Informing Conservation: towards ^{14}C wiggle-matching of short tree-ring sequences from medieval buildings in England

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Abstract

This study tested whether accurate dating by AMS radiocarbon wiggle-matching short tree-ring series (c. 30 annual rings) in the medieval period could be achieved., Scientific dating plays a central role in the conservation of historic buildings in England. Precise dating helps assess the significance of particular buildings or elements of their fabric, thus allowing us to make informed decisions about their repair and protection. Consequently considerable weight, both financial and legal, can be attached to the precision and accuracy of this dating. Dendrochronology is the method of choice, but in a proportion of cases this is unable to provide calendar dates. Hence we would like to be able to use radiocarbon wiggle-matching to provide a comparable level of precision and reliability, particularly on shorter tree-ring sequences (c. 30 annual growth rings) that up until now would not routinely be sampled. We present the results of AMS wiggle-matching five oak tree-ring sequences, spanning the period covered by the vast majority of surviving medieval buildings in England (c. AD 1180–1540) when currently we have only decadal and bi-decadal calibration data

1. Background

Over the past 25 years scientific dating has become an integral part of the processes for conservation and repair of historic buildings in England. Precise dating informs decisions about the preservation of buildings, allows us to identify significant fabric, and aids in the specification of appropriate repair strategies. Small differences in date can lead to great differences in the significance of the extant building, and thus to great differences in the costs of the agreed solution for a particular case.

Outcomes of this sort clearly demonstrate the value of precise dating in informing repair and conservation decisions for historic buildings, and have led to dendrochronology becoming widely applied as part of these processes. In consequence, Historic England (and its predecessor, English Heritage) alone has funded tree-ring dating on more than 1500 buildings over the past 20 years to inform such decisions.

2. The Problem

In providing the required precise dating for historic buildings in England, the scientific dating method of choice is dendrochronology. The vast majority of medieval buildings in England are constructed of oak, which is widely and successfully dated (English Heritage 1998). There are three situations, however, in which tree-ring analysis may fail to produce calendar dating.

1) When a building produces oak tree-ring sequences which simply do not match against the available reference chronologies,

2) When a building is constructed from a species other than oak,

3) When the timbers in a building contain less than the 50 rings which is normally required for successful dendrochronology.

Of these three situations, the length of the available oak tree-ring sequences is by far the most common limitation. It is clear that the probability that an oak sequence will remain undated is inversely related to the number of tree-rings in the sequence (Fig 1), and indeed very short series (<45 rings) would usually not be selected for sampling by the dendrochronologist.

It is clearly important to provide precise dating in those cases where tree-ring analysis cannot, and so we would like to be able to turn to radiocarbon wiggle-matching to provide dating of an equivalent level of precision and reliability. We do not, however, generally need to wiggle-match long tree-ring sequences (as these will normally have been successfully dated by dendrochronology), but rather we wish to date those timbers which have relatively few growth rings.

But substantial weight, both in conservation terms and in financial terms, can rest on our results, so it is essential that the chronologies produced are both sufficiently precise and sufficiently accurate to reliably direct conservation decisions.

3. The Dataset

A previous study, in which we had successfully wiggle-matched part of a 303-ring pine series dating to AD 1367–1670 from Jermyn Street, London (Tyers et al. 2009), suggested that AMS laboratories could now provide the level of precision and accuracy required for such applications. We therefore determined to test whether we can provide accurate dating by wiggle-matching short tree-ring series (*c.* 30 annual rings) in the medieval period. It is in this period that scientific dating is most often required, since later buildings more commonly have associated documentary records.

The relevant period is before the set of radiocarbon measurements on single-year tree-ring samples (Stuiver 1993), which provides such detailed understanding of variations in atmospheric radiocarbon between AD 1510 and 1954. This may be relevant because the placement of short calendar series against the calibration curve is more reliant on the curve accurately reflecting short-term variations in atmospheric radiocarbon than is the wiggle-matching of longer series.

Five oak tree-ring series were selected for sampling to cover the period from which standing buildings commonly survive in England. Evidence for the dendrochronological dating of these sequences is provided in Table 1 (the ring-width data for these series are provided in the referenced reports).

The earliest is a 132-ring core from Rudge Farmhouse, Morchard Bishop, Devon (50.85N, 3.78W) which spans the years AD 1129–1260, as it is included in a 192-year site master chronology dated to AD 1129–1315 (Groves 2005). A core consisting of 89 heartwood ringsfrom Bremhill Court, Wiltshire (51.46N, 2.03W) spans the years AD 1220–1308, as it is included in a 213-ring site master chronology that has been dated to AD 1111–1323 (Hurford et al. 2010). A 126-ring core from Manor Farm Barn, Kingston Deverill, Wiltshire (51.13N, 2.22W) has been dated to spanning AD 1284–1409, as it forms part of a 150-ring site master chronology dated as spanning AD 1260–1409 (Tyers et al. 2014a). A 138-ring core from Blanchland Abbey Gatehouse, Northumberland (54.46N, 2.06W) spans AD 1395–1532, and is included in a 207-ring site master sequence that has been dated to AD 1326–1532 (Arnold et al. 2009). Finally, a 120-ring core from Kilve Chantry, Somerset (51.19N, 3.22W) has been dated as spanning AD 1425–1544, this also being the date range of the two-timber mean site chronology of which it forms part (Arnold et al. 2015)

Radiocarbon measurements were made on a total of 86 single-year tree-ring samples from these cores in 2011–13. The 43 dated at the Scottish Universities Environmental Research Centre were prepared to α-cellulose using Method F outlined in Hoper et al. (1998), combusted to carbon dioxide (Vandeputte et al.

1996), graphitised (Slota et al. 1987), and dated by AMS (Freeman et al. 2010). The 43 dated at the Oxford Radiocarbon Accelerator Unit were processed using an acid-alkali-acid pretreatment followed by bleaching with sodium chlorite as described by Brock et al. (2010, table 1 (UW)), graphitised (Dee and Bronk Ramsey 2000), and measured by AMS (Bronk Ramsey et al. 2004). All $\delta^{13}C$ values, relative to VPDB, were obtained by IRMS from the gas combusted for graphitisation.

