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WIGGLE-MATCHING USING KNOWN-AGE PINE FROM JERMYN STREET, LONDON

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ABSTRACT. A slice of pine from the period covered by single-year calibration data (Stuiver 1993) was selected to serve as part of the quality assurance procedures of the English Heritage radiocarbon dating program, following successful wiggle-matching of ^{14}C measurements from structural 15th century English oak timbers (Hamilton et al. 2007). The timber selected was a roofing element from a house on Jermyn Street, central London, demonstrated by dendrochronology to have been felled in AD 1670. Eighteen single-ring samples were dated by the ^{14}C laboratories at Groningen, Oxford, and SUERC: each laboratory was sent a random selection of 6 samples. This approach was intended to mimic the mix of samples and relative ages incorporated into Bayesian chronological models during routine project research. This paper presents the results of this study.

INTRODUCTION

The building at 107 Jermyn Street, London (Figure 1) formed part of a terrace of townhouses thought to be the first phase of urban settlement in this area, which is situated to the west of the earlier medieval and Roman settlements in London. Jermyn Street was part of London's fashionable designed townscape known as the West End. Documentary evidence suggests that Jermyn Street was planned and the individual buildings erected in the 1660s and 1670s. Number 107 was a 5-storied brick building, with timber floors, framing, and roof structure, exclusively composed of Scots pine (*Pinus sylvestris* [L.]), retaining surprising amounts of early fabric considering its age and conversion from a townhouse to a shop in the 19th century.

The dating of imported conifer is an increasingly important aspect of dendrochronological research being developed for post-medieval building analysis in the UK. Dating of standing buildings constructed from the more usual oak is a well-developed discipline (English Heritage 1998); however, dating buildings constructed from conifer is still somewhat in its infancy (Groves 2000). Therefore, with its impending demolition, 107 Jermyn Street provided a valuable resource for extensive dendrochronological sampling. Fifty-one slices were analyzed (Groves and Locatelli 2005) with dendrochronology identifying and providing precise felling dates for 4 distinct phases of construction or modification (see Figure 2). Twenty-three of the 51 samples, forming 5 groups (Groves and Locatelli 2005: Tables 2–5), were dated by comparison with reference chronologies from Norway eastwards to the shores of the White Sea, indicating different sources for the timbers in the different groups (Groves and Locatelli 2005: Tables 11–12).

In addition to the extensive program of dendrochronology funded by English Heritage, a large-scale program of radiocarbon dating is also undertaken, in support of a wide range of archaeological

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Figure 1 107 Jermyn Street (© Museum of London Archaeology Service)

projects (see e.g. Bayliss et al. 2007a, 2008). This includes field-testing of methodological developments prior to their transfer to the wider Historic Environment sector in England, in addition to more usual site-driven research and quality assurance programs. The ^{14}C results from individual sites are routinely incorporated into Bayesian chronological models (Bayliss and Bronk Ramsey 2004) where prior archaeological information about the relative ages of samples is available. The prior information may not only be from situations in which we have material with known-age increments (e.g. tree rings) but from archaeological sites where we might know that samples lie in a particular order or relate to a single phase of activity (Bronk Ramsey 2008).

Following a number of previously successful wiggle-matching studies using accelerator mass spectrometry (AMS) dating for oak timbers (Arnold et al. 2006; Bayliss et al. 2006, forthcoming; Hamilton et al. 2007), the samples from Jermyn Street were considered to have additional research potential. This material not only provided known-age material, but also fell on a part of the calibration curve where single-year data were available (Stuiver 1993) and consisted of resinous conifers, which might require extensive pre-treatment for such accurate dating (Hoper et al. 1998). Consequently, this material was selected for ^{14}C measurements, assessing agreement between laboratories, and wiggle-matching.

Sample 116.27, a slice from a timber with bark edge and 303 growth rings, was selected for the study following the subsequent reanalysis of its previously unmeasured outermost rings (Tyers, unpublished data). The timber matched well with reference chronologies from southern and eastern Sweden, and it was decided that single-year tree-ring samples (roughly decadally separated) would

