Contribution of ^{14}C wiggle-matching to dendroarchaeology of coastal Birnirk and Thule sites in northern Alaska

Apports du wiggle-matching aux études dendroarchéologiques de sites côtiers Birnirk et Thule dans le nord de l'Alaska

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ABSTRACT. Along the coast of Northern Alaska, wood remains from Birnirk and Thule archaeological sites are extremely well-preserved and have the potential to document climatic variations and cultural transformations in the early 2nd millennium CE in northwest Alaska. In this treeless coastal tundra, the primary wood resource is driftwood that come from the boreal forest carried by major interior rivers and ocean currents. While in northern Alaska, some Birnirk and Thule archaeological wood samples can be dated using the rare existing millennial tree ring master chronologies, many come from geographical areas where tree-ring master chronologies are too short (250-300 years). Here, we explore the potential of high-resolution wiggle-matching to accurately date tree-ring series that cannot be dated by conventional dendrochronology and develop preliminary tree-ring chronologies. We present the wiggle-matching results based on 75 radiocarbon dates for eight archaeological timbers from the Piġniq, Rising Whale and Pingusugruk coastal sites in northern Alaska. Wiggle-matching makes it possible to reduce the calendrical interval of these timbers' last growth ring from centennial to decadal range and position 22 timbers in calendar time. These results open new insights into tree-ring dating of others Birnirk and Thule architectural tree-ring samples and analyzing climatic variations of the early 2nd millennium CE, in different regions of Alaska.

RÉSUMÉ. Le long des littoraux nord alaskiens, les bois d'architecture des sites archéologiques des cultures Birnirk et Thulé sont extrêmement bien conservés et ont le potentiel de documenter les variations climatiques et les transformations culturelles du début du IIe millénaire de notre ère dans le nord-ouest de l'Alaska. Dans ce milieu de toundra sans arbres, les bois flottés provenant de la forêt boréale et transportés par les principaux fleuves de l'intérieur et les courants océaniques constituent la principale ressource en bois. Si, dans le nord de l'Alaska, certains bois archéologiques peuvent être datés à l'aide des rares séquences dendrochronologiques millénaires, beaucoup proviennent de zones géographiques où les chronologies de largeurs de cernes sont trop courtes (300-350 ans). Nous explorons ici les possibilités offertes par la méthode de datation à haute résolution du wiggle-matching pour situer avec précision dans le temps calendaire les bois non datés par la dendrochronologie conventionnelle et pour développer des chronologies préliminaires. Nous présentons ici les résultats du wiggle-matching basés sur 75 datations radiocarbone de huit pièces de bois archéologiques provenant des sites côtiers nord-alaskiens de Piġniq, Rising Whale et Pingusugruk. Le wiggle-matching de ces bois appartenant à des séquences flottantes a permis de contraindre au plus près l'intervalle calendaire dans lequel se situe le dernier cerne de croissance présent et de positionner dans le temps calendaire 22 bois archéologiques. Ces datations ouvrent de nouvelles perspectives pour la datation croisée d'autres bois d'architecture Birnirk and Thule, et pour l'analyse des variations climatiques du début du IIe millénaire de notre ère dans différentes régions d'Alaska.

KEYWORDS. Dendroarchaeology, Wiggle-matching, Northern Alaska, Thule, Coastal wood.
MOTS-CLÉS. Dendroarchéologie, Wiggle-matching, Nord de l'Alaska, Thule, Bois côtiers.

Introduction

Northwest Alaska is a crucial region for understanding the cultural transformation of the early second millennium CE that led to the development of modern Inuit culture in the North American Arctic. During the Medieval Climate Anomaly [MCA] (9^{th}-13^{th} centuries), a period of climatic instability, Thule culture emerged from the Birnirk and Punuk cultures in the Bering Strait region and along the coast of northern Alaska (Mason, 2020; ***figure 1***). People of Birnirk and Thule culture affiliation are genetic and cultural ancestors of the modern Inuit (Raghavan *et al.*, 2014; Unkel *et al.*, 2022).

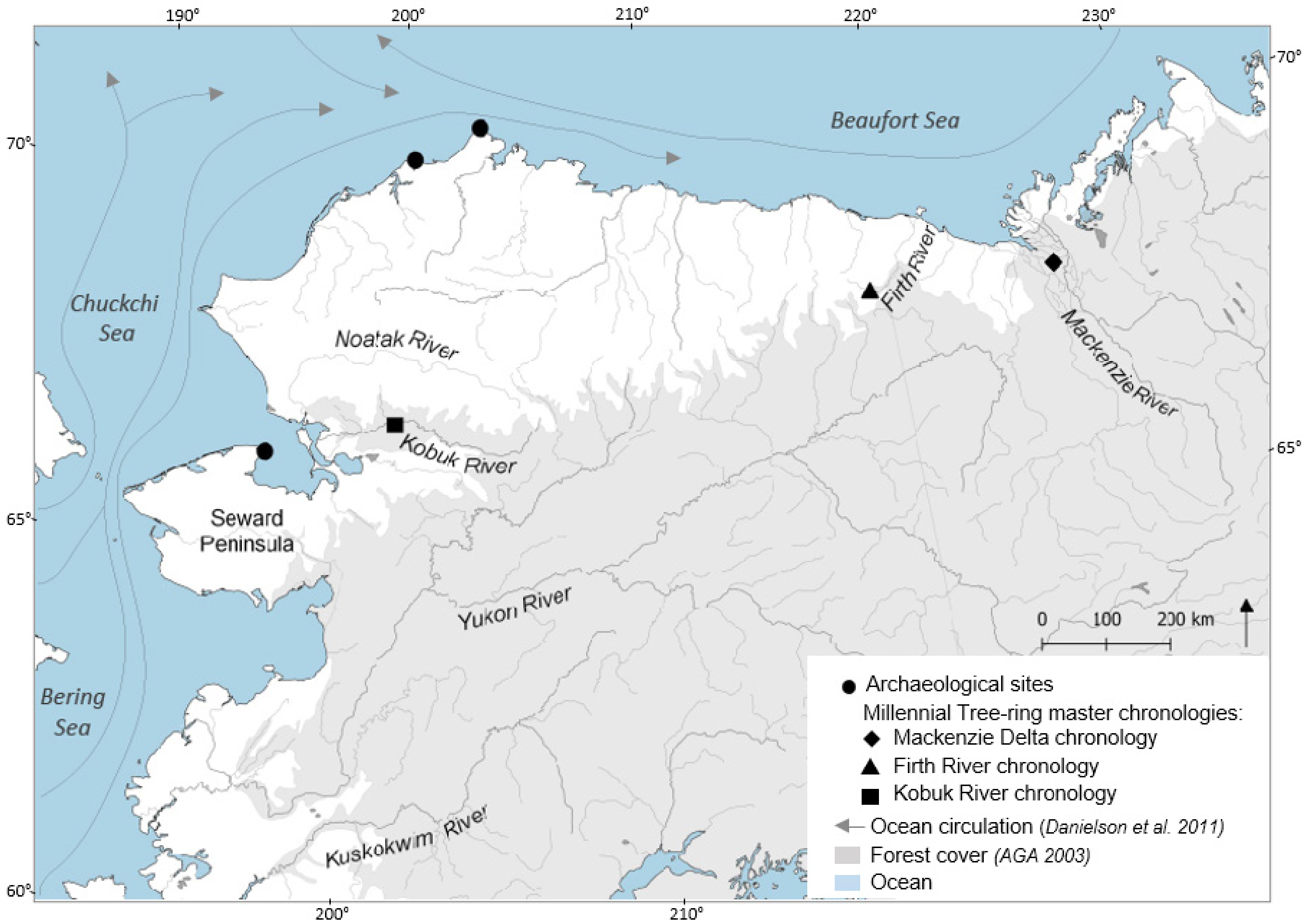


Figure 1. *Geographic map of western North American Arctic, including the three archaeological sites discussed in the paper and the millennial tree-ring master chronologies (*Picea glauca*) of the Kobuk area (978-2002 CE; Giddings, 1948, 1952; Graumlich & King, 1997; D'Arrigo* et al.*, 2005), the Firth River (1067-2002 CE; D'Arrigo* et al.*, 2006) and the Mackenzie Delta (1245-2006 CE; Porter* et al.*, 2013). © J. Taïeb.*

In northwest Alaska, the Medieval Climate Anomaly (ca. 850-1250 CE) is documented in several regional and extra-regional independent records (Nicolle *et al.*, 2018): moraines, glacial and marine sediment cores in Central and South Alaska (Calkin *et al.*, 2001; Wiles *et al.*, 2008, 2010; Vachula, 2015); lake sediments in the Central Brooks Range (Bird, 2009); tree rings and beach-ridges in Northwestern Alaska around the Bering Strait (D'Arrigo *et al.*, 2005; Mason, 1990; Mason & Jordan, 1993; Mason *et al.*, 1995, 2019). The coastal beach-ridge chronologies for northwestern Alaska show that the MCA is a period of climatic instability, alternating between warm and cold fluctuations characterized by an intensification of storms (Mason & Jordan, 1993; Mason *et al.*, 1995, 2019). In Northwestern Alaska, the tree-ring master chronology of the Kobuk River Valley is a 1000-yr long sequence (978-1948 CE) built in the 1940's by archaeologist James Louis Giddings (Giddings, 1941, 1948, 1952b; Oswalt, 1949; Van Stone, 1953; Nash, 1999, 2000; ***figure 1***). In the 1950's, the development of radiocarbon dating rapidly supplanted dendrochronology in Alaska (Nash, 1999, 2000). While dendroclimatologists re-analyzed the Kobuk chronology in the 1990's and early 2000's and contributed to its improvement by adding a larger number of standing trees and historical timbers (Graumlich & King, 1997; D'Arrigo *et al.*, 2005), the early part of the sequence based on a low number of trees is a challenge for climate and standard tree-ring analyses. The sample depth declines from 30 to 4 trees between 1250 and 1100 CE (based on data available at the International Tree-Ring Databank, ITRDB; Zhao *et al.*, 2018). As a result, the chronology and magnitude of the MCA climatic variations require a better resolution in Northwest Alaska to conduct detailed temporal and spatial analyses of the complex interactions between environment and people at this key moment in the development of Inuit culture.

