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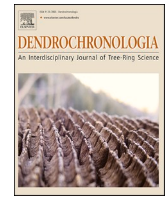

Reconstructing the oaks' growth patterns in Greece with the use of historical timber: Case studies from Western Peloponnese

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ABSTRACT

Southern Greece is a region where available oak reference chronologies are still missing, making dendroarchaeology and dating of historical buildings rather challenging, if not impossible. In the current study we performed wood identification and dendroarchaeological analysis on timber from three historical buildings: the castles of Androusa and Koroni and the Church of Agios Dimitrios, in Western Peloponnese. The three monuments represent buildings of different uses covering different periods, but also sharing a common characteristic: oak was the only timber used in their construction, while the number of preserved timber elements is very limited. A dendroarchaeological examination of these three historical buildings, together with radiocarbon and wiggle-matching analysis, provided valuable chronological information for the local archaeologists, historians, and other scientists. Application of dendrochronological techniques has helped place the three buildings under study into the Ottoman period. Our results also show that timber was acquired most probably from local non-managed forests, which suggests that oak forests were present in the broader area at least from the late 15th to the first half of the 18th centuries. The discordance between dendrochronological and radiocarbon dates in one of the three cases highlights the need for further exploration of the study area through a combined implementation of both dendrochronological and radiocarbon dating analyses in order to develop well-replicated local oak chronologies. Our study also shows that dendroarchaeology can contribute significantly to the cultural and landscape history of Western Peloponnese even with an examination of limited number of preserved timber elements from historical buildings.

1. Introduction

Deciduous oaks are among the most useful and commonly used species in dendroarchaeology (e.g. Čufar, 2007; Haneca et al., 2009; Tegel et al., 2022), the field of science that uses wood for dating historical buildings among others (e.g. Sanjurjo-Sánchez, 2016; Edvardsson et al., 2021). For Central and Northern Europe there are available numerous well-replicated centennial to millennia-long oak chronologies (see Haneca et al., 2009; Tegel et al., 2022 for a review), including the German oak chronology, covering more than 10,500 years, the longest continuous chronology in the world (Friedrich et al., 2004). Multi-centennial oak chronologies have also been developed for several Balkan countries and the southeastern part of Europe (e.g. Čufar et al., 2008; Ważny et al., 2014; Roibu et al., 2021) while efforts have been made for the development of continuous millennia-long oak chronologies based on combined application of dendrochronology and radiocarbon dating (Pearson et al., 2014; Hafner et al., 2021). The existence of such long reference chronologies are of paramount importance for dendroarchaeology and dating of historical buildings from different periods.

In Greece, available multi-centennial oak chronologies have been developed for the northern and western parts of the country, thanks to P. I. Kuniholm and C. L. Striker who were the first to apply dendroarchaeology in Greece during the 1980 s by collecting and analyzing tree-ring series from historical buildings, forests, and archaeological sites (Kuniholm and Striker, 1983, 1987, 1990). Nevertheless, these

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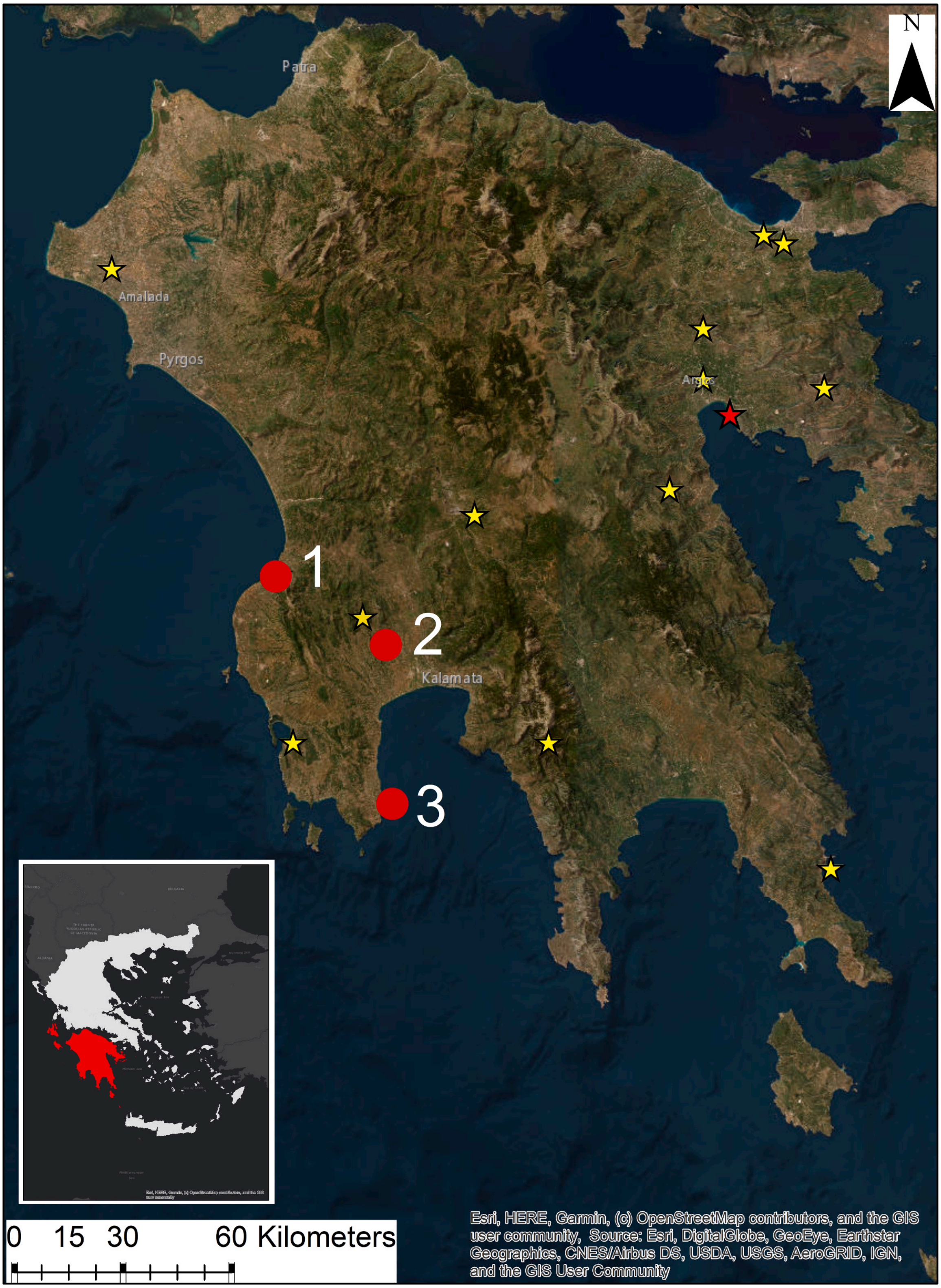

Fig. 1. Historical buildings with oak timbers in the Peloponnese (the area coded with red in the inset figure). Red dots represent the three study sites of the current study (1: Ruins of the Church of Agios Dimitrios; 2: Northwest Tower of the Androusa Castle; 3: Koroni Castle) while yellow stars represent other locations in the Peloponnese where the presence of oak timber has also been either documented or dated. To our knowledge, only results for the Venetian building in Nafplio have been published (indicated with red star).

