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Oxygen isotope dendrochronology of Llwyn Celyn; One of the oldest houses in Wales

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ABSTRACT

We report the application of oxygen isotope dendrochronology to date a high-status and remarkably unaltered late medieval hall house on the eastern border of South Wales. The oak timbers have either short and complacent ring series, or very strong growth disturbance, and none were suitable for ring-width dendrochronology. By using stable oxygen isotopes from the latewood cellulose, rather than ring widths, it was possible to cross-match and date all 14 timber samples and to provide felling dates related to several phases of building. The hall and solar cross-wing were constructed shortly after 1420CE, which is remarkably early. The house was upgraded using timbers felled in the winter of 1695/6CE by ceiling over of the hall and inserting a chimney. A separate small domestic building was added at the same time and the addition of the kitchen is likely to be contemporaneous. A substantial beast house was added a few years before the house was refurbished, emphasising the importance of cattle as the main source of wealth. A small barn with timbers felled in spring 1843 CE was added later. Llwyn Celyn is one of the most important domestic buildings in Wales, but without the new approach none of the phases of its evolution could have been dated precisely. Oxygen isotope dendrochronology has enormous potential for dating timbers that have small numbers of rings and/or show severe growth disturbance and it works well in regions where tree growth is not strongly constrained by climate. The research was generously supported by the Leverhulme Trust, Natural Environment Research Council, Landmark Trust and the UK National Lottery Heritage Fund.

1. Introduction

Llwyn Celyn, in Cwmyoy (Fig. 1), close to the eastern border of South Wales (51.83N, 2.98W), is a remarkably complete and continuously occupied mediaeval house, of high status, that has survived almost unchanged since the late 17th century (Stanford, 2018a). It originally comprised a three-bay hall with central hearth, open to the ornate roof, with service rooms at the lower end and a two-storey solar wing at the high end. The high status is indicated by a decorative spere truss providing a ceremonial entry to the hall, and framing a view of beautifully carved oak door heads leading to the pantry and buttery (Fig. 2). The oak door head leading to the lower rooms of the solar wing is decorated with blank shields and an arched stone doorway may have led to an intramural stair to the upper floor. A fixed bench that served the high table is still *in situ*, with evidence for a dais canopy above. As with almost all medieval hall houses (Suggett, 2005; Alcock and Miles, 2013) a central chimney was added much later, when the hall was ceiled over and a rear kitchen added. There is a detached 'cider house' in the yard behind the kitchen which may be contemporary. The buildings surrounding the house include a substantial 'beast house', for over-wintering cattle, and a large threshing barn and later lower barn that were joined together by a fragmentary and enigmatic 'linking structure' that retained evidence of a domestic fireplace.

Llwyn Celyn was recognized as important in the mid-20th century (Fox and Raglan, 1951: 82-4), but its condition deteriorated and by the late 20th century it was critically endangered and in danger of collapse, with water entering through the roof and coursing through the building from the fields above. Temporary scaffolding was erected to protect the

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Fig. 1. Location of Llwyn Celyn at the entrance to the Honddu Valley. The hall house (A) and solar cross-wing (B) with beast house (C), lower barn (D), the enigmatic linking structure with fireplace (E) and the substantial threshing barn (F), now used as a community centre. Reproduced with permission of the Landmark Trust.

Fig. 2. Internal views of Llwyn Celyn following restoration. Top left: cross passage with ornately carved door heads to the service rooms. The wall on the right is the back of the inserted chimney. Top right: the hall with inserted fireplace and ceiling. The mantel beam over the fireplace yielded sample 9 and the beam in the top foreground sample 8. Bottom left: the back kitchen. Lower right: the ornate soot-blackened roof timbers, with curved wind-braces. The overhang to the left represents the remains of the dais canopy. Reproduced with permission of the Landmark Trust.

roof timbers, and eventually the property was purchased by the Landmark Trust who have renovated it, at great cost, with assistance from the National Lottery Fund and many other donors (Stanford, 2018a). It is now returned to splendour and once again dominates the entrance to the Honddu valley.

Despite several assessments, it was clear that it would not be possible to date any of the building phases at Llwyn Celyn using ring widths. The hall and solar were constructed from large but fast-grown timbers, with wide and generally complacent rings (Fig. 3). Elsewhere in the house and outbuildings there are a few timbers with larger numbers of rings, but most later phases show very strong growth disturbance, presumably due to woodland management (possibly pollarding), and are unsuitable for standard dendrochronology.

The rescue of Llwyn Celyn from dereliction coincided with the development of a new approach to dendrochronology, based on the chemistry of tree rings rather than their width, (Loader et al., 2019), and the results reported here represent the first attempt to date several building phases, of uncertain age, using the new method.

Oxygen isotope dendrochronology works in essentially the same way as traditional dendrochronology (Wigley et al., 1987; English Heritage, 1998; Alcock, 2017), by pattern-matching a time-series of

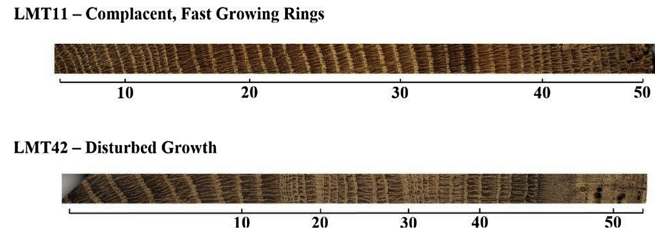

Fig. 3. Examples of the challenging nature of the samples. Wide and complacent rings provide sufficient latewood for isotopic analysis, but the very thin rings caused by disturbed growth do not, leaving gaps in the isotopic series.

measurements from a sample of unknown age against other time-series that have already been firmly dated. Rather than measuring the ring widths, the new method uses the ratio of heavy to light stable oxygen isotopes (^{18}O to ^{16}O). The signal is derived from the oxygen isotope ratios in summer precipitation, which vary from year to year in response to different air pressure patterns and the amount of summer rainfall (Trouet et al., 2018; Dong et al., 2013; Young et al., 2015; Darling and Talbot, 2003). Dry summers give much higher values than wet summers and the results are expressed in units of per mille using the delta notation relative to a standard (δ^{18}O‰ VSMOW).

