Journal of Archaeological Science 39 (2012) 3402–3414

Contents lists available at SciVerse ScienceDirect

Journal of Archaeological Science

journal homepage: http://www.elsevier.com/locate/jas

Dendroarchaeology of the mid-first millennium AD in Constantinople

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ARTICLE INFO

Article history:
Received 15 December 2011
Received in revised form
18 April 2012
Accepted 28 May 2012

Keywords:
Dendrochronology
Constantinople
Istanbul
Yenikapı
Hagia Sophia
First millennium AD

ABSTRACT

The 1st millennium AD was a time of great transition in Europe and the Mediterranean. At the heart of the Byzantine Empire, Constantinople (modern day Istanbul) was a pivotal trade hub for the Aegean region. Establishing a precise and accurate dating framework for the development of this remarkable city and a chronological reference for this critical time period for the Mediterranean region is of great importance to a wide range of scholars. Here we present a new 213 year tree-ring record from 89 oak samples placed in time by dendrochronology and supported by radiocarbon analysis and historical documentation. It represents the middle of the first millennium AD in Constantinople. The tree-ring series are derived from pilings recovered from the extraordinary excavations of the so-called “Theodosian harbor” at Yenikapı, Istanbul, along with timbers from other sites and buildings around the city, including one of the most famous sites on the Istanbul sky-line—Hagia Sophia. They provide potential for new insight into a time period in which earthquakes, the Justinianic plague, and even a possible tsunami struck the city, and during which dramatic changes in climate have been recorded in other paleoenvironmental proxies. The chronology is the first published tree-ring series from the Aegean region to cover the ‘event’ years of AD 536–7 and 542 which are characterized by anomalous growth in other tree-ring series from around the world, but interestingly these event years are not evident in this tree-ring sequence.

1. Introduction

The city of Istanbul, located on either side of the Bosphorus, has long served as a nexus for both Europe and Asia. Originally called Byzantion (Byzantium), the city, developed by Constantine in the early first millennium AD, became known as Constantinople, before being renamed “Istanbul” after the foundation of the Republic of Turkey in the 1920s. Over the years it has served as the capital of the Roman, Byzantine, and Ottoman Empires and stood at the center of trade between the Black Sea, the Aegean, and the Mediterranean.

In 2004 a construction project was begun to ease commuter congestion in modern day Istanbul. The Marmaray project (Sakaeda, 2005) will upgrade approximately 76 km of rail from Halkalı (Europe) to Gebze (Asia) and construct a network of railway tunnels which will pass under the Bosphorus (see Fig. 1). In a city as rich in history as Istanbul, the necessary excavations associated with this project have inevitably led to the discovery of important new archaeological sites, but the harbor unearthed at Yenikapı by the Istanbul Archaeological Museum is extraordinary in geographical, temporal, and artifactual scale.

The complete geoarchaeological record from this site now extends back over 8000 years (Algan et al., 2009, 2011). The remains of the harbor, however, currently exposed across 26,250 square meters (Alguadiş and Batchelder, 2007), date from the time of Constantine (AD 306–337) or Theodosius I (AD 379–395) (Müller-Wiener, 2001) and were in use until the 7th century AD and later.

The Aegean Dendrochronology Project (ADP) has worked in the Aegean and Near East for over 36 years with the aim of constructing a tree-ring derived, absolutely dated time frame for dating archaeological and historic sites of the eastern Mediterranean for the last 9000 years (Kuniholm et al., 2005, 1996; Kuniholm, 1994; Griggs et al., 2009). This work, still in progress, involves the

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[1] From Jan 2013.

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10.1016/j.jas.2012.05.024

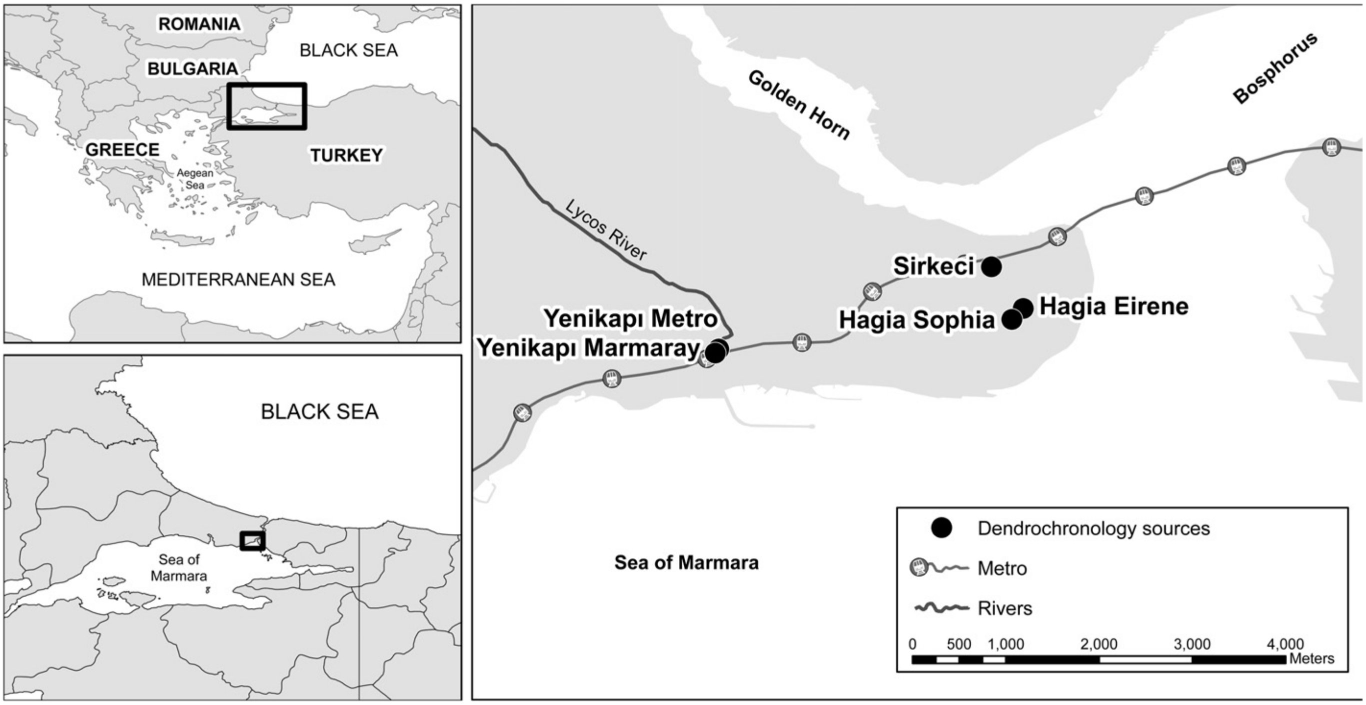


Fig. 1. Locations in Istanbul from which samples used in this paper were derived. This includes three areas along the proposed metro line, two parts of the Yenikapı excavation, Yenikapı Marmaray Kazısı (sample code YMK), and Yenikapı Metro (YMT) and Sirkeci (SMK). We also show the locations of Hagia Sophia (SOF) and Hagia Eirene (IRN).

measurement of the annual tree-ring growth in samples from archaeological sites, buildings, monuments, and forests across this culturally opulent region. The ring-width series are then overlapped by a process of visual and statistical cross-matching with the aim of forming a continuous tree-ring chronology starting with modern forest samples of known calendar dates and extending as far back into the past as available samples permit.

The harbor and estuarine environment at Yenikapı has provided waterlogged conditions, with relatively rapid sedimentation, in which numerous wood samples from docks and other structures are preserved. The majority of the samples are *Quercus* spp. (oak) a genus well suited and widely used for dendrochronological dating (Haneca et al., 2009; Friedrich et al., 2004) although determination to species level is difficult when only wood samples (no leaves or acorns) are available for identification (Ważny, 2009; Griggs et al., 2007; Huber and von Jazewitsch, 1956). In this case, however, the very large number of samples allows a thorough comparison of the macro and microscopic features used to aid species determination, so that samples can at least be grouped into subsets and assigned possible species. Doğu et al. (2011) indicate that *Quercus ithaburensis* Decne. and *Quercus pontica* C. Koch (among other *Quercus* spp.) are found at Yenikapı, both of which are used in tree-ring research (Grissino-Mayer, 1993). The quality of the cross-matches we observe between the *Quercus* spp. found here, and our previous experience in cross-dating mixed oak species from the Mediterranean region (Ważny, 2009; Griggs et al., 2007) indicate that pooling the material into a single chronology is a viable approach. To date, over 2000 samples have been taken for dendrochronological analysis, and the material, whilst presenting a number of difficulties which are discussed in later sections, holds excellent potential to substantiate the chronology of the first millennium AD in the Aegean region (Kuniholm et al., in press).