Fig. 2. (a) The NW Tower of the Androusa Castle under restoration. (b-d) original position of the examined oak timbers inside the walls of the NW Tower.

chronologies show limited correlations with other oak chronologies from Southeast and/or North-Central Europe (Ważny et al., 2014; Roibu et al., 2021), a fact that can be explained by varying degrees of Mediterranean climate regime influence in the region (Roibu et al., 2021). In more recent dendroarchaeological studies in Greece, oak timbers have been found and dated against oak reference chronologies from Turkey (Christopoulou et al., 2020; Makris et al., 2021) or against composite chronologies representative for the Aegean region (Ważny et al., 2020). These studies highlight the common use of imported timber in historical constructions, but at the same time they raise questions about the lack of local oak reference chronologies representative of many regions in Greece. Despite the existence of several deciduous oak species of which *Quercus frainetto* and *Q. pubescens* are the most common (Strid and Tan, 1997), there are not any chronologies developed from living trees, long enough to be used for the dating of historical wood for the Peloponnese region.

In the current study we analyzed timbers from three historical buildings in Western Peloponnese (Fig. 1), a region not sufficiently explored in terms of its potential for dendroarchaeology. Such disregard with the examination of historical buildings in the Peloponnese is most probably due to (i) the scarcity of building timbers suitable for dendrochronological analysis, (ii) the use of tree species not suitable for dendrochronology, (iii) the use of timbers from fast grown trees with an insufficient number of rings, (iv) the lack of appropriate reference chronologies (Christopoulou et al., 2021). To these factors we could also add the irreversible loss of original timbers after restoration work and the possible lack of awareness among archaeologists and architects about the usefulness of dendrochronology in providing important information about the historical interpretation of monuments.

The three buildings under study are not related to each other in terms of their historical context, construction, and original function. What they have in common is their location and the use of oak as a construction timber. The aim of our study is to assess the potential of historical oak wood found in Western Peloponnese for dendroarchaeology and to set a milestone for the development of local reference oak chronologies. The presented research includes the development of chronologies representative of each building, dendrochronological dating and the confirmation or verification of the results using radiocarbon dating. Moreover, it focuses on the analysis and interpretation of timber provenance to distinguish imported wood from material available locally.

1.1. *A historical overview of the buildings under study*

1.1.1. *The northwest Tower of the Androusa castle*

The castle of Androusa is a Frankish castle located in the village of Androusa in Messenia (SW Peloponnese), 21 km from Kalamata, the

Fig. 3. (a) The castle of Koroni. View from the north, (b) The collapse of Bastion III, located on the southern stretch of the fortification wall, (c) A timber element still preserved in its original position in Bastion III.

capital of the regional unit. According to the *Chronicle of Morea*, the castle was constructed by the renowned Frankish ruler Guillaume de Villehardouin around the mid-13th century. Documents from the period of the Principality of Achaia (1205–1428 CE) refer to Androusa as the seat of military commander of the castellany of Kalamata. By the end of the 14th century the castle served as a stronghold of the Navarrese Company in Messenia. From 1417 CE onwards Androusa remained under the control of the Despots of Mistra for a few decades. Afterwards, as the rest of Peloponnese, it was conquered by the Ottomans. During the next centuries, Androusa, now a bishopric, emerged as an important administrative center of the Ottoman-held Messenia. It was also the seat of an administrative district (territorio) during the second period of the Venetian rule (1685–1715). Its fortification, however, gradually lost its defensive significance. Consequently, from the beginning of the 18th century the fortress was left in ruins until recently (Karpodini-Dimitriadi, 1993; Bouza, 2001; Kontogiannis, 2010). In 2020–2022 the Northwest Tower (NW) (Fig. 2), one of the six surviving towers of the castle, was restored within the framework of the restoration works conducted by the Ephorate of Antiquities of Messenia (EFAMES) and funded by the National Strategic Reference Framework (NSRF) as part of the Regional Operational Program “Peloponnese 2014–2020″. The tower is of great interest since its construction incorporates elements of the new defensive techniques that appeared in Greece from the 15th century onwards. The tower is almost rectangular in plan with three levels (EFAMES, 2022). During the recent restoration work timber reinforcement of the masonry was revealed, giving us the opportunity to collect and examine the tower’s original timbers.

1.1.2. *The castle of Koroni*

The castle of Koroni, located at the southwestern tip of the Peloponnese, was built by the Venetians over the site of ancient Asini (Byzantine Koroni). The castle occupies an area of about 6.2 ha surrounded by a 1.2 km-long fortification wall preserved in most parts. It consists of two fortified enclosures, the smaller one in the west, forming the Acropolis of the ancient citadel and the initial nucleus of the original Byzantine fortification, and the larger one in the east, constructed later. The main gate of the castle is located on the north side while a second, smaller one connects the castle with the Livadia peninsula. A moat with an outer curtain wall, together with orthogonal towers, and five strong bastions strengthened the defensive character of the castle (Andrews, 1953; Sfikopoulos, 1968; Karpodini-Dimitriadi, 1993; Papaxantzis, 1994; Kontogiannis, 2000). In Bastion III, located on the southern stretch of the fortification wall partly destroyed in 1944–45 during World War II, some of the timber reinforcements of the masonry are still preserved (Fig. 3). Dendrochronological examination of the preserved timbers was performed for a precise dating of Bastion III, a circular structure possibly built during the First Ottoman Period (1500–1685 CE) as suggested by its architectural style and associated archaeological evidence.

1.1.3. *Ruins of the church of Agios Dimitrios*

The third examined building is an old church, Agios Dimitrios, located in Western Peloponnese, inside the Cemetery of the Upper Town of Kyparissia, also protected under the regional unit of Messenia. The church is classified as a historical protected monument with a protection zone of 20 m. Heavily destroyed in 1825, only the eastern part of the church is preserved, including the eastern wall with a large heptagonal apse and the remains of the north wall. The masonry consists of loose stones, pieces of tiles, and binding mortar (Fig. 4) (http://listedmonuments.culture.gr/monument.php?code=14314). Moreover, a small number of beams inside the walls are still preserved in the ruins of the church. Based on architectural and archaeological evidence, the church is dated to the late post-Byzantine period.

2. Materials and methods

Each of the three sites under study was visited twice: first for an exploration of its dendrochronological potential and then for a second

Fig. 4. (a) Agios Dimitrios – the ruins of the church inside the Cemetery of the Upper Town of Kyparissia, a view from the west, (b) Agios Dimitrios, a view of the gable wall with the apse, (c) A timber element still preserved in its original position inside the walls of the church.

time after the issue of the required permission from the Ephorate of Antiquities of Messenia and the Hellenic Ministry of Culture and Sports for sampling. A total of 16 wood samples (Fig. 5) have been collected from the three study sites, representing the maximum that we could get from the available timber. Six (6) wood samples were collected from an oak framing/woodworking at the NW Tower of the Androusa Castle. Seven (7) samples were collected from different parts of the timber reinforcements of Bastion III in the Koroni Castle. Three (3) samples were collected from the available timber elements from the walls of the ruins of the Church of Agios Dimitrios. All samples were collected in the form of slices – cut with a chainsaw from the part of the timbers preserving the highest number of rings.

After the issue of the required permission, the samples were exported to the Dendrochronological Laboratory in Toruń (UNC, Poland). Sample preparation, measurements, and further analyses followed traditional dendrochronological methods (Baillie, 1982; Schweingruber, 1988). Before measuring, the surface of the samples was prepared with the use of a belt sander and a series of progressively finer abrasive grits papers to have tree rings and cells clearly visible under magnification. Tree-rings width was then measured with the use of Time Series Analysis and Presentation (TSAP) software package (Rinn, 2011) and LINTAB measuring table (Rinntech®). Accuracy of measurements was set to 1/100 mm.

