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RESEARCH ARTICLE

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Establishing a high-resolution stratigraphy in the Holocene marine sequence of the ancient Theodosian harbor of Istanbul with the help of dendrochronology

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Abstract

Salvage excavations in the Theodosian harbor (Yenikapı-Istanbul) have uncovered diverse archaeological objects including 36 shipwrecks and various Byzantine period wooden docks. The sequence of these docks provided a unique opportunity to obtain a high-resolution stratigraphy. The new approach is based on stratigraphic interpretation of deformation patterns created by the posts in soft sediments, combined with dendrochronological dating of the posts. Dendrochronology offers the potential to date the posts to within one calendar year of felling, a level of precision and accuracy rare in sedimentological analysis. The posts, most of them *Quercus*, were rammed during six different time periods. The first period is associated with posts cut in 528 AD. The second and third periods are dated by posts cut in 583 and 594 AD, respectively. The fourth-period dates within 8–10 years of 639 AD. The fifth period could be dated only roughly to between 690 and 770 AD. The last period produced a possible placement of after 778 AD. This new approach helps to establish a high-resolution stratigraphy. Furthermore, it provides information about sedimentation history and specific anthropogenic events.

KEYWORDS

Constantinople, dendrochronology, harbor sediments, high-resolution stratigraphy, Istanbul-Turkey, Theodosian harbor

1 | INTRODUCTION

The Theodosian harbor in Constantinople was built by the Byzantine emperor Theodosius I (379–395 AD) at the end of the 4th century AD, as the older harbors of the town were not able to answer the growing demands of the flourishing new capital of the Eastern Roman Empire (Asal, 2010, 2013; Kızıltan, 2010, 2014). The site is located to the south of the so-called historical peninsula, the old town, the heart of Byzantine Constantinople on the northern coast of the Marmara sea (Figure 1). A natural embayment at the mouth of the small river Lykos provided the perfect protected location for a harbor that was actively used until the end of the 11th century when it was abandoned due to siltation. By the 12th century AD, the whole area was filled in and was used for agriculture until the second half of the last century (Kızıltan, 2010, 2014).

In 2004, the construction of a station for an underground railway system, running through a tunnel under the Bosporus (the Marmaray Project), led to the discovery of extensive archaeological remains, which resulted in a decade of salvage excavations by the Istanbul Archaeological Museum. In Yenikapı an area of almost 58,000 m^2 was uncovered for more than 12 meters to a level of −10 m, i.e., 10 m below today's sea-level (Kızıltan, 2014). These excavations resulted in an array of extraordinarily important findings, ranging in time from the

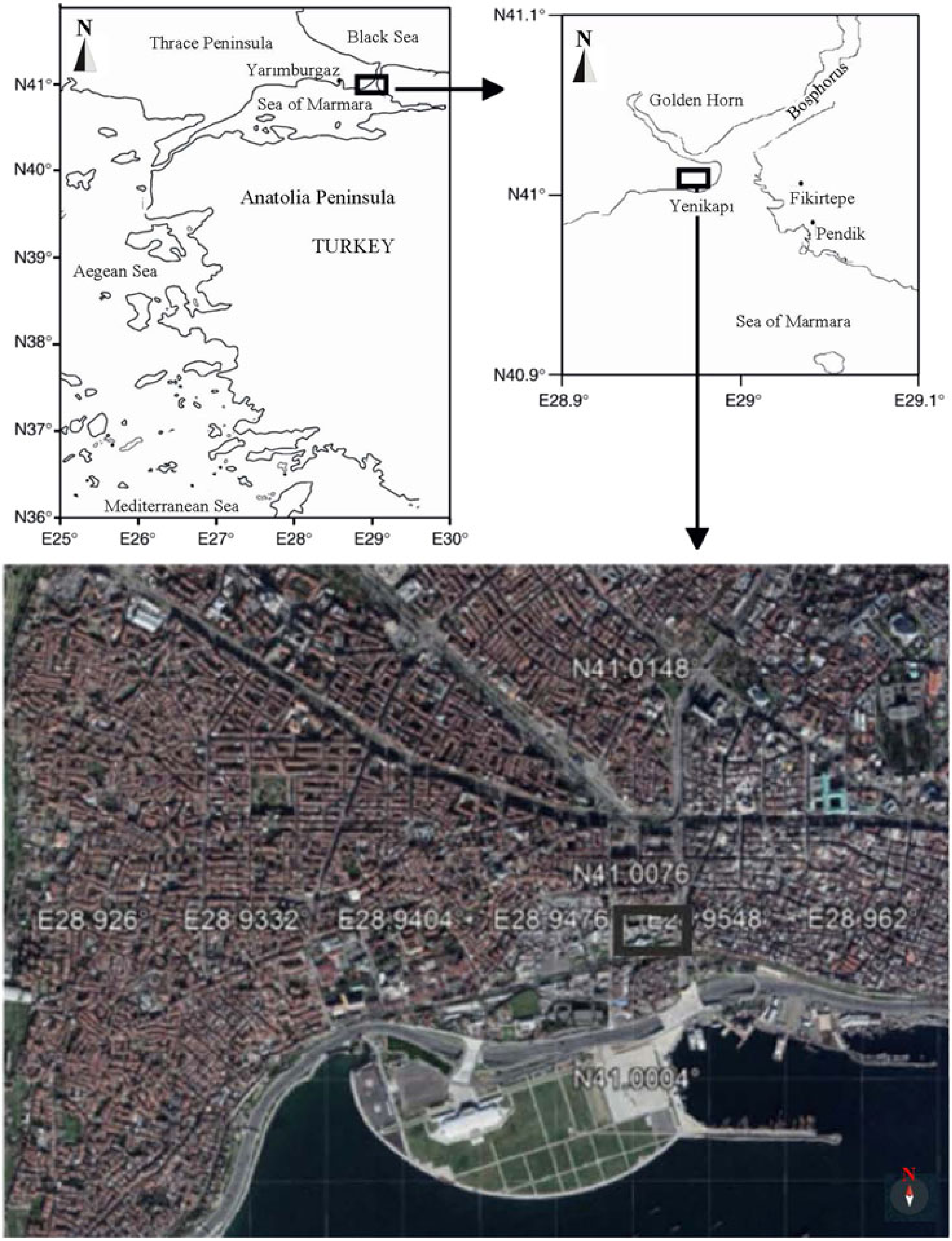

FIGURE 1 The location of the excavation site in Yenikapı, Istanbul. The digital image is produced from Google Earth 7.3.1 [Color figure can be viewed at wileyonlinelibrary.com]