In this paper we present the mid-section of this time period, a 213 year long chronology, constructed primarily of samples from four docks at the site (Fig. 2) plus some additional material from elsewhere in Istanbul, and show how it can be placed in time by a combination of dendrochronological, historic, and radiocarbon dating evidence. Whilst representing only a small portion of the wood samples recovered so far from Yenikapı, and only the middle portion of the possible temporal range for the harbor, this work is important in several respects.

First, the dendrochronologically placed chronology, supported by 16 radiocarbon dates, represents the first secure stepping stone in connecting wood samples from the first millennium AD with oak chronologies anchored in more recent times. Second, it provides a high-resolution framework against which to examine repair phases within the docks (relating to how long each dock was in use) and the deposition of contemporary sedimentary horizons; and third, it represents the first published tree-ring data series for the Istanbul region which covers the years AD 536–7 and 542, characterized by anomalous growth in other tree-ring series from around the world.

2. Method

Cross-sections were cut from posts at Yenikapı and other sites in the city which appeared from an initial field examination to have over 50 rings and/or potential for preservation of the outermost tree rings. Wet wood samples were wrapped in plastic to prevent drying in transit to the laboratory, and stored in a cool, dark environment prior to processing in order to limit deterioration. For the softer of the wet wood samples, radii were selected and prepared with razor blades. Harder, drier samples were prepared with both a sander and razor blades. For each sample, tree-ring widths along two to four radii were measured using a microscope, Henson measuring platform, and the TRiDaS (Jansma et al., 2010) compliant dendrochronological analysis packages CORINA (Brewer et al., 2010) and TELLERVO (http://www.tellervo.org/). For each data series, metadata including the sapwood count, the presence or absence of bark, the shape of the sample, the original excavator tag

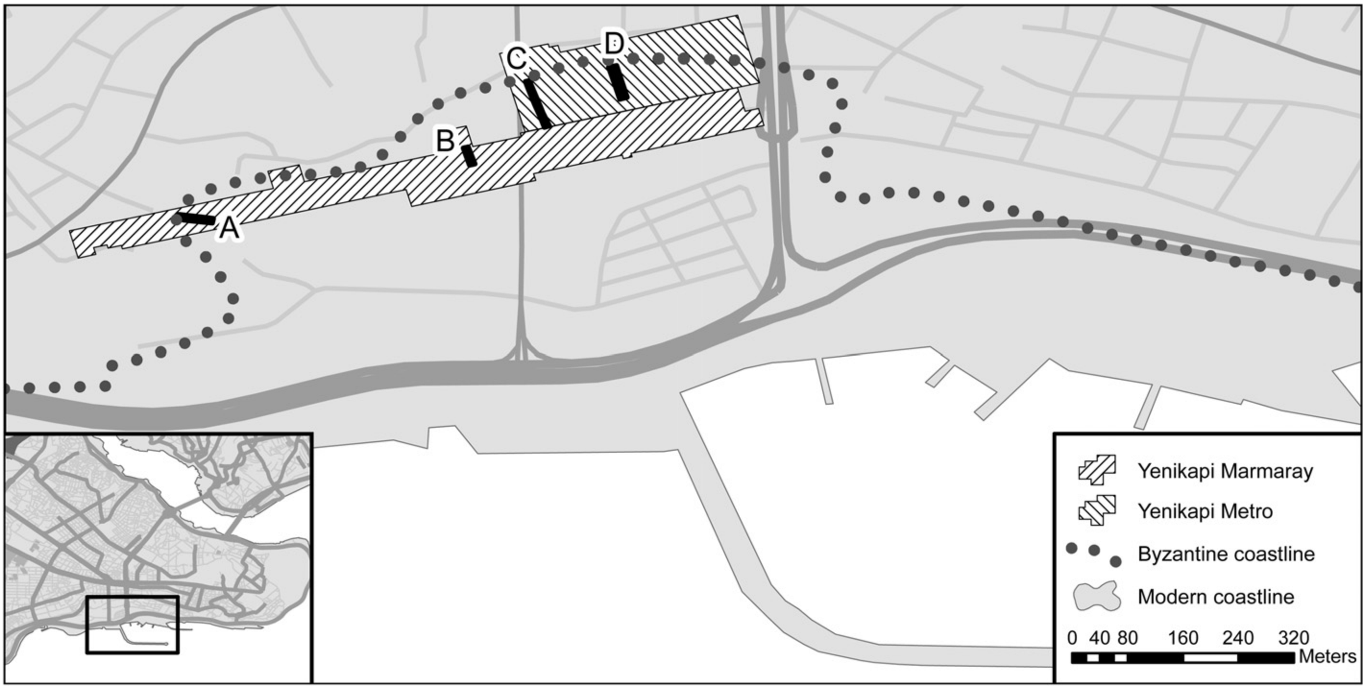


Fig. 2. The locations of the four mid-first millennium docks used in the master chronology. A = Marmaray İskele (*dock*) 1, B = Marmaray İskele 3, C = Metro İskele 3, and D = Metro İskele 24. The approximate coastline for the Byzantine period from Berger (2000) has been adapted to fit the layout of these contemporary structures to present a more informed representation of sea level at the site in the mid-first millennium.

and the location of the sample according to the excavator's grid plan were recorded. Spatial information was explored using the integrated 3D mapping capability within Tellervo and using QGIS (http://www.qgis.org/).

In dendrochronology, the most important metadata for precision dating are associated with the outermost growth rings (sapwood). Where the last grown ring is preserved, the year of felling can be determined, and the degree of development of the tree-ring structure can be used to ascertain the season in which the tree was cut (Eckstein, 2007). In *Quercus* spp. where the outermost ring is absent (due to deterioration in the burial environment or deliberate removal prior to use) an accurate estimation of the year of felling is often possible if sapwood is present (Hughes et al., 1981; Ważny, 1990; Hillam et al., 1987). The physiologically inactive heartwood is distinguished from the sapwood by a change to a paler color and/or decrease in the presence of tyloses. The presence of a number of sapwood rings on the outer edge of the sample indicates that the sample is close to a felling date. Exactly how close can be expressed with some precision if one takes into account the average expected sapwood count of the same age class and preferably from the same species. For a multi-species group of oaks in the Aegean region, the median number of sapwood rings in oaks from 75 to 125 total ring count is $22 + 9/-7$ (Griggs et al., 2009). The sapwood counts of the oaks used in this study show high variability (from 8 to 48 sapwood rings) which is normal for trees in this age class, and a median of $19 + 8/-7$. Where no sapwood is preserved it is possible to provide only a *terminus post quem*, i.e. the date after which the tree must have been cut.

In the Byzantine Aegean, examples of historically-dated or inscriptionally-dated buildings with wooden elements that include the bark or an outermost growth ring have demonstrated that the maximum elapsed time between cutting the wood and using it was generally only one year (Kuniholm and Striker, 1987). At Yenikapı, where the vast majority of our samples are oak pilings for docks, there would have been no need to season the wood for any length of time before use. We therefore suggest use of material within a year of felling (unless there is other evidence to the contrary).

Measurement series from individual samples were cross-matched with others from the same structure using the Student's *t*-test (Baillie and Pilcher, 1973) and the percentage of year-to-year growth trends in common (Fritts, 1976) to indicate possible relative placements. Visual comparison of the data series were then used to confirm or negate the security of the placement. Matches for samples under 50 rings were accepted for dating where the visual match was exceptional (although such short samples were not included in the final chronologies built by overlapping cross-matching samples from each dock). The chronologies from the different docks were then similarly cross-matched with one another and with tree-ring series and chronologies from other locations in the city. The quality of the matches was confirmed using COFECHA version 6.02 (Holmes, 1983), and ARSTAN version 41d (Cook and Holmes, 2006; Cook and Krusic, 2006) was used to further refine the chronologies. The final data set has been submitted to the Digital Collaboratory for Cultural Dendrochronology (DCCD) (Jansma et al., 2011).