As a second step, the measurements of each sample were compared with those from the rest of the samples of each site. Samples that correlate well with each other were used for the development of a mean "floating" chronology per site. The developed chronologies were then cross-dated and synchronized with regional and supra-regional reference oak chronologies (Muigg et al., 2018).

Given the rather small sample depth in all three sites, we used both visual and statistical cross-dating to evaluate our results. For statistical cross-dating we used the following parameters: i) Gleichläufigkeit (Glk), a measure of how well the growth of two trees parallel each other in an overlapping set of years; ii) t-value Ballie-Pilcher (TVBP) (Baillie and Pilcher, 1973) and t–value Hollstein (TVH) (Hollstein, 1980), which are sensitive to extreme values, such as marker years; and iii) Cross-Dating Index (CDI), which combines i and ii (Rinn, 2011). The common interval expressed by the number of overlapping years (OVL) was also taken into account. TSAPWin (Rinn, 2011) and DENDRO for Windows (Tyers, 2004) were used for visualizing our results.

Due to the insufficient length of the developed chronologies and/or the small sample depth, we performed radiocarbon dating and wiggle-matching analysis in order to verify the dates we have obtained by dendrochronology. For the NW Tower of the Androusa Castle we selected two rings representing the innermost and the outermost ring of the developed chronology. From the mean chronology developed for the Koroni Castle we selected three samples, each representing a single ring: the 9th, the 51st and the 122nd rings of the newly developed

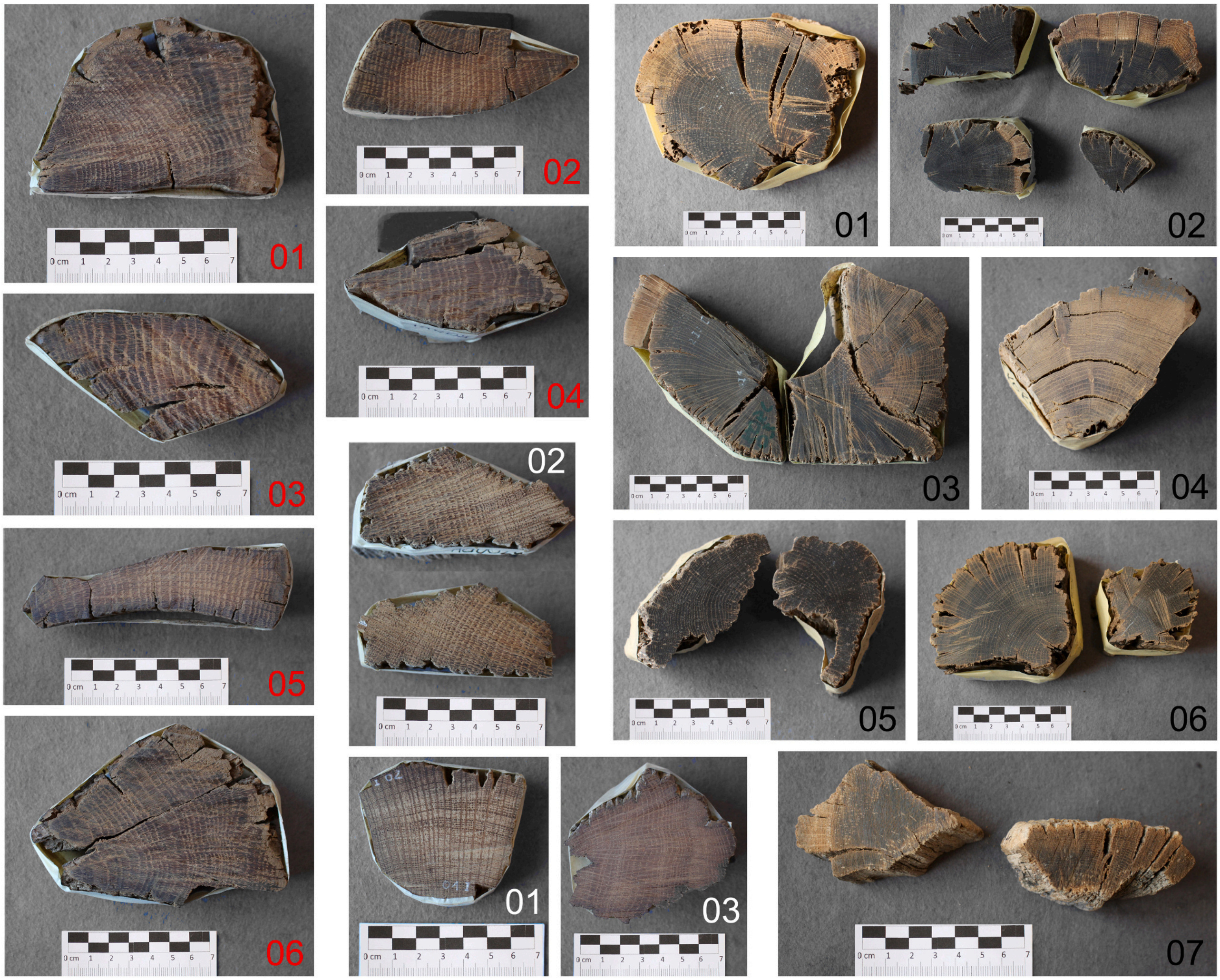

Fig. 5. Oak samples from the three study sites. Samples from the NW Tower of the Androusa Castle shown by red numbers. Samples from the Koroni Castle shown by black numbers. Samples from the Church of Agios Dimitrios shown by white numbers.

chronology. From the mean chronology developed for the Church of Agios Dimitrios we again selected three samples representing single rings: the 11th, the 60th and the 85th rings. After removal and proper preparation, these single rings were sent to the Laboratory of Absolute Dating in Kraków (Poland). From each of the samples, the most stable part of the wood in the form of α-cellulose was selected for the analysis (Santos et al., 2001; Němec et al., 2010). The extraction of α-cellulose from the samples was performed according to the method described by Michczyńska et al. (2018). After the pretreatment, around 4 mg of α-cellulose extracted from each sample were combusted to CO_2 and subsequently reduced to graphite (Krąpiec et al., 2018). The resulting mixture of graphite and Fe powder was pressed into a target holder for AMS C14 measurements. All prepared targets contained approximately 1 mg of carbon and were measured at the Center for Applied Isotope Studies at the University of Georgia, USA (Cherkinsky et al., 2010). Received results were calibrated using OxCal v 4.4 program (Bronk Ramsey, 2009) and the calibration curve IntCal20 (Reimer et al., 2020). Then the radiocarbon dates were wiggle-matched, a method that helps to determine the age of a sequence/chronology with higher precision than the calibration of a single C14 date (Pearson, 1986).

3. Results and discussion

3.1. Tree species identification and tree-ring pattern

All examined samples were deciduous oaks (*Quercus* sp.), a species commonly used for wooden constructions in the Mediterranean region (Ważny, 2009; Macchioni et al., 2012; Bernabei et al., 2020; Tegel et al., 2022), including Greece (Kuniholm and Striker, 1983, 1987; Ważny et al., 2020; Christopoulou et al., 2020; Makris et al., 2021). Oak wood has served many uses across time and societies (Bocsi et al., 2021) and its presence in Greece has been documented from buildings dated to as early as the Bronze Age period (Allen and Forste, 2020). In more contemporary historical buildings oaks are mostly used for timber reinforcements of masonry, beams in the roof and floor construction, and in timber-framed walls (Christopoulou et al., 2022).