The conventional radiocarbon ages reported for these samples, along with the rings dated from each core, are listed in Table 2. The quoted errors are each laboratory's estimates of the total error in their dating systems. Eight pairs of replicate measurements are available on rings dated to the same calendar year (Table 3). Five pairs of radiocarbon ages are statistically consistent at 95% confidence, one pair is inconsistent at 95% confidence but consistent at 99% confidence, and two pairs are inconsistent at more than 99% confidence (Ward and Wilson 1978; T'(5%)=3.8, v=1 for all). The results are therefore more scattered than would be expected on statistical grounds. The quoted $\delta^{13}C$ values are even more dispersed, with only three pairs being statistically consistent at 95% confidence, and the other six being inconsistent at more than 99% confidence (Ward and Wilson 1978; T'(5%)=3.8, v=1 for all). These results cannot be regarded as satisfactorily reproducible.

Five pairs of replicate and two pairs of triplicate measurements are also available on rings dated by AMS (this study) and gas proportional counting Stuiver (1993) to the same calendar year (Table 4). Of these seven sets of radiocarbon ages, five are consistent at 95% confidence, one set is inconsistent at 95% confidence but consistent at 99% confidence, and one set (AD 1541) is inconsistent at more than 99% confidence. These results are again more scattered than would be expected on statistical grounds.

4. Wiggle-matching the entire sequences

The first step in the analysis of this data is to wiggle-match the radiocarbon measurements from each core, combining the radiocarbon dates with the calendar interval between the dated tree-rings known from dendrochronology. This was undertaken using the Bayesian approach to wiggle matching first described by Christen and Litton (1995), implemented using OxCal v4.2 (Bronk Ramsey 2009) and the IntCal113 atmospheric calibration data for the northern hemisphere (Reimer et al. 2013).

Figure 2 shows the model for core MBRU13 from Rudge Farmhouse. This has good overall agreement (Acomb=130.2, An=22.4, n=10; Bronk Ramsey et al. 2001), and estimates the final ring of the sequence to have been formed in *cal AD 1254–1291 (95% probability; MBRU13_end*; Fig 2). This is compatible with the date of AD 1260 produced for this ring by dendrochronology (Table 5).

Figure 3 shows the model for core BCB-C10 from Bremhill Court. This also has good overall agreement (Acomb=45.8, An=17.7, n=16), and estimates the final ring of the sequence to have been formed in *cal AD 1297–1310 (95% probability; BCB-C10_end*; Fig 3). This is not compatible with the date of AD 1323 produced for this ring by dendrochronology (Table 5). The Highest Posterior Density interval for this distribution at 99% probability is *cal AD 1293–1312*, which is similarly incompatible with the tree-ring analysis.

Figure 4 shows the model for core KDM-B11 from Kingston Deverill. This also has good overall agreement (Acomb=25.2, An=14.4, n=24), and estimates the final ring of the sequence to have been formed in *cal AD 1403–1413 (95% probability; KDM-B11_end*; Fig 4). This is compatible with the date of AD 1409 produced for this ring by dendrochronology (Table 5).

Figure 5 shows the model for core BAG-B18 from Blanchland Abbey. Again, this model has good overall agreement (Acomb=33.0; An=14.4; n=24). It estimates that the final ring was laid down in *cal AD 1513–1524 (95% probability; SUERC-40238_BAG-B18_end*; Fig 5). This is not compatible with the date of AD 1532 produced for this ring by dendrochronology (Table 5). The Highest Posterior Density interval for this distribution at 99% probability is *cal AD 1511–1526*, which is similarly incompatible with the tree-ring analysis.

Figure 6 shows the model for core KLV-A06 from Kilve Chantry. This model has poor overall agreement (Acomb=2.8, An: 20.4, n=12), with two samples having particularly poor individual indices of agreement (OxA-28709 (A: 8) and SUERC-48668 (A:0)). This model estimates that the final ring was laid down in *cal AD 1523–1537 (95% probability; KLV-A06_end;* Fig 6). This is not compatible with the date of AD 1544 produced for this ring by dendrochronology (Table 5). The Highest Posterior Density interval for this distribution at 99% probability is *cal AD 1517–1540*, which is similarly incompatible with the tree-ring analysis.

Wiggle-matching of the radiocarbon results quoted by each laboratory separately was then undertaken on the five timbers. Again, the Highest Posterior Density intervals at 95% probability were incompatible with the respective tree-ring dates for the Bremhill Court and Blanchland Abbey Gatehouse cores, and compatible with the respective tree-ring dates for the Rudge and Kingston Deverill cores (Table 5). The Highest Posterior Density interval at 95% probability for the wiggle-match for the core from Kilve Chantry using measurements produced at Oxford included the date for this ring produced by dendrochronology, the wiggle-match for this timber using measurements produced at East Kilbride did not (Table 5).

The indices of agreement provided by OxCal for wiggle matching (Bronk Ramsey et al. 2001, 384) do not indicate that these models are problematic. Of the fifteen models so far described, only two (Kilve Chantry (a) and (c)) have poor overall agreement, although seven produce date ranges that are incompatible with the tree-ring dating at more than 99% probability (Table 5). When the tree-ring date for the final ring of each core is input into the model, using the C_Date function of OxCal, then all five cores produce models with poor overall agreement (even the two cores whose radiocarbon dates are otherwise compatible with the dendrochronology).

5. Wiggle-matching partial sequences

Given that the length of the available oak tree-ring sequence is the usual limitation on successful dendrochronology in historic buildings from England, we ran a series of short wiggle-matches on sequences, between 25 and 35 rings in length, from each core. These models would determine whether accurate results could be obtained by wiggle-matching such short sequences, and also help to identify whether there was any part of the period covered by the dated cores where inaccurate model outputs were more common.

