Archaeometry

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ORIGINAL ARTICLE OPEN ACCESS

Ring-Width Dendrochronology, Isotopic Dendrochronology and Radiocarbon Dating of Timbers From the Spire Scaffold of Salisbury Cathedral, Wiltshire, England

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Received: 6 April 2025 | **Revised:** 29 September 2025 | **Accepted:** 15 December 2025

Keywords: ring-width dendrochronology | radiocarbon dating | stable isotope dendrochronology | Salisbury Cathedral

ABSTRACT

Ten timbers from the spire scaffold of Salisbury Cathedral were dated using a combination of ring-width dendrochronology, stable oxygen isotopic dendrochronology and radiocarbon dating. Seven timbers were coeval and assigned a combined empirical felling date range of 1352–1378, which was further refined to *1351–1359* (OxCal 95.4%). These results would indicate that the scaffold was not a 1320s construction but instead built later in the 14th century. The remaining sampled timbers produced a precise felling date of spring 1737 and are coincident with documented repair work in 1738.

1 | Introduction

1.1 | Previous Dendrochronological Analysis of Salisbury Cathedral

Salisbury Cathedral (Wiltshire, England) is one of the finest examples of an ecclesiastical building in the Early English Gothic architectural style. Its foundation stones were laid on 28th April 1220, after which it underwent two major building campaigns—one between 1220–1266 to construct most of the Cathedral and one ending in the early 14th century, which resulted in the heightening of the tower and addition of the spire, alongside building work in other sections of the Cathedral (Blum 1991; Tatton-Brown et al. 2013). Within the spire sits a nine-stage oak (*Quercus* spp.) timber scaffold. Despite historically being called a 'scaffold', it is in fact not one because it is impossible to build off without constructing additional scaffolds on this framework. However, throughout this paper, the term 'scaffold' will still be used. The spire scaffold consists of timbers dating from its original construction phase but also incorporates timbers recycled from earlier phases and from later repairs (Tatton-Brown 1991a). Analysis of which timbers fall into which categories has only been undertaken for a small number of the more than 275 timbers in this structure (Howard 1991; Miles et al. 2004). Two hypotheses concerning the spire scaffold's construction and timeframe have been given (Cocke 1993).

The first suggests that the spire and its scaffold are contemporaneous and were likely constructed in tandem during the 1320s, where the scaffold was used to build the stone spire itself (Tatton-Brown and Crook 2014). This argument is mainly centred around stylistic analysis of the ballflower decoration and buttresses of the tower and spire's masonry, along with the fact that the same ballflower decoration is found on the tombs of the potential spire architects that are inside the Cathedral (Tatton-Brown 1991b, 1995; Tatton-Brown et al. 2013). This dating is relatively precise, as ballflower decoration was only popular in England for a brief period between the end of the 13th century and the 1330s (Tatton-Brown et al. 2013).

The other theory considers that whilst the masonry spire may have been a 1320s construction, the internal timber scaffold was instead a later addition which was inserted to strengthen the spire and permit access for repairs after masonry damage, possibly following the well-documented hurricane or Great Wind of 1362—a storm responsible for collapsing the spire of Norwich Cathedral, amongst other buildings (Lamb 1991). This second theory is based on dendrochronological and archival evidence. Between 1990–1991, samples from 11 timbers from the scaffold were collected and analysed by Nottingham University Tree-ring Dating Laboratory (NUTRDL) (Howard 1991). The researchers successfully dated one reused 13th century timber inserted into the scaffold's fourth stage. Additionally, the four main cardinal braces from the first stage were only tentatively dated. Matches for these timbers were found, but they were not deemed sufficiently strong enough to publish the felling date ranges (Miles et al. 2004). The unsuccessful dating of the rest of the scaffold was attributed to timbers coming from 'fast-grown, immature oaks' (Simpson 1996, 10). In 2004, the English Heritage Centre for Archaeology revisited Salisbury Cathedral, with all samples obtained in 1990 being reanalysed (Miles et al. 2004). Since 1990, there had been an increase in the number of dendrochronological reference chronologies available for dating, prompting a reassessment of the earlier tentative dates (Miles 2004). Furthermore, nationwide sapwood estimates had been superseded by regional sapwood estimates (Miles 1997), meaning an updated combined empirical felling date range of 1344–1376 could be assigned to the previously tentatively dated four timbers. Simpson and Miles (2005) and Miles (2006a) considered whether the four dated principal braces were potentially later replacements, and that the rest of the timbers in the scaffold would date to the 1320s. However, through considering constructional evidence, they argue that these braces must be original, and thus the scaffold was not built in the 1320s. Since then, no new timbers have been analysed, meaning that up until now only five spire timbers have been scientifically dated.

Jones (2005) has rejected the second school of thought and has argued that the dating of a scaffold which has more than 275 timbers cannot be based on results obtained from four timbers. He further suggests that the dated braces are not from the primary construction phase, citing their appearances, materials and structural fixing methods. Later, Jones (2007) claims that the presence of an internal spire scaffold would not have interfered with construction of the stone spire, further arguing for its use during the 1320s building campaign. Since these interpretations, additional scholarship regarding the scaffold's origins have not been produced and only few published sources have ever acknowledged that two different dates are currently attributed to the spire scaffold (Cocke 1993), including some recent publications (Elliott 2020; Deane and Baillie-Grohman 2020). In this respect, and in light of recent advancements in precision dating techniques, it is therefore an ideal time to revisit this long-standing debate. Determining the stages of construction of the spire and its scaffold would, as Astill (1990, 13) states, 'increase our appreciation of the Cathedral and of the people who built it'.