The age of the oak timbers used and their tree-ring patterns varied among the three study sites. The youngest trees were found in the NW Tower of the Androusa Castle with a number of preserved rings varying from 38 to 44 per sample. In the Church of Agios Dimitrios the number of preserved rings per sample varied from 60 to 91 while in the Koroni Castle we had the oldest trees with amount of rings varying from 45 to 128. Pith was preserved in several of the examined samples, while none of the samples had bark or waney edge. In the Koroni Castle though, sapwood rings were present in four (4) out of the seven (7) samples (57%). The number of preserved sapwood rings per sample diversified

Table 1
Descriptive statistics of the three floating oak chronologies: mean intercorrelation of individual series with the master chronology (MC) and standard deviation (SD). MC and SD are not presented for the Church of Agios Dimitrios because of small sample depth.

Developed mean chronology	Site name	Number of dated series	Average no. of rings per series	Total no. of years	MC	SD
TANQS1m	The Northwest Tower of the Androusa Castle	4	41	49	0.765	0.070
KORC01m	The Koroni Castle	7	84	131	0.516	0.058
AGDC01m	Ruins of the Church of Agios Dimitrios	2	76	91	-	-

from 13 to 34, corresponding to the range of 26 ± 9 sapwood rings suggested for the Aegean region by Kuniholm and Striker (1987). Sample KORC03, one of the two samples with pith, has both the highest number of rings (128) and the highest number of sapwood rings (34).

3.2. Dendrochronological analysis and timber dating

From the NW Tower of the Androusa Castle five (5) of the six (6) measured samples could be synchronized with each other. Nevertheless, one sample with less than 30 rings was excluded from the analysis. The developed mean oak chronology (TANQS1m) (Table 1) therefore consists of four samples and it has a length of 49 years. For the Koroni Castle all seven samples could be synchronized with each other. The developed mean oak chronology (KORC01m) (Table 1) has a length of 131 years. For the Church of Agios Dimitrios two (2) of the examined samples (66.7%) could be synchronized and used for the development of a mean chronology. The developed oak chronology (AGDC01m) (Table 1) has a length of 91 years. Sample AGD03 could not be synchronized with the rest of the samples probably because of the disturbed growth pattern and the presence of several growth anomalies in a relatively short sequence (62 rings). Because of their small sample depth and/or rather short sequence synchronization results, all chronologies were checked with the use of COFECHA (Holmes, 1983) (Tables A1,A2,A3, Appendix A).

The three newly developed floating chronologies were cross-dated against several reference oak chronologies developed mainly from historical buildings in Northern and Western Greece (Kuniholm and Striker, 1983, 1987; Kuniholm, 2000; Kuniholm, unpublished), in addition to reference chronologies from two neighboring countries, Italy and Turkey, as shown in Table 2. Different master chronologies give the best cross-dating results for the three floating chronologies, but the same ending year is confirmed in all three cases against at least five reference chronologies. From a statistical point of view, only t-values over 3.5

Table 2
Cross-dating results of the three developed oak chronologies against reference chronologies from Greece, Italy, and Turkey. For the NW Tower of the Androusa Castle (TANQS1m) cross-dating results against the newly developed oak chronology for Koroni Castle are also provided while cross-dating results for both possible dates are given against all the reference chronologies used. TVBP/TVH are t-values sensitive to extreme values, such as marker years; CDI = Cross-Dating Index; Glk = Gleichlaeufigkeit, a measure of how well the growth of two trees parallel each other in an overlapping set of years; OVL = the number of overlapping years. The reference chronologies giving the same ending year but with t-values lower than 3.5 are marked with gray.

a/a	Study site (and floating chronology)	Code name	Site name	Reference	Dating result	TVBP/TVH	CDI	Glk	OVL
1	Northwest Tower of the Androusa Castle (TANQS1m)	ItalySE	Composite chronology from several sites in SE Italy	Ważny, unpubl.	1403–1451	2.8/1.9	13	54	49
					1447–1495	4.0/3.5	28	74 * **	49
2		GAPN001i	Agios Panteleimon, Larisa	Kuniholm and Striker (1983)	1403–1451	3.4/2.4	18	63 *	49
					1447–1495	4.7/3.4	27	66 *	49
3		ADPoakS0	Composite chronology for Aegean oaks	Kuniholm, unpubl.	1403–1451	1.5/0.8	6	51	49
					1447–1495	3.1/2.9	21	71 * *	49
4		GrNorth1	Chronology for Northern Greece	Kuniholm and Striker (1983, 1987)	1403–1451	0.9/0.5	4	53	49
					1447–1495	3.1/2.8	20	69 * *	49
5		GrThess1	Chronology for Thessaly	Kuniholm and Striker (1983, 1987)	1403–1451	1.0/0.4	4	53	49
					1447–1495	3.1/2.9	22	72 * *	49
6		VEZN002s	Chronology from Vezneciler Metro Station, Istanbul, Turkey	Ważny, unpubl.	1403–1451	0.6/0.3	2	54	49
					1447–1495	3.2/2.9	19	61	49
7		YMTwell1m	Chronology from Yenikapı, Istanbul, Turkey	Ważny, unpubl.	1403–1451	0.5/0.4	2	54	49
					1447–1495	2.6/2.7	17	65 *	49
8		KORC01m	Koroni castle	current study	1403–1451	3.5/3.1	22	71 * *	42
					1447–1495	3.2/2.5	17	60	49
1	Koroni Castle (KORC01m)	GRCWest1	Chronology for Western Greece	Kuniholm and Striker (1983, 1987)	1410–1540	5.1/4.3	29	61 * *	131
2		GAPN001i	Agios Panteleimon, Larisa	Kuniholm and Striker (1983)	1410–1540	4.2/3.3	21	55	131
3		NTurkey1	Chronology for North Turkey	Griggs et al. (2009)	1410–1540	3.7/3.5	22	61 * *	131
4		GrThess1	Chronology for Thessaly	Kuniholm and Striker (1983, 1987)	1410–1540	3.3/2.3	15	55	131
5		TSOFl	Aya Sofya, Turkey	Bannister, unpubl.	1410–1540	3.1/3.0	17	55	131
1	Ruins of the Church of Agios Dimitrios (AGDC01m)	GrThess1	Oak chronology for Thessaly	Kuniholm and Striker (1983, 1987)	1632–1722	4.6/5.7	37	72 * **	91
2		GRCWest1	Oak chronology for Western Greece	Kuniholm and Striker (1983, 1987)	1632–1722	4.8/3.9	27	72 * **	91
3		GrNorth1	Oak chronology for Northern Greece	Kuniholm and Striker (1983, 1987)	1632–1722	4.3/5.1	32	68 * **	91
4		AEGNoaks	Composite chronology from several sites in North Aegean region	Griggs et al. (2007)	1632–1722	3.5/4.7	30	68 * **	91
5		ADRIAS1M	Composite chronology for the southern Adriatic	Ważny, unpubl.	1632–1722	3.4/3.8	23	65 * *	91

Statistical significance of Glk (*** 99.9%; ** 99.0%, *95.0%).