Each core was divided into sequential blocks of approximately 30 years, for which 5 or 6 radiocarbon ages were available (Table 2; Fig 7). The results from each block were incorporated into a wiggle-match model that estimated the date of the final ring of the complete core. These estimates could then be compared with the known date for the final ring as derived from dendrochronology to determine the accuracy of the short wiggle-matches. The results of the 64 wiggle-matches on ‘blocks’ of 25–35 rings are given in Table 5 and summarised in Figure 8. The Highest Posterior Density interval at 95% probability was compatible with the tree-ring date for the final ring of the relevant core in just over half of models (51.6%). All six short sequences from

Rudge and 18 of the 19 short sequences from Kington Deverill produced estimates at 95% probability compatible with the known date of the last ring of their tree-ring sequences. Wiggle-matching short sequences from the other three sites, Bremhill Court, Blanchland Abbey, and Kilve Chantry produced Highest Posterior Density intervals at 95% probability that are incompatible with the tree-ring dates for the final ring of those cores in the majority of cases (76.9%).

6. The longest wiggle-match (AD 1160–1544)

A wiggle-match comprising radiocarbon measurements on 79 dated rings from all five sites is shown in Figure 9. This model has poor overall agreement (Acomb: 1.6; An: 8.0; n: 79). The Highest Posterior Density interval for the final ring is *cal AD 1532–1537 (95% probability; AD 1544*; Fig 9), or *cal AD 1531–1539 (99% probability)*. Neither interval includes the date obtained for this ring by dendrochronology of AD 1544.

Figure 10 shows the radiocarbon ages obtained on single known-age tree-rings as part of this study in comparison to the radiocarbon ages covering this period included in IntCal13 (Reimer et al. 2013). These are on decadal samples (Wk; Hogg et al. 2002), single-year and decadal samples (QL; Stuiver et al. 1998), decadal and bi-decadal samples (UB; Hogg et al. 2002; Pearson et al. 1986), and decadal and 23-year and 24-year samples (van der Plicht et al. 1995).

There are no clear systematic offsets. The short wiggle-matches, might suggest that accurate dating is particularly difficult in the decades around AD 1300 and in the decades around AD 1500 (Fig 8). All radiocarbon data around AD 1300 are, however, tightly grouped. There is more variation around AD 1500, but no more so than, for example, around AD 1400 (where the Kingston Deverill wiggle-matches produce consistently accurate outputs).

7. Conclusions

The difficulty in accurately wiggle-matching the short, 25–35-year, tree-ring sequences that were the objective of this research is not entirely surprising, given the reliance of this approach on a detailed understanding of the structure of the radiocarbon calibration curve (which is currently mostly based on measurements on decadal wood samples). In fact, just under half (47.7%) of the short wiggle-matches produced date ranges at 95% probability which did not include the age of the final tree-ring determined by dendrochronology (Table 6; Fig 8).

Given the good accuracy produced in previous studies on post-medieval buildings (Tyers et al. 2009; Bayliss et al. 2014), the inaccurate results produced by three of the five long wiggle-matches undertaken as part of this study was unexpected (Table 5; Figs 3 and 5–6). It is therefore clear from this study that AMS radiocarbon wiggle-matching in the medieval period cannot be relied upon to produce dating that is accurate to within the precision quoted.

Whilst the causes of the difficulties in accurate wiggle-matching in this period are explored further, we would urge caution to those wishing to use this technique on similar material (cf. Nakao et al. 2014), particularly if the results will inform the long-term preservation and conservation of the structures involved.

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Table 1: Results of cross-matching with relevant independent site reference chronologies the site sequences containing the timbers sampled for radiocarbon dating

Reference chronology	***t*-value**	**Span of chronology**	**Reference**
Rudge, Morchard Bishop, Devon: core MBRU13 part of 192-year 12-timber mean MBRU-T11 (spanning AD 1129–1315)			
Bradworthy Church, Devon	11.5	AD 1125–1367	Tyers 2003
Meare Manor Farmhouse, Somerset	10.5	AD 1156–1315	Bridge 2002a
Wells Cathedral, St Catherine's Chapel, Somerset	10.4	AD 1169–1325	Arnold *et al* 2004
Exeter Cathedral, Devon	10.4	AD 1137–1332	Mills 1988
Glastonbury Abbey Barn, Somerset	9.8	AD 1095–1334	Bridge 2001
Muchelney Abbey, Somerset	7.8	AD 1148–1498	Bridge 2002b
Bremhill Court, Wiltshire: core BCB-C10 part of 213-year 7-timber mean BHBCSQ01 (spanning AD 1111−1323)			
Court Farm Barn, Winterbourne, Gloucestershire	14.2	AD 1177–1341	Miles 2001
Fiddleford Manor, Sturminster Newton, Dorset	10.2	AD 1167–1315	Bridge 2003
The Manor Barn, Avebury, Wiltshire	9.8	AD 1072–1278	Tyers 1999
Abbey Barn, Glastonbury, Somerset	9.8	AD 1095–1334	Bridge 2001
Wells Cathedral, St Catherine's Chapel, Somerset	9.4	AD 1169–1325	Arnold *et al* 2004
Bradford on Avon tithe barn, Wiltshire	8.5	AD 1174–1324	Groves and Hillam 1994
Kingston Deverill, Manor Farm Barn, Wiltshire: core KDM-B11 part of 150-year 8-timber mean KDMBSQ01 (spanning AD 1260−1409)			
Devizes Castle, Devizes, Wiltshire	8.6	AD 1213–1407	Miles *et al* 2006
Old Rectory, Withington, Gloucestershire	6.6	AD 1252–1429	Howard *et al* 1998a
Lodge Farm, Kingston Lacy, Dorset	6.4	AD 1248–1399	Groves 1994
Winchcombe Abbey House, Winchcombe, Gloucestershire	6.2	AD 1250–1499	Arnold *et al* 2008
Lacock Abbey, Lacock, Wiltshire	6.2	AD 1292–1441	Esling *et al* 1990
St Brannock Church, Braunton, Devon	6.2	AD 1215–1378	Tyers 2004
Blanchland Abbey Gatehouse, Northumberland: core BAG-B18 part of a 207-year 28-timber mean BAGBSQQ01 (spanning AD 1326−1532)			
Aydon Castle, Corbridge, Northumberland	10.5	AD 1424–1543	Hillam and Groves 1991
Low Harperley Farmhouse, Wolsingham, Co Durham	9.9	AD 1356–1604	Arnold *et al* 2006
1–2 The College, Cathedral Precinct, Durham	9.6	AD 1364–1531	Howard *et al* 1992
Unthank Hall, Stanhope, Co Durham	9.4	AD 1386–1592	Howard *et al* 2001a
Halton Castle, Corbridge, Northumberland	8.9	AD 1396–1559	Howard *et al* 2001b

