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Dendrochronological dating and provenance determination of a 19th century whaler in Patagonia (Puerto Madryn, Argentina)

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A B S T R A C T

Dendrochronological methods have been widely used to determine the date of construction and provenance of shipwrecks. Despite a large number of shipwrecks, the application of dendroarchaeological techniques is relatively incipient in the coasts of South America. This paper presents the results of a dendroarchaeological study conducted at the shipwreck site "Bahía Galenses" (BG), located in the western sector of Golfo Nuevo, on the Patagonian coast of the South Atlantic Ocean. Based on previous archaeological research, two hypotheses were tested in this study. First, the wreck described in the BG 2 sub-site corresponds to a mid-19th-century whaler built in the northeastern US. Second, these remains correspond to the *Dolphin*, a northeastern American whaler built in Warren (Rhode Island) in 1850 and shipwrecked in the Atlantic coast of Patagonia in 1859. Using dendroarchaeological provenance methods and a novel approach based on the gridded North American Drought Atlas, we found highly significant correlations between the wreck's tree-ring width series and white oak and yellow pine tree-ring reference chronologies from the eastern US. The latest non-cutting dates obtained in this analysis correspond to the year 1849. To our knowledge, our study pioneered the use of dendrochronological methods for dating and establishing the provenance of a whaler's remains on the Atlantic coast of South America and encourages the feasibility for future dendroarchaeological research based on the large number of wooden shipwrecks that occurred in the region.

1. Introduction

Dendrochronological methods have been used to date wooden ships, boats, and canoes across the world. Establishing the location and date of a ship's construction from dendrochronological analysis poses some challenges. A ship is a mobile structure, so the location of a shipwreck is often unrelated to its construction site. In addition, the timbers used to build a ship may come from different geographical areas or even be partly reused, and repairs or replacements of structural elements may come from places distant from the place of construction. However, several studies have provided both dendrochronological dates for construction and determination of timber provenance of shipwrecks (Daly, 2020; Daly and Belasus, 2016; Daly and Nymoen, 2008; Domínguez-Delmás et al., 2014, 2013; Haneca and Daly, 2014; Martin-Benito et al., 2014). In South America, there is a great potential for these studies, although their development has been incipient so far, with only a few preliminary studies: Mundo (2012) and Mundo and Girardclos (2013) regarding the ZenCity shipwreck in Buenos Aires, Argentina and Lira and Lavier (2016) on indigenous canoes in southern Chile.

The worldwide expansion of commercial exploitation of marine resources reached the Southwest Atlantic in the last decades of the 18th century. Based on market demand for oil and furs and the availability of resources, an increasing number of vessels sailed the South Atlantic in search of whales and seals. British, French and North Americans were among the most frequently mentioned whalers in Patagonian waters, the

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latter prevailing from the first decades of 19th century onwards (Quiroz, 2014). By the middle of the 19th century, ships registered in the northeast coast ports of the United States accounted for most of the estimated global whaling activity (Davis et al., 1997). Although the whaling expansion developed worldwide, particularities existed throughout time, and in different geographical contexts in terms of capture and processing techniques, logistics and resupply, among others (Davis et al., 1997; Anon, 1998; Quiroz and Toledo, 2014; Reeves and Smith, 2007). The whaling industry of the 19th century has so far been the subject of numerous studies, but the extent and specific characteristics of the industry in eastern Patagonia are still barely known.

In the last two decades, several wooden shipwrecks have been located along the Patagonian coast of Argentina. The origin and purpose of the voyages of these ships is often unknown. Some of them were the subject of archaeological surveys but, frequently, low structural integrity and scarcity of associated artifacts only allowed a general chronological characterization, mainly based on shipbuilding typology. Nevertheless, there are some shipwreck sites where progress have been made. This is the case of “Bahía Galenses” (BG) shipwreck site, located within a small inlet on the western coast of Golfo Nuevo (Nuevo Gulf), Puerto Madryn city, Chubut, Argentina (Fig. 1). In 2002, the BG shipwreck remains began to be exposed due to sedimentary erosion in the area, so an archaeological project was initiated. The results of the archaeological research conducted in this site indicate that the ship was built in the 19th century with timber from the northern hemisphere (Murray et al., 2009). In particular, the futtocks analyzed were identified as oak (*Quercus* spp.), planks associated with the *Pinus* spp. and treenails identified as black locust (*Robinia pseudoacacia*). Recent surveys have identified two large cast-iron pots associated with brickwork remains, which are interpreted as part of the furnace (“try-works”) that was common on board the whalers of the time (Davis et al., 1997; Grosso and Murray, 2019).

Several historical sources refer to shipwrecks in the Golfo Nuevo during the second half of the 19th century. However, data in this regard are scarce, and it is not even clear if they refer to the same shipwreck event. Written records indicated that the *Dolphin*, a northeastern US whaler built in Warren, Rhode Island in 1850, was wrecked in the Golfo Nuevo in 1859. According to the testimony of Captain Norrie, in charge of this ship, the vessel "lay upon the rocks on the S. W. side of New Bay, Patagonian coast" (Lindsey, 1860). However, the exact point where the ship lay was unknown.

Based on historical and archaeological information, this study postulates two hypotheses. First, the Bahía Galenses wreck site corresponds to a mid-19th century whaler ship built in the northeastern US. Second, these remains correspond to the US whaler *Dolphin*. To test these hypotheses, using dendrochronological methods and a novel approach based on the gridded North American Drought Atlas, we analyzed different pieces of the wreck in BG2 to determine the cutting date of its timbers and to identify its geographical origin.

2. Materials and methods

2.1. Bahia Galenses wreck site

The *Bahía Galenses* wreck site is distributed along a 300 m axis, from the intertidal to the shallow subtidal zone in an inlet located immediately west of Punta Cuevas, on the southern coast of the city of Puerto Madryn, Chubut, Argentina (Fig. 1). The hull of the ship has broken down into two main structures, which were designated BG1 and BG2, and some loose pieces. In addition, an assemblage of artifacts, designated BG3, is located in the area farthest from the shoreline. The BG2 part of the structure, where the investigations were focused, is 28 m long and 4.2 m wide (Fig. 2). It corresponds to the longitudinal half of the bottom of the hull, probably starboard, consisting of at least 33 double frames and parts of the hull planking and the ceiling. The keel and keelson are absent. Dimensions of the individual structural elements suggest that the size of the vessel was 300–500 tons (Murray, 2019).

Wood identification analysis of some pieces with different functions in the ship from BG2 showed a variety of wood types corresponding to non-native botanical species from Patagonia and, specifically, to species

