Absolutely dating the European Neolithic through a rapid 14C excursion

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Abstract

The discovery of abrupt radiocarbon (^{14}C) excursions (Solar Energetic Particle events, or Miyake events) in sequences of radiocarbon measurements from calendar dated tree-rings, has yielded new opportunities to assign absolute, calendar dates to undated wood samples from widely ranging contexts in history and prehistory. We report on an important tree-ring and ^{14}C-dating based study, which secures the Neolithic site of Dispilio, Northern Greece, a key site for the Aegean Neolithic, in absolute, calendar-dated time using the Miyake event of 5259 BC. The last ring of the 303-year-long juniper tree-ring chronology from Dispilio is dated to 5140 BC. Dispilio is thus the first prehistoric site absolutely dated through a ^{14}C signature (Miyake event), but also the first absolutely, calendar-year dated prehistoric site in the wider Mediterranean region.

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Introduction

The Neolithic period in western Eurasia marks one of the most important transitions in human social, economic, and technological history. This transition, lasting several millennia, is chiefly characterized by the appearance and gradual adoption of agriculture and animal husbandry, accompanied with increasing social and material culture complexity. The beginning of the Neolithic in Western Eurasia is dated to before ~9500 BC in the Levant[1], while its appearance on the Aegean coasts and continental Europe is dated to around ~6500 BC[2–5]. The earliest Neolithic sites on the continent are in Southeastern Europe, and their precise dating is essential for our understanding of the Neolithic transitions in Europe and critical to assessments of the environmental footprint of the new farming subsistence practices. However, the temporal resolution of archaeological and environmental proxies in the region is highly variable, producing significant discrepancies between various chronological and terminological systems that deal with the periodisation of the Neolithic[6]. Here we present the absolute dating of the Neolithic site of Dispilio in Northern Greece, via a combination of tree-ring dating (dendrochronology) and rapid ^{14}C excursions. This new data may serve as the basis for absolute dendrochronological dating of other sites from the Neolithic period in the region (Fig. 1).

Tree-rings enable high-resolution dating, the possibility of annually resolved climatic reconstruction and multidisciplinary chronological synchronization to (at best) a single growth season of a specific calendar dated year[7]. Until now, dendrochronological dating was possible only against reference tree-ring chronologies, which are continuous, unbroken sequences of tree-ring width records extending from the present back to the past. In this way, calendar dated tree-ring years can be assigned based on the known date of modern material, and then extended backwards through time using climatically constrained, region specific, tree-ring growth patterns. Long-term concentrated efforts in search for old wood samples has resulted in the construction of long tree-ring records extending for many thousands of years and widely applied to dating[8–10], and in some cases paleoclimatic analyses[11,12] of past human and environmental interactions. These records are however geographically limited and rare, and many prehistoric tree-ring chronologies are only approximately constrained on a calendar time-scale through conventional ^{14}C wiggle-matching and have no absolute calendar anchor.

This limitation can now be overcome by a new hybrid form of dendrochronological and single year radiocarbon analyses. Annual measurements of ^{14}C in dendrochronologically dated Holocene tree-rings have revealed the existence of rapid short-term spikes in atmospheric ^{14}C concentration in the past[13,14]. These ^{14}C spikes – also called Miyake or SEP (solar energetic particle) events – are uniquely suitable for absolute dating of any wooden objects with detectable annual rings[15,16]. The discovery of these short-term events has also led to a proliferation of annual ^{14}C measurements on single tree-rings, now spanning several millennia[17–19]. The mechanisms behind these ^{14}C events are still debated[20,21]. However, a consensus explanation is that they are a result of coronal mass ejections on the Sun[20,22–24] manifested as a surge of SEPs colliding with the Earth's atmosphere, in turn increasing the production of cosmogenic radionuclides [17,24]. To date, there are only five events[13,14,17,25] with an atmospheric ^{14}C increase ≥1% within 2 years[17]. Of these, the two most recently discovered events are in the first half of the Holocene – 7176 BC and 5259 BC[17] – offering for the first time the possibility for absolute annual dating of wood from the European Neolithic and Mesolithic using annual ^{14}C measurements.

