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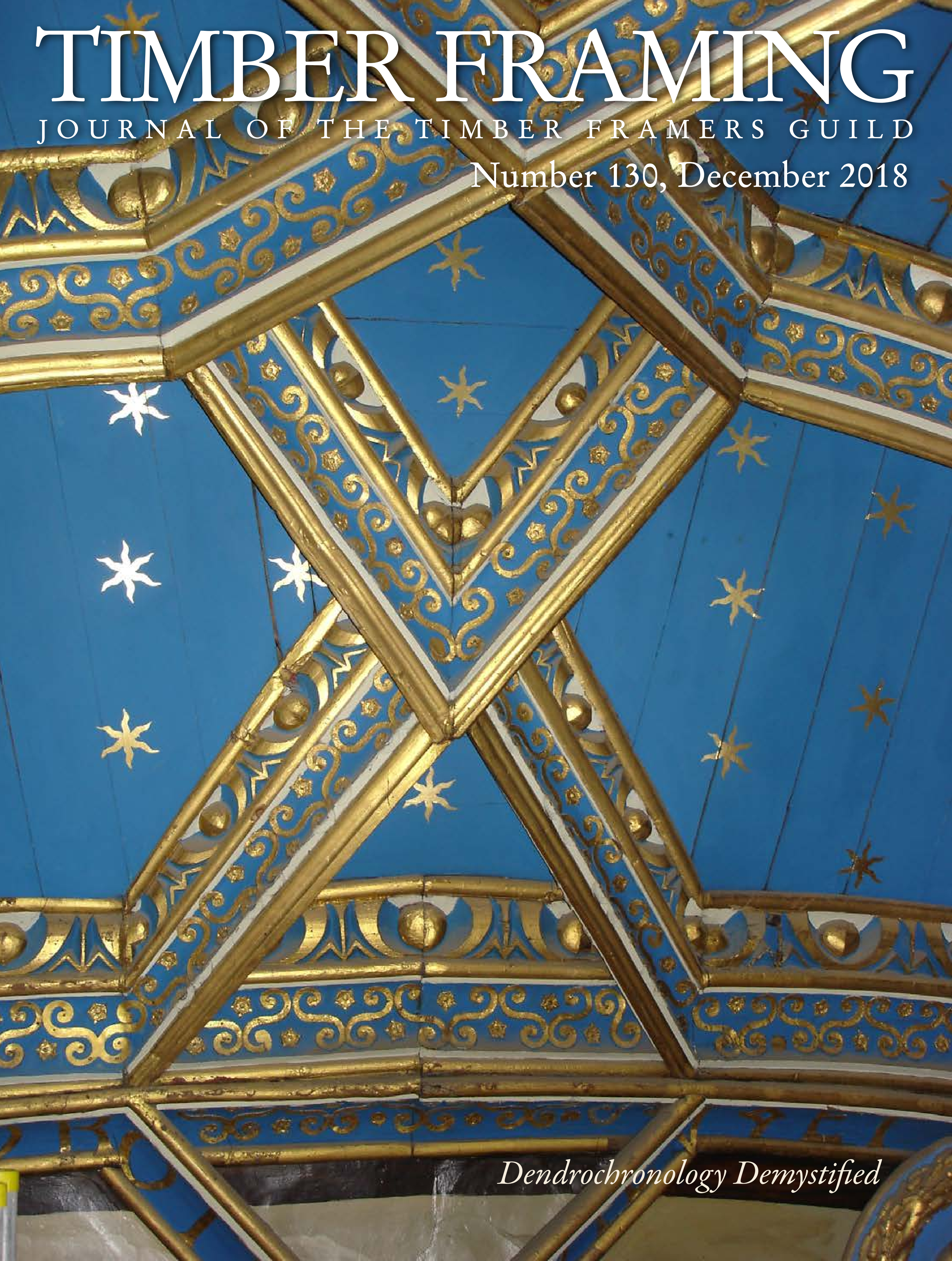
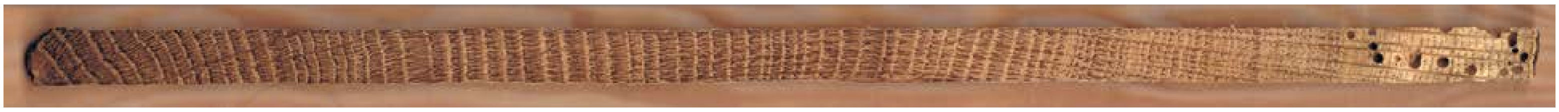


Dendrochronology Demystified



Images by Daniel Miles, except where noted

Unlocking the Hidden History of Timber

BENEATH the surface of every timber lies a volume of history, written in the grain of the wood itself. Secrets teased from tree rings can tell us when a timber frame was first built, and also where and when a tree grew, storms and fires it experienced, and the influence of man on its environment. New research into certain isotope levels can even reveal how much sunlight and rainfall a tree received in each growing season of its life, a record written in wood perhaps hundreds of years ago.

The technique of dendrochronology, or tree-ring dating, is basically a very simple one—it is the variation in the width of annual growth rings which is studied. In a hot, dry, growing season, the growth ring will be very narrow, in warm, wet years, the growth ring will be wider, and all the variations in between. These seasonal variations in climate-induced growth, reflected in the varying width of a series of measured annual rings, are compared with other, previously dated, ring sequences to ascribe precise dates to each ring.

Dendrochronology can illuminate whether variation in felling dates shows that a building was constructed in one concerted campaign, with timber felled for the purpose, or if timbers were gathered over a period of years in anticipation of construction. Sometimes timbers were obtained from a market rather than specifically felled, and that too will show up in the cross-matching. Others could be windfalls which might have lain prone in the forest, partly growing, until salvaged. Or they may have died standing due to old age and competition.

Sometimes other environmental details can be deduced. Trees growing in an established virgin forest will often start with very narrow growth rings for the first few decades, and then suddenly increase in growth rate as the tree reaches the upper story of the canopy. Alternatively, the trees might be second-growth, with wide rings from copious light initially, but narrowing rings as they start to crowd each other, reducing their canopies.

Intrusions in the forest by man are also recorded in the tree rings. When a single tree is felled, its neighbors will have a sudden burst of growth due to the additional light coming down into the forest through the hole left by the felled tree. Sometimes an attack of caterpillars can defoliate a tree, stunting its growth for a year or more. Storm damage can also be recorded in narrower rings, and the ancient custom of pollarding a tree can cause it to almost die, usually taking a decade or more to recover. These sorts of influences will often make a tree undatable.

What Is Dendrochronology and How Does It Work?

Over the past 40 years, dendrochronology has become one of the leading and most accurate scientific dating techniques. The name derives from the Greek *dendron* (tree) and the Latin *chronos* (time). While not always successful, when it does work it is precise, often to the season of the year. Tree-ring dating to this degree of precision is well known for its use in dating historic buildings and archaeological timbers. However, more ancillary objects such as doors, furniture, panel paintings and wooden boards in medieval book bindings can sometimes also be successfully dated.