Along the northern coasts of Alaska, wood remains from Birnirk and Thule sites are extremely well-preserved and are a testimony of their importance in their daily life, architecture and material culture (Giddings, 1941, 1952b; Alix, 2009, 2016; ***figure 2***). In this treeless tundra environment, people collected driftwood from beaches. Timbers stranded on the coast originate mainly in the subarctic boreal forests of Interior Alaska and are transported to the sea by major rivers, *i.e.* the Yukon and Kuskokwim rivers in Interior Alaska and the Noatak and Kobuk rivers in Northwestern Alaska, and to the coast thanks to prevailing sea currents and winds (Giddings, 1943, 1952a; Alix, 2005; ***figure 1***). Consequently, trees that produce the wood found on the Alaskan coast and in archaeological sites grew in various parts of Alaska and potentially elsewhere (Giddings, 1941; Eurola, 1971; Eggertsson, 1995; Alix & Brewster, 2004; Alix, 2005; Sander *et al.*, 2021).

In the northwestern American Arctic, three tree-ring master chronologies are long enough to be used to cross-date archaeological wood from Birnirk and Thule sites (***figure 1***): the Giddings Kobuk River chronology (978-2002 CE) in northwestern Alaska (Giddings, 1948, 1952b; Graumlich & King, 1997; D'Arrigo *et al.*, 2005), the Firth River chronology (1067-2002 CE) in northeastern Alaska (D'Arrigo *et al.*, 2006) and the Mackenzie River drainage chronologies (1245-2006 CE) in northwestern Canada (Porter *et al.*, 2013). Based on the geometry of sea currents, the Kobuk River

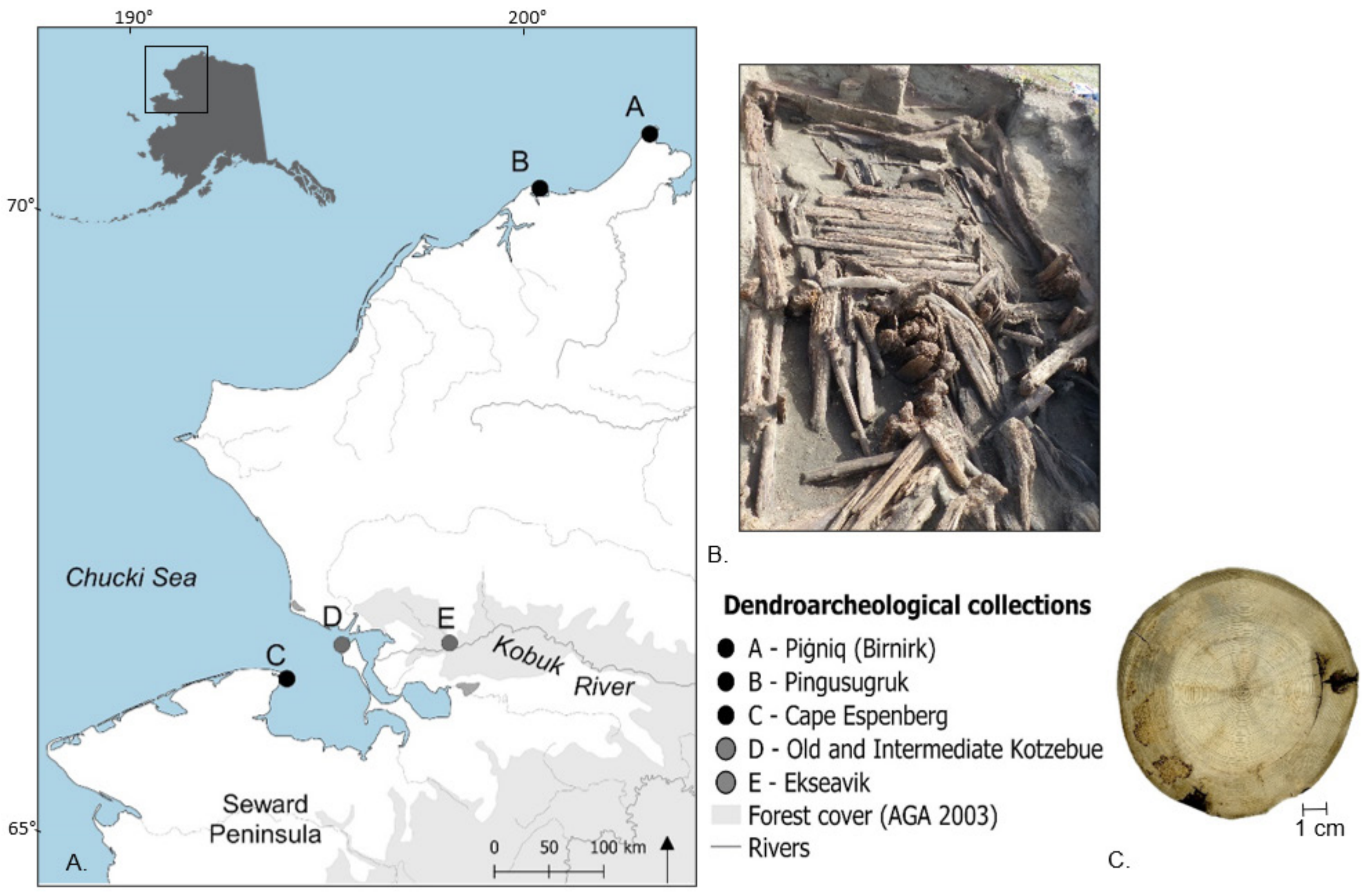


Figure 2. *A. Location of existing tree-ring samples collections from Birnirk and Thule sites in Northern Alaska (black dots: sites discussed in the paper). © J. Taïeb; B. Architectural elements from Birnirk structure F-12 (north-east room) at Cape Espenberg. © C. Alix; C. Cross-section 12w51-22 from structure F-12 at Cape Espenberg. © J. Taïeb.*

Master chronology is the most suited to cross-date wood samples from archaeological sites in northwestern Alaska (***figure 1***). However, a large proportion of the archaeological wood remains found in coastal sites comes from the interior of Alaska, mainly by way of the Yukon River (Giddings, 1941, 1952a; Alix, 2005), where tree-ring master chronologies remain short, 250 to 400 years (Juday *et al.*, 2003, 2015).

While tree-ring master chronologies from regions likely to produce a large number of driftwood logs are too short and cannot be used to cross-date architectural wood remains from Birnirk and Thule coastal sites, our objective is to develop tree-ring chronologies based on these archaeological wood samples using other dating techniques. Ultimately, our goal is to analyze the MCA climate variations in northwestern and Interior Alaska regions. Radiocarbon dating the last year of growth of a wood sample can be an acceptable solution to place in calendar time these preliminary floating chronologies made up of multiple cross-dated archaeological samples. However, the radiocarbon calibration curve of the northern hemisphere is characterized by several plateaus in the first half of the second millennium CE (e.g. between 1040 and 1170 CE), which results in wide calendar age estimates and a poor chronological resolution (Morrison, 1989, 2001; Reimer *et al.*, 2020). We therefore used high-resolution wiggle-matching radiocarbon dating of floating tree-ring sequences to accurately and precisely place them in calendar time. The wiggle-matching dating (WMD) technique combines dendrochronology, radiocarbon dating and Bayesian statistics to overcome challenges of radiocarbon calibration in terms of resolution (Galimberti *et al.*, 2004). The WMD technique highly improves calendar age estimates as testified by its use in various archaeological contexts. Tested here for the first time in Northern Alaska, this approach may be a good alternative to i) access the high chronometric and climatic potential of architectural wood from coastal sites, and thus floating tree-ring width series built from them, and ii) develop master tree-ring chronologies. In this paper, we present the results of high-resolution wiggle-matching dating on eight archaeological wood cross-sections (75 radiocarbon dates) from Birnirk and Thule period sites of Pingusugruk, Rising Whale and Piġniq in northern Alaska (***figure 2***). Then, we provide resulting methodological and archaeological considerations.