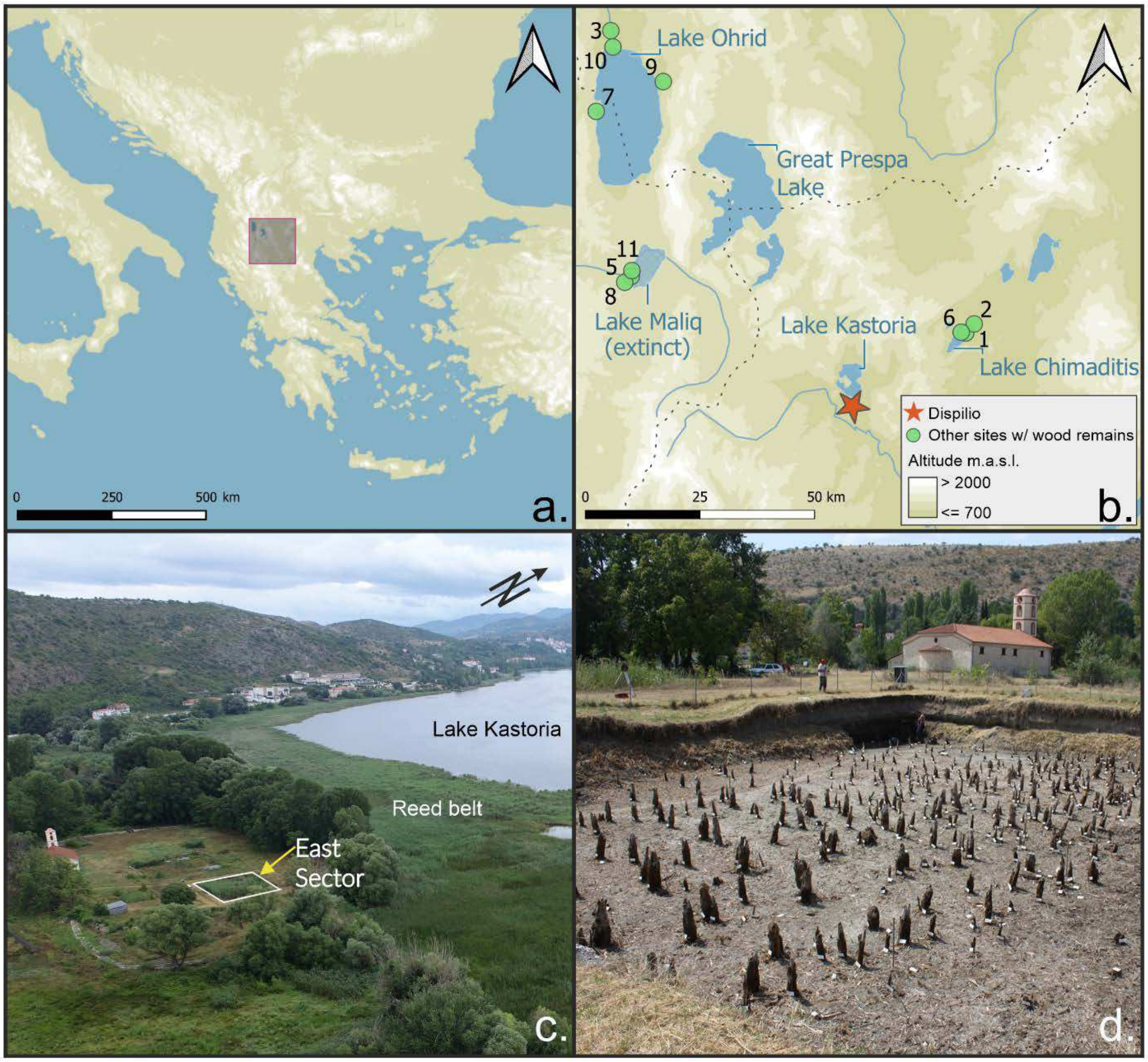

Figure 1 **Location of the archaeological site of Dispilio and detailed view of the analysed trench. a**: *map of S-E Europe marking the location of the enlarged area in b.;* **b**: *Location of Dispilio and other Neolithic sites within ~100 km with reported good wood preservation and similar chronological placement, therefore with high potential for dendrochronological cross-dating with Dispilio (1-Anarghiri III; 2-Anarghiri IXb; 3-Crkveni Livadi; 4-Dispilio; 5-Dunavec; 6-Limnochori II; 7-Lin 3; 8-Maliq; 9-Ohridati/Penelopa; 10-Ustie na Drim, 11-Sovjan; QGIS 3.16, EPSG 32634; Lake Maliq according to Fouache et al. (2010))* **c**: *drone photograph of the site of Dispilio and its surroundings, the dendrochronologically analysed East Sector marked in the foreground;* **d**: *close-up of the East Sector before sampling of wooden elements in 2019, vertical elements are seen sticking out of the ground, each marked with a unique white label. (a.,b.-A. Maczkowski; c.-M. Hostettler; d.-Dispilio Excavation Archive)*

In temperate climates archaeological wood, and organic materials in general, can be preserved only in very stable conditions – such as constant low-oxygen waterlogged sediments at wetland archaeological sites [27–29]. While excavated wetland sites are very numerous and often excavated in Central Europe, several wetland sites have also been found and excavated in Southeastern Europe, notably in the south-western part of the Balkans[30–36]. Dendrochronological work on these sites led to the construction of several tree-ring width chronologies, which were fixed in time by means of ^{14}C modelling (wiggle-matching)[37,38]. The archaeological site of Dispilio on the shores of Lake Kastoria in Northern Greece is a premier prehistoric wetland site in the region. Numerous lines of evidence have yielded detailed results on the geoarchaeology[35], palynology [39,40] anthracology[41,42], woodworking technology[43], and material culture[44,45]. The approximate calendar-age chronology of the site has been established through radiocarbon dates, mostly performed on charcoal samples[35,46]. The calibrated date-ranges point to settlement phases between the later Middle Neolithic (~5600 cal BC[47]) and the Bronze Age (~2100 cal BC[46]). The excavations at Dispilio have also yielded a great number of wood remains, with over 1200 mapped construction elements in the Eastern Sector to date (Fig 1c). Yet despite the extensive remains of wooden construction elements, no systematic sampling and no tree-ring based chronological studies via dendrochronology have yet been conducted at the site. The value of developing a precise and accurate calendar-dated chronological sequence using these wooden remains is further enhanced by the fact that the site of Dispilio with more than 1700 complete ceramic vessels (Fig. 2) boasts one of the largest complete Neolithic ceramic assemblages in Europe. Tree-ring dating at Dispilio can therefore be used, via the existing ceramics network, to underpin and improve the relative chronology of the entire region.

In 2019 a large-scale fieldwork campaign took place at Dispilio's Eastern Sector (Fig. 1d), during which over 900 wooden construction elements (piles) were mapped, of which 787 were sampled for the first dendrochronological analysis. The dendrochronological results provided an oak chronology spanning 120 years, and an overlapping juniper chronology spanning 303 years. This record could not be dated dendrochronologically however, because despite the existence of several millennia-long tree-ring chronologies in the Eastern Mediterranean[11,48,49], none extend back for 7500 years. Here we overcome this limitation by using the combination of dendrochronological and single year radiocarbon analysis, thus providing the first absolute dating of a Neolithic site in the wider Mediterranean region.

*Figure 2, **Archaeological finds from Neolithic Dispilio**. **a**: almost completely preserved ornate anthropomorphic vessel from Late Neolithic, many similar ones have been recovered from the site, scale in cm; **b**: bone spear/harpoon tip with preserved hafting adhesives, scale in cm; **c**.: an assemblage of Late Neolithic personal adornments (a.,b.,c,-Dispilio Excavation Archive)*

Results

Dendrochronology

Of the total wood samples from the archaeological site of Dispilio in 2019 (n=787), 23% were cross-dated into two master tree-ring width (TRW) chronologies. Wood anatomical species determination revealed that the majority of the wooden piles came from oak (*Quercus* spp., 21%) and juniper (*Juniperus* spp., 62%) wood. The third most abundant species are pines (*Pinus* spp., 17%), which were not suitable for dendrochronological cross-dating given the low number of annual rings on most pine samples. The majority of the pine samples could be classified as belonging to the subgenus *Pinus* (cf. *Pinus* *nigra*/*sylvestris*) with several pieces belonging to the subgenus *Strobus* (cf. *Pinus peuce*). Due to the wood-anatomical intra-species similarity of junipers [50,51], and of deciduous oaks from the subgenus *Quercus*[52], a definitive species-level identification was not possible. Based on modern tree species in the region[41,53,54], Dispilio oak wood samples most likely come from *Q. frainetto*, *Q. petraea*, and/or *Q. pubescens* wood, and the junipers are most likely *Juniperus excelsa*, *J. foetedissima*, and/or *J. deltoides* (for the latter cf. *J oxycedrus*).

