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Juliette Taïeb, Valérie Daux, Claire Alix. Dendroarchaeology of Birnirk and Thule Architectural Timbers (10–13th Centuries): Preliminary Results on Oxygen Isotope Cross-Dating. *International Journal of Wood Culture*, 2024, 1, pp.1-22. 10.1163/27723194-bja10029 . hal-04494850

HAL Id: hal-04494850

<https://hal.science/hal-04494850>

Submitted on 10 Mar 2024

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BRILL

INTERNATIONAL JOURNAL OF WOOD CULTURE

(2024) 1–22



The International Journal of
Wood Culture

brill.com/ijwc

Dendroarchaeology of Birnirk and Thule Architectural Timbers (10–13th Centuries)

Preliminary Results on Oxygen Isotope Cross-Dating

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Received 16 March 2023 | Accepted 5 February 2024 |

Published online 23 February 2023

Abstract

Along the coast of northwestern Alaska, architectural wood remains are well preserved in the Birnirk and Thule coastal sites of the early 2nd millennium CE. These structural wood elements are unique archives for documenting climatic variations and cultural transformations during this key development period of Inuit culture. Along this treeless Arctic coast, driftwood accumulates from the subarctic forests of interior Alaska. Except for northwestern Alaska, regional tree-ring chronologies are too short (at best 350–400 years) to successfully date archaeological wood remains from Birnirk and Thule coastal sites using conventional dendrochronology. This paper examines the potential of tree-ring derived $\delta^{18}\text{O}$ signal to annually date eight architectural wood samples from the Rising Whale (KTZ-304) site at Cape Espenberg, northwestern Alaska. We

Published with license by Koninklijke Brill NV | DOI:10.1163/27723194-BJA10029

© JULIETTE TAÏEB ET AL., 2024 | ISSN: 2772-3186 (print) 2772-3194 (online) Brill.com 03/10/2024 03:39:26PM
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developed a $\delta^{18}\text{O}$ master chronology, covering the period 935–1157 CE, using five wood samples from the KTZ-304 site. Blind isotope cross-dating of individual series belonging to this $\delta^{18}\text{O}$ master chronology (one against the other four) showed conclusive dating and a very strong coherence of the isotopic signal. We, then, used the $\delta^{18}\text{O}$ master chronology to cross-date three other wood samples for which we knew, from previous ^{14}C wiggle-matching procedure, the first measured ring to be in this time interval, within a ± 18 to 30-year precision. Oxygen isotope dendrochronology provided a plausible date for one of the samples (the first measured ring at 1073 CE). This preliminary study encourages us to acquire additional data to extend in time and strengthen the $\delta^{18}\text{O}$ master chronology of northwestern Alaska (NWA_{K180}) and help refine our understanding of climate and culture change during the 2nd millennium CE.

Keywords

archaeology – coastal driftwood – dendrochronology – stable isotope – Thule – Western Arctic

1 Introduction

The coasts of northern Alaska contain well-preserved structural wood elements from Birnirk and Thule semi-subterranean houses from the 2nd millennium CE. Archaeologists identify the Birnirk and Thule cultures as direct ancestors of the present-day Iñupiaq culture of northwestern Alaska and Inuit in general (Raghavan *et al.* 2014; Mason 2020; Unkel *et al.* 2022). Birnirk and Thule cultures are present in the Bering Strait region during the Medieval Climate Anomaly (MCA) (9th–13th centuries) and the transition to the Little Ice Age (LIA) (13th–15th centuries) (Alix *et al.* 2015; Mason 2016, 2020). In this treeless tundra environment, people had access to driftwood carried by the main rivers and ocean currents to northern Alaskan beaches (Giddings 1952b; Alix & Brewster 2004; Alix 2009, 2012, 2016). According to the geometry of marine currents and local knowledge, these driftwood logs came mainly from the forest of Interior Alaska via the Yukon and Kuskokwim rivers and that of northwestern Alaska via the Kobuk and Noatak rivers (Fig. 1). To a far lesser extent, in northern Alaska, wood may have also come from northeastern Alaska via northern flowing rivers, such as the Firth River, and northwestern Canada, primarily via the Mackenzie River (Giddings 1943, 1952a; Eurola 1971; Eggertsson 1995; Alix & Koester 2001; Alix 2004, 2005; Alix & Brewster 2004; Hellmann *et al.* 2017; Taïeb *et al.* 2022).