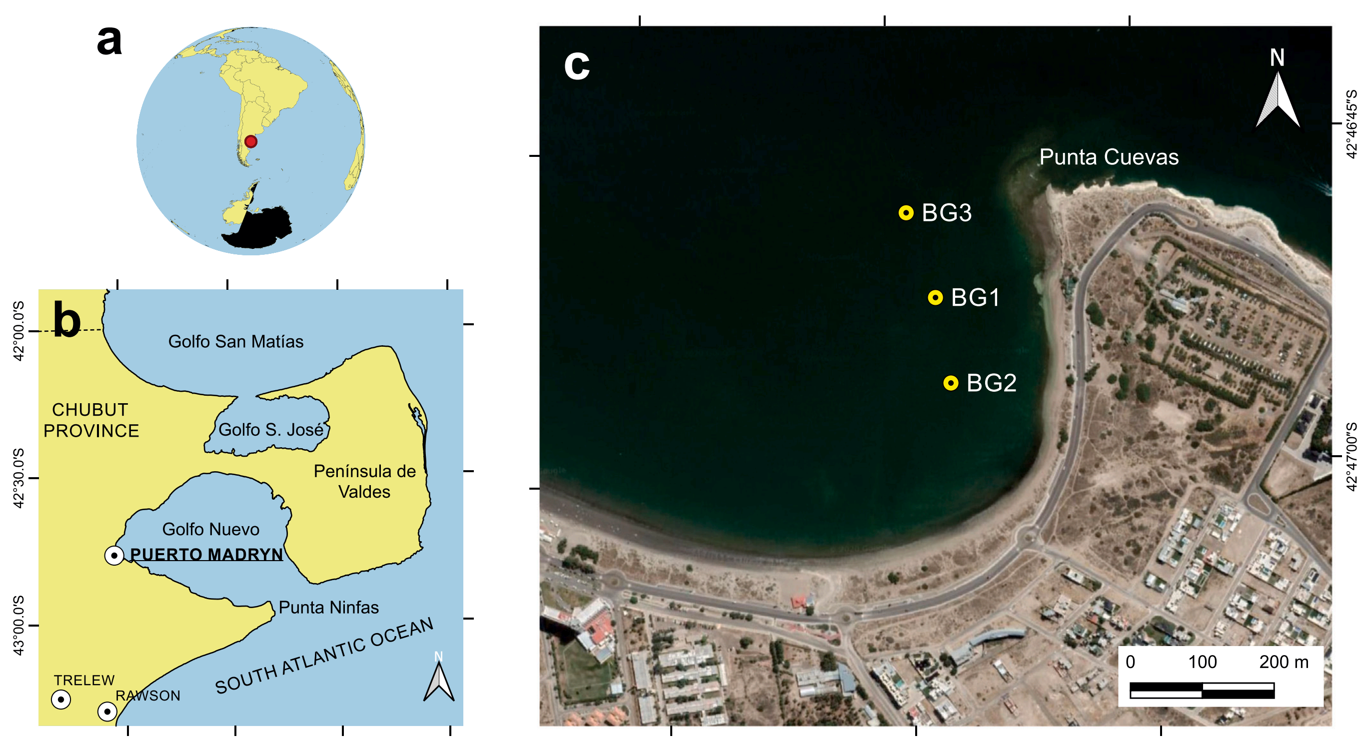

Fig. 1. Maps showing the location of Puerto Madryn in South America (a) and in the northern part of the province of Chubut, Argentina (b). The location of the three sub-sites (BG1, BG2 and BG3) at the “Bahía Galenses” archaeological site on the coast of the city of Puerto Madryn is also shown (c).

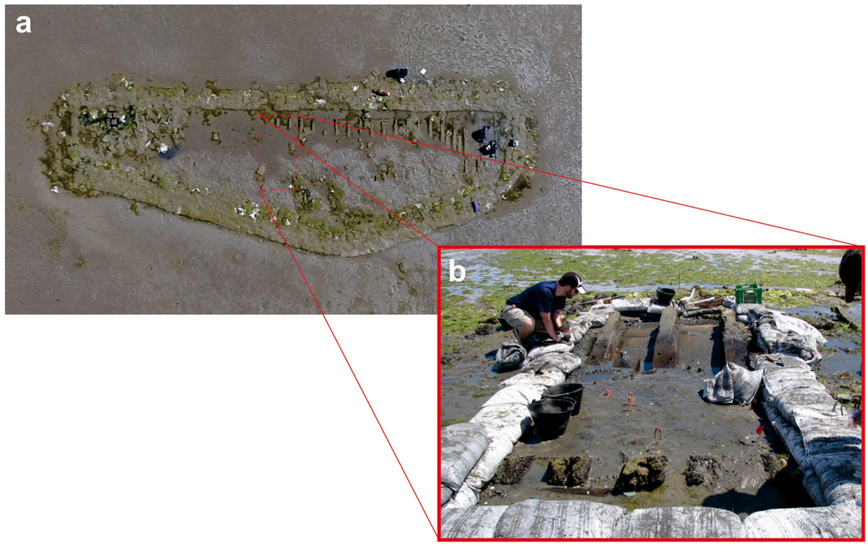

Fig. 2. Pictures of BG2 structure: a) aerial overview of the remains partially covered with protective plastic bags located over the tops of exposed beams in 2013 and b) the T1 trench after removing the sediment and bagging it.

from the northern hemisphere (Murray et al., 2009). In the case of the futtocks, these timbers were associated with a species of white oak that is currently included in *Quercus* subg. *Quercus*. In the case of the hull and ceiling planks, their anatomy correspond to a species of the genus *Pinus* and group taeda *sensu* Phillips (1941). A sheathing plank was assigned to a species of the genus *Pinus* and the group sylvestris *sensu* Phillips (1941). Finally, the wooden treenails were identified as black locust (*Robinia pseudoacacia*).

2.2. Sampling and processing of samples

In November 2019, dendro-archaeological sampling and new surveys were carried out in BG2 structure (Fig. 2). It was decided to sample the BG2 structure, because it is more exposed than the BG1 and therefore more susceptible to the long-term deterioration. Trench T1, which had been excavated in previous years (22 m^2; Murray et al., 2009), was re-excavated for this study, and most of the samples were obtained within this area (Figs. 2 and 3). Those timbers that could contain a reasonable number of growth rings were selected for sampling. Among these, priority was given to the best-preserved pieces to ensure the greatest possible extent of the tree-ring sequence. Within the T1 trench, timbers showing indicators of the presence of waney edge or sapwood were preferred and sampled. To obtain a more representative sampling, additional samples were taken from futtocks found in surveys done in other areas of the ship's hull (Fig. 3). Samples were also taken from a portion of a frame futtock and a sheathing board found loose in the area of BG2 shortly after its discovery and currently held in the Museo del Desembarco at Puerto Madryn. A combination of cross-sections and 5.15 mm increment cores was implemented to comply with UNESCO's guidance for the preservation of underwater cultural heritage (Domínguez-Delmás et al., 2019). Consequently, 31 samples were analyzed in this study (Table 1): 17 cross-sections (15 from T1 and 2 from the museum: 8 corresponding to white oak, 8 to yellow pine and 1 to red pine) and 14 cores (1 from T1 and the rest from the other sampled areas;

Fig. 3. Plan of BG2 structure with the location of the sampled timbers. Trench T1 is located in the central part of the structure (red rectangle). To facilitate the reading of the figure, the legends for the spacer blocks have been omitted (drawing C. Murray).

Table 1
Description of samples analyzed in this study.

ID	Sector	Hull component	Type of sample	Species	Pith	Sapwood
T1-C11	T1	First futtock	Cross section	White oak	Yes	Yes
T1-C13	T1	Third futtock	Cross section	White oak	Yes	Yes
T1-C21	T1	First futtock	Cross section	White oak	Yes	Yes
T1-C23	T1	Third futtock	Cross section	White oak	Yes	Yes
T1-C31	T1	First futtock	Cross section	White oak	Yes	Yes
T1-C32	T1	Second futtock	Cross section	White oak	Yes	Yes
T1-C33	T1	Third futtock	Cross section	White oak	No	No
T1-E21	T1	Spacer block	Cross section	Yellow pine	No	No
T1-E23	T1	Spacer block	Cross section	Yellow pine	No	No
T1-E31	T1	Spacer block	Cross section	Yellow pine	No	No
T1-E33	T1	Spacer block	Cross section	Yellow pine	No	No
T1-Fe1	T1	Hull plank	Cross section	Yellow pine	No	No
T1-Fe2	T1	Hull plank	Cross section	Yellow pine	Yes	No
T1-Fi2	T1	Ceiling plank	Cross section	Yellow pine	No	No
T1-Fi3	T1	Ceiling plank	Cross section	Yellow pine	Yes	No
T1-C34	T1	Fourth futtock	Core	White oak	No	No
S03-C1	S03	Frame futtock	Core	White oak	No	No
S04-C1	S04	Frame futtock	Core	White oak	No	No
S05-C1A	S05	First futtock	Core	White oak	No	No
S05-C1B	S05	First futtock	Core	White oak	No	No
S06-C1	S06	Frame futtock	Core	White oak	No	No
S07-C1A	S07	Frame futtock	Core	White oak	No	No
S07-C1B	S07	Frame futtock	Core	White oak	No	No
S08-C1	S08	First futtock	Core	White oak	No	No
S09-C1	S09	First futtock	Core	White oak	Yes	Yes
S10-C1	S10	First futtock	Core	White oak	No	No
S11-C1	S11	Frame futtock	Core	White oak	No	No
S12-C1	S12	Frame futtock	Core	White oak	No	No
S13-C1	S13	First futtock	Core	White oak	No	No
Museo1	from Museum	Frame futtock	Cross section	White oak	Yes	Yes
Museo2	from Museum	Sheathing board	Cross section	Red pine	No	No

White oak: Quercus subg. Quercus, yellow pine = Pinus - taeda group; red pine = Pinus - sylvestris group

all corresponding to white oak).

Cross-section samples were wrapped with nylon film and core samples were stored in plastic straws to ensure their stability and integrity. Since all the sampled timbers had a high moisture content at the time of sampling, the samples were stored in sealed plastic bags until their analysis at the dendrochronology laboratory of the Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales (IANIGLA), CONICET, Mendoza.