1. Material and Method

1.1. Studied sites and dendrochronological findings

We inventoried existing tree-ring collections from Thule and Birnirk sites in Northern Alaska (***figure 2***) available at the University of Alaska, Fairbanks (UAF). These collections contain archaeological tree-ring cross-sections sampled from the wood frame of winter house structures (Rye, 1950; Giddings, 1952b; Carter, 1966; Sheehan, 1997; Alix *et al.*, 2015; Alix & Mason, 2018; ***figure 2***). We selected and measured the ring-widths of 283 series (*Picea glauca [Moench] Voss*) following standard dendrochronological procedures (Fritts, 1976; Schweingruber, 1988; Cook & Kairiukstis, 1990; Speer, 2012). For the coastal site of Pingusugruk in Northern Alaska (***figure 2***), 86.2 % of the ring-widths series remained floating after their cross-dating with the three-millennial tree-ring chronologies mentioned above (Taïeb *et al.*, 2022; ***figure 1***). The results were identical for Piġniq and Rising Whale coastal sites as many of the timbers come from regions other than northwestern Alaska, where the master tree-ring chronologies are too short (*supra*).

We selected eight timbers from three coastal sites for radiocarbon dating and wiggle-matching analysis (***figure 2; table 1***). One timber is from the Birnirk type site of Piġniq (Birnirk) at Utqiaġvik, Point Barrow (***figure 2; table 1***), which was most likely sampled in the 1940's and 1950's (Rye, 1950; Ford, 1959; Carter, 1966). The site contains nineteen house mounds with archaeological remains from the Birnirk to late Thule cultures. While the Piġniq site is poorly dated (Mason, 2016), its Birnirk cultural component is generally placed roughly between the 8th or 9th and 12th centuries (Ford, 1959; Carter, 1966; Mason, 2000; Morrison, 2001; Mason & Bowers, 2009). The sample selected for analysis is labeled as coming from mound C (Rye, 1950), where archaeologist J. A. Ford (1959: 48-49) only described one house feature with typical early Birnirk harpoon heads. Six cross-sections are from the recent excavation of a Birnirk house (F-12) and an early Thule house (F-21) at the Rising Whale site, Cape Espenberg (***figure 2; table 1***; Alix *et al.*, 2018). Radiocarbon and tree-ring dates place the two houses in the late 10th to the early 14th centuries and provide a precise record of the Birnirk to Thule transition in Northwestern Alaska (Alix & Mason, 2018; Alix *et al.*, 2020). The last wooden sample is from the whaling village of Pingusugruk at Point Franklin (***figure 2; table 1***), a site partially excavated in the 1990's, and recently radiocarbon and tree-ring dated to the 15th-17th centuries (Sheehan, 1997; Krus *et al.*, 2019; Taïeb *et al.*, 2022). This construction timber is from the SL2 single house, and document a Late Western Thule occupation (Sheehan, 1997; Jensen, 2016).

Table 1. *Selected samples and dating strategy. N correspond to the number of series constituting each floating sequence, followed by the length of the sequence. © J. Taïeb.*

Site	Cross-section	Context	Number of Rings	Arguments for selection	Number of sampled rings	Rings interval
Piġniq Mound C (9-13th)	C-7	Unknown Single house	93	Potential correlation with the Firth River master chronology	9	9-10
Cape Espenberg House F-12 (10-12th)	12w107-01	Wall log West room	86	Same tree as another architectural element	9	9-10
	12w51-22	Roof log Tunnel	79	Floating sequence (n=2, 83 years)	9	9-10
	12w62-05	Floor plank West room	118	Floating sequence (n=4, 116 years)	9	14-15
	12w128-03	Wall log East room	151	Floating sequence (n=2, 157 years)	16	9-10
Cape Espenberg House F-21 (13-14th)	21w27-11	Post Main room	120	Floating sequence (n=4, 127 years)	7	9-10
	21w17-06	Wall log Tunnel	154	Same tree as another undated architectural element	8	9-10
Pingusugruk SL2 house (16-17th)	SL2-1986	North-west corner of the single house	73	Floating sequence (n=5, 217 years)	8	9-10

1.2. Relevance of ^{14}C geochronology for our archaeological context

Before using ^{14}C dating and calibration, two points must be clarified: i) the fact that the Piġniq and Pingusugruk sites are located above the 70°N latitude (***figure 2; table 1***) where calibration is questionable (Reimer *et al.*, 2020), and ii) the meaning of a date obtained from archaeological coastal wood. As stated earlier, timbers are driftwood originating from forested regions of Interior Alaska at latitudes well under 70°N. Calibrating raw ^{14}C measurements with the latest ^{14}C curve, IntCal20, is therefore acceptable, even for the northernmost archeological sites. It is unknown how much time elapsed between the death of the tree at its place of growth and its use as timber by coastal inhabitants. Few studies have shown that transit times between death of the tree and its deposition on the beach can be short, from a few months to a few years in some areas (Oswalt, 1951; VanStone, 1958). At the same time, people are looking for quality wood, which suggest "fresh" timbers, recently fallen and stranded (Alix, 2004, 2005). In addition, architectural wood recycling, reuse, or addition to existing features for repair should be considered. Therefore, dates obtained from archaeological coastal wood do not provide the exact date of use by people, but are *terminus post quem* (Desachy, 2012; i.e. the earliest possible felling or dying date of the used tree).

Wiggle-matching dating is a quantitative method developed from a Bayesian process that consists in calibrating together several raw ^{14}C dates whose exact age is unknown, but whose time interval, *i.e.*, the number of rings separating them, is known (Pearson, 1986; Christen & Litton, 1995; Bronk

Ramsey *et al.*, 2001; Galimberti *et al.*, 2004; Bayliss, 2007, 2015; Bronk Ramsey, 2009a; Hogg *et al.*, 2019). In radiocarbon dating, when calibrating a single ^{14}C determination, the precision of the calibrated age estimate depends mainly on the structure of the calibration curve (Hogg *et al.*, 2019). The calibration curve is not linear in time and includes short-term fluctuations (wiggles) related to the variations of past atmospheric ^{14}C concentrations. The calibration of individual dating can thus return several equiprobable intervals of calibrated years. WMD exploits the fluctuations of the ^{14}C calibration curve to model high-precision calendar age estimates, known as *posterior density estimates*. Since the calendar-year interval between the ^{14}C dates is known, the wiggle-matching technique statistically adjusts the cloud of points representing the raw ^{14}C dates to the calibration curve (curve fitting). This grouped calibration reduces the effect of the calibration curve fluctuation and considerably improves the precision of the calendar age estimates of the youngest dated ring.

1.3. Dating strategy, samples preparation and Bayesian modelling

The eight cross-sections were selected based on their potential for wiggle-matching analyses which was measured according to the following criteria: i) state of preservation, ii) presence of the last growth ring, iii) length of tree-ring series, iv) belonging to a floating sequence or to the same tree than another architectural element, and v) inferred chronological time period of the sample based on the archaeological site chronological and spatial information.

Each selected cross-section was measured and checked against previous ring-widths measurement to secure tree-ring cross-dating. Simulations were conducted prior to ^{14}C measurements to test the accuracy of the wiggle-matching approach and obtain the most accurate posterior density estimates (Bayliss & Orton, 1994; Galimberti *et al.*, 2004). We modelled the number and frequency of annual growth rings for each cross-section to be dated with the program OxCal v.4.4 and the IntCal20 atmospheric calibration curve for the northern hemisphere (Galimberti *et al.*, 2004; Bronk Ramsey, 2009; Reimer *et al.*, 2020). Cross-sections were then marked and each annual single ring to be dated (sub-sample) was cut with a scalpel under a binocular microscope. Seventy-five sub-samples were pretreated following the classic acid-base-acid (ABA) procedure and radiocarbon dated in the *Laboratoire de Mesure du Carbone 14* (LMC14, Dumoulin *et al.*, 2017; Moreau *et al.*, 2020) as part of the ARTEMIS program at LSCE-CEA Saclay, France. Raw ^{14}C measurements for each sub-sample are presented in ***appendix 1***.

Once the sub-samples were ^{14}C dated, a grouped calibration per cross-section was performed using software OxCal version 4.4 with the IntCal20 atmospheric calibration curve (Reimer *et al.*, 2020) and following two Bayesian chronological models (Bronk Ramsey *et al.*, 2001; Bronk Ramsey, 2009a, 2009b; see the OxCal 4.4 online manual; ***figure 3***). The first model is the standard "sequential" model, where the grouped calibration is based on the known interval between each ^{14}C dates and constrained by a known duration (the total number of rings; Bronk Ramsey *et al.*, 2001; Bronk Ramsey, 2009a, 2009b). We applied this model using

