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The precise and accurate dating of medieval bridge remains at Ancrum, Scottish Borders, using stable isotope dendrochronology

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ABSTRACT

The discovery of Ancrum Old Bridge (River Teviot, Scotland) in 2018 was a significant archaeological finding for Scotland. Wiggle match radiocarbon dating placed construction of the bridge to around 1340–1360 Cal. AD (95.4 %); a period of political and social instability in the region. Oxygen isotope dendrochronology was applied to refine this date range and to provide a precise felling date for the bridge timbers. Somewhat unexpectedly, a felling date of winter AD 1428/29 was identified. This date was obtained using a reference chronology for the southern United Kingdom and independently verified against a new local isotope chronology developed from native Scottish oak. This new date falls within a more stable period in Scotland's history which may have been more suited to major construction projects such as Ancrum Old Bridge. These results highlight the importance for radiocarbon end users to consider the nature of dating uncertainty when interpreting results, especially when the probability distribution is multi-modal.

1. Introduction

The discovery of bridge remains in the River Teviot near Ancrum (Scotland) in 2018 has been described as "one of the most exciting and significant archaeological discoveries in Scotland in recent years" (Historic Environment Scotland, 2020). The site is believed to have been an important, and at times possibly the only crossing point of the Teviot during the medieval period. As such, Ancrum Old Bridge (AOB), or more simply Ancrum Bridge, would have assumed strategic, ecclesiastical and political importance providing a direct link between the regionally important town of Jedburgh 6 km south of Ancrum and the royal castles and abbeys situated to the north (Ancrum and District Heritage Society, 2023).

The surviving structure, first reported by members of the Ancrum and District Heritage Society (ADHS) in 2018, includes two submerged stone pier bases with multiple timbers preserved within them. It has been suggested that additional piers may survive beneath the current bridge (listed building: LB224) which was constructed in AD 1784 on virtually the same crossing point as the earlier bridge. Subsequent investigation and detailed surveys of the site by ADHS and Wessex Archaeology identified that the bridge was constructed using "branders"; a process whereby a wooden frame is positioned in the river with stone or rubble placed upon it. This is the first record of this construction method being applied in Scotland (Wessex Archaeology, 2020).

The presence of timber preserved in situ provided an opportunity for dating the structure. During 2019 and 2020, seven oak (*Quercus* spp.) timber samples were collected for dendrochronological dating. Sampling of Ancrum Bridge was initially part of the South East Scotland Oak Dendrochronology (SESOD) research project, which aims to expand native oak chronology coverage in southeast Scotland, one of the key geographic gaps in Scotland's patchy and regionally distinct oak tree-ring record (Mills, 2023b, 2024). Of these samples, four (AOB01, AOB03, AOB04, AOB06 comprising 41, 62, 91 and 63 rings) were deemed suitable for ring-width dendrochronology. Two of the samples, AOB03 and AOB06, had bark edge preserved, potentially allowing an exact date for the year of felling to be determined. Some of the ring-width series could be crossmatched, demonstrating that the samples were broadly coeval (Mills, 2020, 2023a; Wessex Archaeology, 2020). However, it was not possible to date these timbers securely by dendrochronology at the time, owing to the relatively short sequences and the absence of local reference chronologies, a common issue affecting ring-width dendro-dating in much of Scotland (Mills and Crone, 2012).

In the absence of a dendrochronological date, radiocarbon dating

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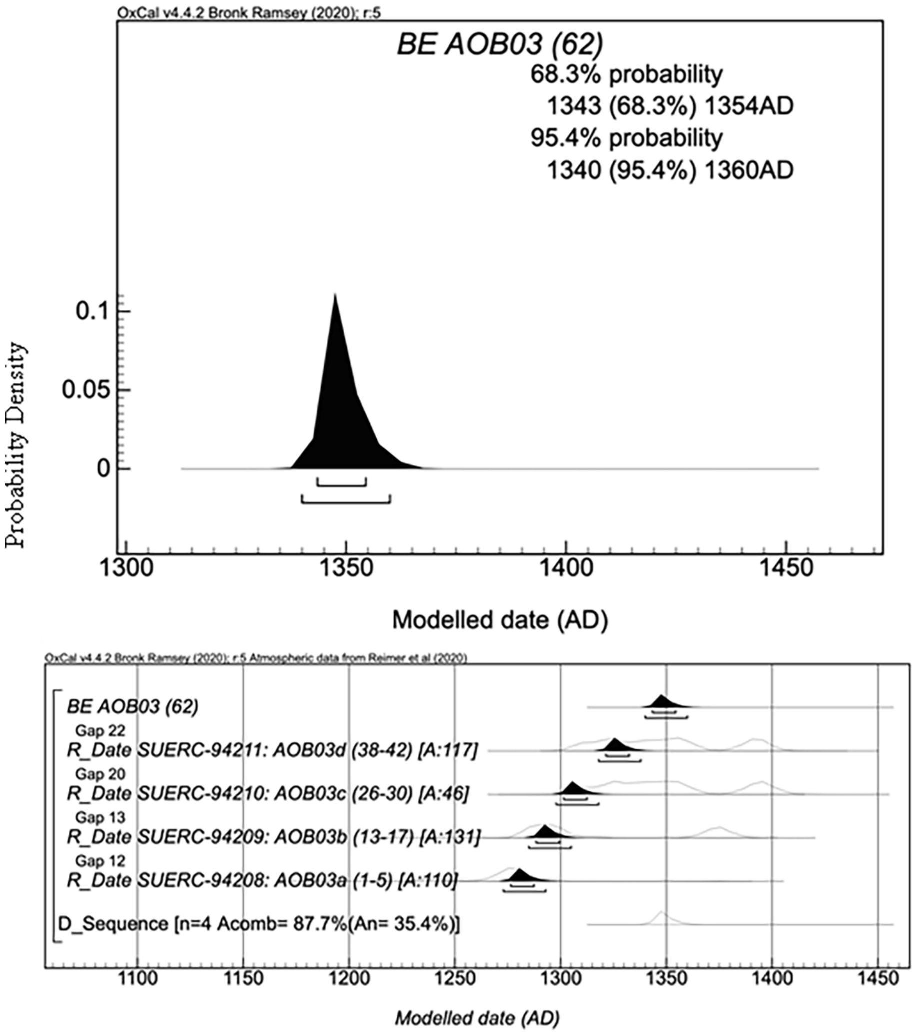