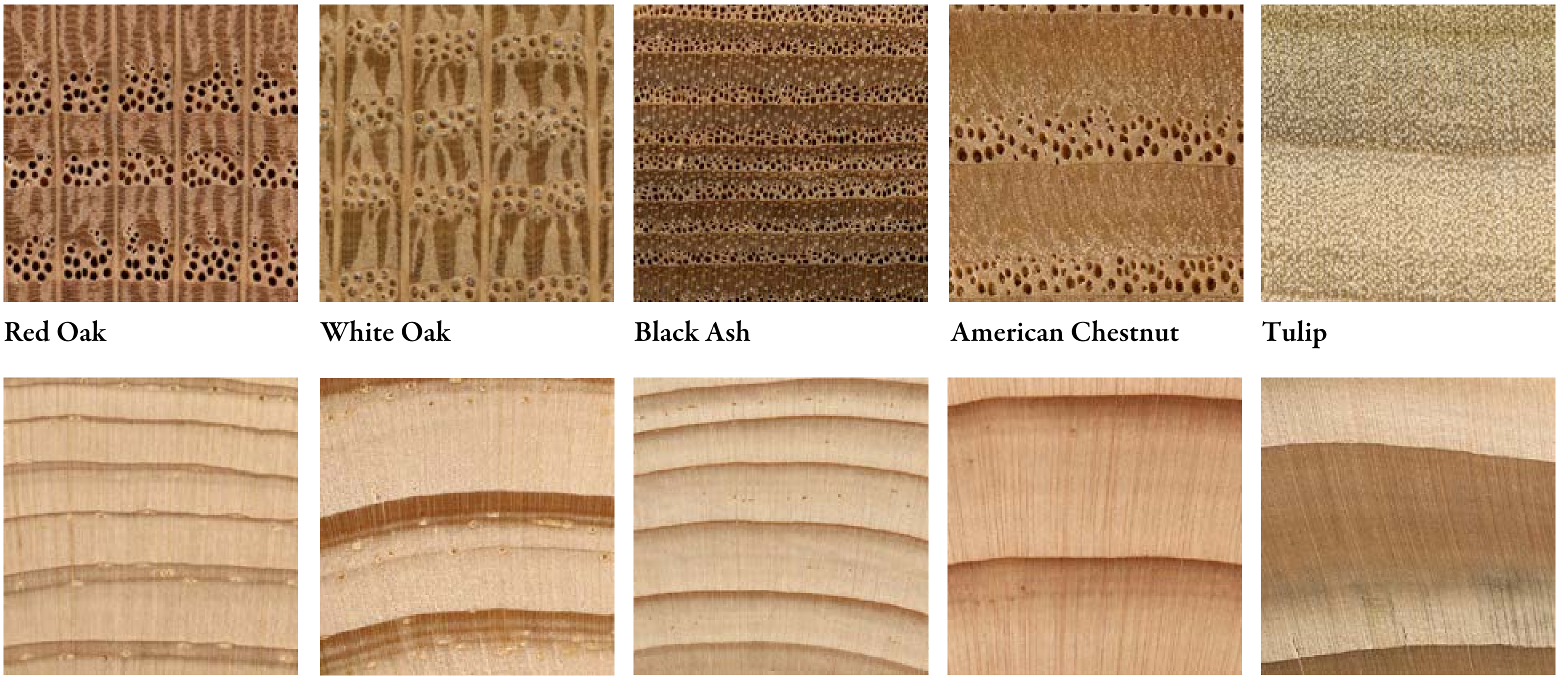
1 Core sample from Chirk Castle, Flintshire, Northeast Wales. With its last full ring dating to 1600, plus large, spring vessels from the following year, this timber was felled in spring 1601. The full sample included 126 growth rings, including 28 full sapwood rings, visible here.

The science of dendrochronology is based on a combination of biology and statistics. Fundamental to understanding how dendrochronology works is the phenomenon of tree growth. Trees grow through the addition of both elongation and radial increments. The elongation takes place at the terminal portions of the shoots, branches and roots, while the radial increment is added by the cambium, the zone of living cells between the wood and the bark. In general terms, a tree can be described as a cone, with a new layer being added to the outside each year in temperate zones, making it wider and taller.

An annual ring is composed of the growth that takes place during the spring and summer, continuing until about November, when deciduous trees shed their leaves, and the tree becomes dormant for the winter. For the two principal American oaks, the white and red (*Quercus alba* L. and *Q. rubra* L.), as well as black ash (*Fraxinus nigra* Marshall), and many other species, the annual ring is composed of two distinct parts: the spring growth or early wood, and the summer growth, or late wood. Early wood is composed of large vessels formed during the period of shoot growth that takes place between March and May, before the establishment of any significant leaf growth, using most of the energy and raw materials laid down the previous year. There is an abrupt change at the time of leaf expansion around May or June, when hormonal activity changes the quality of the spring vessels. This summer, or late wood, becomes increasingly fibrous and contains much smaller vessels. Trees with this type of growth pattern are known as ring-porous, and are distinguished by the contrast between the open, light-colored early wood vessels and the dense, darker-colored late wood (Fig. 2).

Other species of tree are known as diffuse-porous, this group including the tulip, or yellow-poplar (*Liriodendron tulipifera* L.) and beech (*Fagus grandifolia* Ehrh. or *sylvatica* L.). Unlike ring-porous trees, these have very small spring vessels (or early wood) that become even smaller advancing into the summer growth. The annual growth rings are often very difficult to distinguish, even under a powerful microscope.

Then there are the softwoods, which includes the soft pines such as the eastern white pine (*Pinus strobus*) and the hard pines such as the southern yellow pine (*Pinus* spp.), which have large, Images courtesy Wood-Database.com



Red Oak · White Oak · Black Ash · American Chestnut · Tulip

Eastern White Pine · Southern Yellow Pine · Red Spruce · Douglas Fir · Eastern Hemlock

2 Tree ring cross-sections. Hardwoods in top row, all ring-porous except diffuse-porous tulip. In bottom row, the pines have large, evenly-distributed resin canals, whereas these are small in Douglas fir and absent in eastern hemlock.

evenly distributed resin canals (see Hoadley 1990). Softwoods with small resin canals include the Douglas fir (*Pseudotsuga menziesii*) and eastern spruce (*Picae* spp.), while others have no resin canals, including the eastern hemlock (*Tsuga canadensis*) and bald cypress (*Taxodium distichum*).

The species most useful for dendrochronology in timber-framed buildings are the oaks, then the hard and soft pines. Other species, such as ash and walnut, can sometimes be cross-matched with the oak chronologies, while beech and, particularly, elm have proved difficult to date in Britain. The deciduous oak has the extremely useful habit of nearly always putting on a growth ring, no matter how narrow.

Dendrochronology is essentially a two-stage procedure. The first part studies the variation in the width of the annual rings as influenced by climatic conditions common to a large area, as opposed to other more local factors such as woodland competition and insect attack. It is this climate-induced variation in ring widths that allow calendar dates to be ascribed to an undated timber when compared to a firmly dated sequence.

Once the ring sequences have been compared and *cross-dated* with firmly-dated *reference chronologies*, the sample timber requires interpretation regarding its felling date. This second stage depends on the completeness of the final ring and waney, or bark, edge.

If a tree section is complete to the waney edge, an exact date of felling can be determined, precise to the season, depending on the degree of formation of the outermost tree ring. A waney edge with spring vessels formed but no summer growth was felled in the spring, although it is not possible to say in which particular month (Fig. 1). If the last ring beneath the bark edge is complete (and measured), then the tree was felled in the winter, when it was dormant.

Hence, the most important requirement for dendrochronological interpretation is the presence of waney edge and sapwood—the band of growth rings immediately beneath the bark that transports the sap from the roots to the leaves. In time, the sapwood becomes heartwood, which is generally darker in color and often with spring vessels blocked by tyloses, waste products of the tree's growth. The heartwood is dead tissue, whereas the sapwood is living, although the only growing cells are in the cambium, immediately beneath the bark. In the American white oak, the difference in color is sometimes not great, but the spring vessels are often filled by tyloses to within a year or two of the terminal ring. Conversely, the spring vessels in the American red oak are almost all free of tyloses, right to the pith. Generally, the sapwood retains stored food attractive to insect and fungal attack once the tree is felled and, therefore, is often removed during conversion.

The Development of Dendrochronology as a Science

A. E. Douglass began dendrochronology in the US with a careful examination of California's giant sequoias in 1915, initially to aid in the study of sunspots. In 1937, he established the Laboratory of Tree-Ring Research at the University of Arizona to study the pines of the arid southwest. In building up a chronology for this study, older and older sections of wood were used, with the added benefit of being able to ascribe dates to Native American pueblos of New Mexico.