Measurements of the ring widths were conducted in wet conditions and after drying to evaluate the effect of water loss on wood shrinkage and the potential changes in ring widths. Therefore, two cross-section surfaces (T1-C11 and T1-C32) were prepared with surgical blades from the inner to the outermost ring following Domínguez-Delmás et al. (2019). Chalk powder was applied to these surfaces to enhance the contrast between tree-ring boundaries (Fig. 4b). Comparison of ring width between wet and dry samples showed significant and very high correlations (T1-C11: $r = 0.87$, $n = 131$; T1-C32: $r = 0.92$, $n = 103$), so the dry method was applied to all samples. All cross-sections were slowly air-dried under cool temperature, to avoid cracking associated with rapid shrinking. After drying, all samples were sanded with progressively finer sandpaper (up to 1000 grit) until cells in all rings were clearly identifiable under standard 10–50x magnification.

2.3. Measuring and dating of samples

The tree-ring patterns in the cross-sections were visually inspected, and then the annual ring widths were measured to the nearest 0.001 mm using a microscope coupled to a Velmex stage measuring system. Increment cores were scanned at 2400 dpi with an Epson V850 flatbed scanner. Images were saved in JPEG format and measured to the nearest 0.001 mm with CooRecorder 9.6 (https://www.cybis.se/forfun/dendro/). In those cross-sections where it was possible to measure more than one radius, they were visually cross-dated, and their measurements averaged into an individual mean series. None of the samples presented evidence of bark; however, ten samples retained partial sapwood (Table 1), which would allow estimating the felling date of the trees within a specific interval. To facilitate the accurate dating of the samples, all ring width series were standardized by eliminating long-term growth trends and highlighting the high interannual frequency. Tree-ring measurements were standardized using a flexible cubic smoothing spline with a 50% wavelength cutoff at 32 years with COFECHA software (Holmes, 1983).

Firstly, to date and determine provenance, each of the series with more than 75 rings (minimum length to ensure accurate dating of the samples) was individually compared to a network of white oak, red pine and yellow pine chronologies from the eastern United States. Using the records available at the International Tree-Ring Data Bank (ITRDB), World Data Service for Paleoclimatology-NOAA, 26 white oak, 21 yellow pine, and 1 red pine chronologies were compiled, beginning or ending at least in the year 1750 (Supplementary Table 1 and Fig. S1). The year 1750 (i.e., 100 years before the most intense whaling activity in the South Atlantic) provides a sufficiently long and reliable reference for dating the ring-width series from ships of that time. Additionally, to date the white oak samples we also used 7 unpublished regional chronologies developed by E. Cook for the northeastern United States (Supplementary Table 1).

The correlation coefficient and Student's t-value (calculated using CDendro 9.6 and COFECHA) were the statistics used to validate the results of the comparison between the ring-width series from BG2 timbers and the reference chronologies. The "t value" is a descriptive statistic used primarily to measure the strength of association between two tree-ring series after adjusting the correlation coefficient by sample size (Baillie and Pilcher, 1973). The higher the t-value resulting from the comparison between two series, the more reliable the cross-dating. A t-value of 3.5 indicates some match with a small margin of statistical error (Baillie, 1982; Baillie and Pilcher, 1973), while a t-value higher of 6.0 indicates a strong conclusive agreement.

Individual ring-width series were compared with reference

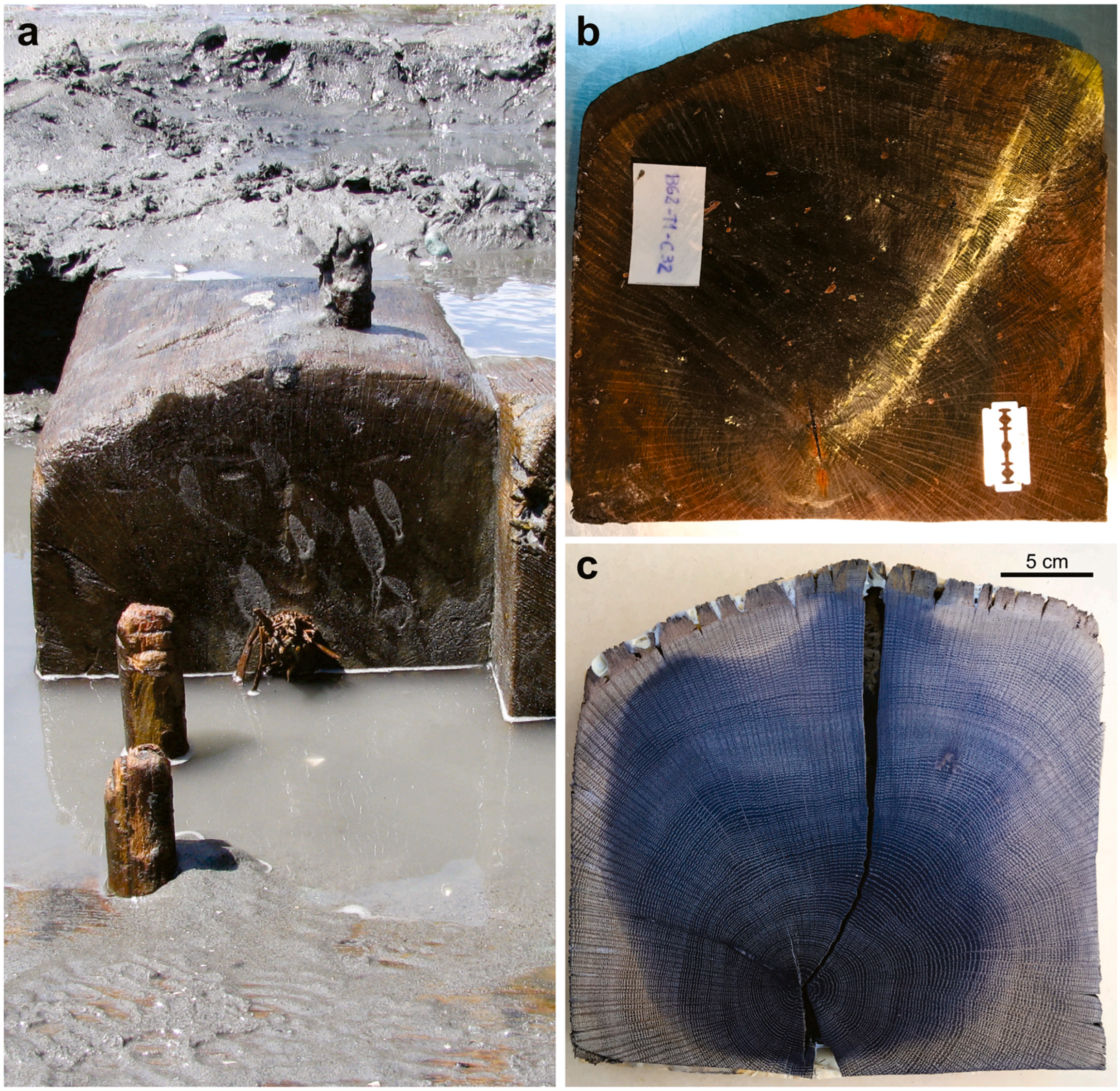

Fig. 4. Processing of the sample obtained from futtock T1-C32. a) Picture before obtaining the sample, b) analyses in wet conditions after preparing the cross-section with surgical blades along a path and applying chalk powder to this surface, c) the perfectly flat and polished sample after gradual drying and sanding with progressively finer sandpaper (photos: I. Mundo).

chronologies based on consecutive 40-year segments (with a 20-year overlap) using the COFECHA program (Holmes, 1983). The most probable dates for the undated series were established when the correlation coefficient with the reference chronology exceeded the critical value of r = 0.37 ($p < 0.01$; Holmes, 1983).

Secondly, BG2 chronologies by species were created based on the series dated individually using the ARSTAN program (Cook,1985), version 4.8d, www.ldeo.columbia.edu/trl). Before combining the individual dated series into species chronologies, the offset between them was corroborated as the relative position where the Spearman's correlation index and t-value were maximized. Mean individual series were detrended using flexible cubic smoothing spline with a 50% wavelength cutoff at 32 years and cross-compared. These detrended series were averaged using a bi-weight robust estimation of the mean to create mean BG2 ring-width chronologies per species. The dating of these chronologies was also tested against the reference chronologies.

Finally, to further validate the dating and provenance of the timbers, we used a novel approach consisting in comparing the BG2 chronologies with an updated version of North American Drought Atlas (NADA; Cook et al., 2004, 2010). The NADA is a spatially gridded dataset of summer wetness and dryness indices (Palmer Drought Severity Index, PDSI) inferred from tree rings over the past two millennia across North America. It was developed using tree-ring chronologies from different woody species in the USA. Therefore, it represents a robust species-independent hydroclimate reconstruction that can be used as a reference pattern to detect the spatial domain of a dendrochronological series (Leland et al., 2021). We computed the Spearman rank correlation between the BG2 chronologies and each grid-cell of the NADA for the dating period obtained previously with the individual and regional tree-ring chronologies.