The advantage of the new method is that the trees record the oxygen isotope signal irrespective of whether they are growing under any environmental stress, and the common signal is very strong between trees, so there is a high signal to noise ratio. The common climate signal in oxygen isotope ratios of UK oaks appears to be as strong as that in conifers growing under extreme environmental stress at the northern timberline of Europe (Young et al., 2015). This means that it is possible to pattern-match using far fewer rings than is the case for ring widths (Loader et al., 2019), making it an ideal method for short and complacent ring sequences, such as those used in the first phase of building at Llwyn Celyn and in many vernacular buildings across the UK. The potential for dating ring sequences that are not suitable for standard dendrochronology because of severe growth disturbance, as is the case for the timbers relating to the insertion of a chimney and ceiling over of the hall, has not previously been assessed.

2. Methods

A total of 42 core samples were taken from the house and outbuildings, but all failed to date using standard dendrochronology. A subset of 14 was therefore chosen for isotopic analysis (Table 1). Two short samples relate to the original hall-house structure: one each from the hall (3) and solar (11), both with complete sapwood. The insertion of the fireplace and ceiling over of the hall is targeted by the mantel beam (9), and a ceiling beam, with complete sapwood, that bears above it (8). Two samples, neither with complete sapwood, come from the added back kitchen, which is likely to be contemporary with the ceiling of the hall. Three samples come from the 'beast house', two from the fragmentary and enigmatic 'linking structure' between the lower barn and large threshing barn and three from the 'lower barn', which clearly post-dates the other phases. The cider house was not accessible at the time of sampling and suitable original timbers could not be found in the large threshing barn.

The new approach of stable isotope dendrochronology is described in detail by Loader et al. (2019). Samples to be dated first need to be ring-counted, as for standard dendrochronology and then each ring is separated and sliced into thin slivers under the microscope into early-wood and late-wood sections, of which only the late-wood is processed further. A series of chemical steps (Loader et al., 1997) isolates the α-cellulose that forms the cell walls and samples are homogenized using an ultrasonic probe, to ensure the fibres are well mixed. After freeze-drying, samples are weighed into small silver cups and pyrolised to produce carbon monoxide (Young et al., 2011; Woodley et al., 2012).

Table 1
Location of the samples used for isotopic analysis. The number of rings includes partial rings if there is latewood, with the number of rings used for isotopic analysis in brackets, minus any that could not be dissected. Number of sapwood rings (sw), noting if they are complete to the bark edge (C).

Sample	Location	Rings	Comments
3	Hall Range: outer- room joist	57 (57), sw17C	Complacent
11	Cross-wing (Solar): principal rafter	50 (50), sw16C	Complacent
8	Hall ceiling: beam	66 (51), sw24C	Disturbed growth
9	Hall: mantel beam	120? (96-22), sw25C	Pollarding?
5	Kitchen: half beam	62 (55), sw1	
13	Kitchen: beam	79 (79), sw0	
21	Beast house: beam	92 (78-5), sw18C	Narrow section, 5 ring gap
22	Beast house: tie beam,	38(33), sw11C	
23	Beast house: beam,	84 (69), sw26C	
41	Linking: purlin	67 (63-24)' sw11C	Very narrow, 24 ring gap
42	Linking: purlin	55 (47-5), sw11C	Gaps of 3 and 2 rings.
31	Lower barn: principal rafter	46 (43), sw13	Sampled ex situ, outer surface damaged
34	Lower barn: principal rafter	44 (40), sw11	Sampled ex situ, outer surface damaged
35	Lower barn: tie beam	53 (53), sw14C	

The isotope ratios are measured using an isotope ratio mass spectrometer (McCarroll and Loader, 2004).

The cutting of the rings is delicate, skilled work and there is a limit to the size of rings that can be dissected manually under magnification, so that very thin rings cannot normally be used when prepared in this way. Since ring widths tend to decline as trees age, it is often only possible to measure isotopically the inner part of the tree, so that the number of rings used for isotope analysis can be many fewer than are available for ring width measurement (Table 1). Also, it is imperative that only the late-wood is incorporated in the samples, because early-wood in oak forms mainly before the leaves open and must thus rely on stored photosynthates from previous years (Richardson et al., 2013; Kimak and Leuenberger, 2015; McCarroll et al., 2017). This is an important constraint because when oaks are stressed they tend to produce only early-wood, which contains the large vessels necessary to maintain efficient water transport, with little or no late-wood. Pollarding, in particular, tends to produce recurrent groups of very thin rings with little or no latewood (Haneca et al., 2009), meaning that isotope series from such disturbed timbers tend to have gaps, where isotope ratios cannot be measured.