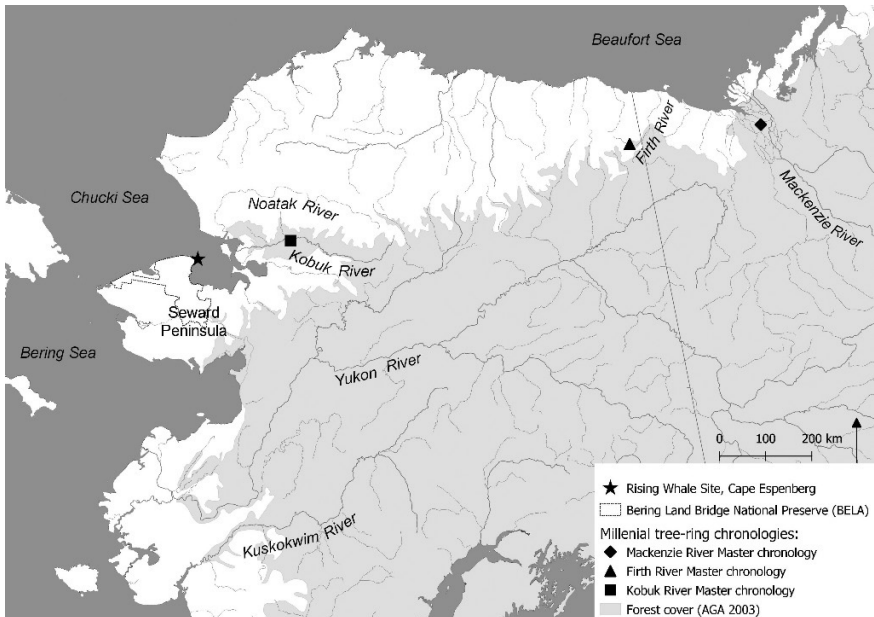


FIGURE 1 Map of Alaska and part of Yukon Territory in Canada, with the location of Rising Whale (KTZ-304) site at Cape Espenberg and the locations of three existing millennial master tree-ring chronologies

Coastal architectural wood remains are unique high-resolution chronometric and paleoclimatic archives. In Alaska, they can be used to (i) refine the chronological and temporal framework for archaeological sites and related cultures in a region where dating techniques face methodological limitations (Morrison 1989, 2001; Nash 2000; Mason 2009, 2020; Mason & Bowers 2009; Krus *et al.* 2019; Taïeb *et al.* 2023) and (ii) document and characterize climatic variations with a yearly resolution in their regions of origin, where climate proxies are rare and have limited temporal resolution (Mason & Gerlach 1995; Nicolle *et al.* 2018; Degroot *et al.* 2021, 2022).

In northern Alaska, conventional dendrochronology (analysis of annual ring-width patterns) successfully dated and determined the origin of coastal archaeological wood in a limited number of cases (Giddings 1943, 1948, 1952a; Oswalt 1951; VanStone 1958; Barber 2003; Griggs *et al.* 2019; Taïeb *et al.* 2022, 2023). Long tree-ring master chronologies in the source regions of driftwood are required to cross-date archaeological wood remains, in other words, to synchronize ring-width series patterns (Douglass 1921; Giddings 1952a; Speer 2012; Eggertsson 1994; Hellmann *et al.* 2016). Today, millennium-long master chronologies are limited to the Kobuk and Firth Rivers in northwestern

and northeastern Alaska (978–2002 CE and 1067–2002 CE, respectively) and the Mackenzie River in northwestern Canada (1245–2006 CE) (Fig. 1) (Giddings 1948, 1952a,b; Graumlich & King 1997; D'Arrigo, Mashing, *et al.* 2005; D'Arrigo, Wilson, *et al.* 2006; Porter *et al.* 2013). These time series are based on white spruce (*Picea glauca* (Moench Voss)), which is the dominant species of the boreal forest in Alaska (Viereck & Little 2007) and the main species identified in driftwood accumulations and coastal archaeological sites (Giddings 1952b; Hopkins & Giddings 1953, 22; Alix 2005, 2016; Griggs *et al.* 2019). So far, master chronologies of interior Alaskan areas, where a large part of the driftwood originates, are at best 400–350-year long. Therefore, they are too short to cross-date archaeological timbers from Birnirk and Thule coastal sites, and a large portion of sampled structural wood elements can not be cross-dated. When these cross-date with each other, they can only be considered as “floating” — that is, undated — chronologies (Giddings 1948; Taïeb *et al.* 2022, 2023).

Therefore, our aim is to develop annually dated tree-ring chronologies that can be used for (i) dating archaeological wood from coastal Inuit sites and (ii) analysing climatic variations during the MCA and LIA. Recent papers demonstrated the potential for oxygen isotope ($\delta^{18}\text{O}$) dendrochronology to date living trees and archaeological wood remains at a yearly resolution and develop tree-ring master chronologies where conventional dendrochronology is limited (Roden 2008; Xu *et al.* 2013; Baker *et al.* 2015; Yamada *et al.* 2018; Loader *et al.* 2019, 2021, 2022). Furthermore, $\delta^{18}\text{O}$ dendrochronology is based on the same principles as conventional dendrochronology but relies on cross-dating $\delta^{18}\text{O}$ rather than tree-ring width (TRW) variations, the $\delta^{18}\text{O}$ signal being often strongly consistent between trees and coherent at larger spatial scales than the ring-width signal (Roden 2008; Xu *et al.* 2013; Loader *et al.* 2019, 2022).

The present study complements another one in which we explored ^{14}C wiggle-matching as a high-resolution chronometric approach to precisely date “floating” sequences of archaeological Birnirk and Thule structural wood remains (Taïeb *et al.* 2023). Here, based on a methodology developed by Loader *et al.* (2019), we explore the potential of the $\delta^{18}\text{O}$ cross-dating approach for dating, at an annual resolution, floating tree-ring series from Birnirk and Thule wood samples. In Alaska, the $\delta^{18}\text{O}$ values of annual and monthly precipitation show a large-scale geographic homogeneity (West *et al.* 2010). The geographical gradient of the isotopic signal is perceptible from south to northeast Alaska (Isomap, ©Bowen 2003–2022, Waterisotopes Database (2023) <http://waterisotopesDB.org> (accessed 2 June 2023)). Therefore, we tested the capacity of the $\delta^{18}\text{O}$ chronology developed in northwestern Alaska to cross-date the $\delta^{18}\text{O}$ series of archaeological wood of unknown geographical origins, which could

not be dated with conventional dendrochronology. We hypothesized that the $\delta^{18}\text{O}$ signal for trees growing in different regions, but influenced by the same mode of climate variability, was sufficiently close. To test this hypothesis, we first evaluated the coherence of the $\delta^{18}\text{O}$ signal using five wood samples dated by conventional dendrochronology. We, then, built a $\delta^{18}\text{O}$ reference chronology with these five individual series (NWAK_{18O} hereafter) and, finally, tested the $\delta^{18}\text{O}$ -based dating approach on three “floating” wood series.