Fig. 1. Radiocarbon dating results for sample AOB03 (wiggle matching). Upper panel shows the combined result and probable calibrated date range (95.4%). Lower panel shows the relative alignment of the individual samples and their probability distributions. Wiggle matching was conducted by D. Hamilton (SUERC) using OxCal v4.4.2. (Bronk Ramsey, 2009, 2020; Bronk Ramsey et al., 2001; Reimer et al., 2020). All dates were determined on wood pretreated with an acid-base-acid protocol (Dunbar et al., 2016). Laboratory sample references and relative ring spacing are summarised in Table S1.

was used to establish chronology for two of the timber samples AOB03 and AOB04. For AOB03, which had bark edge preserved, five subsamples were taken for wiggle match radiocarbon dating. Wiggle matching is the process whereby multiple radiocarbon dates are obtained from a sample or assemblage of samples that differ in age by a known interval. In this case the interval separating each of the five subsamples was determined by counting the number of annual growth rings. The assemblage of results, once aligned relatively in time, can then be modelled to determine the most likely date range which is expressed as a probability. The five samples prepared from AOB03 were ring groups 1–5, 13–17, 26–30, 38–42 and 58–62 (outermost sapwood rings to bark edge). For AOB04 a single sample was taken comprising the outermost heartwood rings 87–91 (at the heartwood-sapwood boundary). All radiocarbon determinations were made on wood pretreated with an acid-base-acid protocol (Dunbar et al., 2016) but without preparation of cellulose.

The four successful (one null result) radiocarbon dates for sample AOB03, were combined and modelled to return a date for the last ring of 1340–1360 Cal. AD (Table S1; Fig. 1). Radiocarbon dating of the outermost rings of AOB04 indicated a most probable date between 1305–1365 or 1383–1410 Cal. AD (95.4 % probability).

Ancrum Bridge is located within 21 km of the modern border with England, an area repeatedly and violently contested over the last *c.*800 years. The well-constrained felling date range indicated by the radiocarbon dating places the construction of the bridge during the reign of David II and the Second War of Scottish Independence (AD 1332–1357), a period of significant political turmoil in the region and around the time of the arrival of the Black Death in AD 1350. In such turbulent times, even with a tightly modelled age range, the radiocarbon dating results were puzzling and open to a wide range of interpretations regarding who built the bridge and why. A more precise date would enable more targeted historical research.

At the same time as these initial investigations at Ancrum Bridge, a new precision dating technique was being developed (Loader et al., 2019). Stable isotope dendrochronology shares many common elements with ring-width dendrochronology, but instead of measuring ring-width, a measure that reflects a tree's response to stress during the growing season, stable isotope dendrochronology measures changes in the stable isotope composition of the wood from year to year and compares these against an independently dated isotopic reference chronology. Trees do not need to be physiologically stressed to record a dating signal in their wood chemistry, meaning that the method works well on fast-grown invariant tree-ring series from trees growing in regions such as the United Kingdom where the moist temperate climate does not strongly limit oak growth. Furthermore, the common isotopic signal is more coherent over a larger geographic area than for tree-ring