Neolithic (c.6,000 BC) up to the late Ottoman period (c.19th century). Among a concentration of smaller archaeological objects, 36 shipwrecks from the Byzantine period, some with their loads intact, and over 4,000 wooden posts, mostly oak (*Quercus* spp.), were recovered from the ancient harbor (Akkemik & Kocabaş, 2013, 2014; Kocabaş, 2010, 2015; Kuniholm, Pearson, & Wazny, 2014; Kuniholm, Pearson, Wazny, & Griggs, 2015; Liphschitz & Pulak, 2007; Pearson et al., 2012; Pulak, 2007; Pulak, Ingram, & Jones, 2015; Pulak, Ingram, Jones, Matthews, & Kızıltan, 2013). During these salvage excavations, it was possible to observe and record a Holocene sedimentary sequence for the first time

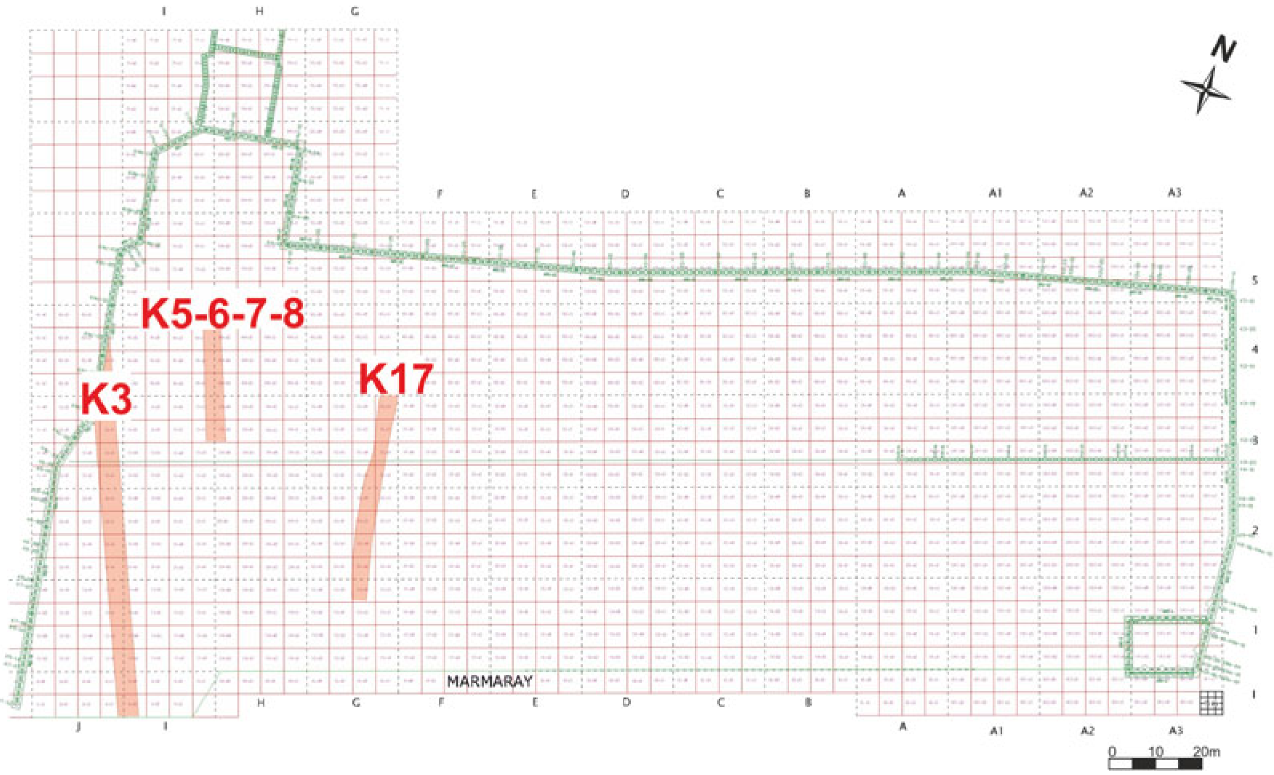

FIGURE 2 Schematic plan of the excavation area and of docks studied (grid-squares K3, K 5–6-7–8, and K 17) [Color figure can be viewed at wileyonlinelibrary.com]

in detail across many sections. The archaeological site of the Theodosian harbor at Yenikapı-Istanbul, therefore, presented a very wide spectrum of unique possibilities for scientific research. In addition to extensive archaeological studies (Kızıltan & Polat, 2013; Özdoğan, 2013), the entire geoarchaeological record extending back to the beginning of the Holocene (Yalçın, Bulkan, Algan, & Konak, 2015) and the first human occupation over 8,000 cal years BP (Algan, et al., 2007, 2009, 2010, 2011; Algan, Yalçın, & Özdoğan, 2014; Bony, Marriner, Morhange, Kaniewski, & Perinçek, 2011; Perinçek, 2010a) were investigated in detail. The wooden posts of several docks were the subject of a dendroarchaeological study which provided a new chronology for the first millennium AD in the Aegean (Kuniholm et al., 2015; Pearson et al., 2012). Three of these docks were studied even further in an attempt to refine the temporal resolution for the sedimentary units using dendrochronology or tree-ring dating and to analyze the depositional environment of the Holocene marine sequence (Sezerer, 2013).

During fieldwork the wooden posts of the docks were observed to have caused characteristic deformation of the pre-existing sediments into which they were rammed, allowing for a novel methodology to be developed. This was based on the analysis of the deformed sedimentary sequence and on the age of the respective wooden posts as determined by analysis of the tree-ring growth patterns or dendrochronology.

The aim of this paper is to demonstrate how sedimentological studies and dendrochronological analyses of the wooden posts of the docks in the Theodosian harbor were used to establish a high-resolution Holocene stratigraphy and to further understand construction and extension/renovation/repair periods of the studied docks.

2 | MATERIAL AND METHODS

Three docks (K1; K5–6-7–8; K17), which were constructed perpendicularly to the coast/quay line of the harbor were selected for detailed investigation (Figure 2). The lithostratigraphy of the respective profiles for each dock and deformational features associated with their wooden posts were systematically examined and posts with strongly associated geological deformations were selected for dendrochronological sampling. Samples for dendrochronological work were taken at the widest part of the post, and where possible, from newly excavated posts to ensure the best preservation possible for the outer edge of the sample, critical for accurate dating. Thirty-six dendrochronological samples were taken from these three docks. The distribution of these samples according to the studied docks is listed in Table 1.