The oak TRW chronology produced was 120-years-long composed of 58 wood samples (Fig 4). It consists of tree-ring sequences with an average segment length of 66 years. Some sapwood was present on most of the oak samples (n=45), however the last growth ring (or "waney-edge"), which is important for archaeological interpretation, was conserved on only 4 pieces either as a result of the lower durability of oak sapwood or its intentional removal. The mean inter-series correlation (leave-one-out principle[55]) of the oak tree-ring sequences is 0.51.

A 303-years-long juniper TRW-chronology was also constructed consisting of 118 tree-ring sequences and an average segment length of 86 years (Fig 4). The mean inter-series correlation (leave-one-out principle [55]) of the juniper chronology is 0.62. Juniper wood, owing to its chemical[56] and physical[57] properties has a higher resistance to degradation. These qualities made juniper wood the material of choice for construction purposes in many ancient societies in the Eastern Mediterranean[58–60]. The preservation of juniper wood in Dispilio is also exceptional and the waney-edge on junipers is quite common, enabling an annually resolved reconstruction of the building phases and occupation duration on the site (Fig 4b).

All samples with a preserved waney edge had a last growth ring terminating with latewood, thus implying a felling date during the dormant period of the trees between late summer and early spring. The juniper and oak tree-ring chronologies have robust dendrochronological dating against each other (t-value = 4.9[61] and = 5.1[62]; GLK = 63%[63]) over a period of 108 years where sample replication is >4, further supported by ^{14}C wiggle-matching (Supplementary Material S1)

Tree-ring ^{14}C cosmogenic signature

Conventional radiocarbon wiggle-matching models[64,65] based on several blocks of 1-11 tree-rings modelled against the atmospheric data for the Northern Hemisphere (IntCal20[66]) produced the initial modelled age-ranges for the tree-ring chronologies. Preliminary annual sampling at test positions on the juniper tree-ring chronology indicated that the last ring of this chronology dated between 5233 and 5137 cal BC (at 95% probability). On this basis, a suite of additional single year ^{14}C measurements were made to pinpoint the exact years surrounding the 5259 BC Miyake event. Four wood samples from the juniper chronology were selected covering the part of the chronology where the 5259 BC Miyake event should be located (Fig. 3a). We present here the final 115 ^{14}C measurements (Supplementary Table T1) performed to locate the 5259 BC Miyake event in all 4 wood samples from the Dispilio juniper tree-ring chronology (Fig. 3a). The ^{14}C measurements were performed at the Laboratory for the Analysis of Radiocarbon with AMS at the University of Bern (LARA)[67] and the Laboratory of Ion Beam Physics at ETH Zürich (ETH)[68,69]. An average year-to-year increase (*sensu* Miayke et al.[13]) of ~15.8 ‰ in $\Delta^{14}C$ was detected in all samples in the exact same dendrochronologically cross-dated tree-rings corresponding to the relative ring 184 of the Dispilio juniper chronology. This increase varies from the lowest of ~11.1 ‰ $\Delta^{14}C$ in DISP-10070, to ~13.1 ‰ in DISP-10206, to ~14.8‰ in DISP-10063, to ~18.6 ‰ in DISP-10611 (Fig. 3a, Supplementary Table T1).

To compare the ^{14}C results from Dispilio with the published reference data for the 5259 BC event, a mean-value annually resolved reference curve (RC) was established from the dataset in Brehm et al. (2022 –

henceforth referred to as 'BR22'[17]). A common approach for verifying the position of Miyake events is wiggle-matching using a goodness-of-fit χ^2 test[15,70,71] against a reference, so that the χ^2 value becomes minimal for the correct placement of the sample's waney-edge[64]. The lowest χ^2 values are reached when the end-dates of the samples are placed at 5240 BC for DISP-10070 and DISP-10063 (Fig. 3b), 5153 BC for DISP-10206, and 5155 BC for DISP-10611 (Fig. 3c), corresponding to their cross-dated position along the tree-ring chronology. The 5259 BC event signal is clearly identified in all wood samples (Fig. 3a).

In order to test how close conventional radiocarbon wiggle-matching would be relative to the absolute calendar dating supplied by the Miyake event, the annual data from all the wood samples were wiggle-matched against the IntCal20 calibration curve[66] using the ^{14}C calibration software OxCal 4.4[64,65]. In none of the cases does the 95% probability end-date range include the actual felling date when IntCal20 is used (Fig. 5, Supplementary Material S4). Longer series of ^{14}C dates which span some years before and after the event (Fig. 3a, Fig 5), as from wood samples DISP-10611 and -10206, yield end-dates which are only ~15-20 cal years older, while shorter series, wood samples DISP-10070 and -10063, result in end-dates over ~40 cal years younger than the actual felling dates (Fig. 5). It has been noted previously[72] that IntCal20 is poorly replicated during the 53rd-52nd century BC. Notably, the 53rd century BC is represented by only 16 measurements, of which 14 are decadal and bi-decadal (i.e. blocks of 10-20 tree-rings), with only two 4- and 5-year blocks[66,73](see Supplementary Material S2.8). The variability in the calibrated end-date ranges suggests that IntCal20 might produce misleading results when wiggle-matching annual data coming from the period in question. The annual ^{14}C dates were also wiggle-matched against a modified IntCal20 – IntCal20plus – where the default IntCal20 multiple-year blocks of BP (Before Present) data for the 82 years period around the event were substituted with the average of the annual BR22 dataset. Calibrating against this dataset predictably yields the accurate and more precise end-date ranges at 95% probability for all wood samples (Fig. 5).