2 Materials and Methods

2.1 Archaeological Site and Wood Sample Selection

The wood samples used to develop NWAK_{18O} and test the $\delta^{18}\text{O}$ -based dating approach were selected from structural remains of a semi-subterranean house (F-12) at the Rising Whale (KTZ-304) site, Cape Espenberg, in the Bering Land Bridge National Preserve (BELA) (Figs 1 and 2; Fig. A1 in the Appendix) (Alix *et al.* 2018). Dated with radiocarbon and dendrochronology, the feature is a late Birnirk house occupied in the early 13th century CE (Alix *et al.* 2018, 2020b). The multi-rooms house has a wood structure with occasional whale bones and most likely a sod cover. Field observations and architectural analysis (including tree-ring analysis) suggest that the frame of the house represents one main building episode (Fig. 2) (Alix *et al.* 2018, 2020a,b).

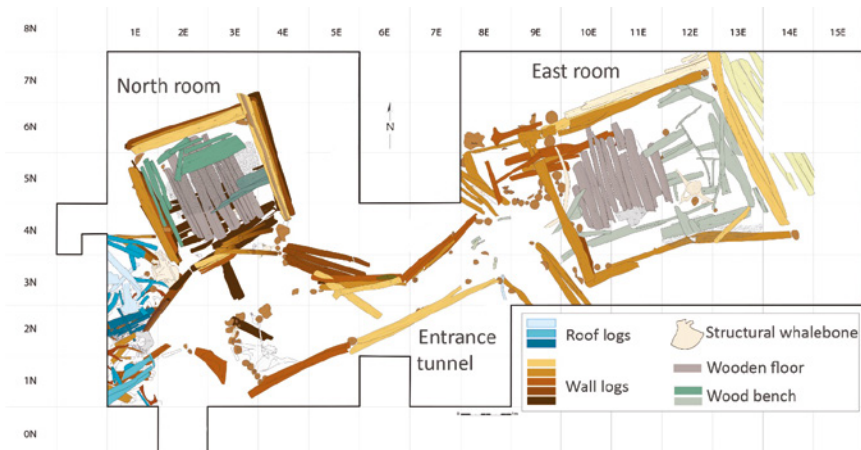


FIGURE 2 Excavation map of the floor of the Birnirk house F-12, Rising Whale site (KTZ-304), Cape Espenberg (field recording C. Alix, CAD S. Eliès and C. Alix). Each type of wooden architectural element is assigned a colour: shades of blue, brown, green and grey-brown for the roof logs, wall logs, wood bench and wooden floor, respectively

Cross-sections were collected from structural logs and planks during field excavations in 2016 and 2017 (Fig. A1 in the Appendix; Alix *et al.* 2017, 2020a,b; Alix & Mason 2018). We analysed the ring-width series of sixty-eight *Picea glauca* cross-sections following standard dendrochronological methods (e.g. Cook & Kairiukstis 1990; Speer 2012). Based on TRW patterns, we grouped the sixty-eight cross-sections into distinct sequences: five sequences of two to four individuals and one sequence of sixteen individuals (hereafter F12_C2). We successfully cross-dated seventeen individual TRW series, including those grouped as F12_C2, by using the TRW Kobuk River master chronology (Giddings 1952a; Graumlich & King 1997; D'Arrigo *et al.* 2005). However, 51 of the 68 individual TRW series could not be dated using conventional dendrochronology. Five wood cross-sections used to build the F12_C2 sequence were selected to develop an exploratory $\delta^{18}\text{O}$ chronology, NWAK₁₈₀ (Table 1; Fig. A1 in the Appendix). The selection criteria included: (i) overlap of periods and (ii) high state of preservation. Hereafter, the five series dated at a yearly resolution by conventional dendrochronology and used to develop NWAK₁₈₀ are individually referred to as $\delta^{18}\text{O}$ -ref series.

To evaluate the potential of the $\delta^{18}\text{O}$ cross-dating approach, we selected three additional undated wood cross-sections. The TRW chronologies of these cross-sections do not cross-date with each other and are part of three distinct tree-ring sequences (Table 1; Fig. A1 in the Appendix). We selected these cross-sections from a set of eight archaeological wood samples previously placed in calendar time using radiocarbon dating and wiggle-matching, with an uncertainty of a few decades (Table 1) (Taïeb *et al.* 2023). We selected these three samples on the following criteria: (i) they could neither be dated with dendrochronology nor provenanced, (ii) they were contemporaneous with NWAK₁₈₀ based on wiggle-matching dating, (iii) their length (>70 rings) ensured a minimum overlap of fifty years with NWAK₁₈₀, and (iv) they were well preserved. Hereafter, the three $\delta^{18}\text{O}$ series corresponding to these undated wood cross-sections are referred to as the $\delta^{18}\text{O}$ -test series.

2.2 TRW and $\delta^{18}\text{O}$ Determination

The selected cross-sections were kept in a freezer following their excavation and freeze-dried before processing (24 h at -25°C). The radii were cut out of the cross-sections with a mechanical bandsaw, manually sanded (grain size of 50–600 grit), and measured to a 0.001 mm resolution with a Velmex measurement table. We used TSAP-WIN and COFECHA software programs to calibrate and verify the tree-ring measurements (Holmes 1983; RinnTech 2000).