Dendrochronological samples were processed according to standard dendrochronological procedures (Kuniholm, 2001). Sample surfaces were prepared with steel razor blades so that the tree rings along the most representative radii for each sample could be accurately measured. Measurements were made using a microscope, digitized Henson measuring platform, and the TRiDaS-compliant (Jansma, Brewer, & Zandhuis, 2010) dendrochronological analysis package Tellervo (http://www.tellervo.org/). A minimum of two radii per sample were measured and these data series were compared and checked for irregularities before either averaging or selection of a preferential radius for further dendrochronological work. Measurement series representing each sample were then compared with one another using visual cross-matching and a range of statistical analyses including the Student's *t* test

TABLE 1 Summary of the data and metadata collected from the samples

YMT No.	Dendro code	Profile No.	Area	Depth	Genus	Shape	Pith?	Sap wood Rings	Waney Edge?	Ring Count	Geological Periods	Dendro dates
YMT 1103	4938	3G-c3	K 17	−2,6	*Quercus*	Beam straightened on one side	y	12	n	63	1st	Not datable so far
YMT 1011	4928	3G-c1	K 17	−2,86	*Quercus*	Beam straightened on one side	n	7	n	63	1st	Dates to after 592 AD
YMT 1012	4935	3G-c1	K 17	−2,86	*Quercus*	Beam straightened on one side	n	11	n	64	1st	Dates to after 593 AD
YMT 1194	4934	3G-a4 / 3G-a3	K 17	−2,9	*Quercus*	Beam straightened on one side	y	13 + 1 partial ring and bark	y	65	1st	End date 593, cutting date late in the growth season of 594 AD
YMT 1167	4943	2G-c4	K 17	−3,32	*Quercus*	Squared beam from whole section	y	10	n	106	1st	Not datable so far
YMT 1055	4937	2G-c2	K 17	−3,4	*Quercus*	Squared beam from whole section	y	14	n	26	1st	Short sequence, not datable
YMT 1034	4936	2G-a2	K 17	−3,04	*Quercus*	Squared beam from quarter section	y	7	n	30	1st	Short sequence, not datable
YMT 1141	4939	1G-c4	K 17	−3,6	*Quercus*	Squared beam from whole section	y	12	n	43	1st	Not datable so far
YMT 1107	4932	3G-a2	K 17	−3,12	*Quercus*	Beam straightened on one side	y	12	n	69	1st	Not datable so far
YMT 1102	4924	4G-a1 / 4F-b2	K 17	−2,21	*Ulmus*	Beam straightened on one side	y	20	n	45	2nd	Non-oak, short sequence, not datable
YMT 1143	4941	3G-a4	K 17	−2,32	*Quercus*	Squared beam from whole section	y	23	n	62	2nd	Dates to after 639 AD
YMT 1142	4940	3G-a4 / 3G-a3	K 17	−2,72	*Quercus*	Squared beam from half section	n	8	n	74	2nd	Not datable so far
YMT 1105	4930	2G-c4	K 17	−2,7	*Quercus*	Beam straightened on one side	y	8	n	73	2nd	Dates after 630, but not in chronology due to erratic ring pattern
YMT 1106	4931	2G-c4	K 17	−2,23	*Quercus*	Half section	n	11	n	63	2nd	Dates to after 640 AD
YMT 1104	4929	2G-c4	K 17	−2,58	*Quercus*	Squared beam from half section	y	12	n	65	2nd	Dates to after 634 AD
YMT 1166	4942	2G-c2	K 17	-	*Quercus*	Squared beam from whole section	y	13	n	76	2nd	Dates to after 639 AD

(Continues)

TABLE 1 (Continued)

YMT No.	Dendro code	Profile No.	Area	Depth	Genus	Shape	Pith?	Sap wood Rings	Waney Edge?	Ring Count	Geological Periods	Dendro dates
YMT 1168	4933	2G-c2	K 17	−2,64	*Quercus*	Squared beam from half section	y	-	n	100	2nd	Dates to after 623 AD
YMT 1121	4925	3H-b4	K 5–6-7–8	−2,7	*Quercus*	Beam straightened on one side	y	12 – 13	y	57	1st	Possible end date of 526 AD with cutting in 527 AD
YMT 1209	4949	3Hb4	K 5–6-7–8-9	−2,56	*Quercus*	Beam straightened on 1 side	y	10 + 1	yposs	44	1st	Not datable so far
YMT 1210	4950	3Hb4	K 5–6-7–8-9	−2,63	*Quercus*	Square beam from whole section	y	13 + 1	y	48	1st	526 AD with cutting in 527 AD
YMT 1214	4951	3Ic1	K 5–6-7–8-9	−2,77	*Quercus*	Square beam from whole section	y	21 + 1	yposs	56	1st	Not datable so far
YMT 1215	4952	3Ic1	K 5–6-7–8-9	−2,68	*Quercus*	Square beam from half section	y	17	y	75	1st	Possible end date of 527 AD with cutting in 528 AD
YMT 1216	4953	3Ic1	K 5–6-7–8-9	−2,7	*Quercus*	Square beam from half section	n	10 + 1	n	70	1st	possible date of after 526
YMT 1020	4927	3H-b4	K 5–6-7–8	−1,6	*Castanea*	Whole section	n	-	n	26	2nd	Non-oak, short sequence, not datable
YMT 1075	4919	3H-b4	K 5–6-7–8	−1,53	*Castanea*	Whole section	y	-	n	31	2nd	Non-oak, short sequence, not datable
YMT 1077	4920	3H-b4	K 5–6-7–8	−1,62	*Castanea*	Whole section	y	6	n	52	2nd	Non-oak, short sequence, not datable
YMT 1079	4921	3H-b4	K 5–6-7–8	−1,56	*Castanea*	Whole section	y	-	n	40	2nd	Non-oak, short sequence, not datable
YMT 1080	4922	3H-b4	K 5–6-7–8	−1,56	*Castanea*	Whole section	y	-	n	32	2nd	Non-oak, short sequence, not datable
YMT 1081	4923	3I-a3	K 5–6-7–8	−1,56	*Castanea*	Whole section	y	6	n	36	2nd	Non-oak, short sequence, not datable
YMT 1123	4926	3H-b4	K 5–6-7–8	−1,56	*Castanea*	Squared beam from whole section	y	-	n	32	2nd	Non-oak, short sequence, not datable
YMT 1009	4918	3H-d4	K 5–6-7–8	−1,04	*Quercus*	Whole section	y	27 – 29	y	51	3rd	Possible end date of 777 AD with cutting in 778 AD
YMT 1200	4944	2Ib2	K 3	−3,24	*Quercus*	Squared beam from half section	y	16 + 1 partial ring	y	113	1st	End date 581 AD, cutting date late in the growth season of 582 AD
YMT 1201	4945	2Ib2	K 3	−3,24	*Quercus*	Squared beam from half section	y	5 + 3	n	82	1st	Not datable so far