3. Results

Twenty-two of the 31 samples collected for this study presented more than 75 tree rings and, therefore, had the potential to be dated with reasonable certainty by dendrochronological methods. These 22 samples corresponded to 13 white oak, 8 yellow pine and 1 red pine wood samples. The 9 samples with less than 75 tree rings (T1-C34, S05-C1A and B, S06-C1, S07-C1A and B, S10-C1, S11-C1, S12-C1) corresponded to cores obtained from 7 futtocks.

Table 2
White oak tree-ring series and dating results ordered by 'Date end'. All correlations are calculated from the detrended tree-ring series using flexible cubic smoothing spline with a 50% wavelength cutoff at 32 years.

Id	N. rings	Mean ring width (mm)	Pith	Sapwood rings	Date end	Reference chronology best match	r	t	*p*
T1-C13	107(1)	1.598 ± 0.032	+	9	1848 (+1ew)	Massachusetts regional	0.33	3.58	< 0.001
T1-C31	124(1)	1.086 ± 0.023	+	19	1848 (+1ew)	New York North regional	0.37	4.40	< 0.001
T1-C21	152	1.085 ± 0.039	+	8	1848	NJ - Hutchenson Forest	0.35	4.50	< 0.001
T1-C32	168	1.236 ± 0.020	+	18	1846	Massachusetts regional	0.41	5.79	< 0.001
T1-C11	156	1.046 ± 0.020	+	13	1845	Massachusetts regional	0.42	5.74	< 0.001
T1-C23	153	0.966 ± 0.036	+	0	1834	Massachusetts regional	0.41	5.52	< 0.001
S13-C1	85(1)	1.522 ± 0.064	–	0	1819 (+1ew)	New York North regional	0.34	3.30	< 0.01
S09-C1	120(1)	0.954 ± 0.044	+	0	1810 (+1ew)	NJ - Greater Hutchenson Forest Region	0.43	5.13	< 0.001
S08-C1	82(1)	1.455 ± 0.040	–	0	1807 (+1ew)	MA - Boston Archaeological Timbers	0.47	4.06	< 0.001
S04-C1	94	0.979 ± 0.035	–	0	1794	NJ - Greater Hutchenson Forest Region	0.48	5.25	< 0.001
S03-C1	77	1.179 ± 0.135	–	0	n.d.	n.d.	n.d.	n.d.	n.d.
T1-C33	77	2.672 ± 0.168	–	9	n.d.	n.d.	n.d.	n.d.	n.d.
Museo1	78	1.503 ± 0.040	+	0	n.d.	n.d.	n.d.	n.d.	n.d.

Pith: present (+)/absent (-)
N. rings: number of rings. Numbers in brackets indicate an incomplete ring towards the outside that was not measured
Mean ring width: mean ± standard error
Date end: ew indicate an incomplete ring towards the outside with earlywood vessels.
r: correlation coefficient
t: Student's t-value according to Baillie and Pilcher (1973)
p: p-value

3.1. Dating of white-oak samples

Ten of the 13 oak samples with more than 75 tree-rings were dated with reference oak chronologies from the northeastern US (Table 2). The dates corresponding to the most recent rings in the samples were limited to the period between 1794 and 1848. The best correlations, for both r and t values, were found comparing with the Massachusetts chronologies. Strong associations were also found with chronologies from the Hutchenson Forest in New Jersey. Only three samples (T1-C33, S03-C1 and Museo1) remained undated.

Once cross-dated against the oak reference chronologies, these series were combined to develop a BG2 white oak chronology (Table 3). Previously, it was corroborated that the differences in the external dating coincided with the relative positions in which the correlation indexes are maximized (Supplementary Material Fig. S2). As an example, between the T1-C11 and T1-C32 series, 1 year was found as the best relative position, which coincides with the individual external dating in which the years 1845 and 1846 were established as the last rings, respectively (Table 2).

All ring-width series are significantly associated with a mean intercorrelation of 0.528, reflecting a consistent common signal to develop a chronology (Supplementary material Fig. S3). This BG2 white oak chronology is highly related to the Massachusetts regional oak chronologies ($r = 0.56$, $t = 8.68$ Figs. 5 and 6a). Spatial correlation patterns showed that geographical locations of the white oak chronologies are significantly associated with the BG2 white oak chronology, which are all around Warren. In addition, the BG2 white oak chronology was significantly related to the NADA grid cells in northeastern USA (Fig. 6b).

Table 3
Internal dendrochronological dating results for white oak samples from BG2 ordered by date end. All correlations (r) are Spearman rank correlations of each individual series against the BG2 white oak chronology (built with all remaining series). These correlations are calculated from the detrended tree-ring series using flexible cubic smoothing spline with a 50% wavelength cutoff at 32 years.

Id	N. rings	Radii measured	Date		r	t	*p*
			Start	**End**			
T1-C13	107	2	1742	1848	0.44	5.60	< 0.001
T1-C31	124	3	1725	1848	0.49	5.69	< 0.001
T1-C21	152	3	1697	1848	0.52	4.49	< 0.001
T1-C32	168	3	1679	1846	0.60	5.83	< 0.001
T1-C11	156	3	1690	1845	0.54	6.36	< 0.001
T1-C23	153	2	1682	1834	0.39	5.35	< 0.001
S13-C1	85	1	1735	1819	0.52	4.63	< 0.001
S09-C1	82	2	1691	1810	0.61	4.54	< 0.001
S08-C1	82	1	1726	1807	0.57	4.88	< 0.001
S04-C1	94	1	1701	1794	0.66	5.31	< 0.001
S03-C1	77	1	n.d.	n.d.	n.d.	n.d.	n.d.
T1-C33	77	1	n.d.	n.d.	n.d.	n.d.	n.d.
Museo1	78	3	n.d.	n.d.	n.d.	n.d.	n.d.

r: mean of Spearman rank correlations between the different radii of the same sample
t: mean Student's t-value between the different radii of the same sample according to Baillie and Pilcher (1973)
p: p-value

3.2. Dating of yellow pine samples

Six of the eight yellow pine samples were significantly associated with the Choccolocco Mountain (AL) and Lake Louise (GA) chronologies with t values above 3.5 (Table 4). However, in these six samples, a 27-year time lag was observed between the dates with each reference chronology. In the case of T1-Fe1, a value of $t = 4.01$ was obtained with Lake Louise, although for a period of 116 years (1421–1537) which represents 45% of its temporal extension. Therefore, it was not considered reliable as a dating.

Consequently, with these six samples, the dating between their tree-ring series was checked according to the chronology of Choccolocco Mtn and Lake Louise to develop two BG2 yellow-pine chronologies, respectively (Table 5, Supplementary material Fig. S4). As it was observed for the white oak series, it was also corroborated that the external dating coincided with the relative positions in which the correlation indexes are maximized for the yellow pine series (Supplementary material Fig. S5). As an example, between the T1-Fe2 and T1-Fi3 yellow pine series, − 2 years was found as the best relative position, which coincides with the individual external dating against the Choccolocco Mtn in which the years 1768 and 1770 were established as the last rings, respectively (Table 4). In both chronologies, the mean intercorrelation was 0.356.

