Dendrochronologia xxx (xxxx) 126095

Contents lists available at ScienceDirect

Dendrochronologia

journal homepage: www.elsevier.com/locate/dendro

Dendroarchaeology at Lake Ohrid: 5th and 2nd millennia BCE tree-ring chronologies from the waterlogged site of Ploča Mičov Grad, North Macedonia

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ARTICLE INFO

Keywords:
Dendrochronology
Dendroarchaeology
Radiocarbon dating
Wetland archaeology
Wiggle-matching
Pile-dwellings
Prehistoric Balkans
Oak
Juniper

ABSTRACT

The prehistoric site of Ploča Mičov Grad (Ohrid, North Macedonia) on the eastern shore of Lake Ohrid yielded a total of 799 wooden samples from a systematically excavated area of nearly 100 square metres. Most of them are pile remains made of round wood with diameters up to almost 40 cm. A comprehensive dendrochronological analysis allows the construction of numerous well-replicated chronologies for different species. High agreements between the chronologies prove that oak, pine, juniper, ash and hop-hornbeam can be crossdated. The chronologies are dated by means of radiocarbon dates and modelling using wiggle matching. An intensive settlement phase is attested for the middle of the 5th millennium BCE. Further phases follow towards the end of the 5th millennium BCE and in the 2nd millennium around 1800, 1400 and 1300 BCE. Furthermore, the exact, relative felling dates allow first insights into the minimum duration of the settlement phases, which lie between 17 and 87 years. The present study lays the foundations for the establishment of a dendrochronological framework for the southwestern Balkans for periods of 6000 years ago. The multi-centennial chronologies presented in this study can be used as a first robust dating basis for future research in the numerous not yet dated prehistoric lake shore settlements of the region with excellently preserved wooden remains.

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https://doi.org/10.1016/j.dendro.2023.126095
Received 1 February 2023; Received in revised form 1 May 2023; Accepted 4 May 2023

1. Introduction

1.1. Cultural and environmental setting of Lake Ohrid

Lake Ohrid (N40°59’’38.8′ E020°47’’51,7′ 693 m a.s.l.) takes its name from the biggest settlement on its shores – the city of Ohrid (Fig. 1). A historic city with a continuous occupation of more than three millennia, Ohrid is also one of the most important cultural and religious centres in the Balkans. The Lake of Ohrid is a deep (289 m) and large (358 km^2) tectonic lake, shared today between Albania and North Macedonia. It is the oldest lake in Europe, as well as one of the most biodiverse in the world (Albrecht and Wilke, 2008). Hence, the Lake Ohrid region was recognised as a mixed natural and cultural World Heritage site by UNSECO in 1979 (extended in 2019). Lake Ohrid and the Small and Great Prespa Lakes form the upper part of the river Drin basin, whose watershed drains into the Adriatic Sea (Fig. 1). The most significant amount of water inflow into Lake Ohrid comes from underwater springs on the east and southeast side of the lake, seeping through the mountain karst. The main feeder of this inflow is the neighbouring Lake Prespa (849 m a.s.l), situated on the eastern side of the Galičica mountain range. The constant inflow of freshwater into the lake contributes to the highly oligotrophic environment, which may positively influence the preservation of organic material.

Within the southern Balkans lie some of the main corridors of the spread of agriculture into Europe (‘Neolithization’), beginning over 8500 years ago (Maniatis, 2014; Karamitrou-Mentessidi et al., 2015; Reingruber, 2018; Krauss et al., 2018; Maniatis and Adaktylou, 2021). Archaeological and palaeoecological investigations have shown that farming in the Lake Ohrid region started during the 6th millennium BCE (Allen and Gjipali, 2014; Brechbühl et al., in press). Besides the numerous dryland prehistoric sites, more than ten shore settlement sites have been identified around the lake (Fig. 2). The site of Ohridati –

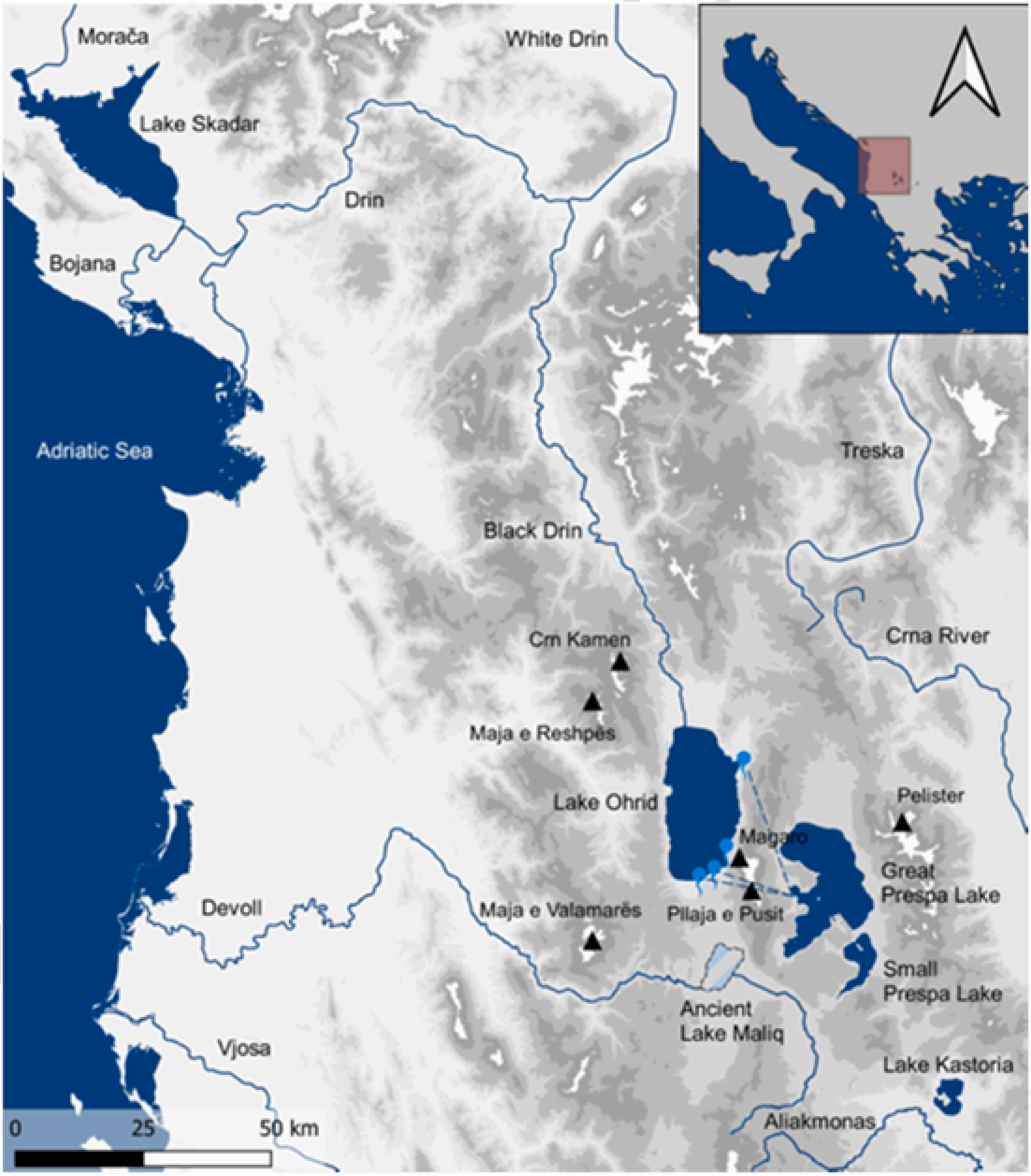


Fig. 1. Location of Lake Ohrid, Prespa Lakes and the Drin river basin in the southwestern Balkans. The dashed lines refer to the most important underground connections between Lake Ohrid and Great Prespa Lake (location of springs and underground connections after Amataj et al., 2007; Hauffe et al., 2011; Eftimi and Zojer, 2015). Map: J. Reich, EXPLO/University of Bern.

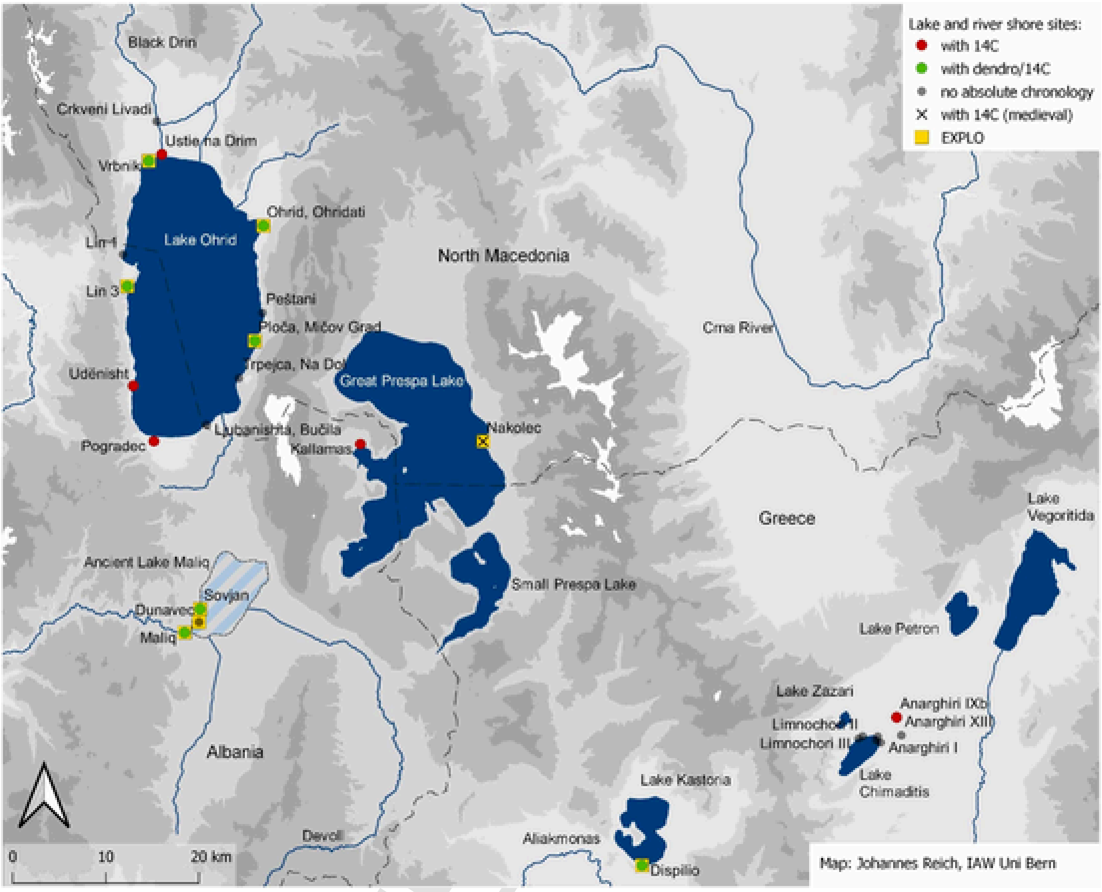


Fig. 2. Lakeshore and wetland archaeological sites from the lakes region of southwestern Balkans. The map summarises the current state of knowledge on the identification and precise location of lakeshore settlement sites (Status 2022). Map: J. Reich, EXPLO/University of Bern.

within the boundaries of the modern city of Ohrid – is the oldest documented shore settlement on Lake Ohrid, and one of the earliest in Europe, dating to around 5500 BCE.

