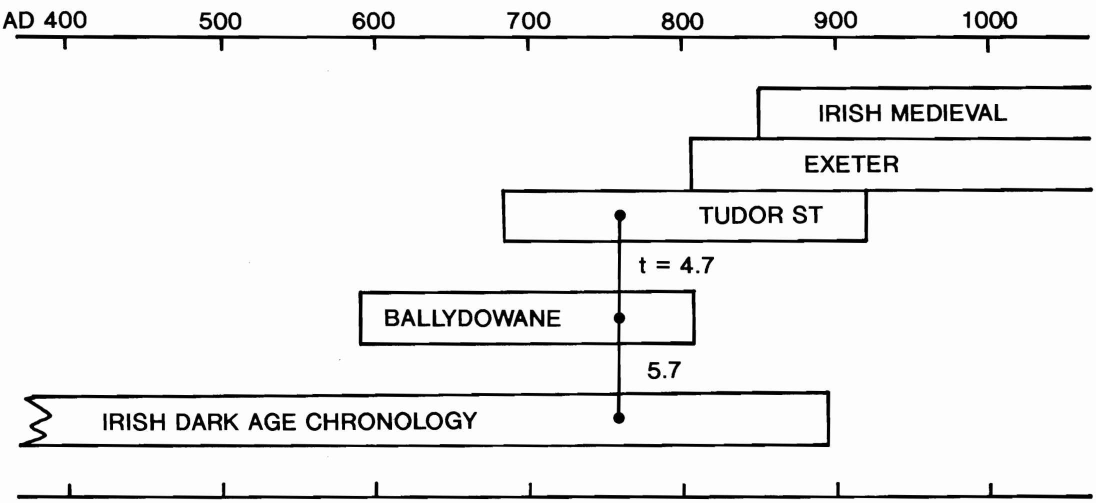
1) Primary replication is provided by the matches between the individual ring patterns which go to make up a site chronology.
2) Secondary replication is provided by comparisons between independent site chronologies which tend to be both longer and, because of their internal replication, more robust than individual ring patterns.
3) Tertiary replication, which provides the ultimate test, involves correlations between the chronologies of independent workers; see Chapter 2.

Replication is the factor which allows dendrochronologists to have confidence in their procedures. A dendrochronologist can not only claim that a chronology is precisely correct on the basis of in-house primary and secondary replication, but can demonstrate independent verification using tertiary replication.

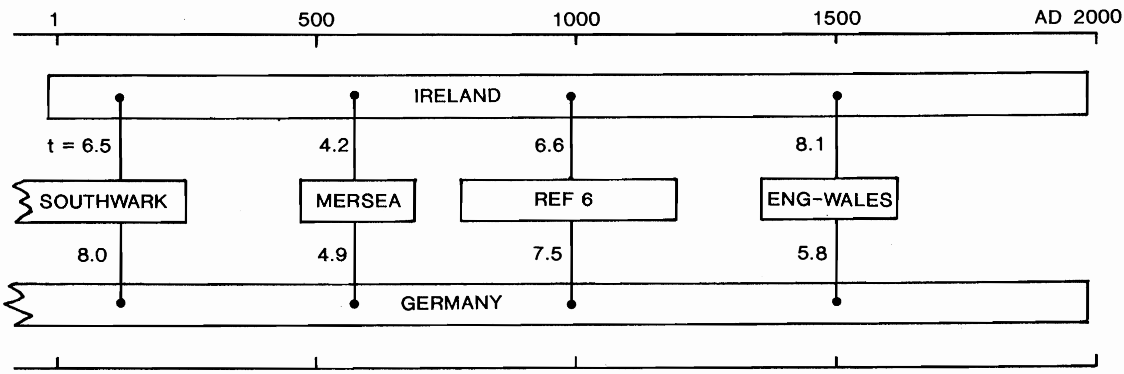
The first millennium AD

With the Irish chronology pushed back to the ninth century AD, another gap problem was encountered. A long archaeological chronology was known, on both general archaeological grounds and on radiocarbon evidence, to span approximately the first eight centuries AD. Continuous sample collection throughout the 1970s failed to provide any link between the Dublin chronology (which ran back to AD 855) and this Dark Age chronology (Baillie 1979). It was clear that the problem was centred on the ninth century AD. At this stage in chronology construction no continuous oak chronologies were published for this period from any part of Europe. Becker and Delorme (1978) had formalized the case for central Europe, showing chronological breaks in the third century and around AD 800. So pushing back into the Dark Ages was literally stepping into the dark!