The combined data-set was then cross-matched against our other unpublished chronologies from the Aegean and surrounding regions and assigned a dendrochronologically dated position within the working version of the Aegean oak master chronology (Kuniholm et al., in press). For an independent confirmation of this tree-ring derived temporal position, 16 groups of tree-rings, spaced by exact ring counts and including 10 or more rings, were dissected from five different cross-dated samples (YMK-353, YMT-263, SMK-659, SOF-14 and IRN-4; see Fig. 7). The dissected groups were sent to the Heidelberg Radiocarbon laboratory for analysis. All samples were pretreated using soxhlet extraction to remove resins, and then put through progressive acid–alkali–acid baths separated by distilled water rinses. After final rinsing to a neutral pH, samples were dried and combusted, and β-decay ages for each sample were measured for 10 days in gas counters. Subsequently derived dates were wiggle-matched (Galimberti et al., 2004; Bayliss, 2007) using OxCal (Bronk Ramsey, 1995, 2009; Bronk Ramsey et al., 2001) and compared with the northern hemisphere standard IntCal09 radiocarbon data set (Reimer et al., 2009).

3. Results

Of more than 2000 dendrochronological samples collected so far from the Marmaray excavations, 286 demonstrably come from mid-first millennium AD contexts, and from four docks in particular: Marmaray İskele 1, Marmaray İskele 3, Metro İskele 3 and Metro İskele 24, labeled A–D in Fig. 2. From the total material measured for the four docks, 28% was selected for chronology building on a basis of whether the sample was oak, the number of rings present, and both visual and statistical cross-matching potential. We also include a singleton piece from Trench A/6 at Sirkeci which cross-matches extremely well with Marmaray İskele 1 phases 3 and 4. The percentages of material which produced good cross-matches varied substantially among the four docks (Marmaray İskele 1: 50%; Metro İskele 3: 31%; Marmaray İskele 3: 21%; and Metro İskele 24: 2%). This was due to several factors. In Metro İskele 3, for example, a large number of the posts were non-oak, and in Metro İskele 24 many of the samples had too few rings for a statistically viable placement. Other samples had to be rejected because multiple scars caused unavoidable distortion of the tree-ring series. Despite difficulties such as these, it was possible to build robust chronologies for the structures, which, when matched against one another, with a small group of samples from the primary building phase of Hagia Sophia, and with a single sample from Hagia Eirene, produced good cross-dating statistics. Table 1 shows the quality of the cross-matches within the docks. Fig. 3 shows the visual and statistical cross-matches between the Marmaray project dock-chronologies, Hg. Sophia and Hg. Eirene. The average of the site chronologies produced a *t*-score of 5.60 with a year-to-year growth trend of 75% (with 115 years overlap) against the Hg. Sophia primary chronology and a *t*-score of 6.56 and growth trend of 67% (with 111 years overlap) against the sample from Hg. Eirene. The combination of the data sets from the Marmaray project sites with material from these two iconic buildings produced a 213 year master chronology.

The data sets for Hagia Sophia and Hagia Eirene, prior to the addition of the Marmaray project material, were included as part of the ADP's working version of the Aegean oak master chronology. This chronology is a solid, published dendrochronological sequence from AD 1089–2007, incorporating 557 samples from 63 sites (Griggs et al., 2007, 2009). Beyond this point it has now been extended back to 357 BC using cross-matches from 490 samples from at least 50 different sites in the Aegean region (Kuniholm et al., in press); however, this portion of the chronology is still regarded as "tentative" because of the low numbers of samples for some of the included site chronologies. Greater overlaps and an increase in sample depth, especially in the 10–12th centuries, is required to fully substantiate the existing cross-matches (see Fig. 5). This being the case, whilst a firm dendrochronological cross-match (*t*-score 6.4) was found at AD 398–610 for the sum of this group of Marmaray project samples against the sum of the remainder of the material in the ADP oak master (see Fig. 4), this date range is subject to the caveat that before it can be cited as an absolute dendrochronological placement, further work is required to substantiate all dendrochronological linkages between this period and the 2007–1089 AD group.

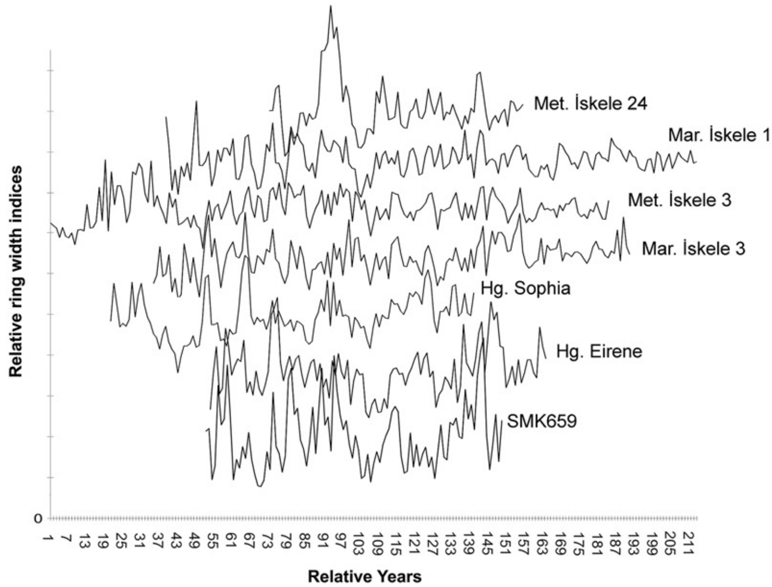
Nevertheless, as can be seen in Fig. 5, many lines of evidence converge to give us particular confidence in the dendrochronologically provided date range, including information from historic sources and radiocarbon analysis. For the group representing 83 trees which we will now refer to as the "mid-first millennium" chronology based on this dendrochronological placement, we have particularly strong supporting evidence from both these sources.

Procopius (Dewing, 1914) records that Justinian began work on the primary phase of Hagia Sophia immediately following the destruction of the original church during the Nika insurrection of AD 532. Mainstone (1988) mentions an inscription of 'AD 534' on a column of the south-west exedra and asserts that the initial setting-out and construction of ground-level piers and colonnades was in this year, drawing on both Procopius and Cedrenus to state that the building was dedicated, completed, and furnished in December 537. This fits well with the dendrochronological placement of sample SOF-14, taken from a ground floor tie-beam for the Hg. Sophia Primary chronology, which has a cutting date of AD 534. Two other samples from the north aisle center bay of the gallery extend the sequence forward for another three to four years. Whilst it was not possible to verify a cutting date for either of these samples due to deterioration, a date of AD 537 would fall within the 1 sigma range of the sapwood count provided by Griggs et al. (2009), given the age of the trees.

Radiocarbon analysis of the 16 dendrochronologically spaced segments of the chronology from five cross-dated samples also provide an independent verification of the dendrochronological placement. Wiggle-matching produced a best fit for the sequence at AD 397–607 $\pm$ 15 at 95.4% certainty ($\pm$22 at 99.7% certainty). See Fig. 6.

Table 1
Table to show the statistical quality of cross-matches between individual samples in the chronologies. The values for the Estimated Population Signal (EPS) generated using ARSTAN (Cook and Holmes, 2006) are consistently well above the standard 0.85 (after the date in the column), indicating that each combined tree-ring series contains enough of the common signal and less "noise" to represent a whole population, The intercorrelation values (between each sample and the average of the rest of the samples) were calculated by COFECHA (Holmes, 1983). Small symbols of the same type mark which chronologies were combined with which for statistical analysis due to their small sample number.

	Chronology	Begins	Ends	Year EPS > 0.85	Total years	Samples	Trees	Inter-correlation
	Marmaray İskele 1 phase 4	436	610	505	175	18	18	0.591
	Marmaray İskele 3	432	588	505	157	6	6	0.507
	Metro İskele 3	398	581	460	184	34	28	0.584
★	Marmaray İskele 1 phase 3	450	579	505	130	11	11	0.517
†	Hg. Eirene	451	561	450	111	1	1	0.530
★	Metro İskele 24	470	553	450	84	2	2	0.517
★	Sirkeci	449	546	450	98	1	1	0.517
	Marmaray İskele 1 phase 2	451	539	450	89	4	4	0.469
†	Hg. Sophia	418	537	450	120	7	7	0.530
	Marmaray İskele 1 phase 1	470	527	450	58	5	5	0.613
	Combined chronology	398	610	440	213	89	83	0.512



	Hg. Eirene	Hg. Sophia	Mar. İskele 3	Mar. İskele 1	Met. İskele 24	Met. İskele 3
Hg. Sophia	t=5.94, tr=73.3% n=87					
Mar. İskele 3	t=7.71, tr=73.6% n=111	t=6.32 tr=75.2% n=106				
Mar. İskele 1	t=3.21 tr=57.7% n=111	t=4.83 tr=68.8% n=102	t=7.31 tr=68.4% n=153			
Met. İskele 24	t=2.96 tr=61.4% n=84	t=1.49 tr=67.9% n=68	t=4.31 tr=62.0% n=84	t=7.76 tr=68.7% n=84		
Met. İskele 3	t=8.89 tr=70.5% n=111	t=6.55 tr=72.7% n=120	t=11.20 tr=81.2% n=150	t=5.15 tr=70.3% n=146	t=3.56 tr=62.7% n=84	
SMK 659	t=4.24 tr=58.9% n=96	t=4.01 tr=67.0% n=89	t=3.76, tr=73.7%, n=98	t=7.73, tr=76.3%, n=98	t=3.92, tr=65.8%, n=77	t=4.61, tr=73.2%, n=98

Fig. 3. Visual and statistical cross-matches (t = t-score, tr = trend, n = total number of rings) between the Marmaray project sub-chronologies, Hagia Sophia and Hagia Eirene. Sample depth for the overall chronology can be seen in Fig. 7.