The average annual precipitation at lake level is ≈ 700–800 mm, significantly increasing with altitude. The wettest month is November and the driest is August. The average yearly temperature is 11.3 °C (Milevski et al., 2015), with the lowest monthly average temperature in January (≈ 1.5 °C), and the highest in August (≈ 22 °C). The local climate conditions can be defined as continental to sub-Mediterranean (Matevski et al., 2011). Within the Köppen climate classification it can be described with several types: as humid subtropical (Cfa), warm-summer Mediterranean (Csb) and humid continental (Dfb) (Beck et al., 2018).

The distinctive environmental setting has provided for a great diversity of the dendroflora on the Galičica mountain range, with 180 woody species (Matevski et al., 2011; Acevski and Mandžukovski, 2019). The range from the lakeshore to mid-altitude mountain slopes is characterised by oak-dominated forests occurring together with other thermophilous species (hornbeams, ash, maple), while on drier sites azonal communities are dominated by Macedonian oaks, hornbeams and several juniper species (Matevski et al., 2011). The higher altitudes (> 1000 m a.s.l) are covered by mixed beech-fir forests (*Fagus sylvatica*, *Abies borisii-regis*), as well as the rarer occurrence of pines (Matevski et al., 2011; Acevski and Mandžukovski, 2019). The treeline reaches its highest altitude of 1880 m a.s.l. on slopes with a northward aspect, representing an anthropogenically lowered treeline (Kolčakovski, 1994).

1.2. *Archaeology of Ploča Mičov Grad*

The site of Ploča Mičov Grad (known colloquially as the 'Bay of Bones') (Fig. 2) is located on the central-eastern lakeshore at ca. 690 m a.s.l., under the slopes of the karstic Galičica mountain range (Magaro Peak: 2255 m a.s.l.). The submerged archaeological site is situated up to 5 m below the present lake water level. It is one of the more than ten prehistoric lakeshore settlement sites spread around the lake (Koco, 1951; Pašić, 1957; Todoroska, 2010; Kuzman, 2013; Naumov, 2016; Hafner et al., 2021). Reports of prehistoric pottery found by fishermen in the surroundings of the Gradište peninsula – forming the northern part of the bay – date to at least the 1970 s (Kuzman, 2013). However, the first underwater archaeological activities on the site took place in 1997 (Kuzman, 2013). In the subsequent decade, several underwater archaeological investigations yielded a more comprehensive picture of the site, documenting and mapping more than 6000 piles and recovering abundant material culture remains (Kuzman, 2013). Based on the relative pottery chronology the site was defined as a Late Bronze/Early Iron Age settlement, dating 1200–700 BCE. Given the large number of wooden piles at a significant depth in the lake, the site was interpreted as a raised pile-dwelling on a platform. Further, these initial data served as a basis for a modern reconstruction of a pile-dwelling on the site which serves as an open-air museum ('Museum on Water'). No systematic dendrochronological analysis was performed on the prehistoric wooden remains in the lake bottom prior to the reconstruction, which damaged one third of the site. However, given the large extent of the site of ca. 8500 m^2 and the high average density of 8.1 piles/m^2, it can be estimated that several tens of thousands wooden piles are still preserved in the lake bottom.

Sampling of wood material for dendrochronological analysis and underwater archaeological excavations took place in 2018 and 2019 (Naumov et al., 2018, 2019). The dendrochronological analysis of 735 wood samples revealed a much longer chronological span of the settlement than previously attested, starting with the first documented occupation during the 5th millennium BCE (around 4400 and 4170 BCE), followed by occupation phases in the 2nd millennium BCE (around 1800, and between ca. 1420 and 1250 BCE). The resulting tree-ring chronologies span several centuries and represent the first and longest tree-ring chronologies for those periods in the wider region.

1.3. Prehistoric dendroarchaeology in the Balkans and Anatolia

The first dendrochronological investigations in the Balkans within historical and archaeological contexts took place in the late 1970 s (Kuniholm and Striker, 1987), as a follow-up of earlier dendroarchaeological studies in Anatolia of the early 1960 s (Kuniholm et al., 2011). The Aegean Dendrochronology Project (ADP) focused on the wider Eastern Mediterranean region. This project provided the first centuries-to-millennia-long tree-ring chronologies based on wood from buildings, archaeological sites, and forests, spanning from the 7th millennium BCE up to modern times (Kuniholm and Striker, 1987; Kuniholm et al., 1996; Griggs et al., 2007; Pearson et al., 2012; Ważny et al., 2014). The most robust of the prehistoric chronologies, such as that of Gordion (Pearson et al., 2020), cover the later periods such as the Bronze and Iron Ages. When it comes to the oldest ADP prehistoric chronologies that span into the Neolihtic, they are mainly charcoal-based and come from Anatolian sites. On the other hand, prehistoric chronologies from the Balkans are scarce, represented by floating oak chronologies from submerged settlements on the Bulgarian Black Sea coast (Kuniholm et al., 2007) and oak wood dredged from big rivers in Bosnia and Croatia (Pearson et al., 2014).

In the past 15 years, several waterlogged archaeological sites in the southwestern Balkans have been sampled for dendrochronological analysis (Westphal et al., 2010; Hafner et al., 2021; Maczkowski et al., 2021). All these chronologies are “floating”, i.e. approximately placed on the calendar time-scale through radiocarbon dating. The only absolutely dated, and most notable prehistoric archaeological TRW chronologies are the centuries-long oak chronologies from Slovenian pile-dwellings (Čufar et al., 2010; Čufar et al., 2015). However, considering the orographic barriers and geographical distance of the Slovenian pile-dwellings from the southwestern Balkan, it is unlikely that deciduous species (i.e. oak) can reliably cross-date between the two areas.

2. Material and methods

2.1. Preservation

Wood preservation in waterlogged environments is influenced by a complex set of biotic and abiotic factors. Inevitably, the usual degradation processes such as bacterial and/or fungal decay and cell wall thinning have set in and influenced the material to varying degrees. But the general preservation state of the wood from Ploča is very good. The partial decomposition did not impede dendrochronological analysis and the woods were rarely penetrated by roots of aquatic plants. Keeping the water-saturated wood constantly in wet conditions after sampling is sufficient for the temporary curation before and after analysis. For permanent archiving or transport the wet wood samples were vacuum sealed in 90 μm-thick plastic bags.

2.2. Sample processing and dating

During the two fieldwork campaigns in 2018 and 2019, a total of 799 vertical piles and horizontal wood were documented on an area of 96 m^2 (Fig. 4 and Fig. 5). The underwater mapping and documenting of the wooden elements consisted of a novel working procedure based on Structure from Motion (SfM) photogrammetry, producing georeferenced orthophoto mosaics (Reich et al., 2021). After setting and documenting the underwater plot, transversal samples were cut from almost all underwater wooden remains by handsaws. The large size of the wood samples and relative hardness of some oak and juniper samples (Fig. 6) made sawing underwater challenging, requiring at times up to 2 h per sample. Therefore, some juniper piles were not sampled for logistical constraints towards the end of the excavation in 2019. The irregularly shaped hand-sawn samples were then transversally cut on an electric bandsaw into 5–8 cm thick slices (Fig. 3). The on-site sample processing consisted of documenting the following features: approximate number of annual rings, shape (full round wood section, half-round section, wedge section, worked on all sides or eroded), surface, presence of waney edge (i.e. the last growth ring) and particular characteristics (e.g. chopping marks, charring, etc.) (S1, Supplementary material). Additionally, samples were sorted by categories according to dendrochronological suitability depending on wood species, preservation, and the number of annual rings. Wood samples with a combination of unsuitable features such as low ring number (<30), no waney edge, growth disturbances or complacent rings were not measured. Tree species determination was based solely on stem wood anatomy since no other tree elements were recovered. The microscopic wood-anatomical features of the samples were identified and compared to standard reference literature (Schweingruber, 1990; Schoch et al., 2004; Akkemik and Yaman, 2012).

The first dendrochronological measurements were carried out in a temporary laboratory in the vicinity of the site in 2018 and 2019 (Naumov et al., 2018; Naumov et al., 2019; Hafner et al., 2021). The remaining samples were measured in the laboratory at the Institute of Archaeological Sciences of the University of Bern and using the infrastructure of the Dendrochronological Laboratory of the Archaeological Service of Canton Bern. Two to four radii per sample were measured and averaged together to represent the mean ring growth of a tree. Measurement was carried out on measuring tables with a precision of 0.01 mm under binocular microscopes. Dendroplus software (Version 2013, Ulrich Ruoff, unpublished) and PAST5 (Version 5.0.610, SCIEM) were used for ring measurement, cross-dating and chronology building. Dendrochronological statistical cross-dating parameters such as t-values (tBP, Baillie and Pilcher, 1973; tHo, Hollstein, 1980) and coefficient of parallel variation (Gleichläufigkeit, GLK) (Eckstein and Bauch, 1969), were used as a guide for the correct cross-dating position which was checked and verified visually in a vector graphics software. Summary dendrochronological statistics of the chronologies were produced with the R dplR package in the RStudio environment (Bunn et al., 2020; R Core Team, 2020). Initially, chronologies were constructed by cross-dating samples with at least 50 rings (e.g. Baillie and Pilcher, 1973; Haneca et al., 2009), but as the chronologies expanded, shorter sequences could also be dated employing methods developed in wetland archaeology (Francuz, 1980; Billamboz, 2008). When comparing many samples from a specific site, it is very likely to detect several trees from the same forest or stand with very similar growth patterns. For this reason, dendrotypological characteristics such as presence of sapwood or waney edge, cambial age and growth trend were considered in the cross-dating process (Billamboz, 2008). Stand-related, as well as individual patterns (Bleicher, 2013) in raw tree-ring series, are essential for the formation of dendrogroups (DGs) based on dendrotypological characteristics. In the context of DGs, additional verification of the cross-dating was done by recalculating the groups and mean curves with high-pass cubic smoothing splines in PAST5 (Version 5.0.610, SCIEM). The quality of the cross-dating is classified in two categories (Francuz, 1980): “a” for unambiguous matches which are averaged into a chronology, and “b” for very probable, but uncertain matches. The same categories, indicated in capital letters, are used for the mean value chronologies, where the “A” class stands for a main chronology, and “B”

Fig. 3. Ohrid, Ploča Mičov Grad. A: The site is situated at the foot of the Galičica mountain range in a small bay on the east coast of Lake Ohrid. The open-air 'Museum on Water' features the reconstruction of a prehistoric settlement on the premises of the archeological underwater site; the slopes of Gradište peninsula in the foreground. B: Collection of a juniper wood sample for dendrochronological analysis (sample no. 1287, now dated to the 45th c. BCE). C: Preparation of a pine sample for dendrochronological analysis (sample no. 1037, now dated to the 15th c. BCE). (A: G. Milevski, Centre for Prehistoric Research Skopje; B: A. Ulisch; C: M. Hostettler; editing A. Bieri; EXPLO/University of Bern).

refers to a probable cross-dating of a smaller group/chronology against the "A" class (Table 1).