(Continues)

TABLE 1 (Continued)

YMT No.	Dendro code	Profile No.	Area	Depth	Genus	Shape	Pith?	Sapwood Rings	Waney Edge?	Ring Count	Geological Periods	Dendro dates
YMT 1202	4946	2Ib2	K 3	−3,02	*Quercus*	Half section	y	30 + 1 partial ring	y	100	1st	End date 581 AD, cutting date late in the growth season of 582 AD
YMT 1203	4947	2Ib2	K 3	−3,2	*Quercus*	Squared beam from half section	y	13 + 1	y	68	1st	Not datable so far
YMT 1205	4948	2Ja1	K 3	−2,72	*Quercus*	Squared beam from quarter section	y	19 + 1	y	95	1st	End date 581 AD, cutting date late in the growth season of 582 AD

Note. Samples are grouped by area (dock) and by geological periods identified within the area of the respective dock. Shape and species information is included in order to see if grouping reflects the geological periods or dendrochronological dating.

(Baillie & Pilcher, 1973) and the percentage of year-to-year growth trends in common (Fritts, 1976). Where data-sets could be combined, chronologies were built for each of the three areas (K17, K-5–6-7–8, and K3) from which the samples came. These dock chronologies were then cross-matched against pre-existing chronologies from the site and surrounding regions with the aim of assigning a dendrochronological date to each dock.

For each data series of tree-ring measurements, metadata including a unique dendrochronological sample identification code, the sapwood count, the presence or absence of bark, the shape of the sample, the original excavator tag, and the location of the sample according to the excavator's grid plan were recorded.

The posts were oak (*Quercus* spp.). In oak, the most important metadata for precision dating are associated with the outermost growth rings or "sapwood." This is recognizable primarily by a change in color, hardness, and/or decrease in the presence of tyloses in the earlywood vessels. Where the last growth ring is preserved, the year of felling can be determined, and the degree of development of the tree-ring structure can be used to estimate the season in which the tree was cut (Eckstein, 2007). Where the outermost ring is absent (due to deterioration in the burial environment or deliberate removal before use) an accurate estimation of the year of felling is often possible if any identifiable sapwood is present (Hillam, Morgan, & Tyers, 1987; Hughes, Milsom, & Leggett, 1981; Wazny, 1990). This is done by counting the number of sapwood rings present and subtracting this from the average number of sapwood rings calculated for samples from the site. The sapwood average is calculated using samples that include both pith and "waney edge" or the outermost growth ring underneath the bark. This means that the total number of years for which the tree lived is known along with the total number of sapwood rings present. For a multi-species group of oaks in the Aegean region, the median number of sapwood rings in oaks from 75 to 125 years old is $22 + 9/-7$ (Griggs, Kuniholm, Newton, Watkins, & Manning, 2009). Where no sapwood is preserved, it is possible to provide only a terminus post quem, that is the date after which the tree must have been cut.

The stratigraphic deformations associated with each sampled post were carefully examined and recorded. Here, we noted which of the sedimentary units were contemporary with the time that the posts were inserted and which were postdepositional. Determinations were made on the basis of the deformation structure as illustrated in Figures 3a,b.

When a post is inserted into an unconsolidated sediment package, it creates a typical deformation, a kind of drag, as shown in Figure 3a for Dock K-5–6-7–8. Subsequent sedimentation after post emplacement (as shown schematically in Figure 3b) will not be affected by the drag. This allows for a clear distinction between sediments which were in place before the post was inserted and sediments that were laid down afterwards. This disconformity can then be dated (at best) to within a year of when the post was cut, because, as a general rule, posts used for this type of construction were used immediately or not later than one year after the trees were felled. Hence, the layer just below and above the disconformity can be dated with a resolution of ±1 year, assuming no postdepositional truncation of the deformed sediments is evident and that the post in question retained the

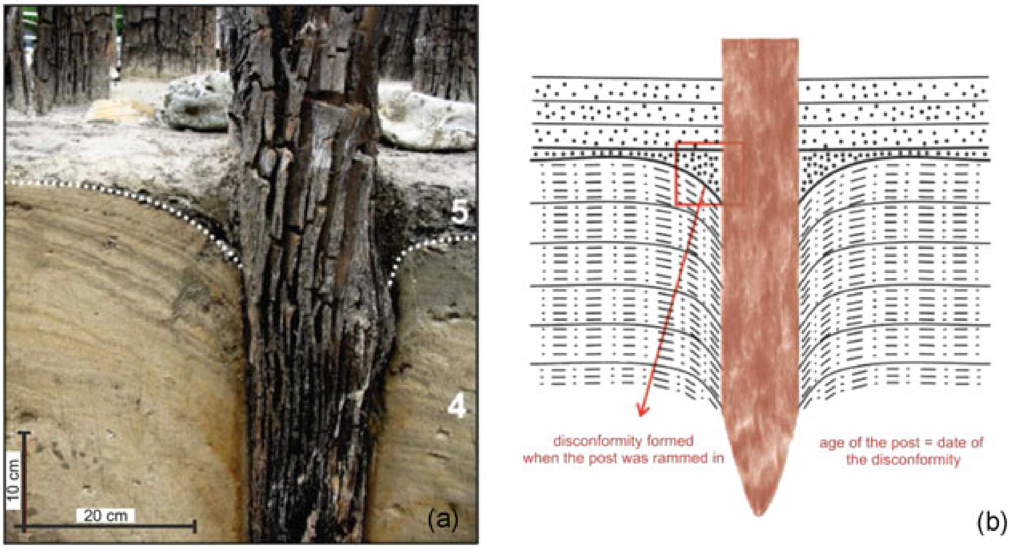

FIGURE 3 (a) Typical deformation caused by wooden posts rammed into the sediments. Notice that units below (older than) unit 5 in this image are deformed. (b) Sketch cross-section of a sedimentary sequence, which was deformed as a post was rammed into it. Notice that a disconformity is created between the deformed sequence and the subsequent sedimentation. The date of the post, as determined by dendrochronology, should be almost equal to the date of the disconformity (age of the top of the deformed unit), as the wooden posts were used immediately (within one year) after the felling of the respective trees. The upper horizontal layers are not deformed and were, therefore, deposited after the post was put in place [Color figure can be viewed at wileyonlinelibrary.com]