2 | Dating Methods for Archaeological Wooden Artefacts

2.1 | Ring-Width Dendrochronology

Ring-width dendrochronology is the most accurate and precise dating method for archaeological wood and utilises the pattern of growth in tree-rings to assign a date range for those rings (Baillie 1983). This is achieved by measuring the ring-widths of undated samples which are statistically cross-matched with known-age reference chronologies. A measure of the strength of match can be described using a statistical parameter known as the Baillie-Pilcher *t*-value (Baillie and Pilcher 1973). Values in the range of 3.5 on a series of 100 rings or more will signify confidence in cross-matching and a value greater than 6 is rarely in error (Pilcher and Baillie 1987). Where a Baillie-Pilcher *t*-value higher than 10 is achieved, this potentially signifies that these samples may have originally been derived from the same tree (Hillam 1998). Depending on whether a timber contains only heartwood, heartwood/sapwood boundary, incomplete sapwood or complete sapwood, several different types of dates can be assigned to it including a *terminus post quem*, an empirical felling date range or a specific felling date (Miles 1997). Felling date ranges can be further refined using Bayesian approaches (Millard 2002; Miles 2006b).

2.2 | Isotopic Dendrochronology

Timbers may be unsuitable for ring-width dendrochronology for reasons including limited regional reference chronologies, species, disturbance or a timber not possessing sufficient rings for reliable dating. To overcome these limitations, researchers have developed stable oxygen isotopic dendrochronology (Loader et al. 2019) (hereafter isotopic dendrochronology). For each annual ring in a sample, the $\delta^{18}O$ value is determined by measuring the ratio of stable oxygen isotopes ^{18}O and ^{16}O (Equation 1). The $\delta^{18}O$ value of the tree-ring latewood represents the isotopic ratio of the water sampled by the tree during photosynthesis. This signal is unaltered as it is taken up through tree roots, but may be modified during photosynthesis and evaporation due to fractionation (McCaroll and Loader 2004). All oxygen isotope ratios are reported with units per mille (‰) and with respect to Vienna Standard Mean Ocean Water (VSMOW) (Coplen 1995).

$$\delta^{18}O\,(‰) = \frac{(^{18}O/^{16}O)_{sample} - (^{18}O/^{16}O)_{VSMOW}}{(^{18}O/^{16}O)_{VSMOW}} * 1000 \qquad (1)$$

Isotopic dendrochronology currently differs from ring-width dendrochronology as the validity of a date is assessed and reported within a framework of statistical tests. If match statistics do not exceed these thresholds, then a sample is considered undated (Loader et al. 2019). Another difference is the use of Student's *t*-value instead of the Baillie-Pilcher *t*-value.

2.3 | Radiocarbon Dating

Tree-ring α-cellulose of individual rings can also be subject to accelerator mass spectrometry (AMS) radiocarbon dating (^{14}C-dating). This is a technique that measures the number of stable ^{12}C and ^{13}C atoms, and radioactive ^{14}C atoms, in samples to determine its age, utilising the half-life of ^{14}C as well as a calibration curve in the dating process. Where α-cellulose is obtained from a series with precisely known calendar age differences between

TABLE 1 | Summary of ring-width dendrochronology results for samples **scss1–12** from the spire scaffold of Salisbury Cathedral.

Sample	Timber and Position	Total Number of Rings	Dated Years Spanning (AD)	Heartwood/sapwood Boundary (AD)	Number of Sapwood Rings[a]	Mean Ring Width (mm)	Standard Deviation (mm)	Mean Sensitivity (mm)	Estimated Empirical Felling Date Range or Date (AD)	Calculated Refined Felling Date Range (AD)
scss1	South corner post, 1st stage	40	—	—	—	2.92	0.81	0.150	—	—
scss2	Centre post, 1st stage	42	—	—	—	4.24	0.91	0.143	—	—
scss3	Centre post, 2nd stage	56	—	—	2	4.15	1.71	0.280	—	—
scss4	East-west floor frame, 1st stage	50	—	—	—	2.88	1.30	0.162	—	—
scss5	East corner post, 1st stage	50	—	—	—	2.69	0.66	0.149	—	—
scss6	West brace, 2nd stage	52	—	—	—	2.74	0.95	0.199	—	—
scss7	Radial strut to north-west corner, 2nd stage	54	—	—	2	1.27	0.33	0.225	—	—
scss8	North-south floor frame, 1st stage	66	—	—	—	1.79	1.30	0.244	—	—
scss9a	North perimeter plank, 1st stage	55	1670–1724	1724	H/S	2.52	1.25	0.230	(Spring 1737)	—
scss9b	As above	54	1683–1736	1725	11¼C	1.73	0.46	0.197	Spring 1737	—
scss9	Mean of **scss9a** and **scss9b**	67	1670–1736	1725	11¼C	2.30	1.18	0.193	Spring 1737	—
scss10a	West perimeter plank, 1st stage	51	1667–1717	1715	2	1.94	0.75	0.216	(Spring 1737)	—
scss10b	As above	52	1681–1732	1708	24 + 4¼C NM	1.24	0.56	0.209	Spring 1737	—
scss10c1	As above	34	1674–1707	1707	H/S	1.85	0.77	0.264	(Spring 1737)	—
scss10c2	As above	26	—	—	26¼C	0.67	0.13	0.196	—	—
scss10	Mean of **scss10a**, **scss10b** and **scss10c1**	66	1667–1732	1710	24 + 4¼C NM	1.64	0.85	0.212	Spring 1737	—
scss11a	South-east perimeter plank, 1st stage	44	1679–1722	1722	H/S	2.38	0.98	0.176	(Spring 1737)	—
scss11b	As above	46	1691–1736	1722	14¼C	2.07	0.59	0.220	Spring 1737	—