The identification of the last growth rings (or waney edge) in the oak samples was recorded to a seasonal level, i.e. the presence of one row of early wood (EW) cells was defined as felling in spring; several rows of EW as felling in spring/summer, and as autumn/winter when last growth ring terminates with fully developed latewood (LW). Sapwood estimation for oaks with missing waney edge but preserved parts of sapwood was done with the integrated feature for sapwood statistics in Dendroplus that is mainly based on samples from wetland sites in Switzerland (Ruoff, 1995; Bleicher et al., 2020). Considering the variable, region-specific sapwood ring number (Haneca et al., 2009; Rybníček et al., 2012; Sohar et al., 2012; Prokop et al., 2016; Nechita et al., 2018; Jevšenak et al., 2019), the underlying data for the sapwood estimation model might lead to slightly different results and a specific statistic for this geographical area will be developed in the future.

Most chronologies were sampled for radiocarbon dating. The tree-ring samples were dated in the Laboratory for the Analysis of Radiocarbon with AMS at the University of Bern (Szidat et al., 2014). The cellulose was extracted from wood samples using the BABAB method (for details see Szidat et al., 2014). The radiocarbon dates were then modelled ('wiggle-matched') using the D_Sequence command in OxCal v.4.4 (Bronk Ramsey et al., 2001; Galimberti et al., 2004; Bronk Ramsey, 2009) and compared to the atmospheric data from the IntCal20 calibration curve (Reimer et al., 2020) with curve resolution set at 1 year.

3. Results

3.1. Wood anatomy

The majority of the recovered wood samples (64.8%) are from the genus *Quercus* sp. (Fig. 7). Today, several oak species are present in the immediate surroundings of the site on the slopes of Galičica (such as *Quercus pubescens*, *Q. petraea*, *Q. trojana*, *Q. frainetto*, *Q. cerris* (Matevski et al., 2011; Acevski and Mandžukovski, 2019). These contemporary oak species belong to the taxonomical sections of Quercus and Cerris. The distinction between the two sections is possible based on latewood pore size and distribution, best observed in wider rings (Akkemik and Yaman, 2012; Merela and Čufar, 2013). Since a big part of our specimen came from trees with narrow rings, overlooking these diagnostic wood-anatomical characteristics was very likely. Additionally, species from both taxonomical sections are usually cross-dated and averaged

Fig. 4. Ohrid, Ploča Mičov Grad. Orthophoto of the archeological site with the underwater excavation area (squares) next to the modern open-air reconstruction. The hatched area marks the approximate extension of the piles at the lake bottom (CRS: EPSG:32634). (G. Milevski, Centre for Prehistoric Research Skopje and J. Reich, EXPLO/University of Bern).

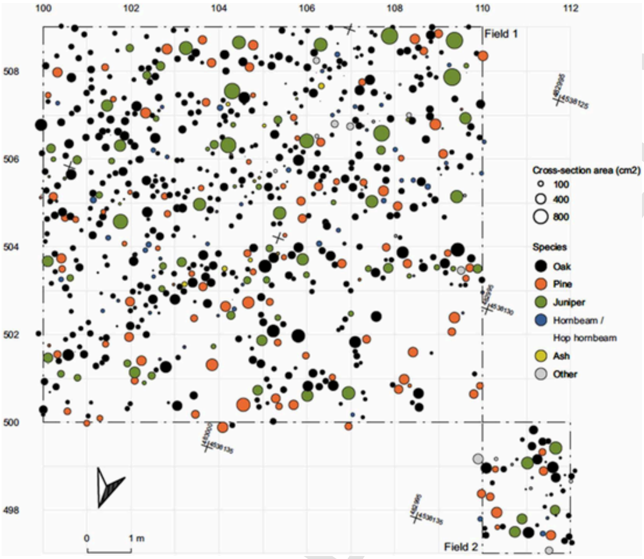


Fig. 5. Ohrid, Ploča Mičov Grad. Plan of the wooden piles documented during the excavation campaigns 2018 and 2019 in Field 1 and 2. Each circle marks the location of a wooden pile, indicating the piles' diameter surface area. The piles reach up to 39 cm in diameter (CRS: local and EPSG:32634). Documentation and mapping: J. Reich, EXPLO/University of Bern).

together (Akkemik and Yaman, 2012; Ważny et al., 2014) and no known significant differences exist in their secondary growth patterns. Therefore, also in this study, all ring-porous oaks were analysed together.

The second most abundant taxon in Ploča is pine (13.3%). Pine species can sometimes be distinguished through wood anatomical characteristics, chiefly in the radial section. Based on the large fenestriform cross-pitting with dentate tracheid walls (Schweingruber, 1990; Schoch et al., 2004), the pine samples were identified as belonging to the subgenus *Pinus* (i.e. *Pinus nigra/sylvestris*-type). Today, pine populations on the Galičica mountain range are very rare and consist mostly of *Pinus nigra*, with occasional occurrence of *P. peuce* and *P. heldreichii* on elevations above 2000 m. *Pinus peuce* (of the subgenus *Strobus*) can be anatomically distinguished based on its smooth and thin tracheid walls in the radial section (Schoch et al., 2004; Schweingruber, 1990). No pines of the subgenus *Strobus* were identified in the archaeological material from Ploča Mičov Grad. However, we cannot rule out the possibility that the characteristic thin tracheid walls were misidentified due to taphonomical alterations. All pine samples in this study are grouped as *Pinus* sp., with *P. nigra* being the most likely species they represent.

The remaining conifer samples are from the genus *Juniperus* (10.3%). It is generally accepted that different juniper species cannot be distinguished solely by stem-wood anatomy (Schweingruber, 1990). However, the absence of intercellular spaces on the transversal section of *Juniperus oxycedrus* (cf. *J. deltoides* Adams) has been suggested as possible discriminant for that species (Akkemik and Yaman, 2012), and our initial field observations on modern junipers on Galičica are in line with these suggestions. Of the tree-like junipers in the region *J. oxycedrus* has a somewhat smaller habitus as compared to the larger diameter stems of *Juniperus excelsa* and *J. foetedissima*. Based on the wood anatomy, and the ecology and distribution of these species on Galičica today (Matevski et al., 2011) all three could have been used at the site as building material, with *Juniperus excelsa* and *J. foetedissima* being the more likely species.

Secondary growth variations and disturbances were present in many wood samples. Intra-annual density fluctuations (junipers) and locally absent or missing rings (junipers and pines) due to partially inactive cambium are very characteristic for conifer species (Sass-Klaassen et al., 2008; Derose et al., 2016; Kahveci et al., 2018). In contrast, missing annual rings in oaks are not reported, at least not for *Quercus robur/petraea* (Leuschner and Schweingruber, 1996; Haneca et al., 2009). However, continued suppressed growth of some oak individuals resulted in interlocked EW vessels, which made recognising tree-ring boundaries challenging. Such tree-ring irregularities were overcome through segment cross-dating, visual inspection, and measurement of multiple radii, made possible thanks to the large sample size and inter-species correlation.

The dominant species in the remaining specimen of deciduous wood are *Ostrya carpinifolia/Carpinus betulus/orientalis* with 62 specimens. Differentiation is often problematic as the wood anatomical features may overlap, especially in younger trees (Schweingruber, 1990; Schoch et al., 2004; Akkemik and Yaman, 2012). A reliable identification characteristic for *Carpinus* is the presence of aggregate rays, while Ostrya has a higher incidence of spiral thickenings. Thus, 41 pieces could be reliably identified as *Ostrya carpinifolia* and 2 as *Carpinus betulus/ornus*. The remaining 19 are categorised as *Ostrya/Carpinus*. A blind selection of 22 samples was additionally analysed by Werner Schoch, confirming the predominance of *Ostrya* (n = 20), followed by *Carpinus* (n = 1) and unidentifiable (n = 1) (Werner Schoch, Labour für quartäre Hölzer, Langnau am Albis, Switzerland, 2022, internal report/personal communication).

3.2. Tree-ring chronologies

Of the total 799 sampled wood remains, 735 were dendrochronologically measured. Almost half of the measured samples (45%, n = 329) were cross-dated with at least two other wood samples, forming 19 groups/chronologies of oak, pine, juniper, hop-hornbeam and ash (Table 1). The two-sample cross-dated pairs are not discussed in the present work.

