^{14}C wiggle-matching of short tree-ring sequences from post-medieval buildings in England

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Abstract

This study tests whether accurate dating by AMS radiocarbon wiggle-matching short tree-ring series (c. 30 annual rings) in the period after AD 1510 can be achieved routinely. Such an approach has proved problematic for some intervals in the period AD 1160–1541 (Bayliss *et al.* 2017), which are before single-year calibration data are available (Stuiver 1993). We suggest that such calibration data are essential if this approach is to be employed for the informed conservation of standing buildings.

Keywords

Introduction

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 structure.

In providing the required precise dating for historic buildings, the scientific dating method of choice is dendrochronology. In some cases, however, tree-ring analysis does not provide calendar dating, usually either because there are insufficient growth rings in the timbers or because they are of a species that is unsuitable for dendrochronology. In these cases, radiocarbon wiggle-matching is needed to provide an equivalent level of precision and reliability.

Material and Methods

Radiocarbon wiggle-matching has previously been undertaken on part of a 303-ring pine series dated by dendrochronology to AD 1367–1670 from Jermyn Street, London (Tyers *et al.* 2009). In this study, measurements from three participating AMS laboratories all provided accurate wiggle-matches from ring series covering a century or more. Insufficient data are available from this core, however, to undertake wiggle-matching on shorter sequences.

For this reason, new measurements were obtained on a 149-ring core, LED-A22, from the east principal rafter in truss 3 of one of the roofs of Ledston Hall, West Yorkshire (1.34104 W, 53.75494 N). The growth-rings in this timber span AD 1520–1668, with 20 rings of sapwood and bark edge surviving. It is part of a site sequence, LEDASQ01, which is dated by dendrochronology to AD 1424–1668 (Table 1). The ring-width data of the series are provided in Arnold *et al.* (2015).

Radiocarbon measurements were made on a total of 60 single-year tree-ring samples from this core in 2016–17. The 17 dated at the Scottish Universities Environmental Research Centre were prepared to α-cellulose, combusted, graphitised, and dated by AMS as described by Dunbar *et al.* (2016). The 18 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). The 14 dated at the Bristol Radiocarbon Accelerator Mass Spectrometry Facility were processed using the base-acid-base-acid-bleach method as described by Němec *et al.* (2010), graphitised using an IonPlus AGE3 graphitisation system (Wacker *et al.* 2010), and measured using a MICADAS AMS (Synal *et al.* 2007). The 15 dated at the TUBITAK were pretreated using the acid-alkali-acid method modified from Hadjas *et al.* (2004), graphitised (Wacker *et al.* 2010) and measured by AMS on a 1 MV NEC Pelletron accelerator.

At Oxford and SUERC, $\delta^{13}C$ values, relative to VPDB, were obtained by IRMS from the gas combusted for graphitisation; at BRAMS and TUBITAK $\delta^{13}C$ values were measured by AMS.

The conventional radiocarbon ages reported for these samples, along with the rings dated, are listed in Table 2. The quoted errors are each laboratory's estimates of the total error in their dating systems. Five pairs of replicate radiocarbon measurements are available on rings dated to the same calendar year, all of which are statistically consistent at 95% confidence (Ward and Wilson 1978; Table 2). This scatter is in line with statistical expectation. Only two of the replicate $\delta^{13}C$ values are statistically consistent at 95% confidence, one is inconsistent at 95% confidence, but consistent at 99% confidence, and two are significantly different at more than 99% confidence (Ward and Wilson 1978; Table 2). These results are more scattered than would be expected on statistical grounds. This suggests that the different pre-treatment protocols used for wood samples by the Oxford and SUERC laboratories may be affecting the $\delta^{13}C$ values, especially since replicate $\delta^{13}C$ values on bone samples reported by the two laboratories in the same period are in much better agreement (Bayliss *et al.* 2016, fig. 14).

Forty-two pairs of replicate measurements, 17 groups of triplicate measurements, and one quadruple group of measurements are also available on rings dated by AMS (this study) and gas proportional counting Stuiver (1993) to the same calendar year (Figure 1). Of these 60 sets of radiocarbon ages, 52 groups are consistent at 95% confidence, 6 groups are consistent at 99% confidence, and two inconsistent at more than 99%. This scatter is rather more than would be expected simply on the basis of statistics. Stuiver (1993) reported counting errors only, however, and, when the errors quoted for this dataset are inflated using the laboratory error multiplier suggested by Stuiver *et al.* (1998, 1045), 56 sets of measurements are consistent at 95% confidence and the remaining four at 99% confidence, which is within statistical expectation.

<u>Wiggle-matching the entire sequence</u>

Wiggle-matching has been undertaken using the Bayesian approach 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 the entire sequence of data from Ledston Hall. This has good overall agreement (Acomb=76.6, An=10.5, n=45; Bronk Ramsey *et al.* 2001), and estimates the final ring of the sequence to have been formed in *cal AD 1663–1671 (95% probability; SUERC-68040*; Fig 2). This is compatible with the date of AD 1668 produced for this ring by dendrochronology (Table 1).

Wiggle-matching was then undertaken separately of the radiocarbon results quoted by each laboratory (Fig. 3a–d). The model composed of measurements made in Bristol has good overall agreement (Acomb: 102.8, An: 18.9, n: 14; Fig. 3a) and estimates that the last ring of the timber formed in *cal AD 1658–1672 (95% probability; Ring 149*), probably in *cal AD 1662–1670 (68% probability)*. The model of measurements made at Oxford also has good overall agreement (Acomb: 30.9, An: 16.7, n: 18; Fig. 3b) and estimates the last ring of the timber to have formed in *cal AD 1655–1670 (95% probability; Ring 149*), probably in *cal AD 1657–1664 (68% probability)*. Results from SUERC also have good overall agreement (Acomb: 109.9, An: 17.1, n: 17; Fig. 3c) and suggest that the last ring of the timber formed in *cal AD 1656–1674 (95% probability; SUERC-68040*), probably in *cal AD 1662–1671 (68% probability)*. The wiggle match for TUBITAK measurements also have good overall agreement (Acomb: 75.0, An: 18.3, n: 15; Fig. 3d) and suggest that the last ring of the timber formed in *cal AD 1661–1679 (95% probability; ring_149*), probably in *cal AD 1665–1674 (68% probability)*. In all cases the estimated date of the final ring *(at 95% probability)* includes the felling date provided by dendrochronology of AD 1668.

<u>Wiggle-matching partial sequences</u>

Given that the length of the available tree-ring sequence is the most common limitation on successful dendrochronology in historic buildings from England, we ran a series of 25 short wiggle-matches on blocks consisting of between 29 and 30 rings. The results on the seven dated rings in 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 (AD 1668) to determine the accuracy of the short wiggle-matches.