(Continues)

TABLE 1 | (Continued)

Sample	Timber and Position	Total Number of Rings	Dated Years Spanning (AD)	Heartwood/sapwood Boundary (AD)	Number of Sapwood Rings[a]	Mean Ring Width (mm)	Standard Deviation (mm)	Mean Sensitivity (mm)	Estimated Empirical Felling Date Range or Date (AD)	Calculated Refined Felling Date Range (AD)
scss11	Mean of **scss11a** and **scss11b**	58	1679–1736	1722	14¼C	2.34	0.87	0.185	Spring 1737	—
scss12	West brace, 1st stage, Primary phase	102	1236–1337	1337	H/S	2.64	1.27	0.240	1346–1378	*1346–1371*
SARUM18	**Site Master (mean of scss9–11)**	**70**	**1667–1736**	—	—	**2.18**	**0.89**	**0.164**	**Spring 1737**	—

[a]¼C = partial bark edge, spring felling; H/S = heartwood/sapwood boundary; NM = not measured.

each of the rings, 'wiggle-matching' may be applied to refine the results through an improved match against the calibration curve, often with higher precision and lower uncertainties (Baillie 1995; Bronk Ramsey et al. 2001; Galimberti et al. 2004).

3 | Samples

All samples were obtained using an electric drill with a hollow 16-mm coring attachment. In total, 17 samples from 12 timbers were taken from the spire scaffold and given the prefix **scss** (<u>**S**</u>alisbury <u>**C**</u>athedral <u>**s**</u>pire <u>**s**</u>caffold) (Table 1). The samples were numbered **scss1–12**. Where multiple cores had been taken from one timber, consecutive lowercase letters are used (e.g., **scss10a** and **scss10b**). Individual segments of cores which had fractured during drilling were labelled with numbers after the code (e.g., **scss10c1** and **scss10c2**).

Five of the sampled 12 timbers were those that had already been sampled in 1990 (sample code *salc*) and re-assessed in 2004 (**scss1** [*salc22*], **scss2** [*salc23*], **scss3** [*salc24*], **scss5** [*salc27*] and **scss12** [*salc19*]) (Howard 1991; Miles et al. 2004). Of these, only one (**scss12** [*salc19*]) had been dated in 1990.

4 | Method

4.1 | Ring-Width Dendrochronology

Samples were prepared and measured using standard dendrochronological techniques (Hillam 1998). Dating was carried out using cross-matching against a database of 2263 reference chronologies from across the British Isles, concentrating on England to establish conclusive sample dating.

For dated timbers with incomplete sapwood, empirical felling date ranges were calculated. Sapwood estimates for southern England were used and these state, with a 95.4% probability, that oak trees will have 9–41 sapwood rings present before felling (Miles 1997). Refined Bayesian felling range estimates were calculated in OxCal (v4.4.4) using the Sapwood_Model() and Sapwood() functions (Miles 2005a; Bronk Ramsey, n.d.-a, 2009). The refined felling range estimates similarly have a 95.4% probability associated with them. This function does assume a priori that all timbers were felled in the same year. Parameters calculated for post-Roman mainland Britain were used for Sapwood_Model() (Bronk Ramsey, n.d.-a):

- $a = 2.77292$
- $b_r = 0.100001$
- $b_m = -0.275445$
- $\sigma = 0.314286377$

4.2 | Isotopic Dendrochronology

Once ring-width dendrochronology had been undertaken, sample cores were mounted and cut lengthways in half, with one half going into a dendrochronology archive and the other being utilised for isotopic dendrochronology. Seven samples were selected for isotopic dendrochronology: **scss1–6** and **scss12**. The procedure outlined in Loader et al. (2019) for sample preparation, extracting α-cellulose from annual latewood component using extraction blocks (Wieloch et al. 2011) and measuring isotopic values was followed. During sample slicing, care was taken to avoid degraded wood and potential contaminants (e.g., charring or beetle frass), which could adversely affect isotopic measurements. Chemical extraction of α-cellulose was carried out using a version of the procedure modified from Loader et al. (1997), primarily the use of hydrochloric acid instead of acetic acid. To calibrate the isotopic measurements, α-cellulose (Sigma Aldrich UK [$\delta^{18}O = 27.30$‰]) and holocellulose (IAEA-C-3 [$\delta^{18}O = 32.60$‰]) (Rozanski et al. 1992; Boettger et al. 2007) were used as the primary in-house and secondary verification standards respectively. Typical analytical precision for isotopic dendrochronology is ± 0.3‰ ($\delta^{18}O$, σ_{n-1}, $n = 10$) (Loader et al. 2013). For dating, Loader et al. (2019) recommends that each ring is analysed at least twice; however, for some rings there was only sufficient α-cellulose for one analysis.