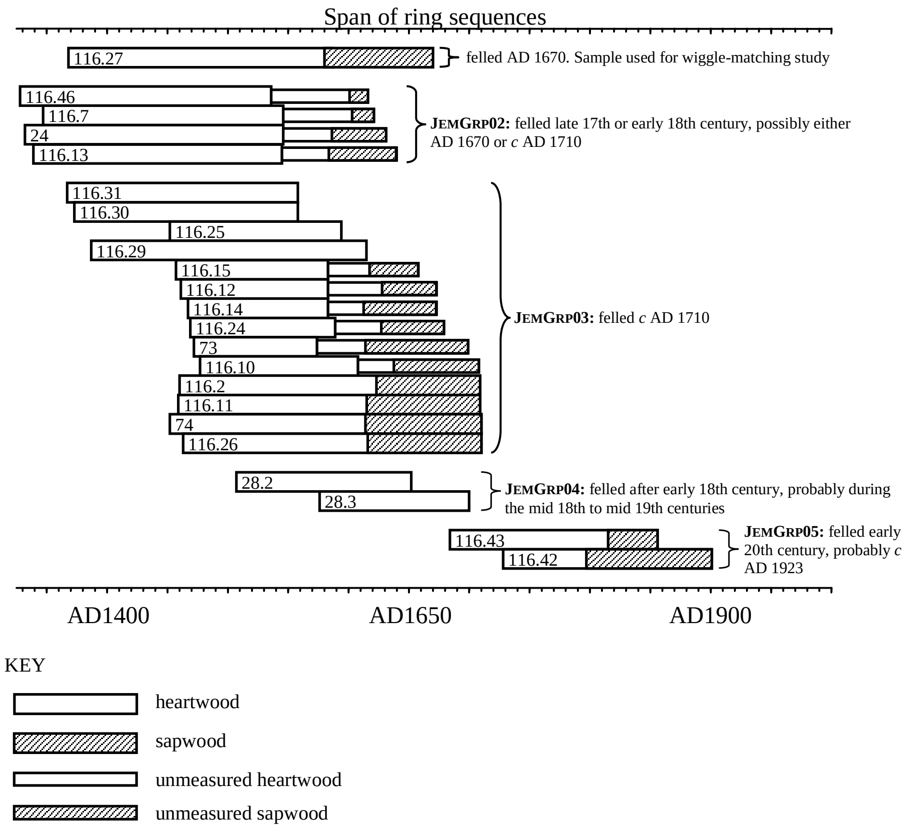

Figure 2 Bar diagram showing the relative positions of all the dated ring sequences from 107 Jermyn Street. The felling dates derived from dendrochronology are given for each group of timbers.

be submitted for ^{14}C dating and wiggle-matching. While sampling very narrow individual growth rings was challenging, 18 samples were obtained and sent at random to the Oxford Radiocarbon Accelerator Unit (OxA-), the Scottish Universities Environmental Research Centre, Glasgow (SUERC-), and the Centrum voor Isotopen Onderzoek, Groningen (GrA-). All the laboratories were informed that the samples came from a standing building and were known-age single-ring samples of Scots pine. They were not informed of the felling date of the timber (AD 1670) or the dates of the rings that were submitted to them for dating.

RADIOCARBON SAMPLING AND ANALYSIS

The samples dated by AMS at SUERC were prepared to α-cellulose following the Belfast protocol (Hoper et al. 1998); combusted to carbon dioxide (Vandeputte et al. 1996), converted to graphite (Slota et al. 1987), and then measured as described by Xu et al. (2004). Samples dated by AMS at the Rijksuniversiteit Groningen were processed using the acid/alkali/acid protocol (Mook and Waterbolk 1985), combusted to carbon dioxide and graphitized as described by Aerts-Bijma et al. (1997, 2001), and then measured as described by van der Plicht et al. (2000). The samples dated by AMS at the Oxford Radiocarbon Accelerator Unit were prepared following the AAA protocol with additional bleaching to holocellulose (T Higham, personal communication) and dated as described by Bronk Ramsey et al. (2004).

All 3 laboratories maintain continual programs of quality assurance procedures, in addition to participation in international intercomparisons (Scott 2003). These tests indicate no laboratory offsets and demonstrate the validity of the precision quoted.

Stuiver and Quay (1981) indicated that without extensive pretreatment to remove resins and lignin, ^{14}C measurements from conifer samples could be biased to slightly older ages. Hoper et al. (1998) further suggest that relatively depleted $\delta^{13}C$ values (up to 1.9‰) may persist in the sample if it is insufficiently processed to remove lignins. It should be noted that Hoper et al. (1998) focused on New Zealand cedar (*Librocedrus bidwilli*), which may not have the same biological characteristics as other conifer species or those from other geographical zones.

The ^{14}C results are presented in Table 1, and are quoted in accordance with the international standard known as the Trondheim Convention (Stuiver and Kra 1986). They are conventional ^{14}C ages (Stuiver and Polach 1977).