The results are given in Table 3 and summarised in Figure 4. The Highest Posterior Density interval at 95% probability includes the tree-ring date for the final ring of LED-A22 (AD 1668) in all cases, and the interval at 68% probability includes the tree-ring date in all but four cases. This correspondence between the results of the wiggle-matching and the dendrochronology is greater than statistical expectation.

<u>The long wiggle-match (AD 1160–1668)</u>

As illustrated in Figure 2, a wiggle-match comprising the radiocarbon measurements on the 45 dated rings from Ledston Hall has good overall agreement (Acomb: 76.6; An: 10.5; n: 45) and produces posterior distributions that are compatible with the dendrochronology (AD 1668). Similarly, the wiggle-match including the results on the 18 dated rings from Jermyn Street (Tyers *et al.* 2009, fig. 4) has good overall agreement when recalculated using IntCal13 (Acomb: 35.3; An: 16.7; n: 18) and also produces posterior distributions that are compatible with the dendrochronology (AD 1670).

In contrast, the wiggle-match including the radiocarbon measurements on the 79 dated rings from the sites considered by Bayliss *et al.* (2017, fig 9) has poor overall agreement (Acomb: 1.6; An: 8.0; n: 79), and the Highest Posterior Density interval for the final ring does not include the date obtained for this ring by dendrochronology (AD 1544) even at 99% probability.

When the entire dataset is combined to form a wiggle-match sequence covering AD 1160–1668, the model has poor overall agreement (Acomb: 1.7; An: 6.4; n: 121), and the Highest Posterior Density interval for the final ring does not include the date obtained for this ring by dendrochronology (AD 1668) even at 99% probability.

Discussion

These studies in combination suggest that wiggle-matching of either short (*c.* 30-ring) or long (more 100-ring) tree-ring sequences produces results that are compatible with dendrochronology in the period after AD 1510. In the centuries before this, there appears to be time periods when wiggle-matching does not produce such accuracy (AD 1240–1306 and AD 1396–1532; Bayliss *et al.* 2017, table 6).

This pattern is observed when considering the datasets measured at Oxford and SUERC separately (Bayliss *et al.* 2017, table 5; Tyers *et al.* 2009, table 3; Fig. 3b–c), and so must derive from the calibration curve used, IntCal13 (Reimer *et al.* 2013).

Figures 5–6 shows the radiocarbon ages obtained on single known-age tree-rings as part of this study and those reported by Tyers *et al.* (2009) and Bayliss *et al.* (2017) in comparison to the radiocarbon ages covering this period included in IntCal13 (Reimer *et al.* 2013). The latter are on decadal samples (Wk; Hogg *et al.* 2002), single-year and decadal samples (QL; Stuiver 1993, corrected as described by Stuiver and Becker 1993; 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 (GrN; van der Plicht *et al.* 1995).

Single-year data clearly dominate the period after AD 1510 (Fig 6), which is the period when wiggle-matching appears to be accurate within the precision quoted and the test data scatter within statistical expectation around the IntCal envelope. In the earlier period, there is more deviation between the test data and the IntCal envelope. As the statistical method of curve construction is the same in both periods (Niu *et al.* 2013), this is unlikely to be the cause of this difference, but rather there appears to be detailed structure in the atmospheric concentration of radiocarbon in the problematic periods which is not apparent from the calibration data currently available.

It should be noted that, if accurate wiggle-matching is possible in the post AD 1510 period because of the availability of single-year calibration data, then it is possible to accurately match measurements on samples of European wood against calibration data measured largely on Douglas fir trees that grew on the west coast of America. This would suggest neither intra-hemispheric locational offsets in the ^{14}C concentration of wood (McCormac *et al.* 1995) nor the translocation of ^{14}C between annual growth rings in trees (Grootes *et al.* 1989) are significant factors preventing accurate wiggle-matching.

A calibration curve based on ^{14}C measurements on single tree-rings appears to be required for wiggle-matching to provide estimates of calendar date that are accurate to within the quoted uncertainty. Such accuracy is essential if the results are to inform the long-term preservation and conservation of historic buildings.

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References

[1] A. Arnold, R. Howard, Auckland Castle, Bishop Auckland, County Durham: Tree-Ring Analysis of Timbers English Heritage Research Report Series, English Heritage, Portsmouth, 2013.
[2] A. Arnold, R. Howard, C. Tyers, Ledston Hall, Hall Lane, Ledston, Leeds, West Yorkshire.Tree-Ring Analysis of Timbers, Research Report Series, English Heritage, Portsmouth, 2015.
[3] A.J. Arnold, R.E. Howard, C.D. Litton, Tree-ring Analysis of Timbers from the Main Guard, Pontefract Castle, Pontefract, West Yorkshire, Centre for Archaeology Report, English Heritage, Portsmouth, 2005b.
[4] A.J. Arnold, R.E. Howard, C.D. Litton, Nottingham Tree-ring Dating Laboratory: additional dendrochronology dates, no 32 Vernacular Architecture, 39 (2008) 107–111.
[5] A.J. Arnold, R.E. Howard, C.D. Litton, Tree-ring Analysis of Timbers from the Roof of the Keep, or Little Castle, Bolsover Castle, Derbyshire, Centre for Archaeology Report, English Heritage, Portsmouth, 2003.
[6] A.J. Arnold, R.E. Howard, C.D. Litton, Tree-ring Analysis of Timbers from the Riding School, Bolsover Castle, Bolsover, Derbyshire, Centre for Archaeolology Report, English Heritage, Portsmouth, 2005a.
[7] A. Bayliss, N. Beavan, D. Hamilton, K. Köhler, K., É.Á.Nyerges, C. Bronk Ramsey, E. Dunbar, M. Fecher, T. Goslar, B. Kromer, P. Reimer, E. Bánffy, T. Marton, K. Oross, A. Osztás, I. Zalai-Gaál, A. Whittle, Peopling the past: creating a site biography in the Hungarian Neolithic, Bericht der Römisch-Germanischen Kommission 94 (2016) 23–91.
[8] A. Bayliss, P. Marshall, C. Tyers, C. Bronk Ramsey, G. Cook, S.P.H.T. Freeman, S. Griffiths, Informing Conservation: Towards ^{14}C Wiggle-Matching of Short Tree-Ring Sequences from Medieval Buildings in England, Radiocarbon, 59 (2017), 985–1007.
[9] F. Brock, T. Higham, P. Ditchfield, C. Bronk Ramsey, Current pretreatment methods for AMS radiocarbon dating at the Oxford Radiocarbon Accelerator Unit (ORAU), Radiocarbon, 52 (2010) 103–112.
[10] C. Bronk Ramsey, Bayesian analysis of radiocarbon dates, Radiocarbon, 51 (2009) 337–360.
[11] C. Bronk Ramsey, J. van der Plicht, B. Weninger, ‘Wiggle matching’ radiocarbon dates, Radiocarbon 43(2A) (2001) 381–389.
[12] C. Bronk Ramsey, T. Higham, P. Leach, Towards high precision AMS: progress and limitations, Radiocarbon 46 (2004), 17–24.
[13] A. Christen, C. Litton, A Bayesian approach to wiggle-matching, Journal of Archaeological Science 22(6) (1995) 719–725.
[14] M. Dee, C. Bronk Ramsey, Refinement of graphite target production at ORAU, Nuclear Instruments and Methods in Physics Research B, 172 (2000) 449–453.
[15] E. Dunbar, G.T. Cook, P. Naysmith, B.G. Tipney, S. Xu, AMS 14C dating at the Scottish Universities Environmental Research Centre (SUERC) Radiocarbon Dating Laboratory Radiocarbon, 58 (2016) 9–23.
[16] P.M. Grootes, G.W. Farwell, F.H. Schmidt, D.D. Leach, Rapid response of tree cellulose radiocarbon content to changes in atmospheric $^{14}C0_2$, concentration, Tellus, 41 (1989) 134–148.
[17] I.Hajdas, G. Bonani, J. Thut, G. Leone, R. Pfenninger, C. Maden A report on sample preparation at the ETH/PSI AMS facility in Zurich, Nuclear