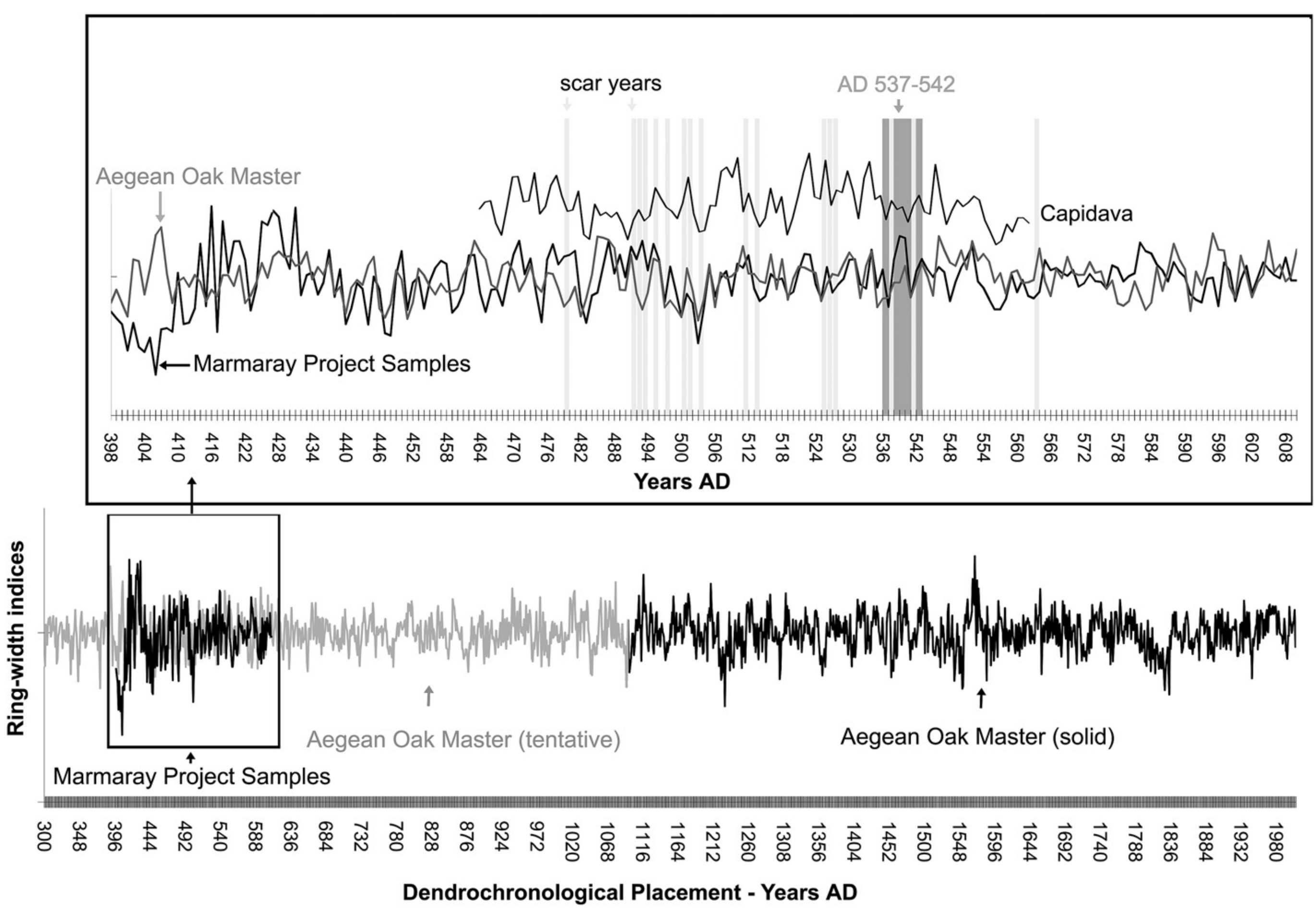


Fig. 4. The cross-match between the Marmaray project material and the sum of all non-Marmaray project samples in the Aegean oak master chronology. The 'solid' part of the oak master, including over 1000 samples representing 22 forests and over 232 dated medieval and post-medieval buildings in Turkey, Greece, and the former Yugoslavia, is shown by the black line, the tentative part by the gray line. Note that the figure represents data back only to AD 300 (not to 375 BC where the data set ends). We provide an enlarged section of the sequence at the top of the figure so that the visual cross-match can be examined. We also single out the cross-match with the data-set for Capidava, Romania. Years in which scarring occurred in multiple samples and 'event' years 537–542 which are highlighted with gray vertical lines.