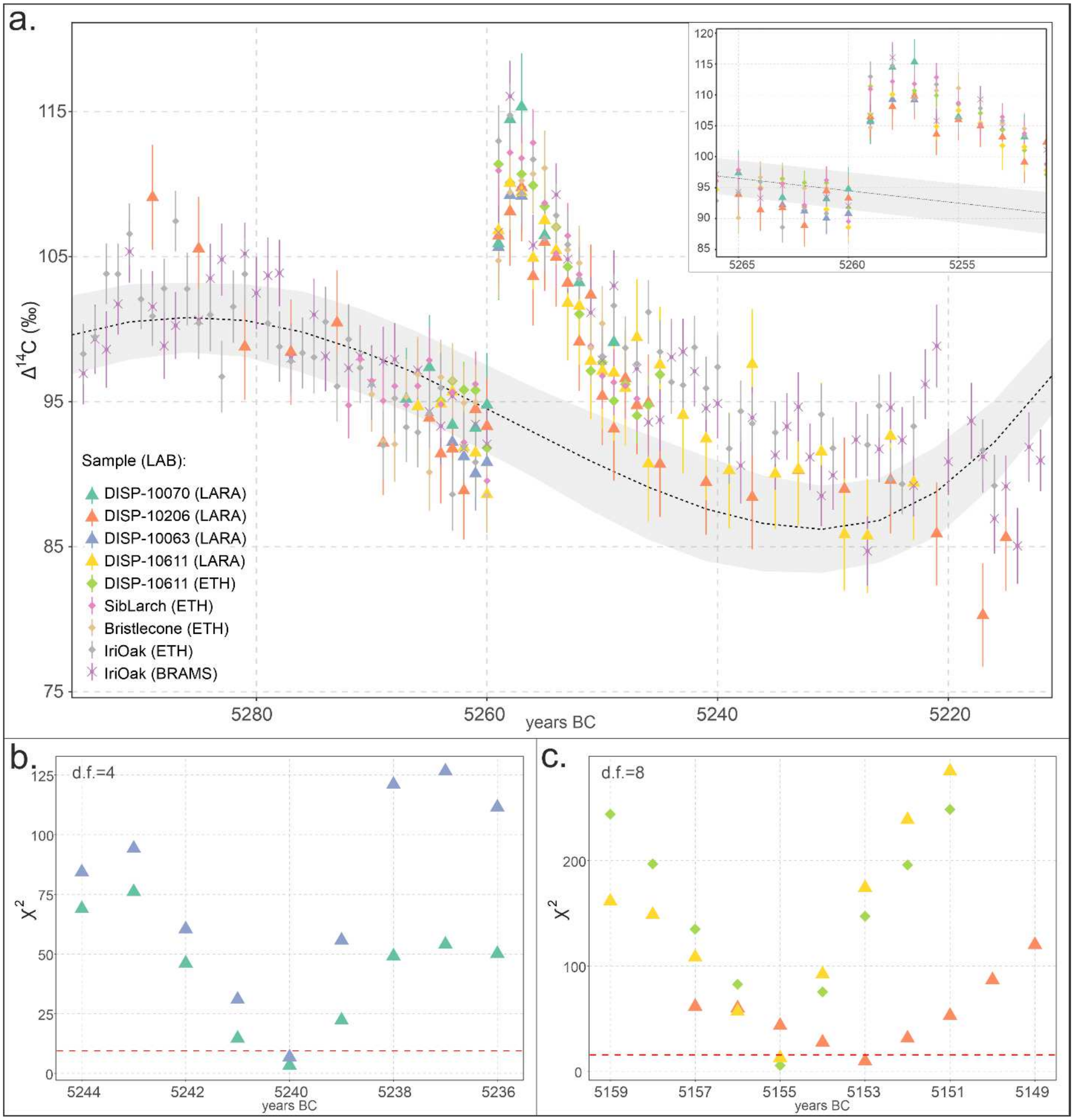

Figure 3, ***Scatter plot of $\Delta^{14}C$ data from Dispilio against reference from Brehm et al. (2022)*** *[17]****, and best last ring fit for the dated wood samples (χ^2). a****: Measured ^{14}C concentrations represented as $\Delta^{14}C$, vertical bars represent 1s uncertainties (Supplementary Table T1); samples marked with "DISP-" refer to measurements on wood samples obtained in this study, other labels represent data from BR22[17] - Bristlecone pine ^{14}C data are shifted forward by 1 year from the original Brehm et al. publication, following a correction to the dating of the master bristlecone chronology (Supplementary Material S3.2); shaded band represents IntCal20 [66]. Panels below,* ***b, c****: chi-squared tests of Dispilio measurements against the average from BR22[17] for wood samples DISP-10070 and -10063 (****b,*** *χ^2 crit. value=9.49), and DISP-10206 and -10611 (****c****, χ^2 crit. value= 15.51). Figure produced in R[74], code and source data available in Supplementary Material 4.*

The growing season of trees is influenced by many factors and can vary between and among species as a function of cambial age, temperature, water, slope, aspect, soil etc. Personal observations of growth termination in modern oaks and junipers in the region have revealed that latewood can be completed in both genera in the beginning of September (Supplementary Materials S2.6-S2.7). While cell-wall thickening in temperate conifers continues for several weeks after the cessation of cell-wall enlargement [75], the amount of cellulose carbon that would be deposited during this last stage of latewood formation constitutes a small percentage of the whole tree-ring[76]. Considering the robustness of the ^{14}C signal in the Dispilio junipers tree-rings (Fig. 3) it is unlikely that it only represents the ^{14}C incorporated at the end of the cell-wall thickening stage. Consequently, it can be stated that the ^{14}C signal of the 5259 BC event in the indeciduate junipers was incorporated in the same growing season characteristic for deciduous species, i.e. spring to late summer/early autumn 5259 BC.

According to the dendrochronologically cross-dated position of all wood samples, the ring in which the Miyake event is detected corresponds to relative year number 184 of the 303-year-long juniper TRW chronology. This allows us to set the absolute end-date of the whole Dispilio juniper tree-ring chronology at 5140 BC. Furthermore, the identification of the event in DISP-10070 and -10063 confirms the correct placement of the better-replicated earlier half of the chronology (Fig. 4a.). Given the dendrochronological cross-dating between the juniper and oak chronologies, also the latter is absolutely dated, placing its last ring at 5311 BC (Fig. 4a.).