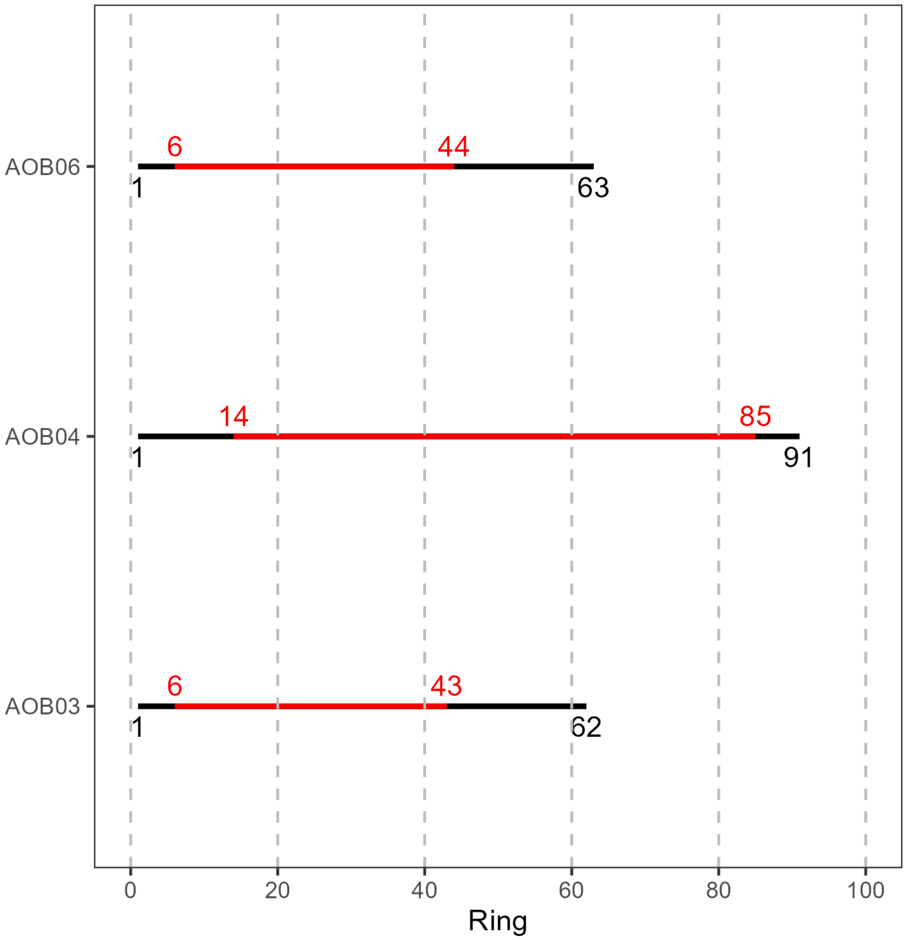

Fig. 2. Ancrum Bridge oxygen isotope series span (red) in comparison to the original ring-width measurement series lengths (black). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

growth meaning that dating may be possible without the need for local reference chronologies. This is important for tree-ring dating in regions such as southeast Scotland, where few native oak structures survive due to historic impacts on woodlands and on the built heritage making development of local reference chronologies for native oak challenging (Mills, 2023b, 2024).

2. Method

Three samples of oak from Ancrum Bridge (AOB03, AOB04, and AOB06) were provided for stable oxygen isotope dating. Samples were stored in a freezer to inhibit deterioration prior to isotopic analysis. Each sample was subdivided using a hand saw and surfaced with an electrical sander and scalpel while frozen to reveal the annual growth-rings. High resolution scans of the samples were made and ring-widths measured using CooRecorder (v9.6; https://www.cybis.se). The data were visually and statistically aligned with the original ring-width measurements to ensure that the isotopic results could be related back to the original measured ring-width series.

The annual rings were dissected under magnification using a scalpel and separated annually, as thin slices, into earlywood and latewood components. The α-cellulose from the latewood was isolated before being homogenised and freeze-dried (modified from Loader et al. (1997)). The dried latewood α-cellulose was weighed into silver capsules prior to high temperature pyrolysis to carbon monoxide gas at 1400° C and isotope ratio mass spectrometry. Results are reported as per mille (‰) deviations relative to the VSMOW standard (Coplen, 1995). Analytical precision (σ_{n-1}) is typically ±0.3 ‰ (Loader et al., 2013).

Sometimes there are differences in the span of ring-width measurements and the rings available for isotope analysis. This could be due to a different sample radius being processed or the loss of outer rings from a sample. It is sometimes not possible to cut every individual ring. This may be due to the absence of latewood, growth disturbances, degradation or contamination. The innermost juvenile rings have also been shown to carry a different isotopic signal from mature trees and under certain circumstances may be excluded from the dating process (Duffy et al., 2017). In this study the potentially juvenile inner rings of AOB03 (rings 2–5) and AOB06 (rings 4–5) were removed prior to isotope dating. Additionally, the latewood of rings 33–36 of sample AOB06 were too narrow to be accurately dissected and were omitted from analyses. The inner rings of the isotope series AOB04 (rings 10–13) were also excluded owing to possible sample preparation issues or contamination. The ring spans used for isotope dating, in relation to the measured sample ring-width series, are given in Fig. 2.

Stable isotope dating was conducted as described by Loader et al. (2019). All analyses were performed using indices (9-year rectangular filter). The degrees of freedom used to calculate the Student's *t*-values and associated probabilities were corrected to account for the loss of observation independence caused by the filtering, and for any autocorrelation that may have remained. Spurious probabilities were mitigated against by using a Bonferroni correction. As multiple samples were available from this site the individual series were first crossmatched and then compiled into a site chronology which was then used for dating.

Table 1
Crossmatching results between the Ancrum Bridge samples that pass the dating criteria of Loader et al. (2019). The minimum number of data pairs for a comparison was set at 20.

	AOB03	AOB04	AOB06	AOB_3_6
AOB03	–		*n* = 34 DF=27 1/p = 125 IF=274	
AOB04		–		*n* = 21 DF=16 1/p = 464 IF=934
AOB06	*r* = 0.61 *t* = 3.98		–	
AOB_3_6		*r* = 0.80 *t* = 5.39		–

n – Paired data points.
r – Pearson's correlation.
t – Student's *t*-value.
DF – Corrected degrees of freedom.
1/p – Bonferroni corrected probability.
IF – Ratio of probabilities between the first and second strongest matches.

3. Results

Through statistical and visual comparison of the isotope data it was possible to position the three samples relative to one another (Table 1; Fig. 3). The most secure match was between AOB03 and AOB06 with the outermost isotopic measurements for the two samples aligning at the same position. This match enabled them to be combined into a single mean series (AOB_3_6) which in turn returned a significant match with AOB04, offset by −18 rings. From these samples a site composite comprising all three samples (AOB_SITE) was created.

AOB_SITE was then compared against the central England isotope reference chronology developed by Loader et al. (2019) (Loader_et_al_2019) to establish the calendar dates of the samples.