The isotope time-series from undated samples are compared with all possible positions of full overlap with a master chronology (1200CE to 2000CE) compiled using oak trees and timbers, of known age (Loader et al., 2019). Stable oxygen isotopes in tree rings tend to be near normally distributed, with very weak autocorrelation, so pre-treatment of sample and master is restricted to a simple nine-year rectangular filter with indices derived by subtraction. We do not use the more common Baillie-Pilcher filter (Baillie and Pilcher, 1973), because it was designed for ring-width data, which tend to be strongly skewed and have very high positive autocorrelation, and applying such a filter to near normally distributed isotope data results in serious distortion and inflation of *t*-values (Loader et al., 2019). The ends of the isotope series are mirrored by four rings, to ensure all rings are included by the filter, and any gaps, due to sample loss, absence of latewood or rings that are too narrow to cut, are ignored (rather than filled with average values). Juvenile effects, which can be prolonged in high latitude conifers (Young et al., 2011) are limited to the first five rings in the oxygen isotopes of UK oaks (Duffy et al., 2017, 2019). Student's t-values are calculated using degrees of freedom that are corrected for both autocorrelation, irrespective of sign, and for the effect of filtering (1/9th of the sample size), so that they conform to a student's *t*-distribution. These can be converted into one-tail probabilities of error (expressed as 1/p for convenience) which are harshly corrected for multiple testing using the 'Bonferroni' method of multiplying the probability by the number of possible matches (McCarroll, 2016). The ratio of probabilities for the first and second highest matches provides an 'isolation factor'. Dates are only considered for acceptance when they yield the strongest match against the full master chronology, have a corrected probability of at least one in a hundred, and an isolation factor of at least 10.

Cross-matching between samples is achieved using the same approach, with the number of possible matches determined by setting a minimum size of overlap. The default value for isotope data that have been pre-treated using a nine-year rectangular filter is 35, ensuring about 25 degrees of freedom remain. For very short samples, or samples with large gaps, it is necessary to reduce the minimum overlap. Student's *t*-values, corrected one-tail probabilities and the isolation factor are reported as well as the highest correlation coefficient, offset in ring number and size of overlap.

3. Results

The individual dating results (Table 2) suggest that the samples fall into three groups. Samples 3 and 11, from the hall and solar, give highest correlations in the 15th century. The three timbers from the lower barn give clear dates in the 19th century. The remaining nine samples, from the ceiling of the hall, fireplace, kitchen, beast house and linking structure all fail to date unequivocally but give strong matches

Table 2
Dating results against the Central England master chronology of Loader et al. (2019). Number of rings measured isotopically (n), corrected degrees of freedom (df), highest Pearson's correlation coefficient (r-value) and Students *t*-value, probability corrected for multiple testing (1/p), dates for the first and second strongest matches and the ratio of probabilities for those dates, providing an isolation factor (IF). Underscored dates pass the threshold criteria.

Sample	n	df	r-value	*t*-value	1/p	First	Second	IF ratio
3	57	48	0.564	4.7	136	**1420**	1977	239
11	50	41	0.550	4.2	20	1418	1623	49
Mean	50	41	0.704	6.3	> 19k	**1418**	1826	> 1000
5	55	46	0.527	4.2	23	1660	1470	12
8	51	40	0.508	3.7	5	1680	1572	7
9	74	63	0.361	3.1	1	1941	1283	2
13	79	67	0.403	3.6	5	1644	1989	2
21	73	61	0.448	3.9	12	1672	1400	20
22	33	23	0.603	3.6	2	1682	1848	2
23	69	59	0.474	4.1	24	1952	1324	14
41	39	30	0.539	3.5	2	1689	1381	2
42	42	34	0.613	4.5	37	1687	1914	11
Step 2	124	104	0.596	7.6	> 1M	**1689**	1674	> 1000
Phase 2	124	104	0.605	7.7	> 1M	**1689**	1674	> 1000
35	52	42	0.685	6.1	9372	**1842**	1471	> 1000
34	40	33	0.826	8.4	> 1M	**1838**	1364	> 1000
31	43	36	0.698	5.8	2321	**1834**	1243	> 1000

Table 3
Cross-matching results showing statistically significant matches (corrected 1/p ≥ 20) where 1/p is < 100 (x), between 100 and 1000 (**XX**) and over 1000 (**XXX**).

	11	5	8	9	13	21	22	23	41	42	31	34	35
3	x	–	–	x	–	–	–	–	–	–	–	–	–
	11	–	–	–	–	–	–	–	–	x	–	–	–
		5	–	x	–	**XX**	–	x	–	–	–	–	–
			8	–	–	**XX**	–	–	**XXX**	**XX**	–	–	–
				9	x	x	–	–	–	–	–	–	–
					13	–	–	**XX**		–	–	–	–
						21	–	**XXX**	–	–	–	–	–
							22	–	–	–	–	–	–
								23	–	–	–	–	–
									41	–	–	–	–
										42	–	–	–
											31	**XXX**	**XXX**
												34	**XXX**

in the 17th century. Seven samples yield the highest match in the 17th century and for the other two a 17th century date is ranked third.

When the timbers are cross-matched (Table 3), the strongest matches confirm the three groupings. Timbers 3 and 11 do not cross-match strongly and consistently with any of the others, though they do match significantly with each other. The three timbers from the lower barn cross-match strongly together, but not with any others. The 9 timbers from phase two show enough very strong cross-matches to allow a site chronology to be constructed.

The two samples that date the first phase of building are short series with broad and complacent rings. The best match for sample 3 gives a final ring date of 1420CE and passes the dating thresholds with a small margin (Table 2). If the five juvenile rings, closest to the pith, are removed the match with the master at the same date is stronger ($n = 52$, $r = 0.68$, $t = 6.1$, $1/p = > 8k$, $IF > 1000$). Sample 11 gives a best match at 1418CE, suggesting a -2 year offset from sample 3, but does not pass the thresholds. Given a minimum overlap of 35 years, there are 38 possible cross-match positions for these two samples and the strongest also gives an offset of -2 years, which is statistically significant, and consistent with the dating results.