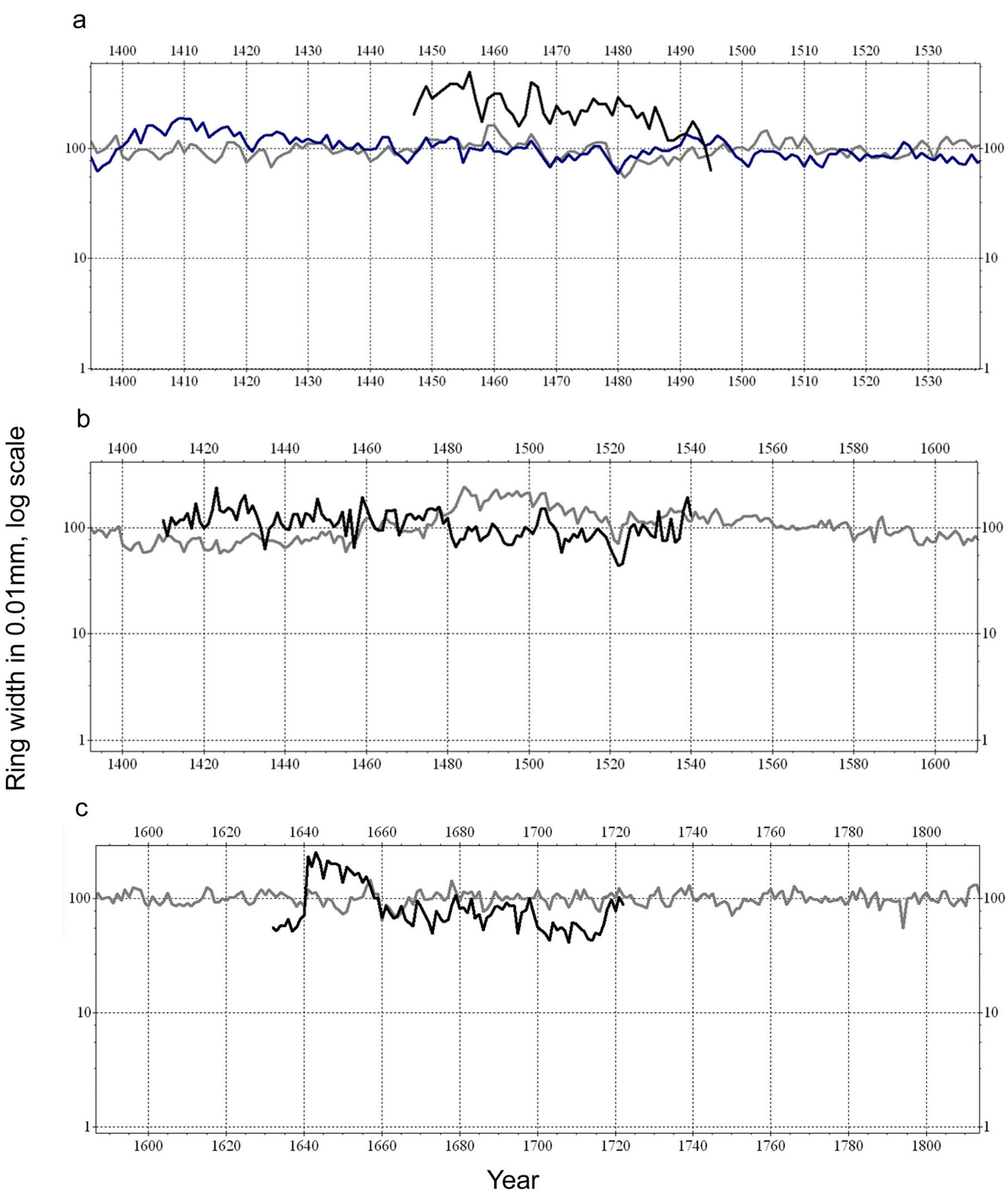

Fig. 6. Visual cross-matching of the developed mean oak chronologies (in black) and the reference chronologies giving the best cross-dating results with different colors. (a) The chronology for the NW Tower of the Androusa Castle (TANQS1m) against GAPN001i from Larisa (Greece) (in grey) (Kuniholm and Striker, 1983) and ItalySE from SE Italy (in blue) (Ważny, unpubl.). Only the overlapping period of the reference chronologies is presented. (b) The chronology for the Koroni Castle (KORC01m) against GRCWest1 for Western Greece (in grey) (Kuniholm and Striker, 1983, 1987). (c) The chronology for the Church of Agios Dimitrios (AGDC01m) against GrThess1 for Thessaly (in grey) (Kuniholm and Striker, 1983, 1987). Only the overlapping period of the reference chronology is presented.

were counted as significant, but the visual cross-matching between the two graphs was also considered (Miles, 1997).

Based on cross-dating results, the developed mean chronology for the NW Tower of the Androusa Castle spans from 1447 to 1495 CE (Fig. 6). The best cross-dating results are achieved against a composite chronology from SE Italy (Ważny, unpublished) and an oak chronology developed by Kuniholm and Striker (1983) from Ag. Panteleimon in Aghia, Larisa (Greece) (Table 2). Nevertheless, the rather low t-values, the small number of rings (49), and the small sample depth make these results, together with the discordance with radiocarbon and wiggle-matching results (see § 3.3) unreliable.

The developed mean oak chronology for the Koroni Castle spans from 1410 to 1540 CE (Fig. 6). The best cross-dating results were achieved against a composite chronology developed by Kuniholm and Striker (1987) for Western Greece (Table 2). The same dates are also confirmed against other chronologies from Greece and Turkey, although with lower t-values.

Since both chronologies overlap in time we decided to cross-date them. Their statistical correlation was weak (t-values<3.5) while visual cross-matching (Fig. 7) suggested two possible dates for the shorter