outermost ring that was growing when it was cut. In each case, the youngest unit deformed by the post was identified and recorded along with the length of the post. This provided some additional evidence for assigning posts to different periods of sedimentation, particularly when the study was limited to areas disturbed by earlier excavation and some information regarding disconformities was lost. Sedimentary units and associated deformations were recorded according to the following stratigraphic subsequence.

3 | THE HOLOCENE SEQUENCE IN YENIKAPI-ISTANBUL

Previous geological and geoarchaeological studies (Algan et al. 2007; 2009, 2010, 2011; Bony et al., 2011; Perinçek, 2010a, 2010b; Yalçın et al., 2015) unanimously differentiated four basic sedimentary packages at the harbor, namely: a basement composed of a Miocene-aged unit and an Early-Mid Holocene dark-colored swamp deposit; then a marine sequence consisting of mainly sands overlying this basement; then a coarse-grained fluviatile sediment package above the marine deposits; and on the top an artificial fill and agricultural soil of the last centuries (Figure 4).

The Holocene marine and fluviatile packages have been further subdivided by the authors of the previous studies into slightly different additional subunits. In this study, we distinguished nine subunits in this sequence. From bottom to top these are;

1) A basement consisting of the Miocene Güngören formation and Early-Mid Holocene dark gray-black mud that overlies the Miocene partly due to its very limited areal extension along a narrow south-north trending axis (Yalçın et al., 2015).
2) A mixture of gravel and sand with some lenticular shell banks, which have been disconformably deposited on the basement. This unit also consists of large, rectangular flat blocks of Silurian-Devonian limestone and Tertiary Bakırköy formation, the corners of which are well rounded. These blocks are spread out onto the Miocene-aged Güngören formation, but also onto the dark gray-blackish clay as sheet-like deposits (Figure 5a). Their rectangular flat shapes and large sizes suggest that they were originally brought to their present location from a nearby area by Neolithic humans for different purposes such as constructing palisades and reinforcing shelters, built in the wattle and daub technique, rather than transported naturally by waves, currents, and riverine input (Algan et al., 2011).
3) Sediments and blocks of Unit 2 are conformably overlain by beige, coarse, marine sand including abundant shells. In the upper part of Unit 3 the amount of shells decreases remarkably. Hence two subunits (3a and 3b) could be differentiated (Figure 4). These subunits are shell hash at the bottom (3a) and coarse sand with shells above it (3b). Unit 3 has a maximum of 1 m thickness. However, the thickness of the unit decreases towards the north, indicating the typical geometry of a transgressive sequence.
4) Unit 4 is composed of light yellowish middle to coarse sands and includes local small-scale cross-bedding. It also includes very fine silt and clay bands. The rusty red color at the base is a characteristic property of this unit. The thickness of Unit 4 varies from 30–120 cm.
5) Unit 5 displays a chaotic deposition containing numerous broken amphorae and glass, different animal bones, marble fragments,

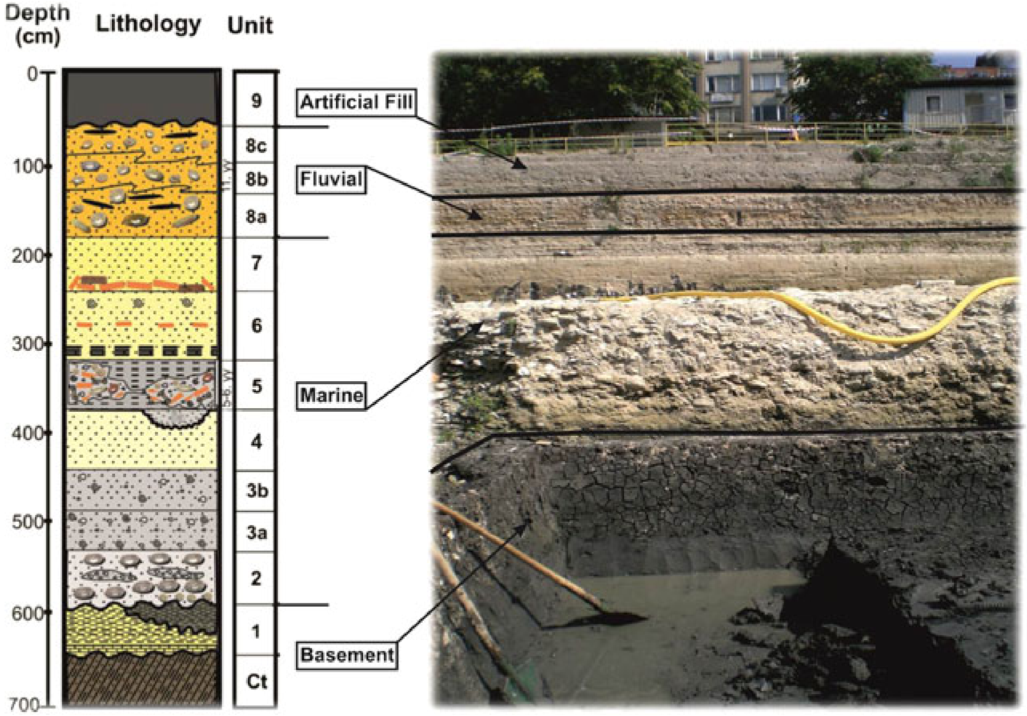

FIGURE 4 Generalized stratigraphic section and view of the sedimentary sequence uncovered in Yenikapı-Istanbul by salvage excavations. (Ct) is the Trakya Formation of Carboniferous age, encountered in deeper bore-holes drilled for engineering geological purposes [Color figure can be viewed at wileyonlinelibrary.com]

stone blocks, and coins in a fine-grained silty matrix. It has an obvious irregular and erosive base. Either the matrix or the underlying Unit 4 is eroded. Unit 5 exhibits a very variable thickness ranging from 10–60 cm. Holes of some removed posts from the docks are also filled in with this chaotic unit (Figure 5b). All these give the impression that Unit 5 was formed by a sudden but very high-energy process, such as a tsunami or a very strong storm or flood, typical of the type of event deposit described by Marriner et al. (2017). Sezerer-Bulut, Yalçın, and Algan (2019) summarized discussions on the origin of this event deposit and came to the conclusion that further studies are required to differentiate between these possible causes. The problematic nature of such deposits is also emphasized by Marriner et al. (2017) as *"These wide-ranging examples underscore the challenges of interpreting the stratigraphic record of high-energy coastal events and demonstrate that careful and detailed multiproxy analyses are important to effectively differentiate between geological archives of storms and tsunamis."*

