



High-precision dendro-¹⁴C dating of two cedar wood sequences from First Intermediate Period and Middle Kingdom Egypt and a small regional climate-related ¹⁴C divergence



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ABSTRACT

Cedar (*Cedrus* sp.) wood from two archaeological contexts in Egypt – (i) the First Intermediate Period coffin of Ipi-ha-ishutef, (ii) a funerary boat at the pyramid of Middle Kingdom king Senusret (or Sesostris or Senwosret) III – form floating tree-ring sequences. Since one of the sample sets had been mounted with Elmer's glue products in core-mounts for dendrochronological examination, we investigate whether pretreatment can remove this potential contaminant before ¹⁴C dating. We find that even in (unrealistic) cases of extensive glue contamination this can be largely/successfully removed – making it likely that the samples in this study, where, moreover, only wood samples without traces of glue were employed, can provide accurate ¹⁴C dates. Dendro-¹⁴C-wiggle-matching was then employed to provide precise calendar dates for the two tree-ring sequences. The last extant ring of the Ipi-ha-ishutef coffin lies ca. 2081–2064 BC (95.4% probability), supporting, but refining, its assumed date. In the case of the Senusret III boat, we find a temporary, small, but important offset within the period ca. 2200–1900 BC in contemporary ¹⁴C ages between the Levant and central and northern Europe. It is suggested this is likely a result of exaggeration of normal seasonal variations in the uptake of ¹⁴C and its latitudinal distribution caused by climate change in the 2200–1900 BC/4200–3900 Cal BP (y2k) interval. A date for the last extant ring of the Senusret III boat is probably around 1898/95–1879/76 BC (95.4% probability) – more consistent with a high Middle Kingdom Egyptian chronology.

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1. Introduction

The general model for radiocarbon (¹⁴C) analysis assumes that the mid latitudes of each hemisphere have an approximately

uniform contemporary ¹⁴C content – allowing use of a single general Northern or Southern Hemisphere ¹⁴C calibration curve. Previous studies have indicated that some regional mid-latitude intra-hemisphere tropospheric offsets in contemporary ¹⁴C ages may, however, occur temporally associated with periods of low solar magnetic activity and general cooling (Kromer et al., 2001). The topic of possible regional offsets in ¹⁴C levels has also received attention with regard to several locations over the past 20 years (e.g. McCormac et al., 1995; Damon, 1995; Stuiver and Braziunas, 1998; Sakamoto et al., 2003; Hua et al., 2004; Ozaki et al., 2007; Suzuki et al., 2010; Dee et al., 2010; Manning et al., 2010, 2012). But, despite circumstantial evidence (timing), no clear link with

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climate change has been established. We report analyses of two objects made of Cedar of Lebanon (*Cedrus libani*) from archaeological contexts in Egypt which we have closely dated via the dendro-¹⁴C-wiggle-matching of sets of tree-ring samples within the period ca. 2227–1949/40 BC (95.4% probability) – placing the last extant tree-rings for each object ca. 2081–2064 BC and 1898–1876 BC respectively. These calendar placements correlate well with the standard historical Egyptian chronology, and in one case provide support for a high Middle Kingdom chronology. Intriguingly, we also observe a small offset in the ¹⁴C data from ca. 2100 BC and changes in the $\delta^{13}\text{C}$ data that are potentially consistent with the effects of a rapid climate change to arid, cooler conditions during this time period as indicated across a wide range of regional climate proxies for the period ca. 2200–1900 BC or 4200–3900 BP (y2k) (e.g. Weiss et al., 1993; Staubwasser and Weiss, 2006: 380–383; Weiss et al., 2012: 185–187; Weiss, 2014; Salzer et al., 2014). These findings are relevant to the possible use of ¹⁴C as a regional climate tracer, and are of importance to archaeological chronologies employing ¹⁴C on samples from the east Mediterranean during such periods of climate change.

2. Materials and methods

2.1. Cedar wood from Egypt

- (i) Cedar wood coffin of Ipi-ha-ishutef. The material from the coffin of Ipi-ha-ishutef comprises 10 cores collected in May 1938 AD, drilled at the request of A.E. Douglass by the Oriental Institute, Chicago (EGY-3 to EGY-12, University of Arizona = CHI-3 to CHI-12 in the Cornell records). Correspondence between Douglass and OI director John A. Wilson regarding the specimens is on file at the University of Arizona, and includes the precise location of each core from the coffin (see Supplementary Figs. S1–S3). Subsequent research by J.A. Larson, the Oriental Museum Archivist, confirmed the coffin sampled as that of Ipi-ha-ishutef. This coffin is believed to have been recovered near the pyramid of King Teti at Saqqara; Ipi-ha-ishutef's title was "Scribe and Overseer of the Expedition [or Army]". The Oriental Institute Museum lists the following basic information on the coffin: First Intermediate Period, Dynasty 9–10, ca. 2213–2035 BC, Wood, carved and painted, 63.5 cm H, 202.0 cm W, Purchased in Cairo, 1923, OIM 12072 (see Mertz, 1964: plate facing p.97). To date it has not been fully published (a current project of one of us: KB). However, it has been included in studies on Middle Kingdom coffin typologies (Lapp, 1993: coffin Sq11; Willems, 1988: coffin Sq1Ch) and Middle Kingdom copies of the Pyramid Texts (Allen, 2006: coffin Sq1Ch). The dating of the Saqqara coffins is very loose due to the limited number of securely dated burials. Compounding this problem is the limited nature of published archaeological data. As a result, the burials at Saqqara have largely been dated by associated grave goods, along with various philological and art historical criteria. Unlike in Middle Egypt, observed typological developments in the Memphite area are more restricted. Two primary studies on Middle Kingdom coffins (cited above) have established broad typological groups, but chronological relationship(s) between them remain uncertain. As a result, the coffin is generally dated as late First Intermediate Period/early Middle Kingdom (Dynasty 11/early Dynasty 12), with the caveat that all of the dating in the Memphite area is fluid.

- (ii) A boat found at the pyramid complex of Senusret (or Sesostris/Senwosret) III (reign ca.1872–1853 BC: Kitchen, 2000, 1837–1819 BC: Hornung et al., 2006). In 1894 Jean-Jacques De Morgan discovered a series of small boats (or barques) at the pyramid complex of king Senusret III at Dahshur (De Morgan, 1895; see generally Ward, 2000: 83–102). The exact number of boats discovered by De Morgan and their precise location has been the subject of some debate, kindled by contradictions in his own reports (Creasman et al., 2010: 516–517). It is apparent, however, that the boats were found in two clusters, the first of which consisted of three burials just beyond the south temenos wall of the pyramid. The second group comprised up to another three vessels approximately 100 m farther to the south (Haldane, 1984a; Creasman et al., 2009). De Morgan excavated all three boats from the first group, two of which ended up in the Egyptian Museum, Cairo (identified as objects CG 4925 and 4926: Creasman, 2005, 2010a). A third boat found its way to Chicago's Field Museum of Natural History (material from this boat was employed by Libby as a source of 'known-age' material in his early ¹⁴C work: Arnold and Libby, 1949). Few records remain about the excavation of the remaining boats, although it is apparent that one was transported to the United States and purchased by philanthropist Andrew Carnegie for his eponymous Museum of Natural History in Pittsburgh (Haldane, 1984b; Patch and Haldane, 1990). The material comes from sampling by Peter Ian Kuniholm in 1988 from this boat (which was disassembled and in storage since 1975). In recent times, an American team has employed ground penetrating radar at Dahshur in the hope of finding the missing boat(s), assuming indeed it ever existed (Creasman et al., 2010).

The cedar wood in each case did not originate from (grow in) Egypt, where it is not native and growth conditions are not suitable. Finds in Egypt represent an early example of timber trade (Kuniholm et al., 2007; Creasman, 2014a). *C. libani* A. Rich occurs only in the northeast Mediterranean, and is found today principally in small areas in the Taurus Mountains of southern Turkey and in the coastal mountains of Cilicia (and a few other scattered areas of Turkey including in the Black Sea region: Boydak, 2003: 232 and refs., Fig. 2; Akkemik, 2003), Syria, and Lebanon, and a subspecies, *C. libani* subsp. *brevifolia* (Hook.f.) Meikle (also e.g. *C. libani* var. *brevifolia* Hook.f.), is found in a small area of western Cyprus (Hajar et al., 2010; Quézel and Médail, 2003). Strontium (Sr) analysis may offer a route to source finds of cedar wood between some of these areas (Rich et al., 2012); Sr analysis indicates a most likely origin for the Senusret III boat cedar timbers in Lebanon (Rich, 2013: 152–154).

Applying standard dendrochronological methods (Cook and Kairiukstis, 1990; Schweingruber, 1988), with crossdating and data quality checked using the program COFECHA (Holmes, 1983; Grissino-Mayer, 2001), a 151-year crossdated tree-ring sequence can tentatively be constructed in relative time from seven of the cedar cores from the Ipi-ha-ishutef coffin (CHI-3, 4, 5, 6, 7, 8 and 11). The one major uncertainty exists with the interval from relative ring 1081–1083 in the CHI-3 core as extant. Here it seems likely that 5 missing rings should be inserted (4 after original ring 1081 and one after original ring 1082). 'Missing rings' or rings which are valid indications of a single growth year but cannot be observed around the entire cross-section of the tree are a frequent occurrence for *C. libani* and especially problematic where the dendrochronological samples taken (as in our case) only represent a small part of the entire cross-section of the trunk. There is therefore reasonable justification that rings present in the original tree were

not present in the location the core was taken. The statistics for cross-dating are improved by the insertion of the rings (the series intercorrelation in COFECHA goes up from 0.543 and one B flag to 0.567 and no flags: see Table 1), as is the visual match for the growth pattern of the wood. We use this as the preferred chronology: Fig. 1. The chronology is by no means certain, but is reasonable given the evidence available.

A 337-year tree-ring sequence can tentatively be constructed from among the set of samples from the Pittsburgh boat, using eight samples (two with measurements on different sub-samples, PIT-6A and 6B, PIT-12A and 12C): Table 2 and Fig. 2a and b. Some of these samples exhibit problems typical of cedar, with irregular growth and a few locally absent rings. The measured ring sequence from PIT3A was truncated (tr) (first 29 rings excluded) and the beginning of PIT-12C was also truncated (first 61 rings excluded), and likely missing (locally absent) rings (mr) were added to PIT-12C, PIT-26A and PIT-27A. The PIT-6AB sample (combining measurements on PIT-6A and 6B) forms the core of the chronology crossdating with PIT-1A, 3A, 21A, 26A, and 27A and tentatively with 18A. The latest part of the chronology is represented by PIT-18A, which crossdates with PIT-12AC (and tentatively with PIT-6AB), which in turn crossdates with PIT-26A and 27A, and these with PIT-6AB. When sampled, possible bark/bark-edge was observed in the area where PIT-12 was drilled, however, the extant core (ending at relative ring 1292) does not include bark or sapwood. Thus, assuming the original observation was correct, it seems probable that a number of outermost rings were lost during coring.

Sample material for $\delta^{13}\text{C}$ and ^{14}C measurements was dissected using a steel blade under a stereo microscope to provide 11 decadal segments of CHI-3 (as indicated in Fig. 1) and 12 decadal samples, one 6-year sample and one 4-year sample of PIT-6B for the Oxford Radiocarbon Accelerator Unit (OxA), and 20 decadal samples and one 11-year sample of PIT-6A for the Vienna Environmental Research Accelerator (VERA) laboratory (as indicated in Fig. 2a). The samples are listed in Tables 3–5.