Site plan and felling phases

By considering the latest juniper felling dates together with the earliest secure felling dates from the oak chronology it is possible to establish a minimum duration of construction activities of 188 years between 5328 and 5140 BC, with intermittent periods of wood felling/construction, which do not necessarily reflect a continuous, uninterrupted occupation at the same location. Such a chronological resolution for a settlement phase duration on a prehistoric site in the Eastern Mediterranean has not been established to date. Plotting of groups of cross-dated wood samples with felling dates within 1-2 years of one another using a GIS software revealed blueprints representing different structures (Fig. 4b). Identification of building outlines was possible only for groups that are composed of a substantial number of cross-dated samples. The structures seem to be oriented along the lakeshore. Of particular note is the concentration of building activities in the eastern part of the Eastern Sector. In this part, building activities on the same spot outline an area with a felling date in 5294 BC, and a felling phase which ends in 5257 BC (Fig. 4a, b). A felling phase ending in 5320 BC precedes the group of 5294 BC, however due to the suboptimal preservation of oak samples only two of this group have preserved waney edge. These are complemented by several oak samples dated between 5328 BC and 5320 BC with at least 20 sapwood rings indicating the proximity of the waney edge. The mapping of the dendrochronological results further implies that building practices in some cases either included short term storage (1-2 years) of timber or consisted of a construction period spread over several years.

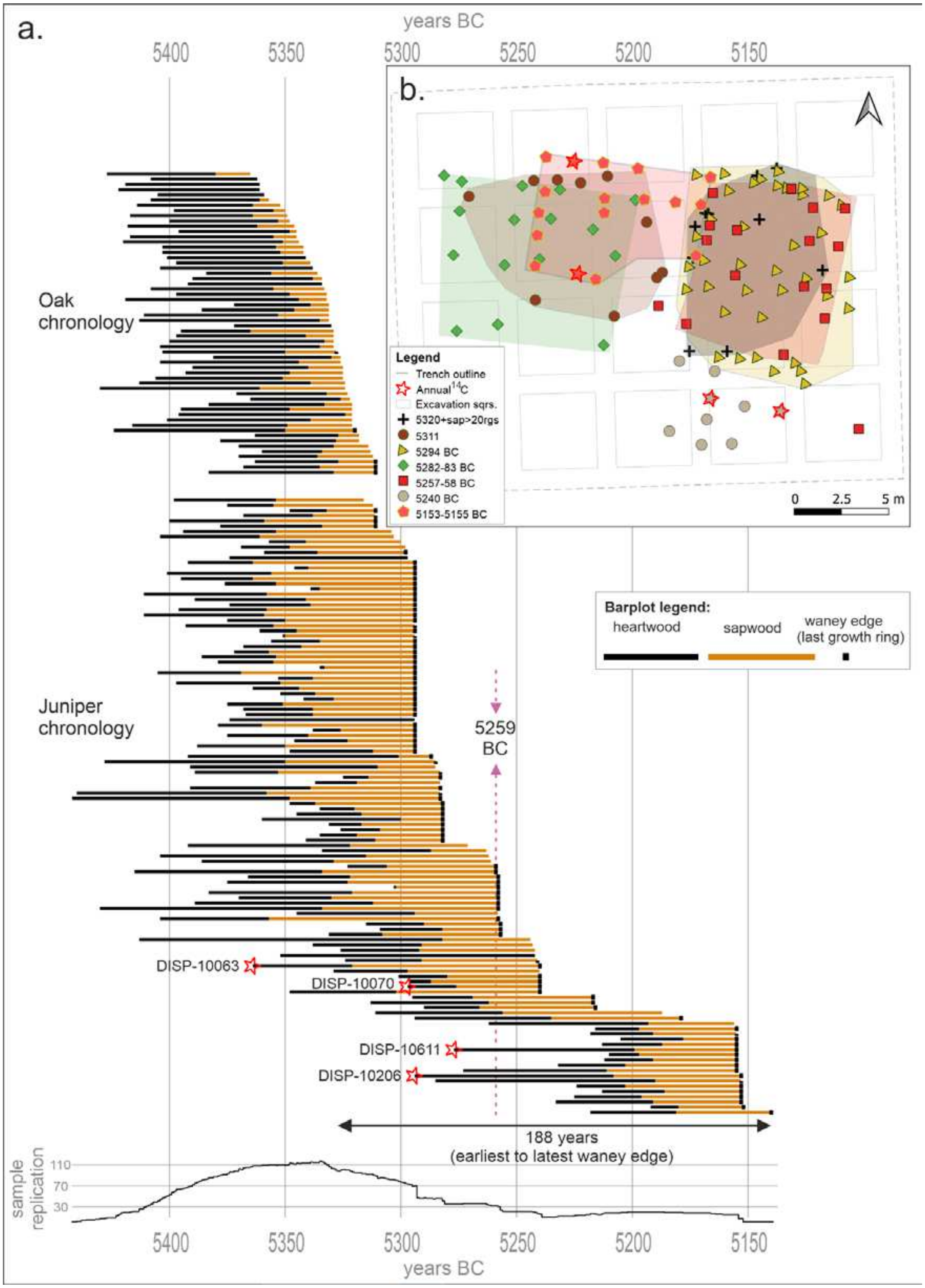

Figure 4, ***Bar chart of tree-ring chronologies, felling dates, and site plan development****.* ***a****: bar plot of Dispilio oak and juniper chronologies; each horizontal bar represents individual wood sample in its dendrochronologically cross-dated position, bar length corresponds to its span in years (i.e., number of tree-rings). Red stars indicate wood samples sampled for annual ^{14}C;* ***b****.: schematic plan of the East Sector (see also Fig. 1c-d); each symbol represents one vertical wooden element, different shapes and colours correspond to a same felling phase spread over 1-2 years; additionally, colour-shaded polygons outline the groups of same symbols (same felling-phase elements), however they do not represent definite structure plans.*