Instruments Methods Phys. Res. Sect. B Beam Interact. with Mater. Atoms, 223–224 (2004) 267–271.
[18] A.G. Hogg, F.G. McCormac, T.F.G. Higham, P.J. Reimer, M.G.L. Baillie, J.G. Palmer, High-precision radiocarbon measurements of contemporaneous tree-ring dated wood from the British Isles and New Zealand: AD 1850–950, Radiocarbon 44 (2002) 633–640.
[19] R.E. Howard, R.R. Laxton, C.D. Litton, Tree-ring analysis of timbers from Clumpcliff Farm, Methley Lane, Rothwell, nr Oulton, West Yorkshire, Ancient Monuments Labratory Report, English Heritage, Portsmouth, 2000.
[20] F.G. McCormac, M.G.L. Baillie, J.R. Pilcher, Location-dependent differences in the ^{14}C content of wood, Radiocarbon, 37 (1995) 395–407.
[21] M. Němec, L. Wacker, I. Hajdas, H. Gäggeler, Alternative Methods for Cellulose Preparation for Ams Measurement, Radiocarbon 52 (2010) 1358-1370.
[22] M. Niu, T.G. Heaton, P.G. Blackwell, C.E. Buck, The Bayesian approach to radiocarbon calibration curve estimation: the IntCal13, Marine13, and ShCal13 methodolodies, Radiocarbon, 55 (2013) 1905–1922.
[23] G.W. Pearson, J.R. Pilcher, M.G.L. Baillie, D.M. Corbett, F. Qua, High-precision ^{14}C measurements of Irish oaks to show the natural ^{14}C variations from AD 1840 to 5210 BC, Radiocarbon, 28 (1986) 911–934.
[24] P.J. Reimer, E. Bard, A. Bayliss, J.W. Beck, P. Blackwell, C. Bronk Ramsey, C.E. Buck, H. Cheng, R.L. Edwards, M. Friedrich, P.M. Grootes, T.P. Guilderson, H. Haflidason, I. Hajdas, C. Hatté, T.J. Heaton, D.L. Hoffmann, A.G. Hogg, K.A. Hughen, K.F. Kaiser, B. Kromer, S.W. Manning, M. Niu, R.W. Reimer, D.A. Richards, E.M. Scott, J.R. Southon, R.A. Staff, C.S.M. Turney, J. van der Plicht, IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP, Radiocarbon, 55 (2013) 1869–1887.
[25] M. Stuiver, A note on single-year calibration of the radiocarbon timescale AD 1510–1954, Radiocarbon, 35 (1993) 67–72.
[26] M. Stuiver, B. Becker, High-precision decadal calibration of the radiocarbon time scale, AD 1950–6000 BC, Radiocarbon, 35 (1993) 35–66.
[27] M. Stuiver, P.J. Reimer, T.F. Braziunas, High-precision radiocarbon age calibration for terrestrial and marine samples, Radiocarbon 40(3) (1998) 1127–1151.
[28] M. Stuiver, P.J. Reimer, E. Bard, W. Beck, G. S. Burr, K.A. Hughen, B. Kromer, G. McCormac, J. van der Plicht, and M. Spurk, IntCal998 radiocarbon age calibration, 24,000–0 cal BP, Radiocarbon 40 (3) (1998) 1041–1083.
[29] H.-A. Synal, M. Stocker, M. Suter, MICADAS: A new compact radiocarbon AMS system Nucl. Instruments Methods Phys. Res. Sect. B Beam Interact. with Mater. Atoms, 259 (2007) 7–13.
[30] C. Tyers, J. Sidell, J. van der Plicht, P. Marshall, G. Cook, C. Bronk Ramsey, A. Bayliss, Wiggle-matching using known-age pine from Jermyn Street, London, Radiocarbon, 51 (2009) 385–396.
[31] J. van der Plicht, E. Jansma, H. Kars, The ‘Amsterdam Castle’: a case study of wiggle matching and the proper calibration curve, Radiocarbon 37(3) (1995) 965–968.
[32] L. Wacker, M. Němec, J. Bourquin, A revolutionary graphitisation system: Fully automated, compact and simple, Nuclear Instruments Methods Phys. Res. Sect. B Beam Interact. with Mater. Atoms, 268 (2010) 931–934.

[33] G.K. Ward, S.R. Wilson, Procedures for comparing and combining radiocarbon age determinations: a critique, Archaeometry, 20 (1978) 19–32.