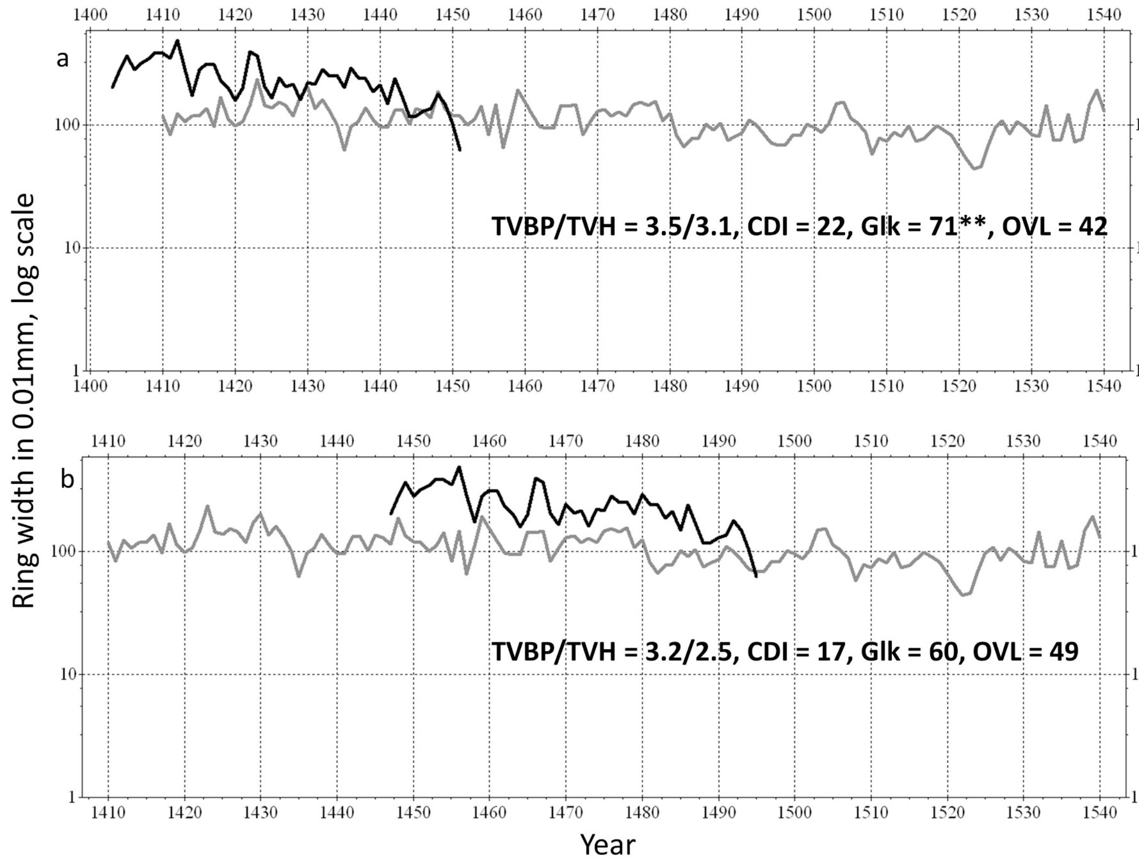

Fig. 7. Visual cross-matching of the two newly developed oak chronologies overlapping in time: the chronology for Koroni Castle (KORC01m) in grey and the chronology for the NW Tower of the Androusa Castle (TANQS1m) in black in two different places. Results of statistical cross-dating are also provided: TVBP/TVH = t-values; CDI = Cross-Dating Index; Glk = Gleichlaeufigkeit; OVL = the number of overlapping years.

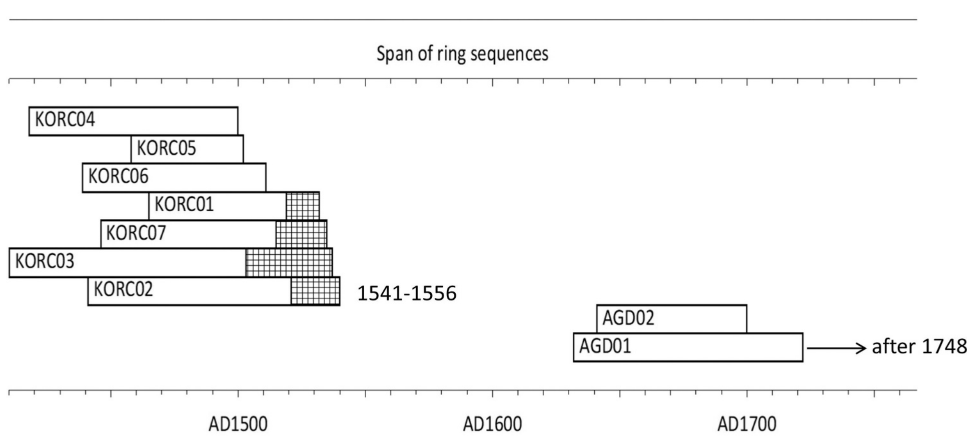

Fig. 8. The chronological span of dated oak timbers from the two of the three buildings under study: KORC for samples from the Koroni Castle and AGD for samples from the ruins of the Church of Agios Dimitrios. Parts of boxplots with hatched squares show the number of sapwood rings. Graph was prepared in DENDRO for Windows (Tyers, 2004).

chronology from the NW Tower of the Androusa Castle (TANQS1m). One of them overlaps with radiocarbon and wiggle-matching results (see § 3.3) while the second one is in accordance with dendrochronological dating against existing reference chronologies.

The developed mean oak chronology for the Church of Agios Dimitrios spans from 1632 to 1722 CE (Fig. 6). The best cross-dating results were achieved against an oak chronology from Thessaly developed by Kuniholm and Striker (1983, 1987) (Table 2, Fig. 6).

Since bark, or waney edge, were absent in all of the examined samples, all given dates should be treated as *terminus post quem* or earliest possible felling dates. In the case of the Koroni Castle the felling date can be estimated with higher precision due to the presence of sapwood rings. Given the number of preserved sapwood rings in Sample KORC02 (Fig. 8), with 19 of them measured and one partly-preserved ring not measured, the felling estimate should be within the age range of 1541–1556 CE. Considering the range of 26 ± 9 sapwood rings, a characteristic for the region (Kuniholm and Striker, 1987), we can suggest that the number of missing sapwood rings and the number of

Table 3
Results of the calibration of the C14 age of the last ring in the developed mean chronologies. Calibration and wiggle-matching modeling: OxCall v 4.4, calibration curve IntCal 20.

Chronology code	Calibration/ wiggle-matching	Length of the modeled chronology	Dating results based on dendrochronological analysis	The results of calibration of the C14 age					
				68.3% of probability (1σ)		95.4% of probability (2σ)		99.7% of probability (3σ)	
				Range of dates	Number of years in the range	Range of dates	Number of years in the range	Range of dates	Number of years in the range
TANQS1m	wiggle-matching	49	1447–1495 with reference chronologies (or 1403–1451 when cross-dated with KORC01m)	1435–1446	12	1405–1412 & 1430–1450	8 & 11	1396–1455	60
KORC01m	wiggle-matching	131	1410–1540	1554–1569	16	1547–1576	31	1539–1588	50
AGDC01m	wiggle-matching	91	1632–1722	1717–1725	9	1713–1729	17	1706–1734	28

