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Research Papers

Oxygen isotope dating of oak and elm timbers from the portcullis windlass, Byward Tower, Tower of London

N.J. Loader [a,*], D. Miles [b], D. McCarroll [a], G.H.F. Young [c,a], D. Davies [a], C. Bronk Ramsey [b], J.G. James [a]

[a] Department of Geography, Swansea University, Singleton Park, Swansea, SA2 8PP, UK
[b] Research Laboratory for Archaeology, Oxford University, 1 South Parks Road, Oxford, OX1 3QY, UK
[c] Natural Resources Institute Finland (Luke), Latokartanonkaari 9, 00790, Helsinki, Finland

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ABSTRACT

A new isotopic method for dating oak and non-oak (elm) timbers is applied to samples from the portcullis windlass mechanism in the Byward Tower, Tower of London. This structure was previously sampled for ring width dendrochronology but failed to date. Successful application of the stable oxygen isotope dating method returns a felling date of winter AD 1656/7 for the oak timbers used to construct the gear wheel and a date of after AD 1648 (*terminus post quem*) for an associated elm shaft. This is the first reported application of oxygen isotope dendrochronology to date elm and confirms the significant potential of the method for dating species other than oak.

1. Introduction

The Tower of London is a UNESCO World Heritage Site and has been an iconic element of the London skyline for almost a millennium. During this time the Tower of London has housed royalty, served as a prison and armoury, provided sanctuary and witnessed many executions. Today the site is managed by Historic Royal Palaces and provides a home to the Royal Armouries and to the Crown Jewels; the material symbols of authority of the British monarchy. Rather than representing a single phase of construction, the Tower of London comprises many phases of development since the construction of the White Tower in the late eleventh century (Miles, 2007). Of these developments, the Byward (originally Bywarden) Tower serves as an imposing public gateway to the tower complex (Fig. 1). During the Peasants Revolt of 1381, it was reported that Richard II and his mother Joan, Countess of Kent sought sanctuary within the Byward Tower.

The Byward tower was first constructed between 1275 and 1281 (Oxford Archaeology, 2008), and is protected by an impressive portcullis (a vertical gate), which still survives (see below). Since then, and until the eighteenth century, the tower is believed to have undergone several phases of minor modification to upgrade its defensive capabilities (Bridge and Miles, 2017; Parnell, 1993). The portcullis, is raised and lowered by a winding mechanism consisting of the first shaft on which the large rope fixed to the portcullis is wound. A lantern and pinion wheel fixed with six radial spokes or arms run from the central shaft to a pair of fellows bolted to either side to create a lantern-pinion wheel. This takes a smaller rope from a second shaft situated to the south where a windlass with projecting arms clasps the shaft. The projecting ends of these clasped arms are finished as handles, as are pairs of intermediate spokes spaced perpendicularly. Again, these are fixed by fellows bolted to each spoke with early screw bolts. The first shaft and compass-armed lantern-pinion wheel is mainly elm, whilst the windlass with its clasped arms is mainly oak. Hewett (1985) proposed a date of *circa* 1260 for the first shaft and wheel, and *circa* 1532 for the windlass on stylistic grounds, although he did state that the dates may well be later. The portcullis gate has been “wiggle-match” radiocarbon dated to yield an estimated felling date range between 1236 and 1302 (95.4% probability).

Whilst the date of the initial construction and portcullis have been established by radiocarbon dating (Miles, 2017), it has so far proved impossible to date the windlass mechanism by ring-width dendrochronology, or with any precision by calibrated radiocarbon dating. The date of the windlass mechanism would provide a valuable insight into the development of early military defensive technology and establish whether it forms part of the original installation, or a later technological enhancement of the portcullis system.

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* Corresponding author.
E-mail address: n.j.loader@swansea.ac.uk (N.J. Loader).