In one of the earliest examples of cross-dating, in 1904, Douglass compared a stump with a yellow pine chronology from Flagstaff, Arizona, and determined that the tree had been felled in 1894 (Baillie 1982, 31). Initially, the Arizona scientists used *skeleton plotting*, where a ring is recorded on a scale plot as being narrow, normal, or wide. Amazingly, some of these pioneers were able to visually identify patterns in the plots corresponding to particular dates. Later, the annual rings were actually measured, and the variations in ring width compared with various statistical methods.

These early practitioners were able to produce chronologies, predominantly for pines, which stretched back to 701 CE, and allowed many earlier Native American structures to be dated, including Aztec ruins and Pueblo Bonito in New Mexico. However, problems included the phenomena of locally absent rings, where, during a particularly severe growing season, a growth ring will only occur on one side of a tree stem, and lensing, where several growth rings will become so narrow in one part of the circumference that they will merge into one band, making it difficult to identify each growth ring conclusively. Replication, both within a single timber or tree and between trees, was essential to allow these chronologies to be constructed.

Research in Europe had begun in the 1880s as Dutch astronomer J. C. Kapteyn measured a series of different radii from a group of Dutch and German oaks and then used cross-dating to confirm the relative matching (Baillie 1982, 37). He constructed and compared a number of *mean site chronologies* extending back several hundred years.

Other related research in Europe led to B. Huber constructing a 1000-year chronology for German oaks in 1963, subsequently extended back to 700 BCE by E. Hollstein. In 2004, M. Freidrich constructed a Holocene oak chronology extending back to 8480 BCE and one for Pre-Boreal pine to 10,461 BCE, mainly based on subfossil trees preserved in waterlogged conditions, such as river terraces.

In Northern Ireland, M. G. L. Baillie managed to build up several well-replicated chronologies: a modern chronology spanning the years 25 CE to present and a prehistoric chronology spanning the years 5150 to 1050 BCE. Baillie also wrote *Tree-Ring Dating and Archaeology*, published in 1982, which is an excellent primer and textbook on all aspects of dendrochronology and dating from an Irish perspective.

In Britain, work was not so straightforward, but pioneers such as Baillie, from Belfast, and J. M. Fletcher, from Oxford, still managed to get the science established in the late 1970s and 1980s. As his last student, the author began working with Fletcher in 1986 and later, on his death, with the Ancient Monuments Laboratory of English Heritage (Historic Buildings and Monuments Commission) in 1987.

Returning to the US, the Lamont-Doherty Earth Observatory at Columbia University, New York, was founded in 1975 by Dr. Edward Cook and Dr. Gordon Jacoby mainly to study paleoclimatology and for climate research. Together with Paul Krusic and others, the Lab produced excellent pioneering work, with a by-product of nine well-replicated regional oak tree-ring chronologies covering the eastern seaboard from Virginia to Maine. In addition, Dr. Cook has contributed vast amounts of tree-ring data to the International Tree-Ring Data Bank (ITRDB) in Colorado.

On the East Coast of the United States, and particularly in the Northeast, historic timbers clung tenaciously to their secrets for some time. Several attempts, initiated by Abbott Lowell Cummings of the Society for the Preservation of New England Antiquities (SPNEA, now Historic New England), were made over the years to build up a reference chronology to accurately date the historic timber-framed buildings of eastern Massachusetts. The first was undertaken in 1968 by Frank Demers. He sampled some seven buildings and attempted to cross-date them to create a *floating chronology*, an established but undated sequence, showing that cross-matching was possible. Unfortunately, skeleton plotting was not an effective method of matching up the more *complacent* (wider growth rings with less variation) hardwood timbers from the East Coast of the United States. A good account of the early days of Massachusetts dendrochronology can be found in Krusic and Cook 2001.

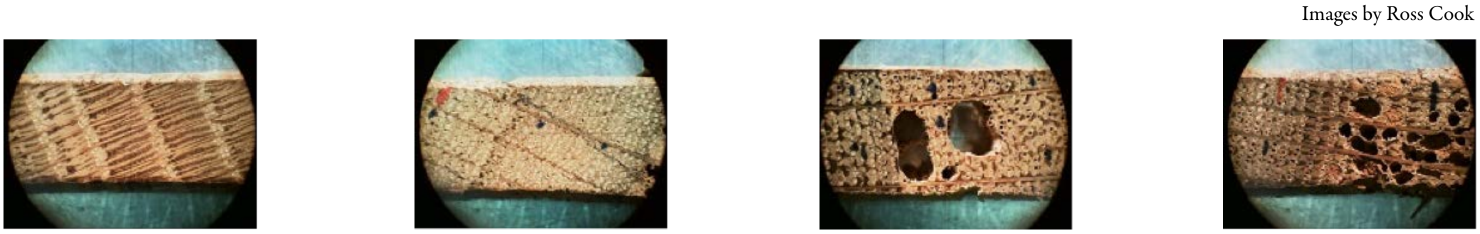
In 1975, a team from the University of Arizona sampled a dozen buildings around Boston, including some of those studied by Frank Demers. Conclusive cross-matching was hampered by the small number of samples and, although the samples were actually measured, no relevant reference chronologies were available at that time. However, this corpus of measured ring sequences has recently proven to be a valuable resource.

The real breakthrough occurred in the 1990s when the Columbia Lab combined the study of the Saugus Iron Works House and site (Saugus, Mass.) with a red oak chronology from standing trees on Mount Wachusett (Princeton, Mass.) dating back to 1672. This is likened to the Rosetta stone for New England dendrochronology and led to the Boston Dendrochronology Project, by the Massachusetts Historic Commission in cooperation with SPNEA's Anne A. Grady. The project sampled six buildings of known construction dates between 1681 and 1785 to bridge the gap between the Saugus and Wachusett chronologies to establish the BOSTON01 chronology, spanning the years 1513–1996 (Krusic and Cook 2001) (see also "Dendrochronology for Timber Frame Dating in the Northeast," TF 81).

Several subsequent projects coordinated by Grady gradually expanded the corpus of dated buildings and individual site chronologies westward to central Massachusetts and into neighboring Maine, Rhode Island, Connecticut and Long Island, New York (Miles et al 2002, 2003, 2005a and 2005b). By 2005, over 60 individual site reference chronologies and two well-replicated regional chronologies had been established.

In 2002, when the author started dating buildings in Virginia and Maryland, the Columbia Lab provided access to these and other unpublished reference chronologies, an offer reciprocated with other material dated from the area. This sort of exchange is vital to the development of dendrochronology, allowing for the expansion and verification of the science in a peer-reviewed manner. Unfortunately, validation in a similar manner never happened with Dr. Jack Heikennan's research, which used his patented "key-year" method of matching, leading to suspicion and discrediting of his

Images by Ross Cook



Rings too wide — Rings too narrow — Beetle-infested sapwood — Beetle-infested sapwood

3 Common problems in core samples. Note the clear transition from beetle-infested sapwood to sound heartwood.

4 Michael Cuba core sampling a floor joist at the Mary Washington House, Fredericksburg, Va.

work, mostly in the Chesapeake area. However, work by the author has corroborated his dating of a few structures, such as the 1724 Lynnhaven House (Virginia Beach, Va.).

The Dendrochronology Process The aim of sampling a phase of building, or an archaeological feature, is to take sufficient samples to ensure that the timbers selected are representative of the structure—to be confident that they have not been reused from an older building, are later repairs, or both. Generally, between six and ten well-provenanced samples are taken from a single phase to ensure that they are primary first-use timbers. This number of samples also gives a good chance to average out any individual growth irregularities in the trees.