The strongest match for the last ring measured isotopically against the reference record was identified at AD 1409 (Table 2, Fig. 4). This match passed the statistical tests outlined by Loader et al. (2019).

Considering the long distance over which these isotopic dates were initially obtained, a further five independent, ring-width dated oak samples from Neidpath Castle (NPC) (43.5 km west of Ancrum Bridge) (Mills, 2024) were analysed to develop a local isotopic reference chronology. This new independent record derived from native Scottish oak would be used to confirm the sample alignments and to provide greater confidence in the isotopic dating.

The five samples were prepared for isotopic analysis using the same

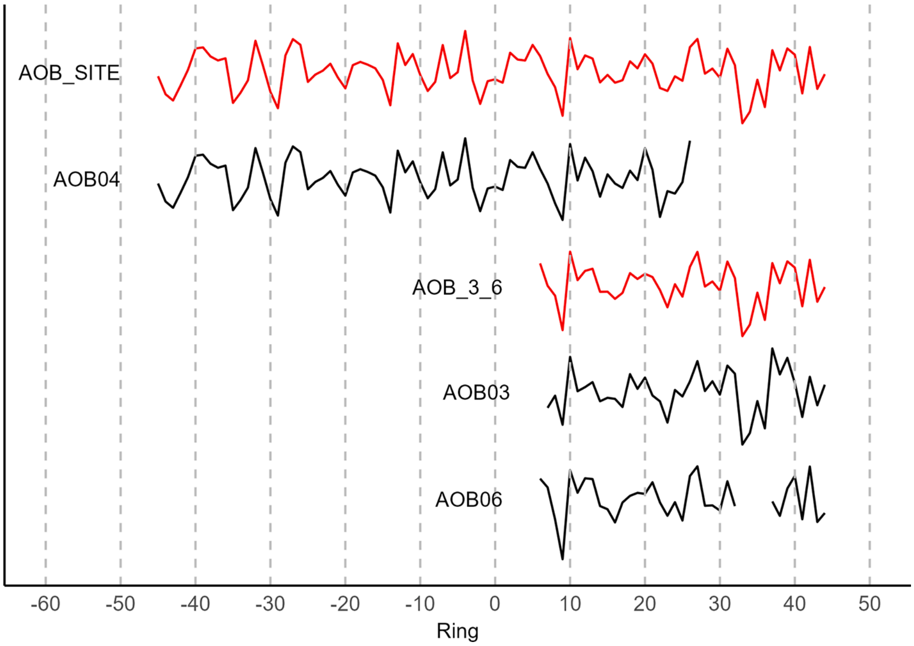

Fig. 3. Aligned filtered oxygen isotope series from Ancrum Bridge. Alignment reflects the internal isotope crossmatching between samples (see Table 1). Series in red represent mean series, while black are individual timbers. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Dating statistics for the Ancrum Bridge site composite (AOB_SITE) against the central England reference stable oxygen isotope chronology.

Reference	Year	*r*	*n*	DF	*t*	1/p	IF	Pass
Loader_et_al_2019	1409	0.48	90	77	4.81	387	159	TRUE

Year – The strongest statistical match year.
r – Pearson's correlation.
n – Paired data points.
DF – Corrected degrees of freedom.
t – Student's *t*-value.
1/p – Bonferroni corrected probability.
IF – Ratio of probabilities between the first and second strongest matches.
Pass – Does the match pass the statistical dating thresholds.

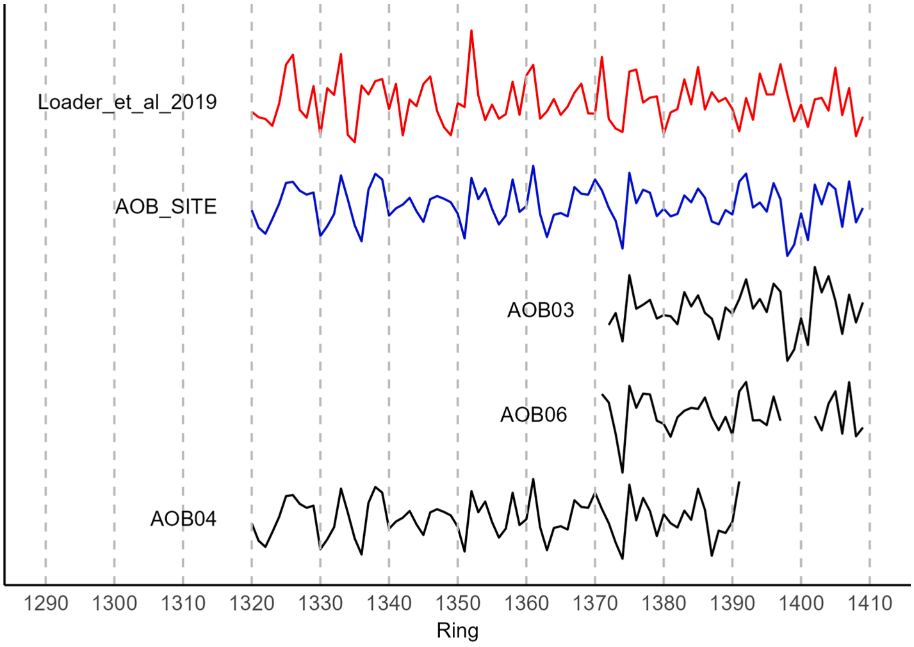

Fig. 4. Alignment of the individual Ancrum Bridge oxygen isotope series (black) and the overall site composite (blue) against the Loader et al., (2019) central England reference (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