Table 1: Results of cross-matching site chronology LEDASQ01 with relevant independent site reference chronologies

Reference chronology	*t*-value	Span of chronology	Reference
Riding House, Bolsover Castle, Derbyshire	12.0	AD 1494–1744	Arnold *et al* 2005a
Pontefract Castle, Pontefract, West Yorkshire	11.0	AD 1507–1656	Arnold *et al* 2005b
Little Castle, Bolsover Castle, Derbyshire	10.4	AD 1532–1749	Arnold *et al* 2003
Clumpcliff Farm, Rothwell, West Yorkshire	10.2	AD 1452–1613	Howard *et al* 2000
Auckland Castle, Bishop Auckland, County Durham	10.1	AD 1425–1698	Arnold and Howard 2013
Nun Appleton, Tadcaster, West Yorkshire	9.6	AD 1478–1657	Arnold *et al* 2008

Table 2: Details of sampled tree-rings and radiocarbon results from LED-A22

Laboratory code	Material	^{14}C age (BP)	$\delta^{13}C_{IRMS}$ (‰)	Tree-ring date (AD)
SUERC-68046	*Quercus* sp. heartwood, ring 1	306±29	−23.5±0.2	1520
TUBITAK-127	*Quercus* sp. heartwood, ring 3	321±29	−24.1±1.0	1522
OxA-34316	*Quercus* sp. heartwood, ring 4	311±33	−23.4±0.2	1523
OxA-34317	*Quercus* sp. heartwood, ring 4	357±35	−23.8±0.2	
Ring 4	333±25BP, T′=0.9; −23.6±0.14 ‰, T′=2.0; T′(5%)=3.8, ν=1			
BRAMS-1230	*Quercus* sp. heartwood, ring 7	315±26	−21.9±0.2	1526
SUERC-68056	*Quercus* sp. heartwood, ring 9	324±29	−24.0±0.2	1528
OxA-34321	*Quercus* sp. heartwood, ring 9	359±33	−24.9±0.2	
Ring 9	339±22BP; T′=0.6; −24.5±0.14 ‰, T′=10.1; T′(5%)=3.8, ν=1			
TUBITAK-128	*Quercus* sp. heartwood, ring 13	276±27	−23.5±1.0	1532
OxA-34275	*Quercus* sp. heartwood, ring 14	262±25	−24.9±0.2	1533
BRAMS-1231	*Quercus* sp. heartwood, ring 15	319±26	−22.9±0.2	1534
SUERC-68044	*Quercus* sp. heartwood, ring 19	282±29	−24.1±0.2	1538
TUBITAK-129	*Quercus* sp. heartwood, ring 21	352±50	−24.5±1.7	1540
BRAMS-1232	*Quercus* sp. heartwood, ring 22	294±26	−25.0± 0.2	1541
SUERC-68054	*Quercus* sp. heartwood, ring 24	315±29	−24.2±0.2	1543
OxA-34323	*Quercus* sp. heartwood, ring 24	380±33	−24.9±0.2	
Ring 24	344±22BP; T′=2.2; −24.6±0.14 ‰, T′=6.1; T′(5%)=3.8, ν=1			
SUERC 68053	*Quercus* sp. heartwood, ring 29	322±29	−25.2±0.2	1548
OxA-34281	*Quercus* sp. heartwood, ring 29	255±25	−26.2±0.2	
Ring 29	284±19BP; T′=3.1; −25.7±0.14 ‰, T′=12.5; T′(5%)=3.8, ν=1			
BRAMS-1233	*Quercus* sp. heartwood, ring 31	302±26	−26.1±0.2	1550

OxA-34277	*Quercus* sp. heartwood, ring 34	328±24	−24.3± 0.2	1553
TUBITAK-130	*Quercus* sp. heartwood, ring 36	307±27	−25.5±0.8	1555
SUERC-68051	*Quercus* sp. heartwood, ring 39	335±29	−24.6±0.2	1558
OxA-34319	*Quercus* sp. heartwood, ring 44	334±32	−25.4±0.2	1563
TUBITAK-131	*Quercus* sp. heartwood, ring 45	310±27	−25.3±0.8	1564
BRAMS-1234	*Quercus* sp. heartwood, ring 47	353±26	−22.4±0.2	1566
SUERC-68034	*Quercus* sp. heartwood, ring 49	306±29	−25.1±0.2	1568
OxA-34457	*Quercus* sp. heartwood, ring 54	364±27	−25.9±0.2	1573
BRAMS-1235	*Quercus* sp. heartwood, ring 56	382±26	−28.4±0.2	1575
TUBITAK-132	*Quercus* sp. heartwood, ring 58	290±48	−25.1±1.5	1577
SUERC-68035	*Quercus* sp. heartwood, ring 59	346±29	−25.8±0.2	1578
TUBITAK-133	*Quercus* sp. heartwood, ring 62	286±27	−26.7±0.8	1581
OxA-34279	*Quercus* sp. heartwood, ring 64	331±26	−25.9±0.2	1583
BRAMS-1236	*Quercus* sp. heartwood, ring 67	336±26	−25.8±0.2	1586
SUERC-68052	*Quercus* sp. heartwood, ring 69	310±29	−25.9±0.2	1588
OxA-34282	*Quercus* sp. heartwood, ring 74	297±26	−27.1±0.2	1593
TUBITAK-134	*Quercus* sp. heartwood, ring 77	396±29	−26.3±0.9	1596
SUERC-68036	*Quercus* sp. heartwood, ring 79	334±29	−25.6±0.2	1598
OxA-34283	*Quercus* sp. heartwood, ring 84	336±26	−26.4±0.2	1603
TUBITAK-135	*Quercus* sp. heartwood, ring 85	336±28	−24.9±0.9	1604
BRAMS-1238	*Quercus* sp. heartwood, ring 86	365±26	−24.4± 0.2	1605
SUERC-68050	*Quercus* sp. heartwood, ring 89	347±29	−25.2± 0.2	1608
OxA-34278	*Quercus* sp. heartwood, ring 94	341±25	−24.8±0.2	1613
TUBITAK-136	*Quercus* sp. heartwood, ring 96	416±42	−26.3±0.9	1615
BRAMS-1239	*Quercus* sp. heartwood, ring 98	370±26	−23.1±0.2	1617
SUERC-68042	*Quercus* sp. heartwood, ring 99	364±29	−23.7±0.2	1618
OxA-34318	*Quercus* sp. heartwood, ring 104	374±31	−24.1± 0.2	1623
TUBITAK-137	*Quercus* sp. heartwood, ring 107	351±27	−23.0±0.7	1626
SUERC-68055	*Quercus* sp. heartwood, ring 109	313±29	−23.8±0.2	1628
OxA-34322	*Quercus* sp. heartwood, ring 109	351±34	−24.1±0.2	
Ring 109	284±19BP; T′=3.1; −24.0±0.14 ‰, T′=1.1; T′(5%)=3.8, ν=1			
BRAMS-1240	*Quercus* sp. heartwood, ring 110	348±26	−23.3±0.2	1629
OxA-34280	*Quercus* sp. heartwood, ring 114	321±26	−25.0±0.2	1633
TUBITAK-138	*Quercus* sp. heartwood, ring 115	312±26	−22.7±0.7	1634
SUERC-68043	*Quercus* sp. heartwood, ring 119	320±29	−22.9±0.2	1638
BRAMS-1241	*Quercus* sp. heartwood, ring 120	291±26	−22.7±0.2	1639
TUBITAK-139	*Quercus* sp. heartwood, ring 122	271±28	−24.0±0.9	1641
OxA-34284	*Quercus* sp. heartwood, ring 124	275±25	−25.7±0.2	1643
BRAMS-1242	*Quercus* sp. heartwood, ring 125	263±26	−25.7±0.2	1644
SUERC-68041	*Quercus* sp. heartwood, ring 129	214±29	−23.7±0.2	1648