To obtain good samples, one needs access to as much of the timber frame as possible, which is often hampered by finishes such as plasterwork, flooring, etc. The rare times when a building is being restored, repaired, or extended and hidden timbers exposed—when Guild members are likely involved—are ideal for sampling.

Buildings are often constructed of large logs quartered or halved, and these typically give the best results for long ring sequences. However, historic timber-framed buildings were usually constructed of whole logs, only just large enough to be squared up, leaving waney edges on most sides. Understanding timber conversion is critical to good dendrochronology sampling. Hewn four sides means that the pith of the tree is in the center of the timber, and only half the diagonal distance of the cross-section is likely available for a ring sequence. Conversely, a sawn side, or two at right angles, will indicate a timber bulk that has been halved, or quartered, and able to yield twice the number of growth rings. Generally, growth rings are between 1mm and 2mm in width. Rings of 10mm are almost generally hopeless, and sometimes there can be too many rings, where the mean ring width is so exceptionally narrow that the rings can hardly be counted, let alone measured confidently. If samples obtained are poor in ring counts or other distortions, any subsequent analysis will be equally poor, or impossible (Fig. 3).

Of course, sampling is often hampered by the lack of suitable ring sequences in the available timbers. The primary strategy in selecting samples within a structure is to choose those with ring sequences that are likely to date. When these are of marginal quality, i.e., less than 75 rings, more than the average number of samples should be taken to increase the likelihood of the site dating. Another factor determining sample number is the presence of sapwood. To better understand the probable construction date of any phase of building, as many samples as possible with complete sapwood need to be taken. In a typical timber-framed building only one or two, and rarely more than five or six, samples with complete sapwood survive the initial conversion of the timbers and subsequent degradation and attrition over the ensuing centuries. Therefore, a priority in sampling is always to try to obtain as many samples as possible with bark edge and high ring counts.

The most economical method of sampling, though rarely the most useful, is to have sections of timber offcuts supplied by the client. However, their removal from a standing building suggests they were already fairly well decayed and the first casualty of decay is the critical outermost sapwood rings.

The most practical method of obtaining quality samples with minimal intervention in a standing historic building is through in situ sampling. While obtaining complete cross-sections is usually impractical and not in the best interest of the building, alternative, more conservative methods do exist. The principal method is using a 16mm hollow corer to extract a core approximately 10mm in diameter. These core bits are specially manufactured, having hardened steel teeth capable of cutting through steel—a necessity to cut through timber hardened by centuries of seasoning.

It can take up to 20 minutes to core sample a timber, so a safe working platform, good lighting and full concentration are essential (Fig. 4). A 1000-watt drill with gear reduction and variable speed is required to maintain low speed and avoid "hot work." Core holes taken from visible timbers in habitable areas of buildings are plugged with a ramin (*Gonystylus* spp.) dowel stained and distressed to match the surrounding surface. Other sampling techniques involve photography, impressions, and direct in situ measurements with a graticule, but these are uncommon or impractical for a variety of reasons.

Quality cores should have a sequence of at least 50 consecutive growth rings—100 is much more promising. The timber must be dry—oak timbers which have been exposed to rain and are damp will not core successfully. Timbers soaked through exposure to the weather can sometimes take a year to dry. Unventilated roof spaces can also build up high moisture levels in timbers. Sampled timbers must be accurately recorded. This is best done by the building recorder, if there is one, or on a set of plans. Latitude and longitude coordinates should also be included.

Once thoroughly dried in the laboratory, samples are prepared on a bench-mounted linisher, using 60- to 1200-grit abrasive paper, and cleaned with compressed air to allow the ring boundaries to be clearly distinguished (Figs. 5, 6). A 10x/30x microscope with traveling stage is used to measure ring width to 0.01mm precision (Fig. 7). Thus, each ring or year of a sample is represented by its measurement, arranged in a ring-width data set, with the earliest ring being placed at the beginning and concluding with the latest or outermost ring.

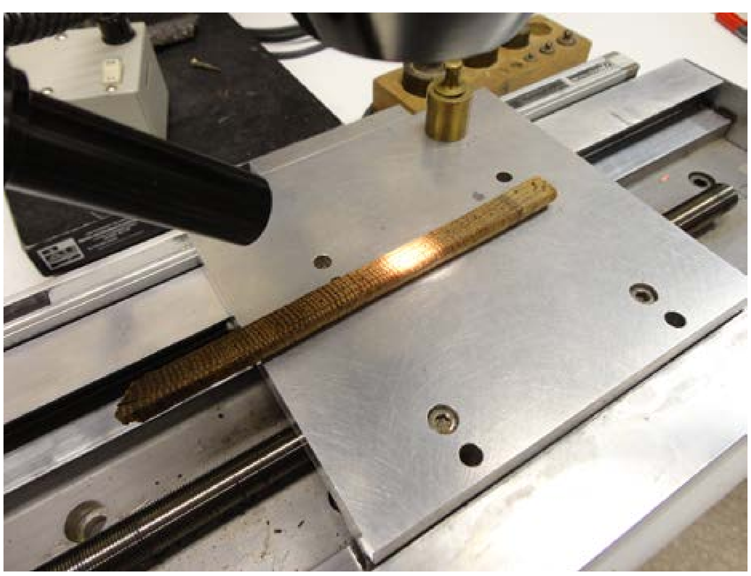
It is general practice to cross-match samples from within the same phase of a building to create a *site master* before comparing with reference chronologies. This has the advantage of averaging out the "noise" of individual trees and is likely to obtain higher *t*-values (see below) and stronger visual matches. To compile a site master, the ring-width series for each sample is plotted width against year on log-linear graph paper. The graphs of each sample are then compared visually at the positions indicated by computer matching and, if found satisfactory and consistent, are averaged to form a mean curve

5 Preparing core sample for analysis with linisher.

6 Core sample prepared for analysis.

for the site or phase. This mean curve and any unmatched individual sequences are compared against dated reference chronologies to obtain an absolute calendar date for each sequence (Fig. 8). Sometimes, especially in urban situations, timbers may have come from different sources and fail to match each other, making the compilation of a site master difficult. In this situation, samples must be compared individually with the reference chronologies.

A reliable and wide-ranging database of reference chronologies is vitally important. Usually, a site will match best with local chronologies. However, that is not always the case—a more replicated reference chronology further afield will often give better matches than a poorly replicated one close to hand (Bridge 2012). Additionally, different growing conditions will sometimes prove difficult to match samples or phases in a similar location, as the case study for Clermont, below, illustrates. Therefore, when cross-matching samples with each other or against reference chronologies, a combination of both visual matching and a process of qualified statistical comparison by computer is used.