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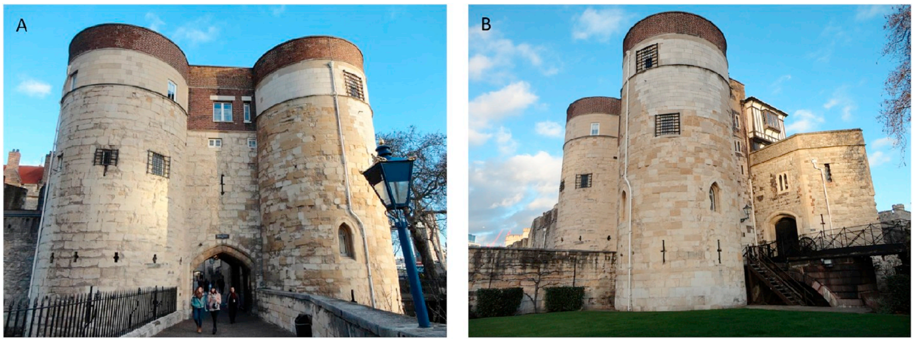

Fig. 1. The Byward Tower, Tower of London. A: Front external view towards portcullis entrance B: West external view © D. Miles.

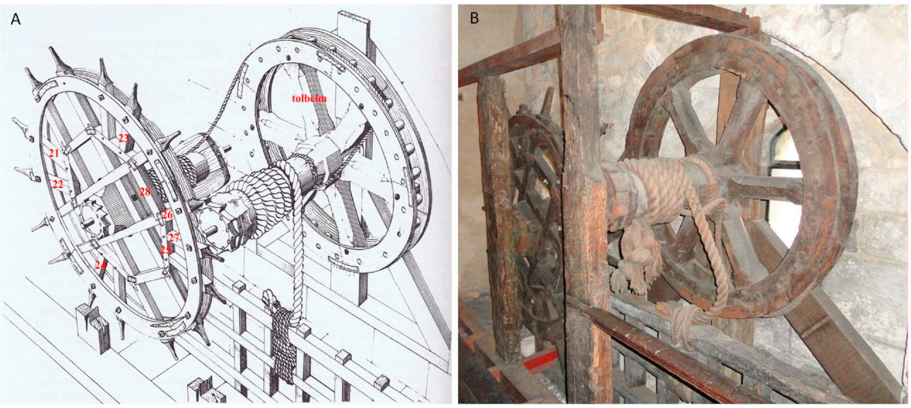

Fig. 2. A: Drawing of the portcullis winding mechanism showing timbers sampled (tol21-tol28 & tolbelm) (after Hewett, 1985) B: Photograph of the mechanism in situ © D. Miles.

A new method for precision dating of historic buildings and wooden artefacts has recently been developed for the UK (Loader et al., 2019a; McCarroll et al., 2019). The method is based on measuring oxygen isotope ratios in tree ring samples and pattern-matching these isotope measurements against a well-replicated isotopic master chronology. The efficacy of the method has been demonstrated by dating oak timbers of known and previously unknown age across the southern and central UK Loader et al., (2019b).

Oxygen isotope dendrochronology differs from conventional ring width-based dendrochronology in that the trees do not need to be under any physiological stress to record a strong common signal. This enables tree ring sequences from short-lived, fast growing timbers to be precisely and reliably dated. Given the failure of previous ring width based dendrochronology to provide a conclusive date for the windlass and its importance in the history and development of the Byward Tower, we applied this new technique in an attempt to address this challenging dating problem. In doing so we also explored the suitability of the method developed using oak for the analysis and dating of a co-located elm timber and the suitability of less-destructive oak microcore samples for isotope analysis.