The longest and most-replicated chronology (MKO-100) consists of 92 oak samples, with an average correlation between non-detrended series (rBar(r_{bt}), Briffa and Jones, 1990; Bunn, 2008; Bunn et al., 2020) of 0.42, which, albeit lower, is comparable to findings in similar studies (e.g. Čufar et al., 2015). The chronology is composed of several dendrogroups of different age classes, which were then averaged together into a 408 years-long tree-ring width (TRW) chronology. Replication is above 10 samples for 274 years (relat. yrs. 90–364). The maximum replication in the middle of the chronology reaches 61 samples. The oak chronology MKO-103 was calculated from three dendrogroups and a

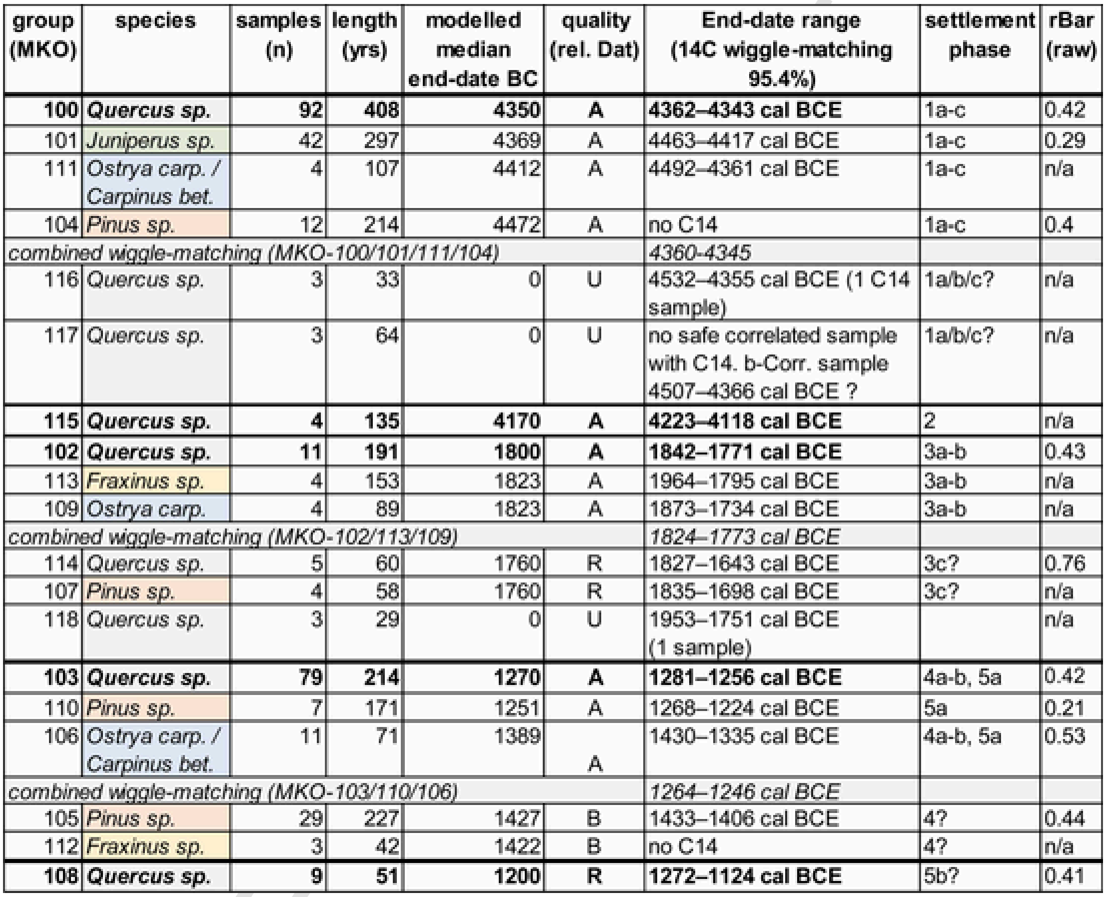
Fig. 6. Ohrid, Ploča Mičov Grad. A: Uncovering, documenting and collecting wood samples in Field 2. B: Sample of an oak pile from the 2nd half of the 2nd millennium BCE. C: juniper and D: pine samples of piles from the 5th millennium BCE. (A: A. Ulisch; B and D: J. Reich/C. Stäheli; C: A. Maczkowski; editing A. Bieri; EXPLO/University of Bern).

few individual samples. It consists of 79 samples, spanning 214 years. Replication above 10 samples spans 185 years (yrs. 12–197, rBar = 0.42) (Table 1). The 7 remaining oak groups/chronologies contain between 3 and 11 timbers. The most robust of these smaller chronologies is MKO-102, spanning 191 years and predominantly composed of samples with more than 100 annual rings (rBar = 0.43).

Chronology MKO-101 is the main juniper chronology, with a total of 42 tree-ring sequences averaged together (rBar = 0.29). The vast majority of the correlated junipers (80%) have more than 100 rings. With increasing replication, numerous missing and/or false annual rings in individual samples could be identified and corrected. The last 20 years of the chronology are represented by only a single sample, and its outer sapwood rings cannot be verified with absolute certainty against other junipers. The same applies to the poorly replicated first 40 years. Additionally, four pine chronologies were constructed. Pine tree-ring growth was noticeably more heterogenous compared to that of oaks or junipers. Of the 92 measured pine wood samples, 52 could be cross-dated into a group/chronology. MKO-105 is the most-replicated pine chronology with 29 samples, spanning 227 years (rBar = 0.44). The two mean curves 104 (214 years) and 110 (171 years) are also useful for further reference chronology building due to the great number of rings. Several chronologies and groups of non-oak deciduous species were also constructed. Of the 49 measured hop-hornbeam and hornbeam samples, three groups with four to eleven timbers each were cross-dated together. Additionally, two groups of ash wood samples were cross-dated. In a few cases when ring boundaries could not be distinguished directly on the sample, measurements were made on thin-sections.

Cross-dating between the chronologies reveals surprisingly high statistical values and visual similarities between different species (heteroconnections). For the statistical comparison, low-replicated sections of chronologies were truncated. A first group of heteroconnections are the correlations between the oak chronology MKO-100, against juniper (MKO-101), pine (MKO-104) and hop-hornbeam (MKO-111) chronologies (Fig. 11). Statistical values (tHo, GLK) between the wood species are all highly significant with a correspondingly sufficient overlap. Visual comparison confirms the cross-dating in all combinations. A second group of heteroconnections includes oak (MKO-102), ash (MKO-113) and hop-hornbeam (MKO-109) (Fig. 12). The same applies to a

Table 1
Ohrid, Ploča Mičov Grad. List of all mean curves with more than 3 samples. The main oak chronologies are marked in bold. The end-date of the chronologies is assigned to a median calendar year based on the ^{14}C wiggle-matching and does not represent absolute BCE dates, therefore indicated as a modelled median and-date BCE. The end-date of the main oak mean curves and safe synchronisations of other species on this oak mean is indicated as grade “A”. “B”: very probable synchronisation. “R”: Possible overlap with the ^{14}C-fixed oak mean curves, but the position may change; “U”: “undated”, i.e not cross-dated with any of the other chronologies. *rBar – an average of all pairwise correlations between all trees/samples in the chronology ($r_{bt,}$ Briffa and Jones, 1990; Bunn, 2008; Bunn et al., 2020)16.



group (MKO)	species	samples (n)	length (yrs)	modelled median end-date BC	quality (rel. Dat)	End-date range (14C wiggle-matching 95.4%)	settlement phase	rBar (raw)
100	***Quercus sp.***	**92**	**408**	**4350**	**A**	**4362–4343 cal BCE**	1a-c	0.42
101	*Juniperus sp.*	42	297	4369	A	4463–4417 cal BCE	1a-c	0.29
111	*Ostrya carp. / Carpinus bet.*	4	107	4412	A	4492–4361 cal BCE	1a-c	n/a
104	*Pinus sp.*	12	214	4472	A	no C14	1a-c	0.4
combined wiggle-matching (MKO-100/101/111/104)						*4360-4345*		
116	*Quercus sp.*	3	33	0	U	4532–4355 cal BCE (1 C14 sample)	1a/b/c?	n/a
117	*Quercus sp.*	3	64	0	U	no safe correlated sample with C14. b-Corr. sample 4507–4366 cal BCE ?	1a/b/c?	n/a
115	***Quercus sp.***	**4**	**135**	**4170**	**A**	**4223–4118 cal BCE**	2	n/a
102	***Quercus sp.***	**11**	**191**	**1800**	**A**	**1842–1771 cal BCE**	3a-b	0.43
113	*Fraxinus sp.*	4	153	1823	A	1964–1795 cal BCE	3a-b	n/a
109	*Ostrya carp.*	4	89	1823	A	1873–1734 cal BCE	3a-b	n/a
combined wiggle-matching (MKO-102/113/109)						*1824–1773 cal BCE*		
114	*Quercus sp.*	5	60	1760	R	1827–1643 cal BCE	3c?	0.76
107	*Pinus sp.*	4	58	1760	R	1835–1698 cal BCE	3c?	n/a
118	*Quercus sp.*	3	29	0	U	1953–1751 cal BCE (1 sample)		n/a
103	***Quercus sp.***	**79**	**214**	**1270**	**A**	**1281–1256 cal BCE**	4a-b, 5a	0.42
110	*Pinus sp.*	7	171	1251	A	1268–1224 cal BCE	5a	0.21
106	*Ostrya carp. / Carpinus bet.*	11	71	1389	A	1430–1335 cal BCE	4a-b, 5a	0.53
combined wiggle-matching (MKO-103/110/106)						*1264–1246 cal BCE*		
105	*Pinus sp.*	29	227	1427	B	1433–1406 cal BCE	4?	0.44
112	*Fraxinus sp.*	3	42	1422	B	no C14	4?	n/a
108	***Quercus sp.***	**9**	**51**	**1200**	**R**	**1272–1124 cal BCE**	5b?	0.41

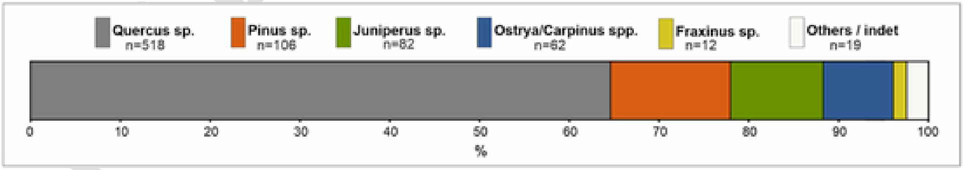


Fig. 7. Ohrid, Ploča Mičov Grad. Stacked percent chart of the tree species distribution among the total of 799 documented wood samples from the excavations in 2018 and 2019. “Others/indet” include few individuals of Acer sp. and Alnus sp., and samples that could not be identified (see Sup. Mat. S1).

third group, in which pine and hop-hornbeam have very similar growth signals to oaks. The pine chronology MKO-105 shows a possible synchronous position with the oak chronology (Fig. 13; for ^{14}C see Sup. Mat. S3.1), and in this case, the temporal gap to the other pine chronology MKO-110 would be 6 annual rings. Intensive efforts to fill this gap with other, undated pines, were not successful. Combining the two pine chronologies (MKO-105 & MKO-110) by inserting virtual rings in the mentioned gap, and thereby enabling the comparison of a combined pine sequence against the oak chronology (MKO-103) did not lead to statistical confirmation. Neither the hop-hornbeam chronology (MKO-106, Fig. 12) is of any further help in this question, even though it is located precisely in this possible gap and can be clearly cross-dated, especially visually, to the oak chronology MKO-103. The cross-dated ashwood group MKO-112 shows high statistical values against the hop-hornbeam (MKO-106) and the oak (MKO-103) in the same area. However, due to the low number of annual rings (n = 37) and a replication of only three samples, this cross-dating is not sufficiently reliable and is thus classified as “B-dated”, i.e. probable. The same applies to the most probably correct, but not absolutely safe, position of the pine chronology MKO-105 (^{14}C wiggle-matching also supports such placement, see Sup. Mat S3.1).