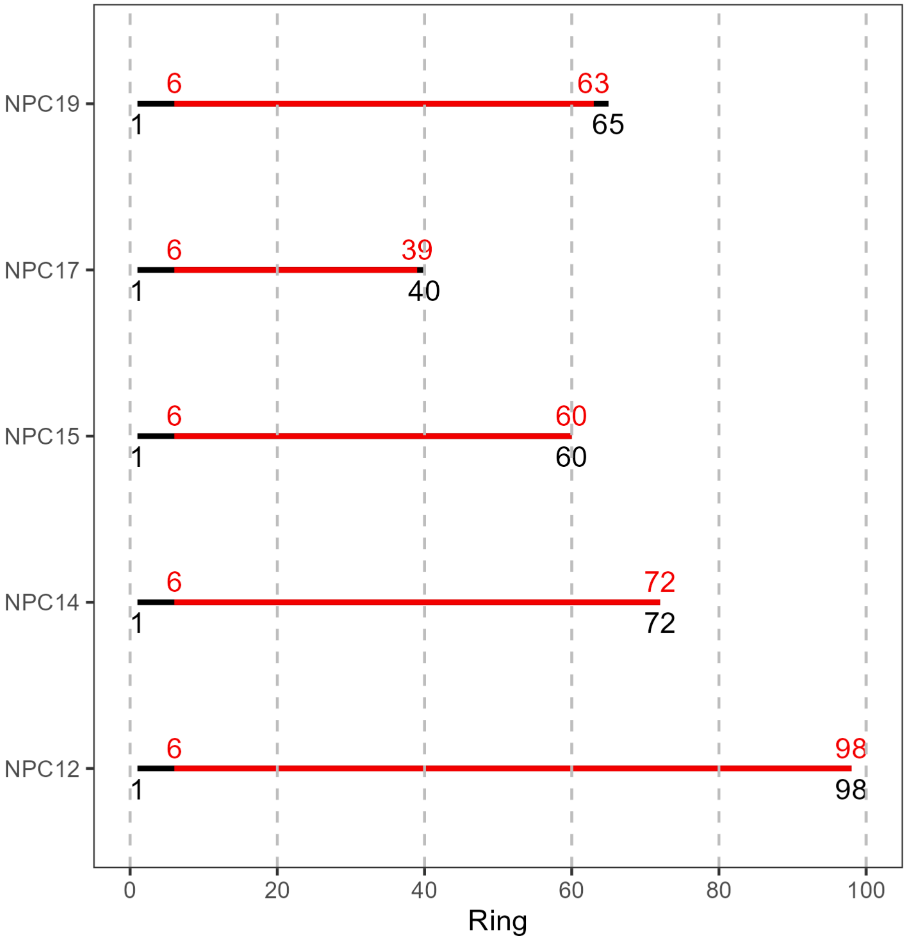

Fig. 5. Oxygen isotope series spans (red) from Neidpath Castle in comparison with the original ring-width data ranges (black). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Crossmatching results between the Neidpath Castle samples that pass the dating criteria of Loader et al. (2019). The minimum number of data pairs for a comparison was set at 20.

	NPC12	NPC14	NPC15	NPC17	NPC19
NPC12	–	$n = 67$, DF=56, 1/p > 1 million, IF>1000	$n = 52$, DF=42, 1/p > 1 million, IF>1000	$n = 34$, DF=27, 1/p > 1 million, IF>1000	$n = 58$, DF=49, 1/p > 1 million, IF>1000
NPC14	$r = 0.81$, $t = 10.44$	–	$n = 52$, DF=39, 1/p > 1 million, IF>1000	$n = 34$, DF=26, 1/p > 1 million, IF>1000	$n = 58$, DF=48, 1/p > 1 million, IF>1000
NPC15	$r = 0.88$, $t = 12.19$	$r = 0.87$, $t = 10.85$	–	$n = 31$, DF=22, 1/p = 103894, IF>1000	$n = 48$, DF=38, 1/p = 2390, IF>1000
NPC17	$r = 0.89$, $t = 10.35$	$r = 0.84$, $t = 8.02$	$r = 0.84$, $t = 7.12$	–	$n = 31$, DF=24, 1/p = 701870, IF>1000
NPC19	$r = 0.72$, $t = 7.30$	$r = 0.74$, $t = 7.65$	$r = 0.63$, $t = 5.05$	$r = 0.85$, $t = 7.76$	–

n – Paired data points.
r – Pearson's correlation.
t – Student's *t*-value.
DF – Corrected degrees of freedom.
1/p – Bonferroni corrected probability.
IF – Ratio of probabilities between the first and second strongest matches.

protocols as for the Ancrum Bridge samples. For all samples, the inner 5-rings were omitted due to potential juvenile effects. The outer 2 rings from sample NPC19 (rings 64 and 65) were removed from further analysis due to potential contamination. Also, rings 34 – 36 were missing from NPC15. The span of rings analysed isotopically, in comparison to the original ring-width measurements, are given in Fig. 5.

All samples crossmatched and passed the statistical dating thresholds for consideration (Table 3, Fig. 6). The strong internal matching enabled a site isotope composite (NPC_SITE) to be compiled (Fig. 6).

The Neidpath Castle site composite was compared against the south UK reference chronology. An end date of AD 1414 was returned for NPC_SITE which exceeded the statistical dating thresholds (Table 4, Fig. 7). Having confirmed the chronology of the Neidpath data through agreement with the ring-width dendrochronology and comparisons against the southern UK isotope reference record, it was then compared against the Ancrum Bridge data.