Calibration

The calibration of the results, relating the ^{14}C measurements directly to calendar dates, is given in Table 1. All have been calculated using the calibration curve of Reimer et al. (2004) and the computer program OxCal v4.0.5 (Bronk Ramsey 1995, 1998, 2001, 2009). The calibrated date ranges for each sample given in Table 1 have been calculated using the maximum intercept method (Stuiver and Reimer 1986). They are quoted in the form recommended by Mook (1986), with the end points rounded outwards to 10 yr. The graphical distributions of the calibrated dates, given in outline in Figure 4 are derived from the probability method (Stuiver and Reimer 1993).

Table 1 Results of ^{14}C dating on single-ring samples of *Pinus sylvestris* from 107 Jermyn Street, London.

Lab #	Ring #	^{14}C age (BP)	$\delta^{13}C$ (‰)	Calibrated date cal AD (95% confidence) IntCal04	Calibrated date cal AD (68% confidence) IntCal04	*Posterior density estimate, cal AD (95% probability)*	Actual date (AD)
OxA-17254	128	337 ± 26	–25.4	1450–1650	1480–1540	*1485–1510*	1495
SUERC-14015	148	330 ± 25	–26.2	1460–1650	1500–1520	*1495–1530*	1515
GrA-34748	168	315 ± 30	–26.2	1470–1650	1520–1540	*1510–1555*	1535
GrA-34751	183	250 ± 30	–24.7	1520–1950	1540–1560	*1525–1570*	1550
OxA-17253	188	271 ± 26	–23.7	1520–1800	1540–1560	*1545–1570*	1555
SUERC-14027	193	320 ± 25	–24.8	1470–1650	1550–1570	*1545–1575*	1560
OxA-17252	203	344 ± 26	–24.0	1450–1650	1560–1580	*1560–1585*	1570
SUERC-14016	208	320 ± 25	–25.0	1470–1650	1560–1580	*1560–1590*	1575
GrA-34753	213	330 ± 30	–25.8	1450–1650	1570–1590	*1555–1600*	1580
SUERC-14020	223	375 ± 25	–24.8	1440–1640	1580–1600	*1570–1605*	1590
GrA-34747	228	335 ± 30	–24.4	1450–1650	1580–1600	*1570–1615*	1595
OxA-17251	233	366 ± 26	–25.0	1440–1640	1590–1610	*1590–1615*	1600
GrA-35286	251	295 ± 30	–25.8	1490–1670	1600–1610	*1580–1630*	1608
SUERC-14026	253	380 ± 25	–24.7	1440–1630	1610–1630	*1600–1635*	1620
OxA-17250	263	352 ± 26	–23.9	1450–1640	1620–1640	*1620–1645*	1630
GrA-34754	273	295 ± 30	–25.1	1490–1660	1630–1650	*1615–1660*	1640
SUERC-14019	283	260 ± 25	–24.1	1520–1800	1640–1660	*1635–1665*	1650
OxA-17249	293	175 ± 26	–23.6	1660–1960	1650–1670	*1650–1675*	1660

RESULTS

It is clear from Table 1 that for each sample the actual calendar date falls within the 2-σ range of the simple calibrated date. Figure 3 shows the difference between pairs of measurements on a single tree-ring from the same year produced during this study and by Stuiver (1993). The paired measurements are in excellent agreement, and the results from all the single years are statistically consistent (following the method of Ward and Wilson 1978), except for those for AD 1550 (T' = 4.0; ν = 1; T'(5%) = 3.8) and for AD 1660 (T' = 6.6; ν = 1; T'(5%) = 3.8). Thus, there appears to be no significant offset between the measurements made for this study and equivalent data included in the calibration curve (Reimer et al. 2004). The single-year measurements of Stuiver (1993) were obtained by gas proportional counting of Douglas fir, from samples processed to α-cellulose (for the period in question here, see Stuiver 1993: Table 1). For this material, there also appears to be no significant difference between samples pretreated simply using acid/base/alkali, and those which underwent an additional bleaching stage.