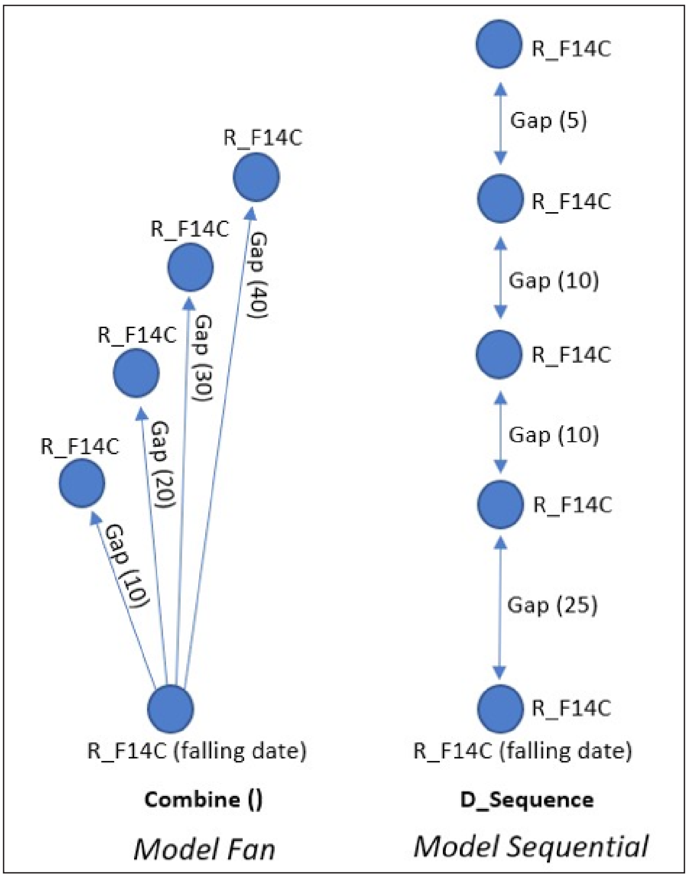


Figure 3. *Hypothesized Bayesian chronological models following the Fan model and the Sequential model. © J. Taïeb.*

the *D_Sequence* function (Bronk Ramsey *et al.*, 2001), because we knew without uncertainty the gap between each ring (***figure 3***). The second conceptual model is called the "fan" model. Instead of considering successive intervals within a same series to evaluate the age of the last point of the series, we consider several age estimations of this last ring by coupling every dated ring to this last ring. All of last ring estimates being for the same event, we can combine (using the *Combine* function) the results to get the best estimate (***figure 3***). Both models were tested to select the one providing the most precise age estimate. The combination agreement index (A_{model} for *D_Sequence* and A_{comb} for *Combine*) gives an indication of the quality of the chronological model. The higher the better and it must be superior to 60 % (Bronk Ramsey, 1995, 2009b; Bayliss, 2007). We identified outliers using both the agreement index and the individual agreement index (individual agreement < 20 %; OxCal 4.4 online manual). We re-ran the model without the identified outliers (Bronk Ramsey, 2009b), and then determined the best model based on three main modalities: presence or absence of outliers, quality of the chronological model according to statistical indices, and model producing the more precise age estimate. In the case where the obtained chronological model provided a finer posterior density estimate with outliers and agreement indices over 60 %, statistics were generally weaker, and we preferred selecting the most robust statistical model to be confident in the accuracy of the model.

2. Results

Between seven and sixteen single rings were extracted from each cross-section and distributed at intervals of 9 to 15 years (***figure 4; table 1***). In ***table 2***, we report the calendar age estimate of the youngest dated ring of each cross-section based on its single calibration, the outliers and the result of wiggle-matching calibration (initial and without outliers). A_{comb} ranges between 63.5 % and 164.4 %, indicating high quality models.

In cross-section C-7 from Piġniq, the outermost subsample was taken from the last growth ring present. The single calibration of the sample gave an age estimate at 5210-4954 BCE (95.4 %). The wiggle-matching calibration with the sequential model of the eight resulting radiocarbon dates for the last dated ring gave an estimate, at 5144-5046 BCE (95.4 %; ***figure 5; table 2***).

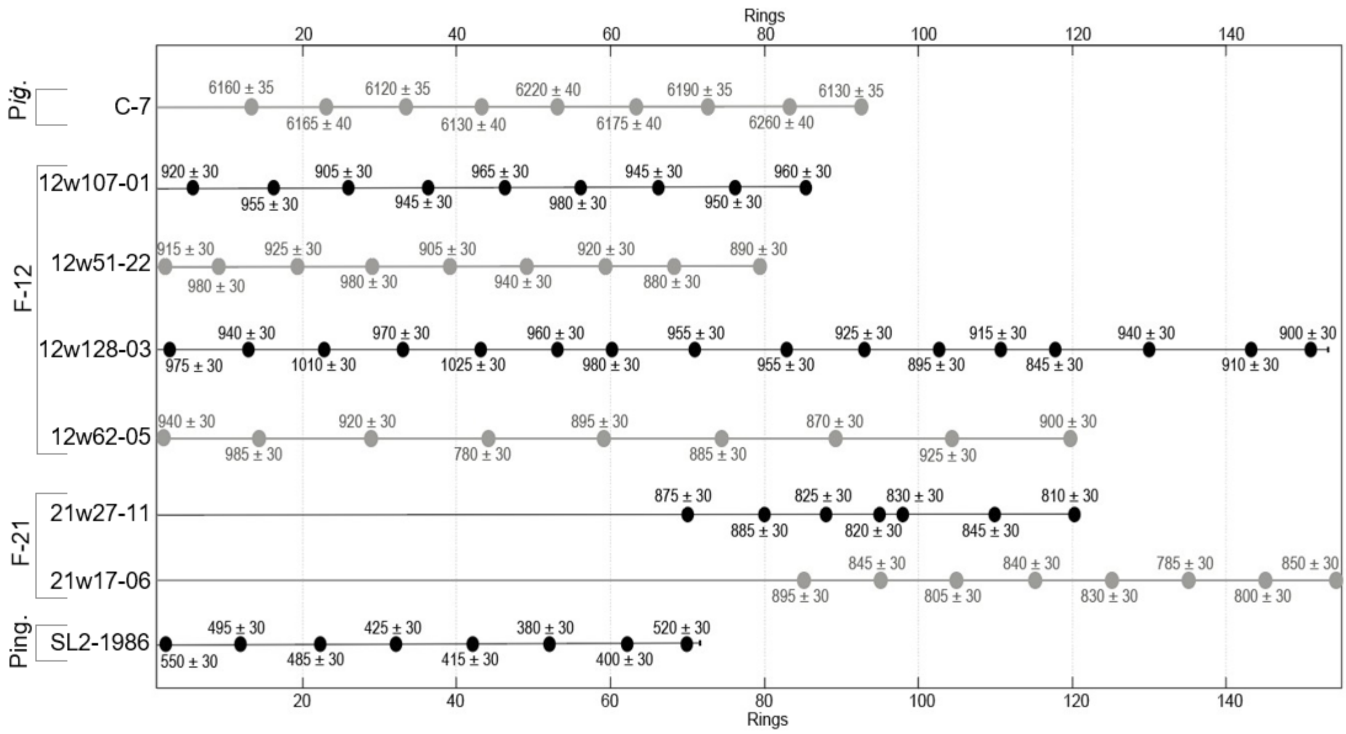


Figure 4. *Results of [14]C dating (n=75) in BP of the 8 tree-ring series. Each tree-ring series is represented by a line and each [14]C-dated single ring by a dot corresponding to its location in the tree-ring series. For the series of structure F-21, which does not correspond to a plateau period of the [14]C calibration curve, we focused on the most recent part of the tree-ring series to perform WMD (diagram inspired from Chochorowski* et al., *2014). [Ping. = Pingusugruk, Piġ. = Piġniq]. © J. Taïeb.*

Table 2. *Results of ^{14}C dating and calendar age estimates of single and wiggle-matching calibrations (95,4 %) for the outermost sub-sample each cross-section. The selected model for each cross-section is in bold and grey. © J. Taïeb.*

Sample identification			Raw data of the youngest ring				Wiggle-matched calibration							
									Sequential model			Fan model		
Site	Cross-section	Last ring dated	^{14}C lab ID	Conventional ^{14}C age (BP)	Determination of Fraction Modern (F14C)	Single calibration Calibrated date (95,4 %)	Number of sub-samples	Run	A_{model}	Outliers	Posterior density estimate (95,4 %)	A_{comb}	Outliers	Posterior density estimate (95,4 %)
Piġniq Mound C	C-7	93	SacA62747-SacA62755	6130 +/-35	0.4661385 +/- 0.0020956	5210 - 4954 BCE (256 yrs)	9	Initial	**66.6 %**	**0**	**5144-5046 BCE (98 yrs)**	66.5 %	0	5137-5043 BCE (94 yrs)
Cape Espenberg F-12	12w107-01	86	SacA62774-SacA62782	960 +/-30	0.8872652 +/- 0.0027468	1027 - 1158 CE (131 yrs)	9	Initial	**107.9 %**	**0**	**1113-1155 CE (42 yrs)**	63.4 %	2	1147-1168 CE (21 yrs)
	12w51-22	79	SacA62765-SacA62773	890 +/- 30	0.8952933 +/- 0.002528	1047 - 1221 CE (174 yrs)	9	Initial	**76.7 %**	**0**	**1165-1190 CE (25 yrs)**	75.2 %	0	1160-1194 CE (34 yrs)
	12w128-03	151	SacA62787-SacA62802	900 +/-30	0.8941104 +/- 0.0026395	1045 - 1219 CE (174 yrs)	16	Initial	8.3 %	3	1198-1216 CE (18 yrs)	7.8 %	4	1209-1219 CE (10 yrs)
								Without the three youngest outliers	**103.2 %**	**0**	**1187-1205 CE (18 yrs)**	76.6 %	0	1186-1215 CE (29 yrs)
	12w62-05	118	SacA62756-SacA62764	900 +/- 30	0.8937875 +/- 0.0027701	1045 - 1219 CE (174 yrs)	9	Initial	0.2 %	3	1227-1246 CE (19 yrs)	0.2 %	3	1231-1258 CE (27 yrs)
								Without both oldest outliers	**107.8 %**	**0**	**1188-1219 CE (31 yrs)**	87.5 %	0	1196-1221 CE (25 yrs)
Cape Espenberg F-21	21w17-06	154	SacA62814-SacA62821	850 +/- 30	0.8995261 +/- 0.0035391	1053 - 1267 CE (214 yrs)	8	Initial	**63.5 %**	**0**	**1246-1274 CE (28 yrs)**	51.2 %	1	1243-1276 CE (33 yrs)
	21w27-11	120	SacA62807-SacA62813	810 +/- 30	0.9038327 +/- 0.0023917	1213 - 1273 CE (60 yrs)	7	Initial	**84 %**	**0**	**1246-1275 CE (29 yrs)**	83.4 %	0	1222-1269 CE (47 yrs)
Pingusugruk SL2	SL2-1986	62	SacA62822-SacA62829	520 +/- 30	0.9374077 +/- 0.0025268	1398 - 1439 CE (41 yrs)	8	Initial	0.3 %	2	1464-1469 CE (5 yrs)	0.0 %	5	1466-1469 CE (3 yrs)
								Without the youngest outlier	120.2 %	0	1467-1480 CE (13 yrs)	**164.4 %**	**0**	**1478-1492 CE (14 yrs)**