All other synchronous positions mentioned so far are classified as safe ("A-dated"). A further correlation between oak and pine chronologies (MKO-114 and MKO-107) yields relatively low statistical values (Fig. 9). However, the last felling dates on both species are all in the same year, supporting the validity of their synchronous position. Although the above mentioned heteroconnections confirm the existence of a common growth signal in pines and oaks, the cross-dating between

MKO-114 and – 107 is classified as being of category "B" correlation, i.e. probable, but uncertain.

The dendrochronological synchronizations of the tree-ring sequences of Ploča Mičov Grad show four temporal blocks (Fig. 8–Fig. 10). In the absence of further safe statistical matches, we expect that these results represent at least four temporally different episodes of settlement activity at the site. As no absolutely dated prehistoric TRW chronology exists for the southern Balkans, radiocarbon dating was used to place our “floating” chronologies and groups on the calendar time-scale.

3.3. *Radiocarbon dating*

Most of the chronologies and some randomly chosen individual timbers were sampled for radiocarbon measurement and wiggle-matching of the subsequent results. The iterative process of measuring, cross-dating and radiocarbon sampling, over a period of two years, resulted in some chronologies having larger number of radiocarbon measurements compared to others. The 62 tree-ring radiocarbon dates (Sup. Mat. S2) allowed for the approximate placement of the chronologies on the absolute calendar time-scale (Fig. 11–Fig. 13; Sup. Mat. S3). The chronological resolution obtained through wiggle-matching depends on the number of ^{14}C measurements across a chronology, the calendar-year distance between them, and the shape of the calibration curve in a given period. This is an effect of the fluctuating levels of ^{14}C in the atmosphere across time and the existence of the so-called plateaus and reversals of the ^{14}C calibration curve (Hajdas et al., 2021). The OxCal CQL code used in the wiggle-matching models is available in the online Supplementary Material (Sup. Mat. S4).

The calibrated end-date ranges for the main oak chronologies MKO-100 and MKO-103 are *4362–4343 BCE cal (95.4% probability)* (Fig. 11) and *1281–1256 BCE cal* (Fig. 13), respectively. This chronological resolution of a few decades is possible thanks to the length of these chronologies as well as the relative overall “stability” of the calibration curve during the respective periods. This however is not the case with chronology MKO-102 whose end-date range is *1842–1771 BCE cal* (Fig. 12). The larger calibrated time-span for MKO-102 can be attributed to the existence of a short radiocarbon plateau in 19th–18th century BCE (see Supplementary Material in Reimer et al., 2020).

Initially, all wiggle-matching models were constructed on single species. In this way, radiocarbon dating served as an independent control for the dendrochronological cross-dating (Sup. Mat. S3.1). However, in many cases, there is robust cross-dating between different species (heteroconnections) with high t-values, long overlap, and good visual match, further supported by ^{14}C. Therefore, where dendrochronological cross-dating between different species was beyond any doubt, we combined the ^{14}C data from different chronologies into a single model (Figs. 8–10; Sup. Mat. S3, S4).

For the late second millennium BC, a combined multi-species chronological model points to an end-date range of *1264–1246 cal BCE* (95.4%) (Fig. 8; Sup. Mat S3.2). The radiocarbon measurements from samples in the pine chronology MKO-105 show that the suggested cross-dating position might be correct, but considering the not entirely convincing overlap with the oak chronology MKO-103, the ^{14}C data from MKO-105 are not included in the final multispecies model.

The resulting end-date from the multispecies wiggle matching of the chronologies ending around 1800 BCE is *1824–1773 cal BCE (95.4%)* (Fig. 12; Sup. Mat. S3).

In a multi-species ^{14}C chronological model, the end-date for the chronologies based on MKO-100 is *4360–4345 cal BCE* (95.4%) (Fig. 11; Sup. Mat. S3). With juniper ^{14}C dates included in the multispecies model, the OxCal agreement index ($A_{overall}$) of the model is outside the conventional 60% threshold (Bronk Ramsey, 1995) (Sup. Mat. S3.2, a.). A closer examination of the raw ^{14}C dates revealed an off-set towards older dates of juniper ^{14}C measurements in comparison to oak in the range of 50–60 ^{14}C years (Sup. Mat. S2, S3.2). Given that both the statistical and visual cross-dating between the oak and juniper tree-ring chronologies are excellent, a cross-dating error can be ruled out as a

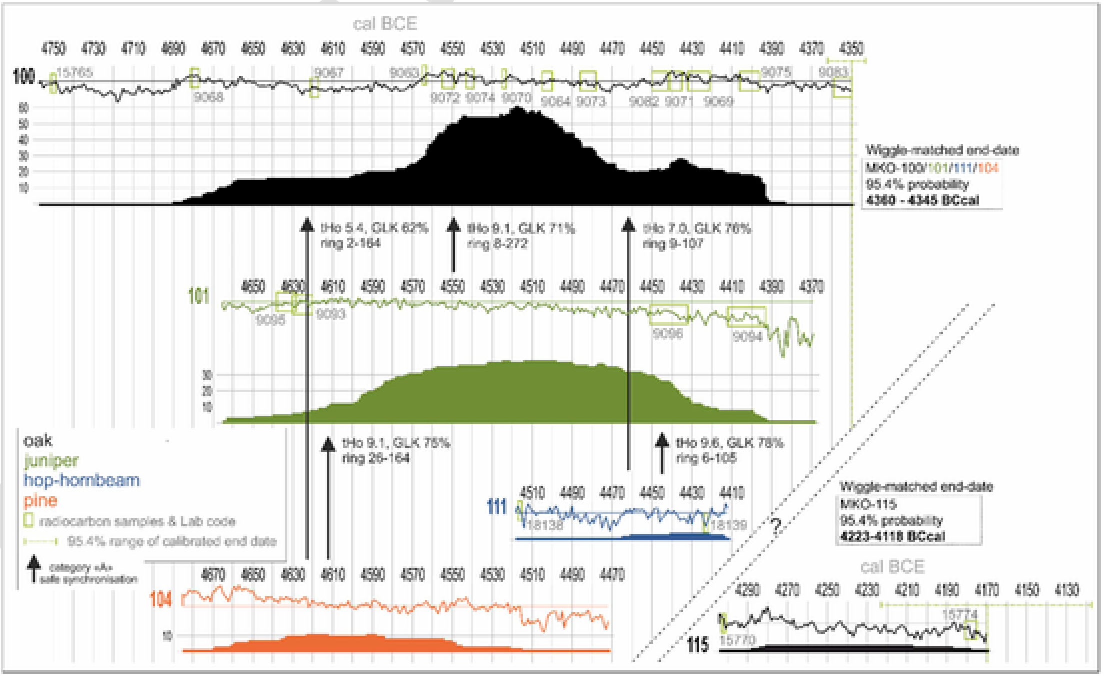


Fig. 8. Ohrid, Ploča Mičov Grad. Chronologies of the 5thmillennium. Coloured replication histograms and chronology mean curve above. Colour of replication histograms corresponds to species, same as in Figs. 11–13. Black vertical arrows indicate dendro cross-dating; next to each arrow the corresponding t-value (tHo, after Hollstein, 1980) and the Gleichläufigkeit (GLK) for the corresponding relative-year comparison range (e.g. rings 8–272 of the juniper chronology MKO-101 yileded t-values 9.1, GLK 71% against the oak chornology MKO-100). Rectangular boxes on the curves with attached numbers: positions and labels of ^{14}C samples. The end-date of the chronologies is assigned to a median calendar year based on the ^{14}C wiggle-matching (green dotted lines, vertical spans represent the 95.4% probability range for the modelled end-date).

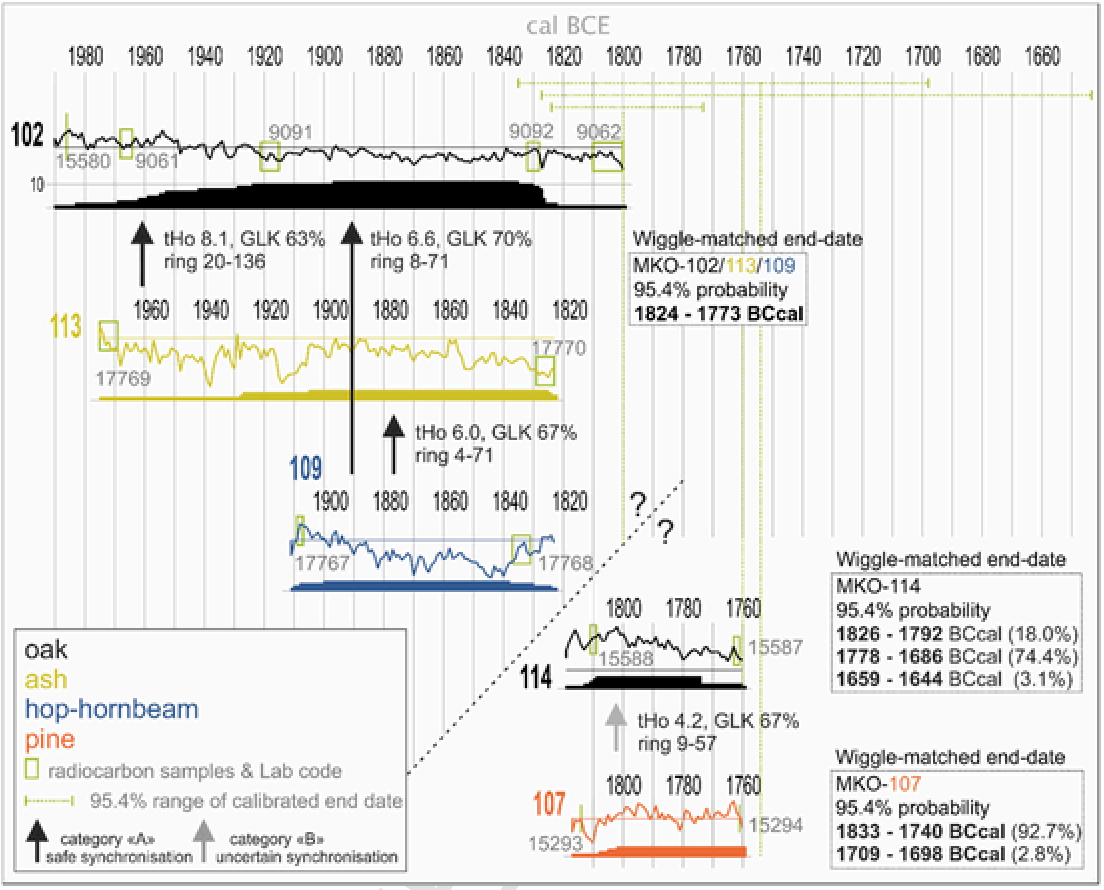


Fig. 9. Ohrid, Ploča Mičov Grad. Chronologies of the 2nd millennium BC, around 1800 BC. Coloured replication histograms and chronology mean curve above. Colour of replication histograms corresponds to species, same as in Figs. 11–13. Black vertical arrows indicate dendro cross-dating; grey vertical arrows indicate B-category cross-dating; next to each arrow the corresponding t-value (tHo, after Hollstein, 1980) and the Gleichläufigkeit (GLK) for the corresponding relative-year comparison range. Rectangular boxes on the curves with attached numbers: positions and labels of ^{14}C samples. The end-date of the chronologies is assigned to a median calendar year based on the ^{14}C wiggle-matching (green dotted lines, vertical spans represent the 95.4% probability range for the modelled end-date).