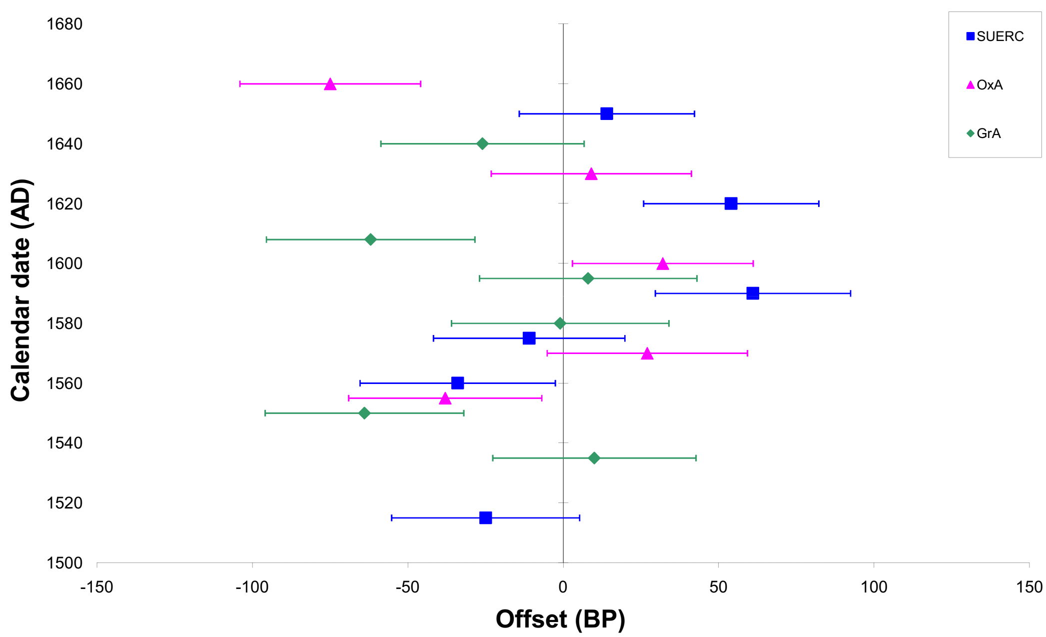

Figure 3 Offsets between ^{14}C results on single-years dated during this study and results on the same single-years dated by Stuiver (1993).

WIGGLE-MATCHING

A Bayesian approach, combining the ^{14}C dates with the relative dating provided by the tree-ring analysis, was employed to wiggle-match the results (see Christen and Litton 1995; Bronk Ramsey et al. 2001; Galimberti et al. 2004). The technique used is a form of Markov chain Monte Carlo sampling, and has been applied using the program OxCal v 4.0.5. Details of the algorithms employed are available from the online manual (http://c14.arch.ox.ac.uk/) or in Bronk Ramsey (1995, 1998, 2001, 2009). The algorithm used in the models described below may be derived from the structures shown in Figures 4 to 8.

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The chronological model for the dating of all samples is shown in Figure 4. It includes the relative dating information provided by tree-ring analysis, e.g. that OxA-17252 is 5 yr younger than SUERC-14016, and was calculated using IntCal04 (Reimer et al. 2004). The model has good overall agreement (A_{comb} = 28.6%), and estimates that the timber was felled in *cal AD 1660–1680 (95% probability; felling date*; Figure 4), consistent with the felling date of AD 1670 produced by dendrochronology. The *posterior density estimates* for the formation of each dated tree-ring also match the actual dates for each ring suggested by dendrochronology (see Table 1), at both 68% and 95% probability. If the felling date for the timber, AD 1670, is also included in this model as "prior" information, then it still has good overall agreement (A_{comb} = 23.6%; Figure 5).