Reference chronology	***t*-value**	**Span of chronology**	**Reference**
35 The Close, Newcastle upon Tyne	8.4	AD 1365–1513	Howard *et al* 1991
Kilve Chantry, Somerset: core KLV-A06 part of 120-year 2-timber mean KLVASQ01 (spanning AD 1425−1544)			
Court House, Shelsley Walsh, Worcestershire	7.7	AD 1387–1575	Arnold *et al* 2008
26 Westgate Street, Gloucester	7.6	AD 1399–1622	Howard *et al* 1998b
Muchelney Abbey, Somerset	7.5	AD 1148–1498	Bridge 2002b
White House, Vowchurch, Herefordshire	7.2	AD 1364–1602	Nayling 1999
Mercer's Hall, Westgate Street, Gloucester	6.9	AD 1289–1541	Howard *et al* 1996
Dauntsey House, Dauntsey, Wiltshire	6.9	AD 1393–1580	Tyers *et al* 2014b

Table 2: Details of sampled tree-rings and radiocarbon results

Laboratory Code	**Material**	**Radiocarbon Age (BP)**	**$\delta^{13}C$ (‰) - IRMS**	**Tree-ring date (AD)**
Rudge, Morchard Bishop – core MBRU13				
OxA-24671	*Quercus* sp. heartwood, ring 32; 160mg	877±27	−25.4±0.2	1160
SUERC-34332	*Quercus* sp. heartwood, ring 40; 240mg	850±25	−25.2±0.2	1168
OxA-24670	*Quercus* sp. heartwood, ring 48; 150mg	838±26	−23.7±0.2	1176
SUERC-34343	*Quercus* sp. heartwood, ring 54; 170mg	820±25	−24.3±0.2	1182
OxA-24673	*Quercus* sp. heartwood, ring 65; 140mg	839±25	−24.6±0.2	1193
SUERC-34336	*Quercus* sp. heartwood, ring 71; 110mg	850±35	−24.6±0.2	1199
OxA-24669	*Quercus* sp. heartwood, ring 81; 120mg	832±26	−24.4±0.2	1209
SUERC-34334	*Quercus* sp. heartwood, ring 88; 80mg	840±25	−25.6±0.2	1216
OxA-24672	*Quercus* sp. heartwood, ring 97; 90mg	818±25	−24.7±0.2	1225
SUERC-34338	*Quercus* sp. heartwood, ring 102; 80mg	795±25	−23.4±0.2	1230
Bremhill Court, core BCB-C10				
OxA-29231	*Quercus* sp. heartwood, ring 2; 40mg	895±26	−25.1±0.2	1221
SUERC-50294	*Quercus* sp. heartwood, ring 6; 40mg	836±27	−24.7±0.2	1225
OxA-29232	*Quercus* sp. heartwood, ring 11; 100mg	882±27	−25.3±0.2	1230
SUERC-50295	*Quercus* sp. heartwood, ring 16; 170mg	792±26	−24.5±0.2	1235
OxA-28370	*Quercus* sp. heartwood, ring 21; 140mg	824±24	−26.6±0.2	1240
SUERC-48673	*Quercus* sp. heartwood, ring 27; 160mg	835±26	−24.7±0.2	1246
OxA-28372	*Quercus* sp. heartwood, ring 34; 40mg	813±24	−24.7±0.2	1253
SUERC-48672	*Quercus* sp. heartwood, ring 39; 50mg	837±26	−25.9±0.2	1258
OxA-28640	*Quercus* sp. heartwood, ring 45; 30mg	779±22	−25.0±0.2	1264
SUERC-48679	*Quercus* sp. heartwood, ring 51; 80mg	845±23	−25.5±0.2	1270
OxA-28371	*Quercus* sp. heartwood, ring 57; 60mg	757±24	−24.3±0.2	1276
SUERC-48677	*Quercus* sp. heartwood, ring 63; 50mg	759±26	−23.6±0.2	1282
OxA-28369	*Quercus* sp. heartwood, ring 70; 160mg	751±23	−25.5±0.2	1289
SUERC-48680	*Quercus* sp. heartwood, ring 75; 180mg	760±26	−24.3±0.2	1294
OxA-28639	*Quercus* sp. heartwood, ring 81; 130mg	632±22	−25.2±0.2	1300

Laboratory Code	Material	Radiocarbon Age (BP)	δ^{13}C (‰) - IRMS	Tree-ring date (AD)
SUERC-48678	*Quercus* sp. heartwood, ring 87; 170mg	644±26	−23.6±0.2	1306
Manor Farm Barn, Kingston Deverill – core KDM-B11				
OxA-24622	*Quercus* sp. heartwood, ring 1; 190mg	686±22	−25.0±0.2	1284
SUERC-40193	*Quercus* sp. heartwood, ring 6; 160mg	655±30	−24.3±0.2	1289
OxA-26415	*Quercus* sp. heartwood, ring 12; 160mg	696±23	−22.6±0.2	1295
SUERC-40188	*Quercus* sp. heartwood, ring 17; 110mg	625±30	−24.3±0.2	1300
OxA-26426	*Quercus* sp. heartwood, ring 23; 110mg	617±22	−23.7±0.2	1306
SUERC-40181	*Quercus* sp. heartwood, ring 29; 90mg	620±30	−24.5±0.2	1312
OxA-26420	*Quercus* sp. heartwood, ring 34; 90mg	658±22	−23.9±0.2	1317
SUERC-40189	*Quercus* sp. heartwood, ring 39; 110mg	585±30	−25.4±0.2	1322
OxA-26419	*Quercus* sp. heartwood, ring 45; 210mg	578±23	−23.0±0.2	1328
SUERC-40194	*Quercus* sp. heartwood, ring 49; 110mg	555±30	−25.8±0.2	1332
OxA-26421	*Quercus* sp. heartwood, ring 55; 110mg	613±22	−24.3±0.2	1338
SUERC-40184	*Quercus* sp. heartwood, ring 60; 110mg	575±30	−26.7±0.2	1343
OxA-26423	*Quercus* sp. heartwood, ring 66; 70mg	561±22	−25.0±0.2	1349
SUERC-40182	*Quercus* sp. heartwood, ring 71; 60mg	545±30	−26.4±0.2	1354
OxA-26417	*Quercus* sp. heartwood, ring 77; 110mg	627±22	−23.5±0.2	1360
SUERC-40183	*Quercus* sp. heartwood, ring 82; 70mg	600±30	−27.0±0.2	1365
OxA-26416	*Quercus* sp. heartwood, ring 88; 70mg	630±22	−24.4±0.2	1371
SUERC-40190	*Quercus* sp. heartwood, ring 93; 60mg	595±30	−26.7±0.2	1376
OxA-26424	*Quercus* sp. sapwood, ring 99; 40mg	673±22	−25.1±0.2	1382
SUERC-40192	*Quercus* sp. sapwood, ring 104; 40mg	635±30	−25.9±0.2	1387
OxA-26425	*Quercus* sp. sapwood, ring 110; 40mg	603±22	−25.7±0.2	1393
SUERC-40180	*Quercus* sp. sapwood, ring 115; 40mg	530±30	−26.7±0.2	1398
OxA-26418	*Quercus* sp. sapwood, ring 120; 50mg	560±23	−24.9±0.2	1403
SUERC-40191	*Quercus* sp. sapwood, ring 125; 30mg	475±30	−26.5±0.2	1408
Blanchland Abbey Gatehouse – core BAG-B18				
OxA-26403	*Quercus* sp. heartwood, ring 2; 80mg	636±22	−25.7±0.2	1396