2.2. Elmer's Glue test

The core samples from the Pittsburgh boat, including PIT-6A and PIT-6B which were employed in analyses reported below, were kept in standard dendrochronological core-mounts. One drawback of this (standard) practice is that parts of the core were exposed to Elmer's Wood Glue™ or Elmer's Glue-All®, polyvinyl acetate adhesives. Previous analyses at ORAU had suggested such contamination was removed when a solvent extraction was

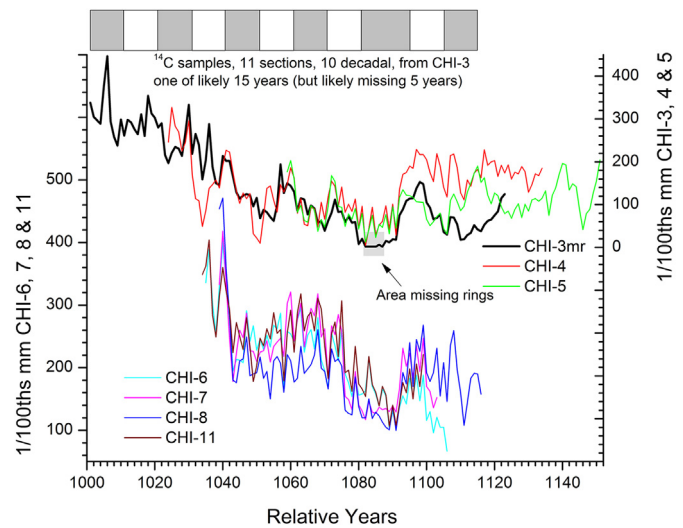


Fig. 1. Ring-width sequences for CHI-3mr (with 5 likely missing rings), 4, 5, 6, 7, 8 and 11 in 1/100ths of a mm in the proposed crossdated positions relative to each other (see Table 1). One group, CHI-6, 7, 8 and 11 appear likely to be from the same tree, and another group, CHI-4 and 5, are likely from another tree. The 10-year segments (and one likely 15-year segment – but missing 5 rings) dissected from CHI-3 for ^{14}C dating and $\delta^{13}\text{C}$ data are indicated: rings 1001–1010, 1011–1020, ..., 1106–1115 inclusive.

included prior to the standard aqueous pretreatment. Nonetheless, in order to ensure that this was indeed the case, two investigations against control series of known-age wood (from similar conifer species) were carried out as part of this project. At Oxford, known age (AD 1641–1650) *Pinus leukodermis* wood from northern Greece, some that had been liberally treated with Elmer's Wood Glue™, and some not, was also pretreated and dated in parallel with the boat core material: Table 6. In Vienna, samples from known age (AD 1640–1649) *Pinus nigra* from Çatacık in northwest Turkey – the same tree-rings used as a known age spot test in Manning et al., 2006: Fig.1 nos. 20–24) – treated with Elmer's Glue-All®, were analysed using different pretreatments (to establish the most effective pretreatment) and compared with the previous measurements on samples with no Elmer's Wood Glue™ or Elmer's Glue-All®: Table 7.

2.3. Laboratory procedures – Oxford Radiocarbon Accelerator Unit (ORAU) – OxA

Using a steel blade, about 20 mg was shaved from each of the samples in a transverse direction to ensure each of the rings was

Table 1

Crossdating statistics (*t* values and Pearson correlation coefficients from COFECHA: Holmes, 1983; version 6.06P, default settings) for the best matches for the tree-ring sequences comprising CHI-3, 4, 5, 6, 7, 8 and 11 (see Fig. 1) from the Ipi-ha-ishutef coffin: *t* values of ≥ 3.5 or correlation coefficients ≥ 0.32 , which potentially indicate crossdates, are shown. Where the best crossdate is for the proposed chronology but is less than 3.5/0.32, then this is also shown but with grey shading. The overall chronology is 151 years, and the series intercorrelation is good at 0.567, with no A or B flags in Cofecha. The values in parentheses for CHI-3 versus CHI-4, 5, 6, 7, 8 and 11 are without the inserted missing rings to CHI-3 – nv = no crossdate value in best 5 possibilities in Cofecha. Tree-ring data to be submitted to the International Tree-Ring Data Bank on publication.

	CHI-3mr							
	RY1001-1123							
CHI-4	<i>t</i> = 7.5 (5.3)	CHI-4						
	<i>r</i> = 0.61 (0.48)	RY1024-1134						
CHI-5	<i>t</i> = 4.2 (4.8)	<i>t</i> = 7.7	CHI-5					
	<i>r</i> = 0.47 (0.53)	<i>r</i> = 0.67	RY1059-1151					
CHI-6	<i>t</i> = 2.8 (nv)							
	<i>r</i> = 0.32 (nv)							
CHI-7	(nv)		<i>t</i> = 2.5					
	(nv)		<i>r</i> = 0.36					
CHI-8	<i>t</i> = 2.8 (nv)	<i>t</i> = 2.9	<i>t</i> = 2.3					
	<i>r</i> = 0.31 (nv)	<i>r</i> = 0.31	<i>r</i> = 0.30					
CHI-11	<i>t</i> = 2.2 (nv)							
	<i>r</i> = 0.27 (nv)							
			CHI-6					
			RY1035-1106					
			<i>t</i> = 6.6					
			<i>r</i> = 0.64					
			<i>t</i> = 8.1	CHI-7				
			<i>r</i> = 0.7	RY1039-1103				
			<i>t</i> = 10.7	<i>t</i> = 11.0				
			<i>r</i> = 0.8	<i>r</i> = 0.81	CHI-8			
				<i>t</i> = 5.6	RY1039-1116			
				<i>r</i> = 0.59	<i>t</i> = 6.4			
					<i>r</i> = 0.64			
						CHI-11		
						RY1034-1099		

Table 2
Crossdating statistics (t values and Pearson correlation coefficients from COFECHA: Holmes, 1983 – version 6.06P) for the best matches for 8 samples from the Pittsburgh boat. Best cross-dates with either/or t values of 3.5 or greater or correlation coefficients above 0.32 are shown (no other best cross-dates exist for the cross-dated chronologies). These values are the threshold values potentially indicative of a crossdate (COFECHA default settings). The overall chronology is 337 years, and the series intercorrelation is good at 0.584. Running COFECHA in default mode (50 year segments, lagged successively by 25 years), three segments are flagged as possible problems (first and last segments of PIT-12 and second last segment of PIT-26), but the above crossdates seem to represent the best solution evident given the extant wood. Tree-ring data to be submitted to the International Tree-Ring Data Bank on publication.

	PIT-6AB RY1001-1247								
PIT-1A	$t = 5.6$	PIT-1A							
	$r = 0.57$	RY970-1065							
PIT-3Atr	$t = 6.2$		PIT-3Atr						
	$r = 0.50$		RY1096-1212						
PIT-12AC	$t = 5.1$			PIT-12ACtr					
	$r = 0.4$			RY1108-1292					
PIT-18A	$t = 2.8$			$t = 4.4$	PIT-18A				
	$r = 0.35$			$r = 0.40$	RY1191-1306				
PIT-21A	$t = 7.0$	$t = 4.9$	$t = 5.8$			PIT-21A			
	$r = 0.51$	$r = 0.5$	$r = 0.66$			RY993-1140			
PIT-26Amr	$t = 8.6$		$t = 7.1$	$t = 4.3$		$t = 7.9$	PIT-26Amr		
	$r = 0.54$		$r = 0.55$	$r = 0.31$		$r = 0.68$	RY1066-1281		
PIT-27A	$t = 10.6$		$t = 8.3$	$t = 3.8$		$t = 7.4$	$t = 10.0$	PIT-27Amr	
	$r = 0.69$		$r = 0.61$	$r = 0.35$		$r = 0.74$	$r = 0.67$	1092-1217	

evenly selected. To remove any non-polar contamination, the samples were then solvent washed as follows: acetone (45 °C, 45 min); methanol (45 °C, 45 min) and chloroform (RT, 45 min). After being left to dry overnight, the samples were then subjected to the Oxford Radiocarbon Accelerator Unit's routine aqueous pretreatment procedure for wood (Bronk et al., 2010). The key steps of the procedure are as follows: HCl (1 M, 80 °C); NaOH (0.2 M, 80 °C); HCl (1 M, 80 °C); and NaOCl₂ (5% w:vol, 80 °C). The extracted holocellulose was then freeze-dried, and approximately 5 mg quantities weighed into tin capsules for combustion in an elemental analyser coupled to a mass spectrometer. The CO₂ liberated was collected cryogenically, graphitised and dated at ORAU's accelerator mass spectrometer (AMS) facility (see Bronk Ramsey et al., 2004).

The control samples from Greece were treated in exactly the same manner, except that subsamples D-F were pretreated in duplicate (D1-F1, and D2-F2), with only the first subsample (D1-F1) receiving a solvent wash. This was to make sure that no solvent had remained that could affect the final date.

2.4. Laboratory procedures – Vienna Environmental Research Accelerator – VERA

From the Çatacık tree-ring samples slices of wood (~150 mg) including all 10 tree-rings were cut with a saw. One of the two large planes of the section thus obtained was covered with a layer of Elmer's Glue-All[®]. After allowing for hardening for several days the sample was treated with boiling H₂O_{bi-distilled} over 3 days and a large part of the glue was removed in flakes from the sample surface. Subsequent to the H₂O treatment the sample was chopped up and the different pretreatments listed in Table 4 were applied to the Çatacık test samples. The individual chemical steps combined in these pretreatment tests are described in the Supporting Online Materials in Bronk Ramsey et al. (2010).

The pretreatment for the PIT samples was selected on the basis of these Elmer's Glue-All[®] tests (see below for discussion). As a result, all the PIT samples (starting amounts between ~50 mg and ~35 mg, obtained like the test samples), except VERA-3130, have been treated consecutively with hot H₂O_{bi-distilled}, Soxhlet extraction with acetone, methanol and H₂O_{bi-distilled} in sequence, the VERA standard ABA method (Wild et al., 2008) and then bleaching with NaClO₂. From VERA-3130 only a 16 mg sample amount was

available, therefore to minimise sample losses the final bleaching step was omitted.

After the chemical pretreatment, 5 mg–10 mg of the samples were further processed as described for example in Wild et al. (2008). The ¹⁴C measurement was performed with the AMS system of the VERA laboratory (Steier et al., 2004). ¹³C/¹²C isotope ratios were also determined via AMS measurement in the graphitised sample for isotope fractionation correction of the ¹⁴C data. Separate high-precision δ¹³C analyses were not performed on the PIT samples at VERA. To test the reproducibility of the applied sampling and the pretreatment method for the PIT samples, a second independent ¹⁴C age determination was performed for those samples where a larger quantity of initial material was available (10 out of 21 samples).

3. Results

3.1. Removal of Elmer's Wood Glue[™] and Elmer's Glue-All[®]

The conventional radiocarbon ages (CRAs) of the samples testing the dating effect of Elmer's Wood Glue[™] and Elmer's Glue-All[®], are listed in Tables 6 and 7. The Oxford results on the known age control sample clearly show that Elmer's Wood Glue[™] was labile to solvent pretreatment. If any adhesive had remained, the CRAs of the corresponding samples would have been higher than expected, as the polymer is a product of the petrochemical industry and hence depleted in ¹⁴C. As shown in Fig. 3, the measurements obtained on the control samples were similar to the reference values for this period of time (AD 1641–1650). If anything, the highest measurements were obtained on values that had neither been exposed to the adhesive nor the solvents, which were also ¹⁴C-free (see Fig. 3). There is thus no evidence that the samples treated with Elmer's Wood Glue[™] yielded inappropriately old ¹⁴C ages and no evidence that any old carbon contaminant applies after pretreatment.