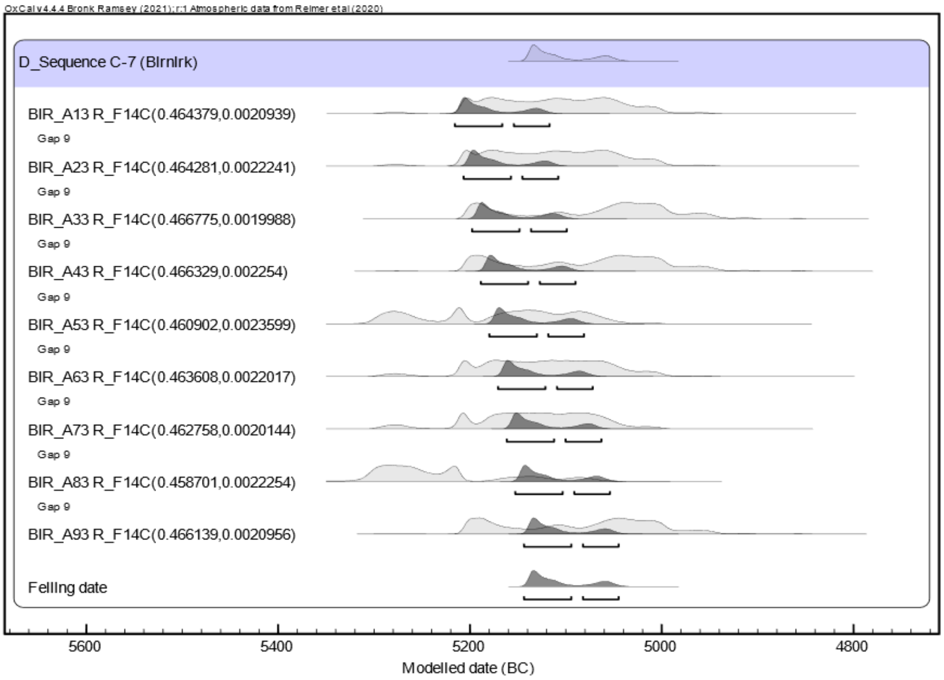
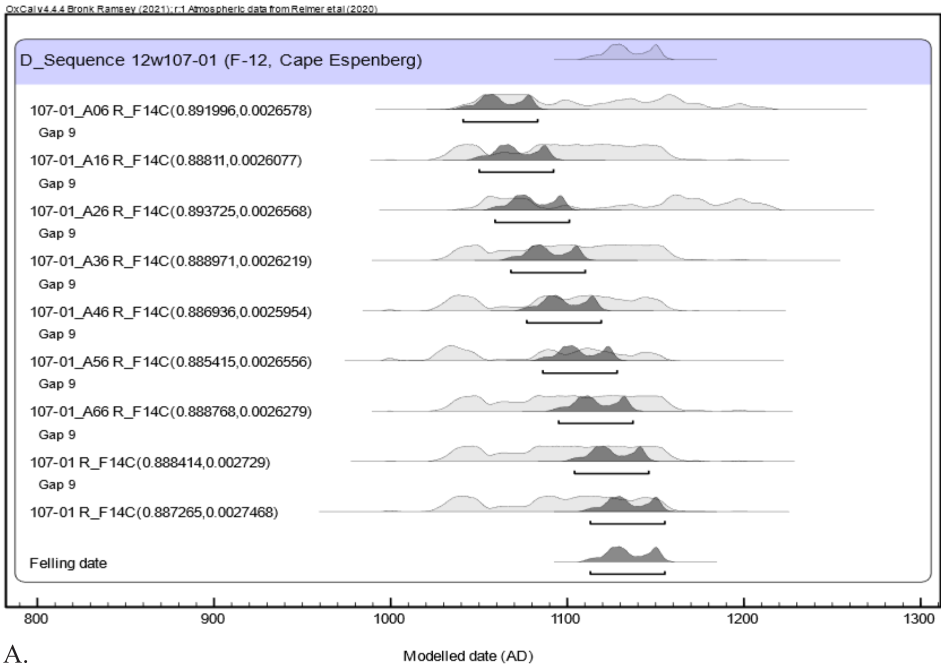


Figure 5. *Probability distributions of ^{14}C sub-samples of cross-section C-7 (Piġniq site). In light grey, the single calibration of each sub-sample. In dark grey, the wiggle-matched calibration. The wiggle-matching calendar age estimate for the outermost sub-sample (A93) is 5144-5046 BCE. © J. Taïeb.*

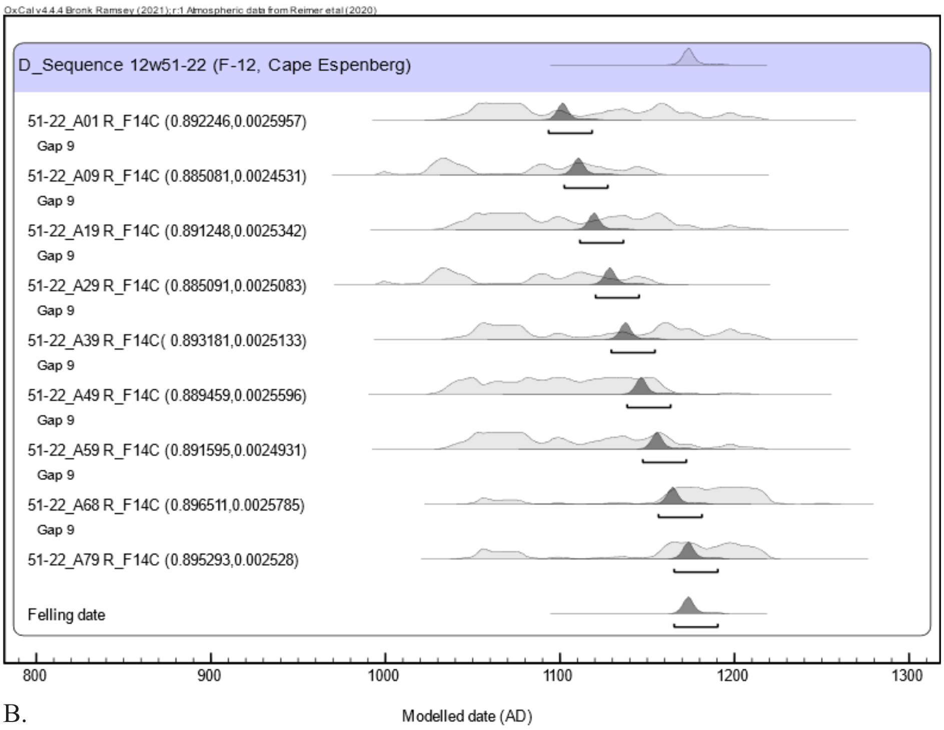
In three cross-sections from house F-12 at the Rising Whale site, the outermost subsamples were the last growth ring present. In cross-section 12w107-01, a single calibration gave an age estimate of 1027-1158 CE (95.4 %), and the wiggle-matching calibration with the sequential model of nine radiocarbon dates narrowed the age estimate of the last dated ring down to 1113-1155 CE (95.4 %; ***figure 6A; table 2***). In cross-section 12w51-22, single and wiggle-matching calibration with the sequential model of the last dated ring estimate yielded 1047-1221 CE (95.4 %), and 1165-1190 CE (95.4 %; 9 dates) respectively (***figure 6B; table 2***), while cross section 12w62-05 yielded an age of 1045-1219 CE (95.4 %) and 1188-1219 CE (95.4 %) with the sequential model (***figure 6D; table 2***). In this latter case, we excluded two individual outliers, the second outermost sub-samples which provided an older ^{14}C age and the sixth outermost sub-samples which provided a younger ^{14}C age (***figures 4; table 2***). In cross-section 12w128-03, the outermost subsample was taken from a ring, placed two rings prior to the last growth ring and did not have enough wood for dating. A single calibration gave an age estimate of 1045-1219 CE (95.4 %), and the wiggle-matching calibration with the sequential model of 13 out of 16 radiocarbon dates narrowed the age estimate down to 1187-1205 CE (95.4 %; ***figure 6C; table 2***). We excluded three individual outliers, the third, the twelfth and the fourteenth outermost sub-samples which provided older ^{14}C ages (***figure 4; table 2***). The last growth ring of 12w128-03 was then dated at 1190-1221 CE. The wiggle-matching calibration procedure for the four F-12 cross-sections helped reduce the age estimate models from 174-131 years down to 42-18 years with an A_{comb} between 76.7 % to 107.9 % (***figures 6; table 2***).