2. Methods

2.1. Conventional dendrochronology

Eight samples were taken for conventional ring-width dendrochronology (Fig. 2). To minimise damage to the very small scantling of the windlass components, a specially machined silver-steel micro-borer bit was used. The drill holes are only 8 mm in diameter and provide 6 mm diameter core samples. The timbers were numbered **tolb21** – **tolb28** but some samples fractured during coring. The individual segments of the fractured cores were labelled '**a1**', '**a2**', etc. (Table S1) Three samples retained bark edge, including **tolb22**. The samples were mounted and prepared and the ring widths measured to 0.01 mm. These were then compared with each other using standard dendrochronological techniques as outlined by English Heritage (1998), and with measurements from an earlier study of the Byward Tower Postern Gates (Miles, 2017). A conventional-size (10 mm diameter) core sample was also taken from an elm spoke (or arm) from the rear wheel (**tolbelm**). This did not retain any detectable sapwood (which is hard to identify on elm) or bark edge, but did have 70 growth rings (Fig. 2).

2.2. Oxygen isotope dendrochronology

Three samples were used for oxygen isotope dating comprising two samples of oak; **tolb22** (72 rings with 27 sapwood rings complete with bark edge), **tol25** (46 rings no sapwood or heartwood/sapwood boundary but with a tentative overlap with **tolb22**) and a sample of elm **tolbelm** from the portcullis gearwheel arm (70 rings no sapwood evident).

Using the method described by Loader et al. (2019a) the latewood of each ring was manually removed and prepared to alpha-cellulose. All of the samples contained sections with narrow ring groups (and limited latewood), which may reflect past woodland management or disturbance. These narrow rings and the smaller diameter of the microcores limited the amount of latewood available for analysis and made α-cellulose preparation challenging. Loader et al. (2019a) recommend that all samples are analysed in duplicate, but the application of the technique to microcores meant that for some rings it was only possible to retrieve sufficient cellulose for a single isotopic measurement. Latewood was absent from one ring of sample **tolb25** leaving a gap in the isotope sequence. The elm sample was obtained using a standard corer, so