Given the available evidence, the bark-edge date of 1418CE for timber 11 from the solar wing is very likely to be correct. The evidence of the carpentry suggests that the main hall and solar wing are contemporaneous and a difference in felling age of two years is not unusual for timber that is worked green. The cross-match between the two timbers is consistent with the dating results, in suggesting a two-year offset, justifying combining the two isotope series (Fig. 4). When the isotope ratios of the two trees are combined, by taking the simple average of the filtered ratios over the 50 years of overlap, the date of

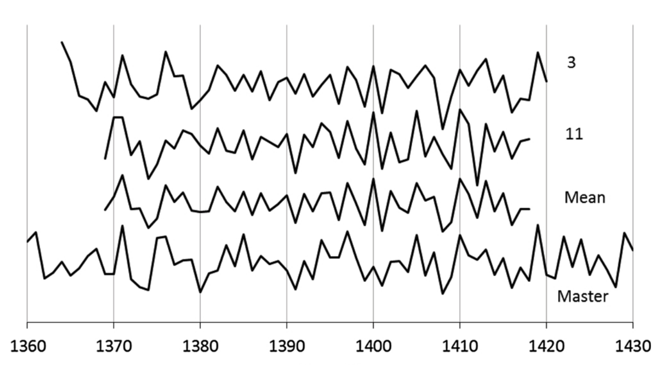

Fig. 4. The two phase-one timbers aligned with a two-year offset, averaged and compared with a section of the Central England master chronology. All data are indices derived by subtraction from a 9 yr rectangular filter.

1418CE for the last ring of sample 11 is unequivocal, with a probability of error of less than one in 19,000 and a best match more than one thousand times more likely than any other (Table 2, Fig. 5).

Given the importance of Llwyn Celyn, and the novelty of oxygen isotope dendrochronology, the dates for samples 3 and 11 were checked using radiocarbon dating. Four samples of latewood cellulose were submitted to the Oxford Radiocarbon Accelerator Unit (ORAU). From each core a ^{14}C sample early in the sequence and another towards the bark edge allows OxCal modelling, which uses the number of rings between the samples to refine the combined dating result. By assuming that the isotope dates are correct it was possible to consult the radiocarbon calibration curve and choose rings that would maximise the effectiveness of the "wiggle matching" approach and provide dates with unusually high precision. For sample lmt3 to reach the required sample size material was pooled from years 1377–1379 and 1416–1419 and for lmt11 1369–1371 and 1416-1418. Calculating the relative contributions of each year by mass the targets for the radiocarbon dating of lmt3 are 1378 and 1417 and for lmt11 1370 and 1417. The resulting radiocarbon dates were combined using a wiggle-match approach and the position of best fit with the calibration curve (95.4 % probability) was 1407–1428 AD. The combined data agreed perfectly with the sampled years (Agreement $A_{comb} = 161.8$ % $n = 4$), confirming that the felling dates for timbers 3 and 11 are 1420CE and 1418CE.

Since none of the timbers tentatively assigned to phase-two (on the basis of sampling locations, strong matches with the master chronology and on the cross-matching results) gives an unequivocal date individually, it is necessary to combine them on the basis of the cross-matching results.

Many pairings return no strong match (Table 3), but given the short series, and presence of gaps, that is not unexpected. However, even ignoring matches with a corrected probability of error of less than one in 100, there are still six very strong matches that allow 7 of the timbers to be combined (Table 4). The strongest link is between samples 21 and 23, with no offset and a probability of error of less than one 600,000 and the weakest is between samples 8 and 21, which still has a probability of error of one in 180 dates.

Samples 9 and 22 do not cross-match strongly enough with the other individual series to be included. However, when the other 7 timbers are aligned and the indexed values are averaged they give a series of 124 years (Fig. 6) which yields an unequivocal date for the last ring of sample 41 of 1689CE ('step 2' in Table 2). The probability of error is less than one in a million. When matched against this 'step 2' chronology sample 22, with just 33 rings, gives an end date of 1682CE ($1/p = 138$, $IF = 158$).

The mantel beam (sample 9) is the most challenging of all the timbers. It has several sections with very narrow rings, presumably due to pollarding, and even counting the rings in these bands is difficult. The isotope data fall into five sections, separated by the pollarding events. Taking just the first four sections (Fig. 6), with 54 measured values, the cross-match with the 'step 2' chronology clearly places the last ring at 1646CE, with a corrected probability of error of less than one in four thousand and an isolation factor of more than 100. This section of the core can be considered as dated, but to assign a felling date the rest of the ring count must be added. In the first count the next pollarding event was assigned 6 very narrow rings, and if that is accepted and the next set of 20 isotope values are added to the time-series, the lower sections remain in the same place but the overall match is weakened ($r = 0.520$, $df = 62$, $t = 4.8$, $1/p = 1715$) and visual inspection suggests that the final section may be displaced by one year. Taking just the last 20 years, the correlation with the relevant section of the 'step 2' chronology (using both Pearson's r and Spearman rho), assuming 6 missing values in the gap, is very weak and not statistically significant ($r = 0.23$, $p = 0.16$, $rho = 0.07$, $p = 0.39$). However, when one ring is added to the count of missing rings the correlation is statistically significant ($r = 0.43$, $p = 0.03$, $rho = 0.49$, $p = 0.01$). Given the difficulty of the sample a counting error in the