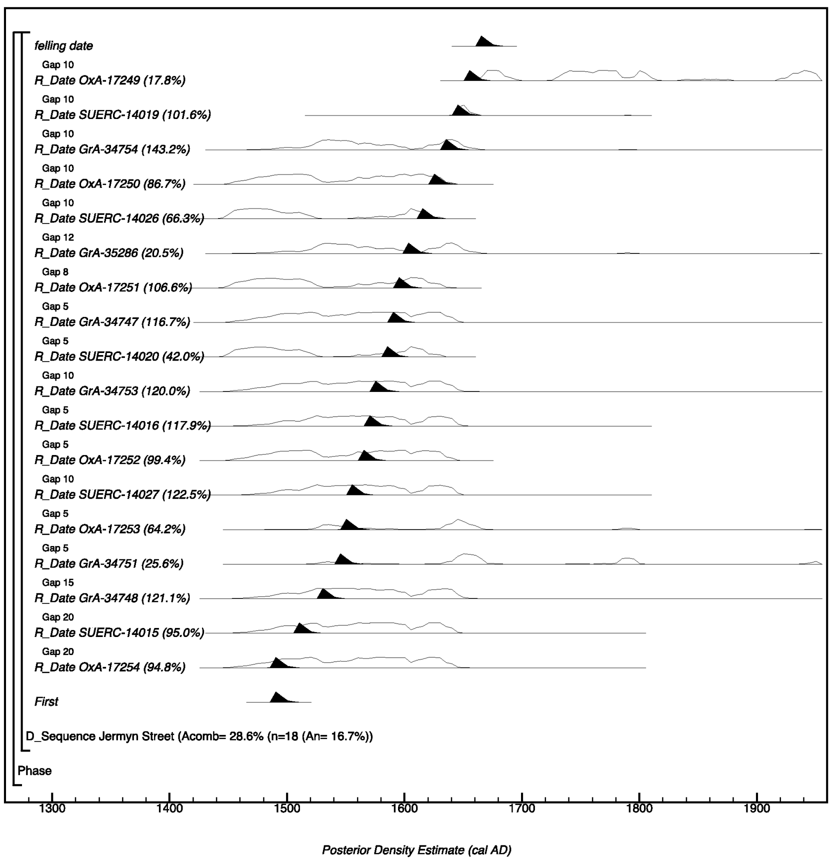

Figure 4 Probability distributions of dates from timber slice 116.27. Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates, 2 distributions have been plotted: one in outline, which is the result of simple ^{14}C calibration, and a solid 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 "*felling date*" is the estimated date when the timber was felled. The large square brackets down the left-hand side along with the OxCal keywords define the model exactly.

In order to evaluate the internal consistency of measurements from each of the 3 laboratories, wiggle-matching the 3 sets of results obtained was undertaken separately. The resulting 3 chronological models are shown in Figure 6. They all show good agreement (SUERC A_{comb} = 85.1%; Groningen A_{comb} = 52.4%; Oxford A_{comb} = 51.3%) and give accurate felling estimates for the timber (see

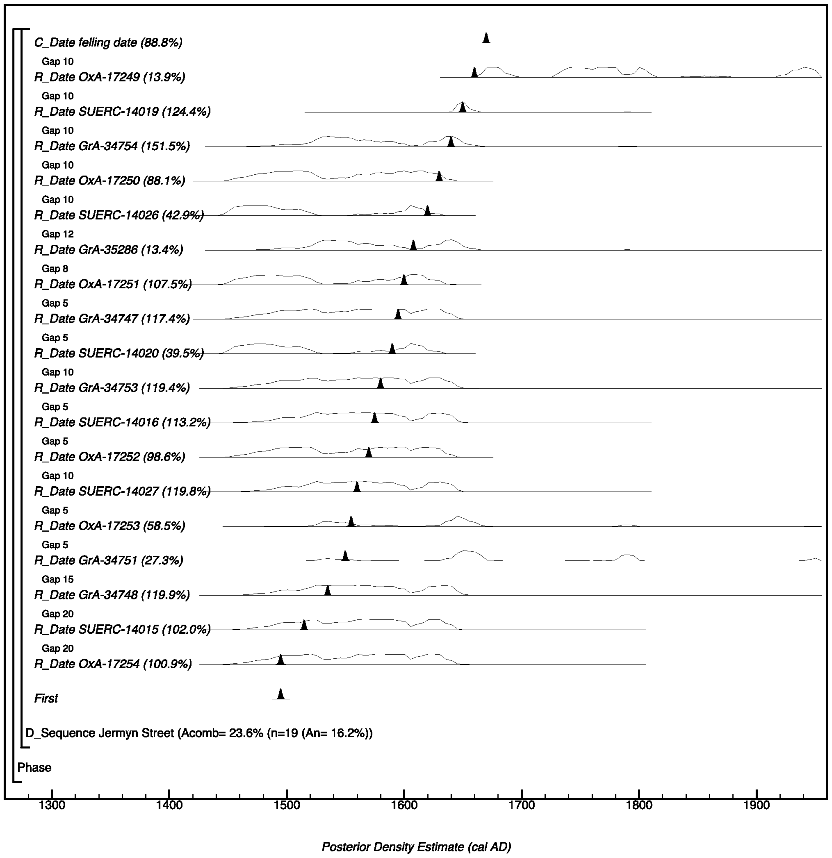

Figure 5 Probability distributions of dates from timber slice 116.27. The format is identical to that of Figure 4. *C-Date felling date* has been included to test whether the ^{14}C dates agree with the felling date, AD 1670 provided by tree-ring analysis. The large square brackets down the left-hand side along with the OxCal keywords define the model exactly

Table 2). If the felling date is included in each chronological model they once again demonstrate good overall agreement (SUERC A_{comb} = 67.4%; Groningen A_{comb} = 38.0%; Oxford A_{comb} = 35.9%). This confirms the accuracy of the quoted measurements suggested by comparison with the calibration data. The overall agreement A_{comb} is a product of the individual agreement values for the samples in each wiggle-match. Each individual agreement value is a test for the goodness of fit (in effect a pseudo-Bayes factor) that relates the posterior density estimate distribution to the calibrated date distribution for individual measurements (Bronk Ramsey et al. 2001). The use of the *a-prior* felling date in the wiggle matches strongly effects the overall agreement (A_{comb}) of the models because it is informative prior information (Bayliss et al. 2007b).