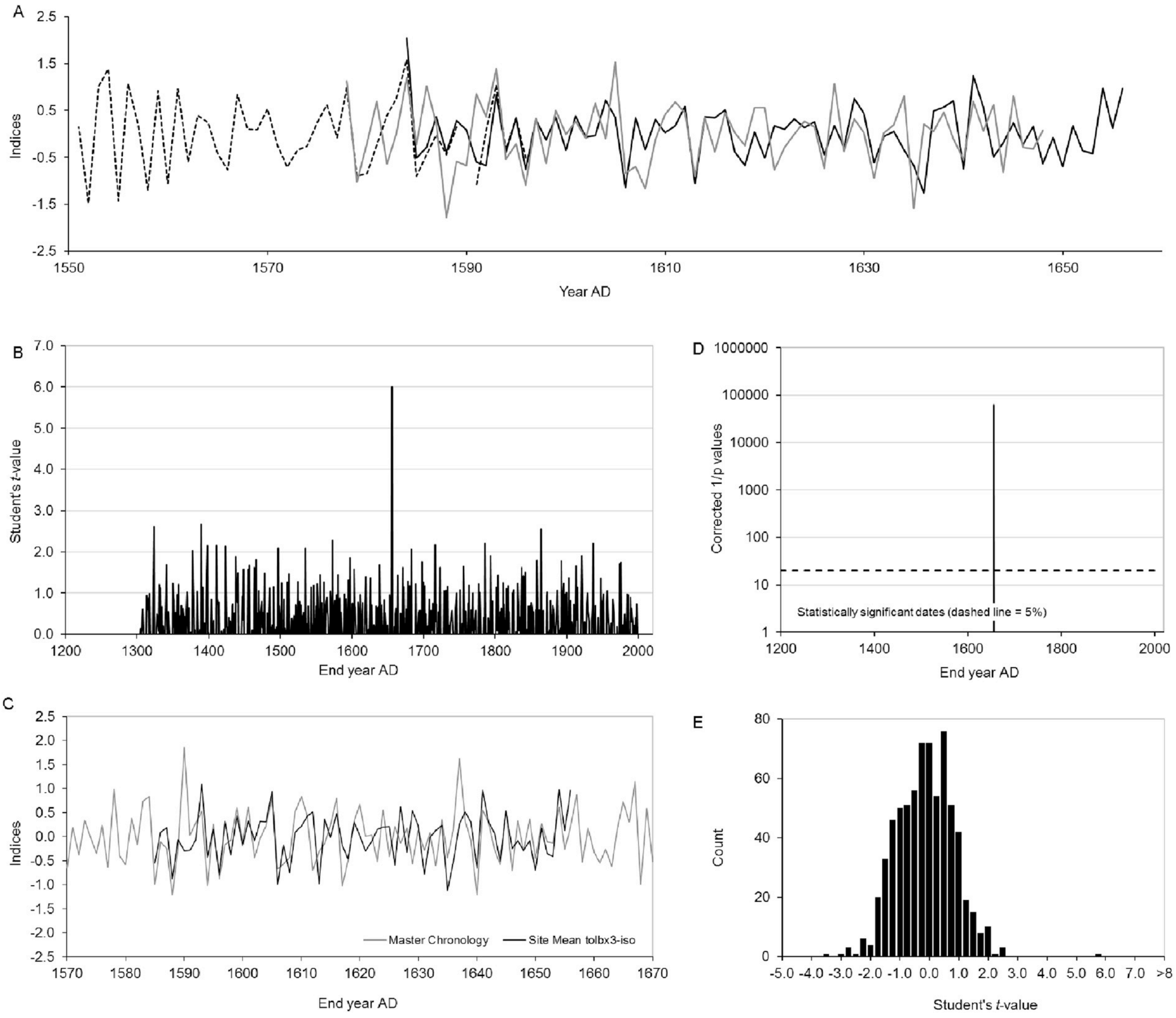

Fig. 3. (Upper panel A): Comparison of the three individual isotope series tolb22 (solid black line) (oak), tolb25 (dashed black line) (oak) and tolbelm (grey line) (elm). (Lower panels B–D) Dating results for tolbx3-iso, the 106-year site mean isotope chronology of tolb22, tolb25 and tolbelm. B: Student's *t*-values for all possible end dates with full overlap against the master chronology. C: Time series of the sample plotted against the master chronology (indices). D: End dates with corrected probabilities (1/p) of more than one. Those values below the dashed line (1/p = 20) are not statistically significant. E: Distribution of Student's *t*-values for all possible matches.

provided more material for analysis. Cellulose was prepared from the latewood of each elm tree ring using the same method as for oak.

The resulting latewood α-cellulose samples were homogenised and freeze-dried. 0.30–0.35 mg of dry α-cellulose was weighed into silver foil capsules prior to on-line pyrolysis to carbon monoxide gas at 1400 °C over glassy carbon using a Flash HT elemental analyser. Oxygen isotope ratios were measured using a Thermo Delta V isotope ratio mass spectrometer. Results are expressed as per mille (‰) deviations from the Vienna Standard Mean Ocean Water (VSMOW) reference using the delta (δ) notation. Typical analytical precision for this method is 0.3 per mille n = 10 (σ_{n-1}).

The Loader et al. (2019a) isotope master chronology was developed by combining isotope measurements from dendrochronologically-dated samples of oak latewood. Samples were sourced principally through the Oxford Dendrochronology Laboratory and were distributed evenly across a region covering *c.* 33,600 km^2 centred on Oxfordshire (51.488°N −1.035°E). Each year in the chronology represents values from 10 individual tree rings, and the 10-tree replication is maintained throughout the record. The exact provenance of the timbers used to construct the windlass is not known, it is highly unlikely that the timber originated from within the city of London, but rather sourced from trees growing across southeastern England.