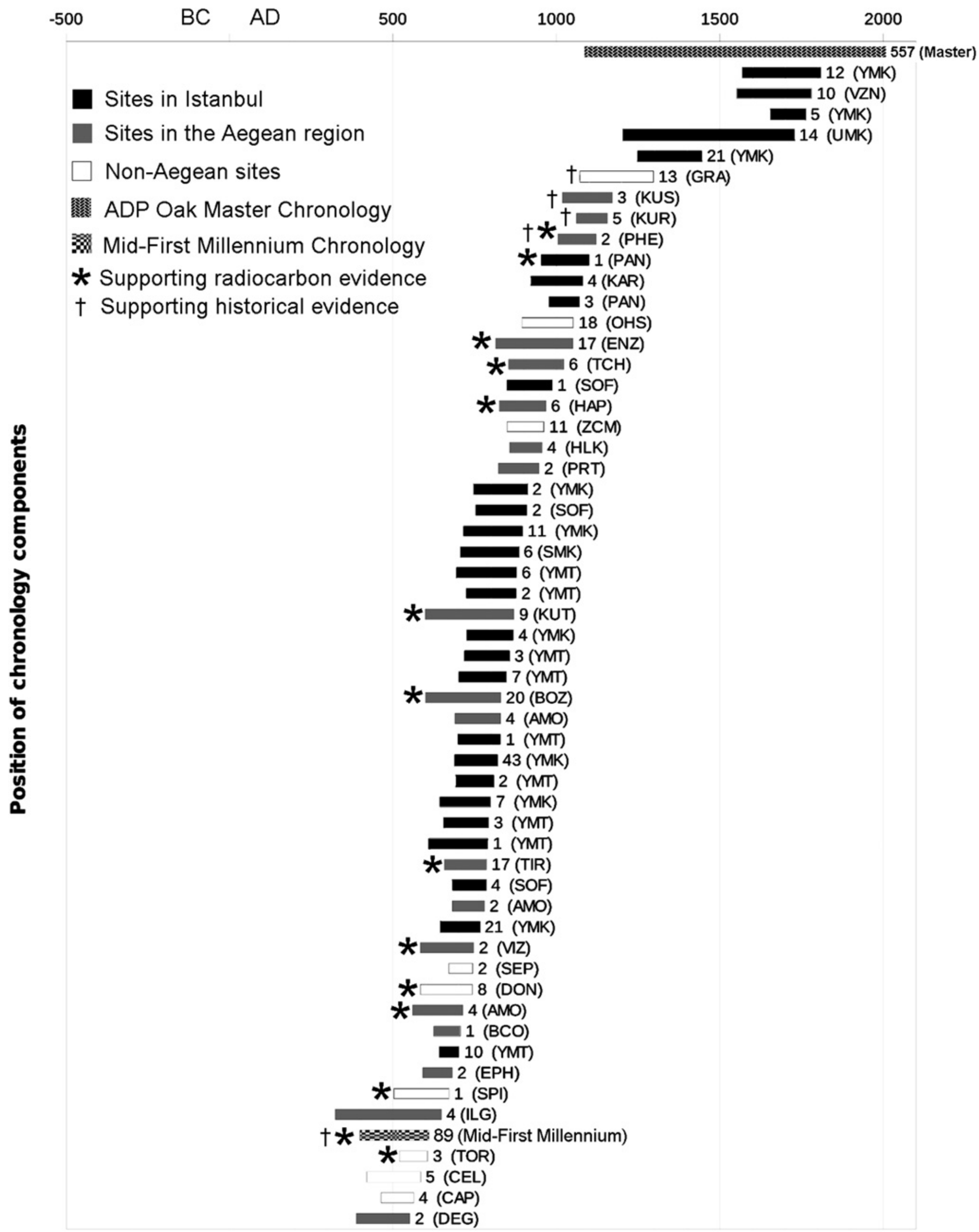


Fig. 5. Bars represent sub-chronologies from a section of the latest working version of the ADP oak master chronology, from AD 398–2007. The number after each bar is the number of samples represented. The 3 character code is the ADP site code for the material. Note the presence of later material from the Marmaray project excavations (YMT, YMK, UMK, VZN) that has made it possible to extend this sequence. Bars are color coded to reflect the geographic origin of the material. Asterisks note where there is additional radiocarbon evidence to support the position of the chronology. Note the low numbers of samples in many of the sub-chronologies and the fact that some of the material was sourced outside Turkey. For these reasons, although we are confident (on the basis of cross-matching) that the majority of the material is correctly placed in this absolutely dated sequence, we will continue to refer to data before AD 1089 as 'tentative' until the full data-set is sufficiently well replicated for publication via submission to the DCCD. The 89 samples included in the mid-first millennium chronology clearly make a significant contribution to sample depth for this part of the sequence.

4. Discussion

4.1. Dating evidence

The excellent dendrochronological cross-matches between the sample groups of the 213 year sequence demonstrate the contemporaneity of the wood samples. The strong cross-match between this chronology and other independently placed components of the current ADP Aegean Oak Master chronology indicates a probable absolute placement for the material at AD 398–610. Given that this is supported by evidence from both historic sources and analysis of 16 radiocarbon samples taken at precise spacings throughout the chronology, we now feel sufficiently confident about the placement for it to be used for a high-resolution analysis of associated dendroarchaeological and paleoenvironmental ramifications.

4.2. Dock construction

The new chronology opens up possibilities for exploring phases of use and/or repair at Yenikapı. Fig. 7 shows the samples used, arranged in temporal order by structure, with sapwood, waney edge, and pith information for each. Please note that where samples are marked as having waney edge, actual cutting dates may be plus one year if a partial, unmeasured ring was present at the end of the sequence.

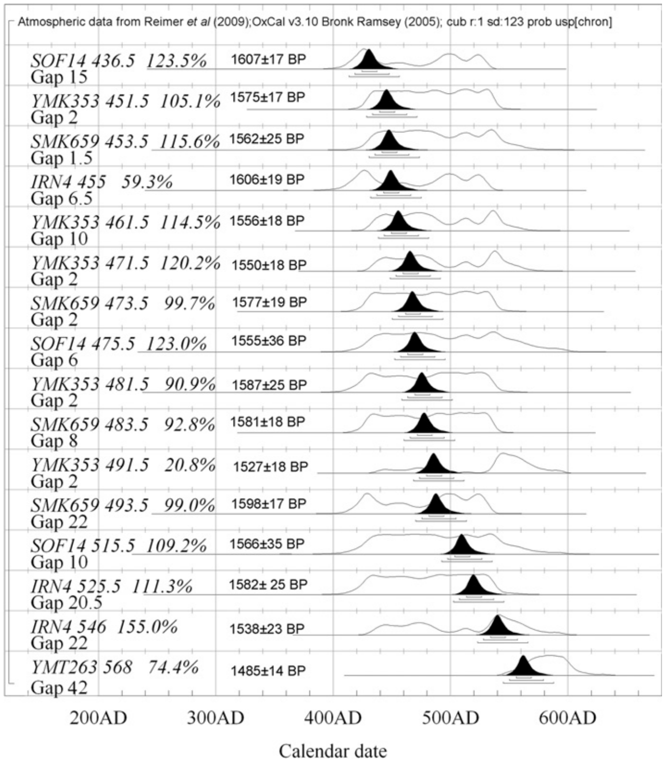


Fig. 6. OxCal derived plot for 16 radiocarbon samples taken at intervals through the chronology. The calibrated range is shown in outline and the modeled range as a solid curve. The middle year of the segment used for the last 14C date is 42 years away from the end of the chronology, at 610 RY. The 2σ range, used here for dating, puts the 610 RY at 607 $\pm$ 15 calibrated years AD. Numbers next to the sample identification codes represent the dendrochronological placement for the middle year of each segment. We note that YMK-353 (at 491.5) has a very poor agreement with the model (20.8%). This sample had some fungal contamination which it was hoped would be removed during the radiocarbon pre-treatment phase. This result suggests this was not the case.

Clear phases can be seen in the construction of Marmaray İskele 1, which when cross-referenced with a plan of the posts in *situ* (see Fig. 8) showed no structural correlations that would indicate a change in the function of the dock over time (as might be interpreted from clear extension or widening at one particular cutting date). Rather, this analysis shows repairs on a post-by-post basis around several distinct points in time, with the implication that this dock was in use for at least 83 years. This is borne out by the other docks, which, whilst they do not show use over such a long time span, do fall within it in terms of construction phases. Metro İskele 3, for example, may have been in use for at least 45 years if the single samples YMT-281 and YMT-3560 indicate earlier construction phases, but alternatively, these two posts could be re-used older material combined in a single construction phase using wood from AD 581/2. Sampling of further posts from this structure in association with geologists at the site should help to determine which of these scenarios is most likely.

When plotted on the excavation plan, Marmaray İskele 1 is in a different location and shows a different orientation than the three others which are commonly aligned (see Fig. 2). Several things can be implied from this, within the limitations of the record from these four datable structures. First, for the docks to have all been in use around the same time at these orientations, the shoreline must have been relatively constant over this period. Secondly, the area in which Marmaray İskele 1 is located was in use for the longest time, and the fact that phases 3 and 4 (plus sample YMK-353) of this dock broadly correlate with construction of the other three docks, may suggest an increase in use of the harbor from c. AD 570–590, which, from the lack of phases in the other docks, may have been fairly short lived.

The most recent set of replacement posts in Marmaray İskele 1, phase 4, on Fig. 7 (with a spring cutting date of AD 611, AD 610 being the last measurable ring) were found to be predominantly of a different, undetermined species of oak to that used in other phases, which may indicate a change in raw material sourcing at this time. The elevations of the tops of these posts were relatively even to one another when compared with the undulating elevations recorded for the other phases. This may indicate more rapid burial, or less erosion of this phase, which may be indicative of some sudden change in the depositional regime, or that the oak species used was more resistant to erosion than the other samples.