The isotopic analyses were conducted at the Laboratoire des Sciences du Climat et de l'Environnement (LSCE, Gif sur Yvette, France). For each radius,

TABLE 1 Selected samples used for geochemical and oxygen isotope analyses (reference and test $\delta^{18}\text{O}$ individual series)

	Tree-ring sample ID	Number of annual rings	Context: location in house feature	Mean tree-ring sequence ID	Dating method	Date or age interval of first year of growth (CE)
$\delta^{18}\text{O}$ -ref series	12W126-04	203	Wall log North room	F12_C2 ($n = 16$, 375 years)	Dendro	935
	12W62-04	105	Floor plank North room	F12_C2 ($n = 16$, 375 years)	Dendro	974
	12W57-06	115	Undetermined structural element North room	F12_C2 ($n = 16$, 375 years)	Dendro	1041
	12W52-03	81	Log Outside west area	F12_C2 ($n = 16$, 375 years)	Dendro	1042
	12W128-43	91	Half-split post East room	F12_C2 ($n = 16$, 375 years)	Dendro	1066
$\delta^{18}\text{O}$ -test series	12W128-03	153	Undetermined structural log East room	F12_C4 ($n=2$, 157 years)	^{14}C Wiggle- matched	1034–1052
	12W62-05	120	Floor plank North room	F12_C3 ($n=4$, 120 years)	^{14}C Wiggle- matched	1071–1102
	12W51-22	79	Roof cross-piece Entrance tunnel	F12_C1 ($n=2$, 83 years)	^{14}C Wiggle- matched	1087–1112

Note: In the last column, the calendar interval years for the first year of growth of test samples are provided based on ^{14}C wiggle-matching analysis (see Taïeb *et al.* 2023).

the rings were individually split using a scalpel under a binocular magnifier ($\times 10/\times 20$). Each ring was placed in a bag made from a Polytetrafluoroethylene (PTFE) filter (47 mm diameter, 10 μm porosity), closed by a PTFE ribbon to which a PTFE label was attached. We extracted wood α -cellulose from the whole ring of each annual growth ring following the Jayme-Wise method of delignification with an acidified sodium chlorite solution (NaClO_2), purification with sodium hydroxide (NaOH), and neutralization with acetic acid over three days (Leavitt & Danzer 1993; Boettger *et al.* 2007). After drying in an oven for two days, the cellulose bags were transferred to individual Eppendorf tubes with deionized water and placed in a refrigerator overnight. Then, α -cellulose was homogenized ultrasonically with a sonotrode apparatus (max. 2 min/sample) and freeze-dried (24 h at -25°C).

The cellulose of each ring was, then, weighted in silver capsules (between 10–20 µg/sample), and the isotopic composition of oxygen of α -cellulose was determined by pyrolysis (1400°C) with a High-Temperature Conversion Elemental Analyzer (TC-EA, Thermo Scientific) associated with a mass spectrometer (IRMS, IsoPrime). Each cellulose sample was measured at least twice and up to four times. A reference material (Whatmann CC31), which was used for an intercomparison between nine European laboratories (Boettger *et al.*, 2007), was included in the analysis sequences. The $\delta^{18}\text{O}$ of CC31 (set by consensus between the nine laboratories) is 31.85‰. A one-point calibration was performed using these reference values. The long-term analytical precision based on repeated measurements of CC31 cellulose was within 0.20‰. The study precision based on the aggregates of repeated measures of study samples is equal to 0.15‰ (see Brooks *et al.* 2022, for calculation details and equation).

The oxygen isotopic composition is expressed as $\delta^{18}\text{O}$ per mill (‰). The $\delta^{18}\text{O}$ of each sample is calculated by reference to the Vienna Standard Mean Ocean Water (V_{SMOW}) as:

$$\delta = (R_{\text{sample}}/R_{V_{\text{SMOW}}}-1) \times 1000 \quad (1)$$

where R_{sample} is the oxygen isotope ratio ($^{18}\text{O}/^{16}\text{O}$) of a sample cellulose.

2.3 Wood Dating Using Oxygen Isotopes

To test the potential of oxygen isotope dendrochronology for archaeological wood remains from northwestern Alaska, we followed the methodology developed for archaeological oak wood remains in Central England (Loader *et al.* 2019) and replicated on New Zealand matai trees (Loader *et al.* 2022). A detailed and explicit presentation of these calculations, including their rationale, can be found in these two publications.

First, the $\delta^{18}\text{O}$ individual chronologies were filtered to eliminate the low-frequency variability and highlight the interannual variations. We tested nine filters from the five main filter categories (Table A1 in the Appendix) as discussed by Loader *et al.* (2019). The ends of the $\delta^{18}\text{O}$ individual chronologies were mirrored to deal with end effects. Finally, we selected a 9-year rectangular filter, which produced the chronology with the lowest first-order autocorrelation (AR_1 ; Table A1 in the Appendix). Data were indexed by subtracting the 9-year filter. In the following, we add the subscript “i” to the name of a series to indicate it is indexed (e.g. $\delta^{18}\text{O}\text{-ref}_i$).