6) Unit 6 contains dominantly light colored, well-sorted sands and silty clayey bands. It includes shells, both scattered and as discrete layers. The unit thickness changes laterally, ranging between 0.6 and 3.00 m. In the upper parts of Unit 6 and in the lower parts of the overlying Unit 7 more than 20 shipwrecks of different sizes were uncovered (Kocabaş, 2010; Pulak, 2007; Pulak, et al., 2015). Such a great number of sunken ships are explained by a very big storm, when high waves passed over the breakwater, reached the harbor and caused the ships to sink and to be buried under the sands stirred up by the waves. Most of these ships are dated to the 10th–11th century (Algan et al., 2009; Kocabaş, 2010; Perinçek, 2010a; Pulak, 2007). Therefore, this exceptional storm must have happened during the 11th century.

7) Unit 7 is lithologically quite similar to Unit 6. But the lowermost parts of it consist of coarse sands, broken ceramics, rock and marble pebbles, and shells. It continues towards the top with beige-colored fine sands with local cross-bedding. These sands include lateral silt and clay bands. These silty intervals exhibit "seismites", soft deformational sedimentary structures formed by so-called "liquifaction" caused by big earthquakes (Algan et al., 2011; Perinçek, 2010b). The thickness of Unit 7 varies from 40–80 cm.

8) A fluvial sedimentary sequence (8) is found on top of Unit 7 (Figure 4). It has a thickness of about 1 meter and was formed by terrigenous and anthropogenic material carried by the former Lykos River. In this unit several small channels were observed, suggesting the existence of a high-energy fluvial system in the study area. The fluvial unit is subdivided into three subunits, namely 8a, 8b, and 8c. These subunits consist of black, burned organic material between the sandy and pebbly layers at the bottom (8a), pebbly coarse sand above it (8b), and small pebbles on top (8c), also coarse-grained layers containing broken and rounded orange ceramic sherds, fragments of various anthropogenic objects, and shells as food waste.

9) Artificial fill of up to 1 meter thick including an agricultural soil from the Ottoman period and debris from the Byzantine up to the present.

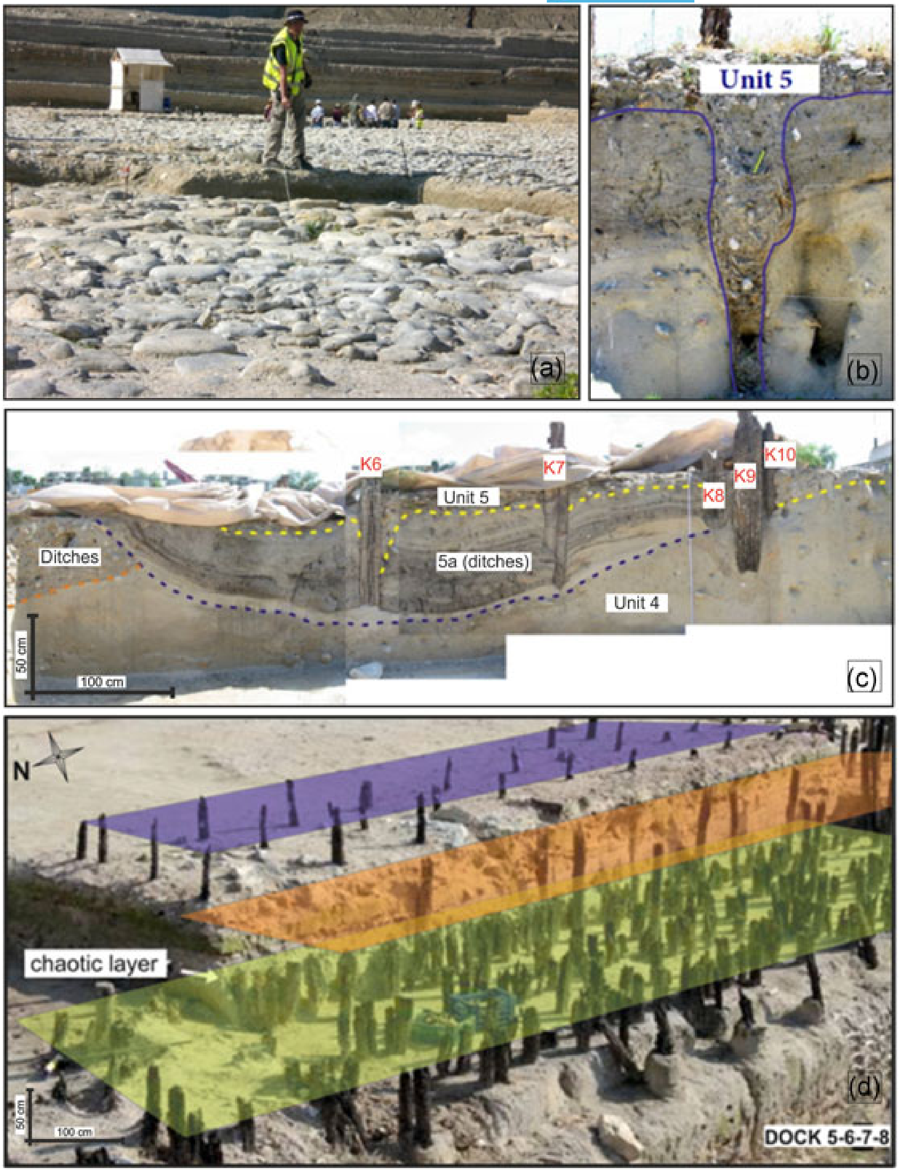

FIGURE 5 (a) Large, well rounded, rectangular flat blocks of Silurian-Devonian limestone and Tertiary Bakırköy formation spread out on the Miocene-aged Güngören formation, but also onto the dark gray-blackish clay as sheet-like deposits. These blocks are found in two intervals that are separated by marine Holocene sands in between. (b) The process that was responsible for the chaotic nature of Unit 5 also resulted in the dislodging of some posts. The holes of such posts are also filled with debris from Unit 5. Hence the dislodging and filling must have been contemporaneous. (c) E-W cross-section of the ditch infilled by well-bedded fine sand and silt (Unit 5a) before the deposition of Unit 5, exhibiting an obvious discordance with sands of Unit 4. (d) General view of Dock K 5–6–7–8 with posts of three different periods. Note that posts of different periods can also be distinguished by the height of their tops [Color figure can be viewed at wileyonlinelibrary.com]