There is a benefit to including as many rings as possible in a series to aid in improving the statistical match during dating individual samples, as well as cross-matching with other samples. However, some researchers have identified short-lived juvenile effects in oak trees to occur mostly within the first formed 10 rings (Duffy et al. 2017). These can cause anomalous $\delta^{18}O$ values in these near-pith rings, and as a precaution, where evidence indicates, Loader et al. (2019) suggested that it may be necessary to omit the five closest rings to the pith during dating. In this study, there was no evidence of juvenile growth, and so no such adjustments were required as part of the dating process.

Following the methodology outlined in Loader et al. (2019), isotopic dendrochronology was conducted using ISODATE (v2.0.2) (Davies et al. 2025). For dating the isotope chronologies, each sample isotope series was compared against the reference chronology for South Central England (Loader et al. 2019). A potential cross-match with the reference chronology, or between two individual series, is considered acceptable when the match's Bonferroni-corrected probability ($1/p$) and isolation factor (IF) are greater than or equal to 100 and 10, respectively (Loader et al. 2019). As each core's ring-width series was linked annually to its isotopic record, it was possible to use the dates obtained through isotopic dendrochronology to assign a calendar date to its partner ring-width measurement chronology. This meant that empirical and refined felling date ranges (see Section 4.1) could be calculated for dated timbers, where incomplete sapwood was present.

4.3 | Radiocarbon Dating

^{14}C-dating was carried out on the α-cellulose that had been prepared for isotopic dendrochronology (see Section 4.2). This was undertaken at the Oxford Radiocarbon Accelerator Unit with an Ionplus+ 200-kV MiCaDaS AMS using the methodology outlined in Dee and Bronk Ramsey (2000) and Brock et al. (2010).

To calibrate the ^{14}C-dating measurements, SIRI Sample H, a single-year ring sample from a medieval period house oak floor joist dating to 1475, is used as the known age sample (Scott et al. 2017, 2019). In addition, samples from ancient kauri (*Agathis australis*) trees found at the Renton Road site in New Zealand are used as the background age calibration sample (Marra et al. 2006). The α-cellulose from both samples was extracted using the methodology described in Section 4.2. Furthermore, oxalic acid was used as a standard reference against which all samples are measured, and alanine standard is additionally used to measure stable carbon isotope values against.

TABLE 2 | Cross-matching matrix of Baillie-Pilcher *t*-values and overlaps for (a) same-timber means of **scss9**, (b) same-timber means of **scss10**, (c) same-timber means of **scss11** and (d) site master **SARUM18**.

(a)	Sample	**scss9b**	(b)	Sample	**scss10b**	**scss10c1**
	Last Ring Date (AD)	1736		Last Ring Date (AD)	1732	1707
	scss9a	6.46		**scss10a**	6.69	11.62
	1724	42		1717	37	34
					scss10b	7.28
						27
(c)	Sample	**scss11b**	(d)	Sample	**scss10**	**scss11**
	Last Ring Date (AD)	1736		Last Ring Date (AD)	1732	1736
	scss11a	3.19		**scss9**	3.05	3.90
	1722	32		1736	63	58
					scss10	3.98
						54

Key: Baillie-Pilcher *t*-value (1973)

Overlap

Wiggle-matching of tree-ring ^{14}C-dating results was undertaken in OxCal (v.4.4.4) using the D_Sequence(), R_Simulate() and R_Date() functions (Bronk Ramsey, n.d.-b). Wiggle-matching simulations of all samples subject to isotopic dendrochronology were performed using intervals of every 5, 10 and 20 rings to select a single sample for ^{14}C-dating. An estimated uncertainty of 20 for the radiocarbon measurement was used in all simulations.

5 | Results

5.1 | Ring-Width Dendrochronology

Several samples (**scss1–8**) taken from integrated main structural timbers did not cross-match between themselves, nor did they match against any of the reference chronologies (Table 1). A main brace to the west post (**scss12**) with 102 rings, whilst not matching with any of the above samples, did match with reference chronologies spanning the years 1236–1337, matching with a Baillie-Pilcher *t*-value of 6.03 with **CL_QMF1** (Tyers 1999), 5.89 with **ALWCSO01** (Arnold and Howard 2009) and 5.83 with **SARUMBP1** (Miles and Worthington 2000) (Table 1). It also matched conclusively with the sample *salc19* taken by NUTRDL in 1990 and dated in 2004 (Miles et al. 2004). The sample was assigned an empirical felling date range of 1346–1378 and a refined OxCal felling date range of *1346–1371* (Table 1).