Second, the indexed series were cross-dated isotopically and evaluated using various statistical indices to assess the match probability of the dates and avoid spurious correlations. In the Results section, we include the correlation coefficient r , the Student’s t -value, the degrees of freedom (df; adjusted for

TABLE 2 Results of the cross-dating of the five individual series dated by dendrochronology

TVBP (RWI)	12W126-04	12W57-06	12W128-43	12W52-03	12W62-04
12W126-04	–	6.4	3.3	6	6
12W57-06	8.76	–	4.1	5.6	2.8
12W128-43	6.19	7.29	–	3.5	2.4
12W52-03	10.77	10.74	8.3	–	2.3
12W62-04	4.1	2.15	2.63	3.06	–

Note: The TVBPs calculated for standardized TRW series (RWI) and $\delta^{18}\text{O}$ -ref_i series are, above and below the diagonal, respectively.

TABLE 3 Results of blind cross-dating of one $\delta^{18}\text{O}$ -ref_i series against the other four

Series	Strongest match	OVL	<i>r</i>	df	Student's <i>t</i> -value	1/ <i>P</i>	IF
12W126-04	935	164	0.55	140	7.75	>1M	>1,000
12W128-43	1066	91	0.74	79	9.70	>1M	>1,000
12W52-03	1042	82	0.85	70	13.58	>1M	>1,000
12W57-06	1041	116	0.75	101	11.39	>1M	>1,000
12W62-04	974	106	0.39	92	4.11	11,456	26.71

Note: The match result reported for each sample corresponds to the date of the oldest (first) year of growth of the cross-section. OVL is the length of the overlap between one $\delta^{18}\text{O}$ -ref_i and the mean of the other four.

filtering), the inverse probability (1/*P*; the probability that a match of equivalent value occurs at an incorrect position), and the isolation factor (IF; the ratio of the best to the second-best probabilities; Loader *et al.* 2022). We calculated the degrees of freedom using a corrected sample size N_{COR} , which is an adjustment that considers any remaining AR₁ and the statistical cost of the filter. The N_{COR} values reported here are related to the series length at the position of the strongest association. We used two strict thresholds as validation of the match probability: 1/*P* ≥ 100 and IF ≥ 10 (Loader *et al.* 2019).

We evaluated the dating procedure on the five $\delta^{18}\text{O}$ -ref_i series. Each series was blindly cross-dated with a mean chronology obtained by averaging the other four. The minimum overlap between the individual series and mean chronologies was 82 years (Table 2). Then, we conducted the oxygen isotope

cross-dating between $NWAK_{180}$ and the three $\delta^{18}O$ -test_i series. This cross-dating was performed on both the total period of $NWAK_{180}$ (935–1157 CE) and the better-replicated section (BRS) of $NWAK_{180}$ ($n > 3$; 1040–1137 CE). We assessed the match probability for a minimum common overlap period of 50 years (Loader *et al.*, 2019). The results were assessed based on the calculated match probability and statistics, visual year-to-year congruence between individual series and $NWAK_{180}$, and consistency of potential dates with wiggle-matching calendar intervals (Table 1).

3 Results and Discussion

3.1 Evaluating the Approach with the Five $\delta^{18}O$ -Ref Series

The mean $\delta^{18}O$ values of the five $\delta^{18}O$ -ref series range from 23.23‰ to 23.99‰. The $\delta^{18}O$ -ref_i correlate well with each other with a mean standard deviation of 0.85 and a mean Pearson coefficient of the pairwise correlations (\bar{R}) of 0.62 over the entire analysis period (935–1157 CE) (Cook *et al.* 2000: 81). The running expressed population signal (EPS) (Wigley *et al.* 1984; Speer 2012) was higher than 0.85 for the period 1048–1118 CE where the sample depth for each year was at least 4. The cross-dating of the five tree-ring series corresponding to the five $\delta^{18}O$ -ref series show Baillie Pilcher *t*-values (TVBP) between 2.3 and 6.4 (Table 2; Baillie & Pilcher 1973; Sander & Levanic 1996) and a medium to strong inter-series signal. The cross-correlation of the five $\delta^{18}O$ -ref_i series show *t*-values between 10.77 and 2.15 (Table 2), thus, presenting a stronger inter-series coherence than the ring-widths.

The blind cross-dating of the five $\delta^{18}O$ -ref_i series (one against the other four) yielded the same dates as conventional dendrochronology (Tables 1 and 3). The correlation coefficients between one $\delta^{18}O$ -ref_i series and the mean of the other four were between 0.39 and 0.85, and the IF between 26.71 and over 1000 (Table 3). These results indicate the medium-to-high strength of cross-dating matches (Table 3). For 12w62-04, the match statistics were low even though the known date of the first year of growth was accurate.

The strong coherence between the $\delta^{18}O$ -ref_i series supports averaging them into an $NWAK_{180}$ chronology, the $\delta^{18}O$ master chronology for northwestern Alaska (Fig. 3). $NWAK_{180}$ is 223 years long and extends from 935 to 1157 CE. The sample depth ranged from one to five trees. $NWAK_{180}$ is almost normally distributed, with close mean and median values (0.05 and 0.02), low skewness (−0.04), and low excess Kurtosis (0.37).