However, it was noted by Jennifer Hillam that the Dublin chronology cross-dated extraordinarily well with a chronology from Exeter, in the south-west of England, which in turn matched with a chronology from Tudor Street, London, which spanned AD 682–918 (Hillam 1981). Combined with the successful stepwise correlations from Dublin to Ref. 6 to Germany, it seemed possible that the solution to the ninth-century Irish gap lay in links to English chronologies. The crucial breakthrough came in early 1980 when a new chronology, from Ballydowane West, Co. Waterford, cross-dated against both the existing Irish Dark Age chronology and against Tudor Street. This link, from the south-east of Ireland, confirmed that the Dark



1.10 English chronologies, from Tudor Street, London, and Exeter, provided a key link across the ninth-century Irish 'gap'



1.11 Full tertiary replication of the European oak chronologies for the last two millennia showing consistent stepwise correlations from Ireland to England to Germany

Age chronology spanned AD 894–13 BC (**Fig. 1.10**). So the chronology had overlapped, by 40 years, with the older end of the Dublin chronology; an overlap much too short to serve as a basis for a substantive dendrochronological link.

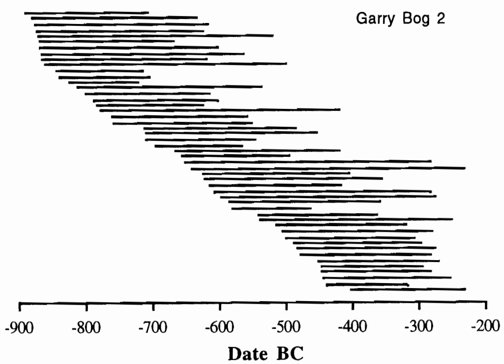
As with so much research, any glory associated with the completion of a two-millennia chronology was short-lived: in 1980 Hollstein published his German oak chronologies back to 724 BC. However, this independent German chronology, and others dated against it, did allow confirmation of the dating of the Irish chronology by further stepwise correlations (**Fig. 1.11**) (Baillie 1982). So 1980 saw a major consolidation phase in the dendrochronology of the first millennium AD in northern Europe. Precise dating was available, against replicated chronologies, for the whole of the last 2000 years.

Prehistoric chronologies

During the 1970s, while a lot of effort was going into the completion of the AD chronologies, workers in Ireland and Germany were pushing ahead with the construction of long prehistoric oak chronologies. There were different reasons for the work in different areas. In Ireland the principal aim was high-precision radiocarbon calibration, with archaeological dating viewed as a natural spin-off. In Germany there was a wide range of motivation, which included radiocarbon calibration and studies of river valley development as well as quests for palaeoecological and archaeological information.

The approach to building prehistoric chronologies was necessarily different from that applied to the last two millennia. In the AD era most of the timbers were archaeological and at least some general time-control was available from archaeological evidence and building history. In the prehistoric period most of the timbers were sub-fossil. These are naturally preserved oak trunks which occur in two principal contexts, namely peat bogs and river gravels. In the former case the oaks originally grew on the surface of peat bogs; though just to complicate matters some grew on mineral soils and were subsequently buried in peat. After death and burial, bog oaks were preserved as stumps or trunks at the spot where they grew. With river-gravel oaks the trees were presumably washed out from eroding river banks by fluvial action so that they are no longer *in situ*. Such different sources suggest that different types of environmental information may be recorded by these trees, in terms both of climate response and the information contained in their accumulated growth initiation and death phases.

The approach to building sub-fossil chronologies was conditioned by the fact that most of the trees came without stratigraphic or other dating information. As a result they had to be treated as random samples. However, it was quickly apparent that 'random' did not imply 'completely different dates'. It was observed that trees from one location tended to cluster in time, i.e. many of their ring patterns cross-dated. In retrospect this is sensible because, at any given location, the



1.12 The individual tree-ring patterns making up the Garry Bog 2 chronology, plotted by start-year, showing regeneration over five centuries