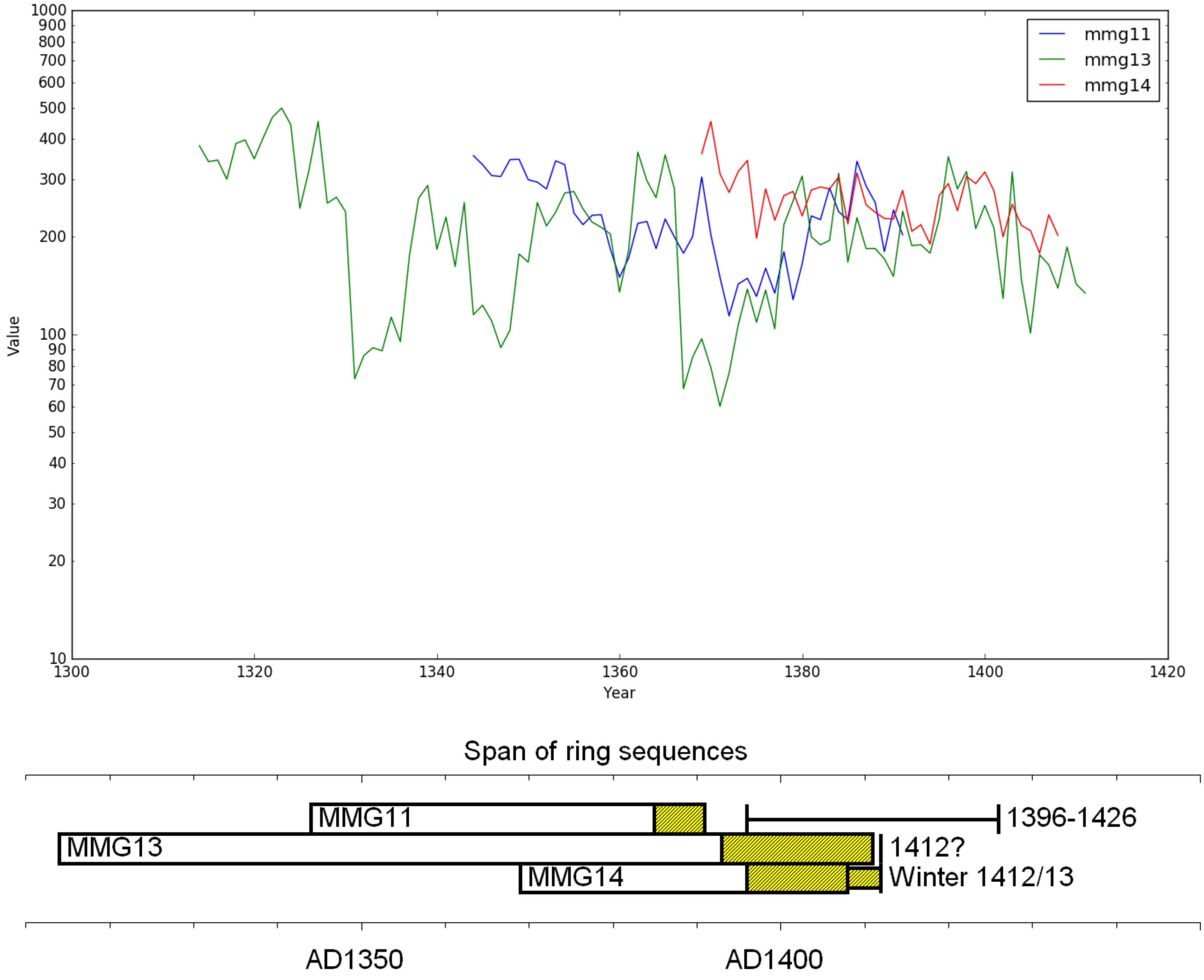


7 A traveling microscope stage facilitates accurate measurement of ring widths in each sample.

Student's *t*-value has been widely used among British dendrochronologists to statistically cross-correlate site masters with reference chronologies, commonly using algorithms derived from Baillie and Pilcher's CROS program (Baillie and Pilcher 1973), which vary slightly from the original Student's *t*. This has the distinct advantage of representing the strength of the match with a single short number, the *t*-value. In the United States, an alternative program, COFECHA, is often used. While COFECHA's output of a match between two sequences can fill half a page, and require a university degree to understand, it is designed for use with living trees, often pines, which have locally absent rings, and this program is ideal at identifying where in a data set such a defect might occur.

Generally, *t*-values over 3.5 should be considered significant, with a one-in-1000 chance of being incorrect given an overlap of 85 years, although in reality it is common to find demonstrably spurious *t*-values of 4 and 5 when more than one matching position is indicated. For this reason, dendrochronologists prefer to see some *t*-value ranges of 5, 6 or higher, and for these to be well replicated from different, independent chronologies with local and regional chronologies well represented. Users of dates also need to assess their validity critically. They should not have great faith in a date supported by a handful of *t*-values of 3 with one or two of 4, nor should they be entirely satisfied with a single high match of 5 or 6. Examples of spurious *t*-values in excess of 7 have been noted, so it is essential that matches with reference chronologies be well replicated, and that this is confirmed with visual matches between the two graphs. Matches with *t*-values of 10 or more between individual sequences usually signify having originated from the same parent tree when comparing oak.

In reality, the probability of a particular date being valid is itself a statistical measure depending on the *t*-values. Consideration must also be given to the lengths of the sequence being dated and the reference chronologies (e.g., Fowler and Bridge 2017). A sample with 30 or 40 years growth is likely to match with high *t*-values at many positions in a reference chronology, whereas a sample with 100 consecutive rings is much more likely to match significantly at only one unique position. Samples with ring counts as low as 50 may occasionally be dated, but only if the matches are very strong, clear and well replicated, with no other significant matching positions. This is essential for intra-site matching when dealing with such



Figures by Martin Bridge

8 Plots of ring width measurements for three samples from Maestorglwyd Barn, Breconshire, UK (1412), and corresponding bar diagram.

short sequences. Consideration should also be given to evaluating the reference chronology against which the samples have been matched—those with well-replicated components geographically near to the sampling site are given more weight than an individual site or sample from the opposite end of the country.

However, when timber has been imported from a distance, this will show up in the distribution of regional matches, allowing *dendro-provenancing* of sampled timbers (Bridge 2012). The case studies from England's Salisbury Cathedral and Virginia's Sherwood Forest Plantation illustrate this.

Once a tree-ring sequence has been firmly located in time, a felling date, or date range, is ascribed where possible. For samples complete to a waney edge, or including bark, this process is relatively straightforward. Depending on the completeness of the final ring, a precise felling date and season can be given. If, however, the sapwood is partially missing, or if only a heartwood/sapwood transition boundary survives, an estimated felling date range can be given for each sample. In Britain and northern Europe, the number of sapwood rings can be estimated by using a statistically derived sapwood estimate with a given confidence limit. The author's research has resulted in a method of estimating individual sapwood ring counts depending on the age of the tree and the mean ring width of the heartwood. These can range from four to 57 rings of sapwood in southern Britain, with a logarithmic mean of 19.4 (Miles 2006). If no sapwood or heartwood/sapwood boundary survives, then the minimum number of sapwood rings from the appropriate sapwood estimate is added to the last measured ring to give a *terminus post quem* (tpq), or felled after date.

A major problem with American dendrochronology is that there are no extensive studies of sapwood estimates for American oak. So, it is all the more important to obtain samples with bark edge when working in the United States.

Brief Dendrochronological Case Studies Hampton Court Palace, Richmond, London, with its nine acres of roof, is probably the largest single building in England. Primarily started in 1515 for Cardinal Thomas Wolsey, it was acquired by Henry VIII in 1529 and later greatly enlarged. Here, dendrochronology uncovered two structures by Inigo Jones, Surveyor of the King's Works, known as the first English architect.

Work in the Chapel Royal showed that Henry VIII constructed the magnificent oak fan-vaulted ceiling, documented between 1535 and 1536 (Thurley 2003, 63) (Fig. 9; front and back covers), but that the Chapel had been started by Wolsey, with dates ranging from spring 1525 to winter 1525–26. One of these timbers, a great beam 40 feet long by 16 inches square, was felled in spring 1525. Careful study of seasoning evidence showed that these timbers were not used until the time of Henry VIII who then worked with the now-seasoned timber to fabricate the existing Royal Pew. However, the roof over this section of the Chapel was found to have been reconstructed by Inigo Jones with timbers felled in 1633–34 (Miles et al. 2007).

Another surprise is the date of the Royal Tennis Court (Fig. 10). Thought to have been built between 1660–89, possibly during Christopher Wren's tenure as Surveyor of the King's Works (Thurley 2003, 137, 207), the Historic Royal Palaces administration was excited to learn that this was in fact also designed by Inigo Jones, with felling dates of winter 1634–35 and winter 1635–36 (Miles and Bridge 2011). This research showed that the Royal Tennis Court followed on in 1636 from the Chapel Royal, which was completed the year before, and expanded the corpus of surviving timber-framed roofs by Jones in England from three to five (Fig. 11).