BRAMS-1243	*Quercus* sp. heartwood, ring 131	301±26	−21.7±0.2	1650
OxA-34320	*Quercus* sp. heartwood, ring 134	292±32	−24.3±0.2	1653
TUBITAK-140	*Quercus* sp. heartwood, ring 135	212±29	−23.8±1.1	1654
SUERC-68045	*Quercus* sp. heartwood, ring 139	267±29	−23.4±0.2	1658
OxA-34276	*Quercus* sp. heartwood, ring 144	214±24	−24.2±0.2	1663
TUBITAK-141	*Quercus* sp. heartwood, ring 146	248±55	−26.3±2.3	1665
BRAMS-1244	*Quercus* sp. heartwood, ring 148	214±26	−21.9±0.2	1667
SUERC-68040	*Quercus* sp. heartwood, ring 149	222±29	−24.0±0.2	1668

Table 3: Summary of the estimated dates for the final ring of LED-A22 (dated by dendrochronology to AD 1668) from wiggle-matching 29–30-year blocks (An: 26.7, n: 7 for all).

Rings	Acomb	***Highest Posterior Density interval (cal AD)***	
		68% probability	***95% probability***
1–29	48.0	*1660–1676 (59%)* or *1683–1688 (9%)*	*1655–1709 (89%)* or *1760–1770 (6%)*
4–34	51.5	*1659–1675*	*1655–1693 (93%)* or *1700–1706 (2%)*
9–39	50.8	*1660–1675 (60%)* or *1683–1687 (8%)*	*1655–1706*
14–44	63.2	*1664–1676*	*1657–1694*
19–49	83.3	*1655–1689*	*1645–1699*
24–54	72.3	*1650–1657 (10%)* or *1665–1694 (58%)*	*1643–1706*
29–59	90.6	*1653–1678 (58%)* or *1686–1692 (10%)*	*1647–1700*
34–64	102.7	*1655–1704*	*1596–1620 (11%)* or *1634–1723 (84%)*
39–69	95.1	*1599–1615 (20%)* or *1651–1682 (38%)* or *1697–1704 (8%)* or *1719–1721 (2%)*	*1593–1636 (27%)* or *1642–1725 (68%)*
44–74	95.7	*1598–1617 (42%)* or *1662–1670 (9%)* or *1709–1722 (17%)*	*1595–1631 (44%)* or *1640–1677 (26%)* or *1695–1724 (25%)*
49–79	91.5	*1599–1617 (39%)* or *1649–1670 (29%)*	*1592–1675 (80%)* or *1694–1715 (15%)*
54–84	98.4	*1597–1618 (43%)* or *1651–1668 (16%)* or *1698–1707 (9%)*	*1576–1675 (81%)* or *1692–1711 (14%)*
59–89	103.6	*1605–1613 (8%)* or *1627–1668 (60%)*	*1576–1586 (2%)* or *1596–1677 (92%)* or *1696–1702 (1%)*
64–94	118.4	***1621–1659***	*1601–1676*
69–99	116.8	***1623–1659***	*1607–1672*
74–104	114.1	***1637–1664***	*1563–1569 (1%)* or *1611–1672 (94%)*
79–109	117.0	***1555–1567 (18%)* or *1637–1667 (50%)***	*1544–1573 (25%)* or *1617–1675 (70%)*
84–114	115.5	*1551–1568 (31%)* or *1649–1668 (37%)*	*1538–1573 (37%)* or *1616–1677 (58%)*
89–119	117.5	*1548–1568 (35%)* or *1650–1670 (33%)*	*1529–1574 (46%)* or *1609–1635 (11%)* or *1646–1675 (38%)*
94–124	124.8	*1553–1564 (36%)* or *1658–1670 (32%)*	*1546–1574 (50%)* or *1649–1677 (45%)*
99–129	92.7	*1664–1674*	*1555–1557 (1%)* or *1657–1679 (94%)*
104–134	78.3	*1662–1674*	*1552–1563 (6%)* or *1656–1679 (89%)*
109–139	97.7	*1664–1673*	*1656–1678*
114–144	104.1	*1665–1673*	*1659–1675*
119–149	98.8	*1664–1671*	*1659–1675*

Figure 1: Offsets between radiocarbon ages on single tree-ring from this study and measurements on single tree-rings of the same calendar date reported by Stuiver (1993, corrected as described by Stuiver and Becker 1993).