Wiggle-Matching and the Radiocarbon Calibration Curve

IntCal04 (Reimer et al. 2004) uses a more sophisticated statistical method, based on a random walk model, for the estimation of errors on the calibration curve by interpolating data points at 5-yr bin widths using a smoothing function (Buck and Blackwell 2004). This introduces a small amount of smoothing to the data, although it better reflects the underlying data with an annual scale input when compared to IntCal98 (Bronk Ramsey et al. 2006). However, because the data points are interpolated using a smoothing function, they are not statistically independent.

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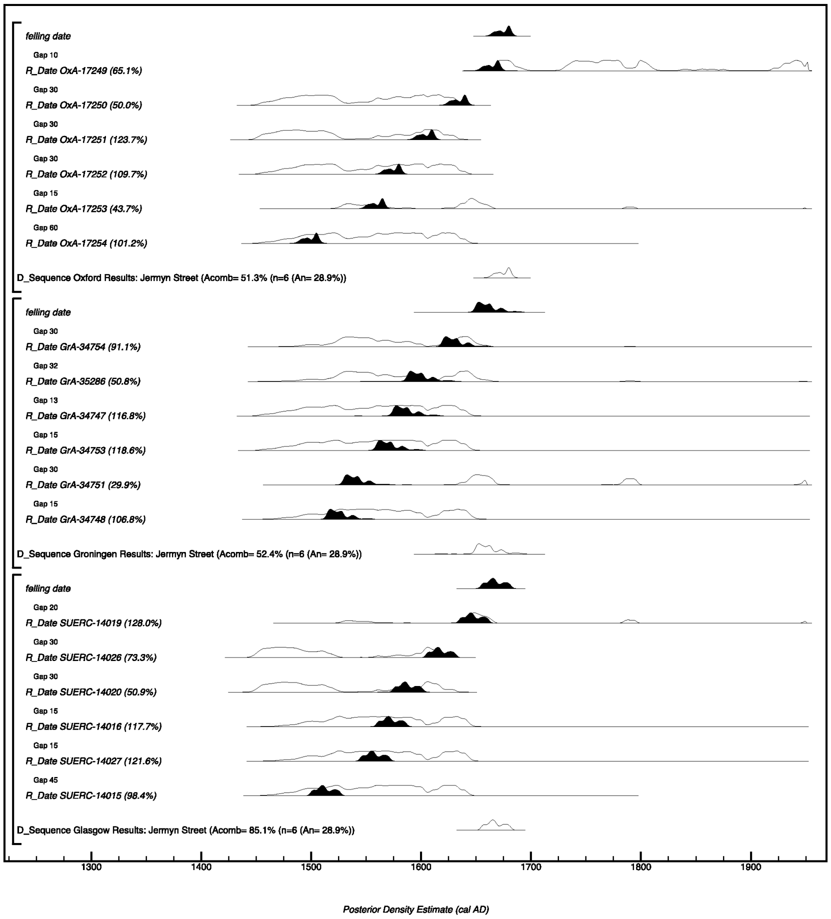

Figure 6 Probability distributions of dates from each laboratory from timber slice 116.27. The format is identical to that of Figure 4. The large square brackets down the left-hand side along with the OxCal keywords define the model exactly.

Table 2 Estimated felling dates obtained using data from each laboratory in isolation.

	IntCal04 (68% probability)	IntCal04 (95% probability)
Glasgow estimated felling date	*cal AD 1655–1680*	*cal AD 1650–1685*
Groningen estimated felling date	*cal AD 1645–1675*	*cal AD 1645–1690*
Oxford estimated felling date	*cal AD 1665–1685*	*cal AD 1660–1685*
All samples estimated felling date	*cal AD 1660–1675*	*cal AD 1660–1680*

In order to assess the effects of the statistical dependency between the data points in the IntCal04 calibration curve, the model (shown in Figure 4) was re-run using the IntCal98 calibration data set (Stuiver et al. 1998). The resulting model (see Figure 7) shows good agreement (A_{comb} = 25.1% (A_n = 16.7.9%, n = 18) and produces an accurate estimate, *cal AD 1650–1685* (*95% probability; felling date*; Table 3), for the felling of the timber. This demonstrates empirically that this theoretical statistical concern is perhaps unlikely to be of great practical significance when undertaking even highly constrained Bayesian models.