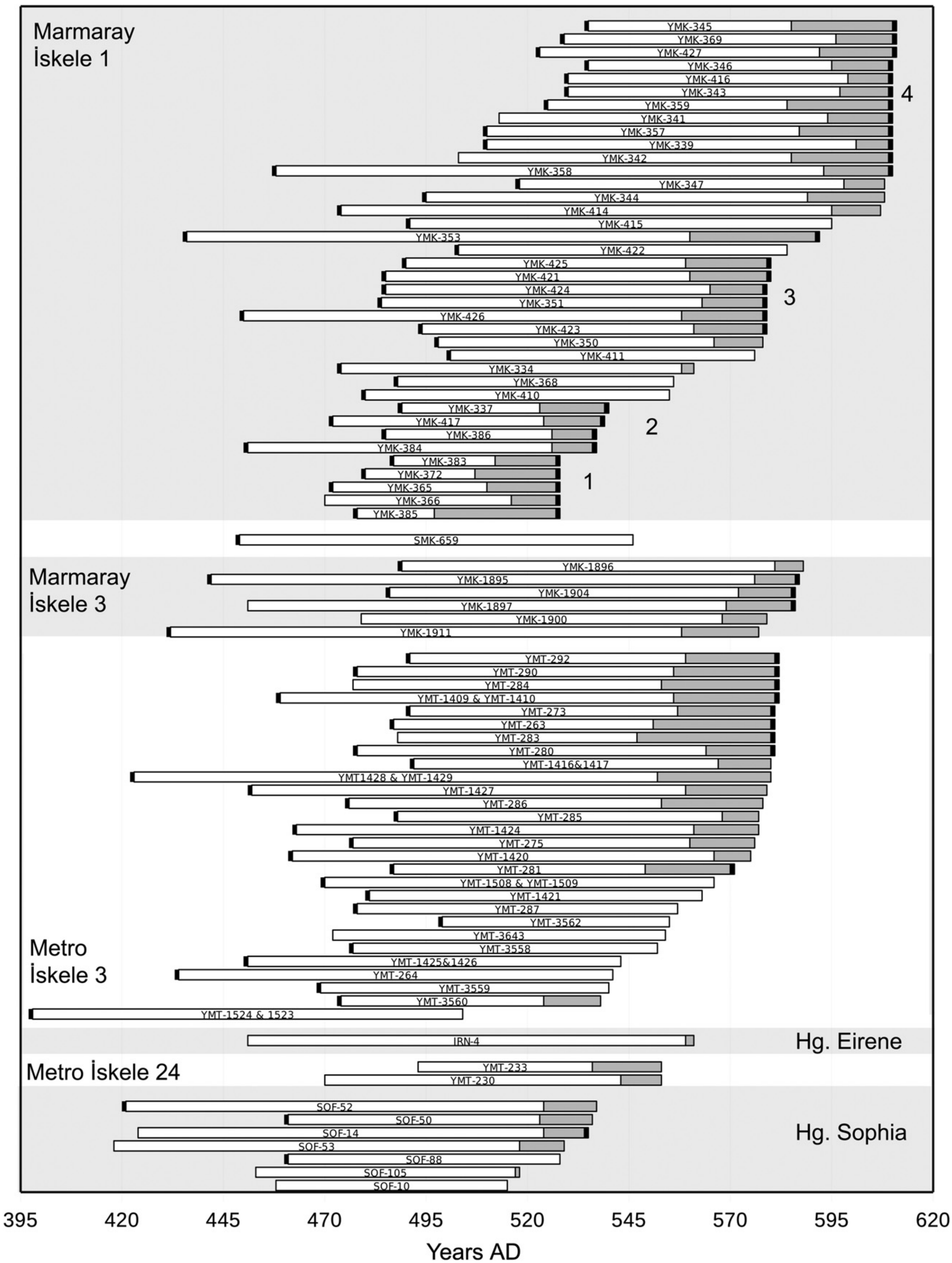
This type of interpretation is of course shaped by the material we have been able to date so far and much future work remains on filling out the details for docks which have not yet been dated in association with stratigraphic information provided by the excavators.

4.3. Events

The period covered by the chronology was particularly tumultuous for Constantinople, a time of fires, plague, and numerous earthquakes. Of the former, the new record at present shows no indication. A major fire in AD 465 destroyed the neighboring Port of Julianus (Mango, 1986), which might have increased the use of Yenikapı, but this data set provides no obvious construction phases associated with this date—the first building phase represented in the chronology is AD 527. Similarly none of the dock phases (or hiatuses) reported here (with the exception of one sample in Marmaray İskele 1) are associated with the years AD 541–542 when the Justinianic plague killed approximately 40% of Constantinople's population (Magdalino, 2000).

Earthquakes are relatively common phenomena around the tectonically active Sea of Marmara (e.g. Utkucu et al., 2008; Ambraseys, 2002b), but the mid-fourth to mid-sixth centuries AD saw an unusual clustering of destructive events (the Early Byzantine Tectonic Paroxysm) (Pirazzoli et al., 1991, 1996; Guidoboni et al., 1994; Stiros, 2001). It is possible that the destruction wrought may go some way to explaining the previously observed regional scarcity of dendrochronological material at this time, though a preference for other construction materials, destructive use as fuel, or export of Anatolian timber to Egypt as in the late Ottoman centuries (Mikhail, 2011), may provide further explanation. In terms of the existing dendrochronological evidence however, although repair phases in the great buildings of Istanbul might reasonably be expected to reflect earthquake damage

Fig. 7. Samples in the mid-first millennium master chronology. Each bar represents sample length and is labeled with a unique sample code. Where two codes are present, averaged data represents the same tree. A black line at the start of the bar denotes 'pith present', a black line at the end of the bar denotes 'waney edge'. Sapwood is gray. YMK/YMT: Yenikapı material, SMK: Sirkeci material, IRN: Hg. Eirene, SOF: Hg. Sofia. Note the relative positions of samples SOF-14, IRN-4, YMK-353 and SMK-659 which were dissected for radiocarbon analysis. SOF-14 dates securely but is not used in the final chronology due to anomalous growth disturbance in part of the ring pattern. YMT-1523 & 1524 include a further 70 rings which were truncated from the dataset used in the chronology due to anomalously narrow growth. We also note that contextual information for these two samples is currently incomplete. They are included as part of Metro İskele 3 on the basis of a strong visual and statistical cross-match and we are awaiting a radiocarbon date for additional confirmation of this placement.


Marmaray İskele 1
YMK-345
YMK-369
YMK-427
YMK-346
YMK-416
YMK-343
4
YMK-359
YMK-341
YMK-357
YMK-339
YMK-342
YMK-358
YMK-347
YMK-344
YMK-414
YMK-415
YMK-353
YMK-422
YMK-425
YMK-421
YMK-424
3
YMK-351
YMK-426
YMK-423
YMK-350
YMK-411
YMK-334
YMK-368
YMK-410
YMK-337
YMK-417
2
YMK-386
YMK-384
YMK-383
YMK-372
1
YMK-365
YMK-366
YMK-385
SMK-659
Marmaray İskele 3
YMK-1896
YMK-1895
YMK-1904
YMK-1897
YMK-1900
YMK-1911
YMT-292
YMT-290
YMT-284
YMT-1409 & YMT-1410
YMT-273
YMT-263
YMT-283
YMT-280
YMT-1416&1417
YMT1428 & YMT-1429
YMT-1427
YMT-286
YMT-285
YMT-1424
YMT-275
YMT-1420
YMT-281
YMT-1508 & YMT-1509
YMT-1421
YMT-287
YMT-3562
YMT-3643
YMT-3558
Metro İskele 3
YMT-1425&1426
YMT-264
YMT-3559
YMT-3560
YMT-1524 & 1523
IRN-4
Hg. Eirene
Metro İskele 24
YMT-233
YMT-230
SOF-52
SOF-50
SOF-14
Hg. Sophia
SOF-53
SOF-88
SOF-105
SOF-10
395
420
445
470
495
520
545
570
595
620
Years AD

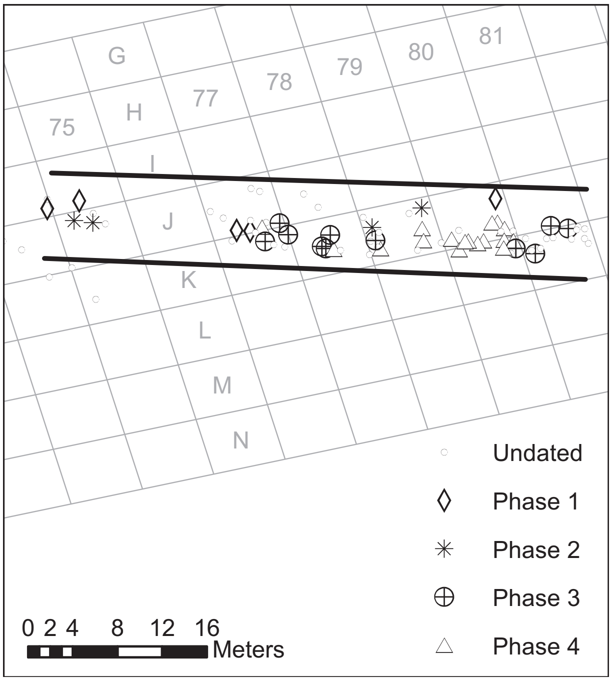


Fig. 8. Marmaray İskele 1 within the excavator's grid plan showing four phases of repair identified by the dating process.

(corroborated by written records) it seems unlikely that such damage would affect the construction history of structures such as docks in a harbor. That is until one considers an equally well (and controversially) reported natural hazard associated with these phenomena—tsunami.

There is no argument that tsunami waves have inundated Constantinople at various times in the past; for example on the 10th of September 1509, following an earthquake under the Sea of Marmara (Altinok and Ersoy, 2000), a wave of over 6 m (Öztin and Bayülke, 1991) washed over the sea walls at Yenikapı. However, going further back in time there is a lack of agreement in the cataloging of such events (Ambraseys, 2002a).