Stable isotope dating was conducted as described in Loader et al. (2019a) using the south central-England master chronology (AD 1200–2000). Trends in the isotope series are removed using a 9-year rectangular filter with indices derived by subtraction. The filtered series were compared at all possible positions of full overlap with the filtered master chronology spanning AD 1200–2000. Strength of match was defined using Pearson's correlation coefficients and translated into Students *t*-values, after correction of degrees of freedom for autocorrelation and filtering. Probabilities, expressed as 1/p, were corrected to take account of multiple testing and an 'Isolation Factor' reported the ratio of corrected probabilities for the best and second-best matches. As in standard dendrochronology, individual samples that can be aligned by cross-correlation were combined to form a site chronology by simple averaging of the index values prior to dating. Cross-correlation *t*-values and probabilities were corrected in the same manner as those used for dating against the master. In ring-width dendrochronology the strength of the match between series is measured using a *t*-value calculated after Baillie and Pilcher (1973). The statistical properties of the stable isotope data are very different from those of ring-widths, so it is possible to express the strength of match using a Student's *t*-value (Loader et al.,

Table 1
Cross-matching matrix for the individual oak micro-core sample ring width measurements used to develop TOLBx3. Baillie and Pilcher (1973) *t*-values (upper) and relative position of each series (lower) are listed. Samples tolb22 and tolb25 were measured isotopically. Ring widths for sample tolb22 correlate best (Baillie-Pilcher *t*-value of 7.02) at ring position 12 in tolb25. See also Fig. 4 for relative position of dated ring width sequences.

Sample:	tolb22	tolb23	tolb25	tolb27	tolb28a1
tolb21	6.69	5.57	0.00	2.69	0.00
	61	59	0	33	0
	tolb22	4.98	7.02	3.81	0.00
		59	12	44	0
		tolb23	0.00	2.73	0.00
			0	31	0
			tolb25	5.14	6.18
				46	38
				tolb27	5.11
					38

Oxygen isotope dendrochronology.

2019a) which provides an estimate of the probability that such a match could occur by chance. Secure dates are indicated by a single high *t*-value, with a very small probability of error, surrounded by much lower values (Fig. 3).

3. Results

3.1. Conventional dendrochronology

The ring-width samples were cross-matched using both statistical and visual methods to produce three mean sequences, with 49 (**tolb24**), 64 (**tolb26**) and 79 (**tolb27**) rings, and compared with the other ring-width sequences that contained between 25 and 72 rings. A total of six timber sequences were successfully matched together (Table 1, S1) to form a 106-year combined oak site master **TOLBx3**. Despite this long and well replicated site master, no conclusive or consistent match was found with British Isles or mainland European reference chronologies. The elm ring widths were compared with the site master from the windlass, and reference chronologies, but again no conclusive match was found.

The isotope results from the two oak samples cross-match each other with an offset of 60 years, which agrees with the offset based on ring widths, producing a 106-year combined oak chronology (tolbx). Although the overlap between the oak samples is short (13 years, 12 pairs of values), it is very strong ($r = 0.901$, corrected $t = 5.49$). The combined series (tolbx-iso) dates against the isotope master chronology at AD 1656 with a probability of error of less than one in 5000. The two individual oak samples also produce best matches at 1656 and 1596, respectively, independently confirming the 60-year offset observed in the ring-width dendrochronology (Table 2).

The elm sample cross-matches with the combined oak series with an offset of 8 years ($n = 71$, $r = 0.45$, corrected $t = 3.8$), suggesting a date of AD 1648 for the final ring measured isotopically (not the bark edge) and this was confirmed by comparison with the master isotope chronology, which also gives a best match at AD 1648. When all three timbers are combined (tolbx3-iso) they give an unequivocal felling date of AD 1656/7 (Table 2).