Laboratory Code	**Material**	**Radiocarbon Age (BP)**	**$\delta^{13}C$ (‰) - IRMS**	**Tree-ring date (AD)**
SUERC-40240	*Quercus* sp. heartwood, ring 7; 70mg	665±30	−26.7±0.2	1401
OxA-26409	*Quercus* sp. heartwood, ring 13; 90mg	615±22	−25.0±0.2	1407
SUERC-40232	*Quercus* sp. heartwood, ring 19; 130mg	580±30	−26.9±0.2	1413
OxA-26410	*Quercus* sp. heartwood, ring 25; 70mg	508±22	−25.1±0.2	1419
SUERC-40236	*Quercus* sp. heartwood, ring 31; 60mg	515±30	−25.7±0.2	1425
OxA-26408	*Quercus* sp. heartwood, ring 37; 30mg	532±22	−25.4±0.2	1431
SUERC-40242	*Quercus* sp. heartwood, ring 43; 50mg	515±30	−26.6±0.2	1437
OxA-26406	*Quercus* sp. heartwood, ring 49; 30mg	486±23	−26.2±0.2	1443
SUERC-40230	*Quercus* sp. heartwood, ring 55; 80mg	375±30	−27.5±0.2	1449
OxA-26412	*Quercus* sp. heartwood, ring 61; 100mg	462±23	−25.7±0.2	1455
SUERC-40246	*Quercus* sp. heartwood, ring 67; 70mg	430±30	−25.7±0.2	1461
OxA-26405	*Quercus* sp. heartwood, ring 73; 30mg	400±23	−26.2±0.2	1467
SUERC-40241	*Quercus* sp. heartwood, ring 79; 50mg	410±30	−27.1±0.2	1473
OxA-26414	*Quercus* sp. heartwood, ring 85; 80mg	395±22	−25.9±0.2	1479
SUERC-40239	*Quercus* sp. heartwood, ring 91; 40mg	420±30	−26.9±0.2	1485
OxA-26404	*Quercus* sp. heartwood, ring 97; 70mg	365±22	−25.8±0.2	1491
SUERC-40231	*Quercus* sp. sapwood, ring 103; 60mg	395±30	−28.1±0.2	1497
OxA-26407	*Quercus* sp. sapwood, ring 109; 40mg	423±23	−26.6±0.2	1503
SUERC-40247	*Quercus* sp. sapwood, ring 115; 50mg	330±30	−27.2±0.2	1509
OxA-26411	*Quercus* sp. sapwood, ring 121; 40mg	382±24	−26.2±0.2	1515
SUERC-40237	*Quercus* sp. sapwood, ring 127; 40mg	350±30	−26.6±0.2	1521
OxA-26413	*Quercus* sp. sapwood, ring 133; 40mg	332±22	−24.3±0.2	1527
SUERC-40238	*Quercus* sp. sapwood, ring 138; 50mg	360±30	−25.8±0.2	1532
Kilve Chantry – core KLV-A06				
OxA-28706	Quercus sp, heartwood, ring 2; 210mg	535±23	−24.5±0.2	1426
SUERC-48663	Quercus sp, heartwood, ring 12; 330mg	522±26	−25.5±0.2	1436
OxA-28707	Quercus sp, heartwood, ring 22; 170mg	465±21	−24.8±0.2	1446
SUERC-48667	Quercus sp, heartwood, ring 33; 90mg	442±21	−25.1±0.2	1457

Laboratory Code	**Material**	**Radiocarbon Age (BP)**	**$\delta^{13}C$ (‰) - IRMS**	**Tree-ring date (AD)**
OxA-28708	Quercus sp, heartwood, ring 43; 90mg	407±22	−25.1±0.2	1467
SUERC-48668	Quercus sp, heartwood, ring 55; 30mg	497±26	−23.7±0.2	1479
OxA-28709	Quercus sp, heartwood, ring 64; 70mg	317±23	−25.8±0.2	1488
SUERC-48669	Quercus sp, heartwood, ring 74; 80mg	422±23	−25.0±0.2	1498
OxA-28710	Quercus sp, heartwood, ring 84; 140mg	332±22	−25.6±0.2	1508
SUERC-48670	Quercus sp, heartwood, ring 95; 140mg	400±26	−25.0±0.2	1519
OxA-28711	Quercus sp, heartwood, ring 106; 60mg	352±23	−25.5±0.2	1530
OxA-28712		297±23	−25.5±0.2	1530
Ring 106	Weighted mean (T'=2.9; T'(5%)=3.8; v=1)	325±17	-	1530
SUERC-48671	Quercus sp, heartwood, ring 117; 80mg	367±26	−25.1±0.2	1541

Table 3: Statistical consistency of radiocarbon ages and δ^{13}C measurements on rings of the same calendar date (Ward and Wilson 1978; T'(5%)=3.8; v=1); values in **bold** indicate that the relevant replicate pair are statistically inconsistent at 95% confidence.