The blind dating of the dendro-dated $\delta^{18}O$ series from northwestern Alaska demonstrated that the $\delta^{18}O$ -based cross-dating method was very efficient for

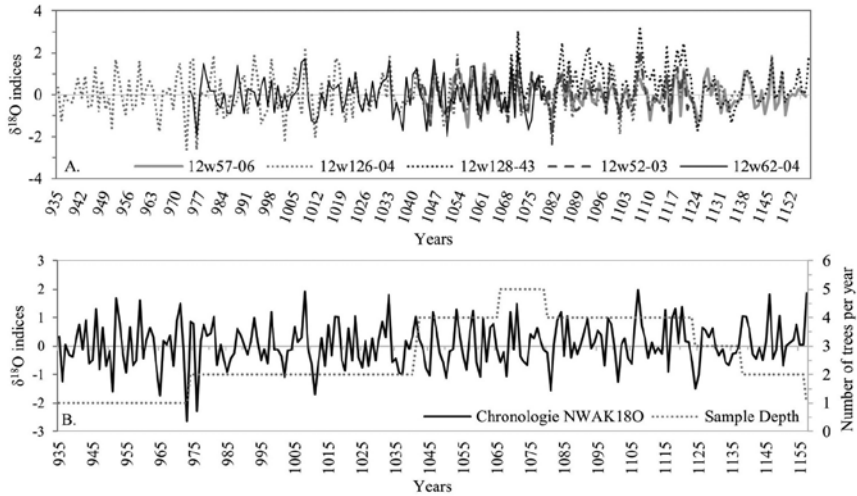


FIGURE 3 Northwest Alaska $\delta^{18}\text{O}$ master chronology and individual series. (A) The five individual $\delta^{18}\text{O}$ -ref_i series positioned in calendar time. (B) NWAK₁₈₀ chronology (935–1157 CE) (black line) and sample depth (grey dotted line)

dating archaeological timbers from coastal sites when they came from trees with the same geographical origin. Each dating match probability exceeded the statistical thresholds of validation indicated by the authors, supporting the hypothesis of a strong $\delta^{18}\text{O}$ signal, at least, at the regional scale (Table 3). The length of the chronology and the number of trees per year do not seem to be an obstacle for cross-dating contemporary $\delta^{18}\text{O}$ series from northwestern Alaska trees. This supports the hypothesis of very strong inter-tree isotopic signal coherency at the regional scale.

3.2 Evaluating the Approach with the $\delta^{18}\text{O}$ -Test Series

The cross-dating of the three floating $\delta^{18}\text{O}$ -test series with NWAK₁₈₀ yielded low statistics for 12w128-03 and 12w51-22. The match probabilities did not pass the statistical thresholds of validity, either on the whole chronology (935–1157 CE) or on the BRS chronology ($n > 3$; 1040–1137 CE) (Table 4). The dates obtained for the first ring of the series, respectively 937 and 1074 CE for the entire chronology and 948 and 1065 CE for the BRS chronology, did not fall in their wiggle-matching intervals, 1034–1052 and 1087–1112 CE, respectively (Tables 1 and 4). Visually, some pointer years were common to both the series and NWAK₁₈₀, but the overall congruency was low (Fig. 4A, B). Given the low statistics and disagreement with the wiggle-matching time intervals, we did not validate these results.

TABLE 4 Results of the cross-dating of NWAK₁₈₀ chronology and floating $\delta^{18}\text{O}$ -test_i series

Series	Chronology	Strongest match	OVL	r	df	Student's t -value	$1/P$	IF	^{14}C WM interval
12W128-03	Whole	937	154	0.24	128	2.76	150.84	1.02	–
	BRS	948	62	0.38	53	3	240.13	2.16	–
12W51-22	Whole	1074	79	0.32	66	2.77	137.58	1.27	–
	BRS	1065	73	0.31	61	2.51	67.65	1.59	–
12W62-05	Whole	1073	85	0.37	72	3.42	979.84	4.61	X
	BRS	1073	65	0.40	54	3.18	404.76	7.65	X

Note: x indicates agreement between the age of the first year of growth (or first dated ring) and the wiggle-matching calendar interval for that first ring. Whole and BRS indicate that the whole NWAK₁₈₀ chronology (935–1157 CE) and the better-replicated section of the NWAK₁₈₀ chronology ($n>3$; 1040–1137 CE) are used for the cross-dating respectively.

For the 12W62-05 series, the statistics were moderately good, and the match probabilities stronger than those of the other two (Table 4). This match probability with the whole NWAK₁₈₀ chronology relies on an 85-year overlap, an $r = 0.37$, and a $t = 3.42$, which is close to the performance of sample 12W62-04 that was successfully dated using TRW standard dendrochronology and $\delta^{18}\text{O}$. The inverse probability was close to 1,000; however, the IF was less than 10 (the validity threshold proposed by Loader *et al.* 2019). When the $\delta^{18}\text{O}$ cross-dating was calculated with the BRS NWAK₁₈₀ chronology, we obtained the same match probability date with statistics slightly stronger for r (0.40 instead of 0.37) and IF (7.65 instead of 4.61) but slightly lower for t (3.18 instead of 3.42) and the inverse probability (404.76 instead of 979.84) (Table 4). The number of trees for each year of the chronology likely played a role in the strength of the correlations obtained. The date of the first year of growth at 1073 CE is consistent with the wiggle-matching interval of 1071–1102 CE (Tables 1 and 4). The first year of growth at 1073 CE for this series provides a date of 1192 CE for the last measured growth ring, which is consistent with the youngest timber date for F-12 house (Alix *et al.* 2020a,b). Some pointer years are common between the 12W62-05 series and NWAK₁₈₀, and there is overall consistency of the two signals, especially between 1073 and 1121 CE and between 1138 and 1157 CE (Fig. 4C). The agreement with the wiggle-matching interval and elements of similarity advocates 1073 CE as the first year of growth of sample 12W62-05. However, this result must be confirmed by further analyses.