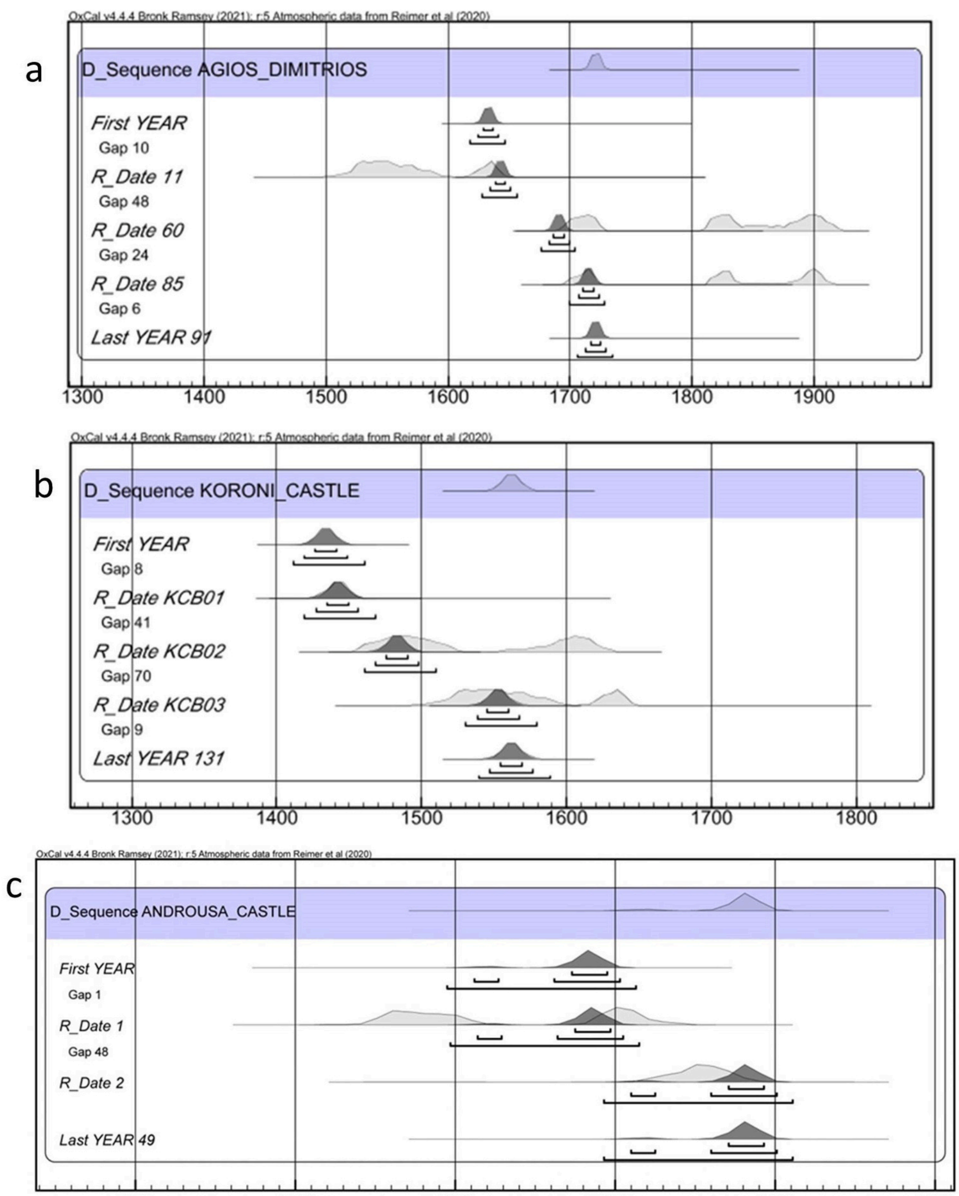

Fig. 9. Calibration of the age of the three developed oak chronologies: (a) AGDC01m; (b) KORC01m, and (c) TANQS1m. Wiggle-matching modeling – multiple plot: OxCall v 4.4 (Bronk Ramsey 2001), calibration curve IntCal 20 (Reimer et al., 2020).

Table A1
Results of COFECHA for the Northwest tower of Androusa castle chronology (TANQS1m). Correlations of 50-year dated segments, lagged 25 years.

Sequence	Series	Time span	1425–1450	1474–1499
1	TAN01	1452 1495		0.61
2	TAN02	1447 1486	0.74	
3	TAN05	1447 1487	0.87	
4	TAN06	1454 1491		0.66
Average segment correlation			0.81	0.63

missing years in the developed mean chronology is between 0 and 15. For the NW Tower of the Androusa Castle and the Church of Agios Dimitrios no sapwood rings were present, so estimations of the felling date are characterized by lower precision. In the case of Agios Dimitrios we consider that an average of 26 rings is at least missing in all samples, which would place the earliest possible cutting year around 1748 CE (Fig. 8). In the case of the NW Tower of the Androusa Castle where trees were younger in age and rather fast growing, fewer sapwood rings should be calculated (Haneca et al., 2009). Thus, we considered that an average of 17 rings is at least missing. However, we did not include dating results in Fig. 8 since the dating of the building remains uncertain.

3.3. Radiocarbon dating and wiggle-matching analysis

The selection of samples sent for radiocarbon analysis was based on the results of our previously conducted dendrochronological analysis. The results of radiocarbon dating of all the selected rings per study site are shown in Table B1 (Appendix B).

They were the basis for determining the calendar ages of the chronologies using the wiggle-matching (WM) analysis. The results of Bayesian fitting of C14 determinations with known relative age spacing to a C14 calibration curve are shown in Table 3 and Fig. 9.

The highest agreement between WM result and dendrochronological dating was obtained for the Church of Agios Dimitrios (AGDC01m). Based on WM, the dating of the last ring of the chronology was in the range of nine (9) years between 1717 and 1725 CE, with a probability of 68.3%, (1σ), and in the range of 17 years between 1713 and 1729 CE, with a probability of 95.4%, (2σ) (Table 3, Fig. 9a).

For the Koroni Castle calibration of the radiocarbon age of the last ring of the chronology, using WM analysis, resulted in a range of 16 years between 1554 and 1569 CE, with a probability of 68.3%, (1σ), a range of 31 years between 1547 and 1576 CE, with a probability of 95.4%, (2σ), and a range of 50 years between 1539 and 1588 CE, with a probability of 99.7%, (3σ) (Table 3, Fig. 9b). The agreement between the results of dendrochronological dating of the mean chronology, KORC01m (1540 CE), and the results of WM of the C14 dates representing our chronology, appeared only in 3σ, which gives the highest probability.

In the case of the NW Tower of the Androusa Castle the calibration of the radiocarbon age of the last ring of the chronology using WM analysis is between: 1435 and 1446 CE, with a probability of 68.3%, (1σ), 1430–1450 CE with a probability of 95.4%, (2σ) and between 1396 and 1455 CE, with a probability of 99.7%, (3σ) (Table 3, Fig. 9c). Both

Table A3
Results of COFECHA for the ruins of the Agios Dimitrios church chronology (AGDC01m). Correlations of 50-year dated segments, lagged 25 years.

Sequence	Series	Time span	1625–1674	1650–1699	1675–1724
1	AGD01	1632–1722	0.52	0.64	0.65
2	AGD02	1641–1700	0.52	0.64	0.65
Average segment correlation			0.52	0.64	0.65

radiocarbon dates used in the model fall within the steep section of the calibration curve, and the critical value for this modeling of 50% was not reached. The determined ranges do not include the date of the last tree-ring in the dendrochronologically established chronology. That radiocarbon fitting (WM) of short dendrochronological series can be problematic was shown by Bayliss et al. (2017). There are several possible reasons for this situation. It may be that there are high levels of annual C14 variation not currently captured by the calibration curve as they are not identifiable from the blocked decadal data used in its construction. Such hidden annual variations have the potential to shift a wiggle-match by a considerable margin (see e.g. Pearson et al., 2018). However, alternatively, it may be that there are additional sources of variation present in the data—such as geographic offsets, seasonal effects, or laboratory biases—that are not suitably recognized (Hogg et al., 2019). As previously mentioned, it is not certain whether the dendrochronological dating for the NW Tower of the Androusa Castle is correct. When TANQS1m was compared with the longer chronology developed from the Koroni Castle (KORC01m), cross-dating gave 1451 CE as the ending year (Fig. 7), which falls within the 3σ results of WM analysis. Therefore, dendrochronological results for the NW Tower of the Androusa Castle should be treated with caution.

3.4. Timber origin

The timber origin may be interpreted based on dendrochronological analysis and the results of synchronization with reference chronologies, following the idea of dendroprovenancing (Bonde et al., 1997; Daly, 2007; Eckstein and Wrobel, 2007) and by taking the limitations of this method into account (e.g. Bridge, 2012; Domínguez-Delmás, 2020; Daly et al., 2022). For the NW Tower of the Androusa Castle several reference chronologies give the same ending year (Table 2). This allows us to make some prudent suggestions concerning the possible timber origin due to short tree-ring series and the lack of confirmation by radiocarbon dating. The correlation with the oak chronology from Agios Panteleimon in Larisa could possibly indicate timber originating from central Greece. Nevertheless, the origin of the timber used in this particular building in Larisa is also unknown. On the other hand, the correlation with the composite chronology from SE Italy may suggest a timber trade via the Adriatic and the Ionian Sea. Timber trade between the Greek and the Anatolian sides of the Aegean Sea during the Ottoman period has also been suggested in previous studies (e.g. Akkemik et al., 2019; Akkemik et al., 2020; Christopoulou et al., 2021; Makris et al., 2021). The use of imported timber is also documented from regions with Mediterranean climate and long-lasting impacts of human activity, which has strongly reduced the presence of wooden species suitable for construction

Table A2
Results of COFECHA for the Koroni castle chronology (KORC01m). Correlations of 50-year dated segments, lagged 25 years.