Discussion

According to the archaeo-chronological periodisation in the region, for which there is no universal absolute timeframe[6], the occupation phases of Dispilio discussed here would fall at the later Middle Neolithic and/or Late Neolithic. The absolute dating and duration of the Middle/Late Neolithic occupation phase in Dispilio is unique in the context of the Balkans, but also in the wider Eastern Mediterranean Neolithic. The site also provides sufficiently replicated dendrochronological information to allow independent controls for settlement duration estimates. The felling dates in the excavated sector indicate activity over a period of at least 188 years, with indications from oak sapwood estimates to extend this backwards by a further 30 years. Of particular interest is the succession of 2 construction phases in the western half of the analysed trench and 3 construction phases in its eastern half (Fig. 4a, b). Although the nature of these structural outlines (Fig. 4b) is not clear at present, a timespan between the construction episodes of 29 years in the western half (5311 and 5282 BC), and 35-37 years in the eastern half (5320, 5294 and 5257 BC) is consistent with the few available estimates of house lifespans in Neolithic S-E Europe[77,78]. However, determining whether these contemporary structure outlines with same felling dates correspond to one or multiple buildings will require further detailed multidisciplinary work. Intermittent periods without felling dates may simply be a result of preservation or the limited size of the excavated area, but may also reflect a hiatus in occupation or indicate a non-perennial character of the settlement. Detection of annual or decadal-scale hiatuses is extremely difficult in archaeological stratigraphy, with settlement phase duration usually derived from ^{14}C sequence models based on organic samples from consecutive stratigraphical units. This approach can lead to interpretations of centuries-long settlement continuities[4,79]. Such interpretations may underestimate settlement discontinuities of durations shorter than the associated precision of ^{14}C measurements and calibration. This underlines the importance of the annually resolved data from Dispilio.

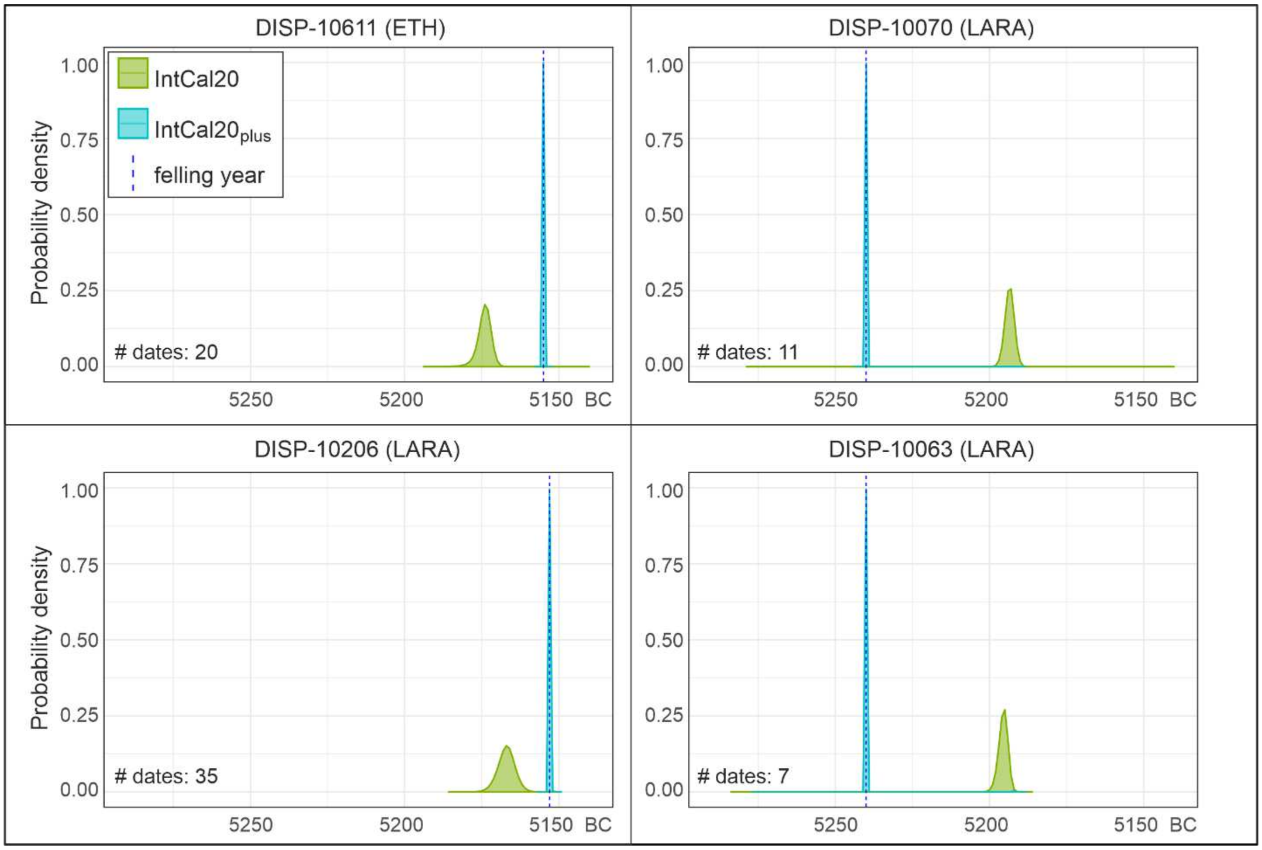

Figure 5 ***Wiggle-matching of different sets of annual ^{14}C data from Dispilio modelled in OxCal v4.4, against IntCal20[66], and IntCal20plus****. IntCal20plus has the non-annual IntCal20 data for a 82-year period around the 5259 BC Miyake event replaced by annual average of Brehm et al. (2022)[17] annual data. Dotted blue lines represent actual felling dates determined through dendrochronology and Miyake event-matching. Acronyms in brackets next to sample name refer to AMS lab that furnished the measurements. Data for figure obtained from OxCal [65,66]. Figure produced in R[74], code and data in Supplementary Material 4.*