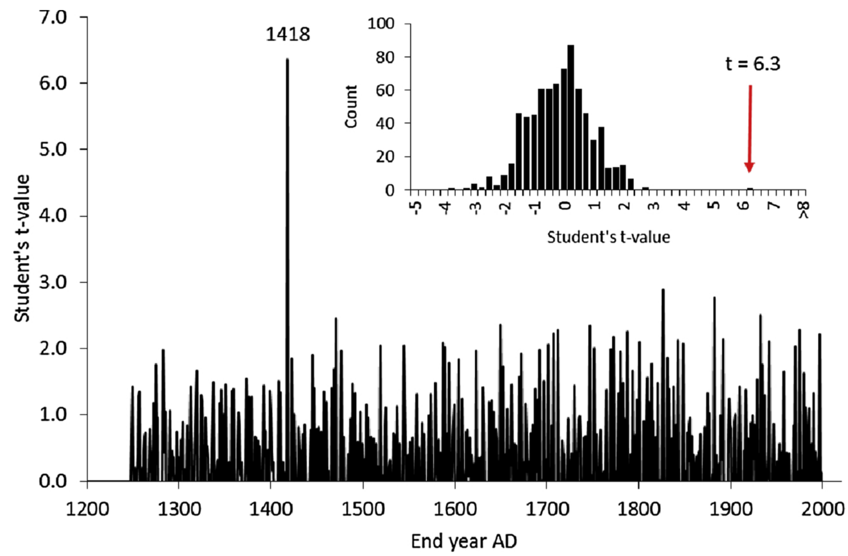

Fig. 5. Dating results for the combined phase-one timbers. Main graph shows Student's t-values for all possible matches with complete overlap and inset shows the distribution of Student's t-values.

Table 4
Strongest cross-matches (1/p > 100) for phase two. The offset (os), of sample B relative to A, for the highest correlation (Pearson's r) given a minimum overlap (w). The Student's *t*-value is calculated after correcting degrees of freedom (df) for autocorrelation and filtering and the one-tail probability, expressed as 1/p, is 'Bonferroni' corrected according to the number of possible match positions (k). The isolation factor (IF) is the ratio of probabilities for the first and second strongest matches.

A	B	os	r	n	df	*t*	k	1/p	IF	w
5	21	12	0.550	50	42	4.27	59	312	194	35
8	21	−8	0.603	38	31	4.21	55	180	152	35
8	41	9	0.819	27	20	6.39	41	> 15k	> 1000	25
8	42	7	0.607	35	28	4.04	19	276	251	35
13	23	28	0.602	41	34	4.39	79	243	313	35
21	23	0	0.655	64	54	6.37	73	> 600k	> 1000	35

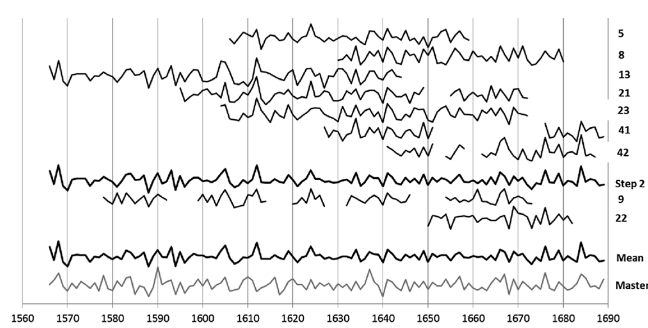

Fig. 6. Phase two timbers aligned by age. Step two is the mean of 7 timbers that cross match strongly with each other. The 'Mean' series also includes the final two timbers. All data are indices derived by subtraction from a nine-year rectangular filter.

final pollarded section is likely. If that section is assigned 7 rings, then the cross-match of the full sample 9 series with the step 2 chronology is much stronger, giving a probability of error of less than 16,000 to one and an isolation factor of more than 1000. The original count would give a felling date for this timber of 1694CE and the corrected ring count would give a felling date of 1695CE, which is the same as the felling date of sample 8, from a longitudinal beam that bears directly above the mantel. We consider the latter date to be most likely, based on the cross-matching results. In Tables 2 and 3 and in Fig. 6 we use the adjusted ring count.

When the final two timbers are added to the step-2 chronology, to give a 'phase 2 site master', that includes all nine timbers, the final ring of sample 41 still dates to 1689CE and the match with the master chronology (Fig. 7) is slightly strengthened (Student's t-value rises from 7.6–7.7).

As a final check, each timber in turn was removed from the 'phase-2 site master' and compared individually with the mean of the remaining timbers. When comparing short individual timbers with a 124-year long version of the site master there are many possible positions for a match ('k' in Table 5), so the Bonferroni correction to the probabilities is strong. Nevertheless all samples show a very strong match at a single position. Even samples 22 and 41, with just 33 and 37 measured isotope values, cross-match with the mean of the remaining series very strongly, with probabilities of error of less than one in a hundred (1/p = 106 and 188). It is notable that for seven of the phase-2 timbers the final end date is the same as the original best match with the master chronology (Table 2). For samples 9 and 23 the correct date was ranked third.

The three samples from the lower barn all give unequivocal dates when compared individually with the master chronology (Table 2), with the shortest sequence (sample 34, 40 values) yielding the strongest match (t = 8.4, 1/p > 1 million). The cross-matching results (Table 3) confirm the offsets and when the index values are averaged (Fig. 8) the date of 1842CE for the final value of sample 35 is confirmed and Student's *t*-value rises to 9.0 (Fig. 9).

Despite the difficult nature of the samples, including short and complacent series and longer sequences with severe growth disturbance, it has been possible to assign firm dates to the last isotopically measured rings of all 14 samples. When the extra rings that were not analysed isotopically are added to the counts, and the number of sapwood rings, and presence or absence of the bark edge (Table 1) is taken into account, it is possible to assign firm dates to all of the structures and events that were targeted (Table 6).