In the two cross-sections from house F-21 at the Rising Whale site, the outermost subsample was taken from the last growth ring present. For the cross-section 21w27-11, a single calibration gave an age estimate of 1213-1273 CE (95.4 %), and the wiggle-matching calibration with the sequential model of seven radiocarbon dates narrowed the age estimate of the last dated ring down to 1246-1275 CE (95.4 %; ***figure 7A; table 2***). For cross-section 21w17-06, results were 1053-1267 CE (95.4 %) for a single calibration, and 1246-1274 CE (95.4 %) for the posterior density of the last dated ring with the sequential model (***figure 7B; table 2***). The wiggle-matching calibration helped reduce the age estimate models of the two cross-sections from 214-60 years down to 29-28 years with an A_{comb} between 63.5 % and 84 % (***figures 7; table 2***).

In cross-section SL2-1986 from Pingusugruk site, the outermost subsample was taken from the penultimate growth ring present. The single calibration provided an age estimate of 1398-1439 CE (95.4 %), and the wiggle-matching calibration with the fan model using seven of the eight radiocarbon dates (one outlier) narrowed the age estimate down to 1478-1492 CE (95.4 %; ***figure 8; table 2***). We excluded the first outermost sub-samples as it provided an older ^{14}C age (***figure 4***). The last growth ring present on SL2-1986 is then dated at 1489-1503 CE (95.4 %). The wiggle-matching calibration helped reduce the age estimate models from 41 down to 14 years with an A_{comb} of 164.4 % (***figure 8; table 2***).



A.



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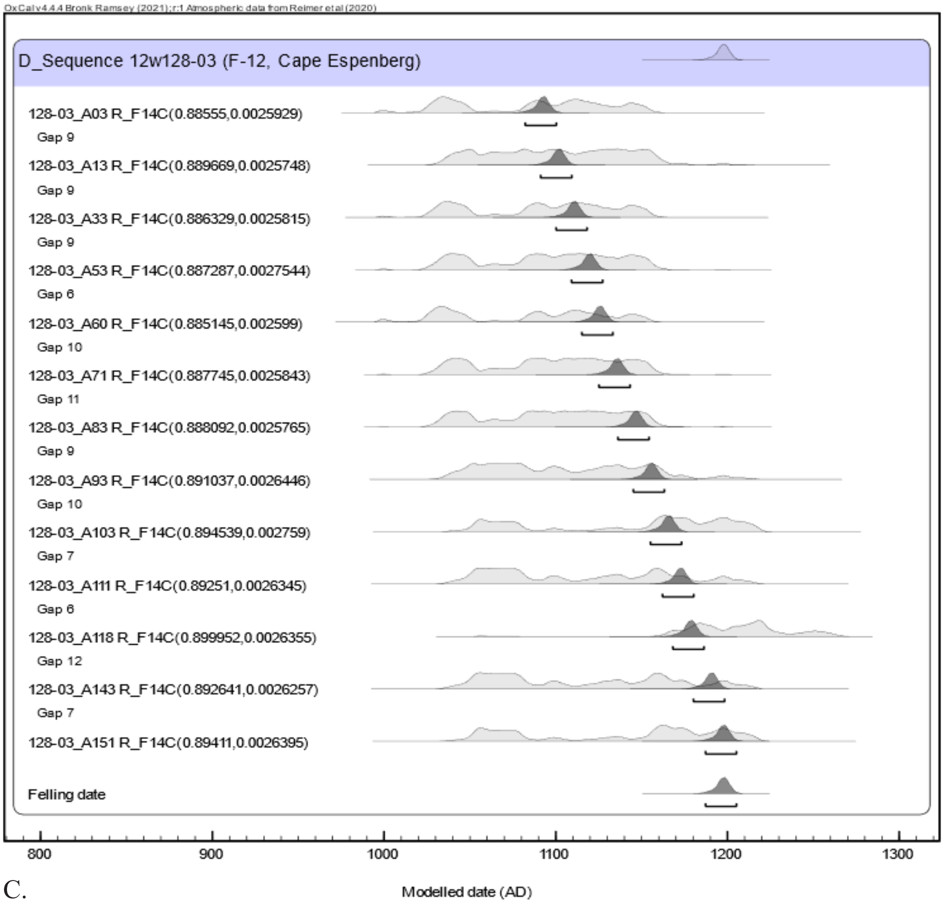

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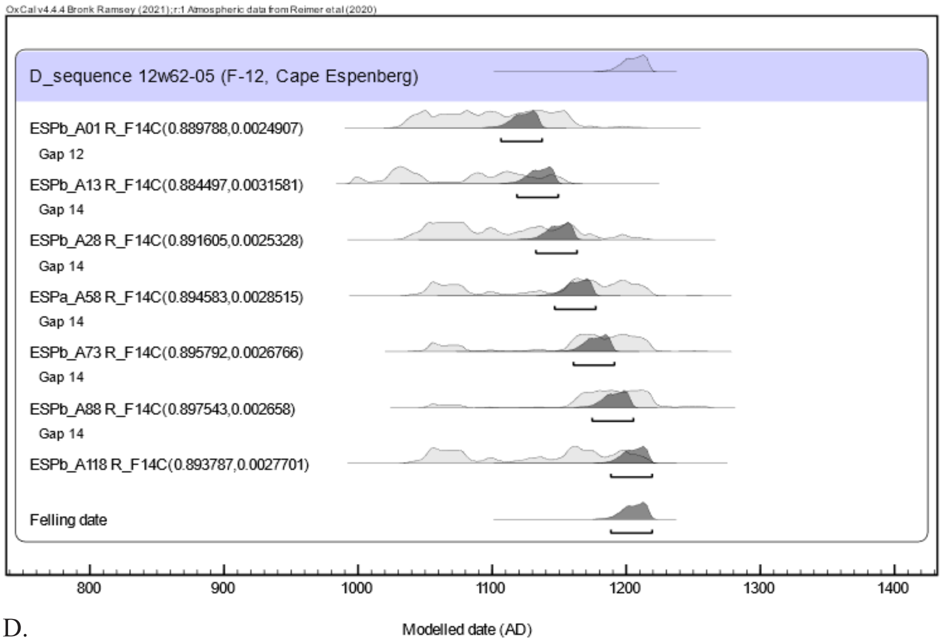
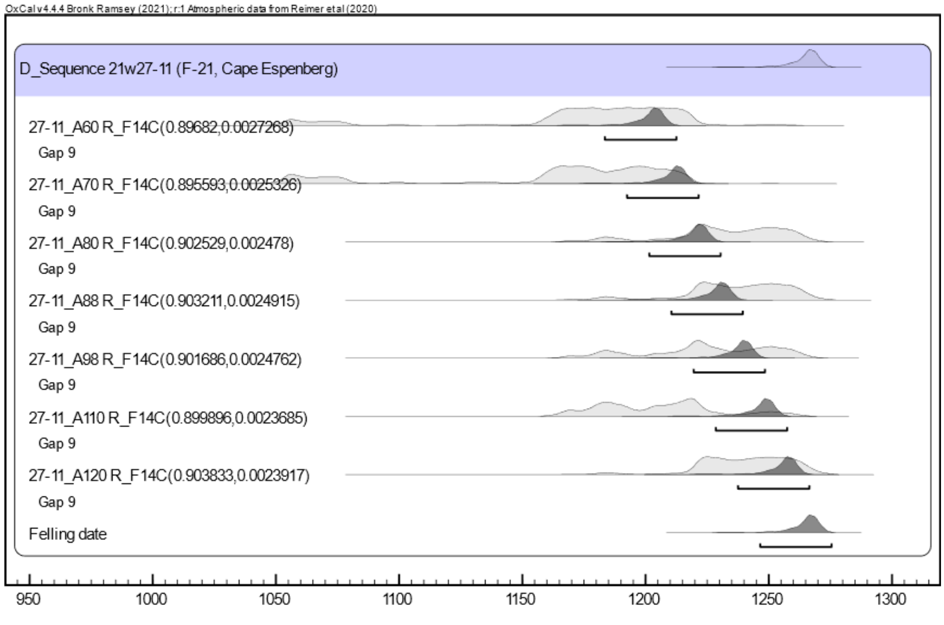
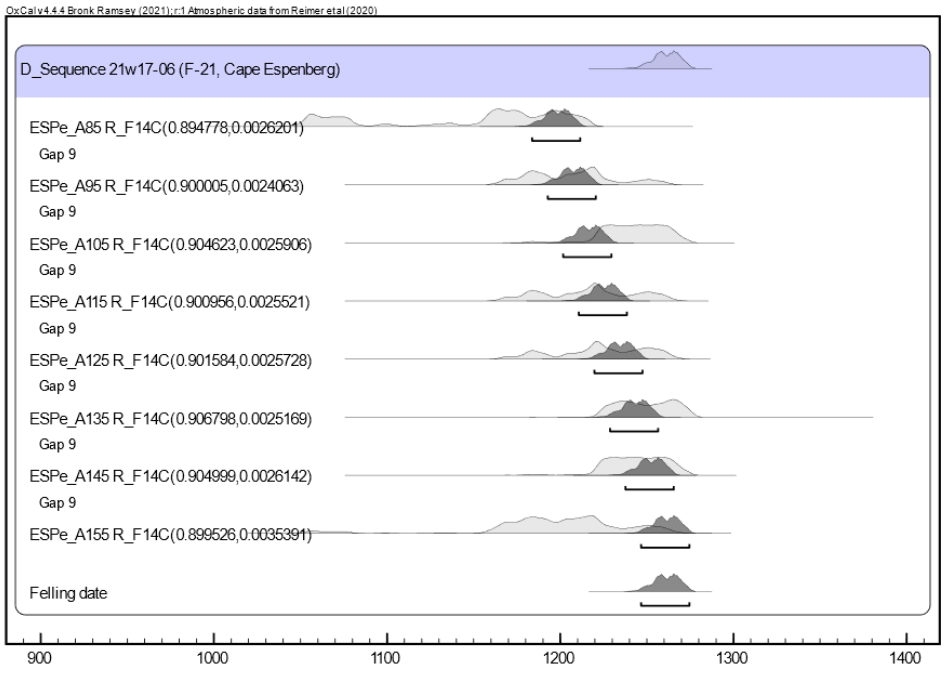