The last centuries of the 6th millennium BC mark an important change within the Neolithic period in the southern Balkans. It is a period of a steep increase in the number and size of settlements, associated with a demographic boom[6,80–82]. Anthropogenic influence on the local environment becomes more pronounced during this period[83,84], as documented also in Dispilio[39,40]. Diversity increased in all aspects of human behaviour, from pottery production techniques and styles[85], architecture[81], settlement organisation[81,86,87], to the first signs of metallurgy[88]. Evidence from this transitional period also points to a shifting social focus from the collective to the domestic[89,90]. In this setting, high-resolution chronological data can improve our understanding of societal changes, human land use, and intensifying influence on the local and regional environment. For instance, the preference of settling in the proximity of wetlands has been documented in the Early Neolithic[3,91], a practice continuing in subsequent Neolithic subperiods[32,91]. Wetland and shoreline locations would have represented ideal catchment areas for the Neolithic subsistence, providing various soil types that could be exploited for cultivating crops with different requirements, serve as pasture lands, or supply aquatic resources as a dietary complement[91]. A number of wetland sites with similar chronology to Dispilio (2nd half of the 6th millennium BC) have been documented or excavated in existing or former lakes in the region, some of them yielding large amounts of well-preserved wooden construction elements (Fig. 1b,[32–34,92–94]). Although the dating of these sites has much lower chronological resolution than at Dispilio, some of them would have been in use for centuries before and/or after the 54th-52nd century BC phases in Dispilio. It is highly likely that it will be possible to cross-date the tree-ring widths of the wood remains from these peripheral sites with the now absolutely dated tree-ring chronologies from

Dispilio, and thus extend the absolutely dated chronological network for the region well beyond the 6th millennium BC.

Beyond the chronological significance, absolutely dated tree-ring records are one of the most utilized proxies for high-resolution climate reconstructions offering unique insights into the relationship between humans and climate. Precipitation is a limiting factor for most low and mid-altitudes trees in the Eastern Mediterranean. In fact, it has been shown that modern juniper [49] and oak [11,95] tree-ring sequences are good predictors of precipitation in the Eastern Mediterranean. Precipitation was a crucial factor in early agriculture which mainly consisted of rain-fed [96] and flood-water [97] farming. Preliminary observations of the Dispilio TRW chronologies imply a period of suppressed growth in both the juniper and oak tree-ring sequences for a period of around 20 years between 5360 and 5340 BC. Such suppressed growth period can be associated with decrease in precipitation, which may significantly influence the water table of small water bodies such as Lake Kastoria. A short-term Mid/Late Neolithic eutrophication of the lake previously inferred from increased presence of green algae[35] could potentially be correlated with this tree-ring width suppression. Although the Neolithic tree-ring sequences from Dispilio are relatively short if compared to modern tree-ring proxies used in climate reconstructions, they still may provide valuable absolutely dated, annually resolved information on environmental conditions during the Neolithic in Kastoria Basin and the surrounding region.

Finally, the results from this study underline the value that single year measurements of radiocarbon in tree-rings can have for radiocarbon calibration and dendrochronological dating. Significant advances in AMS technology[68], have made it possible to create long and continuous time-series of annual radiocarbon that are constantly improving the accuracy of the radiocarbon calibration process. More than this though, the utilization of SEP events in anchoring regional timelines through hybrid tree-ring and radiocarbon studies is once again demonstrated. The ^{14}C-anchored Dispilio tree-ring chronologies now provide a calendar dated reference for dendrochronological dating of other sites from the time period. This provides the opportunity to extend calendar dated chronologies across the region further back into prehistory. Such high-resolution dating, especially in cases where it can be coupled with stratigraphic information or used to derive climatic indicators, will elucidate a more nuanced understanding of deterministic interpretations of the environmental influence on societies in the past (e.g. for the 6.2 ka BC cooling event). This study demonstrates how the discovery of the new SEP events in this time period creates new possibilities in prehistoric archaeology and offers the construction of historical-timescale narratives for societies and their environments from the very distant past.

Materials and Methods

Wood samples

The wood material analysed in this study was sampled in August and September 2019 from wooden piles remains at the archaeological site of Dispilio, near Kastoria, Greece (40.485444 N, 21.289694 E; h=627 masl). The site is one of the best-known prehistoric sites in the country and has been investigated, almost continuously, since 1992. Excavations and sampling that took place on the site were performed in full compliance with the regulations of the Greek Ministry of Culture concerning archaeological material. Whole cross-section discs (n=787) were sampled from the wooden remains with handsaws and chainsaws during the 2019 fieldwork campaign. The wood samples documentation, cleaning, preparation, and sealing in plastic bags with water, took place on-site during the 2019 field campaign. Dendrochronological measurement took place initially on-site and continued at the University of Bern. Tree-ring width (TRW) measurements were performed according to standard dendrochronological procedures [98,99], by means of a measuring table under a binocular stereo microscope. TRWs were recorded with a precision of 0.01 mm. Two to four radii were measured per sample and averaged together to represent the sample. Descriptive dendrochronological statistics were performed in the dplR package in R[55,74,100] . The TRW measurements of DISP-10611, -10206, 10070, and -10063 are available in the Supplementary Material S3.3.

Wood taxonomy was determined based on stem wood anatomy. Each measured wood sample was sectioned with a razor blade and cell arrangements in the transversal, radial, and tangential sections were identified and compared with references in wood-anatomical atlases[51,52,101]. Given the wood anatomical similarity of different deciduous oak species from the subgenus *Quercus*[52], and considering the high dendrofloristic diversity of oaks in the region[53,54] it is not possible to distinguish them to species level. However, it is likely that several deciduous oak species from the subgenus *Quercus* are represented, notably *Q. frainetto*, *Q. petraea*, and/or *Q. pubescens*. Oak trees from the subgenus *Cerris* are one of the more abundant groups of oaks in the region, however no wood samples from Dispilio could be assigned to this group which is anatomically characterised by larger and solitary latewood pores. Similarly, wood anatomical differentiation between different juniper species is not possible[50,51,101]. Considering todays distribution of tree-like junipers in the region, the most likely species utilized in Dispilio are *Juniperus excelsa*, *J. foetedissima*, and/or *J. deltoides* Adams (cf. *J oxycedrus* L.). While majority of the pine samples exhibited denticulate walls on end-tracheids, a characteristic of the pine subgenus *Pinus* (cf. *Pinus nigra*/*sylvestris*-type), several pine wood samples could be identified as members of the Subgenus *Strobus* (cf. *P. peuce*) based on the presence of smooth-walled end-tracheids.

Local climate in the Kastoria Basin can be defined as continental to sub-Mediterranean, with temperate weather, continental winters, and warm and dry summers. The yearly average precipitation of ~600 mm increases with altitude, with the wettest months being November and December, while July and August are the driest and hottest months. Yearly average temperature is ~12.5 ̊C. Main climate classes according to the Köppen system[102] are Cfa, Cfb, Csa.