4. Discussion and conclusion

Conventional ring-width dendrochronology failed to date the construction wood from the slow-grown tree samples from the portcullis windlass, despite six samples matching together to form a 107-ring site master. However, given the firm dates obtained for two of those oak samples using the oxygen isotope approach, it is now possible to assign felling dates of winter 1656/7 to the four timbers with complete sapwood (Fig. 4), suggesting that the windlass was constructed in 1657 or shortly thereafter. Although the elm sample from the rear lantern wheel does not have sapwood, it must have been built after the date assigned to the last measured ring (1648), so it is reasonable to conclude that it is contemporary with the windlass.

The previously obtained ^{14}C felling date range of 1236–1302 for the portcullis accords well with the documentary evidence for the initial

Table 2
Oxygen isotope dendrochronology results using the master chronology for south central England presented by Loader et al. (2019a). Bold font represents robustly dated composite series.

Sample Identifier	No. Rings	r-value	Student's *t*-value	Match Probability (1/p)	Degrees of Freedom (df)	Best Match (Date AD)	Isolation factor (IF)
tolb22	73	0.445	3.9	10	60	1656	6
tolb25	45	0.596	4.4	26	35	1596	18
tolbelm	71	0.475	4.1	24	59	1648	51
tolbx-iso	**106**	**0.503**	**5.4**	**5522**	**87**	**1656**	**>1000**
tolbx3-iso	**106**	**0.543**	**6.0**	**61685**	**86**	**1656**	**>1000**

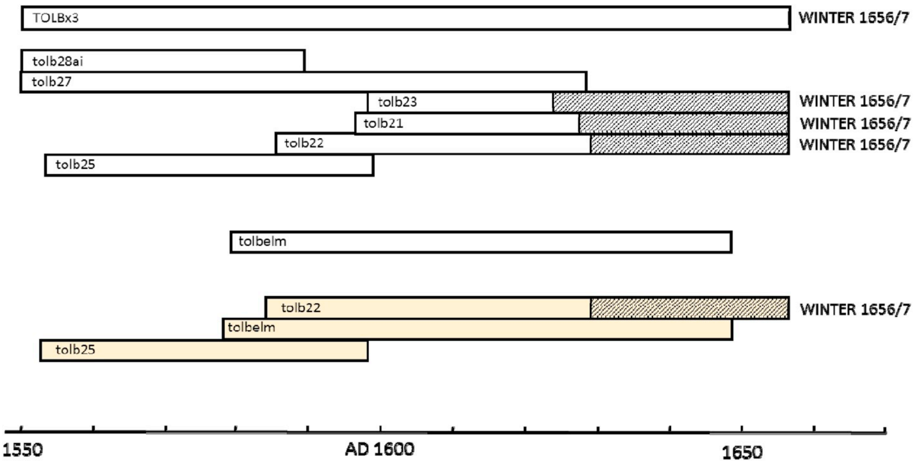

Fig. 4. Bar diagram of timber sequences aligned relatively by ring-width and dated by isotope dendrochronology. White bars show the relative position of the individual ring-width series. Yellow bars show the absolute dating of the latewood oxygen isotopes samples used to date the internally-matching ring-width sequences. Sample identifiers are located to the left hand side of each bar. Sapwood (shaded) and felling dates for the assemblage are presented. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

construction of the Byward Tower in 1275–81 and shows that the original portcullis has survived. However, the original winding gear mechanism has been replaced at least once, with the present arrangement dating to 1656/7 or shortly thereafter. The estimated dates of *c.* 1260 for the rear wheel and *c.* 1532 for the windlass, as proposed by Cecil Hewett, are incorrect (Hewett, 1985, 197–9). The new dates show that the winding mechanism was replaced during the Commonwealth or Interregnum period when records kept by the Protectorate Parliament were particularly poor, thus revealing a phase of activity previously unknown in the history of the Tower.

This study has demonstrated the potential for using oxygen isotope dendrochronology on oak, even where the timbers have very narrow wings and only small core samples are available. It also demonstrates the potential for dating elm, which is an important building timber but is rarely dateable using ring-widths, by means of an isotopic master chronology comprised entirely of oak.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jas.2020.105103.

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