Then, these two BG2 yellow pine chronologies based on the individual dating with the Choccolocco Mtn and Lake Louise chronologies were compared respectively with these reference chronologies (Fig. 7). Both dates were highly significant (Choccolocco Mtn: $t = 8.45$ and Lake Louise: $t = 7.41$), but 27 years out of date. Therefore, a problem of ambiguity was found in the dating of the yellow pine samples from BG2

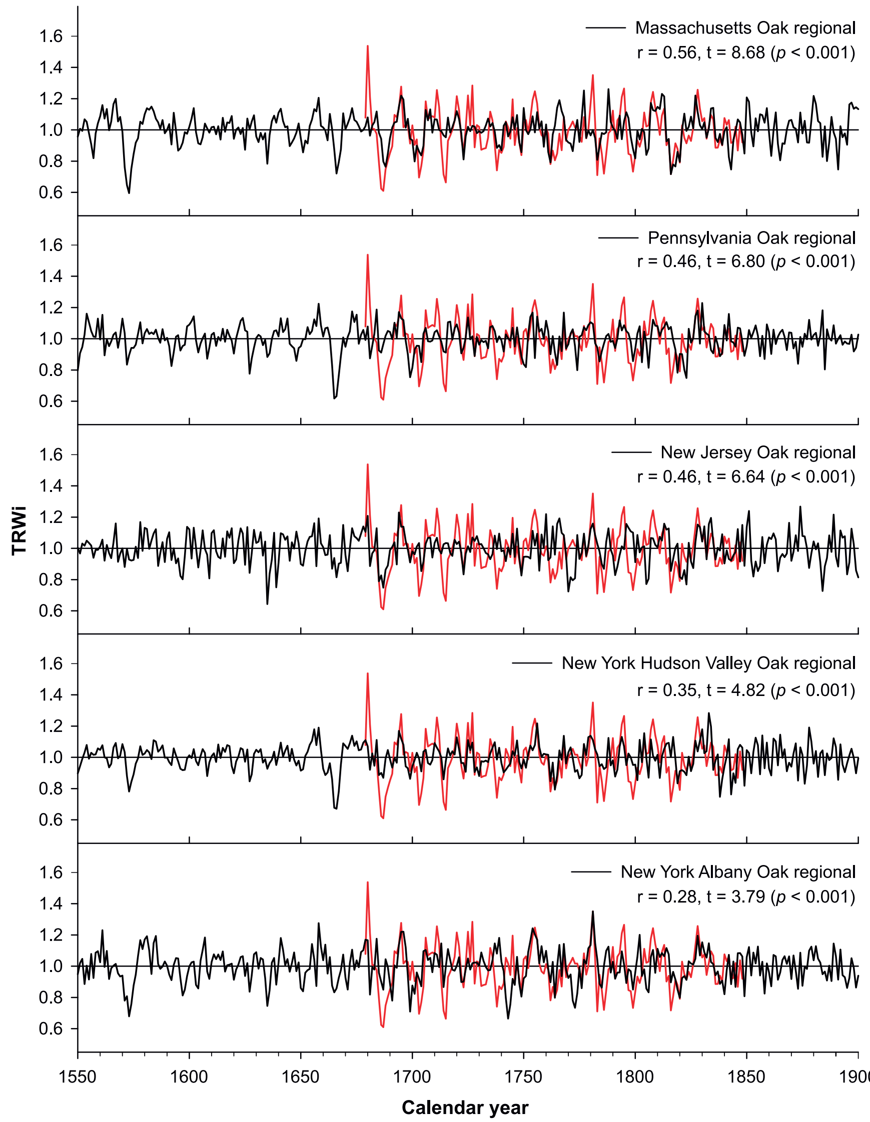

Fig. 5. Comparisons between the BG2 white oak chronology against five master regional chronologies based on living trees and independent archaeological samples. The Spearman rank correlations between the series are highly significant (r, t and p-values shown in each panel) over a 170-year common period.

with the two reference chronologies.

Spatial correlation analysis with the NADA gridded record showed that the Choccolocco Mountain-based dating for the BG2 yellow pine chronology (period 1638–1810) was highly significant and spatially dominant for the southeastern USA. In contrast, no statistical significance was found for the period 1665–1837 as suggested by the Lake Louise dating (Fig. 8).

3.3. Dating of red pine sample

Although the red pine sample (Museo2) presented 89 tree rings, it was not possible to significantly date it with the only long reference chronology (Rattlesnake Mountain and Town Pound, NH) for this species available for this study.

3.4. Cutting dates

Although the bark was absent in all the samples, the bark edge - corresponding to the outermost ring under the bark - was observed on a number of framing elements. Therefore, all individual end dates correspond to non-cutting dates (Fig. 9). However, in those cross-sections of white oak containing sapwood, certain particular features were observed.

The number of sapwood rings is constant in those samples in which the sapwood covers an important part of the contour of the piece, something that would have been very fortuitous as a result of the timber conversion process. Particularly, in T1-C32 the entire edge is curved (when it should have been straight) and has a constant sapwood thickness (Figs. 4 and 10). In addition, in five white oak samples corresponding to frame futtocks, there were signs of bark edge. For example, in four samples (T1-C13, T1–31, T1-C21, and T1-C11), it was observed that some of the edges adjacent to the outer planks have curvature just in proximity to the sapwood when the cut should have been straight, i.e. missing corners (Fig. 10).

Due to the presence of an unmeasured incomplete ring in some samples, a year must be added to estimate the closest date to the cut. Thus, the most recent and closest year to the cutting date in all BG2 structures corresponds to 1849.

4. Discussion

Our results suggest that the wood remains found in Bahía Galenses BG2 sub-site correspond to a vessel built with timbers from the white oak group in the northeastern United States and the yellow pine group in

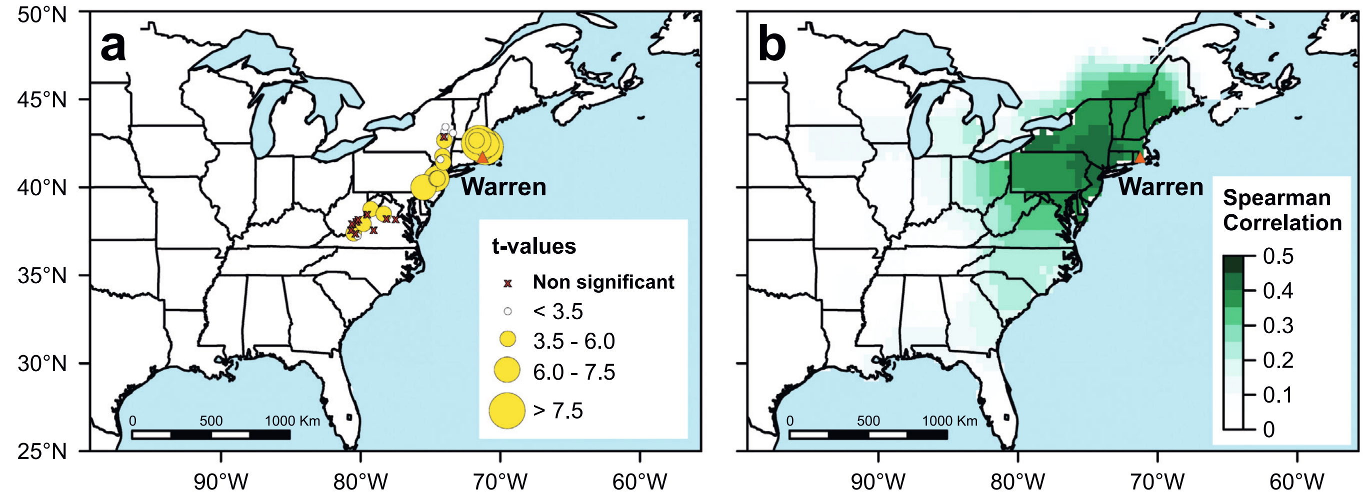

Fig. 6. Spatial correlation analyses of dendroprovenance for BG2 white oak chronology. a) Map of Eastern US showing the t-values between the BG2 and the white-oak reference chronologies according to chronology locations estimated over the common 1679–1848 common period. Dot sizes are proportional to t-values. b) Spatial correlation pattern between the BG2 white oak chronology and the gridded North American Drought Atlas reconstructions between 1679 and 1848 (maximum r = 0.49 and maximum t = 7.3 (p < 0.001).

Table 4
Yellow pine tree-ring series and best dating results based on the two reference chronologies. All correlations are calculated from the detrended tree-ring series using flexible cubic smoothing spline with a 50% wavelength cutoff at 32 years.

Id	N. rings	Mean ring width (mm)	Pith	Choccolocco Mountain (AL)				Lake Louise (GA)			
				Date end	r	t	*p*	Date end	r	t	*p*
T1-E21	141	1.154 ± 0.057	–	1784	0.38	4.84	< 0.001	1811	0.41	5.30	< 0.001
T1-E23	169	0.912 ± 0.032	–	1810	0.46	6.69	< 0.001	1837	0.36	4.99	< 0.001
T1-E31	148	1.280 ± 0.078	–	1797	0.48	6.61	< 0.001	1824	0.52	7.36	< 0.001
T1-E33	133	1.185 ± 0.054	–	1749	0.27	3.21	< 0.010	1610	0.27	3.21	< 0.010
T1-Fe1	258	0.680 ± 0.029	–	1770	0.22	3.08	< 0.010	1537	0.35	4.01	< 0.001
T1-Fe2	99	2.021 ± 0.065	+	1768	0.61	7.58	< 0.001	1795	0.37	3.92	< 0.001
T1-Fi2	105	1.385 ± 0.045	–	1742	0.54	6.51	< 0.001	1769	0.43	4.83	< 0.001
T1-Fi3	108	0.745 ± 0.029	+	1770	0.50	5.94	< 0.001	1797	0.29	3.10	0.001

Pith: present (+)/absent (-)
N. rings: number of rings.
Mean ring width: mean ± standard error
r: correlation coefficient
t: Student's t-value according to Baillie and Pilcher (1973)
p: *p*-value

Table 5
Internal dendrochronological dating results for yellow pine samples from BG2 ordered by date end based on the best two reference chronologies. All correlations (r) are Spearman rank correlations of each individual series against the BG2 yellow pine chronologies (built with all remaining series). These correlations are calculated from the detrended tree-ring series using flexible cubic smoothing spline with a 50% wavelength cutoff at 32 years.