The individual Ancrum Bridge samples and the site composite were successfully crossdated isotopically with the Neidpath Castle site record, and the results independently confirmed the original isotope dating (Table 5, Fig. 8).

In confirming the isotopic chronology for Ancrum Bridge, it was then possible to derive isotope dendro-dates for each individual sample, by adding on the count of outer rings that were not measured isotopically (Fig. 2). Felling dates could also then be given if the bark edge was present on a sample or an estimate if there was sapwood present. Samples AOB03 and AOB06 with bark edge preserved, were felled in the winter AD 1428/29. The outermost ring for AOB04 represented the heartwood/sapwood boundary and was dated to AD 1397. It was therefore possible to report an estimated felling date range (Hillam et al., 1987) of between AD 1407-1443 for this sample. This date range is consistent with the bark edge dates found for AOB03 and AOB06.

4. Discussion

Stable isotope dendrochronology has conclusively shown that timbers with intact bark edge used to construct the sub-structure of the medieval bridge at Ancrum were felled during winter AD 1428/29. Given that wood was generally worked “in the green” (unseasoned) it is highly likely that the bridge would have been constructed within 12–18 months after felling (Miles, 2006). Significantly, this result shows that the bridge is approximately 80 years younger than the date indicated by wiggle match radiocarbon dating (95.4 % range).

The initial objective of this study was to apply stable isotope dendrochronology to refine the wiggle match date range and provide a

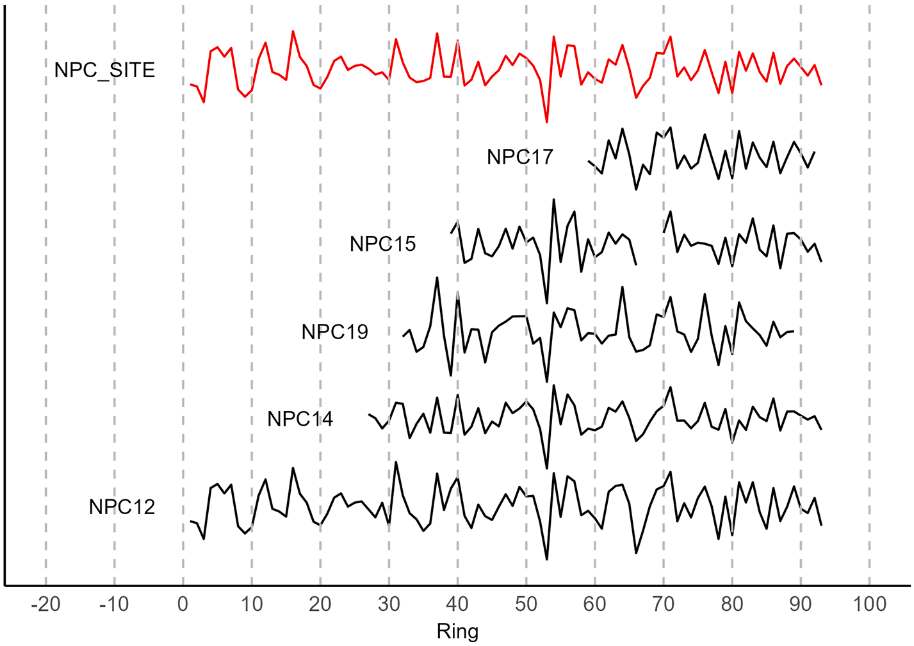

Fig. 6. Aligned filtered stable oxygen isotope series from Neidpath Castle. Alignment is in reference to the internal isotope crossmatching between samples (Table 3). The red series represents the site average chronology, while the black chronologies are individual timbers. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
Dating statistics for the Neidpath Castle site chronology against the central England stable oxygen isotope reference chronology.

Master	Year	*r*	*n*	DF	*t*	1/p	IF	Pass
Loader_et_al_2019	1414	0.48	93	80	4.90	577	875	TRUE

Year – The strongest statistical match year.
r – Pearson's correlation.
n – Paired data points.
DF – Corrected degrees of freedom.
t – Student's *t*-value.
1/p – Bonferroni corrected probability.
IF – Ratio of probabilities between the first and second strongest matches.
Pass – Does the match pass the statistical dating thresholds.