Salisbury Cathedral, in Wiltshire, was constructed in one concerted building campaign from east end, with felling dates of spring 1222, to west end, where substantial completion was recorded in 1265. Subsequent repair phases range from the 14th to the 18th centuries. Over 600 samples were taken from this building from 2000 to 2010. One significant discovery was the use of imported Irish oak for both the eastern chapel roofs of 1220–25 and the roof boarding of the north nave triforium and north porch roofs in 1250. This was only revealed through the use of dendro-provenancing (Miles 2002).

There is an immensely complex scaffold inside the spire at Salisbury (Fig. 12). Previously thought to have been used to build the 404-foot-high spire, the felling date range of 1344–76 is a generation later than the stonework. The scaffold likely relates to repairs carried out following the Great Storm of 1362, providing tensile restraint for the spire capstone and giving internal access to the top of the spire (Miles et al. 2004). Additionally, England's earliest dated Arabic assembly marks were found in the western end of the nave roof, north porch and north nave triforium (spring 1251, winter 1251–52, and winter 1254–55).

Mary Arden's House in Stratford-upon-Avon was for centuries thought to be the home of Shakespeare's maternal grandmother, Mary Arden. When the house next door, Glebe Farm, thought to be a Victorian farmhouse enclosing an earlier core, was found to have been a hall house dating to 1514, historian Nat Alcock suggested that this date fits the real Mary Arden house, and further suggested that the other house was incorrectly identified. Therefore, a course of dendrochronology was commissioned on this house to test this hypothesis. The earliest date was winter 1568–69, built after the 1556 death of Mary Arden's father, Robert. Thus, one of Stratford-upon-Avon's most well-known houses was found to be incorrectly identified, but as luck would have it, still in the ownership of the Shakespeare Trust, who bought it some years ago as a buffer against unwanted development to the former Mary Arden House. It was a "simple" matter of renaming Glebe Farm as the real Mary Arden's House, and the Mary Arden's House that was, Palmer's Farm. So all was well in the end (Miles 2000).

In the United States, following the pioneering work of the Columbia Lab, a substantial amount of work has been undertaken in both Massachusetts and Virginia.

Robin Forster, © Historic Royal Palaces

9 Oak fan vaulting, Chapel Royal (1535–36), Hampton Court Palace.

In Massachusetts, a large number of white and red oak buildings have been dated and the BOSTON02 reference chronology constructed, spanning the years 1454–1769. This work spread to Newport, R.I., and Long Island, N.Y., identifying a climatic anomaly centered on southeastern Massachusetts causing some buildings in this area to be quite difficult, if not impossible, to date.

Information gained from this work contributed to our understanding of precise felling dates. In many cases, timbers with complete sapwood were felled one, two, or more years before the latest felling dates represented in the building frame. This is inconsistent with the conventional wisdom that early buildings were built with green timbers because they were easier to work than seasoned wood. Where records are available, as for meetinghouse construction, documents often refer to "getting out timbers" for the construction in the same year that the frame was raised. One explanation is that the earlier timbers might be the smaller members, joists, studs and the like which were sawn on speculation at sawmills, or were those that were lying around in framers' yards waiting to be used up.

An extreme example is the Bardeen-Culver barn at West Newbury, Mass. The primary phase of this barn is represented by four tie beams, all dating to the winter of 1714–15. However, a number of posts and a longitudinal beam dated 15 to 20 years earlier. The ash summer beam and an ash post dated to the winter of 1693–94, two oak posts to the summer of 1699, and one further ash post to the winter of 1699–1700. Dendrochronology alone cannot tell whether these circa 1693–94 and 1700 timbers were stockpiled or represent an earlier phase of the building, which had a new roof constructed over it in 1715. However, subsequent restoration work on the frame, by David Lanoue, has shown that the barn was originally constructed in 1693–94, but altered in 1715 (Miles et al. 2003).

Another extreme example is the Gilman Garrison House in Exeter, N.H. Here, eight white oak timbers were sampled from the structural frame of the building, four producing felling dates ranging from summer 1706 to winter 1708–09, suggesting the primary construction phase taking place during 1709. However, two corner posts were felled some 40 years earlier, during the spring of 1668. It is hard to imagine stockpiling timber for even a fraction of this time, suggesting that these represent reused timbers (Miles et al. 2003).

Analyses of 21 buildings in New England confirm that timber was often stockpiled for at least a short period of time. Of the fifty timbers in those buildings felled early, 60 percent were major framing members and 40 percent were secondary ones. Sixty-two percent were felled one year before construction, 20 percent felled two years early, 12 percent three years early. Only four percent were felled more than three years before construction.

These examples demonstrate the importance of taking a selection of samples where possible—for if only the 1668 corner posts of the Gilman Garrison House had been sampled and dated, the whole building would have been dated 40 years too early.

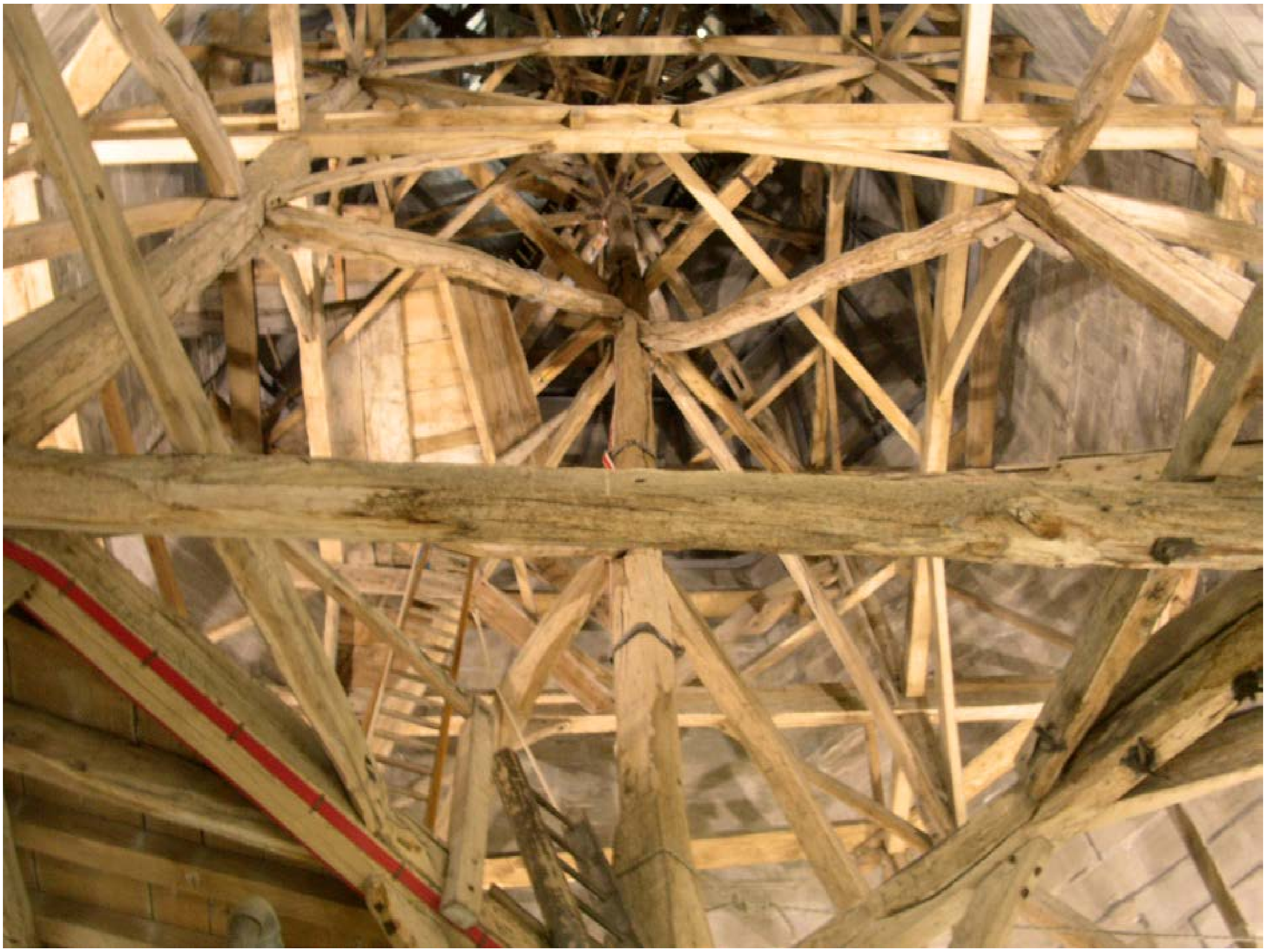
The Bradford House (1714) in Plymouth, Mass., shows that there is potential in sampling small scantling timbers. All of the major structural timbers were fast-grown, boxed-heart timbers with less than 30 rings—utterly hopeless for dendrochronology. However, the floor joists were cut from larger, slower-grown trees and, while each joist might have only 40 or 50 rings, by sampling a larger number of timbers it is possible to create a longer site master. Hence, 12 small joists at the Bradford House managed to make a 97-year chronology that dated extremely well with the reference chronologies.