3.1 | Results

3.1.1 | Phases of post emplacement

The stratigraphic sequence for the site was used in assigning "periods" to groups of posts along selected profiles of each dock. The studied dock locations are shown in Figure 2. Profiles S2-A, B, C, D, E; S3-A, B, C, D, E, F and S4-A, and B were investigated across docks K3, K 5–6–7–8, and K 17, respectively. Here, the phases of each dock were distinguished separately and named in sequential order as "first, second, and third period" for each dock.

3.1.2 | Dock K3

In the area of dock K3, the upper part of the sedimentary sequence had already been removed down to Unit 5 when the study was begun. Hence, a sequence consisting of only Units 1–5 was represented. This was further complicated by a ditch or dredging channel, dug out just before the deposition of Unit 5. This ditch was filled with well-bedded fine sand and silt exhibiting an obvious discordance with sands of Unit 4 (Figure 5c). The fill of the ditch was named Unit 5a. To the east of this ditch, another ditch from an earlier period was identified. Both are likely the result of dredging to combat siltation of the harbor.

In total 16 posts from this dock were investigated. Posts K4, K5, K6, K7, K8, K9, and K10 along the east-west profiles S2-A and S2-B, were noted to have deformed the upper parts of Unit 5a, the ditch-fill. The disconformity created is approximately 10 cm below the base of Unit 5 (Figure 5c). After the posts were rammed in, deposition of the upper parts of Unit 5a and of Unit 5 continued. These posts represent the first phase of posts driven into the sediments to form dock K3.

Along the S2-C, S2-D, and S2-E profiles, which were perpendicular to profiles S2-A and S2-B, only Units 4 and 5a were represented. Unit 5a, the ditch-fill, was at the surface of the excavations at the time of sampling for this study. The posts deformed the entire remaining part of Unit 5a, but the disconformity could not be observed, as it had been removed by the excavations before this study. However, comparisons considering the lengths of the posts and the deformed intervals allowed us to conclude that all the posts, except one, belong to the first period.

Post K36 on the S2-D profile is of a different species of tree, chestnut (*Castanea* sp.) and is longer than the others. Similar posts are observed in dock K3 running N-S in three parallel lines. As some of these posts run through the ceramics of the chaotic Unit 5, it is evident that they represent a second period. Consequently, in dock K-3, posts were rammed in in at least two different periods.

3.1.3 | Dock K 5–6–7–8

In the area of dock K 5–6-7–8, we studied 30 posts along six profiles (S3-A, B, C, D, E, and F). In profile S3-A of the dock, the Holocene marine sequence is almost complete. Units from 2 to 7 are represented here. Posts K1, K2, and K3 along profile S3-A produced a disconformity in the upper parts of Unit 6, 5cm below the boundary of Unit 7. The second group of seven posts from profile S3-B, (K20, 21, 22, 23, 24 25, and 26) were also investigated. These posts created disconformities in the upper part of Unit 4 at 20 cm below the boundary of Unit 5, indicating that they are older than the group mentioned above. Chaotic Unit 5 covers both Unit 4 and the posts of this group. Therefore, we hypothesize that here a sudden event (tsunami or flood) damaged and buried an earlier dock. Along the profiles S3-C, S3-D, S3-E, and S3-F the sequence above Unit 4 was excavated before this study. Therefore, only the deformation features created in Unit 4 by posts K27, K28, K29, K32, K43, K44, K45, K46 K47, K48, K49, K50, and K53 could be observed. The disconformity however could not be observed, because it had already been removed as part of the younger units. The tops of these posts, at approximately − 1.20 and − 0.90 m, were above the two other groups (Figure 5D).

Consequently, in the area of Dock K 5–6-7–8 posts were interpreted as having been put in place during three different periods. The oldest of these groups was rammed in towards the end of the deposition of Unit 4, the middle ones just before Unit 7 was deposited, and the youngest ones much later.

3.1.4 | Dock K17

In the area of Dock K17 a sequence composed of Units 2–5 was exposed. Nine posts were sampled from two profiles. Posts K12, K13, K14, K15, K16, and K17 created a disconformity within the upper part of Unit 4, approximately 13 cm below the boundary of Unit 5. This unit again covered both Unit 4 and the posts. As in the case of Dock 5–6-7–8, the event responsible (tsunami or flood) destroyed the pre-existing dock before the deposition of Unit 5. Post K11, on the other hand, deformed the entire existing sequence inclusive of Unit 5. Therefore, this and additional posts from the same group as K11 were put in place much later than the posts of the first period. When exactly these posts were rammed in cannot be defined, as all the younger units, including the disconformity, were removed during archaeological excavations before this study. Deformational features for posts K18 and K19 could not be analyzed, because they were not well developed due to localized coarse sand accumulations that did not retain the deformation structures. The existence of two different periods of post insertion could be clearly determined, however, confirmed by the different levels of the tops of the respective posts.

In total the geological investigation of features created by post emplacement in the Theodosian harbor of Constantinople showed that the posts of the three studied docks were inserted during seven different periods. The stratigraphic equivalents of these periods can be determined as follows:

Period 1: An interval in the upper parts of Unit 4, (Dock K 5–6-7–8).
Period 2: Upper parts of Unit 5a, which is the fill of a dredging channel excavated before the deposition of Unit 5, (Dock K3).
Period 3: The uppermost part of Unit 4, (Dock K17).
Period 4: Could not be determined exactly, but definitely after the deposition of Unit 5, (Dock K3).
Period 5: Could not be determined exactly, but definitely after the deposition of Unit 5, (Dock K17).
Period 6: The upper part of Unit 6, (Dock K 5–6-7–8).
Period 7: Could not be determined exactly, but probably after the deposition of the lower parts of Unit 7, (Dock K 5–6-7–8).