possible reason for the ^{14}C divergence. However, due to the relatively low number of exactly overlapping ^{14}C measurements between juniper and oak (3 instances; see Fig. 8, rectangles indicating ^{14}C samples), this discrepancy could not be analysed in greater detail. Another limitation is the bulk nature of our juniper ^{14}C measurements, performed on 11–19 annual rings each. In other studies (Pearson et al., 2020), comparisons on long series of annual ^{14}C measurements have revealed an average off-set between juniper and oak ^{14}C of only 9 ± 3.5 radiocarbon years (Pearson et al., 2020). However, in the dataset of Pearson et al. (2020), few individual juniper measurements deviate up to a 100 ^{14}C-years from the oak ^{14}C (cf. Fig. 2 in Pearson et al., 2020). Since the majority of the 5th millennium data in IntCal20 calibration curve is based on oak wood measurements (Reimer et al., 2020), it is expected that modelling non-annual, non-oak dates can result in lower agreement values. Hence, a wiggle-matching model excluding the juniper ^{14}C passes the OxCal agreement index (Sup. Mat. S3.2, b.), however, the end-date range does not differ from the range output when all species are included (Sup. Mat. S3.2, 5th mill. insets a.-b.). In all other instances, dendrochronologically determined synchronous positions were clearly supported by the ^{14}C data.

The last annual ring of each group was placed on a median calendar year based on the wiggle-matching models outputs. This is to be understood explicitly as an approximate temporal indication, with the actual temporal range and error defined by the wiggle matching model (Table 1; Sup. Mat. S3–4). Non-oak chronologies were assigned relative end-years according to their dendrochronological cross-dating with the respective oak chronologies. This allows the exact sequence of felling dates to be represented across all wood species relative to each other on a quasi-absolute time-scale.

3.4. *Settlement phases of the 5th and 2nd millennia BC*

Three distinct temporal blocks of settlement activity are clearly visible from the dendrochronological cross-dating and ^{14}C wiggle-matching at Ploča Mičov Grad, in the mid-5th millennium, beginning, and end of the 2nd millennium BC. The results can be complemented by a few ‘floating’ chronologies that do not cross-date with any of the larger groups but may well have overlapped in time. This concerns MKO-108 around 1200 BCE (Fig. 13), as well as MKO-114 and MKO-107 around 1800 BCE (Fig. 12). Another chronology, MKO-115 (Fig. 11), shows no overlapping with the other references for the 5th millennium based on the dendrochronological and ^{14}C data, and points to another settlement phase.

The minimum duration of the settlement phases can also be established based on the felling data. However, it must be considered that the size of the investigated area (96 m^2) is quite limited in relation to the extent of the pile field (8500 m^2) allowing only partial insights into the settlement activity. Thus, temporal gaps in the data cannot be equated with an occupation hiatus. Although on the well-studied Circum-alpine wetland settlements, gaps of 10 or more years are often interpreted as an interruption of settlement activities (Ebersbach, 2013; Hafner, 2019; Heitz et al., 2021), gaps of similar length in Ploča Mičov Grad must be interpreted with caution.

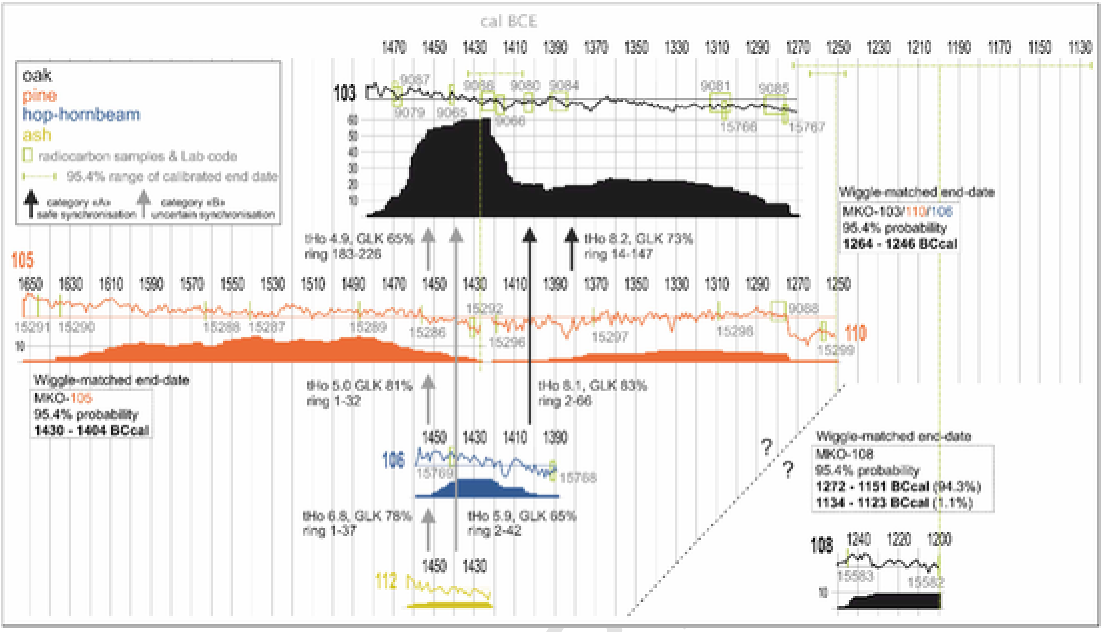


Fig. 10. Ohrid, Ploča Mičov Grad. Chronologies of the 2nd millennium BC, around 1400–1200 BC. Coloured replication histograms and chronology mean curve above. Colour of replication histograms corresponds to species, same as in Figs. 11–13. Black vertical arrows indicate dendro cross-dating; grey vertical arrows indicate B-category cross-dating; next to each arrow the corresponding t-value (tHo, after Hollstein, 1980) and the Gleichläufigkeit (GLK) for the corresponding relative-year comparison range. Rectangular boxes on the curves with attached numbers: positions and labels of ^{14}C samples. The end-date of the chronologies is assigned to a median calendar year based on the ^{14}C wiggle-matching (green dotted lines, vertical spans represent the 95.4% probability range for the modelled end-date).

3.4.1. Settlement phases of the 5th millennium BC, around 4500 cal BCE

A median end-date of 4350 cal BC was assigned to the mid-5th millennium chronologies, based on the wiggle matching models. Most of the trees with a preserved waney edge (WK) from the 5th millennium BCE chronologies were cut between 4469 and 4383 cal BCE (Fig. 11). This indicates continuous settlement activities for at least 87 years. Whether the two younger dates of 4369 cal BCE and 4349 cal BCE (based on sapwood estimation) can also be assigned to this phase and proving an uninterrupted occupation of more than 100 years is not clear at present. Due to the preservation condition, numerous oaks of the 5th millennium BCE have no sapwood left. This does not allow an assignment of approximated felling dates. Likewise, the last growth rings are missing on all the pines from this period. In the case of the oaks, the grouping of samples in dendrogroups (see sect. 2.2) shows that timbers from the same group, with similar growth patterns, have similar proportions of sapwood or even waney edge. This is not a definite argument for adding missing rings, but it does show that woods with the same growth patterns may well still be missing up to 100 annual rings to the waney edge. Even among the pine groups, a lack of more than 100 annual rings is quite possible in individual cases due to sporadic narrow-growth ring patterns. Earlier terminations of measured tree-ring series can therefore not indicate any earlier beginning of settlement phases.

Chronology MKO-115, mentioned above, consists of only four samples and follows towards the end of the 5th millennium with a length of 135 years (Fig. 11). Since it does not cross-date with any of the other chronologies, the median end-year of MKO-115 was assigned to 4170 cal BCE, based on the wiggle-matching. One of the samples in this group has several preserved sapwood rings, therefore the felling date must be a few years after the last preserved ring.

3.4.2. Settlement phases of the 2nd millennium BCE around 1800 BCE

The settlement phases in the early 2nd millennium BCE are defined by felling dates of three chronologies of oak, ash and hop-hornbeam (Fig. 12). Through a multispecies wiggle-matching model the median calendar end-date for this settlement phase is placed at 1800 cal BCE. According to the felling dates, the minimum duration of this settlement phase is 17 years between 1839 and 1823 cal BCE. Whether the younger felling date of 1800 cal BCE can also be assigned to this phase and prove an uninterrupted occupation of 40 years is not clear at present due to missing felling dates in between (Fig. 12). According to the radiocarbon dates (Table 2; Sup. Mat. S4), the other groups, MKO-107 (pine) and MKO-114 (oak), could overlap with the main early 2nd millennium chronologies, but no dendrochronological cross-dating was found. Thus, it remains unclear whether MKO-107 and MKO-114 represent another settlement phase, with at least two felling events within 11 years. To further clarify this open question, more cross-dated wood samples with waney edges from this specific period would be needed.

3.4.3. Settlement phases of the 2nd millennium BCE around 1400–1200 BCE

A total of 64 felling dates provide clear evidence of continuous settlement activities for at least 36 years between 1424 and 1389 cal BCE (Fig. 13). In the pine chronology MKO-105 no samples with waney edge are present. The wide dispersion of the last preserved annual rings over 167 years does not allow a statement of whether it is possible to assign all timbers to the settlement phase around 1400 BCE or whether they contain individual trees felled earlier. Following the previously mentioned settlement phase, after a gap of 26 years, a single, isolated felling date of the year 1363 cal BCE is present. It cannot yet be supplemented with other timbers by sapwood estimates. 48 years later, around 1315 cal BCE, a new group of felling dates between 1315 and 1270 cal BCE emerges and testifies to new settlement activities of at least 46 years (Fig. 13, settlement phase 5a). The mean curve MKO-108 contains nine oaks with the same felling date, which, according to the radiocarbon dates, could overlap with the settlement phase between 1315 and 1270 cal BCE (settlement phase 5a), but no correlation can be detected. One pine tree was certainly felled after settlement phase 5a, so another, somewhat younger settlement phase can possibly be recorded also with the oaks.