Sequence	Series	Time span	1400–1449	1425–1474	1450–1499	1475–1524	1500–1549
1	KORC01	1465–1532			0.61	0.58	0.53
2	KORC02	1441–1540		0.78	0.76	0.67	0.58
3	KORC03	1410–1537	0.55	0.50	0.54	0.45	0.41
4	KORC04	1418–1500	0.46	0.52	0.69	0.70	
5	KORC05	1458–1502			0.56		
6	KORC06	1439–1511		0.65	0.60	0.45	
7	KORC07	1446–1535		0.46	0.43	0.39	0.31A
Average segment correlation			0.51	0.58	0.60	0.54	0.46

Table B1
Results of radiocarbon dating. The Accelerator Mass Spectrometry (AMS) method was used in this analysis.

Study site (and floating chronology)	C14 sample code	Position of C14 samples (selected rings) in the mean chronology	Lab code	C14 age (BP)±	Calendar age 2σ (cal CE)
Northwest tower of Androusa castle (TANQS1m; 49 rings)	ANT02_S02R01	1	MKL-A5939	567 ± 19	1321–1359 (54,5%) 1390–1420 (40,9%)
	ANT01_S01R49	49	MKL-A5938	498 ± 19	1409–1442 (95,4%)
Koroni castle (KORC01m; 131 rings)	KCB01	9	MKL-A5935	455 ± 19	1426–1457 (95,4%)
	KCB02	51	MKL-A5936	369 ± 21	1455–1524 (56,1%) 1560–1564 (0,8%) 1571–1631 (3805%)
	KCB03	122	MKL-A5937	309 ± 19	1505–1596 (74,9%) 1616–1645 (20,6%)
Ruins of the Agios Dimitrios church (AGDC01m; 91 rings)	AGDM01_S01	11	MKL-A5961	307 ± 18	1509–1594 (74,6%) 1618–1645 (20,8%)
	AGDM03_S02	60	MKL-A5962	94 ± 19	1694–1726 (26,5%) 1811–1917 (68,9%)
	AGDM02_S01	85	MKL-A5963	75 ± 18	1695–1725 (29,5%) 1811–1855 (30,2%) 1869–1871 (0,4%) 1876–1917 (35,4%)

purposes (Bernabei et al., 2020). However, given the low quality of the timber and the fact that the chronology also correlates with reference chronologies both to the west and the east of Greece, the most probable conclusion is that the oak timber used was local and it synchronizes with oaks from elsewhere only because of similar climatic conditions. This argument is supported if the cross-date with the newly developed chronology from the castle of Koroni is correct, but also by the young age of the timber used. The growth pattern observed in the examined material suggests an origin from a non-managed forest.

Regarding the castle of Koroni, three reference chronologies from Greece and Turkey give the same ending year: 1540 CE (+1 because of an unmeasured ring). While two subsequent chronologies support this finding, the results of statistical evaluation were not significant (Table 2). Given the length of the chronology (131 rings), however, we would expect to have much better correlations. The lack of stronger correlations suggests that the timber used in Bastion III of the castle of Koroni was most probably of local origin.

The synchronization with oak chronologies from different areas can be explained by similar climatic conditions. Such correlation results can also be attributed to the possible existence of different *Quercus* species among the examined samples. Based on the current distribution of deciduous oaks, six species of the genus *Quercus* are present in the Peloponnese (Flora of Greece Web, 2023), with *Quercus frainetto* and *Quercus pubescens* being the two most common species. Although there are some anatomical differences among these species (Merev, 1988), it is difficult to differentiate them based on their wood anatomy (Schoch et al., 2004). Moreover, there are not any studies to our knowledge suggesting different growth patterns between different oak species under similar growing conditions in Greece. The existence of different *Quercus* species has been documented for some of the oak reference chronologies developed for Greece (Akkemik et al., 2019), which makes timber provenancing even more challenging.

Finally, for the Church of Agios Dimitrios four reference chronologies from Greece and a composite oak chronology for the southern Adriatic give the same ending year: 1722 CE (plus 26 ± 9 rings because of the absence of sapwood rings). Therefore, and despite the very small sample depth, we have strong evidence that the oak timber used for the reinforcement of the masonry in this church originates from oak forests in Greece. Tree-ring pattern and especially the existence of several growth anomalies, particularly evident in Sample AGD03, further suggest that the timber originates in this case from a non-managed local forest.

4. Conclusions

The current study shows that dendrochronology can still be applied even when the quantity of preserved timber in a historical building is low. However, results should be treated with caution. Radiocarbon and wiggle-matching (WM) can be a solution, especially when developed chronologies are not well-replicated in terms of low sample depth. In the current study radiocarbon dating and WM analysis confirmed dendrochronological results in two of the three cases. In the case of the NW Tower of the Androusa Castle the discrepancy between the results of the two dating methods is within a minimum of 22 years and a maximum of 58 years. Both dates fall within the First Ottoman period for the broader area (1500–1685 CE). The results of both dendrochronological analysis and radiocarbon dating show that the timber used in the construction of Bastion III of the Koroni Castle dates back to the 1540 s CE, more precisely after the year 1541 CE, the felling date of one of the collected samples. Our date falls again within the First Ottoman Period for the broader area, confirming the previously made archaeological interpretation. Nevertheless, and despite the fact that the two newly developed oak chronologies overlap in time, their statistical correlation is weak (t-values<3.5), confirming our cross-dating results suggesting that the timber used in these two buildings is of different origin and quality. Dating results of timber from the Church of Agios Dimitrios fall within the first half of the 18th century, hence, the Second Ottoman Period for the region (1715–1828 CE).

Collecting and analyzing more material from the wider area may help us develop new oak reference chronologies for Western Peloponnese and Southern Greece and expand the existing tree-ring database for historical timber from Greece (Kuniholm and Striker, 1983, 1987). Historical timber seems to be the only available archive to develop long local oak chronologies since the present oak forests in the broader study area are rather small and scattered, mostly due to human activities and forest fires (Pantera et al., 2008). Based on palaeoenvironmental records, the distribution of deciduous oak forests has also changed several times in the past (Weiberg et al., 2016). Historical wood may also contribute to the reconstruction of such changes and the vegetational history of the region, at least for the recent centuries.

The development of local reference chronologies would allow for a better connection between Greek and Aegean oak chronologies with the other Balkan countries and Europe (Ważny et al., 2014; Roibu et al., 2021). Collaboration with experts from different fields, such as archaeologists, historians, and restoration architects, may allow for a deeper understanding and interpretation of results dendrochronology and timber examination can offer (Edvardsson et al., 2021) and help identify and resolve problems and inconsistences in dating results.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Anastasia Christopoulou, Barbara Gminska-Nowak, Yasemin Ozarslan, Tomasz Wazny reports financial support was provided by National Science Centre Poland.

Data Availability

Data will be made available on request.

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Appendix A

Results of COFECHA software (Holmes, 1983) used to validate the synchronization of all the series used for the development of the three oak chronologies.

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Appendix B

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