The remaining timbers had mean sequences combined from two (**scss9** and **scss11**) or three (**scss10**) individual radii taken to obtain bark edge (Table 2). These timbers came from the large perimeter planks on the first stage which included the north plank (**scss9**) with 67 rings, the west plank (**scss10**) with 66 rings and the south-east plank (**scss11**) with 58 rings. These three mean timber sequences were combined to form the site master **SARUM18** with 70 rings (Table 2) and were dated conclusively to span the years 1667–1736. The best matches were a Baillie-Pilcher *t*-value of 8.13 with **CBMASQ02** (Howard et al. 2003), 7.79 with **SINAI** (Tyers 1997) and 6.97 with **SARUM13** (Miles 2005b). As the three timbers comprising the site master **SARUM18** retained bark edge with the final unmeasured ring being the spring growth completely formed, a precise felling date of spring 1737 could be ascribed to them all (Table 1).

5.2 | Isotopic Dendrochronology

For **scss5**, the second run of ring 25, and for **scss12**, both runs of ring 20, along with the first run of rings 89 and 90 (there was insufficient α-cellulose for a second run of rings 89 and 90), had anomalous δ^{18}O values believed to indicate the presence of contaminants, and these values were omitted from the respective series prior to dating. The seven individual timbers (**scss1–6** and **scss12**) date independently against the reference chronology, each passing the statistical threshold for consideration of a date (Table 3). The isotopically dated last measured ring of timber **scss12** was the same as the result obtained by ring-width dendrochronology (Table 1), independently providing evidence that ring-width dendrochronology was secure.

All but one of the individual timbers (**scss12**) cross-matched with one another passing above the criteria specified by

TABLE 3 | Summary of isotopic dendrochronology dating results for samples **scss1–6** and **scss12** from the spire scaffold of Salisbury Cathedral against the South Central England master chronology (Loader et al. 2019).

Sample	Number of Rings in Best Match	Best Match (AD)	Dated Years Spanning (AD)[a]	Pearson Correlation Coefficient	Student's *t*-value	Degrees of Freedom	Bonferroni-corrected Match Probability (1/*p*)	Isolation Factor (IF)	Estimated Empirical Felling Date Range (AD)	Calculated Refined Felling Date Range (AD)
scss1	41	1337	1297–1337	0.68	5.46	34	615	489	1346–1378	*1345–1367*
scss2	43	1339	1297–1339	0.68	5.62	36	1184	> 1000	1348–1380	*1346–1366*
scss3	56	1341	1286–1341	0.71	6.76	46	127,184	> 1000	1350–1382	*1346–1367*
scss4	50	1337	1287–1337	0.74	6.88	40	97,888	> 1000	1346–1378	*1345–1368*
scss5	51	1343	1293–1343	0.67	5.92	43	5574	> 1000	1352–1384	*1351–1374*
scss6	54	1338	1285–1338	0.63	5.41	44	1078	> 1000	1347–1379	*1346–1369*
scss12	93	1337	1235–1337	0.62	7.09	80	> 1,000,000	> 1000	1346–1378	*1346–1371*
$SARUM1_I$	**108**	**1343**	**1235–1343**	**0.70**	**9.40**	**93**	**> 1,000,000**	**> 1000**	**1352–1378**[b]	***1351–1359***[c]

[a]Range is the first and last isotopically dated ring, and may include any years where no date was assigned to a specific ring due to insufficient α-cellulose or anomalous δ^{18}O values.
[b]Period of common overlaps of individual felling date ranges.
[c]OxCal combined felling date range (Miles 2006b).

TABLE 4 | Cross-matching matrix of Student's *t*-values, offsets, Pearson Correlation Coefficient and Degrees of Freedom for samples **scss1–6** and **scss12**. The minimum number of data pairs for a comparison between series was set at 20.

Sample	**scss2**	**scss3**	**scss4**	**scss5**	**scss6**	**scss12**
Last Ring Date (AD)	1339	1341	1337	1343	1338	1337
scss1	5.99 | 2	7.80 | 4	4.11 | 0	6.26 | 6	5.66 | 1	—
1337	0.72 | 34	0.81 | 33	0.59 | 32	0.73 | 34	0.70 | 33	
	scss2	4.91 | 2	4.05 | 2	6.73 | 4	5.85 | 1	—
		0.64 | 35	0.58 | 33	0.75 | 36	0.71 | 34	
		scss3	5.86 | 4	6.80 | 2	5.04 | 3	—
			0.68 | 40	0.73 | 41	0.61 | 43	
			scss4	6.62 | 6	5.37 | 1	—
				0.74 | 37	0.64 | 41	
				scss5	7.40 | 5	4.29 | 6
					0.77 | 38	0.62 | 29
					scss6	—

Key: Student's *t*-value | Offset

Pearson Correlation Coefficient | Degrees of Freedom

Loader et al. (2019) (Table 4). The timbers cross-matched at the same positions as indicated by the dating against the reference chronology. Timber **scss12** did not cross-match with **scss1–4** or **scss6**, but it did cross-match with **scss5**, and also matched strongly against the reference chronology. The likely reason for the lack of cross-matching is that the series align with the section of **scss12** that contains gaps due to insufficient α-cellulose extraction (Figure 1). After cross-matching, the seven oxygen isotope series were combined into a single site composite $\mathbf{SARUM1_I}$, which contains 108 rings. This composite series spans 1235–1343 and matched strongly against the South Central England reference chronology (Loader et al. 2019) with a Student's *t*-value of 9.40, a $1/p$ of > 1 million and an IF of > 1000 (Table 3 and Figure 1).