Overall, none of the results are convincing for the three $\delta^{18}\text{O}$ -test series of unknown geographical origins and need to be refined. Only one of the

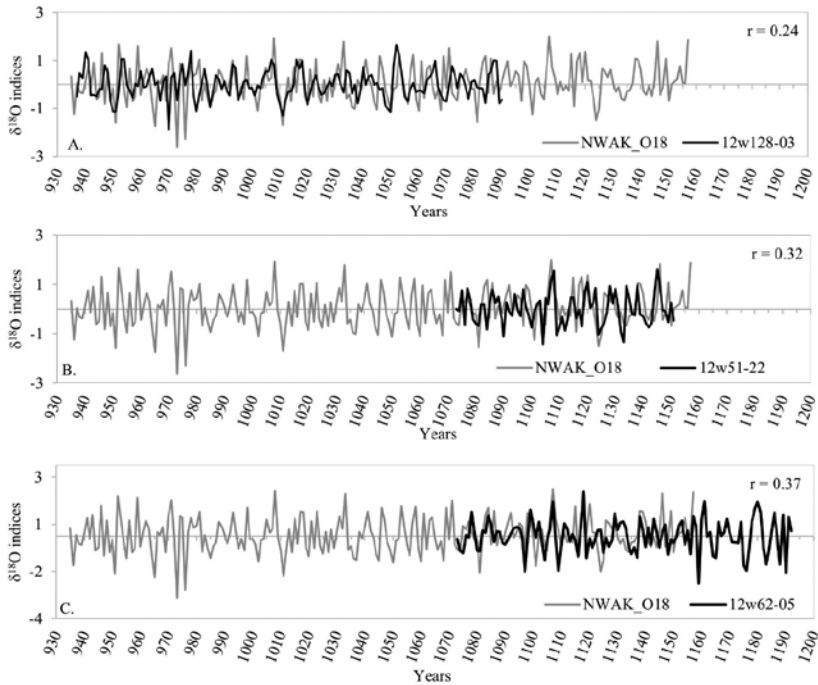


FIGURE 4 Comparisons of the whole NWAK₁₈₀ chronology (grey) and δ¹⁸O–test_i series (black). (A) 12w128-03, beginning in 937 CE (undated, fails statistics and ¹⁴C wiggle-matching disagreement). (B) 12w51-22 beginning in 1074 CE (undated, fails statistics and ¹⁴C wiggle-matching disagreement). (C) 12w62-05 beginning in 1073 CE (plausible, low statistics but ¹⁴C wiggle-matching agreement)

three samples showed an agreement. The reference chronology, NWAK₁₈₀, is 223 years old with a sample depth of only 1 to 5 trees per year. As a result, when the sample depth is less than four trees, the chronology may not be representative of the tree population (EPS=0.85). Based on the wiggle-matching interval in which the first measured ring was most likely dated (Table 1), series 12w51-22 (wiggle-matching: 1087–1112 CE) was located in the younger part of NWAK₁₈₀ where the series is of less quality (sample depth lower than four trees). This may explain why we found no significant matches with NWAK₁₈₀. The series 12w128-03 (1034–1052 CE) and 12w62-05 (1071–1102 CE) are contemporaneous with more robust portions of NWAK₁₈₀ (four to five trees) over a longer period. The poor agreement between 12w128-03 and NWAK₁₈₀ may indicate that the origin of these trees is far beyond the geographic area in which NWAK₁₈₀ is representative. This suggests that the samples are from trees that grew in regions influenced by a different mode of climate variability than that in northwestern Alaska.

The validity area of the reference series $NWAK_{18O}$ may not be wide enough (geographically). This is not what we anticipated from the distribution of $\delta^{18}O$ in precipitation depicting a gradual southwest-to-northeast ^{18}O progressive depletion (West *et al.* 2010; Isomap ©Bowen 2003–2022), which should be consistent with high correlations of $\delta^{18}O$ chronologies over large distances. Thus, the distribution of $\delta^{18}O$ in precipitation may be more heterogenous than expected or the precipitation $\delta^{18}O$ signal may be transformed by trees in such a way that the distribution of $\delta^{18}O$ in tree-rings may not be as spatially consistent as that of precipitation. This should be further investigated in the future.

4 Conclusion

This preliminary study indicates a strong and regionally consistent $\delta^{18}O$ signal at the regional scale between dendro-dated series from northwestern Alaska during the early 2nd millennium CE. The blind dating of each individual series contributing to $NWAK_{18O}$ with the mean of the other four provided the same dating results as the conventional TRW dendrochronology. With medium-to-high cross-dating strength, blind dating supports averaging the individual series into one $NWAK_{18O}$ master chronology. The results of the three cross-dating floating $\delta^{18}O$ -test series from unknown geographic origins with $NWAK_{18O}$ are unconvincing for two samples which suggests that they are from regions where the isotopic signal differs from that of northwestern Alaska. The likely date of $\delta^{18}O$ -test series 12w62-05 is plausible. However, the low strength of cross-dating advocates the acquisition of new data to extend and strengthen the $NWAK_{18O}$ chronology and possibly increase the strength of cross-dating matches. We used an approach based on multiple proxies using dendro-dated timbers to evaluate the performance of oxygen isotope cross-dating. To obtain secure and independent dating results using oxygen isotope ($\delta^{18}O$) dendrochronology, it is necessary to develop a longer and well-replicated chronology.