The Vienna results on the known age control sample also indicate that the samples which had been exposed to Elmer's Glue-All[®] returned acceptable results under several slightly different pretreatment regimes, with all dates but one (VERA-2754T5) similar to the reference values for this period (Fig. 4), and all but VERA-2754T5 including the expected calendar age range within their most likely 68.2% ranges when calibrated (using OxCal 4.2, Bronk Ramsey, 1995; 2009a; IntCal13, Reimer et al., 2013). However, at

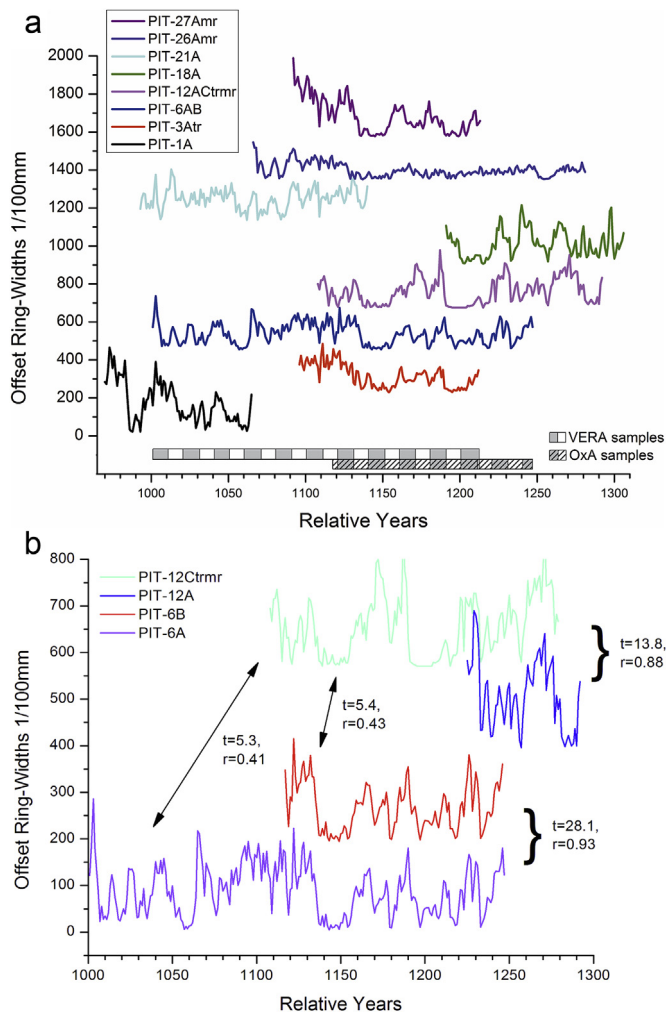


Fig. 2. a. Ring-width sequences for PIT 1A, 3A truncated, 6AB, 12AC truncated and missing rings inserted, 18A, 21A, 26AC missing rings inserted and 27A missing rings inserted in 1/100ths of a mm in the proposed crossdated positions (see Table 2) relative to each other. The tree-ring segments dissected from PIT-6A (VERA ^{14}C dates) and PIT-6B (OxA ^{14}C dates and $\delta^{13}\text{C}$ data) for ^{14}C dating are indicated, from relative rings 1001 to 1247 inclusive. b. Individual tree ring-width sequences for PIT 6A and PIT-6B and PIT-12A and PIT-12Ctrmr (truncated and with 12 missing rings inserted) which have been combined in Fig. 2a. Data shown in 1/100ths of a mm in the proposed crossdated positions (see Table 2 and Fig. 2a) relative to each other. Crossdating statistics from COFECHA are also indicated for the substantive overlaps. PIT-6A and PIT-6B are visually very similar and clearly derive from the same sample and tree: the samples dissected from PIT-6A and PIT-6B for analysis (see Fig. 2a) can therefore be regarded as identical tree-rings.

Table 3

Samples and ^{14}C and $\delta^{13}\text{C}$ data from the CHI-3 core from the Oxford Radiocarbon Accelerator Unit. As supplied to Oxford, the samples had labels with relative rings 974–1083; the CHI-3 sample is shown instead dated 1001–1115 in Table 1 and Fig. 1 and the corrected rings numbers are also listed above. The ^{14}C dates listed are corrected for isotopic fractionation using the $\delta^{13}\text{C}$ values measured in the AMS (not quoted). The $\delta^{13}\text{C}$ values listed are those measured separately on a stable isotope mass spectrometer with a precision of approximately 0.3‰ relative to Vienna Pee Dee Belemnite (VPDB).

OxA-	Species	Adhesive present	Tree-ring nos.	Rings between sample centres	^{14}C Date Years BP	SD	$\delta^{13}\text{C}$ (‰)
14629	<i>Cedrus</i> sp.	Y	974–983 = 1001–1010	–	3833	28	–20.6
14630	<i>Cedrus</i> sp.	Y	984–993 = 1011–1020	10	3807	29	–20.5
14631	<i>Cedrus</i> sp.	Y	994–1003 = 1021–1030	10	3752	30	–20.4
14632	<i>Cedrus</i> sp.	Y	1004–1013 = 1031–1040	10	3688	33	–19.8
14633	<i>Cedrus</i> sp.	Y	1014–1023 = 1041–1050	10	3746	30	–19.6
14634	<i>Cedrus</i> sp.	Y	1024–1033 = 1051–1060	10	3793	31	–19.8
14635	<i>Cedrus</i> sp.	Y	1034–1043 = 1061–1070	10	3772	30	–20.2
14636	<i>Cedrus</i> sp.	Y	1044–1053 = 1071–1080	10	3747	30	–20.0
14637	<i>Cedrus</i> sp.	Y	1054–1063 = 1081–1095	12.5	3743	30	–19.9
14638	<i>Cedrus</i> sp.	Y	1064–1073 = 1096–1105	12.5	3757	33	–19.7
14639	<i>Cedrus</i> sp.	Y	1074–1083 = 1106–1115	10	3649	32	–20.0

the same time, on average, it is apparent that the VERA ^{14}C ages on the samples treated with Elmer's Glue-All[®] are very slightly older (weighted average 293 ± 13 ^{14}C years BP, taking into account correlated uncertainties) versus those dates measured at VERA with no Elmer's Glue-All[®] (weighted average 250 ± 13 ^{14}C years BP), suggesting either some small contaminant effect; or, more likely since the dates correspond well with the IntCal reference curve and the range of the Oxford dates on a tree-ring block only offset by 1 year, a slight change in the performance of the VERA AMS between 2003 when the control samples were run and 2012 when the other data were run. Based on this test, it was decided to adopt the pretreatment regime described in Section 2.4 above for the PIT samples run at VERA as most likely to remove or minimize any Elmer's Glue-All[®] contaminant issue.

These tests on the pretreatment and dating of known age wood treated with Elmer's Wood Glue[™] or Elmer's Glue-All[®] provide evidence of the integrity of the resultant ^{14}C and $\delta^{13}\text{C}$ measurements following appropriate pretreatment, and their suitability for high-precision analysis. It should further be noted that the test samples reviewed above were liberally coated in Elmer's Wood Glue[™] or Elmer's Glue-All[®], whereas only minimal amounts were ever applied to the PIT cores, and the material sampled for analysis avoided any wood where adhesive traces were visible. Thus any potential issue is inherently unlikely.

3.2. Dating the coffin of Ipi-ha-ishutef

The set of dendro-sequenced ^{14}C dates along the CHI-3 core (Table 3) can be closely dated in calendar years employing the technique of dendro- ^{14}C -wiggle-matching (Bronk Ramsey et al., 2001; Galimberti et al., 2004; Bayliss and Tyers, 2004; Tyers, 2008), using OxCal (Bronk Ramsey, 1995; 2009a) and the IntCal13 (Reimer et al., 2013) ^{14}C calibration curve: Fig. 5. The data fit well to the calibration curve (no outliers applying the simple or general outlier models of Bronk Ramsey, 2009b). There is no indication of a ^{14}C offset – a ΔR test indicates effectively a zero offset: Fig. 5 (bottom left). The sequence of dated wood segments from the CHI-3 sample is placed applying the dating model with the midpoint of the first 10-year sample at 2222–2213 BC at 68.2% probability (2227–2209 BC at 95.4% probability) and the mid-point of the last sample at 2117–2108 BC at 68.2% probability (2122–2104 BC at 95.4% probability). The last extant tree-ring in the CHI chronology (40.5 years after the mid-point of the last dated decade) lies 2076–2068 BC at 68.2% probability (2081–2064 BC at 95.4% probability). No bark or other indications of terminal rings are present, thus this date is a *terminus post quem* by an unknown amount. This date is consistent with the general calendar date

Table 4
Samples and ^{14}C and $\delta^{13}\text{C}$ data from the PIT-6B core from the Oxford Radiocarbon Accelerator Unit. The ^{14}C dates listed are corrected for isotopic fractionation using the $\delta^{13}\text{C}$ values measured in the AMS (not quoted). The $\delta^{13}\text{C}$ values listed are those measured separately on a stable isotope mass spectrometer with a precision of approximately 0.3‰ relative to Vienna Pee Dee Belemnite (VPDB).

OxA-	Species	Adhesive present	Tree-ring nos.	Rings between sample centres	^{14}C Date Years BP	SD	$\delta^{13}\text{C}$ (‰)
20133	<i>Cedrus</i> sp.	Y	1117–1120	–	3738	29	–20
20215	<i>Cedrus</i> sp.	Y	1121–1130	7	3759	29	–19.8
20134	<i>Cedrus</i> sp.	Y	1131–1140	10	3747	26	–19.7
20135	<i>Cedrus</i> sp.	Y	1141–1150	10	3687	26	–20.6
20136	<i>Cedrus</i> sp.	Y	1151–1160	10	3719	27	–20.5
20137	<i>Cedrus</i> sp.	Y	1151–1160	0	3750	29	–20.4
20138	<i>Cedrus</i> sp.	Y	1161–1170	10	3657	27	–19.8
20139	<i>Cedrus</i> sp.	Y	1171–1180	10	3702	28	–19.6
20140	<i>Cedrus</i> sp.	Y	1181–1190	10	3674	29	–19.8
20141	<i>Cedrus</i> sp.	Y	1191–1200	10	3675	29	–20.2
20142	<i>Cedrus</i> sp.	Y	1201–1210	10	3678	30	–20
20143	<i>Cedrus</i> sp.	Y	1211–1220	10	3670	27	–19.9
20144	<i>Cedrus</i> sp.	Y	1221–1230	10	3628	27	–19.7
20145	<i>Cedrus</i> sp.	Y	1231–1240	10	3688	29	–20
20146	<i>Cedrus</i> sp.	Y	1241–1246	8	3581	27	–19.9

range applied for this coffin on the basis of style and associations in the First Intermediate Period, Dynasties 9–10, or early Middle Kingdom, Dynasty 11, and would indicate that it is likely the coffin in fact belongs at the later end of this range around the mid 21st century BC (or a little later if the *terminus post quem* is longer).

3.3. Dating the Pittsburgh boat

There is a large set of ^{14}C data from both the Vienna and Oxford laboratories on the PIT-6 sample: Fig. 6. Where the two

Table 5
Samples and ^{14}C data from the PIT-6A core from the Vienna Environmental Research Accelerator. The ^{14}C dates listed are corrected for isotopic fractionation using the $\delta^{13}\text{C}$ values measured in the AMS (not quoted). Samples with a_2 label are duplicates measured a second time.