The samples from a principal rafter in the cross-wing chamber (solar) and a joist in the south-east service room of the hall range, give clear felling dates of winter 1418/19CE and winter 1420/21CE respectively, confirming that they are broadly contemporaneous and that the main house was built in a single campaign. A timber from the subsequently inserted hall ceiling yields a felling date of winter 1695/

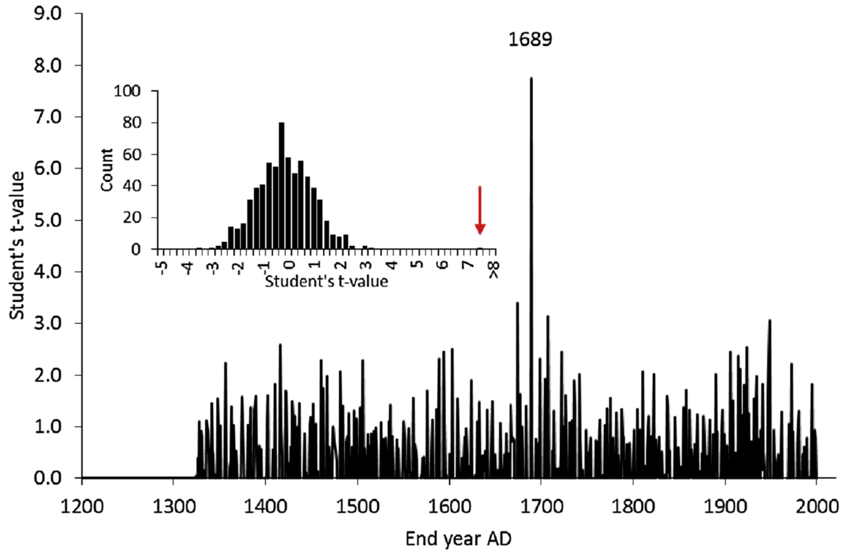

Fig. 7. Dating results for the phase two site chronology. Main graph shows Student's t-values for all possible matches with complete overlap and inset shows the distribution of Student's t-values.

Table 5
Cross correlation results for each timber compared with the aligned mean of the filtered values of the other 8 timbers from phase two. Number of measured rings (n), degrees of freedom (df), number of possible match positions (k) probability of error (as 1/p) and the isolation factor (IF), which is the ratio of probabilities for the best and second best match positions.

Sample	r-value	n	df	Student's *t*-value	k	1/p	IF	End date
5	0.580	55	46	4.83	110	1190	175	1660
8	0.605	51	41	4.86	106	1071	585	1680
9	0.569	74	62	5.45	133	> 16k	> 1000	1673
13	0.520	65	55	4.51	120	482	584	1644
21	0.608	73	61	5.98	128	> 123k	> 1000	1672
22	0.666	33	24	4.37	92	106	133	1682
23	0.619	69	59	6.05	124	> 148k	> 1000	1672
41	0.637	37	28	4.38	70	188	31	1689
42	0.605	42	35	4.49	92	294	661	1687

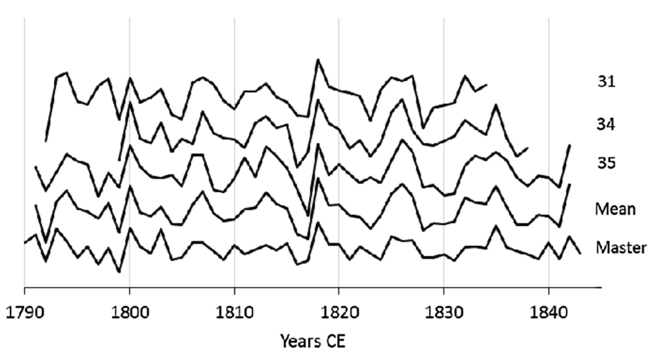

Fig. 8. Phase three timbers aligned by age, averaged and compared with a section of the master chronology. All data are indices derived by subtraction from a nine-year rectangular filter.

6CE and it bears directly above the mantel beam that has an identical likely felling date, albeit with an uncertainty of one year. The timbers from the enigmatic linking structure below the threshing barn give identical felling dates of winter 1695/6CE. None of the kitchen timbers had complete sapwood, so a precise felling date is not possible, but the date range estimate, based on the presence of a sapwood ring in sample 5, is consistent with the contention that the kitchen was inserted when the hall was ceiled over and the central hearth was no longer available for cooking. The beast house gives clear felling dates for all three timbers of winter 1688/9CE, pre-dating the renovation of the house by a few years. The lower barn was added much later, using timbers felled in 1843CE.

4. Discussion

The dating results, based on the new approach of oxygen isotope dendrochronology and confirmed by very precise radiocarbon dates, clearly demonstrate that the original high status hall house was built shortly after 1420CE rather than c1480CE as seemed plausible from the wider context, radically altering interpretation of the site. A 1420CE construction date is remarkably early for Wales, falling in a time when the economy of the region was still suffering from the aftermath of successive waves of plague in the 14th century and the catastrophic destruction that accompanied the revolt of Owain Glyndŵr. There is little evidence of building at this time and at first sight it is difficult to explain who would have had the resources to invest in such a grand house.

A possible explanation lies in the location of Llwyn Celyn on land that was owned by Llanthony priory. The priory owned substantial estates in present-day Monmouthshire and Herefordshire, including the upper part of the Honddu (Llanthony) valley where the priory was sited. The upper Honddu valley was a semi-autonomous part of the marcher lordship of Ewyas and was controlled by the priory. The construction of Llwyn Celyn on the southern edge of the valley may mark the prior's reassertion of authority in the area, although the priory itself appears to have been in disarray and suffering from poor administration at this date. It may have served as lodgings for the prior or as the residence of a secular official; it may indeed have had both functions. Certainly hall houses of this type - having a large hall with spere-posts at the entry and a solar cross-wing - were exceptional and were houses of lordship status (Suggett, 2005: 37–56).