Other woods may also be studied. Three buildings studied in Massachusetts had both ash and oak: the Coffin House (1678, 1713) in Newbury, the Bardeen-Culver Barn in West Newbury and the House of Seven Gables (1668, 1677) in Salem (Fig. 13). Although only a few ash timbers were sampled in the first two examples, virtually the entire addition to the Salem house was constructed of black ash. We sampled seven ash and two oak timbers from the addition. The oak dated nicely with other chronologies and the first phase of the house, which was all oak. The ash timbers also matched, but not as well as the oak, probably due to the exceptionally narrow growth-rings. Nevertheless, we did find a correlation of $t = 4.55$ between the ash site master and the oak site master from this house.

Moving south into Virginia, one notable building with a surprising date is Mount Vernon. An initial study of trees around the mansion found most were not planted in 1786, as previously thought by historians. While work dated the Spinning House to between winter 1763–64 and spring 1767, and the Gardener's House to 1775–76, the most surprising results were from the mansion itself, believed to have been constructed in the 1740s (Dalzell and Dalzell 1998). Timbers accessed in the cellar ranged from spring 1732 to spring 1734, and were initially assumed to represent earlier, reused timbers. Work during the following year revealed more timbers of the same period beneath lifted floorboards. These timbers were clearly primary to the structure, suggesting that Mount Vernon dates from about 1734, a decade earlier than thought. This example clearly illustrates that even the most famous of houses is not as well documented as historians might think.

10 Royal Tennis Court (1636), Hampton Court Palace.

11 Royal Tennis Court roof framing, designed by Inigo Jones.



Ann Montgomery Jones

12 Fourteenth-century scaffold within the Salisbury Cathedral spire.

Clermont Plantation is a large, rambling, multiphased house in Clarke County, Va. (Fig. 14). The land was originally surveyed by George Washington for Lord Fairfax in October 1750. The building was the subject of a 2008 partial historic structures report by Maral S. Kalbian and a team of professionals that thoroughly sets out the likely construction history of the house and outbuildings. A total of nineteen individual phases of construction have been identified and sampled for dendrochronological dating, ranging from 1756–1849 for the main house to 1857 for the spring house (Figs. 15, 16).

All nineteen phases at Clermont were dated from 100 sampled timbers. This resulted in a 258-year composite site chronology, CLRMONTX, spanning from 1599 to 1857—an excellent reference chronology for the region. It is interesting to note that the correlation between some of the individual components was not significant, despite being basically coeval. This is surprising considering that most of the oak would have been obtained locally, probably from the 400 acres comprising the farm during most of the period under study, likely indicating a diversity of growing conditions and management within the relatively small confines of a single farm in mid-18th-century to mid-19th-century Virginia (Miles 2010).

Of course, these are the big places. Of equal interest are smaller, more vernacular buildings. A multidisciplinary research project was carried out in 2007–8 on eight surviving pre-Civil War Virginia slave cabins by Doug Sanford and Dennis Pogue. Samples dated ranging from 1785 to 1858, although the earliest of these are reused timbers. Both oak and pine were dated in this study.

The earliest cabin was found at Walnut Valley Plantation, now located on Chippokes Plantation State Park in Surry County, a small single-story cabin dating to 1816 (Fig. 17). At Logan Farm, Ivor, Isle of Wight County, is a framed duplex slave quarters of 1837–38, but with some structural timbers reused from an earlier structure of 1785–86.

The most surprising result was from the slave quarters at Sherwood Forest Plantation in Stafford County. This is a one-story frame building, with garret under a gabled roof. Framing methods and nail types, along with documentary evidence, suggest that the building was constructed between the 1830s and early 1850s, and accorded well with the tree-ring date of 1846. Not anticipated was that dendro-provenancing suggested the white pine studs and rafters originated from around Maine, as evidenced from *t*-values of 7.1 and 9.3 from Maine white pine chronologies. For whatever reason, it was more economical to purchase sawn white pine shipped down the coast from Maine than to use more local hard pine from farther inland to the west.

A total of 111 timbers were sampled from the eight Virginian slave quarters. Of these, 65 timbers dated, representing a total of

12 phases of construction. Of the timbers sampled, 52 were of oak, both white and red, while 59 were of pine, mostly southern yellow pine, although ten from Sherwood Forest were of Maine white pine. The rest of the timber was most probably obtained locally.

The Future of Scientific Dating Sometimes, seemingly suitable and long-lived timbers fail to date. The tree may have been stressed too much and barely living, or the rings are simply too complacent, not adequately reflecting the prevailing climatic influences. The tree's growth may have been adversely affected by the actions of humans or other nonclimatic factors such as disease, defoliation or forest disturbance. The tree may simply have been too young to have a ring-width sequence long enough to uniquely match the reference chronologies. There are also surely reasons we simply do not understand.

One avenue of research currently being carried out by the author and colleagues at Swansea University, in Wales, and the Archaeology Research Laboratory at Oxford University is the use of tree-ring chemistry, in the form of stable isotopes, to support dendrochronology (Loader et al.).

Broadly, stable-isotope dating relies upon the same fundamental principles, limitations and assumptions as conventional (ring-width-based) dendrochronology. However, the ring-width match is supported by measurement and matching of the inter-annual differences in wood chemistry. Like ring widths, these chemical signals carry a strong common environmental signal between contemporary trees. But, importantly, this chemical signal, as stable oxygen and carbon isotopes in the tree rings, preserves information that is different from that recorded in the ring-width record (McCarroll and Loader 2004). To date, two chronologies spanning the last millennium have been constructed centering on Oxford in southern England, and extending back to 825 CE with reduced replication due to dearth of material.

The stable (nonradioactive) isotopes are inherent chemistry locked into each tree ring. Through a long and complicated process each ring is prepared, recorded and reference sampled. Then, the actual sample is dissected under a microscope to obtain a clean piece of only the late wood (summer wood), because early wood, formed during the spring, tends to have a chemical influence from the previous year. The small individual samples are then converted to cellulose prior to analysis by isotope-ratio mass spectrometry.

Stable isotopes of both carbon and oxygen can be measured. In the UK, oxygen ($\delta^{18}O$) isotopes largely reflect rainfall taken up by the tree during the summer growth period and are proving more representative across a wide geographical area than simple ring widths, whereas carbon ($\delta^{13}C$) isotopes typically reflect the amount of sunshine during the growing season. The isotope signal is common to many tree species and, in addition to oak, dating success has been had with beech and elm, two species hitherto very difficult to date using conventional dendrochronology.