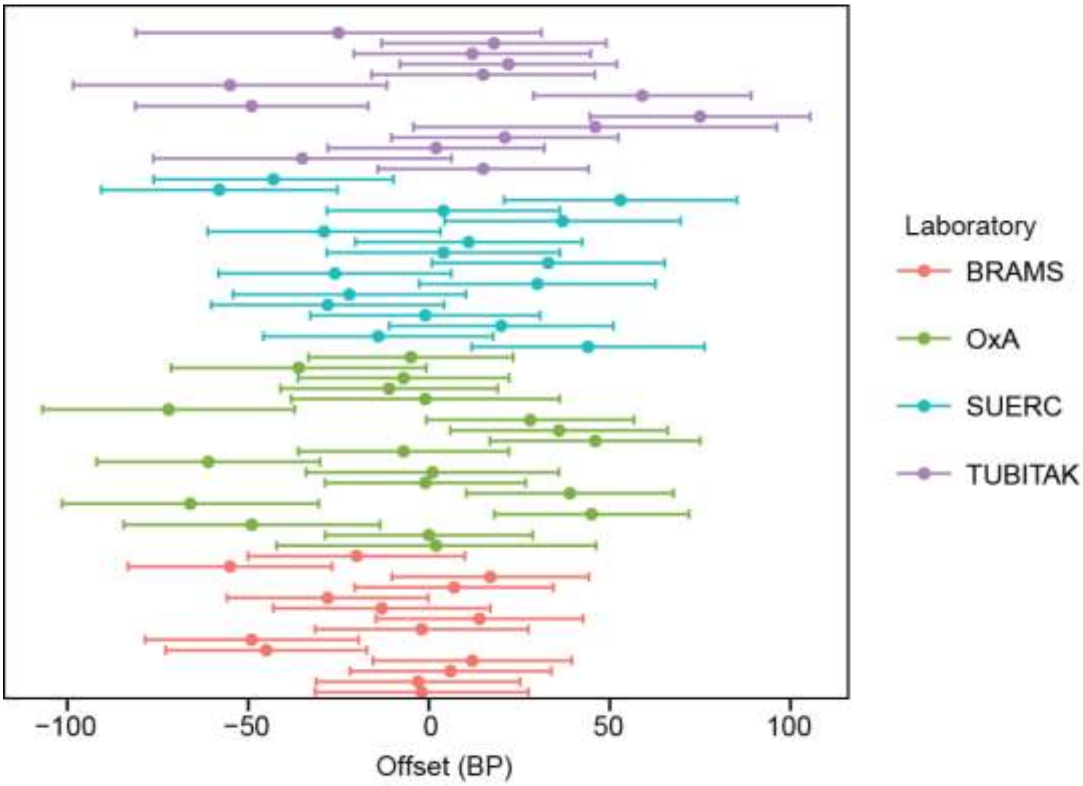
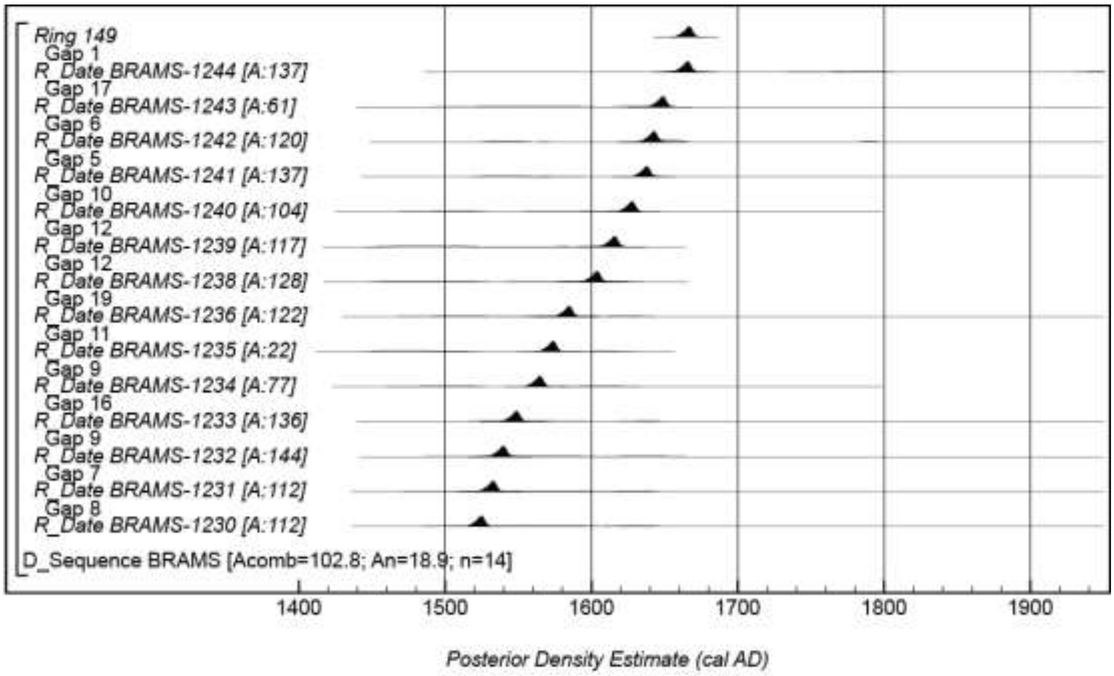
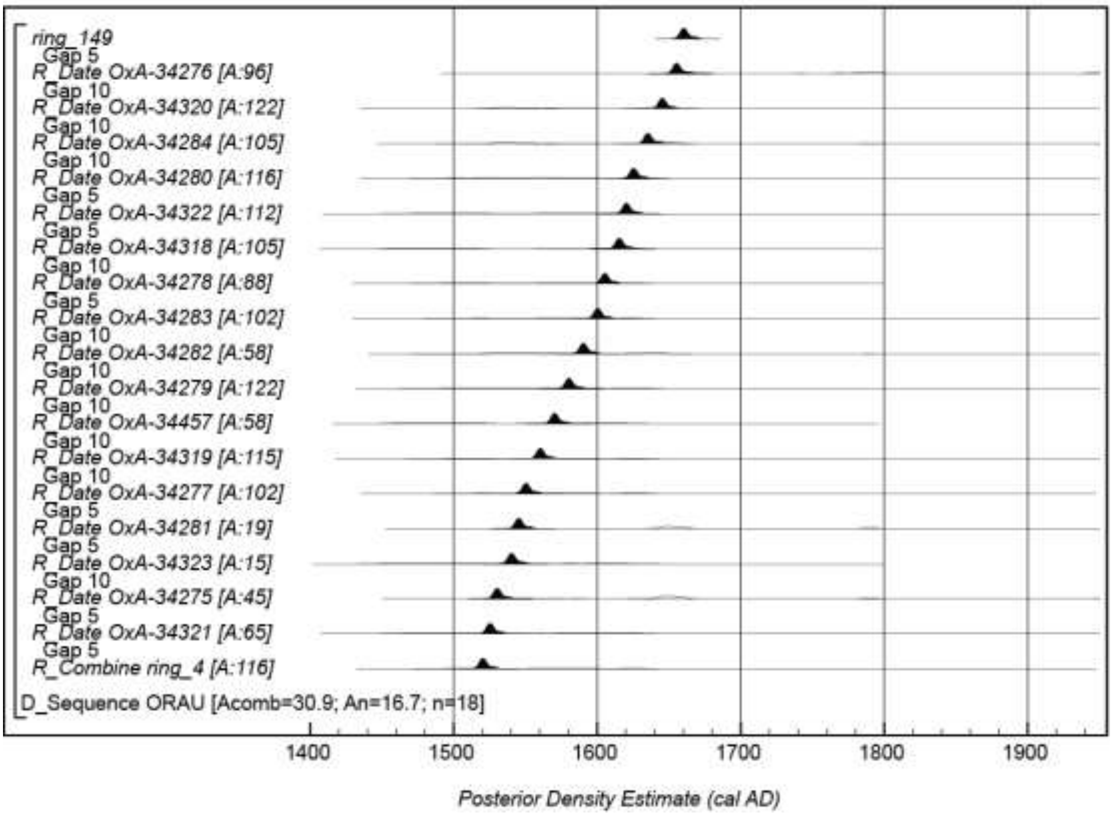
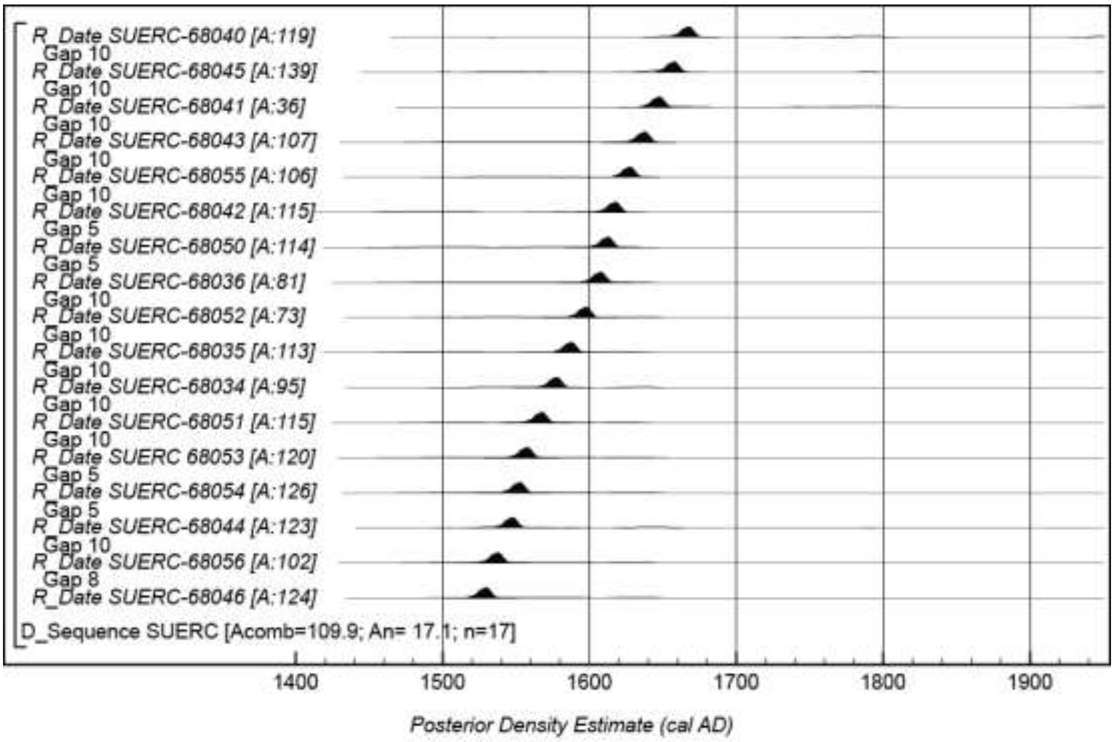