By the later 17th century most Welsh hall houses had already been modernised to include an upper floor, adding chimneys and often an adjoining kitchen (Suggett, 2005). Within the Honddu Valley, high status two-storey farmhouses with integral chimneystacks were being built from at least 1600CE. The renovation of Llwyn Celyn around 1696CE was unusually late, even overdue, but it came at a time when the local economy was thriving. Cattle farming was profitable and long leases with low rents meant that much of the profit stayed with the

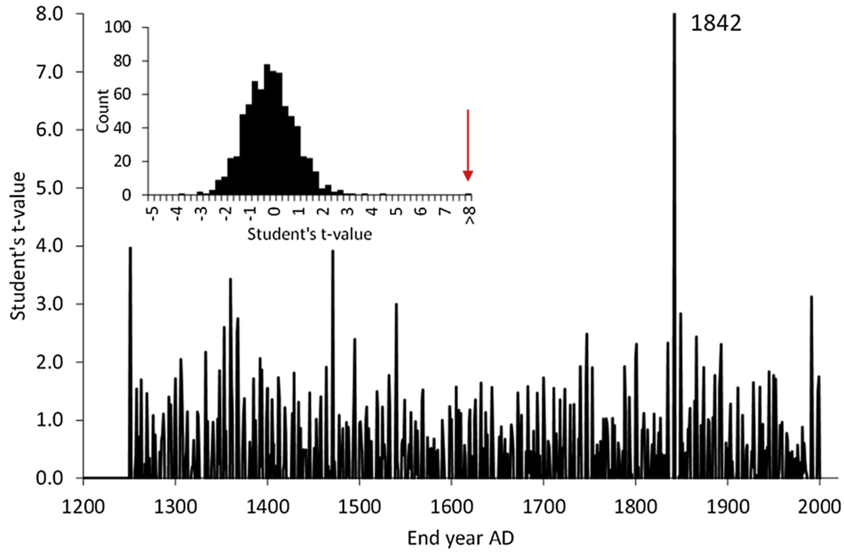

Fig. 9. Dating results for Phase 3. Main graph shows Student's t-values for all possible matches with complete overlap and inset shows the distribution of Student's t-values.

Table 6
Felling dates obtained from oxygen isotope analysis of timbers from Llwyn Celyn.

Sample	Location	Felling dates
First phase of building		
3	Hall Range: south-east service room joist	Winter 1420/21
11	Cross-wing (Solar): principal rafter	Winter 1418/19
Construction of the 'beast house'		
21	Beast house: beam above door	Winter 1688/9
22	Beast house: tie beam, lower end	Winter 1688/9
23	Beast house: beam, lower end	Winter 1688/9
Ceiling of hall and insertion of chimney		
8	Hall ceiling: longitudinal beam	Winter 1695/6
9	Hall: mantel beam to inserted fireplace	Winter 1695/6 or 1694/5
Addition of the back kitchen		
5	Kitchen: half beam	1678-1708
13	Kitchen: longitudinal beam	After 1655
Enigmatic 'linking structure'		
41	Linking structure, purlin	Winter 1695/6
42	Linking structure, purlin	Winter 1695/6
Addition of the lower barn		
31	Lower barn: principal rafter	1838-65
34	Lower barn: principal rafter	*circa* 1843
35	Lower barn: tie beam	Spring 1843

tenants, rather than the landlords (Suggett, 2005). The timing of the improvements at Llwyn Celyn would certainly have been related to the terms of the copyhold lease under which it was held in the successor (post-Reformation) manor of Cwmyoy. Llwyn Celyn was held by a lease for lives (usually the lives of father, son and grandson). There was a high entry fine but afterwards the rent was low. Llwyn Celyn was assigned to William Watkins in 1656 and the family held it for three more generations until 1762 (Austin, 2014).

After over thirty years farming, and with the family succession to the farm assured, William Watkins had accumulated sufficient capital to systematically improve the house and farm buildings. His first priority was a new and capacious beast-house for the profitable cattle, which was built from timber felled in 1688-9. Improvements to the house followed in 1695-6, when a much-needed hall fireplace and ceiling were inserted during a severe decade of the 'little Ice Age'. Cooking was transferred to a new back kitchen and a service courtyard took shape on the north side of the house. At the same time, on the other (south) side of the house, across the yard, a subsidiary domestic range with large end fireplace was built. Parallels at other substantial farmsteads (Suggett, 2007) suggest that this was a dower-house, presumably intended for William Watkins' widow. William Watkins, his work done, was evidently thinking of his own mortality.

The placing of this link building also has implications for the construction date of the fine stone threshing barn it abuts, today much altered and with no timbers suitable for dendrochronology. This barn was assumed to date to the 18th century (a near identical one on a nearby farm is dated 1704). However, from their junction, it is clear that the link building postdates the lower end of the barn against which it was built. Thanks to the isotope dating, we now know that the barn (or part of it) was originally constructed before 1695/6 (the date of the link) but it was much altered subsequently.

Llwyn Celyn, as we know it today, had therefore taken shape by 1700. In 1762 the terms of the lease required the farm to be surrendered to the Lord of the Manor. After this the conditions for tenant farmers were much less favourable, with higher rents that were paid by the year. It was not in the tenants' interest to invest in buildings and it is probably for this reason that so many medieval and sub-medieval houses survive in the area. The Stable and 'Lower Barn', partly a cart-shed, built from timber felled in 1843, may therefore have been improvements made by the landlord.