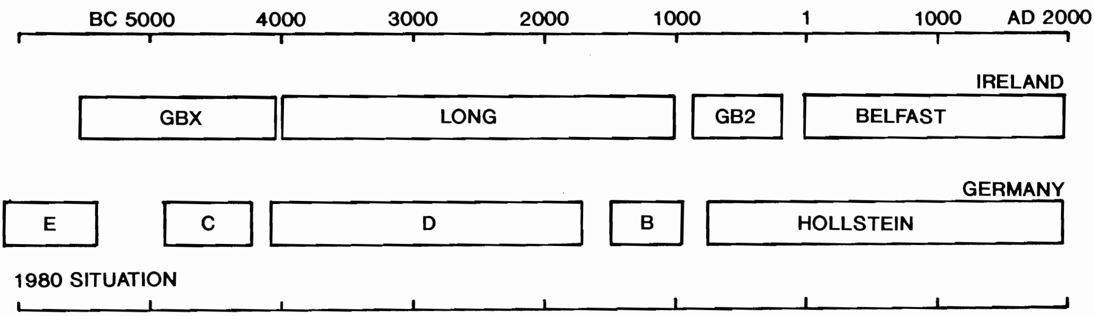
trees were originally part of a regenerating system. This is demonstrably the case because at most sites the trees not only cluster but tend to be staggered through time (**Fig. 1.12**).

Inevitably all workers aimed towards the construction of robust site chronologies, exploiting the regenerating character of the assemblages. Sub-fossil site chronologies could be much longer than the lifespan of individual trees and were, of course, more robust units because of their internal replication. So workers built site chronologies and used these long series as the building blocks of the overall chronology. Computer comparisons allowed the testing of every possible position of chronology overlap. Matches between site chronologies extended site chronologies into major units of chronology, while further site chronologies provided secondary replication confirming established links, and so on.

By 1980 it was clear that the Irish and German prehistoric chronologies were at a very similar stage of near completion (**Fig. 1.13**). The problem was, of course, that they were *not* complete. By that stage the whole nature of chronology construction had changed. While all the early work had relied on random sampling to 'fill up time', by 1980, with only a few specified gaps remaining, it became necessary to find timbers of specific ages to bridge those gaps. That posed a whole new set of problems; for example, where do you go to find timbers which grew across the tenth century BC? Were the gaps purely a sampling problem, whereby more and more samples would eventually bridge the remaining gaps, or was there something more to the gaps? Was it possible that environmental events had interrupted the survival of oaks so severely at some points that it would prove impossible to complete the chronologies? These were some of the questions which were current when *TRDA* (Baillie 1982) was being written.

1980 conclusions

It is interesting from the perspective of the 1990s to look back at the conclusions which were written in 1980. Firstly, there were questions hanging over the completion of the long chronologies. If the gaps in the Irish chronology, in the first centuries BC and in the tenth century BC, were due to some sort of widespread depletions, then it might never be possible to bridge those gaps within Ireland. There is no doubt that at that time there



1.13 The 1980 status of the European long chronologies showing almost equal progress, and very similar distributions of remaining gaps. Chronology sections E, C, D and B from Becker and Delorme (1978) were grounds for pessimism.

The failure to complete the prehistoric chronologies left another piece of unfinished business. Until the European oak chronologies were complete and replicated, it was not going to be possible to complete the high-precision radiocarbon calibration curves. As an independent European calibration was necessary to check the original Suess calibration (Suess 1970), the completion of the tree-ring chronologies was fundamentally important.

The one other outstanding problem, in 1980, was that relating to the so-called art-historical chronologies in England (Fletcher 1977, 1978a). These chronologies, constructed from art-historical boards, failed to show any cross-dating with the other, apparently indigenous, oak chronologies from the British Isles. One obvious solution was that the art-historical chronologies represented imported timbers from an 'exotic' source. Unfortunately, because such a suggestion had implications for the dating of the same chronologies, this suggestion was bitterly contested. This was obviously a question which was going to have to be resolved (see Chapter 3).

The two other future projections, back in 1980, related to the possibilities of climatic reconstruction and chronological coverage. It is interesting to see statements such as 'It seems likely that between the three methods, widths, densities and isotopic ratios, notwithstanding other approaches which may become available [*sic*], it should be possible to make adequate reconstructions for the last thousand years with thinner but none-the-less useful extrapolations well back into the post-glacial' (Baillie 1982: 250). In some ways we are only marginally further forward today although one of those 'other approaches' does appear to have paid off handsomely (see Chapters 5, 6 and 7). In the following chapters I will deal with the unfinished business from the early 1980s and show how dendrochronology has moved forward on many fronts.