Calendar date	Laboratory Code	Radiocarbon Age (BP)	T'	δ^{13}C (‰) - IRMS	T'
AD 1225	SUERC-50294	836±27	0.2	−24.7±0.2	0.0
	OxA-24672	818±25		−24.7±0.2	
AD 1230	OxA-29232	882±27	**5.6**	−25.3±0.2	**45.1**
	SUERC-34338	795±25		−23.4±0.2	
AD 1289	OxA-28369	751±23	**6.4**	−25.5±0.2	**18.0**
	SUERC-40193	655±30		−24.3±0.2	
AD 1300	OxA-28639	632±22	0.0	−25.2±0.2	**10.1**
	SUERC-40188	625±30		−24.3±0.2	
AD 1306	OxA-26426	617±22	0.6	−23.7±0.2	0.1
	SUERC-48678	644±26		−23.6±0.2	
AD 1467	OxA-26405	400±23	0.0	−26.2±0.2	**15.1**
	OxA-28708	407±22		−25.1±0.2	
AD 1479	SUERC-48668	497±26	**9.0**	−23.7±0.2	**60.5**
	OxA-26414	395±22		−25.9±0.2	
AD 1530	OxA-28711	352±23	2.9	−25.5±0.2	0.0
	OxA-28712	297±23		−25.5±0.2	

Table 4: Statistical consistency (Ward and Wilson 1978) of radiocarbon ages (this study and Stuiver 1993) on rings of the same calendar date; values in **bold** indicate that the relevant measurements are statistically inconsistent at 95% confidence.

Calendar date	Laboratory Code	Radiocarbon Age (BP)	T'(5%)	T'
AD 1515	OxA-26411	382±24	3.8	1.0
	QL-10315	355±13		
AD 1519	SUERC-48670	400±28	3.8	1.0
	QL-10311	367±16		
AD 1521	SUERC-40237	350±30	3.8	0.4
	QL-10309	329±16		
AD 1527	OxA-26413	332±22	3.8	3.0
	QL-10303	319±14		
AD 1530	OxA-28711	352±23	6.0	3.0
	OxA-28712	297±23		
	QL-10300	316±14		
AD 1532	SUERC-40238	360±30	3.8	**4.1**
	QL-10298	293±14		
AD 1541	SUERC-48671	367±26	6.0	**9.8**
	QL-10289	282±13		
	QL-10289	318±13		

Table 5: Summary of wiggle-matching the five timbers sampled for radiocarbon dating, (a) all radiocarbon measurements, (b) OxA- only, (c) SUERC-only, (d) all radiocarbon measurement with known tree-ring end date of sequence

Data	Acomb {An, n}	*Highest Posterior Density interval (cal AD)*			Tree-ring end date (AD)
		68% probability	***95% probability***	***99% probability***	
Rudge, Morchard Bishop – core MBRU13					
(a)	130.2 {22.4, 10}	*1258–1281*	*1254–1291*	*1251–1300*	1260
(b)	154.7 {31.6, 5}	*1260–1286*	*1252–1295*	*1247–1306*	1260
(c)	90.9 {31.6, 5}	*1255–1284*	*1252–1299*	*1247–1305*	1260
(d)	**3.0** {21.3, 11}	-	-	-	1260
Bremhill Court – core BCB-C10					
(a)	45.8 {17.7, 16}	***1301–1307***	***1297–1313***	***1293–1312***	1323
(b)	82.3 {25.0, 8}	***1294–1305***	***1288–1309***	***1281–1312***	1323
(c)	48.1 {25.0, 8)	***1303–1311***	***1299–1314***	***1294–1317***	1323
(d)	**0.0** {17.1, 17}	-	-	-	1323
Kingston Deverill, Manor Farm Barn – core KDM-B11					
(a)	25.2 {14.4, 24}	*1405–1411*	*1403–1413*	*1401–1415*	1409
(b)	64.3 {20.4, 12}	***1402–1408***	*1399–1411*	*1396–1413*	1409
(c)	34.6 {20.4, 12}	*1409–1419*	*1406–1424*	*1402–1429*	1409
(d)	**8.8** {14.4, 24}	-	-	-	1409
Blanchland Abbey Gatehouse – core BAG-B18					
(a)	33.0 {14.4, 24}	***1515–1522***	***1513–1524***	***1511–1526***	1532
(b)	50.5 {20.4, 12}	***1514–1522***	***1511–1525***	***1508–1528***	1532
(c)	44.7 {20.4, 12}	***1516–1524***	***1512–1528***	*1508–1533*	1532
(d)	**2.0** {14.1, 25}	-	-	-	1532
Kilve Chantry – core KLV-A06					
(a)	**2.8** {20.4, 12}	***1526–1533***	***1523–1537***	***1517–1540***	1544
(b)	60.9 {28.9, 6)	***1531-1541***	*1527–1546*	*1523–1552*	1544
(c)	**14.1** {28.9, 6)	***1505–1515***	***1501–1522***	***1498–1531***	1544
(d)	**0.0** {19.6, 13}	-	-	-	1544

Table 6: Summary of the results of wiggle-matching 25–35-year blocks from the five timbers sampled for radiocarbon dating (see Figs 7–8) with dendrochronological date for the final tree-ring