VERA-	Species	Adhesive present	Tree-ring nos.	Rings between samples centres	^{14}C Date Years BP	SD
VERA-3116	<i>Cedrus</i> sp.	Y	1001–1010	–	3745	36
VERA-3117	<i>Cedrus</i> sp.	Y	1011–1020	10	3752	37
VERA-3118	<i>Cedrus</i> sp.	Y	1021–1030	10	3766	36
VERA-3118_2	<i>Cedrus</i> sp.	Y	1021–1030	0	3767	30
VERA-3119	<i>Cedrus</i> sp.	Y	1031–1040	10	3814	36
VERA-3119_2	<i>Cedrus</i> sp.	Y	1031–1040	0	3725	31
VERA-3120	<i>Cedrus</i> sp.	Y	1041–1050	10	3740	39
VERA-3120_2	<i>Cedrus</i> sp.	Y	1041–1050	0	3771	32
VERA-3121	<i>Cedrus</i> sp.	Y	1051–1060	10	3748	36
VERA-3122	<i>Cedrus</i> sp.	Y	1061–1070	10	3732	37
VERA-3122_2	<i>Cedrus</i> sp.	Y	1061–1070	0	3629	35
VERA-3123	<i>Cedrus</i> sp.	Y	1071–1080	10	3736	37
VERA-3123_2	<i>Cedrus</i> sp.	Y	1071–1080	0	3684	31
VERA-3124	<i>Cedrus</i> sp.	Y	1081–1090	10	3667	36
VERA-3124_2	<i>Cedrus</i> sp.	Y	1081–1090	0	3719	28
VERA-3125	<i>Cedrus</i> sp.	Y	1091–1100	10	3706	38
VERA-3125_2	<i>Cedrus</i> sp.	Y	1091–1100	0	3698	31
VERA-3126	<i>Cedrus</i> sp.	Y	1101–1110	10	3702	37
VERA-3126_2	<i>Cedrus</i> sp.	Y	1101–1110	0	3707	29
VERA-3127	<i>Cedrus</i> sp.	Y	1111–1120	10	3736	38
VERA-3127_2	<i>Cedrus</i> sp.	Y	1111–1120	0	3677	32
VERA-3128	<i>Cedrus</i> sp.	Y	1121–1130	10	3751	39
VERA-3128_2	<i>Cedrus</i> sp.	Y	1121–1130	0	3718	35
VERA-3129	<i>Cedrus</i> sp.	Y	1131–1140	10	3747	35
VERA-3130	<i>Cedrus</i> sp.	Y	1141–1150	10	3694	35
VERA-3131	<i>Cedrus</i> sp.	Y	1151–1160	10	3725	39
VERA-3132	<i>Cedrus</i> sp.	Y	1161–1170	10	3679	37
VERA-3133	<i>Cedrus</i> sp.	Y	1171–1180	10	3618	35
VERA-3134	<i>Cedrus</i> sp.	Y	1181–1190	10	3627	37
VERA-3135	<i>Cedrus</i> sp.	Y	1191–1200	10	3698	39
VERA-3136	<i>Cedrus</i> sp.	Y	1201–1211	10.5	3671	38

laboratories dated the identical (or almost identical) sets of tree-rings ($n = 9$) the results are all consistent with being estimates of the same real ^{14}C age within 95.4% probability limits (Ward and Wilson, 1978) – Table 8 – and indeed all but one set overlap even within their 1σ ranges (note: the VERA samples for rings 1201–1211 includes one extra ring, 1211, compared to the Oxford sample for rings 1201–1210). Out of the set of instances of multiple measurements on the identical or almost identical tree-rings ($n = 18$) only one pair – two VERA measurements on rings 1061–1070 – narrowly fail to meet this test ($t = 3.869 > 5\%$ value of 3.8). We have therefore treated the Oxford and Vienna data as one set for the purposes of a dendro- ^{14}C -wobble-match analysis to provide a best date in calendar years for the wood from the Pittsburgh boat: Fig. 7. The last extant (and non-terminal) tree-ring in the PIT chronology is ring 1306 (from PIT-18A). Thus the minimum felling date (+1 year) for this timber provides us with a best estimate *terminus post quem* date only – we do not know how many rings are missing to bark and it could be some to many – for the Senusret III boat (Fig. 7B): 1896–1889 BC at 68.2% probability and 1898–1885 BC at 95.4% probability.

However, it is evident from Fig. 7A that the ^{14}C dates from about 2123 BC and especially ca. 2080 BC and later tend mainly to be above, that is older than, the IntCal13 values. A neutral ΔR test running the whole PIT dating model, using a test value of 0 ± 20 ,

Table 6
Tree-ring subsamples and ^{14}C dates from a block of known age (AD 1641–1650) pine wood from Greece (Salatoura Papagianni Forest, northwest of Milea) from the Oxford Radiocarbon Accelerator Unit, comparing results on samples with no Elmer's Wood Glue™ (samples D–F) versus those treated with Elmer's Wood Glue™ (samples A–C). Sub-samples D2, E2 and F2 did not undergo a solvent wash prior to aqueous pretreatment. The ^{14}C dates listed above are corrected for isotopic fractionation using the $\delta^{13}\text{C}$ values measured in the AMS (not quoted). The $\delta^{13}\text{C}$ values listed are those measured separately on a stable isotope mass spectrometer with a precision of approximately 0.3‰ relative to Vienna Pee Dee Belemnite (VPDB).

Sub-sample No.	Species	Adhesive present	OxA-	$\delta^{13}\text{C}$ (‰)	^{14}C Date Years BP	SD
A	<i>Pinus leukoderms</i>	Y	20222	–21.5	281	23
B	<i>Pinus leukoderms</i>	Y	20223	–22.0	210	23
C	<i>Pinus leukoderms</i>	Y	20224	–21.6	237	23
D1	<i>Pinus leukoderms</i>	N	20225	–21.3	254	22
E1	<i>Pinus leukoderms</i>	N	20227	–21.2	235	22
F1	<i>Pinus leukoderms</i>	N	20229	–21.1	316	28
D2	<i>Pinus leukoderms</i>	N	20226	–21.3	262	24
E2	<i>Pinus leukoderms</i>	N	20228	–21.2	266	23
F2	<i>Pinus leukoderms</i>	N	20230	–21.3	315	30

Table 7

Tree-ring subsamples and ^{14}C dates from a sample of known age (AD 1640–1649) *P. nigra* from Çatacak in northwest Turkey comparing results on samples with no Elmer's Glue-All® (in italics) versus those treated with Elmer's Glue-All® under differing pretreatment strategies. The VERA-2753... and VERA-2754... samples are all using the identical tree-rings, with the samples with the suffixes T... treated with Elmer's Glue-All® and then variously pretreated as summarised above. The samples marked with an * were pretreated in a manner similar to VERA-2754T6 but with the second acid step skipped. VERA-2751, 2752 and 2755 were also run on the same tree-rings (no Elmer's Glue-All®) and are shown for comparison. The same tree-rings were also dated at the Heidelberg Radiocarbon Laboratory (no Elmer's Glue-All®) and again this date, Hd-19597, is listed for comparison (from Manning et al., 2010, 2006). The VERA ^{14}C dates listed above are corrected for isotopic fractionation using the $\delta^{13}\text{C}$ values measured in the AMS (quoted with 1SD measurement uncertainties). VERA-2751, 2752, 2753, 2754 and 2755 and Hd-19597 were previously reported in Manning et al. (2006). VERA data are rounded off according to the recommendations of Stuiver and Polach (1977).

Lab no.	Species	Adhesive	Pretreatment summary	$\delta^{13}\text{C}$ ‰	^{14}C Date Years BP	SD
<i>VERA-2753 measured in 2003</i>	<i>Pinus nigra</i>	<i>N</i>	<i>soaked in Acetone + ABA sample not treated with Elmer's Glue-All®</i>	<i>-22.1 ± 0.5</i>	<i>250</i>	<i>30</i>
VERA-2753T1	Pinus nigra	Y	H ₂ O – Soxhlet (Acetone-MeOH-H ₂ O) cellulose	-19.8 ± 1.2	280	30
VERA-2753T2	Pinus nigra	Y	H ₂ O – Soxhlet (Acetone-MeOH-H ₂ O) cellulose	-16.5 ± 2.6	305	40
VERA-2753T3	Pinus nigra	Y	H ₂ O – Soxhlet (Acetone-MeOH-H ₂ O) cellulose	-20.6 ± 0.7	290	35
VERA-2753T4	Pinus nigra	Y	H ₂ O – Soxhlet (Acetone-MeOH-H ₂ O) AB + bleaching with NaClO ₂ *	-19.6 ± 1.7	305	35
VERA-2753T5	Pinus nigra	Y	H ₂ O – Soxhlet (Acetone-MeOH-H ₂ O) AB + bleaching with NaClO ₂ *	-19.3 ± 1.1	295	30
VERA-2753T6	Pinus nigra	Y	H ₂ O – Soxhlet (Acetone-MeOH-H ₂ O) AB + bleaching with NaClO ₂ *	-21.1 ± 0.5	265	35
<i>VERA-2754 measured in 2003</i>	<i>Pinus nigra</i>	<i>N</i>	<i>soaked in Acetone + ABA sample not treated with Elmer's Glue-All®</i>	<i>-22.4 ± 0.7</i>	<i>260</i>	<i>30</i>
VERA-2754T3	Pinus nigra	Y	H ₂ O – Soxhlet (Cyclohexan/EtOH–EtOH–H ₂ O) cellulose	-22.4 ± 0.7	295	25
VERA-2754T4	Pinus nigra	Y	H ₂ O – Soxhlet (Acetone-MeOH-H ₂ O) cellulose	-21.5 ± 0.7	260	25
VERA-2754T5	Pinus nigra	Y	H ₂ O – Soxhlet (Cyclohexan/EtOH–EtOH–H ₂ O) ABA bleaching	-23.4 ± 0.7	335	25
VERA-2754T6	Pinus nigra	Y	H ₂ O-Soxhlet (Acetone-MeOH-H ₂ O) ABA bleaching	-22.7 ± 0.7	265	30
<i>VERA-2751 measured in 2003</i>	<i>Pinus nigra</i>	<i>N</i>	<i>soaked in Acetone + ABA sample not treated with Elmer's Glue-All®</i>	<i>-22.1 ± 0.7</i>	<i>225</i>	<i>30</i>
<i>VERA-2752 measured in 2003</i>	<i>Pinus nigra</i>	<i>N</i>	<i>soaked in Acetone + ABA sample not treated with Elmer's Glue-All®</i>	<i>-21.5 ± 0.6</i>	<i>270</i>	<i>35</i>
<i>VERA-2755 measured in 2003</i>	<i>Pinus nigra</i>	<i>N</i>	<i>soaked in Acetone + ABA sample not treated with Elmer's Glue-All®</i>	<i>-23.7 ± 0.5</i>	<i>245</i>	<i>30</i>
Hd-19597	Pinus nigra	N	Modified de Vries (AAA, or ABA) sequence with NaOH overnight; HCl, NaOH, and HCl (Manning et al., 2010: 1573 and references cited). No Elmer's Glue-All®	-23.64	246	13

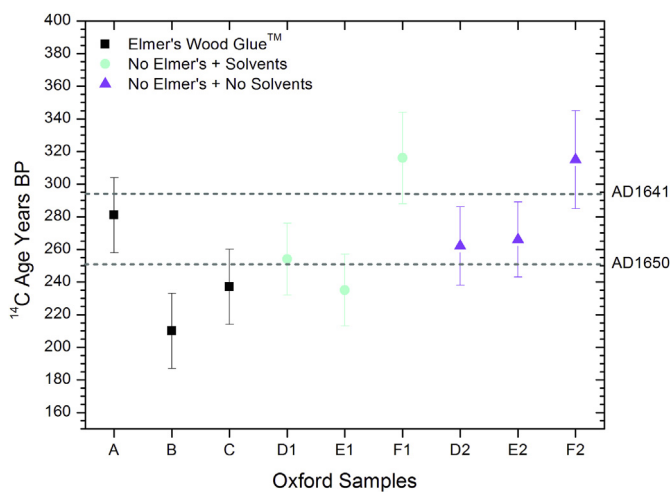


Fig. 3. The Conventional Radiocarbon Ages (CRAs) of the Elmer's Wood Glue™ test at the Oxford Radiocarbon Accelerator Unit on known age control samples of pine from Greece with their 1σ measurement uncertainties (see Table 6). The dashed lines indicate the northern hemisphere calibration curve central (no uncertainties included) values (IntCal13, Reimer et al., 2013) for the two outermost rings of these known age samples (linear annual interpolation where relevant between IntCal data points). The samples that had not been exposed to either Elmer's Wood Glue™ or solvent returned, on average, the highest dates.