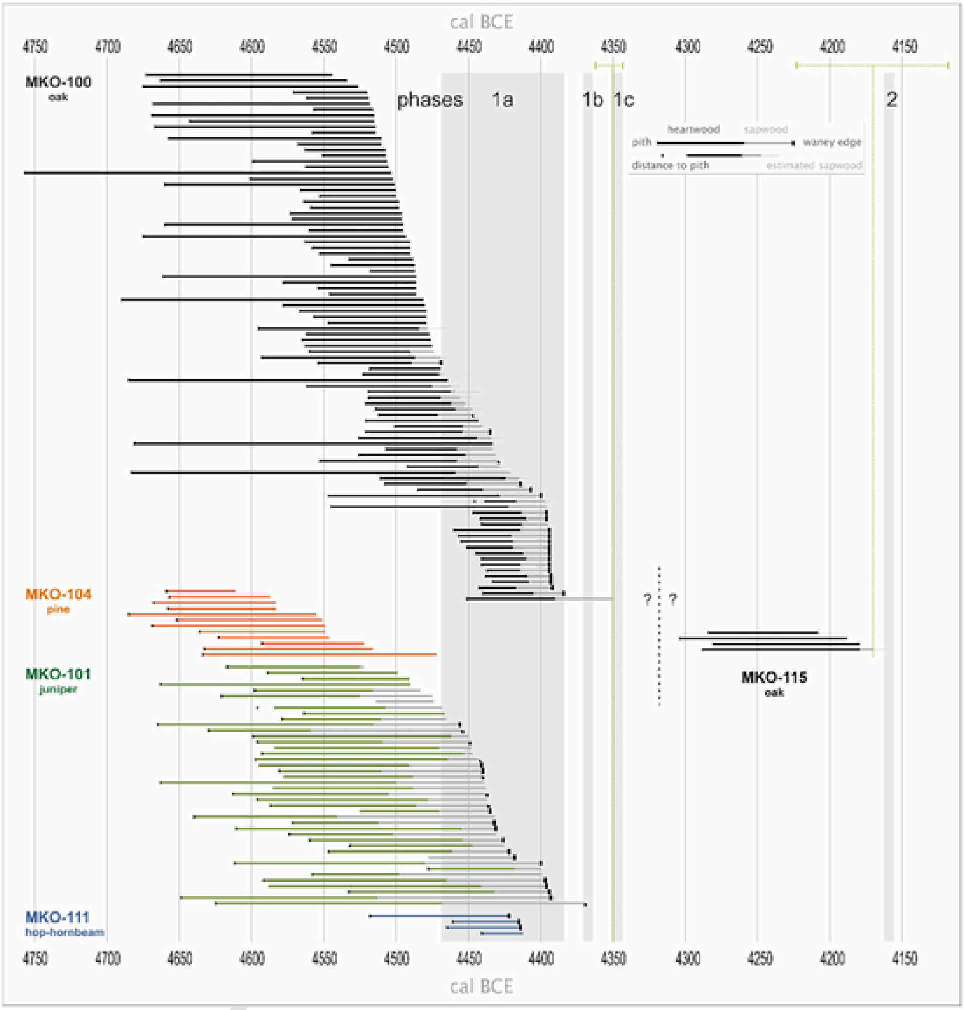


Fig. 11. Ohrid, Ploča Mičov Grad. Barplot of all individual tree-ring series of the 5th millennium BCE in their relative position on a calendar timescale. Felling activities are highlighted with grey vertical bars and are assigned to a settlement phase (see Table 2). The end-date of the radiocarbon dated chronologies is assigned to a median calendar year based on the ^{14}C wiggle-matching (green dotted lines, vertical spans represent the 95.4% probability range for the modelled end-date, see Table 1).

4. Discussion

The predominance of oak woods allows the formation of a robust chronological basis that can be linked to other wood species of the same site. The significance of this work lies on the one hand in the formation of this solid, basic framework for further regional dendrochronological dating. In total, the chronologies cover more than 1100 years, divided into at least four distinct temporal blocks with internal subdivisions. On the other hand, the numerous individual felling dates allow for the first time in-depth insights into the prehistoric intra-site dynamics not only at Lake Ohrid but in the wider region of the southwestern and central Balkans. Although the excavated section is still small in relation to the total extent of the site, it is clearly possible to outline specific building activities. Thus, at least five temporally separated settlement phases can be differentiated (Table 2). According to the felling data, the occupation periods on the site have a time-spans as low as at least 17 years, or up even up to 87 years, at least. A clear dating focus can be discerned in the middle of the 5th millennium BCE. These dates correspond well with the radiocarbon dates sampled from the up to 1.7 m thick preserved organic cultural layer (Hafner et al., 2021). Therefore, the finds of the cultural layer represent the best dated reference complex of the 5th millennium BCE in the southestern Balkans, especially for the classification of ceramics but also for archaobotanical, -zoological and pollen remains.

Other phases may remain hidden in the undated or the not sampled piles. Additionally, if piles made from juvenile trees with few annual rings were used in a settlement phase, they may elude dating. Dating success can also be significantly lowered if the piles are heavily eroded. Therefore, in this section of the pile field, we would expect only a small number of additional, unrecorded phases. According to the pollen data, however, earlier human activity in the period around 5500 BCE can be assumed in the bay of Ploča Mičov Grad (Brechbühl et al., accepted). This period of plausible human activity was not recorded in the area sampled for dendrochronology, and may be preserved in another area of the site.

The findings of the wood species identification in the present study are in line with palynological results for the 5th millennium BC, based on cores extracted from the edge of the site (Brechbühl et al., accepted). The high percentage of oak wood among the piles, which is both strong and durable, is no surprise. It can be easily worked with stone axes after cutting, as long as it is not completely dried out. Oak was used intensively across Europe in all the periods, as documented by dendrochronological dating (e.g. Haneca et al., 2009; Ljungqvist et al., 2022). Preliminary observations of synchronous growth release or suppression events in oak tree-ring sequences from the 2nd millennium BCE suggest a possible intentional woodland management and selection.

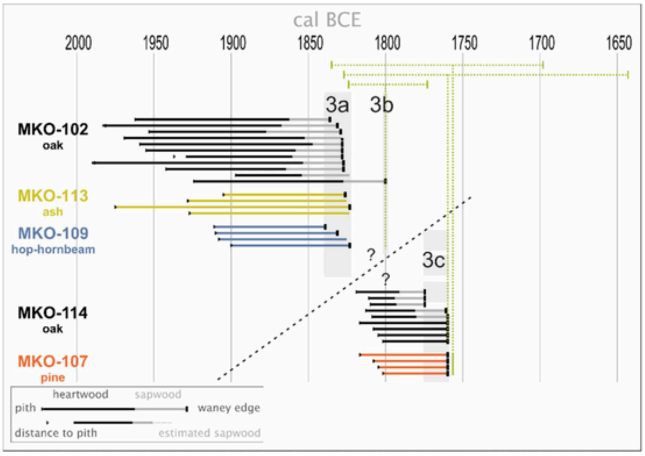


Fig. 12. Ohrid, Ploča Mičov Grad. Barplot of all individual tree-ring series of the 2nd millennium BCE (around 1800 BC) in their relative position on a calendar timescale. Felling activities are highlighted with grey vertical bars and are assigned to a settlement phase (see Table 2). The end-date of the radiocarbon dated chronologies is assigned to a median calendar year based on the ^{14}C wiggle-matching (green dotted lines, vertical spans represent the 95.4% probability range for the modelled end-date, see Table 1).

Pine wood was also regularly used at Ploča, with its percentage being highest towards the end of the 2nd millennium BCE. Ash and hop-hornbeam are of lesser importance, but with the exception of ash in the 5th millennium, they are documented in all periods. In contrast, the evidence of junipers seems exclusive to the oldest phase in the 5th mill. BCE. It is clear that this wood was specifically chosen as construction material. Juniper trees with diameters up to almost 40 cm have been felled for use in construction. Waterlogged juniper wood has very high durability, as even after drying it does not shrink substantially. Today, no juniper trees of this size are growing in the vicinity of the site, but can be found on the eastern slopes of Galičica around Lake Prespa.

Not much is known about the ecology of the tree-like junipers (such as *J. excelsa* and *J. foetedissima*), compared to some other tree species. Junipers' significance in pollen spectra seems also to be neglibile when compared to its abundance as construction wood. In this regard, statements of human induced control and/or extinction of junipers in the area are difficult to support. However, a decrease in the *J. excelsa* coverage around Lake Ohrid can be preliminary deduced during the 20th century CE, which may be related to intensified human impact (cf. distribution maps in Košanin, 1926 vs. Matevski et al., 2011). It remains to be confirmed whether the use of juniper trees in the Balkan prehistory was a cultural preference, a technical one, or an expedient choice.

5. Conclusion

The dendrochronological processing of 735 wood samples from a systematically documented area of nearly 100 m^2 at the Lake Ohrid archaeological site of Ploča Mičov Grad allowed the construction of reference chronologies for several wood species. High statistical values (often $>$tHo 8.0) and excellent visual matches of the growth patterns of oak, pine, juniper, ash, and hop-hornbeam indicate that similar environmental factors influenced the secondary growth of all these species in the past. This shows that the most abundant species are all suitable for dendrochronological analyses and no specific selection is needed, although oak wood forms the basic framework for cross-dating. The exact temporal placement of these chronologies through wiggle-matching of radiocarbon dates establishes them as local and regional references for high-resolution dendrochronological dating.

The methodology of tree-ring chronology building followed in this study will be applied also to other sites investigated within the EXPLO project (Fig. 2), which will enable further linking of regional archaeological chronologies and the establishment of a solid dating framework for the southwestern Balkans. Recent developments in ^{14}C dating of tree-rings through rapid annual spikes of radiocarbon level – known as Miyake events (Brehm et al., 2022) – may greatly accelerate the process of absolute dating of floating chronologies, and soon enable the absolute yearly dating of prehistoric wood constructions globally.

The concentration of the felling dates proves that at least five temporally independent settlement phases are documented in the sampled area of the site. This is not surprising given the high density of wooden piles (8.1/m^2). The minimum duration of each phase is between 17 and 87 years. Further phases are to be expected, from the undated timbers or from the unexcavated areas of the site. Missing felling dates are therefore not to be explained by absence, as settlement events in the bay could have shifted around the site. Considering the small size of the excavated area, it is not yet possible to decide whether the durations of individual buildings and their repairs would be comparable to those in the numerous wetland settlements investigated in the northern Alpine foreland lakes. However, the extent of the pile field as well as the indications from the palynological investigations suggest that there are other settlement phases hidden in the bay of Ploča Mičov Grad that have not yet been recorded by archaeology nor dendrochronology.