Id	Radii	N. rings compared	Based on Choccolocco Mtn. (AL)					Based on Lake Louise (GA)				
			Date		r	t	*p*	Date		r	t	*p*
			Start	**End**				**Start**	**End**			
T1-E23	1	156	1642	1810	0.23	2.79	< 0.010	1669	1837	0.23	2.79	< 0.010
T1-E31	1	148	1650	1797	0.36	4.35	< 0.001	1677	1824	0.36	4.35	< 0.001
T1-E21	1	141	1644	1784	0.28	3.30	< 0.010	1671	1811	0.28	3.30	< 0.010
T1-Fi3	1	108	1663	1770	0.54	5.52	< 0.001	1690	1797	0.54	5.52	< 0.001
T1-Fe2	2	99	1670	1768	0.53	5.18	< 0.001	1697	1795	0.53	5.18	< 0.001
T1-Fi2	1	101	1638	1742	0.30	2.96	< 0.010	1665	1769	0.30	2.96	< 0.010

r: Spearman rank correlation coefficient
t: mean Student's t-value according to Baillie and Pilcher (1973)
p: p-value

the southeastern United States.

The significant relationships between the BG2 white oak chronology and the Massachusetts and New York white oak reference chronologies indicate, primarily, that the most recent and closest date to the logging of the timbers is 1849.

4.1. Dating and provenance

The white oak timbers analyzed in the BG2 shipwreck came from the northeastern United States, most likely from Massachusetts, Pennsylvania, New York, or New Jersey states. Individual dating of 11 white oak

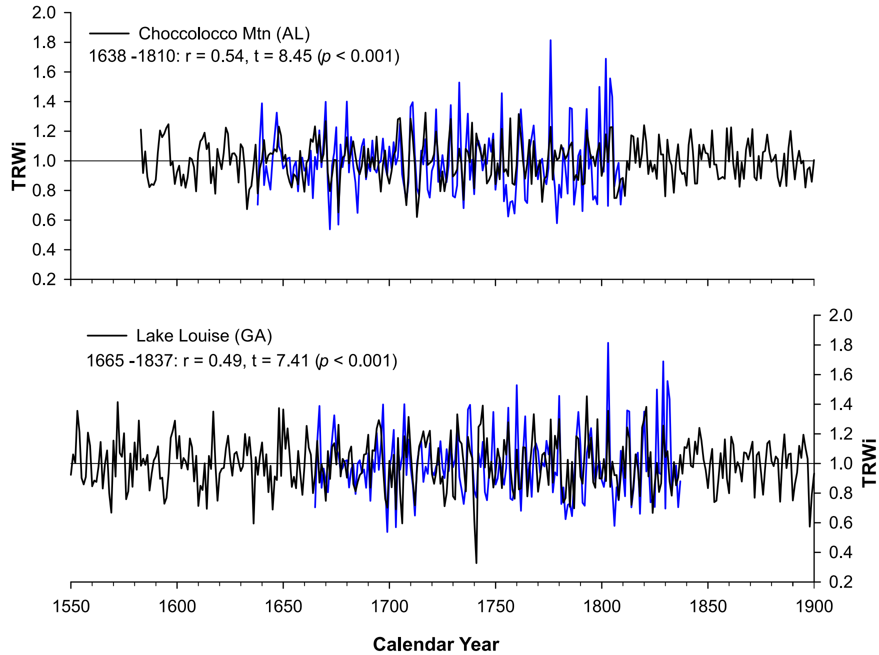

Fig. 7. Significant comparisons between the BG2 yellow pine chronology (6 samples crossdated) against the Choccolocco Mtn and Lake Louise tree-ring reference chronologies.

samples showed highly significant correlations with several geographically close reference chronologies within the northeastern United States. Cross-dated BG2 samples cover the period between 1679 and 1848. The association between the individual series and the reference chronologies, evaluated using both *r* and *t* statistics, is similar to those reported in other archaeological studies dating material from the same region (Leland et al., 2021), including the shipwreck at the World Trade Center in New York (Martin-Benito et al., 2014). With the individual samples correctly dated against the reference chronologies, it was possible to assemble a white oak chronology from BG2 site showing a mean intercorrelation of $r = 0.528$, a value within the expected range for the species in the region or even higher than, for example, those observed by Dewitt and Ames (1978) for *Quercus alba* ring-width chronologies in a network of sites from the northeastern United States. Therefore, we can affirm that the BG2 white oak ring-width chronology has a high degree of common signal between samples, an indication of commonalities in time and spatial region. In turn, the BG2 white oak chronology showed over the period 1679–1848 very significant associations with regional chronologies from Massachusetts ($t = 8.68$), Pennsylvania ($t = 6.80$), and New Jersey ($t = 6.64$), reinforcing the common origin of the samples. A close examination of the white oak chronologies from the BG2 and Massachusetts shows close similarities in ring-width patterns including three simultaneous low-growth periods in the late 1680–1690 s, 1700 s, and 1810 s, supporting the hypothesis that the trees used to develop both chronologies originated from the same region (Fig. 5). The use of the NADA as a climatic reference (reconstructed from many tree-ring chronologies of various species) showed for the period 1679–1848 a highly significant association between the BG2 and the northeastern US chronologies (Fig. 6). Considering that the NADA includes chronologies from different species as predictors, the spatial correlation patterns also represent complementary indicators for a common provenance between these records. Therefore, either through the white oak reference chronologies or the NADA, it can be stated that the dated BG2 white oak timbers are from the northeastern United States.

The very narrow tree-ring widths in the BG2 white oak samples (with an overall mean and standard error of 1.144 +/- 0.011 mm yr^{-1}; Table 2) suggest that timbers came from trees in dense slow-growing forests. Significant major releases associated with natural or anthropogenic disturbances are present in white oak samples older than 75 years that remained undated (e.g. T1-C33 and Museo 1; Supplementary material Fig. S6). The pristine or primary forests in the northeastern United States were substantially affected by European settlers since the beginning of the 17th century. Williams (1989) cites earliest records of clear-cutting by settlers in Pennsylvania in 1692. Therefore, forest disturbances associated to human activities during the 18th century could have introduced changes in tree growth patterns, which in turn make difficult to date and to establish the provenance of their timbers.

The BG2 yellow pine timbers were obtained from forests in the southeastern United States (Alabama, Georgia, or northern Florida), with a non-cutting date of 1810. Despite the problem of ambiguity in relation to the dating against the Choccolocco Mtn and Lake Louise chronologies with a date-lag of 27 years, the large area of significant correlation with the NADA for the period 1638–1810 (based on the initial dating with the Choccolocco Mtn, AL, reference chronology) allowed us to affirm that this period corresponds to the BG2 yellow pine tree-ring chronology. Using the same methodological approach, Leland et al. (2021) identified the provenance of southeastern US yellow pine timbers from the Terminal Warehouse, Chelsea, New York City. The dating of both BG2 white oak and yellow pine tree-ring chronologies against a Drought Atlas, such as NADA, is a completely novel approach for shipwreck dating. It provides a frame of reference for wood dating when reference chronologies from a particular species are not available at regional scale.