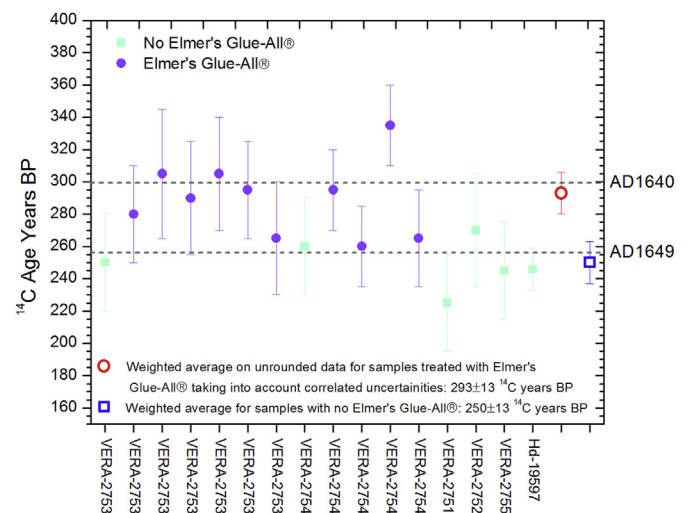


Fig. 4. The CRAs of the Elmer's Glue-All® test at the Vienna Environmental Research Accelerator on known age control samples of pine from Turkey with their 1σ measurement uncertainties (see Table 7). The dashed lines indicate the northern hemisphere calibration curve central (no uncertainties included) values (IntCal13, Reimer et al., 2013) for the two outermost rings of these known age samples (linear annual interpolation where relevant between IntCal data points).

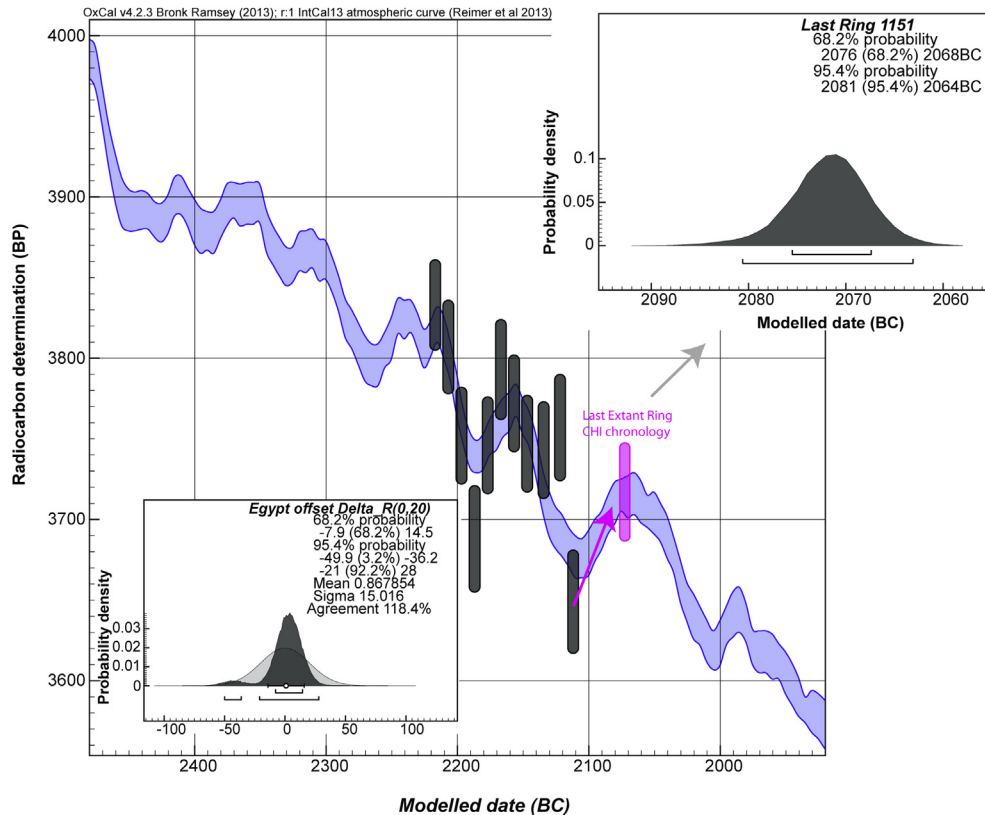


Fig. 5. Main panel: ^{14}C -wiggle-match best fit of the 11 dendrosequenced ^{14}C dates on the CHI-3 sample (Table 3) against the IntCal13 ^{14}C calibration curve (Reimer et al., 2013) employing OxCal (Bronk Ramsey, 1995, 2009a) – the grey bars for each date illustrate the 1σ uncertainties in both the ^{14}C and calendar timescales. Top right: the modelled calendar date of the last extant tree-ring of the overall CHI chronology (as shown in Fig. 1). Bottom left: a re-run of the wiggle-match testing for a possible ^{14}C offset allowing for a ΔR of 0 ± 20 ^{14}C years – almost no offset is evident with the distribution centred close to zero. A very small possibility (3.2%) for a substantive offset (36.2–49.9 ^{14}C years) can be dismissed as an artifact of the wiggly calibration curve shape at this period.

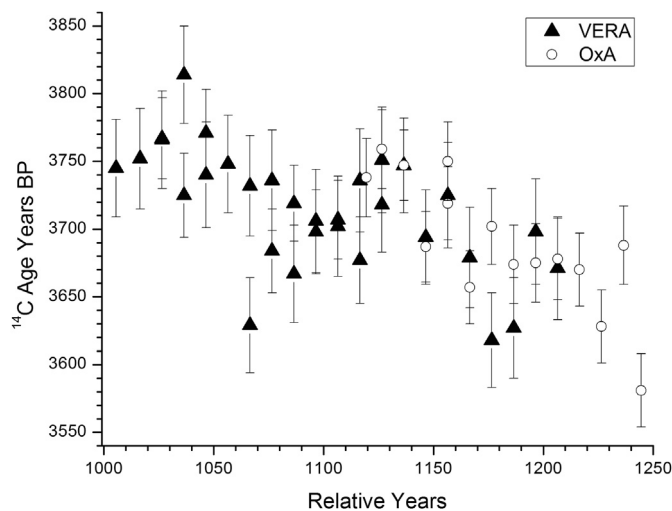


Fig. 6. Comparison of the ^{14}C dates on the PIT-6A (VERA) and PIT-6B (OxA) samples (Tables 4 and 5). See also Table 8. 1σ uncertainties shown. All samples on the same or almost the same years measured at both Vienna and Oxford offer age estimates which are consistent with the hypothesis of representing estimates of the same ^{14}C age at 95.4% probability (Ward and Wilson, 1978); one pair of dates on the same sample both run at VERA (relative years 1062–1071) narrowly fails such a test ($t = 3.869 > 3.8$ for chi-squared test at $df=1$). Note the VERA sample for rings 1201–1211 includes one more ring (1211) than the Oxford sample (rings 1201–1210).

indicates an apparent and substantive offset of around 17 ^{14}C years: Fig. 7C (using the mid-point of the 68.2% range). Repeated runs indicate an average most likely 68.2% probability value around 17 ± 6 ^{14}C years (in rounded terms). The placement of the PIT-6 wiggle-match series in calendar time is, however, only slightly affected, moving the minimum felling date TPQ on typical runs just a few years later to e.g. 1892–1884 BC at 68.2% probability and 1896–1879 BC at 95.4% probability (note repeated different runs get 0–3 year variations in some cases, to ca. 1876 BC). The quality of the fit is much improved, however, by allowing either a 0 ± 20 or 17 ± 6 ΔR offset, with, for example, the OxCal Aoverall statistic improving from around 42.9 with no ΔR , to around 100.5 with ΔR 0 ± 20 to around 135.8 with ΔR 17 ± 6 . Fig. 8 shows the combined placements of both the CHI-3 and PIT-6 ^{14}C data against IntCal13 (no ΔR allowance), and the differences in ^{14}C age between the dates on CHI-3 and PIT-6 versus the midpoint values of the IntCal13 curve for the contemporary year (employing 1 year linear interpolation where necessary). The least squares linear fit line through the difference data in the lower part of Fig. 8 clearly shows the trend towards an offset as one moves through the series.

This tendency towards slightly older ^{14}C ages from the later part of the PIT sequence is evident in both the Vienna and Oxford datasets, even though it is more pronounced in the Oxford set which overall comprises slightly older ^{14}C ages for the same (or almost the same) tree-ring years: Table 8. Fig. 9A shows the fit of just the VERA data against IntCal13, and it is evident from about the date placed ca. 2117 BC, and certainly from the date placed ca.

Table 8

Comparison of the Oxford and Vienna ^{14}C data on the same or almost the same tree-rings (see also Fig. 6). In each case the data can reasonably be combined as estimates of the same ^{14}C age (Ward and Wilson, 1978). The OxA data are, however, overall slightly older than the VERA data across the comparison set (mean + 14 ± 16 ^{14}C years). However, as discussed in the text and see Fig. 9 (compared to Fig. 7), the ^{14}C offset from around 2100 BC onwards in the PIT data is evident, regardless, in both the VERA and OxA data, and thus appears to be real.

Relative yr.	Oxford			Vienna			Offset		Ward & Wilson test			
	OxA-	^{14}C Date	$\pm\sigma$	VERA-	^{14}C Date	$\pm\sigma$	Date	$\pm\sigma$	μ	$\pm\sigma$	t-Score	χ^2 test
1121–1130	20215	3759	29	3128 & 3128_2	3733	28	+26	40	3746	20	0.4	Pass
1131–1140	20134	3747	26	3129	3747	35	+0	44	3747	21	0.0	Pass
1141–1150	20135	3687	26	3130	3694	35	-7	44	3689	21	0.0	Pass
1151–1160	20136 & 20137	3733	22	3131	3725	39	+8	45	3731	19	0.0	Pass
1161–1170	20138	3657	27	3132	3679	37	-22	46	3665	22	0.2	Pass
1171–1180	20139	3702	28	3133	3618	35	+84	45	3669	22	3.5	Pass
1181–1190	20140	3674	29	3134	3627	37	+47	47	3656	23	1.0	Pass
1191–1200	20141	3675	29	3135	3698	39	-23	49	3683	23	0.2	Pass
1201–1210/11	20142	3678	30	3136	3671	38	+7	48	3675	24	0.0	Pass
					$\mu \pm \sigma$:		+14	16				

2074 BC, and later, that, like the Oxford data, many of the VERA data indicate a systematic offset to older values, as seen in the combined OxA-VERA data in Fig. 7. Considering all the VERA data, the offset is smaller than for the combined OxA-VERA set; testing with a ΔR value of 0 ± 20 , as above, yields around 9 ^{14}C years (Fig. 7C), but, if even the oldest five VERA dated segments are excluded (so data placed ca. 2187–2147 BC in Fig. 9A), then the ΔR starts to rise towards that found for the combined OxA-VERA set: Fig. 9D. There does seem to be a real, replicated, small ^{14}C offset taking effect especially from the 21st century BC.

3.4. $\delta^{13}\text{C}$ and possible climate indications

$\delta^{13}\text{C}$ data measured separately on a stable isotope mass spectrometer $\pm 0.3\%$ relative to Vienna Pee Dee Belemnite (VPDB) are available for the decadal CHI-3 and PIT-6B samples dated at the Oxford laboratory: Fig. 10. These Oxford $\delta^{13}\text{C}$ data represent chronologically separate periods (see the OxA data in Fig. 8) and come from single samples of single trees for which the exact growth environment is not known, therefore any interpretations must be regarded as highly tentative. In an ideal world we would have analysed several samples per tree and several trees from the same artifact for each measured interval over a common period, following best practice from numerous studies over the past several decades (e.g. Leavitt and Long, 1984, 1988; Saurer et al., 1995; McCarroll and Loader, 2004; Loader et al., 2007). However, with archaeological material which is irreplaceable it is not practical/possible to complete such a rigorous sampling protocol. Working with what we have we can merely observe that there is a difference between the data from the two different cedar samples, with the average of the CHI-3 data at -20.81% and the average of the PIT-6B data at -19.99% . It is entirely possible that the difference merely reflects natural variability between trees due to a number of possible site and individual specific variables. Yet if we make the (big) assumption that these two cedar trees did come from similar growth locations (e.g. the mountains in Lebanon), it is interesting to note that there is an apparent trend to increasing $\delta^{13}\text{C}$ values over time for the combined dataset. This is worth noting, despite the caveats noted, because this increase appears to match with the 2080 BC and later period during which the ^{14}C data exhibit an offset (see Figs. 7 and 9). For trees in areas where precipitation is the critical control on growth, increased $\delta^{13}\text{C}$ values correlate with a reduction in available moisture, i.e. more arid conditions (previous references; also e.g. Leavitt, 2007; Liu et al., 2008).