Llwyn Celyn continued as a tenant farm through various changes in the estate ownership, until it was sold to the parents of its last residents in 1958. From around 1980, the farm buildings entered a downward spiral of dereliction and neglect. By 2004, when the Landmark Trust was first contacted about Llwyn Celyn, the main house having been swathed in emergency scaffolding for a decade, water was running through its ground floor and the roof was leaking.

Even though Llwyn Celyn is listed Grade I (the UK's highest category for heritage protection), the Landmark Trust's commitment to save it through its restoration was something of an act of faith at the beginning. It took a campaign of some five years to resolve ownership issues and raise the £4.2 million required to restore the house, and to transform the threshing barn into a community centre and the beast house into an interpretation room. The oxygen isotope research, which came relatively late in the project, transformed understanding by placing Llwyn Celyn's original construction 60 years earlier than the earliest estimate, and allowing its later adaptation in the 1690s to be married with the documentary evidence. It provided final vindication of the importance of this site to Welsh vernacular architecture and of the effort required to save it.

5. Conclusions

Llwyn Celyn has been confirmed as one of the oldest surviving houses in Wales, and is an important part of the historical and cultural heritage of the nation. However, without the new approach of stable isotope dendrochronology, all the phases of its evolution would have remained undated. Traditional dendrochronology failed because the ring width sequences, in all samples, were either too short and complacent, because oak trees grow so happily in the moist mild climate of Wales, or were too disturbed because of the intense management of the local oak forests.

Although the new approach is in its infancy, and currently relies on a single master chronology based on only ten-sample replication, with all of the constituent trees and timbers sourced from central southern England, well to the east of the Welsh border, it was possible to provide dates for every timber and felling dates as a guide to dating all of the structures and events that were targeted. The constraints imposed by the need to dissect sufficient latewood for analysis means that the number of rings that could be measured isotopically was often far fewer than were available for ring width measurement. However, the signal to noise ratio in the oxygen isotopes is much stronger than that in ring widths, so that even very short sequences can provide very secure dates. Two timbers with less than 45 rings dated directly with the master chronology and others with as few as 33 rings could be cross-matched with a high degree of confidence and combined into chronologies that dated well.

The new method has not previously been applied to timbers that show extreme growth disturbance, and such timbers are generally not dateable using standard dendrochronology. Using oxygen isotope dendrochronology such timbers are challenging because the groups of very narrow rings cannot be used, leaving isotope series with gaps and in the worst cases short sections of isotope data separated by several gaps. Using time-series with gaps is inconvenient, but their presence does not actually violate the assumptions of the correlation analysis on which the dating is based, and such series can still be cross-matched and/or compared with a master chronology.

In contrast to traditional dendrochronology, where it is difficult to define the probability of an erroneous date (Fowler and Bridge, 2017), the favourable properties of stable isotope data allow the calculation of Student's *t*-values that, after careful correction of the degrees of freedom, conform to a Student's *t*-distribution, allowing probabilities of error to be calculated (Loader et al., 2019). These are the probabilities that a correlation coefficient as high as that observed could have occurred by chance, given the usual assumptions of correlation analysis. The probabilities are harshly corrected for the multiple testing involved in comparing each isotope series with every possible position of full overlap over the entire master chronology, 1200 to 2000CE. The threshold, below which a date is not considered for acceptance, is a corrected probability of error of one in 100. The probability associated with the highest correlation must also be at least an order of magnitude less likely to have arisen by chance than the next highest match. The difficult samples that were successfully dated at Llwyn Celyn suggest that the threshold criteria are not just robust but conservative. Of the 14 samples, only four passed the thresholds for acceptance when compared individually with the English master chronology, but 12 samples actually returned the correct date as the highest correlation.

In comparison with standard dendrochronology the work involved in dating a building like Llwyn Celyn, with several phases of construction, is very substantial. However, old buildings are a vitally important part of our heritage, and without firm dating their value is diminished. Without precise dating, Llwyn Celyn would of course have been recognized as a late medieval house that was probably upgraded in the 17th century (Fox and Raglan, 1951: 82-4; Smith, 1988: 617-9). With the new dates, however, we are able to place the building of the house within its true historical context. In this case the house is substantially earlier than expected (*c*. 1500 according to Fox and Raglan, 1951: 107) and it falls in a time of social and economic uncertainty. The reason for the building, the source of the wealth for its construction, and the status and identity of the original owner is all still a mystery, but with a firm date we now know exactly where to focus the historical investigations.

The later phases of building, in the late 17th and 19th centuries, fall in times when we have clear records of precisely who owned the house (Stanford, 2018b). The evidence allows us not just to assign the building work to a particular individual, but also to interpret the evolution of the house within the context of the economic and social conditions that prevailed.

Llwyn Celyn is a beautiful house, now fully restored to look much as it did in the late 1690s when the Watkins family ate the first loaf of bread baked in the new oven attached to their magnificent new fireplace, spread with butter from their own cows housed in their recently built cow-house and washed down with cider pressed in their own cider house. Those who rent this house, and thus ensure its future survival, can sit at the high end of the hall, perhaps on the very bench that the first master of the house sat on in the 1420s, or on the window seat in his bedroom and enjoy the same view. Or they can stroll up the valley to the little crooked church and visit the graves of the prosperous Watkins family, or down to the Skirrid Inn to enjoy a pint at the bar where Benjamin Davies likely celebrated the construction of his new barn in 1843CE. The dates that stable isotope dendrochronology has provided are not just numbers assigned to timbers, they provide a link to real people, with whom we share our history and that of the Welsh landscape.

Declaration of Competing Interests

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.

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