D.

Figure 6. *Probability distributions of ^{14}C sub-samples for the four cross-sections of F-12 (Rising Whale site). In light grey, the single calibration of each sub-sample. In dark grey, the wiggle-matched calibration. A. Wiggle-matching of 12w107-01. The calendar age estimate for the outermost sub-sample (A86) is 1113-1155 CE; B. Wiggle-matching of 12w51-22. The calendar age estimate for the outermost sub-sample (A79) is 1165-1190 CE; C. Wiggle-matching of 12w128-03. The calendar age estimate for the outermost sub-sample (A151) is 1187-1205 CE; D. Wiggle-matching of 12w62-05. The calendar age estimate for the outermost sub-sample (A118) is 1188-1219 CE. © J. Taïeb.*



A.



B.

Figure 7. *Probability distributions of ^{14}C sub-samples for the two cross-sections of F-21 (Rising Whale site). In light grey, the single calibration of each sub-sample. In dark grey, the wiggle-matched calibration. A. Wiggle-matching of 21w27-11. The calendar age estimate for the outermost sub-sample (A120) is 1246-1275 CE; B. Wiggle-matching of 21w17-06. The calendar age estimate for the outermost sub-sample (A154) is 1246-1274 CE. © J. Taïeb.*

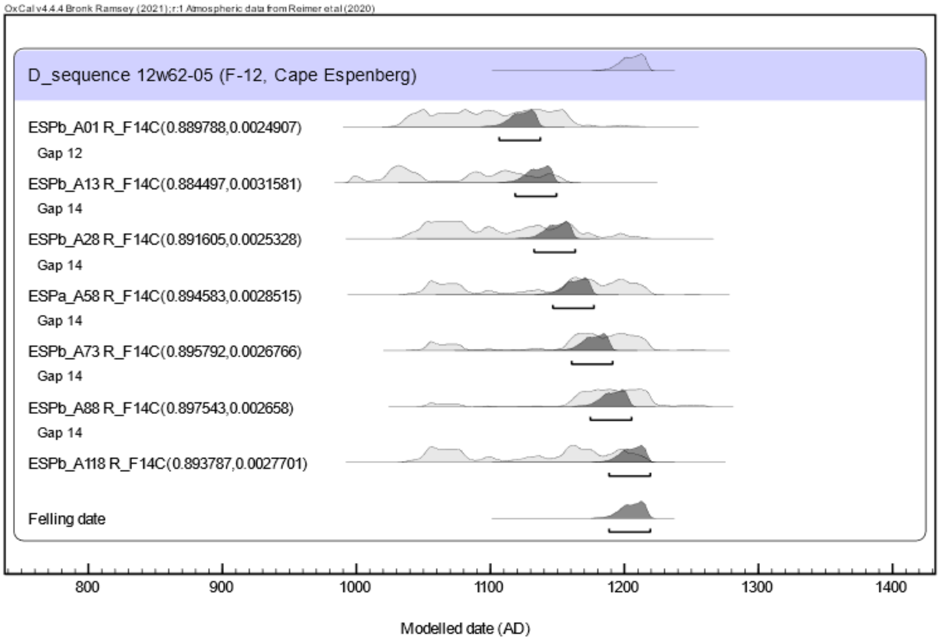


Figure 8. *Probability distributions of ^{14}C sub-samples of cross-section SL2-1986 (Pingusugruk site). In light grey, the single calibration of each sub-sample. In dark grey, the wiggle-matched calibration. The wiggle-matching calendar age estimate for the outermost sub-sample (A62) is 1478-1492 CE. © J. Taïeb.*

3. Discussion

Our wiggle-matched age estimates results support the importance of this precise chronometric technique to date coastal archaeological timbers when standard tree-ring dating cannot be applied successfully, and the calibration curve presents short plateau periods.

In the case of the Rising Whale and Pingusugruk sites, the seven dated cross-sections belong to floating tree-ring sequences made up of 2 to 8 individual tree-ring series, (***table 1***). It was thus possible to position precisely in calendar time the relative floating sequences (a total of 22 timbers) from these two sites. The 22 relative age estimates produced new *terminus post quem* allowing to discuss the relationships and temporality of construction/repair/occupation of house structures for each site and to discuss the inter-site relationships and temporality. Four dated cross-sections from Birnirk house F-12 provide a calendar information for logs in three areas of the house (wall log and floor plank from the west room, wall log from the east room, and roof log from the connecting tunnel; Alix *et al.*, 2018). The two dated cross-sections from the early Thule house F-21 provide *TPQ* for the tunnel (wall log) and the main room (corner post) of the house (Alix *et al.*, 2018). In the Late Thule house at Pingusugruk (SL2 area), the dated cross-section is an architectural element from the north-west corner of the room. In both sites, the age calendar intervals obtained by wiggle-matching dating are consistent with previously known dating and chronological information (Sheehan, 1997; Alix *et al.*, 2015; Alix & Mason, 2018; Krus *et al.*, 2019; Taïeb *et al.*, 2022). Wiggle-matching dating thus offers new opportunities to improve the dating of archaeological timbers from coastal Birnirk and Thule sites, and to analyze contemporaneous climatic variations in geographic areas yet to be determined.

The resulting calendar estimate for the last ring of the Piġniq sample (5144-5046 BCE) is surprising since the site is supposedly dated between the 9th-12th centuries CE (Ford, 1959; Mason, 2020). Several lines of thought are open to us. The wood may have come from a tree preserved for a long time in permafrost (Reuther *et al.*, 2020: 1) prior to its use by Birnirk-Thule people in the construction and/or repair of the house. Alternatively, the wood may have stayed an unusually long time in seawater, which modified its ^{14}C composition. However, this hypothesis seems unlikely as supported by our study's results and those of other arctic driftwood radiocarbon dating which are in agreement with dendrochronological dates and radiocarbon dating of terrestrial mammal bones, and have been long used to date beach ridges formation systems (see Alix & Mason, 2018; Sander *et al.*, 2021; Taïeb *et al.*, 2022). The same argument applies to the possible effect of permafrost burial in time. Another possible alteration of the ^{14}C content of the wood may come from contamination by external elements in the house, such as marine mammal oil, but the offset of marine carbon measurements is a few hundred years, not several thousand (Dumond & Griffin, 2002; Krus *et al.*, 2019; Reuther *et al.*, 2020). Moreover, wood cross-sections were not impregnated with chemicals in the 1950's as it was usual to glue archaeological cross-sections to consolidate them. If the issue does not lie with sample contamination, it may be related to assigning the sample to the Piġniq site. We question whether the cross-section belongs to Mound C at Piġniq. Could it be from a different site sampled in the 1950's? Sample C-7 is part of a collection of 40 fairly well-preserved samples, and additional radiocarbon dating could help determine whether C-7 is representative of the rest of the collection.

Wiggle-matching dating allowed reducing significantly the uncertainty on the age estimate of the last ring present in samples from Cape Espenberg and Pingusugruk archaeological sites (***table 2***). Although the precision of these age estimates depends on the precision of the age measured by the laboratory (+/- 30 years in our case) and the structure of the calibration curve (Hogg *et al.*, 2019), our results confirm that during plateau periods of the calibration curve, it is worthwhile to date a tree-ring series over the longest possible sequence. In a plateau period of the calibration curve, the longer the series, the more constrained the edges of the plateau (Goslar & Mądry, 1997; Galimberti *et al*., 2004; Jacobsson *et al*., 2018). This is the case in feature F-12 at the Rising Whale site (10-12th centuries), located on a plateau period, where the age estimates obtained for cross-section 12w128-03 (16 dates every 9-10 years over 151 years) and cross-section 12w62-05 (9 dates every 14-15 years over 118 years) span respectively 18 and 31 years. In comparison, the ages obtained for timbers dated outside of a plateau period, such as that of F-21 in the 13-14th centuries, are nearly as precise (***table 2***).