4. Discussion

4.1. Dating

Kuniholm (2001: 79–81) reported provisional calendar dates of 2430–2286 BC for the overall CHI dendrochronology and 2439–2104 BC for the overall PIT dendrochronology based on supposed cross-dating placements against a number of unpublished chronologies linked to the Anatolian Middle Bronze Age–Iron Age juniper chronology as dated in Kuniholm et al. (1996). The dendro- ^{14}C -wobble-matches reported above render both these date placements highly unlikely. We find a good date placement for the CHI chronology ending about 2076–2068 BC (68.2% probability) and 2081–2064 BC (95.4% probability), more than 200 years later than the Kuniholm placement. We find that the chronology from the Senusret III boat also ends in the early 19th century BC (ca. 1898–1876 BC at the limits of the 95.4% ranges whether with or without allowing for the apparent ^{14}C offset, ΔR either of 0 ± 20 , 17 ± 6 or, see Section 4.2 below, 21 ± 7 ^{14}C years), again more than 200 years later than the Kuniholm placement. Our findings indicate that these samples should not – contrary Kuniholm (2001) – be associated with the Anatolian juniper chronology.

Part of the issue with the previous dendrochronological work has already been addressed. The core Gordian juniper chronology running from the 17th through 8th centuries BC, has been constructed twice, independently, by two different methods (first by skeleton plotting at Arizona, and then independently using ring-width comparisons by Kuniholm: see Kuniholm et al., 2011: 80–82), and so can be regarded as sound. There are substantial numbers of samples of the same tree type (*Juniperus* spp.) from a similar area which crossdate well (e.g. Kuniholm et al., 2011: Table 5.6; Manning et al., 2010: Tables 2 and 3), and a highly detailed ^{14}C wiggle-match investigation employing 128 ^{14}C dates over almost a millennium provides further independent confirmation that this chronology is well constructed and placed in time. The date for this sequence is now placed some 22 to 23 ± 1 years earlier than in Kuniholm et al. (1996), as set out in Manning et al. (2001, 2003; 2010). The remainder of the difference for the earlier dendrochronological placement (Kuniholm, 2001) may be explained by a variety of problems (as in some previous cases of problems with Kuniholm's work: e.g. Griggs and Manning, 2009; Manning et al., 2009), such as site sequences constructed from relatively small numbers of samples, less than sufficient overlaps both within the respective site chronologies and between the site chronologies, and use of different species from widely spaced areas from diverse elevations and growth contexts (from northwest

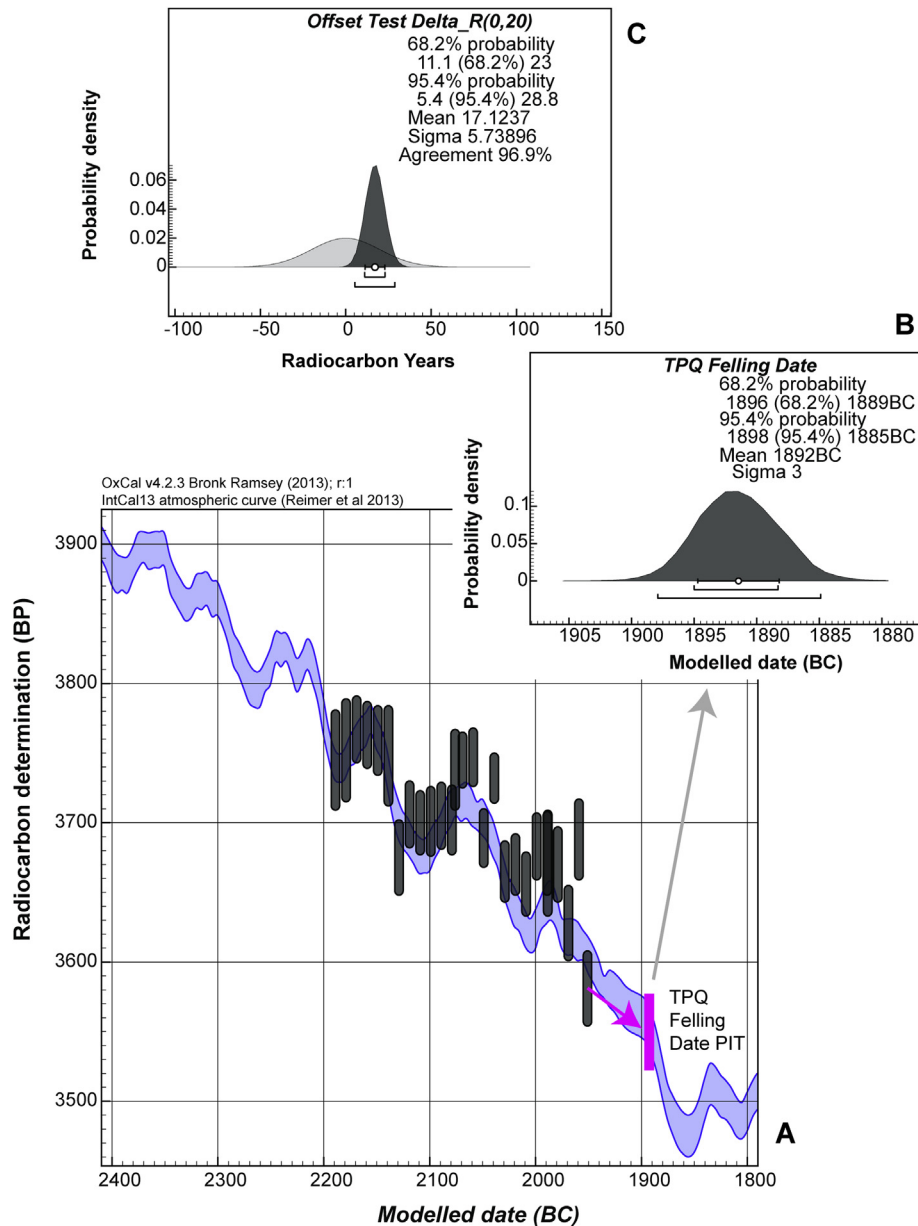


Fig. 7. A: ^{14}C -wiggle-match best fit of the dendro sequenced ^{14}C dates on the PIT-6 sample (Tables 4 and 5) against the IntCal13 ^{14}C calibration curve (Reimer et al., 2013) employing OxCal (Bronk Ramsey, 1995, 2009a) – the grey bars for each date illustrate the 1σ uncertainties in both the ^{14}C and calendar timescales. B: the modelled calendar date of the minimum felling date for the last extant tree-ring of the overall PIT chronology (as shown in Fig. 2a). C: a re-run of the wiggle-match testing for a possible ^{14}C offset allowing for a ΔR of 0 ± 20 ^{14}C years – a noticeable offset is evident (as visually apparent looking at most of the dates from ca. 2123 BC and later, and certainly ca. 2080 BC and later), with multiple runs of the model typically finding a ΔR offset of (mid-point of the 68.2% ranges) ca. 17 ^{14}C years.

Anatolia to the Levant in the case of Kuniholm, 2001). There is no reason to expect all or any of these trees to exhibit close similarities in growth patterns.

The PIT chronology ends at relative year 1306, and there is no bark or other indication of a terminal ring. Thus the minimum felling date for the relevant timber (+1 year) is merely a *terminus post quem* (TPQ), and the actual felling date was another few-several years later (unknown amount). It is also evident that there is a ^{14}C offset applying over most of the period of the PIT ^{14}C time-series. Allowing for this yields very slightly later modelled calendar age ranges for the minimum felling date TPQ (compared to Fig. 7B):

- (a) allowing for a ΔR test range of 0 ± 20 ^{14}C years: 1892–1884 BC at 68.2% probability and 1896–1879 BC at 95.4%

probability (with about a 0–3 year variation on the 95.4% ranges over multiple runs);

- (b) allowing for an estimated PIT-relevant ΔR of 17 ± 6 ^{14}C years (from repeated runs of the 0 ± 20 ΔR model): 1892–1884 BC at 68.2% probability and 1895–1879 BC at 95.4% probability. (Note: very similar age ranges usually result when a ΔR of 21 ± 7 ^{14}C years is employed – see below for this figure.)

If we compare the PIT minimum felling dates with the calendar date ranges calculated from ^{14}C and historical reign length information (Bronk Ramsey et al., 2010; Dee, 2013), or from historical-astronomical information alone (e.g. Huber, 2011; Gautschy, 2011a; 2011b; Kitchen, 2000; Hornung et al., 2006), for Senusret III and his successor Amenemhat III, we see that the minimum

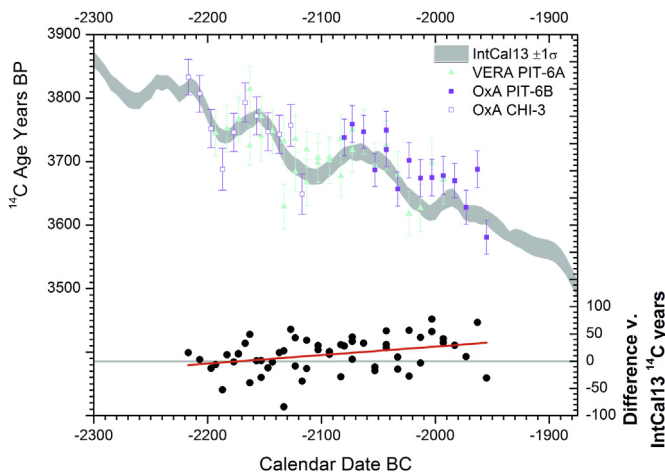


Fig. 8. Top: Best fit placements of the CHI-3 and PIT-6 ^{14}C dates in Fig. 5 and 7 against the IntCal13 ^{14}C calibration curve (1σ band) (Reimer et al., 2013). Bottom: Differences of each of the CHI-3 and PIT-6 ^{14}C dates to the mid-point value of the IntCal13 curve (1 year linear interpolation where necessary). There is a clear (if noisy) trend towards mainly positive differences (PIT ^{14}C dates older than the contemporary IntCal13 values) as indicated by the least squares linear fit line in red placed through the data (and contrast with grey zero difference line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

felling date TPQ ranges for the PIT timbers lie from a little before, to perhaps into, the start of the reign of Senusret III, especially when compared either to the ^{14}C and reign length chronology of Bronk Ramsey et al. (2010) and most recently Dee (2013), or the higher historical dates of e.g. Huber (2011); Gautschy (2011a; 2011b) or Kitchen (2000): Fig. 11. It is important to note that there was no terminal ring in the PIT sequence, thus an unknown number of tree-rings are missing after relative year 1306 – hence the real bark date for the latest trees cut down for this boat could well lie very comfortably into the reign of Senusret III. The historical-astronomical date of the accession of Senusret III is of course a long debated topic, focused on a Sothic date attributed to his Year 7 (Krauss, 2006: 448–450; Shortland, 2013: 26–27), and lunar data related to Senusret III and Amenemhat III (Luft, 1992). There are arguments against some previous solutions including the 1866 BC date employed by Kitchen or the 1872 BC date in Parker (1950, 1976) and as employed in Ryholt (1997: 184–185). As Krauss (2006: 448–450) summarises, there are possible Sothic dates from ca. 1882–1830 BC, although the later dates rely on an observation point in the south of Egypt at Elephantine, rather than in the Illahun (or general Memphis) area – where the record of the observation was found. There are good arguments to doubt the southern/Elephantine hypothesis at this time (e.g. Huber, 2011: 224; Gautschy, 2011a: 54; Rose, 1994; Luft, 1992; Leitz, 1989). If we accept a general Memphis area observation, and the good recent evidence for a 30-year sole reign for Senusret III (Gautschy, 2011a: 56–58), this gives a range of ca. 1882–1865 BC for Senusret Year 7 (Gautschy, 2011a: 59 – note typo in her Fig. 3 where “1 Senwosret III” option 1 should be 1872 BC – compare Gautschy, 2011b: 11–18), and a seemingly most plausible solution (despite imperfect data) for an accession date for Senusret III of ca. 1873/1872 BC (Huber, 2011: 211–225), with 1883 BC the next most likely date (Gautschy, 2011a: 59 – note these 1872 BC and 1883 BC dates, options 1 and 2, are instead called options 3 and 4 in Gautschy, 2011b), and both of these dates within a possible range from ca. 1889–1871 BC. A date of accession in this range and likely ca. 1873/72 BC, allowing even for just a few missing outer rings to bark on PIT-18A, could see the latest timbers in the boat comfortably felled in the earlier part of his reign. As noted above, PIT-12 potentially

originally had bark edge before coring, but has (as now extant) lost some original outer rings – amount unknown. Based on outer ring-widths of 220+ year-old cedars (as PIT-12 was – note record shown in Fig. 2a and b has been truncated by 61 rings at the start) from Lebanon analysed by R. Touchan and M. Hughes (<ftp://ftp.ncdc.noaa.gov/pub/data/paleo/treering/measurements/asia/leba004.rwl>; and <ftp://ftp.ncdc.noaa.gov/pub/data/paleo/treering/measurements/asia/leba002.rwl>), even a missing 2–8 mm (the sort of amount easily lost when drilling a dry-wood core) could represent around 2–20 rings. If PIT-12 was felled within ca. 2–20 years of the last extant ring, or perhaps close to a likely felling date for PIT-18, then there is an argument that both could easily represent felling dates in (or after) the 1880s BC to 1860s BC close to, or in, the earlier part of the reign of Senusret III.