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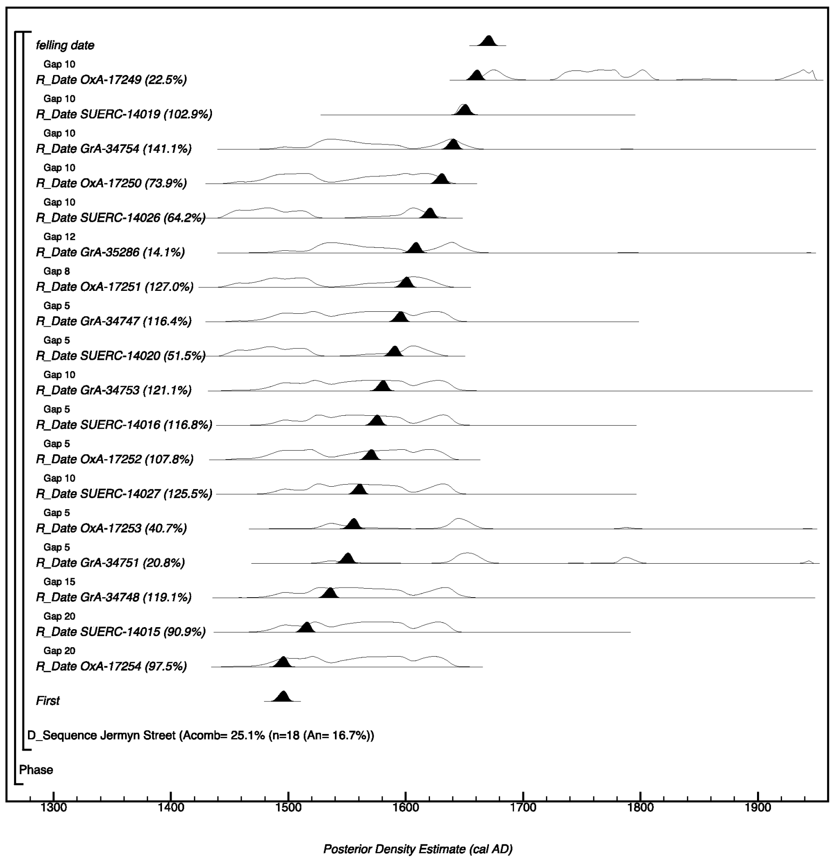

Figure 7 Probability distributions of dates from timber slice 116.27 (IntCal98). The format is identical to that of Figure 4. The large square brackets down the left-hand side along with the OxCal keywords define the model exactly.

Finally, the analysis was repeated using the single-year data of Stuiver (1993; see Tables 2 and 3). Although as a single record, there is considerable random noise in this data set, the resultant model (shown in Figure 8) also exhibits good agreement (A_{comb} = 54.7%; A_n = 16.7%, n = 18; Figure 8) and provides an accurate estimate for the felling date of the timber of *cal AD 1660–1675 (90% probability)*. As the data of Stuiver (1993) was from USA west coast wood and the wiggle-match material from higher-latitude Scandinavian material, we might expect to see slightly more recent ^{14}C ages for the wiggle-match samples due to stratospheric-tropospheric exchange in high latitudes (Levin and Hesshaimer 2000; Kromer et al. 2001). The fact that the wiggle-match result is consistent with the dendrochronological date suggests that small regional offsets in ^{14}C levels are not significant enough, in this period, to effect the calibration of ^{14}C ages into calendar years.

Table 3 Estimated felling dates using different calibration curves. *Posterior density estimates* from the model shown in Figure 5 were exactly the same using either IntCal04 or IntCal98.

Curve	*(68% probability)*	*(95% probability)*
IntCal04	*cal AD 1660–1675*	*cal AD 1660–1680*
IntCal98	*cal AD 1655–1680*	*cal AD 1650–1685*
Stuiver 1993	*cal AD 1663–1666* (12%) or *cal AD 1667–1673* (56%)	*cal AD 1656–1659* (4%) or *cal AD 1660–1675* (90%) or *cal AD 1676–1677* (1%)