At Yenikapı a distinctive chaotic sedimentary unit has been argued to represent the impact of a tsunami at the site (Perinçek et al., 2007; Bony et al., 2011). This stratigraphic unit is darker in color than the surrounding units, poorly sorted and rich in anthropogenic, terrestrial, and marine materials. In a field determination at the time of the dendrochronological sampling, Metro İskele 3 and Metro İskele 24 were interpreted as having been put in place before this sedimentary unit was laid down, and one sample, YMT-236, was determined to been put in place some time afterwards (see Fig. 9). Based on this initial interpretation, the dendrochronological analysis provides a time window for the deposition of the layer after AD 581 (Metro İskele 3) and before AD 846 ± 7 (YMT-236; last measured ring AD 829 including two sapwood rings, adjusted to the 19 average sapwood count for Yenikapı samples). Anthropogenic material within the layer (which would of course pre-date the deposition of the layer) dates to c. 5th–7th century (Perinçek, 2008; Algan et al., 2009; Alguadiş and Batchelder, 2007), which is consistent with deposition after AD 581.

This dating evidence has interesting implications because although the written records indicate a proliferation of possible tsunami from AD 358–557 (Downey, 1955; Papazachos and Papazachou, 1997; Ambraseys, 2002a), records after AD 557 indicate several hundred years without any such events. The one possible exception is AD 740 (Papadopoulos and Chalkis, 1984; Yalçıner et al., 2002), where a lowering of sea level is noted, but we can find no mention in the literature of tsunami inundation associated with this. Instead it may simply describe coastal uplift caused by the quake (Ambraseys, 2002a). It could be that this was a period in which records of tsunami were not so well maintained; however, given that earthquakes in AD 580, 583, 611, 740, 780, and 790 were all recorded in detail (Downey, 1955; Ambraseys, 2002b), this seems unlikely.

Given the scarcity of historic references to tsunami during the period indicated by the dendrochronological research, it could be argued that the dates better support the growing geoarchaeological evidence, such as excavation of sequentially stratified coins (Sırrı Çölmekçi and Mehmet Ali Polat *pers. comm.*) and detailed studies by Algan et al. (2011, 2009), that the chaotic sedimentary unit represents a longer duration of deposition than for a single catastrophic event. Algan et al. (2009, 2011) do not rule out the possibility that tsunami or flood events (intense rainfall is possible in the area (Göktürk et al., 2011)) may be present within the unit; however, they suggest that the majority of the material was deposited as a result of day-to-day activities within the Byzantine breakwater. In this scenario our current data may point to a change in depositional regime (perhaps caused by construction of a new harbor wall) sometime after AD 588.

Further dendrochronological research in collaboration with geological specialists at the site holds much potential to construct absolutely dated time frames for the deposition of the various sedimentary units. Work is already underway to improve our understanding of the stratigraphic context of datable dendrochronological samples for several docks, including a more detailed study of the contexts for posts from Metro İskele 3. A particular point for further research is to ascertain if there are other posts within this dock which date, along with sample YMT-3560, to AD 543 ± 7, a period for which there are several tsunami records, including one in AD 543 (Altinok and Ersoy, 2000) itself.

4.4. Climate

Over the past few years a number of scholars working on tree-ring chronologies from around the globe have observed anomalous downturns in tree-ring growth in the years AD 536–537 and 542 (D'Arrigo et al., 1999; Eronen et al., 2002; Baillie, 1994; Scuderi, 1993; Salzer and Hughes, 2007). Combining evidence from the paleoenvironmental archive with historic literary sources, various hypotheses have been put forward to explain this, including volcanic eruptions and cometary impact (Baillie, 1999, 2006; Keys, 1999; Stothers and Rampino, 1983). Much of this has revolved around texts describing phenomena associated with these dates, many of which come specifically from Constantinople. For example Zacharias, Bishop of Mytilene, recounts a visit from Pope Agapetus to Constantinople in March of AD 536 when

> "…*the sun began to be darkened by day and the moon by night, …from the 24th of March in this year till the 24th of June in the following year*…" (Hamilton and Brooks, 1979).and Michael the Syrian (reproducing the text of John of Ephesus) wrote

> "…*In the year 848 [AD 536/37] there was a sign in the sun the like of which had never been seen and reported before in the world… it is said that the sun became dark and its darkness lasted for one and a half years, that is, eighteen months. Each day it shone for about four hours, and still this light was only a feeble shadow. Everyone declared that the sun would never recover its original light. The fruits did not ripen, and the wine tasted like sour grapes*…" (Chabot, 1899).

Although these two examples do not agree on the exact duration, it seems clear that something significant occurred around this time, something which according to tree-ring records in many parts

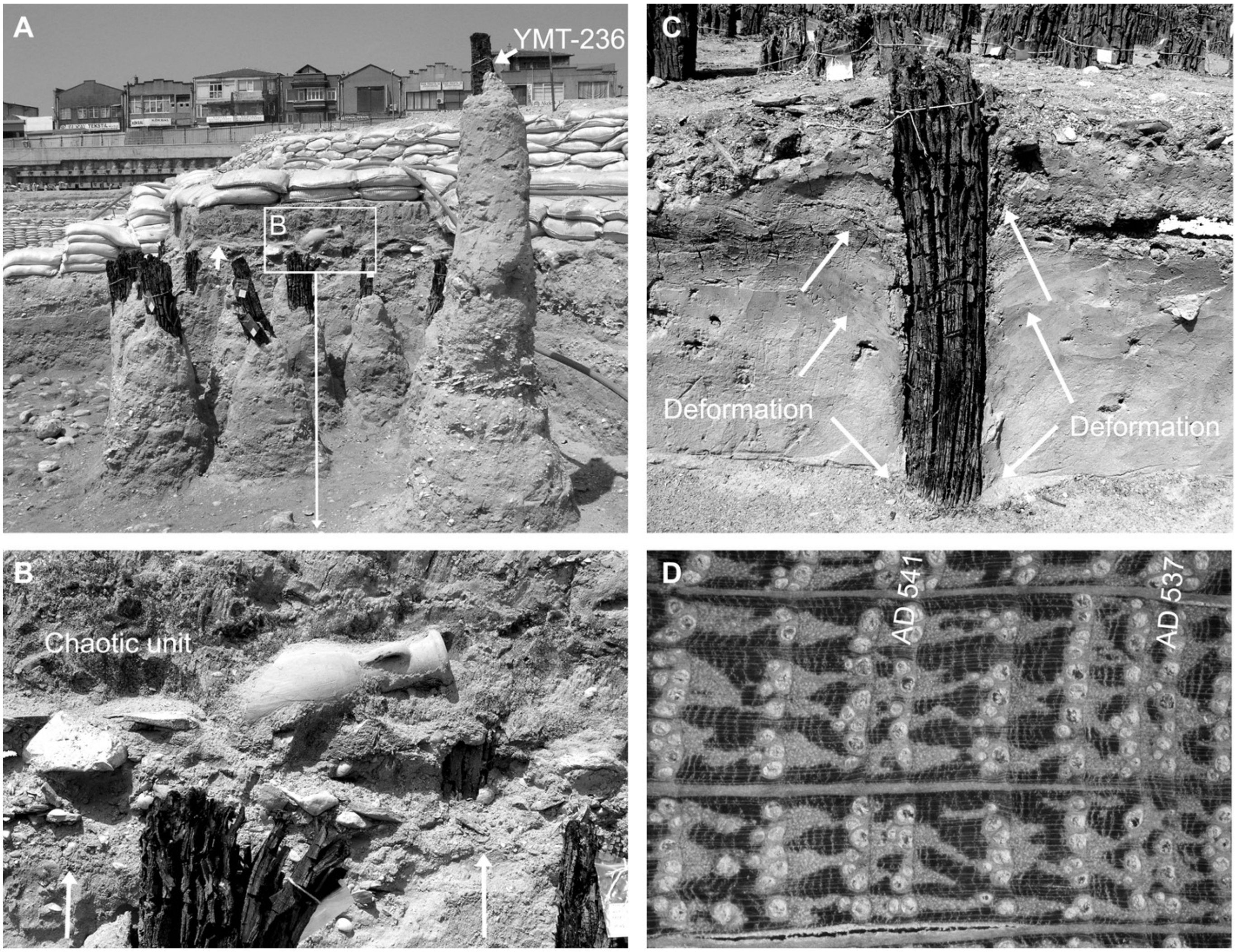


Fig. 9. A: Metro İskele 24 when excavated in 2007 with overlying 'chaotic layer' including a partially intact amphora, the larger post in the right foreground is a later addition to the dock. Note the level of the tops of the post appear to directly underlie the unit—i.e. these posts were in place and eroded before the deposition of the unit. B shows an enlarged section of this image for a better view of the 'chaotic layer'. C shows deformation of the unit underlying the chaotic layer caused by emplacement of the post. D shows the growth pattern typical of the years AD 537 and AD 541.

of the world had distinct short-term repercussions on climate. Up until now, however, it has not been possible to examine securely dated patterns of tree-ring growth from trees which grew in the region from which so many of the historical references are cited.