Conclusion

The combination of dendrochronology and wiggle-matching dating of tree-ring sequences made it possible to: i) accurately place these tree-ring sequences in calendar time and significantly reduce the uncertainty of the age estimate of the last present growth ring compared to single radiocarbon dating of that last present growth ring; and ii) develop preliminary master chronologies that can be used for dendrochronological dating of other architectural timbers from Thule and Birnirk coastal sites. Their biogeographic region of origin has yet to be determined, but these preliminary chronologies can be useful for cross-dating wood from other contemporary archaeological sites from areas where master chronologies do not exist or are too short. At terms, these wiggle-matched tree-ring sequences will provide new contemporaneous climatic information on the early second millennium for geographic areas, yet to determine.

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Conflict of interest

No conflict of interest to declare.

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Appendix 1. *Raw ^{14}C measurements for each sub-sample. Sub-samples are ordered from the youngest to the oldest single ring dated per cross-section.*

^{14}C lab ID	Sub_sample ID	Cross-section	Mg C	Delta C13	F14C	Error F14C	Conventional ^{14}C age (BP)	Error age BP
62747	Bir_A93	C-7	0.99	-27.90	0.4661385	0.0020956	6130	35
62748	Bir_A83	C-7	1.11	-25.70	0.4587012	0.0022254	6260	40
62749	Bir_A73	C-7	1.10	-22.90	0.4627582	0.0020144	6190	35
62750	Bir_A63	C-7	0.95	-25.90	0.4636079	0.0022017	6175	40
62751	Bir_A53	C-7	1.02	-26.90	0.4609023	0.0023599	6220	40
62752	Bir_A43	C-7	1.05	-27.80	0.4663293	0.002254	6130	40
62753	Bir_A33	C-7	1.10	-26.70	0.466775	0.0019988	6120	35
62754	Bir_A23	C-7	1.12	-22.00	0.4642806	0.0022241	6165	40
62755	Bir_A13	C-7	1.09	-25.80	0.4643794	0.0020939	6160	35
62756	ESPb_A118	12w62-05	1.01	-24.60	0.8937875	0.0027701	900	30
62757	ESPb_A103	12w62-05	1.08	-24.50	0.8914168	0.0026147	925	30
62758	ESPb_A88	12w62-05	1.01	-25.30	0.8975425	0.002658	870	30
62759	ESPb_A73	12w62-05	1.04	-25.00	0.8957918	0.0026766	885	30
62760	ESPb_A58	12w62-05	1.08	-26.20	0.8945826	0.0028515	895	30
62761	ESPb_A43	12w62-05	0.99	-27.80	0.9074547	0.0025588	780	30
62762	ESPb_A28	12w62-05	1.06	-28.30	0.8916046	0.0025328	920	30
62763	ESPb_A13	12w62-05	1.19	-25.60	0.8844965	0.0031581	985	30
62764	ESPb_A01	12w62-05	1.04	-24.20	0.8897879	0.0024907	940	30
62765	ESPa_A79	12w51-22	1.10	-24.70	0.8952933	0.002528	890	30
62766	ESPa_A68	12w51-22	0.88	-24.20	0.8965114	0.0025785	880	30
62767	ESPa_A59	12w51-22	1.09	-24.30	0.8915949	0.0024931	920	30
62768	ESPa_A49	12w51-22	0.95	-26.20	0.8894595	0.0025596	940	30
62769	ESPa_A39	12w51-22	1.07	-25.50	0.8931811	0.0025133	905	30
62770	ESPa_A29	12w51-22	1.09	-23.90	0.8850907	0.0025083	980	30
62771	ESPa_A19	12w51-22	0.98	-26.60	0.8912483	0.0025342	925	30
62772	ESPa_A09	12w51-22	1.03	-26.00	0.8850813	0.0024531	980	30
62773	ESPa_A01	12w51-22	1.13	-25.10	0.8922457	0.0025957	915	30
62774	ESPc_A86	12w107-01	0.91	-27.80	0.8872652	0.0027468	960	30
62775	ESPc_A76	12w107-01	0.98	-27.10	0.8884143	0.002729	950	30
62776	ESPc_A66	12w107-01	0.98	-26.20	0.888768	0.0026279	945	30
62777	ESPc_A56	12w107-01	1.06	-25.40	0.8854151	0.0026556	980	30
62778	ESPc_A46	12w107-01	1.01	-23.50	0.8869358	0.0025954	965	30
62779	ESPc_A36	12w107-01	1.06	-25.90	0.8889708	0.0026219	945	30
62780	ESPc_A26	12w107-01	0.94	-23.80	0.8937248	0.0026568	905	30
62781	ESPc_A16	12w107-01	1.00	-22.50	0.8881104	0.0026077	955	30
62782	ESPc_A06	12w107-01	0.95	-25.30	0.8919956	0.0026578	920	30
62787	ESPd_A151	12w128-03	1.04	-24.70	0.8941104	0.0026395	900	30
62788	ESPd_A143	12w128-03	0.97	-23.70	0.8926409	0.0026257	910	30
62789	ESPd_A130	12w128-03	1.05	-22.50	0.8898015	0.0026394	940	30
62790	ESPd_A118	12w128-03	1.00	-23.20	0.8999522	0.0026355	845	30
62791	ESPd_A111	12w128-03	0.96	-27.20	0.89251	0.0026345	915	30
62792	ESPd_A103	12w128-03	1.06	-24.20	0.8945386	0.002759	895	30
62793	ESPd_A93	12w128-03	1.32	-22.20	0.891037	0.0026446	925	30
62794	ESPd_A83	12w128-03	1.27	-23.70	0.8880917	0.0025765	955	30

62795	ESPd_A71	12w128-03	0.93	-24.80	0.8877449	0.0025843	955	30
62796	ESPd_A60	12w128-03	1.02	-24.40	0.8851446	0.002599	980	30
62797	ESPd_A53	12w128-03	0.97	-21.50	0.8872873	0.0027544	960	30
62798	ESPd_A43	12w128-03	0.97	-22.30	0.87998	0.0025642	1025	30
62799	ESPd_A33	12w128-03	1.11	-18.60	0.886329	0.0025815	970	30
62800	ESPd_A23	12w128-03	0.98	-22.20	0.8819397	0.0025842	1010	30
62801	ESPd_A13	12w128-03	1.05	-23.60	0.889669	0.0025748	940	30
62802	ESPd_A03	12w128-03	1.18	-19.30	0.8855502	0.0025929	975	30
62807	ESPf_A120	21w27-11	1.17	-23.60	0.9038327	0.0023917	810	30
62808	ESPf_A110	21w27-11	1.04	-23.90	0.8998957	0.0023685	845	30
62809	ESPf_A98	21w27-11	1.01	-23.30	0.9016865	0.0024762	830	30
62810	ESPf_A88	21w27-11	0.88	-25.80	0.9032108	0.0024915	820	30
62811	ESPf_A80	21w27-11	1.03	-23.80	0.9025293	0.002478	825	30
62812	ESPf_A70	21w27-11	1.04	-24.20	0.8955928	0.0025326	885	30
62813	ESPf_A60	21w27-11	1.16	-22.00	0.8968204	0.0027268	875	30
62814	ESPe_A155	21w27-06	0.96	-26.70	0.8995261	0.0035391	850	30
62815	ESPe_A145	21w27-06	1.06	-23.30	0.9049992	0.0026142	800	30
62816	ESPe_A135	21w27-06	0.96	-26.00	0.9067979	0.0025169	785	30
62817	ESPe_A125	21w27-06	1.06	-25.50	0.9015838	0.0025728	830	30
62818	ESPe_A115	21w27-06	0.95	-24.60	0.9009564	0.0025521	840	30
62819	ESPe_A105	21w27-06	0.96	-22.50	0.9046229	0.0025906	805	30
62820	ESPe_A95	21w27-06	0.94	-23.90	0.9000047	0.0024063	845	30
62821	ESPe_A85	21w27-06	0.93	-21.90	0.8947776	0.0026201	895	30
62822	Pin_A72	SL2-1986	1.00	-25.00	0.9374077	0.0025268	520	30
62823	Pin_A62	SL2-1986	0.96	-22.80	0.9512696	0.0025914	400	30
62824	Pin_A52	SL2-1986	0.92	-22.10	0.9535169	0.0025385	380	30
62825	Pin_A42	SL2-1986	0.91	-24.50	0.9497308	0.0025671	415	30
62826	Pin_A32	SL2-1986	0.99	-22.60	0.9486208	0.0025156	425	30
62827	Pin_A22	SL2-1986	0.99	-21.90	0.9414175	0.0026125	485	30
62828	Pin_A12	SL2-1986	1.07	-23.40	0.9403496	0.0026262	495	30
62829	Pin_A02	SL2-1986	1.04	-19.50	0.933697	0.0025715	550	30

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