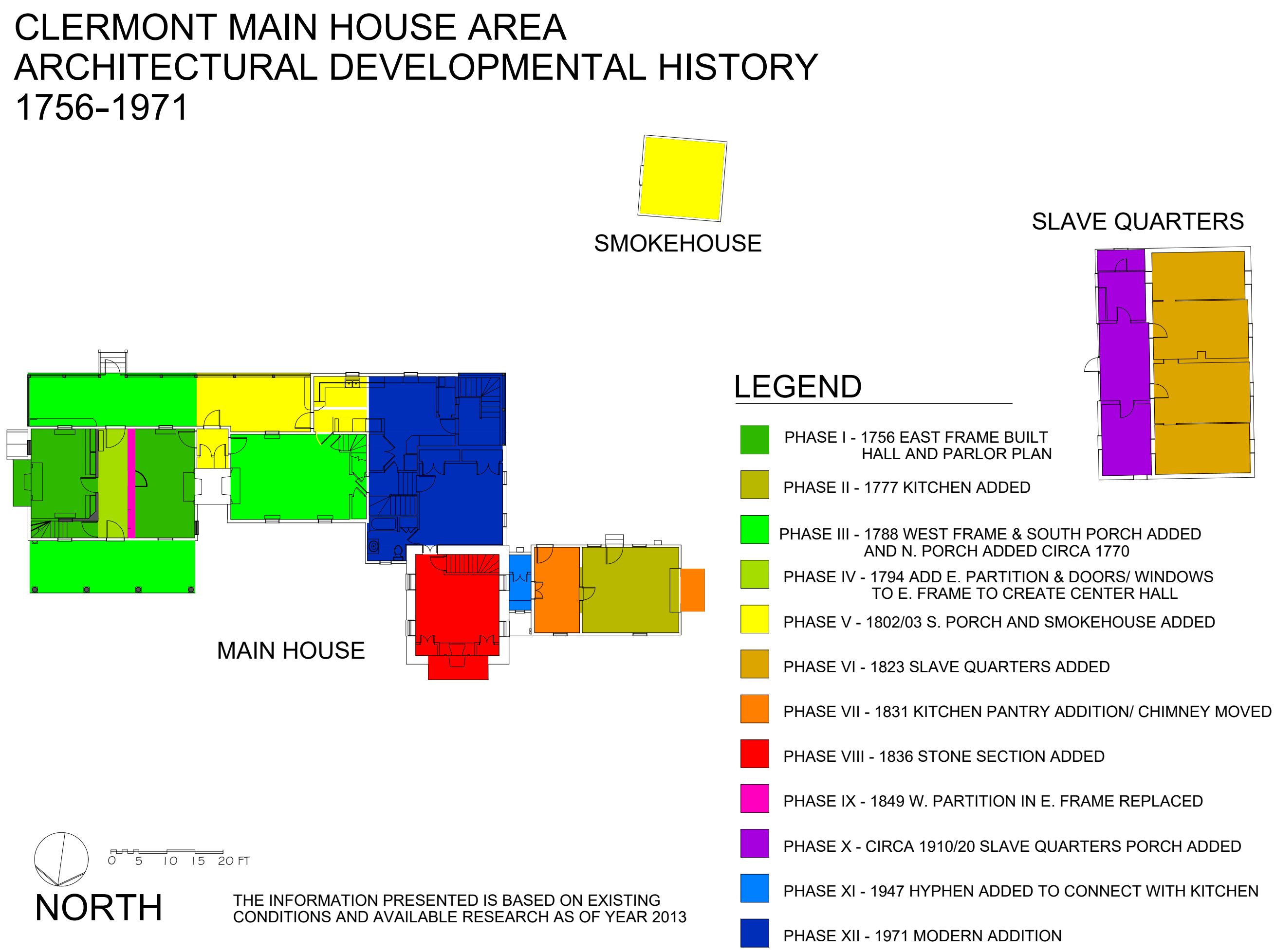
Part of The Vyne, a large Tudor country house in Hampshire, was substantially rebuilt during the 1650s (Fig. 18). Two timber samples taken from the portico 20 years ago failed to date through conventional ring-width dendrochronology, or even to match each other, despite both having waney edge or bark. However, isotope-supported dendrochronology using $\delta^{18}O$ has revealed that both timbers were felled in the winter of 1655–56, dating this as the earliest portico on an English country house (Fig. 19). Furthermore, in a simple comparison, both timbers match each other with a Student's t-value of 8.06 using the oxygen isotopes ($\delta^{18}O$), but only a t=1.68 using the relative ring widths.

Another spectacular result came from dating Llwyn Celyn, Monmouthshire, UK (Fig. 20). This very fine medieval hall house in southeast Wales had been assessed for dendrochronology on several occasions and rejected due to there being too few and complacent rings. The owners, The Landmark Trust, requested that dendrochronology be tried—but it failed, as predicted. Therefore, an attempt was made to use stable oxygen isotopes to crack this enigma. Two samples, one of 57 rings from the hall range and one from the solar wing with only 50, both with waney edge, were analyzed, and two samples from each were also submitted for ^{14}C analysis, a well-established dating technique based on the deterioration of the unstable ($\delta^{14}C$) isotope. The results were impressive.

In the solar wing samples, the isotopes provided a match giving a precise felling date of winter 1418–19. The hall similarly gave a felling date two years later, to winter 1420–21, suggesting that

13 The House of Seven Gables (1668, 1677), Salem, Mass.

14 Main house, Clermont Plantation, Clarke County, Va., clearly showing numerous phases of building (1756–1849).



Courtesy The Clermont Foundation

15 Plan figure of dendrochronologically dated building phases at Clermont Plantation.

they were coeval, or one built immediately after the other. It is not possible to be more conclusive without additional precise dates.

High-precision ^{14}C analysis was performed on the two samples from the solar wing, and the results subjected to Bayesian modelling using OxCal (which combines multiple probability ranges into one which is more accurate), giving a combined felling-date range for the outermost ring of 1407–28 with a high degree of confidence (95.4 percent). The last ring derived from dendro-isotope analysis of the second sample was 1418, which is in the center of the 21-year felling-date range given by the ^{14}C dating.

16 Spring house (1857) at Clermont Plantation.

17 Slave cabin (1816) from Walnut Valley Plantation, Surry County, Va., relocated to Chippokes Plantation State Park.

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18 The oldest documented country-house portico in England (1656), The Vyne, Hampshire.

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19 Portico roof framing (1656) at The Vyne.

The two samples from the hall were also subjected to ^{14}C dating followed by OxCal modelling, giving a combined felling-date range for the outermost ring of 1404–32 (95.4 percent). Again the dendro-isotope dating was almost exactly in the center of this 28-year ^{14}C period.

Isotope-supported dendrochronology has come through and produced absolute dates where conventional dendrochronology has failed. This method is looking very promising, and some results suggest it may even allow shorter samples to be dated.

Conclusions Dendrochronology is an accurate and precise scientific dating method that has been revolutionizing the study of historic architecture and timber framing. Cultural history has a habit of becoming lost and blurred over time, even for some of our most well-known buildings. Tree-ring dating has been able to unravel many of these mysteries, giving firm foundation to serious historical analysis.

Isotope dating is equally accurate as conventional tree-ring dating and may prove to be the most significant advance in scientific dating of this past century. Although currently only applicable in England and Wales, where we have constructed a reference chronology, similar research in the eastern United States is possible and might help to unravel dendrochronological problem areas, such as the southeastern coast of Massachusetts.

—Daniel Miles

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20 Llwyn Celyn (1419, 1421), Monmouthshire, UK.

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