Sample preparation and radiocarbon measurement

Individual tree-rings were dissected by hand under a binocular microscope with a one-sided razor blade (Supplementary Material S2.5). Whole rings were used for all ^{14}C measurements (Supplementary Table T1). About 30-70 mg of material were sampled per ring, depending on its width. Earlywood comprises ca. 80-90% of a juniper tree-ring. Since most of the of the ring-structure of junipers growing on mesic sites is completed by the end of September[103] (see also Supplementary Material S2.6-S2.7), the tree-ring structural carbon concentration should reflect temperate spring-to-late summer carbon uptake.

Wiggle-matching of several ^{14}C dates provided the initial estimate of the 40-rings segment of the tree-ring chronology where the event will be located. A “buffer zone” of 15 rings at each limit was added to the estimate, and 70 individual rings were sampled centred around the estimated “event ring” from the first wood sample that was analysed (DISP-10206, Supplementary Material S2.1). The ^{14}C content of every 4th sampled ring was subsequently measured until the ^{14}C spike was located, after which the ^{14}C in 20 consecutive annual rings around the event was measured. The “event ring” on all the other wood samples (DISP-10611, -10070, -10063, Supplementary Material S2.2-S2.4) was identified according to the samples’ cross-dating position along the tree-ring chronology.

Cellulose from wood samples analysed at the Laboratory for the Analysis of Radiocarbon with AMS at the University of Bern (LARA)[67] was extracted following the BABAB method[104] including the modifications of Sookdeo et al. (2020) at 70°C for all steps. Samples were submerged in a 1M NaOH overnight and treated in 1M HCl followed by 1M NaOH in a shaker for one hour each. Bleaching of the samples was performed on addition of 5 mL water, a few drops of 1M HCl to reach pH 2-3 and 100 mg NaClO2 by shaking for at least two hours or until the colour of the wood samples turned white. Drying of the material was achieved by lyophilisation overnight. Samples were measured using the LARA MICADAS AMS system. DISP-10070, -10206 and a first run of -10611 was analysed together with three oxalic acid II (SRM 4990C, NIST) standards and three chemical blanks. Later, a second run of DISP-10611 and -10063 was dated together with five oxalic acid II standards and four chemical blanks that were used for blank subtraction, standard normalization, and correction for isotope fractionations as well as two IAEA-C5, two IAEA-C7, two 1515 CE reference samples and two cellulose blanks as secondary standards and blanks, respectively. For details, see Supplementary Material S3.1 and Supplementary Table T1.

For the analyses performed at ETHZ, the tree-ring samples were prepared in 15 ml glass test tubes together with four wood blanks (2 BC and 2 KB) and 2 1515 CE reference samples each weighing 30–60 mg[68]. In a slightly modified procedure following[104], samples were first soaked in 5 ml 1M NaOH overnight at 70 °C in an oven. Then the samples were treated with 1M HCl and 1M NaOH for 1 hour each at 70°C in a heat block, before they were bleached at a pH of 2–3 with 0.35M NaClO2 at 70 °C for 2 h. The remaining white holo-cellulose was then freeze-dried overnight. About 2.5 mg dried holo-cellulose was wrapped in cleaned Al capsules and converted to graphite using the automated graphitization line AGE-3. A measurement set was made up of the tree-ring samples, three oxalic acid one (OX1) and four oxalic acid two (OX2) standards, two cellulose blanks, two chemical blanks, and two 1515 CE reference samples and measured in the MICADAS accelerator mass spectrometer.

Radiocarbon matching and modelling

The new ^{14}C measurements presented in this study were matched to the constructed reference curve [17](see also Supplementary Material S4) using a common χ^2 test approach so that the χ^2 value becomes minimal for the correct placement of the sample's waney-edge [15,64,71]:

$$\chi^2(\mathrm{x}) = \sum_{i=1}^{n} \frac{(R_i - C_{(x-r_i)})^2}{\delta R_i{}^2 + \delta C_{(x-r_i)}{}^2}$$

Where $R_i \pm \delta R_i$ represent the new ^{14}C measurements, and $C_{(x-r_i)} \pm \delta C_{(x-r_i)}$ represent the reference curve ^{14}C concentrations in the year $(x - r_i)$; r_i stands for the tree ring number starting with 0, representing the last growth ring of the tree (waney-edge).

The Bayesian wiggle-matching was performed in the software OxCal 4.4 with the inbuilt D_Sequence command against the atmospheric data from IntCal20[65,66], for the CQL code see Supplementary Material S1 and S4.

The year-to-year increase in $\Delta^{14}C$ presented in the Results section was calculated as a difference between the values in 5260 BC and 5259 BC (*sensu* Miyake et al.[13]). For a detailed discussion on the magnitude and ^{14}C production during the 5259 BC Miyake event see[17], and [105].

Data uncertainty

The genus *Juniperus* is known to produce intra-annual density fluctuation ('false rings') or have 'missing rings' [106] in parts of the stem. Missing rings are very often a product of the stem growth habit of junipers, so-called 'lobate growth', which consists of higher cambial activity and faster growth in certain areas of the stem, resulting in an undulating cross-section of the stem in older tress, where the less active areas may not produce rings in certain years. However, missing rings or measuring false rings can be accounted for when sufficient numbers of wood samples with complete stem cross-sections are available, as in Dispilio. The correct location of the "event ring" on all wood samples based on their cross-dated position is further supporting a correct ring count. Moreover, the dendrochronological cross-dating of the first half of the juniper chronology against the oak chronology serves as an additional control for the correct ring count, considering that oak trees almost never have missing rings [107].

Data availability

Supplementary Material, including code, text, figures, and datasets referred to and presented in this paper are available at the following repository: 10.5281/zenodo.8407222.

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Contributions

A.M., together with C.P, A.H. conceived and designed the study. K.K. & T.G. led the fieldwork, while A.M. and J.F. participated in part of it. J.F. & A.M., together with M.B., performed the dendrochronological and wood-anatomical analyses. A.M. sampled individual tree-rings. S.S. and L.W. performed and provided the 14C measurements. A.M., & C.P., drafted the manuscript, and all authors edited and contributed to the manuscript. A.H. and K.K. obtained funding.

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