The mean inter-correlation between samples in the BG2 yellow pine chronology ($r = 0.356$) is below the mean for reference chronologies from the same species (mean ± SE: 0.539 ± 0.018). A lower common signal in this BG2 chronology could be related to the presence of non-synchronous releases among the samples from 1725 onwards (Supplementary material Fig. S7a) associated with low-medium intensity disturbances in the forest. However, only two of these releases correspond to moderate growth rate changes (between 100% and 199% of PGC, Supplementary material Fig. S7a). Moreover, the mean growth rate observed (mean ± SE: 1.196 ± 0.027) is very close to the mean values of the reference chronologies (mean ± SE: 1.041 ± 0.116). In the case of the undated samples T1E33 and T1Fe1 showing 133 and 257 rings

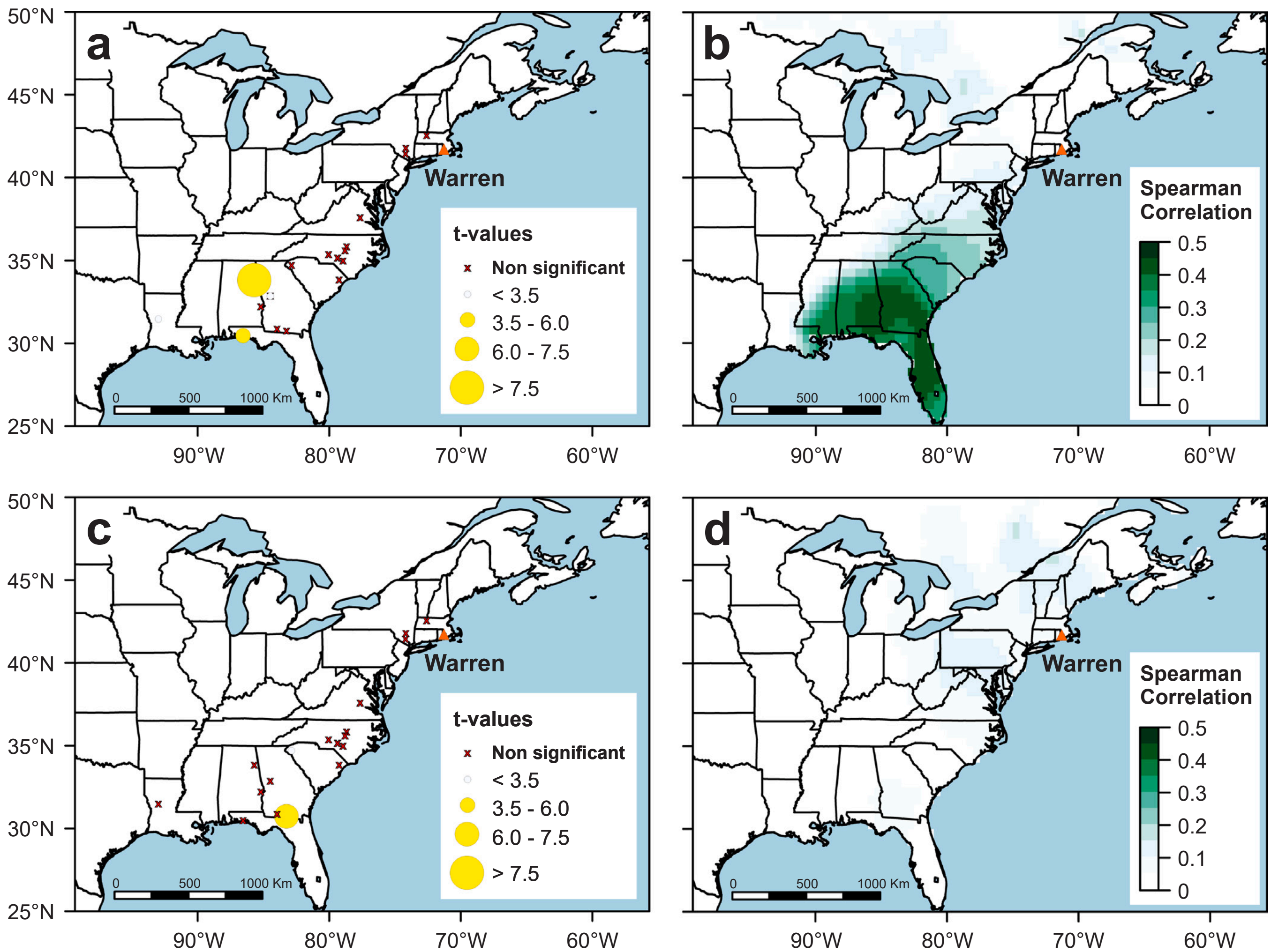

Fig. 8. Spatial correlation analyses for dendroprovenance of BG2 yellow pine chronologies based on the dating with Choccolocco Mtn (a and b) and Lake Louise (c and d) chronologies. Left panels: Maps of eastern US showing the locations of site chronologies compared with the BG2 yellow pine ring-width chronologies for the common period between 1638 and 1810 (a) and 1665–1837 (c), respectively. Dot sizes are proportional to t-values. Right panels: Correlations between the BG2 yellow pine chronologies and the gridded North American Drought Atlas reconstructions between 1638 and 1810 (b, maximum r = 0.45 and maximum t = 6.5) and 1665–1837 (d, maximum r = 0.16 and maximum t = 2.1), respectively.

respectively, the lack of relationships with the reference chronologies could be due to the recorded very low growth (mean ± SE: 0.851 ± 0.029). Low rates of growth occur in high-density forests with a high level of competition between trees. Major releases (in T1E33, Supplementary material Fig. S7b) could be associated with the occurrence of major disturbances in the stand. We suspect that the growth patterns in these samples are affected by local disturbance not present in the cores that constituted the BG2 yellow pine chronology.

In contrast to the white oak, the BG2 yellow pine samples showed non-cutting dates well before the white oak samples (Fig. 9). This should not be related to an earlier logging but the cutting design of the yellow pine logs. Most yellow pine samples correspond to hull and ceiling planks and spacer blocks, with a large amount of peripheral wood removed, including the bark.

The only red pine sample (Museo 2) corresponding to a sheathing board (also known as sacrificial planks), remained undated. Although a sheathing board is not ideal for dating and provenance determination since this vessel's piece is replaced frequently due to external deterioration, they could provide valuable information about the life span of the ship. Unfortunately, we only had access to one reference chronology covering the span 1690–2008 (NH005, Table S1), which failed to provide a date for the Museo 2 sample.

4.2. Sapwood in samples

Sapwood was identified in six cross-sections and one core from the futtocks. The presence of sapwood in structural timbers is considered inappropriate since it is prone to rot. However, sapwood has often been found in shipwreck sites (Adams, 2003; Daly, 2007; Daly and Nymoen, 2008; Domínguez-Delmás et al., 2013; Haneca and Daly, 2014; Martin-Benito et al., 2014). This constructive characteristic is beneficial for dendrochronological analysis by providing the date of the outermost ring or at least one very close to the bark. Some BG2 cross-sections show sapwood on one or more of the four corners and, in some cases, on one complete side. As shown in the theoretical diagram in Fig. 10, this feature could be a consequence of using logs with a smaller diameter and/or curvature than that required by the piece. In addition, the fairly constant number of sapwood rings observed along different radii in the curved-edge of oak samples suggests that in these samples the sapwood is complete. In consequence, this suggests that the cutting date corresponds to the last dated ring since the outermost tree ring represents the bark edge. This is of great importance when selecting pieces or sampling positions for dating the construction date of a vessel, as highlighted by Domínguez-Delmás et al. (2019). In the future, priority should be given to sampling in curved faces areas.

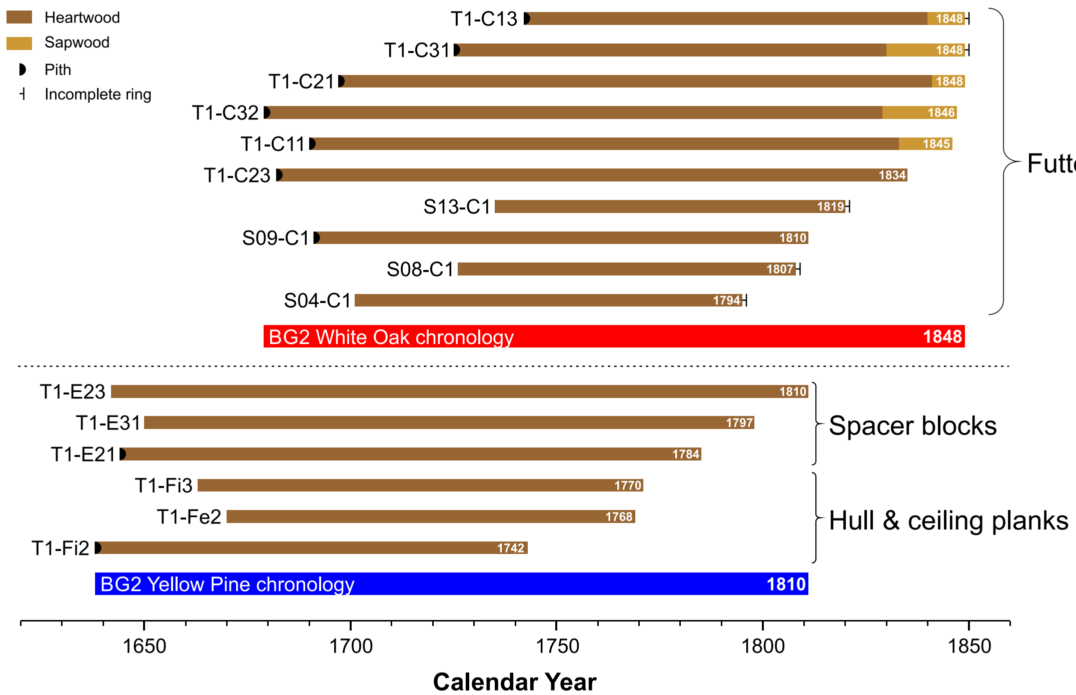

Fig. 9. Bar graph showing the time span covered by the different dated samples from BG2 grouped based on their species and function. Dark brown filling represents the portion of heartwood, light brown corresponds to the sapwood and the half-black dot indicates that the pith is present in the sample. Numbers on the right of each horizontal bar (in white) corresponds to the date end.