Core	**Block**	**Rings**	**Acomb; An**	***Highest Posterior Density interval (cal AD)***			**Tree-ring date (AD)**
				68% probability	***95% probability***	***99% probability***	
MBRU13	A	32–65	129.4; 31.6	*1273–1292 (38%) or 1294–1307 (30%)*	*1259–1311*	*1251–1320*	1260
MBRU13	B	40–71	110.7; 31.6	*1261–1287 (55%) or 1295–1304 (13%)*	*1254–1311*	*1248–1321*	1260
MBRU13	C	48–81	105.5; 31.6	*1263–1290 (47%) or 1293–1306 (21)*	*1249–1308*	*1245–1316*	1260
MBRU13	D	54–88	94.8; 31.6	*1255–1287*	*1249–1307*	*1243–1314*	1260
MBRU13	E	65–97	146.7; 31.6	*1249–1276*	*1234–1289*	*1225–1299*	1260
MBRU13	F	71–102	148.7; 31.6	*1251–1272*	*1245–1291*	*1225–1299*	1260
BCB-C10	A	2–27	64.9; 28.9	*1292–1314*	*1269–1317*	*1256–1321*	1323
BCB-C10	B	6–34	88.7; 28.9	*1295–1313*	*1279–1323*	*1264–1335*	1323
BCB-C10	C	11–39	73.2; 28.9	*1294–1313*	*1274–1320*	*1256–1328*	1323
BCB-C10	D	16–45	102.7; 28.9	*1307–1323*	*1292–1328*	*1279–1331*	1323
BCB-C10	E	21–51	72.8; 28.9	*1286–1304*	*1279–1313*	*1266–1321*	1323
BCB-C10	F	27–57	55.9; 28.9	*1286–1298 (35%) or1301–1312 (33%)*	*1280–1316*	*1271-1321*	1323
BCB-C10	G	34–63	62.5; 28.9	*1300-1314*	*1285–1317*	*1273–1321*	1323
BCB-C10	H	39–70	64.6; 28.9	*1301–1311*	*1292–1315*	*1278–1318*	1323
BCB-C10	I	43–75	60.8; 28.9	*1299–1309*	*1291–1312*	*1282-1316*	1323
BCB-C10	J	51–81	64.0; 28.9	*1295–1305*	*1289–1308*	*1279–1312*	1323
BCB-C10	K	57–87	70.7; 28.9	*1300–1308*	*1296–1311*	*1293-1314*	1323
KDM-B11	A	1–29	112.1; 28.9	*1405–1415*	*1401–1420 (92%) or 1489–1495 (3%)*	*1399–1425 (93%) or 1484–1500 (6%)*	1409
KDM-B11	B	6–34	56.8; 28.9	*1402–1411*	*1397–1417 (90%) or 1476–1487 (5%)*	*1394–1421 (91%) or 1465–1495*	1409
KDM-B11	C	12–39	64.8; 28.9	*1400-1410*	*1394–1416 (91%) or 1476–1485 (4%)*	*1392–1420 (92%) or 1467–1492 (7%)*	1409
KDM-B11	D	17–45	83.4; 28.9	*1403–1414 (32%) or 1470–1481 (36%)*	*1398–1420 (46%) or 1465–1487 (49%)*	*1394–1428 (47%) or 1440–1492 (52%*	1409

Core	**Block**	**Rings**	**Acomb; An**	***Highest Posterior Density interval (cal AD)***			**Tree-ring date (AD)**
				68% probability	***95% probability***	***99% probability***	
KDM-B11	E	23–49	85.1; 28.9	*1402–1413 (35%) or 1472–1482 (33%)*	*1398–1418(49%) or 1468–1487 (46%)*	*1392–1426 (51%) or 1463–1492 (48%)*	1409
KD-B11M	F	29–55	62.3; 28.9	*1397–1414 (56%) or 1472–1477 (12%)*	*1391–1420 (72%) or 1468–1481 (23%)*	*1385–1440 (75%) or 1462–1485 (24%)*	1409
KDM-B11	G	34–60	64.6; 28.9	*1395–1413 (54%) or 1471–1477 (14%)*	*1388–1419 (72%) or 1467–1480 (23%)*	*1383–1429 (74%) or 1462–1483 (25%)*	1409
KDM-B11	H	39–66	78.7; 28.9	*1397–1416*	*1391–1423 (88%) or 1469–1477 (7%)*	*1386–1428 (90%) or 1464–1482 (9%)*	1409
KDM-B11	I	45–71	69.9; 28.9	*1392–1405 (41%) or 1467–1475 (27%)*	*1387–1414 (60%) or 1463–1478 (35%)*	*1382–1421 (62%) or 1459–1481 (37%)*	1409
KDM-B11	J	49–77	65.6; 28.9	*1392–1405*	*1387–1414*	*1380–1421*	1409
KDM-B11	K	55–82	86.3; 28.9	*1389–1401*	*1382–1410*	*1372–1418*	1409
KDM-B11	L	60–88	98.3; 28.9	*1394–1404*	*1387–1410*	*1381–1416*	1409
KDM-B11	M	66–93	76.9; 28.9	*1390–1402*	*1384–1408*	*1373–1419*	1409
KDM-B11	N	71–99	67.6; 28.9	*1393–1404*	*1388–1409*	*1382–1416*	1409
KDM-B11	O	77–104	83.9; 28.9	*1395–1407*	*1389–1412*	*1337–1352 (1%) or 1380–1419 (98%)*	1409
KDM-B11	P	82–110	77.6; 28.9	*1395–1408*	*1336–1342 (2%) or 1382–1413 (93%)*	*1329–1350 (4%) or 1374–1417 (98%)*	1409
KDM-B11	Q	88–115	49.1; 28.9	*1338–1340 (2%) or 1401–1413 (66%)*	*1301–1346 (23%) or 1398–1417 (72%)*	*1325–1352 (245%) or 1394–1422 (74%)*	1409
KDM-B11	R	93–120	51.7; 28.9	*1401–1414*	*1330–1345 (21%) or 1399–1416 (74%)*	*1324–1350 (24%) or 1396–1420 (75%)*	1409
KDM-B11	S	99–126	36.1; 28.9	*1406–1414*	*1403–1418*	*1328–1342 (1%) or 1399–1422 (98%)*	1409
BAG-B18	A	2–31	47.7; 28.9	*1513–1523*	*1508–1528*	*1435–1451 (3%) or 1505–1531 (96%)*	1532
BAG-B18	B	7–37	52.7; 28.9	*1513–1522*	*1510–1526*	*1506–1532*	1532
BAG-B18	C	13–43	79.9; 28.9	*1516–1526*	*1512–1530*	*1508–1533*	1532
BAG-B18	D	19–49	108.3; 28.9	*1519–1528*	*1514–1531*	*1510–1535*	1532
BAG-B18	E	25–55	49.9; 28.9	*1524–1532*	*1521–1535*	*1516–1538*	1532
BAG-B18	F	31–61	44.5; 28.9	*1519–1528*	*1514–1531*	*1510–1535*	1532
BAG-B18	G	37–67	46.6; 28.9	*1517–1526*	*1513–1530*	*1509–1534*	1532