A longer and more robust chronology could, then, be used to date other archaeological wood samples, thus contributing to refining the chronological and climatic framework of the 2nd millennium CE in Alaska that saw the emergence of the Inuit culture. Oxygen isotope cross-dating, with a longer reference chronology, may help overcome the absence of sufficiently long reference ring-width chronologies for dating Birnirk and Thule structural wood elements originating from various regions, where ^{18}O progressive depletion shows a gradual southwest-to-northeast distribution.

Stable isotope dendrochronology is a developing tool complementary to conventional dendrochronology that can help date additional archaeological wood in the future. It is an expensive and time-consuming method that

can only be used as a complement to conventional dendrochronology, not as a replacement tool. At this stage, it is important to strengthen and lengthen the $\text{NWAK}_{18\text{O}}$, establish a gradient of $\delta^{18\text{O}}$ isotopic signal in western Alaska and record its spatio-temporal variability. This will help understand the factors contributing to this variability. In the future, further development of $\text{NWAK}_{18\text{O}}$ and its contribution to the annual dating of Birnirk and Thule architectural timbers from coastal sites may contribute to a broader geographic identification of multiple driftwood source regions.

Acknowledgements

The Cape Espenberg tree-ring samples were collected as part of the Cape Espenberg Birnirk Project (CEBP), PIS: C. Alix and O.K. Mason. Our deepest thanks go to the communities of Shishmaref, Deering, and Kotzebue for their participation in and contribution to the consultation process during the preparation stages of the project. We especially thank the families with ancestral links and ties to Cape Espenberg for supporting our archaeological efforts and for their collaboration. The Cape Espenberg archaeology project (CEBP Project) was funded by a collaborative grant (ARC-1523160, ARC-1523205 and ARC-1523059) from the Office of Polar Programs Arctic Social Sciences at the National Science Foundation (NSF) and received funding from the Archaeology Commission of the French Ministry of Foreign Affairs. This research was part of J. Taïeb doctoral research which was supported by a 3-year PhD fellowship from the University of Paris 1 Pantheon-Sorbonne and two grants from the World Wood Day Foundation and International Wood Culture Society for the project "Let the Wood Speak: Dendro-Archaeology, Climate and Culture in Northwestern Alaska at the Beginning of the Second Millennium AD". Radiocarbon dating for ^{14}C wiggle-matching analyses was funded by CEA-Saclay and conducted at the Laboratoire de Mesure du Carbone 14 (CEA-Saclay, Gif-sur-Yvettes, France). We are grateful to Glenn P. Juday, Emeritus Professor at the University of Alaska Fairbanks (UAF), for his advice on conventional tree-ring analyses, as well as Nancy Bigelow at the Alaska Quaternary Center at UAF and Owen K. Mason (INSTAAR, University of Colorado-Boulder and co-lead PI of the CEBP Project) for their continued support. We also thank Ryan Jess and Mike Lorrain at UAF who prepared and measured parts of the Cape Espenberg samples. Finally, we would like to thank Monique Pierre, Michel Stievenard, and Tiphaine Penchenat from the dendro team of the Laboratoire des Sciences du Climat et de l'Environnement (LSCE) for their valuable help with the various geochemical analyses. The CEBP Project was conducted in accordance with the Memorandum Of Agreement between the National Park Service, the NSF,

and the Alaska State Historic Preservation Officer regarding Data Recovery and Intentional Excavation of sites KTZ-304, KTZ-094 and KTZ-157 at Cape Espenberg Bering Land Bridge National Preserve, and the NAGPRA Plan Of Action for Intentional Excavation of Human Skeletal Remains from House-Pit Features at KTZ-304 and Surface Remains from KTZ-094 and KTZ-157 at Cape Espenberg Bering Land Bridge National Preserve (Agreement). It complies with the National Park Service research requirements and receives Research Permit and Reporting System Permits #BELA2-16_SCI_0002, BELA2017_SCI_0003, and BELA2018_SCI_0005 for the project's three field seasons.

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Appendix



FIGURE A1 Left: Three of the eight *Picea glauca* cross-sections presented here are from the architectural elements of Birnirk house F-12 (KTZ-304). Right: North room of F-12 at the end of the 2017 excavation (C. Alix)

TABLE A1 Categories of tested filters and first-order autocorrelation AR₁ of the NWAK₁₈₀ chronology according to the different filters tested

Filter	Definition by Loader <i>et al.</i> (2019)	Formula	AR ₁
Raw data	–	–	0.1861
1st Diff	First-order difference	$year_n - year_{n-1}$	-0.4184
Prop2years	Proportion of last two years, the default filter in CDendro	$year_n / (year_n + year_{n-1})$	-0.4166
Hollstein	Hollstein (1980)	$\ln(year_n + year_{n-1})$	-0.4165
BP5	Baillie and Pilcher (1973): Index for year _n is 'logarithm of the percentage of the mean of the five rings of which it is the center value'	$\ln(100 * (year_n / ((year_{n+2} + year_{n+1} + year_n + year_{n-1} + year_{n-2}) / 5)))$	-0.2558
R5div	Rectangular 5-year filter with indices derived by division	–	-0.2551

TABLE A1 Categories of tested filters and first-order autocorrelation AR_1 (*cont.*)

Filter	Definition by Loader <i>et al.</i> (2019)	Formula	AR_1
R5sub	Rectangular filter, each year	–	–0.2587
R7sub	equally weighted, with indices	–	–0.1358
R9sub	derived by subtraction	–	–0.0330
R11sub		–	0.0227

Note: The filters used are described in the Supporting Information (Table S1) of Loader *et al.* (2019). Italics, AR_1 denotes the selected filter.