Previous scholarship has noted extensive evidence for reuse of timbers among the cedar wood used in the Dahshur boats (e.g. Creasman, 2005: 36–37, 83; 2010a: 113; 2013; 2014a) – although reportedly less so for the Carnegie and Chicago boats (Creasman, 2010b: 99). Reuse of cedar wood is very likely since it was so valuable in antiquity. Even within the selected PIT chronology employed here (Fig. 2a), the wood comprising PIT-1A and PIT-21A ends much earlier than several of the other timbers and may well represent reused wood. Since Kuniholm (2001) seems to have failed to account for serial reuse (Creasman, 2013, 2014b, in press), and now that those dates may be rejected, it is no longer necessary to try to account for a supposed general 200+ years discrepancy in age between timber cutting date and final use. Instead, the dates achieved by this project indicate that the original bark and so cutting/felling dates for the latest trees employed in the Pittsburgh boat probably lay at the earliest just before the reign of Senusret III, and in fact likely during his reign (allowing for missing wood to bark). Although missing a terminal ring, and although the timber might also have been stored for a few years before use, the dating of the Pittsburgh boat is noticeably more consonant with a high chronology date for Senusret III (e.g. Huber, 2011; Gautschy, 2011a,b) in line with the recent ^{14}C -based findings of Bronk Ramsey et al. (2010) and Dee (2013).

4.2. ^{14}C offset and climate

The PIT ^{14}C data exhibit an offset towards slightly older ^{14}C ages versus the mid-latitude northern hemisphere standard (IntCal13: Reimer et al., 2013). Of the 46 individual measurements on PIT samples (Fig. 8), 32 are older than the central IntCal13 value (82.6%). This pattern is especially clear from around 2100 BC: from the data placed ca. 2103 BC onwards in Fig. 8 and 24 of the 31 data are older than the central IntCal13 value (77%), and the average offset is $+22.2^{14}\text{C}$ years. If the dating model in Fig. 7 is re-run excluding the data placed before ca. 2120 BC, then a ΔR test of $0 \pm 20^{14}\text{C}$ years returns, on average over multiple runs, an offset in round terms of $21 \pm 7^{14}\text{C}$ years (1SD). This offset is evident, especially from around and after ca. 2100 BC, in both the OxA and VERA data (Figs. 7 and 9). In contrast, the CHI data do not exhibit any systematic offset. In a more recent period, cedar from Lebanon (AD 1800–1859) and pine from Cyprus (AD 1801–1930) also exhibit no systematic offset (Manning and Kromer, 2012: 456 and Figs. 7 and 8 [note: there is a typo on p.456 where it should read Fig. 8 regarding the cedar]) The good general accuracy and precision of the Oxford and VERA ^{14}C laboratories, both on known age samples, and relative to each other, is well established from several major projects (e.g. Bronk Ramsey et al., 2010; Manning et al., 2006). Thus it is likely that this observed offset within the PIT ^{14}C time series is real and indicates a causal mechanism (as suggested for other datasets from some other periods and circumstances: Kromer et al., 2001; Dellinger et al., 2004). On the basis of all the PIT data we estimate the offset (ΔR)

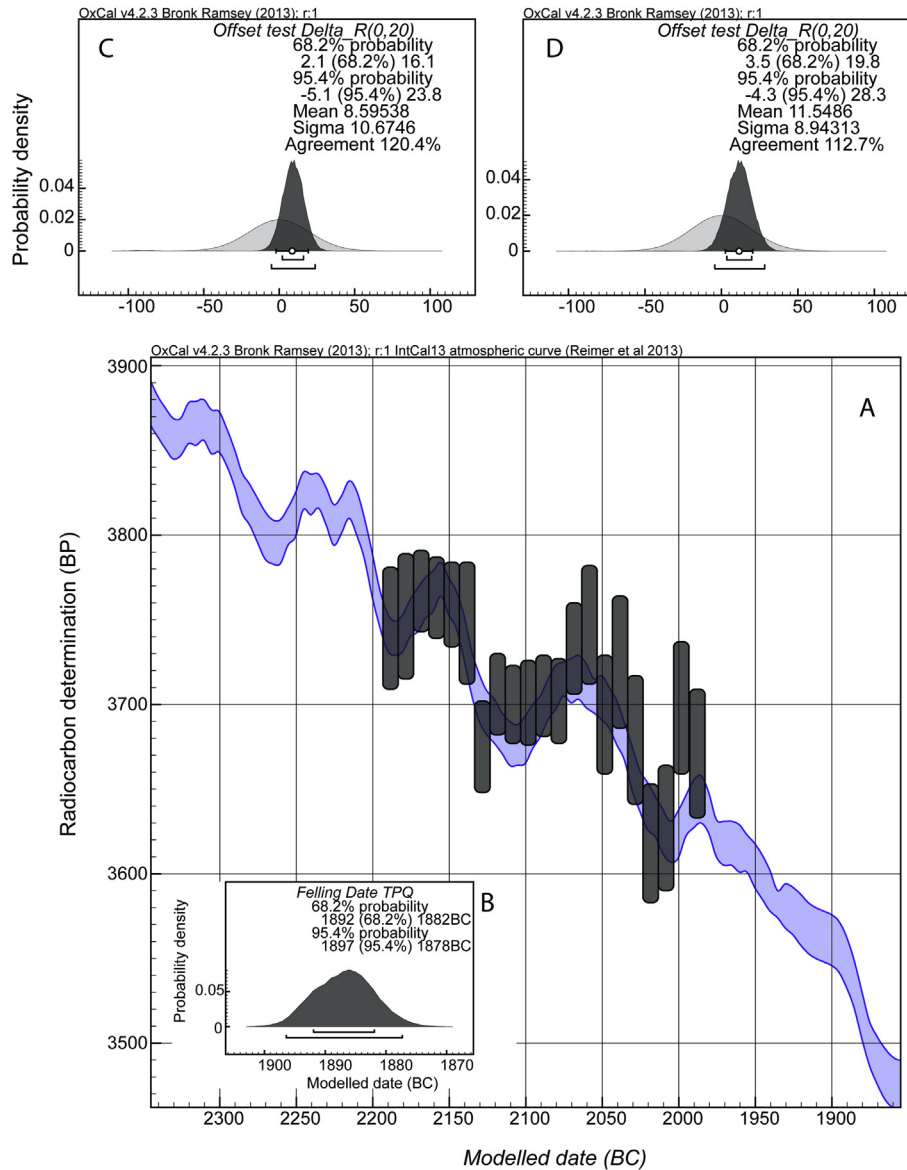


Fig. 9. A. Best fit placement of the VERA-only data from PIT-6A against IntCal13 (Reimer et al., 2013) employing OxCal (Bronk Ramsey, 1995; 2009a) – compare with Fig. 7A above where OxA + VERA combined data). The grey bars for each date illustrate the 1σ uncertainties in both the ^{14}C and calendar timescales. Note the same tendency to older ^{14}C ages versus IntCal13 from around and after 2117 BC and certainly ca. 2074 BC as in Fig. 7A. B. Minimum Felling Date TPQ from the model in A. C. A re-run of the wiggle-match testing for a possible ^{14}C offset allowing for a ΔR of 0 ± 20 ^{14}C years – a small offset is evident, but much less so than in Fig. 7. D. A further re-run of the wiggle-match, excluding the oldest (first five) VERA data placed ca. 2188–2148 BC in Fig. 9A, testing for a possible ^{14}C offset allowing for a ΔR of 0 ± 20 ^{14}C years, produces a somewhat larger offset, heading more to the scale of the one in Fig. 7. The offset appears to take effect from about the 21st century BC onwards and to be real in the data from both laboratories.

as about 17 ± 6 ^{14}C years, and for the data after ca. 2120 BC it is about (rounded) 21 ± 7 ^{14}C years. These numbers are similar to the ^{14}C offset of 19 ± 5 ^{14}C years determined for samples growing in Egypt (Dee et al., 2010). The mechanism in Egypt likely relates to the (pre-modern-dam) Nile hydrologic cycle which places the growing season in Egypt largely opposite to that in central/northern Europe, and thus allows the ^{14}C measurements to reflect the small known intra-annual variations in ^{14}C , between a winter/spring ^{14}C low versus a summer ^{14}C high (Dee et al., 2010: 689–690). A growing season issue, linked to a climate change episode, seems the likely explanation for the PIT case as we now outline.

Intra-annual sampling of the troposphere in the recent past (Levin et al., 1992; Levin and Hesshaimer, 2000; Levin and Kromer, 2004) indicates the scale of intra-annual ^{14}C variations in the modern period. If we then approximately exclude the effects of

modern fossil fuel contribution (Levin et al., 2003; Randerson et al., 2002), and atmosphere-biosphere exchange, the underlying (pre-modern) seasonal *maximum* intra-annual variation – that is northern hemisphere seasonal variability between the March minimums and August maximums – due to recurrent changing stratosphere–troposphere exchanges in the extra-tropical and sub-polar region allows for a variation on the order of up to $\leq 4\text{‰}$ and likely more typically 2–4 ‰ (or around 16–32 ^{14}C years). The intra-hemispheric location-dependent (regional) differences identified in the study of McCormac et al. (1995) were of a similar order (ca. 2.5 ‰) – which provides further confirmation and guidance as to scale. Thus intra-annual variations of up to around 20 ^{14}C years are plausible and even expected where samples reflect the intra-annual low versus high in ^{14}C levels, and this annual cycle may be further exaggerated where there are latitude and/or substantial

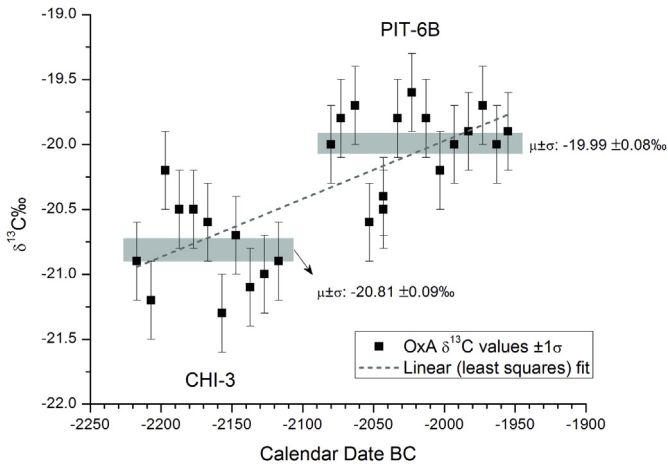


Fig. 10. $\delta^{13}\text{C}$ values for the CHI-3 and PIT-6B samples as measured separately (i.e. not in the AMS) on a stable isotope mass spectrometer at Oxford with a precision of $\pm 0.3\text{‰}$ relative to Vienna Pee Dee Belemnite (VPDB).

elevation differences during periods of high ^{14}C production (major solar minima: Kromer et al., 2001; Dellinger et al., 2004).