Figure 2: Probability distributions of dates from LED-A22. Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the result of simple radiocarbon calibration, and a solid one, based on the wiggle-match sequence. Distributions other than those relating to particular samples, correspond to aspects of the model. For example, the distribution '*SUERC-68040*' 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 LED-A22 (a) BRAMS-, (b) OxA-, (c) SUERC, and (d) TUBITAK. 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






R_Date SUERC-68040 [A:119]
Gap 10
R_Date SUERC-68045 [A:139]
Gap 10
R_Date SUERC-68041 [A:36]
Gap 10
R_Date SUERC-68043 [A:107]
Gap 10
R_Date SUERC-68055 [A:106]
Gap 10
R_Date SUERC-68042 [A:115]
Gap 5
R_Date SUERC-68050 [A:114]
Gap 5
R_Date SUERC-68036 [A:81]
Gap 10
R_Date SUERC-68052 [A:73]
Gap 10
R_Date SUERC-68035 [A:113]
Gap 10
R_Date SUERC-68034 [A:95]
Gap 10
R_Date SUERC-68051 [A:115]
Gap 10
R_Date SUERC 68053 [A:120]
Gap 5
R_Date SUERC-68054 [A:126]
Gap 5
R_Date SUERC-68044 [A:123]
Gap 10
R_Date SUERC-68056 [A:102]
Gap 8
R_Date SUERC-68046 [A:124]
D_Sequence SUERC [Acomb=109.9; An= 17.1; n=17]
1400
1500
1600
1700
1800
1900
Posterior Density Estimate (cal AD)

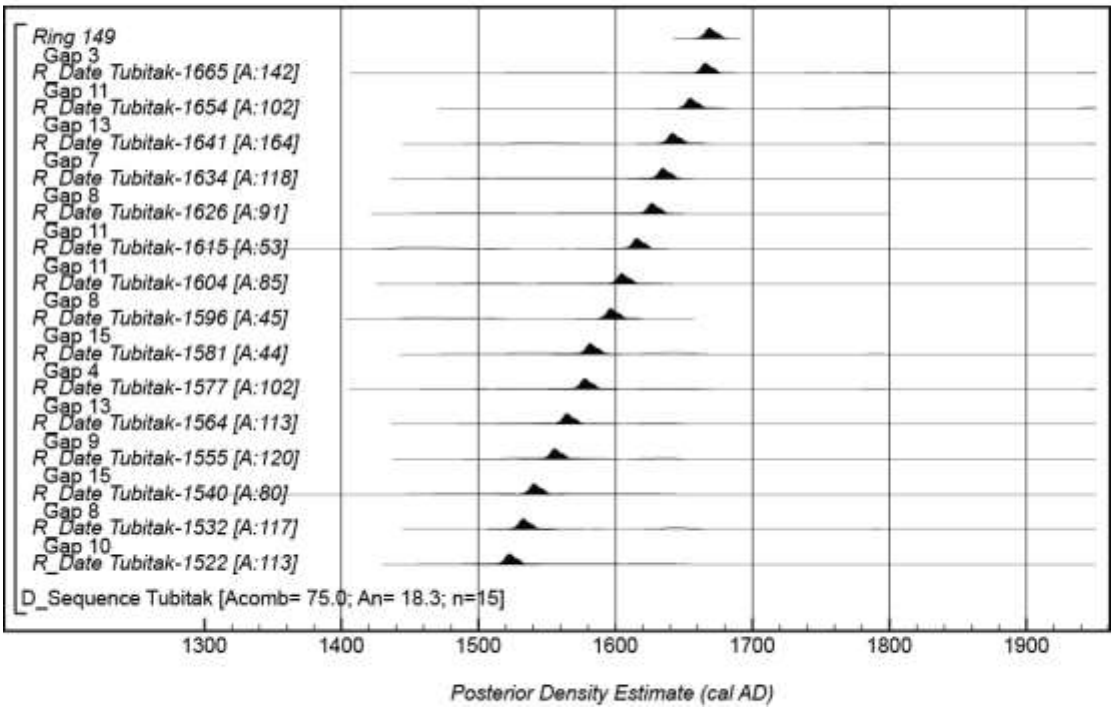

Ring 149
Gap 3
R_Date Tubitak-1665 [A:142]
Gap 11
R_Date Tubitak-1654 [A:102]
Gap 13
R_Date Tubitak-1641 [A:164]
Gap 7
R_Date Tubitak-1634 [A:118]
Gap 8
R_Date Tubitak-1626 [A:91]
Gap 11
R_Date Tubitak-1615 [A:53]
Gap 11
R_Date Tubitak-1604 [A:85]
Gap 8
R_Date Tubitak-1596 [A:45]
Gap 15
R_Date Tubitak-1581 [A:44]
Gap 4
R_Date Tubitak-1577 [A:102]
Gap 13
R_Date Tubitak-1564 [A:113]
Gap 9
R_Date Tubitak-1555 [A:120]
Gap 15
R_Date Tubitak-1540 [A:80]
Gap 8
R_Date Tubitak-1532 [A:117]
Gap 10
R_Date Tubitak-1522 [A:113]
D_Sequence Tubitak [Acomb= 75.0; An= 18.3; n=15]
1300
1400
1500
1600
1700
1800
1900
Posterior Density Estimate (cal AD)

Figure 4: Posterior density estimates for the final ring of LED-A22, derived from the short wiggle-matches based on sequences of 29–30 tree-rings.