Based upon the strength of these independent matches and the inter-series cross-matching, it was possible to securely date each timber. Due to the presence of a heartwood/sapwood boundary in all timbers, individual empirical and refined OxCal felling date ranges could be assigned to the samples, which all spanned the third quarter of the 14th century (Table 3). Additionally, a combined empirical felling date range of 1352–1378 was calculated based on the period of common overlap in the individual felling date ranges (Table 3). Similarly, a combined refined OxCal felling date range of *1351–1359* was calculated for the group (Table 3).

5.3 | Radiocarbon Dating

Wiggle-matching simulations showed that **scss12** produced the narrowest date range for its last ring. This was likely achieved because **scss12** was the sample that had the most rings and as its first 30 rings coincided with a prominent excursion in the IntCal20 ^{14}C-calibration curve (Reimer et al. 2020). Thus, only **scss12** was subject to ^{14}C-dating. To obtain the strongest result with the prominent wiggle in the calibration curve, every 5 rings of **scss12** from rings 2–32 inclusive, along with rings 42, 52, 67, 86 and 92, were subject to ^{14}C-dating and subsequent wiggle-matching. The results of ^{14}C-dating show that the dendrochronologically determined calendar age of each ring falls within the range of dates calculated by wiggle-matching (Table 5). Additional independent evidence has therefore been provided that the dating of **scss12** using both ring-width and isotopic dendrochronology has been successful. The accuracy of ^{14}C-dating is further supported by the perfect agreement between the uncalibrated radiocarbon date for SIRI Sample H with the consensus value in Scott et al. (2019) (386 ± 3), and the infinite radiocarbon age for the Renton Road sample (Table 5).

6 | Interpretation

6.1 | Fourteenth-Century Samples

The 14th century timber samples, which were successfully dated, included two braces (**scss6** and **scss12**), two centre posts (**scss2** and **scss3**) and two corner posts (**scss1** and **scss5**). These were all from the scaffold's lowest two sections and are clearly primary well-integrated structural framing timbers. Therefore, it is improbable that they could have been seamlessly replaced without jacking up the entire scaffold and dismantling the structure above. The results of isotopic dendrochronology of the investigated primary phase timbers highlight that their combined empirical felling date range spans 1352–1378 (Table 3). However, by using the combined OxCal felling date function, a refined range of *1351–1359* can