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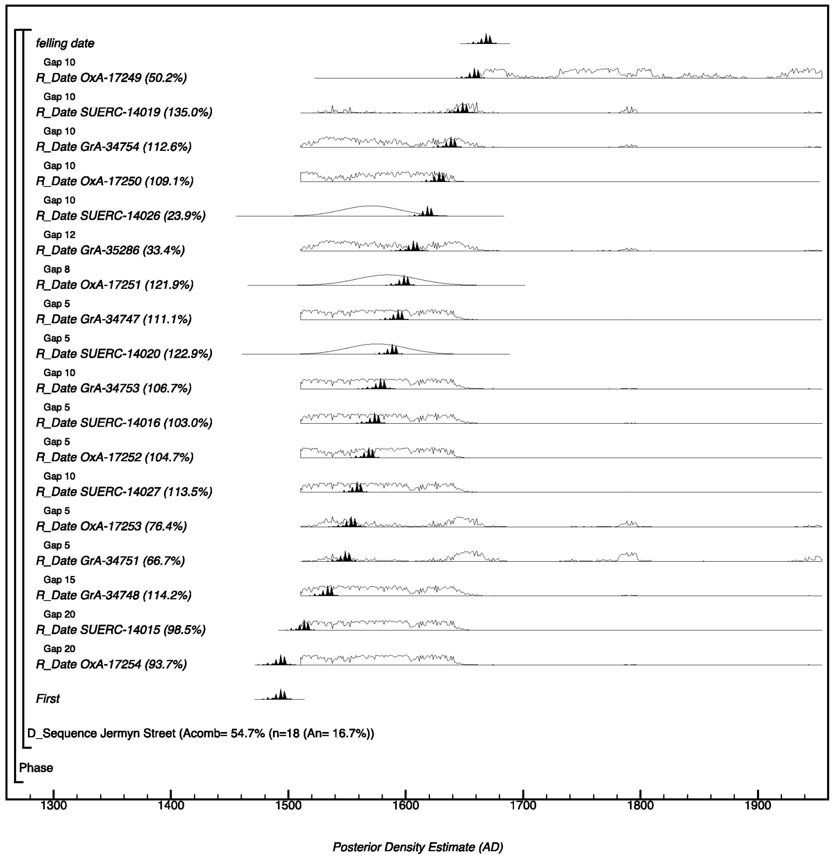

Figure 8 Probability distributions of dates from timber slice 116.27 (Stuiver 1993). The format is identical to that of Figure 4. The large square brackets down the left-hand side along with the OxCal keywords define the model exactly.

The reproducibility of the analyses of these ^{14}C data suggests that the existing calibration data and methodology are adequate for accurate wiggle-matching in the post-medieval period. This application may not, however, be typical as it falls during the currency of single-year calibration data, which only exist (at present) between AD 1510–1954.

CONCLUSIONS

This study has confirmed the agreement of the ^{14}C measurements obtained from the 3 collaborating laboratories (Figure 9). It has established the potential that AMS wiggle-matching of single-year samples has for providing precise and accurate dating of post-medieval standing buildings that cannot be dated by dendrochronology. In addition, for relatively recent conifer timbers from buildings at least, these data suggest a full α-cellulose extraction might not be essential for applications that require this level of accuracy. However, it is not yet clear whether this type of application can be carried out with the same expectation of absolute accuracy in earlier periods, beyond the limit of the single-year calibration data (currently AD 1510–1954).

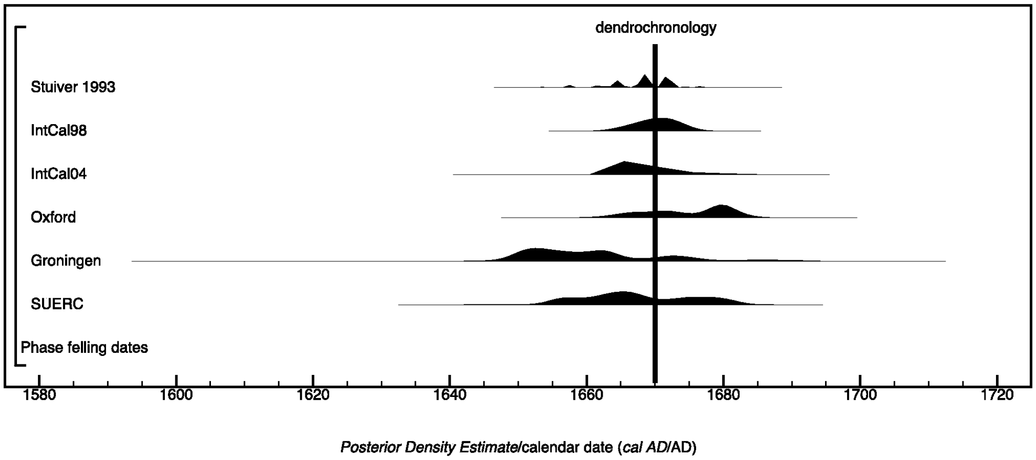

Figure 9 Summary of estimated felling dates. The distributions are derived from the models shown in Figures 4–8.

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