Tree-ring records in northern latitudes show regional variation in response during these event years, but broadly speaking a growth decrease in AD 536/7 is followed by recovery in AD 537/8 and then by a more serious plunge with the worst years around AD 541 (corresponding to the time of the Justinianic plague in Constantinople). Within the mid-first millennium chronology, at the current temporal placement, no anomalous growth of this sort can be identified (Fig. 4). Examination of the individual samples showed that the growth pattern in 68% of them is consistent with the trend reported for contemporary growth years in other regions (D'Arrigo et al., 1999; Eronen et al., 2002; Baillie, 1994; Scuderi, 1993; Salzer and Hughes, 2007), with narrower rings in AD 537 and AD 541 (see Fig. 9D), but these rings are not anomalous when compared with the rest of the series. Indeed there are several other years in the sequence which show much more significant growth disturbance (e.g. AD 440–447 and in AD 503). Equally, when other cross-matching sites from the ADP master chronology, such as Capidava, (see Fig. 4) are examined for this time period, no anomalous growth patterns can be observed for these years.

There are several possible reasons why events which are so well described for this region may not show up in local, contemporary tree-rings. First, while a sudden change to cool, dry conditions might have a negative impact on tree growth in northern climates (Baillie, 2006) where baseline conditions are colder, trees in the warmer Aegean region might be unaffected or actually experience an improvement in growth conditions. For example Fleitmann et al. (2009) show how negative temperature anomalies from the north can interact with Black Sea surface waters to result in increased precipitation along the Black Sea coast. In this case, however, we might expect to see an increase in the widths of the growth ring series around these two points in time. We do not.

Perhaps the growth-patterns from our trees reflect a localized micro-climate, or other site-specific factors more strongly than a broader regional or hemispheric signal. The growth rings certainly include many instances of scarring in response to some sort of site-specific physical damage, see Fig. 4, and are relatively wide and complacent when compared with the more sensitive growth of marginal geographic regions. Alternatively the absence of response may reflect that in spite of the colorful literary descriptions, the actual climatic impact of the strange optical effects described in this region were negligible as far as the trees were concerned. This last point would be in line with the findings of Arjava (2005) who concludes that although the mystery cloud of AD 536/7 was a phenomenon, it does not appear from the historical records to have been a pivotal point in the region's history.

Future work may include the construction of an isotopic time series from the new chronology for a more thorough exploration of changes in climate during the mid-first millennium. This would include not only the event years mentioned but also the more general trends recorded in the wider region of a dry period c. AD 300–500 changing to wetter conditions from c. AD 560–750 (Göktürk et al., 2011; Fleitmann et al., 2009). The ring-widths show a slight decrease in amplitude from AD 550 onwards which may reflect the impact of this broader climatic switch and it is interesting to note that the majority of scars cluster around the transitional period, see Fig. 4, so it may be that the changing conditions favored certain insects or pathogens or influenced anthropogenic use of the forest.

4.5. Provenance

As the tree-rings do not record the specific globally-reported events discussed in the previous section, establishing the exact provenance of the timbers used in the mid-first millennium chronology is of great importance to establish site-specific controls on growth. Unfortunately, we have so far been unable to assign an exact provenance to this material. Species identification would be helpful since most deciduous oak species found in the eastern Mediterranean region have relatively small or limited geographic ranges. However, the fact that the growth patterns of the samples from Hg. Sophia, Hg. Eirene and Yenikapı securely match indicates that the timbers came from a common region, and are of species that respond similarly to climate conditions. The area around the west end of the Black Sea is such a region, thus a possible candidate for the source of the timbers supplying the construction needs of Constantinople. The fact that these timbers also match remarkably well—t-score 6.12 on a 101 year overlap (see Fig. 4)—with wood samples from Capidava, Romania, also provides an important clue. Capidava is a Justinianic site about 100 km up the Danube from the Black Sea. It is in the Dobrudja, a region notorious for the absence of trees (James Crow *pers. comm.*). These two lines of evidence imply that the source supplying both this region and Constantinople most likely lies on one of the many trade routes around the Black Sea.

During the late Ottoman period, Egypt and Anatolia exchanged grain for timber from forests along the Black Sea coast (Mikhail, 2011), Anatolian wood went to construct Egyptian irrigation channels, dams, waterwheels and ditch re-enforcements to maintain the grain supply. While we have not found specific references for this exchange at Yenikapı in Byzantine times, Mango (1986) suggests that by the middle of the 5th century, in order to sustain a population of c. 350,000, some 500 ships full of grain would have to have docked simultaneously in Constantinople. The Theodosian harbor was probably the largest of its time, built next to two huge granaries, and it is logical to suggest the exchange of grain for timber which had been brought down from the Black Sea as a return cargo from trade visits to the garrisons on the lower Danube. Petrus Gyllius describes wood supply from both Europe and Asia, in particular from "*woods of an unmeasurable length extending from Propontis* [Sea of Marmara] *beyond Colchis* [Georgia]" (Gilles and May, 2008, p. 8), so the Pontic Mountains of North Eastern Anatolia are a likely source, or, alternatively, the forested Haemus/Balkan mountains which come down to the sea north of Messembria Nessebre (Jim Crow *pers. comm.*).

5. Conclusions

The 213 year chronology presented here represents a key step towards confirming an accurate annually resolved chronology for the first millennium AD in the Aegean. Although we would prefer to have further replication to strengthen the overall dendrochronological placement (as and when new dendrochronological material becomes available) the radiocarbon dating and historic evidence provide strong support for the current placement. This data set represents the first temporally-secured tree-ring series from this region to include the growth event years of AD 536–537 and 542 and contributes to the ongoing geoarchaeological investigations of construction and other key events at Yenikapı.

The main limitation to future chronology building with Yenikapı samples is the high percentage of material with under 60 rings. Dating such material can be very difficult, especially when compounded by a high incidence of scarring and strong juvenile growth trends (Billamboz, 2003). One future approach may be to employ several cross-dating techniques simultaneously (e.g. König et al., 2008) for these samples. Future work will also include more integrated collaboration with site geologists so that key stratigraphic sequences may be linked more accurately with specific felling dates. The aim here will be to develop a dendrochronological framework in which to examine sediment accumulation and potential event layers at the site.

What we present here is a work in progress that is already promising to be an invaluable resource for archaeological, historical, economic, architectural, and climatological research in Istanbul and across the entire Aegean region.

Acknowledgments

The analysis of tree rings from Yenikapı has dominated the work load of the Malcolm and Carolyn Wiener Laboratory for Aegean and Near Eastern Dendrochronology at Cornell University for the last 6 years and will now continue to completion at the Laboratory of Tree-Ring Research at the University of Arizona as part of the CMATE initiative. This research would not have been possible without the long-term support of the National Science Foundation, the National Endowment for the Humanities, the National Geographic Society, the Malcolm H. Wiener Foundation and numerous individual patrons of the Aegean Dendrochronology Project. For support of this initial phase of research we would particularly like to thank student employees Kate Seufer, Kayla Altland, Xan Stepp, Jessica Herlich, and Jennifer Watkins. Also Ariel Aicher, Marc Dominianni, Sam Fuller, Carrie Atkins-Fulton, Perri Gerard-Little, Ryan Hunter, Katie Kearns, Brita Lorentzen, Alison Petrucci, Sarah Johnson, Sarah Simpson, Becky Wrench, and Rebecca Wall, for their great contributions in preparation and measurement of samples. We also thank Berndt Kromer for providing the radiocarbon dates and Sturt Manning for his permission to use them in our wiggle-match. At Yenikapı we thank the archaeological team, in particular: Zeynep Kızıltan, Mehmet Ali Polat, Filiz Yalçındağ, and Sırrı Çölmekçi. We also thank specialists Oya Algan, Namık Yalçın, Jim Crow, Doğan Perinçek and Alex Bayliss. Finally we are particularly indebted to Mary Jaye Bruce and three anonymous referees who have greatly helped to improve the original manuscript.

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