Core	Block	Rings	Acomb; An	*Highest Posterior Density interval (cal AD)*			Tree-ring date (AD)
				68% probability	***95% probability***	***99% probability***	
BAG-B18	H	43–73	54.5; 28.9	*1518–1528*	*1514–1532*	*1511–1536*	1532
BAG-B18	I	49–79	59.7; 28.9	*1519–1528*	*1514–1533*	*1511–1538*	1532
BAG-B18	J	55–85	71.6; 28.9	*1518–1530*	*1514–1539*	*1510–1547*	1532
BAG-B18	K	61–91	200.4; 28.9	*1512–1522*	*1508–1526*	*1504–1532*	1532
BAG-B18	L	67–97	182.3; 28.9	*1512–1524*	*1508–1533*	*1504–1542*	1532
BAG-B18	M	73–103	159.8; 28.9	*1510–1524*	*1506–1533*	*1501–1545*	1532
BAG-B18	N	79–109	90.1; 28.9	*1503–1515*	*1498–1522*	*1493–1535*	1532
BAG-B18	O	85–115	64.6; 28.9	*1501–1517*	*1495–1524*	*1492–1539*	1532
BAG-B18	P	91–121	69.4; 28.9	*1493–1508*	*1489–1520*	*1485-1536*	1532
BAG-B18	Q	97–127	61.0; 28.9	*1494–1513*	*1489–1529*	*1484–1540 (97%) or 1630–1647 (2%)*	1532
BAG-B18	R	103–133	64.7; 28.9	*1490–1511*	*1479–1526 (94%) or 1633–1636 (1%)*	*1475–1537 (97%) or 1628–1645 (2%)*	1532
BAG-B18	S	109–138	61.0; 28.9	*1490–1513*	*1477–1524 (94%) or 1630–1635 (1%)*	*1471–1537 (96%) or 1619–1641 (13%)*	1532
KLV-A06	A	2–33	165.2; 35.4	*1527–1537*	*1523–1541*	*1518–1545*	1544
KLV-A06	B	12–43	162.3; 35.4	*1527–1537*	*1523–1541*	*1519–1546*	1544
KLV-A06	C	22–55	4.6; 35.4	*1525–1535*	*1520–1540*	*1514–1545*	1544
KLV-A06	D	33-64	1.5; 35.4	*1525–1535*	*1519–1543*	*1512–1552*	1544
KLV-A06	E	43–74	2.3; 35.4	*1511–1518 (19%) or 1522–1533 (49%)*	*1507–1538*	*1504–1551*	1544
KLV-A06	F	55–84	2.4; 35.4	*1506–1515*	*1503–1521 (88%) or 1523–1533 (7%)*	*1499–1548*	1544
KLV-A06	G	64–95	13.9; 35.4	*1523–1540 (37%) or 1627–1633 (7%) or 1648–1657 (24%)*	*1509–1548 (52%) or 1621–1638 (43%)*	*1505–1559 (54%) or 1603–1661 (45%)*	1544
KLV-A06	H	74-106	31.5; 35.4	*1504–1519 (50%) or 1523–1537 (18%)*	*1492–1543*	*1487–1550 (97%) or 1628–1657 (2%)*	1544
KLV-A06	I	84–117	52.8; 35.4	*1507–1520 (16%) or 1598–1614 (20%) or 1621–1641 (32%)*	*1502–1541 (30%) or 1583–1619 (29%) 1621–1641 (36%)*	*1488–1552 (33%) or 1568–1646 (66%)*	1544

Figure 1: The proportion of oak samples dated by dendrochronology in England compared to the number of rings contained in the measured sequence.

Figure 2: Probability distributions of dates from MBRU13. Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the result of simple radiocarbon calibration, and a solid one, based on the wiggle-match sequence. Distributions other than those relating to particular samples, correspond to aspects of the model. For example, the distribution '*MBRU13_end*' is the estimated date of the final ring of this core. The large square brackets down the left-hand side of the diagram along with the CQL2 keywords (Bronk Ramsey 2009) define the model exactly.

Figure 3: Probability distributions of dates from BCB-C10. The format is identical to that of Figure 2. The large square brackets down the left-hand side of the diagram along with the CQL2 keywords define the model exactly

Figure 4: Probability distributions of dates from KDM-B11. The format is identical to that of Figure 2. The large square brackets down the left-hand side of the diagram along with the CQL2 keywords define the model exactly

Figure 5: Probability distributions of dates from BAG-B18. The format is identical to that of Figure 2. In this case the final ring of the core has a radiocarbon date and so '*SUERC-40238_BAG-B18_end'* is the estimated date for the end of the sequence. The large square brackets down the left-hand side of the diagram along with the CQL2 keywords define the model exactly

Figure 6: Probability distributions of dates from KLV-A06. The format is identical to that of Figure 2. The large square brackets down the left-hand side of the diagram along with the CQL2 keywords define the model exactly

Figure 7: Schematic diagram showing the blocks of 25–35 tree-rings used for the short wiggle-matches (radiocarbon results are given in Table 2); each model estimates the date of the final ring of the sampled core (Table 5) which is known by dendrochronology (Table 1).

Figure 8: Posterior density estimates for the final ring of each sampled core, derived from the short wiggle-matches based on sequences of 25–35 tree-rings (Fig 7). Distributions where the Highest Posterior Density interval at 95% probability includes the tree-ring date for this ring are shown in black, those where it does not in red (Table 6).

Figure 9: Probability distributions of dates from the five-core combined English tree-ring sequence (AD 1160–1544). The format is identical to that of Figure 2. The large square brackets down the left-hand side of the diagram along with the CQL2 keywords define the model exactly

Figure 10: Radiocarbon ages known-age tree-ring rings AD 1150–1550: single years (OxA, SUERC; this study), decadal samples (Wk; Hogg et al. 2002), single-year and decadal samples (QL; Stuiver et al. 1998), decadal and bi-decadal samples (UB; Hogg et al. 2002; Pearson et al. 1986), decadal and 23-year and 24-year samples (GrN: van der Plicht et al. 1995)