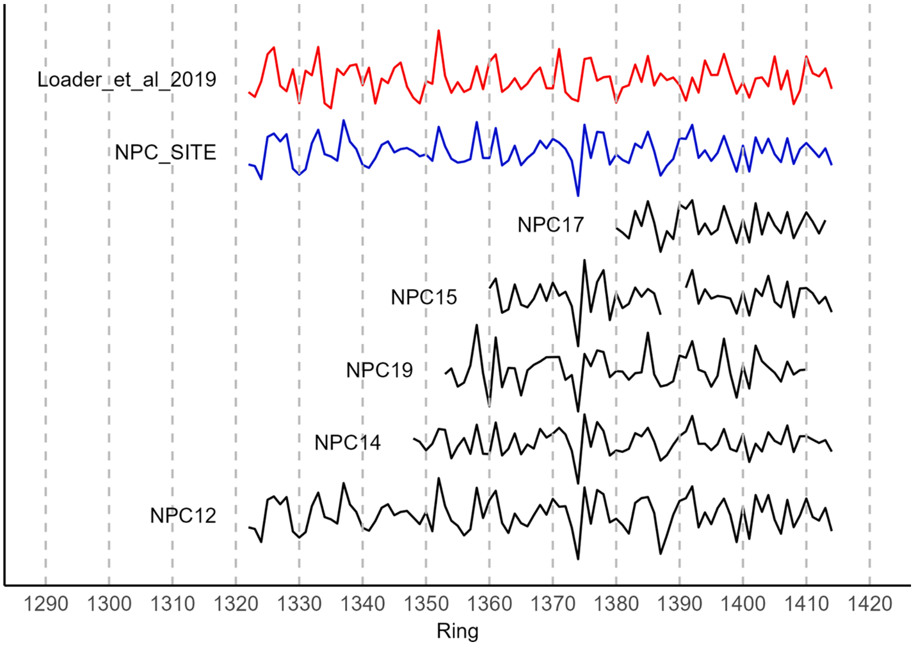

Fig. 7. Alignment of the individual Neidpath Castle stable oxygen isotope records (black) and the overall site composite (blue) against the Loader et al. (2019) central England reference (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 5
Dating statistics for the Ancrum Bridge stable oxygen isotope chronologies against the Neidpath Castle stable oxygen isotope composite chronology. The minimum number of data pairs for a comparison was set at 20.

Ancrum sample	Year	*r*	*n*	DF	*t*	1/p	IF	Pass
Site	**1409**	**0.74**	**88**	**75**	**9.59**	**> 1 million**	**>1000**	**TRUE**
3	1409	0.72	38	31	5.70	7472	>1000	TRUE
4	1391	0.76	70	59	9.00	>1 million	>1000	TRUE
6	1409	0.73	35	29	5.67	5696	>1000	TRUE

Year – The strongest statistical match year.
r – Pearson's correlation.
n – Paired data points.
t – Student's *t*-value.
DF – Corrected degrees of freedom.
1/p – Bonferroni corrected probability.
IF – Ratio of probabilities between the first and second strongest matches.
Pass – Does the match pass the statistical dating thresholds.

felling date that could allow historians to undertake targeted research on the social and political context surrounding construction of the bridge. Somewhat unexpectedly, the stable isotope dendrochronology returned a date well outside the most likely modelled radiocarbon date range, a finding independently confirmed against a regional reference chronology and a local isotope site chronology developed from ring-width dated records.

Isotope dendrochronology indicates that AOB03 and AOB06 are contemporary and share the same felling date. Sample AOB04 can also be precisely aligned using the oxygen isotopes and an estimated felling date range assigned. Prior to any scientific dating, redundant woodworking features observed on AOB04 were interpreted as evidence of re-use (Mills, 2020), but rather than representing a much earlier phase of construction, it is shown here to belong broadly to the same construction

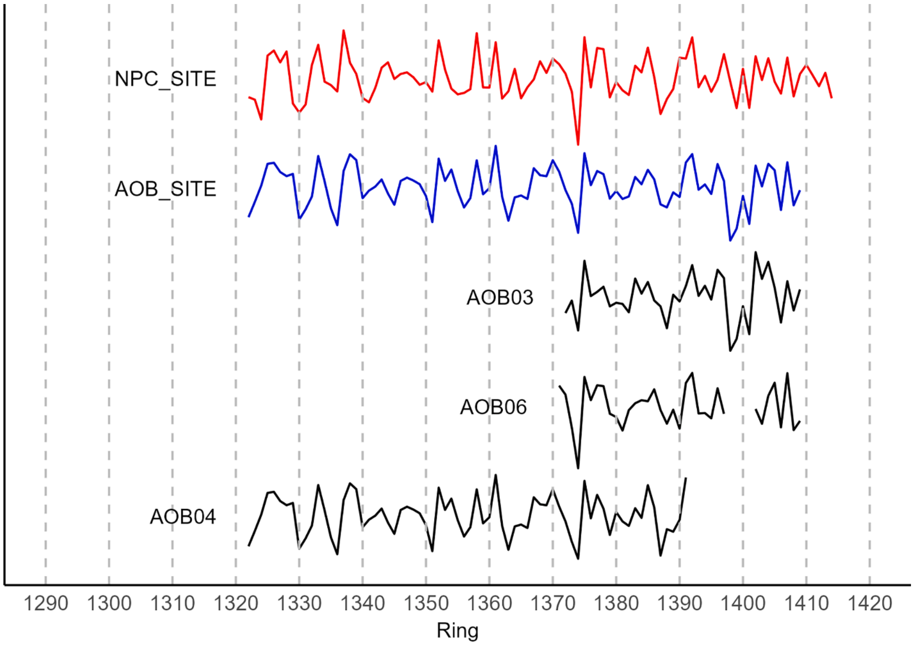

Fig. 8. Alignment of the individual (black) and composite Ancrum Bridge site (blue) chronologies against the Neidpath Castle site composite (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