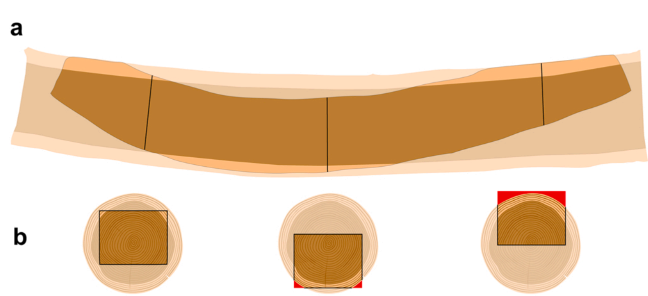

Fig. 10. Theoretical design of the use of a log to obtain a futtock and the different proportion of sapwood and contour of the piece based on the original shape of the log. a) Longitudinal cut of a log with the superimposed shape of a futtock. The vertical lines represent different cross-sections. b) Cutting diagrams based on different positions of the futtock over the cross-section of the log. In a) and b) the heartwood area is shown in dark brown whereas the sapwood in light brown. The red areas in b) indicate the sectors of the outer surface of the samples that coincide with the original edge of the tree section.

4.3. Selection of species in the 19th century northeastern US shipbuilding

Both white oak and yellow pine timber was extensively used in 19th-century shipbuilding in North America (Chapelle, 1982; Crothers, 2000; Desmond, 1919). These species are strong and durable and they were abundant in the eastern and southeastern United States, respectively. White oak was the most prized by American shipbuilders, primarily for keels, frames, beams, and, in some cases, planking. Yellow pine was widely used for keelsons, planking, beams, and other large inboard timbers, in addition to masts (Crothers, 2000). Various historical and archaeological sources refer to the recurrent use of these timbers in the construction of ships in the 19th-century whaling industry in northeastern United States (Church, 1938; Erskine, 1997; Hegarty, 1964; Jackson, 2012; McAllister, 2013). Most whalers were built in New York and the New England states (extreme northeastern US). Yellow pine wood and other lumber from the southeastern states were transported by sea to the northern shipyards (Burns, 2003). Recently, Leland et al. (2021), through the dating and provenance determination of timbers from the Terminal Warehouse in New York City, demonstrated that in the 19th century there was a significant commercial exchange of yellow pine timbers from the southeastern United States for building construction.

4.4. Possible connection between the BG2 remains and the US whaler Dolphin (1850–1859)

In order to discuss the possible correspondence between the wreck BG2 and the US whaler *Dolphin* (1850–1859), the results of the present dendrochronological analysis must be analyzed in relation to the available historical information. So far, the American Lloyd's Register of American and Foreign Shipping (Board of American Lloyd's, 1859) is the only source, among those consulted, that refers to the types of wood used to build the *Dolphin*, indicating that white oak and cedar timbers were used. However, the species used to build the different parts of the ship is not specified. The white oak is compatible with the identifications made on the framing elements of BG2, but the cedar does not match any of the other identifications (yellow pine for hull planks, ceiling planks, and spacer blocks; red pine for sheathing boards; and black locust for treenails). Pinewood is mentioned in the American Lloyd's Register among the ten different types of wood used in shipbuilding and it is assumed that this genus groups the different wood anatomical types of *Pinus* sp. described by Phillips (1941). "Cedar" was probably used to refer to Atlantic white cedar (*Chamaecyparis thyoides*) or Eastern red cedar (*Juniperus virginiana*), woods frequently used in shipbuilding in the 19th century (Crothers, 2000; Steffy, 1994). However, it does not seem reasonable that the term "Cedar" was cited to refer to the pine types identified in BG2. As mentioned above, it is possible that cedarwood may have been used in parts of the BG2 hull that have not been preserved, such as the hull planking above the waterline or the deck planking. Moreover, we have found no information on the accuracy of the American Lloyd's surveys in the botanical identification of timbers used in shipbuilding.

As for the *Dolphin*'s construction date, Nebiker (1990), relying on The Northern Star newspaper of October 19, 1850, states that its keel was laid on August 8, 1850, and that the ship "was launched in ten weeks and five days", on October 21, 1850. Beyond the remarkable brevity of the construction time, it seems worth discussing whether the later cutting dates from our dendrochronological study on the BG2 remains are compatible with the construction dates of the *Dolphin*. It is reasonable to assume that trees were felled during the previous late fall or winter months, a common practice in the eastern United States during the 19th century. In fall and winter, the sap is not flowing through the xylem of the tree making the wood have a lower overall moisture content when compared to woodcut in the spring. Also, tree removal is hard work and cooler temperatures are appreciated when cutting and hauling logs.

If we assume that the last cutting date from the dendrochronological analysis corresponds to 1849, the felling would have taken place between the end of the growing season of 1849 and February 1850. In the latter case, which is the most compromising, the time elapsed between felling and the start of construction in the shipyard (assuming that all the timber for the framing had been stockpiled at the time of keel laying) would have been between 6 and 9 months. This is a short time, considering that it should have included transportation to the shipyard and time for the timber seasoning. Since ancient times, timber used in shipbuilding has been seasoned or treated. Green wood was avoided because it was considered to have a tendency to premature rot, which was one of the main causes for a vessel to become unseaworthy (Moll, 1926). The most common procedure was "air seasoning", i.e. natural drying in the open air for a certain period of time until most of the sap was removed. In the 19th-century other methods were also used, although not always effective, such as immersion of the wood in seawater, girdling of trees, charring of wood surfaces, salting (i.e. filling the spaces between frames with salt), or treatment with products such as creosote. Some of these treatments were chosen to shorten or eliminate the time required for the use of timbers. The appropriate air seasoning time, based on Desmond (1919), varied according to the type and quality of the wood, the climatic conditions, and the piling method. It was also recommended at least six months for 6 in. square pieces and twelve to fifteen months for 12 in. square pieces (Desmond, 1919). Nevertheless, the use of green or poorly-seasoned timber was not unusual, especially in periods of strong demand for ship construction (Chapelle, 1982; Desmond, 1919; Oster, 2015). In the case of the *Dolphin*, the very short time between keel laying in the shipyard and setting sail for her maiden voyage (99 days, according to what is mentioned in the sources) suggests that her owners or agents were in a great hurry to send her to the whaling voyages. This could explain the use of wood that was seasoned only for a few months. In summary, the later cutting date (1849) proposed for the BG2 shipwreck would be compatible with the start of the *Dolphin*'s construction on August 8, 1850.

Finally, it should be considered the possibility that the BG2 shipwreck might correspond to another ship built in North America in the same period. In this regard, it is worth remembering that, as we have already mentioned previously, different written sources refer to the presence of wreck remains in the area. However, due to their vagueness, it is not possible to discern whether they refer to the same vessel or to different ships. Therefore, in order to elucidate this issue, it will be necessary to conduct further archaeological surveys in the area and to continue with the investigation of historical sources.

5. Conclusions

In this dendroarchaeological study, we were able to determine, with a high level of statistical significance, that the BG2 remains correspond to a vessel built with white oak and yellow pine woods from the northeastern and southeastern United States, respectively, showing a most recent non-cutting date for the year 1849. These results, together with the historical information examined, allows us to confirm that these remains correspond to a 19th century vessel built in the northeastern United States. Moreover, the most recent non-cutting dates are consistent with the date of construction of the US whaler *Dolphin* (1850–1859) wrecked in the area. However, further research is required to unequivocally attribute the BG2 remains to the *Dolphin*.

This study represents a pioneering work in the use of dendrochronological methods for the dating and provenancing of nautical remains on the Atlantic coast of Argentina and encourages future research based on the large number of wooden shipwrecks in this region.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dendro.2022.125980.

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