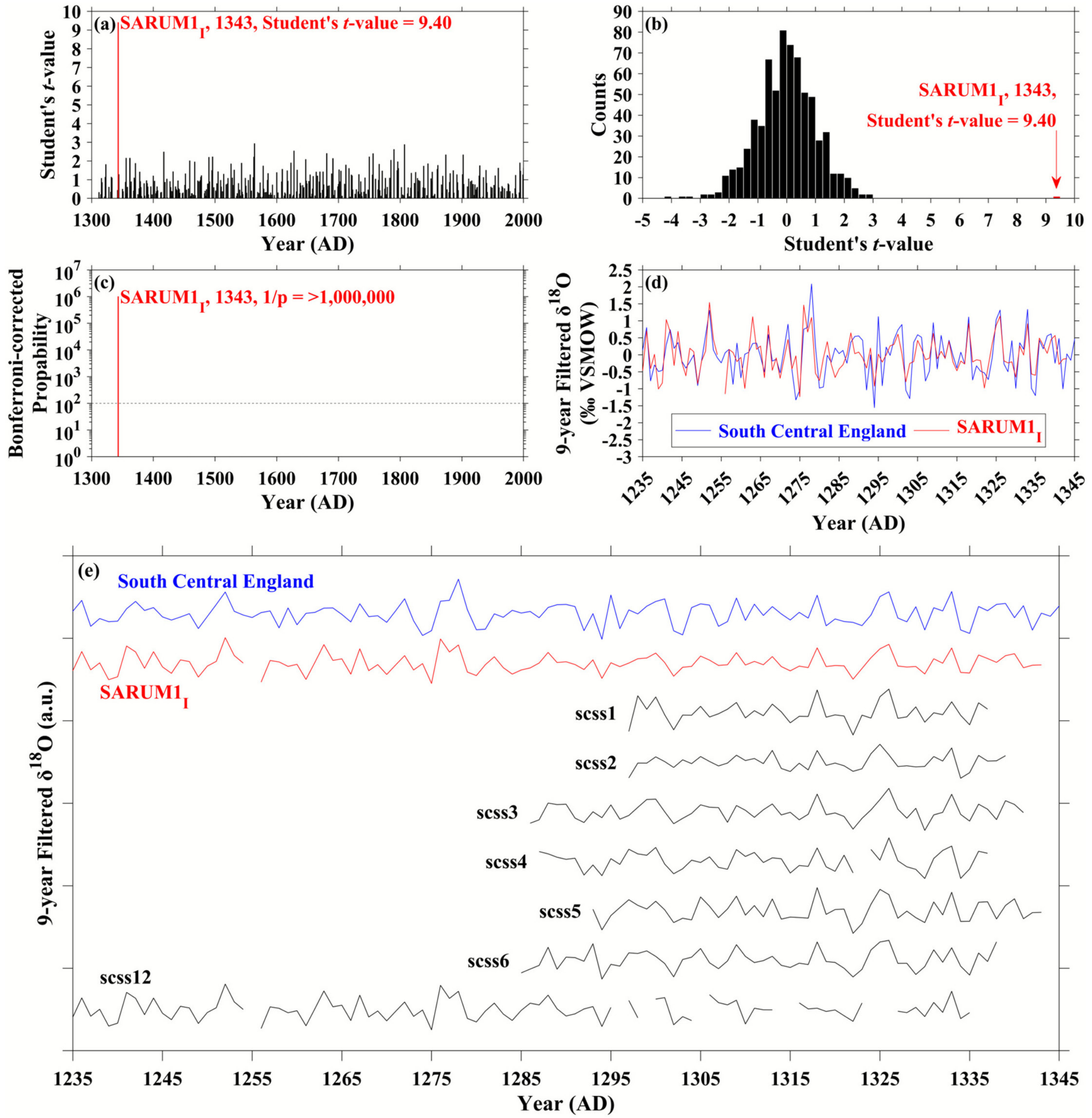

FIGURE 1 | Isotopic dendrochronology dating results for the spire scaffold of Salisbury Cathedral. (a) Distribution of positive Student's t-values against calendar year. (b) Distribution of both positive and negative cumulative Student's t-values for all calendar year matches. Each bar has a width of 0.25. (c) Distribution of Bonferroni-corrected match probabilities ($1/p$) for dates with $1/p \geq 1$. The dashed horizontal line represents the significance threshold ($1/p = 100$). (d) Filtered oxygen isotope data of series **SARUM1$_I$** and the South Central England master chronology (Loader et al. 2019) against calendar year. (e) Filtered oxygen isotope data of samples **scss1–6** and **scss12**, series **SARUM1$_I$** and the South Central England master chronology (Loader et al. 2019), against calendar year.

be given for this group (Table 3). Construction of the spire scaffold could have occurred within the confidence range (95.4% for both empirical and refined ranges) at any point during the proposed felling date ranges for the timbers, or very shortly thereafter. These dates span roughly the third quarter of the 14th century for the combined empirical felling date range, and even tighter to the 1350s using the combined refined felling date ranges.

Based on these felling date ranges and last measured ring dates, the trees from which these primary-phase timbers were constructed would still have been growing through the late 1330s,

TABLE 5 | Summary of radiocarbon dating wiggle-matching results for sample **scss12** from the spire scaffold of Salisbury Cathedral, along with the known and background age intercomparison standards.

Sample	Laboratory Code	$\delta^{13}C$ (‰)	C (%)	Amount Used in Analysis (mg)	Real Calendar Year (AD)	Uncalibrated Age (BP)	Calibrated Age (AD)	Wiggle-matched Year Range (AD)
scss12, ring 2	OxA-V-3191-7	−22.7	38.00	4.37	1237[a]	806 ± 18	*1219–1269* (95.4%)	*1235–1244*
scss12, ring 7	OxA-V-3191-8	−22.7	38.60	4.35	1242[a]	829 ± 18	*1177–1193* (8.4%) *1203–1266* (87.1%)	*1240–1249*
scss12, ring 12	OxA-V-3191-9	−22.9	38.30	4.43	1247[a]	862 ± 19	*1159–1225* (95.4%)	*1245–1254*[b]
scss12, ring 17	OxA-V-3191-10	−22.7	39.60	4.38	1252[a]	828 ± 18	*1179–1191* (6.6%) *1205–1265* (88.9%)	*1250–1259*
scss12, ring 22	OxA-V-3191-11	−23.1	37.90	4.32	1257[a]	800 ± 18	*1221–1271* (95.4%)	*1255–1264*
scss12, ring 27	OxA-V-3191-12	−24.0	40.10	4.54	1262[a]	762 ± 19	*1228–1281* (95.4%)	*1260–1269*
scss12, ring 32	OxA-V-3191-13	−24.3	38.80	4.67	1267[a]	773 ± 19	*1226–1279* (95.4%)	*1265–1274*
scss12, ring 42	OxA-V-3191-14	−23.1	39.20	4.57	1277[a]	742 ± 20	*1230–1243* (4.0%) *1257–1293* (91.5%)	*1275–1284*
scss12, ring 52	OxA-V-3191-15	−23.5	38.70	4.57	1287[a]	668 ± 19	*1281–1316* (50.8%) *1360–1388* (44.7%)	*1285–1294*
scss12, ring 67	OxA-V-3191-16	−23.2	39.80	4.68	1302[a]	641 ± 19	*1290–1325* (40.5%) *1352–1394* (55.0%)	*1300–1309*
scss12, ring 86	OxA-V-3191-17	−23.1	34.70	4.63	1321[a]	610 ± 19	*1302–1369* (75.1%) *1380–1400* (20.4%)	*1319–1328*
scss12, ring 92	OxA-V-3191-18	−23.3	40.00	4.67	1327[a]	577 ± 19	*1317–1360* (65.7%) *1387–1412* (29.8%)	*1325–1334*
Renton Road	OxA-V-3191-19	−22.7	29.40	4.63	—	> 50,300	—	—
SIRI Sample H	OxA-V-3191-20	−24.9	39.10	4.90	1475	386 ± 18	*1449–1515* (75.4%) *1590–1620* (20.1%)	—