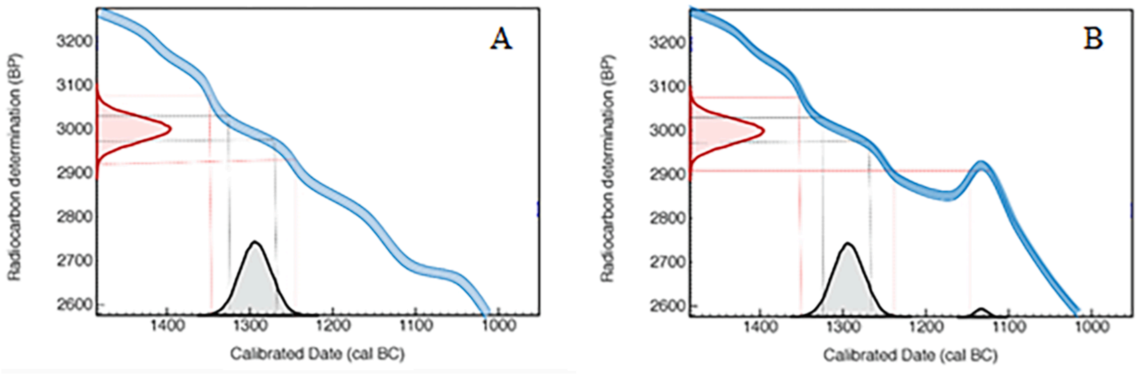

Fig. 9. A schematic to demonstrate the effect of widening the calibration uncertainty under different calibration curve conditions. A) demonstrates a simple unimodal calibration with the effect of standard and extended probabilities (black and red dashed lines respectively) on the resulting calibrated age. In this example extending the probability simply results in a wider calibrated date range. B) demonstrates the effect of calibrating a radiocarbon date where there is an inflection in the calibration curve. In this example a single date is returned using standard probabilities, but multiple discrete dates are identified when the range is extended. Note: Calibration curves and dates are for demonstration only. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

phase as AOB03 and AOB06. The redundant features on AOB04 are now interpreted as representing a prior brief use, perhaps in ancillary construction works (Mills, 2024). This re-evaluation of AOB04 accords with the radiocarbon dating of the outermost rings of AOB04, giving a date that falls into the more recent peak of the bimodal probability distribution for this sample (Table S1).

Whilst cellulose is the preferred medium for wiggle-match radiocarbon dating, it is important to stress that neither the radiocarbon results nor the wiggle matching are errant or necessarily in conflict with the stable isotope dendrochronological dating. The wiggle-match determined range 1340–1360 Cal. AD reports only that there is a 95.4 % chance that the date would lie within this range. In other words, there is an approximately 1 in 20 chance that the true date lies outside of 1340–1360 Cal. AD. In this case the date for the sample falls outside of the modelled most probable range.

Whilst radiocarbon and tree-ring dating methods routinely return coherent and accurate results (Hamilton et al., 2013; Tyers and Alcock, 2021; Tyers et al., 2016) discrepancies between ring-width dendrochronology and wiggle match radiocarbon dating have been reported previously (Bayliss et al., 2017; Marshall et al., 2019). Working with the IntCal13 (non-annual) dataset, Bayliss et al. (2017) concluded that “AMS 14C wiggle-matching in the medieval period cannot be relied upon to produce dating that is accurate to within the precision quoted”, highlighting the non-annual resolution of the calibration curve as a possible cause for this inaccuracy. As an annually resolved calibration curve was applied here (to non-annual data) it is therefore likely that the discrepancy between the radiocarbon and dendrochronologically determined felling dates is related to the presentation and interpretation of the dating results.

Fig. 9 schematically shows how calibrating a radiocarbon date exhibiting a simple unimodal probability distribution, results in a modelled uncertainty that reflects the relationship between the radiocarbon date and the calibration curve (Fig. 9A). In this case the distribution follows closely the Gaussian distribution transposed via the calibration curve to a calibrated radiocarbon age. Widening the confidence limits for the radiocarbon measurement widens the resulting uncertainty in the calibrated age, but the likely date will still fall close (adjacent) to the original 95.4 % range. By contrast, in cases where the calibration curve is not monotonic, a bi- or multi-modal probability distribution may result (Fig. 9B). Here, widening the uncertainty may identify additional peaks for consideration. Unlike a unimodal distribution, these "new" dates will not all fall adjacent to the 95.4 % distribution, but may, as in the case of Ancrum Bridge, fall far from the 95.4 % range. It may therefore be beneficial when working with multimodal age distributions to consider the implications of a wider probability range.

In this specific case, using the 'standard' probability range resulted in a misinterpretation of the age of the timber samples and therefore the social and political context in which the bridge was built. Given the strong isotopic dendrochronological evidence we now know that rather than being constructed during a period of instability and conflict during the reign of David II, the timbers used to construct the bridge at Ancrum were felled during a less turbulent period of King James I's reign. From this new insight it is now possible to redirect archaeological and archival research to focus on this later period and in doing so develop a better understanding of the role that the bridge played in the social and cultural history of the region (see Mills (2024)).

5. Conclusion

This study highlights the importance for end-users of radiocarbon dating to consider result probabilities when assessing calibrated radiocarbon dates, particularly in cases where the probability distribution is multi-modal. In this study, the 'standard' 95.4 % probability range failed to capture the true date. This represents a 1 in 20 chance that the date falls outside of this range, and arguably there is merit in exploring the impact of widening the range of uncertainty when considering and interpreting calibrated dates with multi-modal distributions.

Isotope dendrochronology shows that timbers used to construct Ancrum Bridge were felled in winter AD 1428/29. This accurate and precise dating differs by decades from the felling date derived by radiocarbon wiggle match dating. Whilst these findings will necessitate a revision to the current interpretation of Ancrum Bridge, and an update to the details of its Scheduled Monument designation, this site remains a discovery of national importance and a rare example of medieval bridge construction methods in Scotland.

CRediT authorship contribution statement

D. Davies: Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **C.M. Mills:** Writing – review & editing, Resources, Methodology, Investigation, Formal analysis. **D. McCarroll:** Writing – review & editing, Investigation, Formal analysis. **N.J. Loader:** Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Indexed site dating chronologies are available in Table S2 of the supplementary materials.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2024.104753.

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