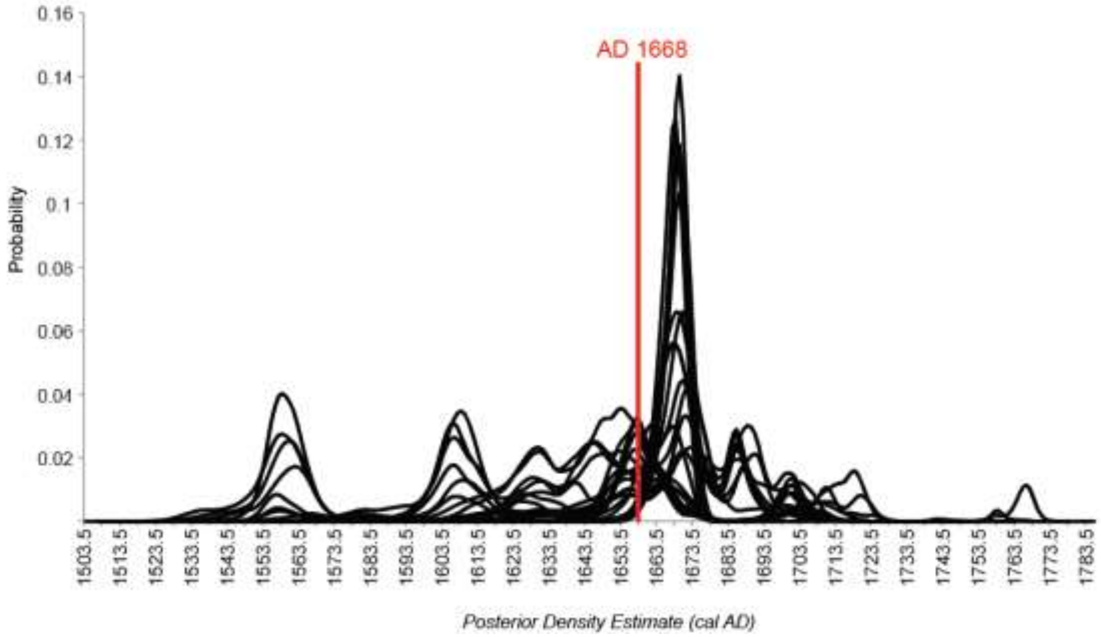


Figure 5: Radiocarbon ages of known-age tree-ring rings AD 1150–1668: single years (OxA-, SUERC-, GrA-, BRAMS-, TUBITAK-; this study, Bayliss *et al.* 2017, Tyers *et al.* 2009), decadal samples (Wk; Hogg *et al.* 2002), single-year and decadal samples (QL; Stuiver 1993 as corrected by Stuiver and Becker 1993; 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). Inset shows detail of period AD 1510–1670.

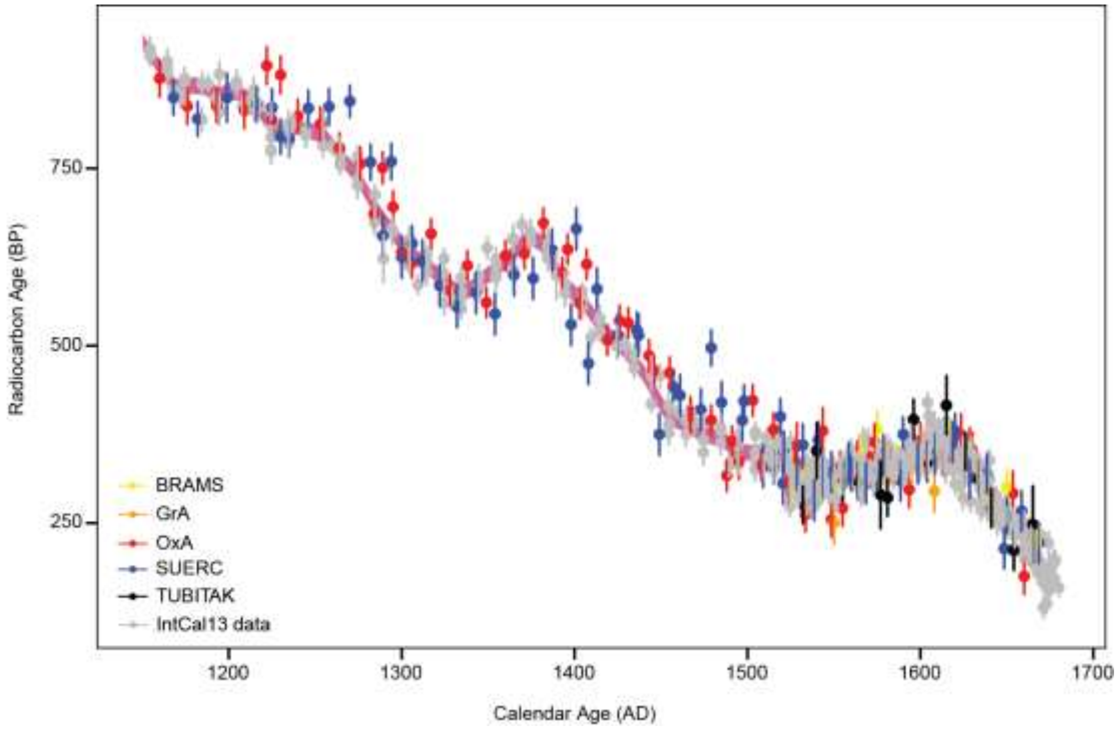


Figure 6: Radiocarbon ages of known-age tree-ring rings AD 1510–1670: single years (OxA-, SUERC-, GrA-, BRAMS-, TUBITAK-; this study, Bayliss *et al.* 2017, Tyers *et al.* 2009), decadal samples (Wk; Hogg *et al.* 2002), single-year samples (QL; Stuiver 1993 as corrected by Stuiver and Becker 1993; Stuiver *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).