The trees supplying the wood employed in the IntCal13 ^{14}C calibration curve for the period relevant to the CHI and PIT samples come from central and northern Europe and primarily Germany (Reimer et al., 2013). The typical growing season in this region is late spring and especially summer. For example: oaks in Germany and other temperate areas of Europe (north of the Alps) – the backbone of the IntCal13 dataset – typically start annual growth in late April to early May and stop annual growth around the end of August to mid-September (Eckstein, 2007: 55–56; Haneca et al., 2009: 4). This (later) spring and summer period (especially August) is when annual northern hemisphere ^{14}C levels

peak (e.g. Randerson et al., 2002; Levin and Hesshaimer, 2000). As a result, the ^{14}C recorded in the tree-rings employed in IntCal13 more or less offers a record of the annual peak summer ^{14}C for the mid-latitude northern hemisphere (Hua and Barbetti, 2004: 1279). An example is the good correspondence of the ^{14}C levels in summer atmospheric samples from Germany with the ^{14}C levels measured in the annual tree rings of a nearby tree (Levin and Kromer, 1997: Fig. 2).

However, the PIT trees were growing during a period when climate conditions in southwest Asia have been widely argued to reflect increased aridity and cooler conditions as part of a wider rapid climate change episode (e.g. Weiss et al., 1993; Dalfes et al., 1997; Bond et al., 1997; Cullen et al., 2000; Haug et al., 2001; Thompson et al., 2002; Staubwasser et al., 2003; Stanley et al., 2003; Mayewski et al., 2004; Booth et al., 2005; Arz et al., 2006; Drysdale et al., 2006; Staubwasser and Weiss, 2006: 380–383; Parker and Goudie, 2008; Magny et al., 2009; Weiss et al., 2012: 185–187; Weiss, 2014; Marriner et al., 2013; Salzer et al., 2014). In previous work an offset towards older ^{14}C ages for tree-ring samples from Anatolia has been observed during two periods of major reduced solar irradiance and broadly coinciding with Bond ice-rafted debris (IRD) events 0 and 2 (Bond et al., 1997, 2001). As noted above, this was suggested to link with increased intra-annual differences in the growing seasons over the relevant period for the trees employed for the IntCal ^{14}C dataset versus the trees analysed from the east Mediterranean (Kromer et al., 2001, 2010; Manning et al., 2010; Manning and Kromer, 2011). The PIT ^{14}C offset correlates with Bond IRD event 3. In general, this was a period when conditions were cooler (and especially at higher latitudes) and more arid at lower latitudes and in southwest Asia in particular. During this period it might be anticipated that the growing seasons of the *Quercus* sp. trees in central Europe and Ireland employed for IntCal, affected by cooler conditions, typically shifted to a slightly later start to the growing season, with maximum growth centred around the August ^{14}C high. In contrast, cedar trees in the east Mediterranean, which normally reflect primarily a spring/summer (April/May–June) versus summer growing season (Hughes et al., 2001; Touchan et al., 2003), when affected by drier conditions probably started growing slightly earlier (since there was less snow pack) and probably ceased growth earlier due to less available water (for example, in the Taurus Mountains, precipitation is the key limiting factor for cedar growth: Hughes et al., 2001: Fig.3). This would cause these cedar trees, during such a period, to reflect more closely the early spring ^{14}C low (and in contrast to the central and northern European oaks reflecting the summer, especially August, ^{14}C maximum). The net effect would be typically that the difference in growing seasons between central Europe and Ireland versus the east Mediterranean would be exaggerated during such a period, as in the two time intervals discussed in Kromer et al. (2001), sufficient that they are able to be distinguished in ^{14}C terms (at around or above about 2‰). Although inadequate (as discussed above), the limited independent $\delta^{13}\text{C}$ data available from the CHI-3 and PIT-6 samples could be compatible with the suggestion of increased aridity on average from after 2100 BC as affecting the PIT-6 tree compared to the CHI-3 tree.

These findings suggest (again) that ^{14}C may offer a useful climate tracer when comparing different areas and latitudes, and not only in the modern period (as e.g. Levin and Hesshaimer, 2000; Hua and Barbetti, 2007). In particular, regional expressions of processes associated with major solar minima and/or Bond events might be elucidated. More work on regional ^{14}C time-series in the pre-modern period is desirable to enable detailed investigation of such potential.

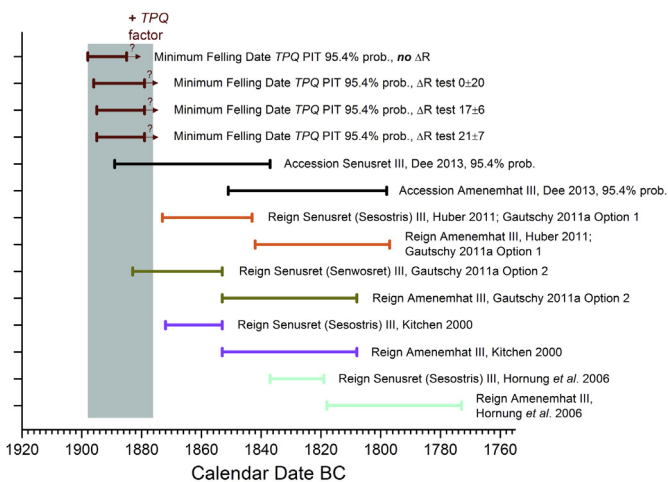


Fig. 11. Comparison of the typical 95.4% modelled calendar age ranges for the minimum felling date *terminus post quem* (TPQ) for the latest PIT timber (+1 year from last extant ring of PIT-18A) given no ΔR offset, a test ΔR of 0 ± 20 ^{14}C years, an estimated ΔR of 17 ± 6 ^{14}C years, and an estimated ΔR of 21 ± 7 ^{14}C years (the grey box delimits the maximum 95.4% range found in any model run) versus the 95.4% probability modelled accession dates for Senusret III and Amenemhat III from the MKM1 model in Dee (2013) (note the ranges in Bronk Ramsey et al., 2010 are the same within 0–1 year), and versus the reign dates proposed from historical-astronomical evidence for Senusret III and Amenemhat III by Huber (2011); Gatschy (2011a,b – note: options 1 & 2 in the 2011a paper = options 3&4 in the more detailed 2011b paper); Kitchen (2000) and Hornung et al. (2006).

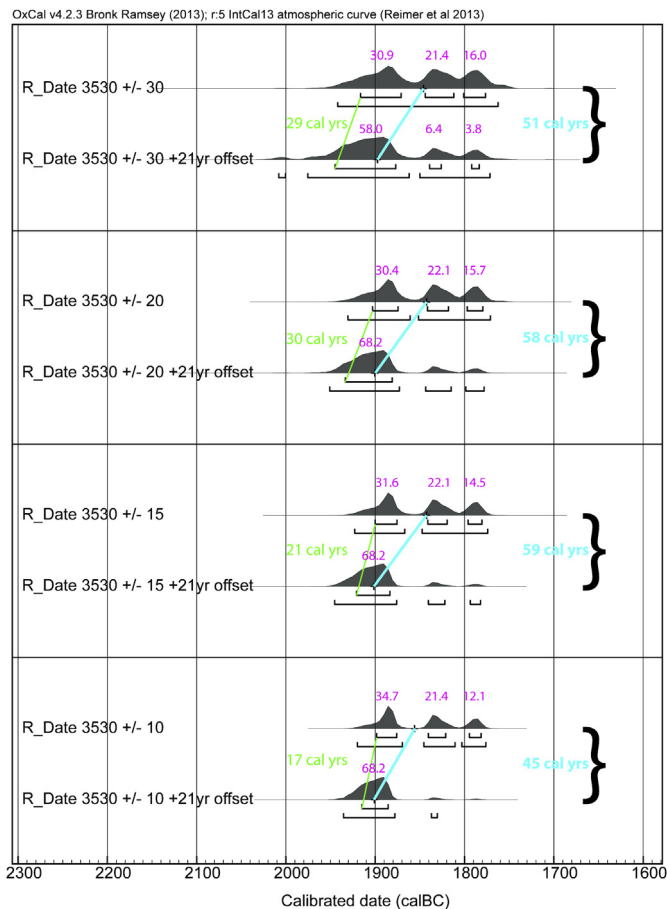


Fig. 12. Comparison of the calibrated calendar dating probability distributions and (upper and lower lines under each distribution respectively) the 68.2% and 95.4% most likely calibrated age ranges for a ^{14}C age of 3530 BP at four levels of uncertainty (± 30 , ± 20 , ± 15 and ± 10) versus the same if a $+21$ ^{14}C offset applies. The magenta numbers above the probability distributions indicate the distribution of probability within the most likely 68.2% ranges. Calibration employs IntCal13 (Reimer et al., 2013) and OxCal (Bronk Ramsey, 1995; 2009a) with curve resolution set at 5. The cyan lines link the medians of the respective probability ranges and the cyan text indicates the calendar years offset between the pairs when the $+21$ ^{14}C years offset is applied. The Green lines link the start of the most likely 68.2% ranges and the green text indicates the calendar years offset between the pairs when the $+21$ ^{14}C years offset is applied.

At the same time, the apparent substantive ^{14}C offsets in the east Mediterranean region at certain periods is a matter of some relevance to archaeological dating in these periods (Reimer, 2001). When dating time-series (wiggle-matching), as in this paper, the effects on the chronological placement are minimal, as noted above in the PIT case. However, when dating individual contexts by ^{14}C , as common in archaeology, the effects could become relevant at higher resolutions. Fig. 12 provides one illustrative case. The calendar age ranges for ^{14}C dates of 3530 BP at four levels of uncertainty are compared with the results if a 21 ^{14}C year offset is applied. We see that in broad terms the 95.4% probability ranges are largely similar until high-resolution is employed (± 10 ^{14}C years), but, comparing the distribution of the probability (shape of the calibrated probability distributions) and the most likely date ranges at 68.2% probability, especially as precision increases (for example when ^{14}C dates on several seed samples from a single context are combined), we see scope for clear differences in likely calendar dates: see Fig. 12. While overall relatively modest differences, this scale of variation is potentially relevant in cases where precise dates are required, or are debated, in the relevant interval (ca. 2100–1900 BC on the basis of the PIT data).

5. Conclusions

The precise near-absolute dating of the coffin of Ipi-ha-ishutef and the Pittsburgh boat provides good agreement with the standard range of the Egyptian historical chronology. The Pittsburgh boat, in particular, offers a set of circumstances which clearly favours a high Egyptian Middle Kingdom chronology (as other recent ^{14}C work: Bronk Ramsey et al., 2010; Dee 2013). At the same time, the ^{14}C data from the Pittsburgh boat indicate a temporary small but important offset within the period ca. 2200–1900 BC in contemporary ^{14}C ages between the Levant and central and northern Europe. This seems likely due to exaggeration of normal seasonal variations in the uptake of ^{14}C and its latitudinal distribution caused by climate change in the 2200–1900 BC/4200–3900 BP (y2k) interval, and conforms to other such findings of small offsets. This finding illustrates the potential of ^{14}C as a tracer of regional climate change episodes in the past. The regional ^{14}C offset has in general terms only a small impact for ^{14}C dating in the east Mediterranean in the period, but can be relevant to higher-precision cases. The effect of this offset is that in some periods – like ca. 2200–1900 BC – trees in the Levant offer ^{14}C ages approximately similar with ^{14}C ages on contemporary plants growing in Egypt (with its Nile pre-modern-dam hydrologic growing season offset), whereas in other periods they match the general mid-latitude northern hemisphere record and are offset from contemporary Egyptian samples (by about the Egyptian offset factor of 19 ± 5 ^{14}C years reported in Dee et al., 2010).

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