CRediT authorship contribution statement

Bolliger Matthias : Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualisation. **Maczkowski Andrej :** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualisation. **Francuz John :** Validation, Software, Formal analysis, Investigation, Writing – review & editing. **Reich Johannes :** Methodology, Software, Validation, Investigation, Writing – review & editing, Visualisation. **Hostettler Marco :** Methodology, Investigation. **Ballmer Ariane :** Investigation, Project administration. **Naumov Goce :** Investigation, Project administration, Writing – review & editing. **Taneski Bojan :** Project administration. **Todoroska Valentina :** Investigation. **Szidat Sönke :** Validation, Investigation. **Hafner Albert :** Resources, Writing – review & editing, Supervision, Funding acquisition, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

For their technical, personnel and administrative support in 2018 and 2019 field campaigns, thanks are due to the following institutions: Association of Swiss Underwater Archaeology; Archaeological Service Canton of Bern, Underwater Archaeology and Dendrochronology; Department of Underwater Archaeology and Dendroarchaeology, Office for Urbanism Zurich; Diving Center Amfora, Ohrid; Embassy of Switzerland in North Macedonia, Skopje; Institute of Geodesy and Photogrammetry of the Swiss Federal Institute of Technology Zurich; Institute for Protection of Monuments and Museum - Ohrid; Space Research & Planetary Sciences, Physics Institute, University of Bern. The following people have actively contributed to the archaeological field work in 2018 and 2019: M. Andriiovych, M. E. Castiello, B. Eberschweiler, L. Emmenegger, J. Fandré , S. Geiser, P. Georgiev, D. Kaufmann, B. Kiefer,

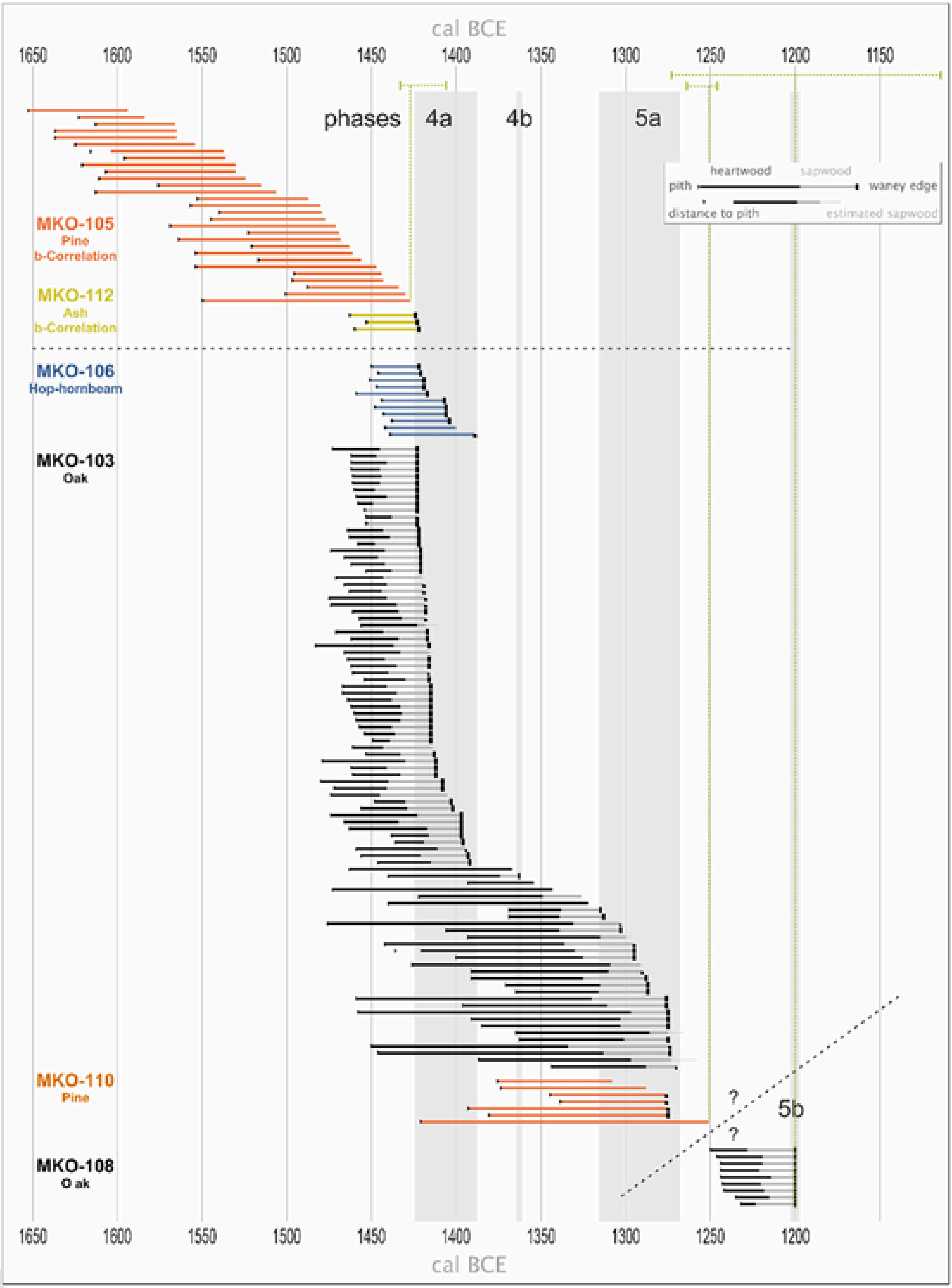
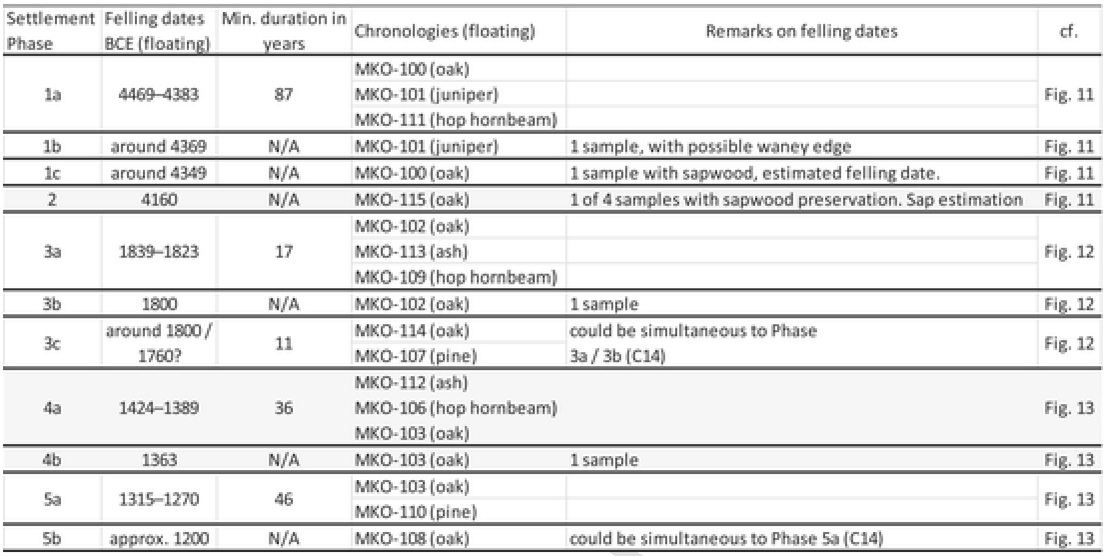


Fig. 13. Ohrid, Ploča Mičov Grad. Barplot of all individual tree-ring series of the 2nd millennium BCE (around 1400–1200 BC) in their relative position on a calendar timescale. Felling activities are highlighted with grey vertical bars and are assigned to a settlement phase (see Table 2). The end-date of the radiocarbon dated chronologies is assigned to a median calendar year based on the ^{14}C wiggle-matching (green dotted lines, vertical spans represent the 95.4% probability range for the modelled end-date, see Table 1).

Table 2
Ohrid, Ploča Mičov Grad. Settlement phases of the investigated excavation areas in the centre of the settlement site between 4500 and 1200 BCE. The end-date of the radiocarbon dated chronologies is assigned to a median calendar based on the ^{14}C wiggle-matching, see Table 1). Min. duration in years = minimal duration of the settlement phase based on dendrochronological dating. NA: Only one felling date, or simultaneous position with existing phase possible. 29.



Settlement Phase	Felling dates BCE (floating)	Min. duration in years	Chronologies (floating)	Remarks on felling dates	cf.
1a	4469–4383	87	MKO-100 (oak) MKO-101 (juniper) MKO-111 (hop hornbeam)		Fig. 11
1b	around 4369	N/A	MKO-101 (juniper)	1 sample, with possible waney edge	Fig. 11
1c	around 4349	N/A	MKO-100 (oak)	1 sample with sapwood, estimated felling date.	Fig. 11
2	4160	N/A	MKO-115 (oak)	1 of 4 samples with sapwood preservation. Sap estimation	Fig. 11
3a	1839–1823	17	MKO-102 (oak) MKO-113 (ash) MKO-109 (hop hornbeam)		Fig. 12
3b	1800	N/A	MKO-102 (oak)	1 sample	Fig. 12
3c	around 1800 / 1760?	11	MKO-114 (oak) MKO-107 (pine)	could be simultaneous to Phase 3a / 3b (C14)	Fig. 12
4a	1424–1389	36	MKO-112 (ash) MKO-106 (hop hornbeam) MKO-103 (oak)		Fig. 13
4b	1363	N/A	MKO-103 (oak)	1 sample	Fig. 13
5a	1315–1270	46	MKO-103 (oak) MKO-110 (pine)		Fig. 13
5b	approx. 1200	N/A	MKO-108 (oak)	could be simultaneous to Phase 5a (C14)	Fig. 13

S. Kurmann, G. Milevski, C. Nymann, C. Rösch, L. Schalbetter, L. Schärer, C. Stäheli, M. Staub, M. Tymoshenko, A. Ulisch, T. Wehrle, J. Wendling.

Grant information

The pilot study in 2018 was funded by the Institute of Archaeological Sciences, University of Bern, the Association of Swiss Underwater Archaeology and the Johanna Dürmüller-Bol Foundation, Muri b. Bern. From 2019 on the research was conducted in the framework of the project 'Exploring the dynamics and causes of prehistoric land use change in the cradle of European farming' (EXPLO). This project was financially supported by the European Union's Horizon 2020 research and innovation programme under the grant agreement No 810586 (project EXPLO).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dendro.2023.126095.

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