[a]Determined with ring-width dendrochronology (Section 5.1) and isotopic dendrochronology (Section 5.2).
[b]This sample had poor agreement (Overall agreement index for this sample = 6%; Minimum overall agreement index = 60%).

and some (**scss3** and **scss5**) even growing into the early 1340s. Assuming that the spire itself was built during the 1320s based on architectural evidence, and there is no current reason to question this, the theory that the scaffold was assembled during the construction of the masonry spire has been shown to be likely incorrect.

The dating results using the three different proxies do not rule out the possibility that the spire scaffold was erected following damage by the 1362 storm, but they do not provide conclusive proof. Moreover, the OxCal combined felling date range would suggest an earlier felling date in the decade prior to the hurricane—a period upon which to focus future documentary and historical investigations. If a pre-1362 construction is correct, then this might help to explain why there was limited damage to the spire during the storm, which would be more in line with the sparse contemporary documentary evidence. Alongside the discovery of further contemporaneous archival documentation which may shed light on the scaffold's construction, only further dating of samples with retained bark edge would allow the felling dates obtained in this study to be tightened further.

6.2 | Eighteenth-Century Samples

A precise felling date of spring 1737 for the three 18th century perimeter planks from the first stage comprising site master **SARUM18** proves that these timbers are a later phase insertion in the scaffold. These clearly relate to a repair campaign carried out by the then Clerk of Works, Francis Price, in 1738, when 'all the timbers within the cavity of the spire, were substantially repaired' (Price 1753, 61). However, due to a lack of additional archival evidence, it is currently not known whether these timbers are replacements of earlier planks or were first introduced in the 18th century.

7 | Conclusion

Ten timbers from the spire scaffold of Salisbury Cathedral have been dated using ring-width dendrochronology, isotopic dendrochronology and radiocarbon dating. Of the analysed timbers, seven main structural elements all dated to the third quarter of the 14th century with a combined empirical felling date range of 1352–1378. This range becomes even tighter, dating to the first half of that quarter (*1351–1359*), when a combined OxCal Bayesian refined felling date range is calculated. Construction of the spire scaffold may have occurred at any point within this range of dates, or very shortly after. These timbers could not have been replaced without major dismantling of the frame above; hence, it is likely that the date range is applicable to the entire spire scaffold. In light of this, it would have been virtually impossible for the frame to have existed in the 1320s when the stone spire itself was most likely constructed, disproving a currently proposed theory. Moreover, the empirical combined felling date range does not rule out another existing school of thought that the spire scaffold was erected in response to the Great Wind of 1362 to strengthen the damaged spire. Importantly, however, it does not provide definitive proof, and the refined OxCal felling date range of these timbers indicates that the spire scaffold may have instead been erected in the decade prior to the hurricane of 1362.

A further three timbers replaced or introduced by Francis Price have all produced precise felling dates of spring 1737, confirming a documented repair campaign in the 18th century.

Of the seven 14th century samples dated using isotopic dendrochronology, six were unable to be dated using ring-width dendrochronology due to the timbers being composed of few, complacent juvenile growth rings. This study has thus demonstrated the importance of revisiting contested sites, where previously unsuccessfully dated timbers may undergo further analysis with newly developed techniques such as stable oxygen isotopic dendrochronology to provide new scientific evidence, or to strengthen the existing scientific evidence with which to inform continued or future debate.

Acknowledgements

This work was supported by UKRI Frontiers Grant UKRI EP/X025098/1, with additional support from UKRI Grants EP/X525637/1 and AH/X00354X/1 and Social Sciences and Humanities Research Council (Canada) Grant 895-2019-1015. We thank the QUERCUS project team for laboratory support. We are hugely grateful to Gary Price, Clerk of Works at Salisbury Cathedral, for allowing access to the building for sampling. We also extend many thanks to Nigel and Sarah Fradgley for generously providing accommodation and subsistence during our time in Salisbury for sampling. Funding for travel between Oxford and Swansea, travel within Swansea and accommodation in Swansea was provided by a Keble Association Grant. Additional funding for journeys between Oxford and the Oxford Dendrochronology Laboratory (Mapledurham) was provided by Keble College, University of Oxford. We would like to thank Dr. David Chivall and Diane Baker for their technical and administrative support regarding radiocarbon dating.

Funding

This work was supported by UK Research and Innovation (EP/X025098/1, EP/X525637/1, AH/X00354X/1), the Social Sciences and Humanities Research Council of Canada (895-2019-1015), The Keble Association Icw Oxford University and Keble College, University of Oxford.

Data Availability Statement

The data that supports the findings of this study are available in the supplementary material of this article.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** Supporting Information.