Although the exact stratigraphic position of three periods could not be determined, for the other four periods the stratigraphic equivalents are clear. Dendrochronological analysis of all the posts was then carried out to see if precise calendar dates could be assigned to the periods.

3.2 | Dendrochronological dates

3.2.1 | Dock K3

From Dock K3 five posts were selected for dendrochronological analyses, all representing the first period of this dock. All samples were oak with sapwood present, and four of the samples had the last formed growth-ring under the bark, offering the best potential for an absolute dendrochronological placement. Three of the samples, YMT1200, YMT1202, and YMT1205 produced strong cross-matches with one another. Combined, this group produced a convincing fit (*t* score 10.31 on a 114-year overlap) with material collected and measured in other excavation seasons from other parts of this structure in Area K3 (Metro iskele 3; Figure 6).

This cross-match provides an end date for the sequence in 581 AD, with an additional partial ring showing that the cutting was at or near the end of the summer growing season of the following year (582 AD). The infilled ditch that the posts deform must, therefore, have been dredged and almost completely filled before autumn 582 AD (Table 1).

3.2.2 | Dock K 5–6–7–8

From Dock K 5–6-7–8, 14 posts, representing three different periods were selected for dendrochronological analyses. Unfortunately, a large number had too few tree-rings or were of a species unsuitable for

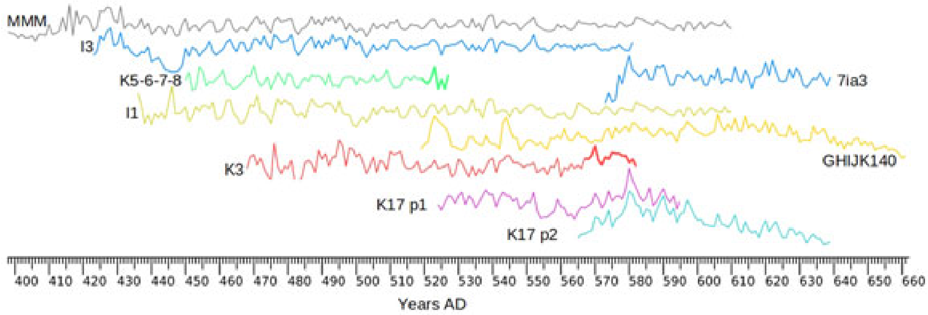

FIGURE 6 Tree growth ring measurements in 1/100 mm (vertical axis) for the combined tree-ring series for K3, K5–6-7–8, and K-17 (groups 1 and 2) against other tree-ring groups from the Yenikapı harbor (with Metro İskele 3 (I3), Metro İskele 1 (I1), Group 7ia3 (7ia3), and Group HIJK140 (HIJK140) and the ADP mid-first Millennium Chronology (MMM) [Color figure can be viewed at wileyonlinelibrary.com]

cross-matching, so only four oak samples could be dated (Table 1). Samples YMT 1210, YMT 1215, YMT 1216, and YMT 1121 from the first time period produced strong cross-matches to form a 75 ring sequence. This small group fits with a *t* score of 5.26 on a 58-year overlap at 527 AD, with Marmaray İskele 1 (Figure 6). These posts deformed the upper part of Unit 4, so logically these sediments should date before 527 AD, representing an earlier phase of Unit 4 than present for dock K3. A fourth sample (YMT 1009) assigned to the third period, has a potential dating placement at 778 AD; however, as this sample has only 51 rings the cutting date offered of 778 AD, cannot be stated with the same certainty as for the other docks.

Samples which were put in place in the third period were squared beams of *Quercus* sp., whereas the posts put in place in the second period were dominantly whole sections of *Castanea* sp. (chestnut). Unfortunately, none of the *Castanea* samples cross-matched with one another, nor do we have an established reference chronology from which to derive dates, so it was not possible to assign a dendrochronological age to the second period. All that can be noted is the fact that the posts deform the upper parts of Unit 6, which has been dated using the C14 data from *Cerastoderma glaucum* shells (Algan et al., 2011) to an age interval ranging from AD 690–900 cal. years (at 68% certainty) and AD 610–1030 cal. years (at 95% certainty).

3.2.3 | Dock K17

From Dock K17, 17 posts representing two time periods, were analyzed. All but one of the samples were *Quercus* sp., and almost all had several sapwood rings present (Table 1). Strong cross-matches were found between six of the samples. Combined, these produced a chronology with two clear construction phases (Figure 6). Samples YMT 1011, YMT 1012 and YMT 1194 make up the first phase. As post YMT 1194 has the terminal growth ring present (Figure 7) we can date the first period to an end date of 593 AD (the last fully measurable ring of the sample), with cutting late in the growth season of 594 AD (the partially formed ring at the waney edge). Samples YMT 1104, YMT 1105, YMT 1143, YMT 1166, and YMT 1168 make up the second phase at 639 (but possibly as late as 647). The combined chronology has a provisional cross-match (*t* score 4.98) with a *terminus post quem* of 639 AD with samples collected in previous excavation years from Metro İskele 3 (Pearson et al., 2012) (Figure 6). The K17 group also cross-matches with a group of samples from YMK areas GHIJ140 (collected in 2009) and YMT area 7Ia3 (collected in 2011) which have been provisionally dated against Marmaray İskele 1 to end in 661 AD. This confirms the placement at 639 AD via a *t* score of 5.28 on a 116-year overlap (Figure 6) and constrains the age of the second phase to 639 AD or very shortly thereafter.

As the first period posts were put in place when the upper part of Unit 4 was being deposited, the implication is that the deposition of Unit 4 began before, and was still occurring in, 594 AD. As the second-period posts were put in place in 639 or slightly thereafter, just after the deposition of Unit 5, the dendrochronological spacing can be used to indicate that it took only 45–55 years to complete the deposition of Unit 4 and for Unit 5 to be deposited.

4 | DISCUSSION

4.1 | Dating of periods

Dendrochronological dating of the posts from different periods in different docks showed that the first period was before 528 AD in dock K 5–6-7–8, with a possible date of 778 AD related to the latest phase of construction of this dock. It was not possible to date the middle period for this group, but a C14 age obtained from Unit 6 supports the possible dendrochronological match at 778 AD. If this was the case a combination of radiocarbon and dendrochronology

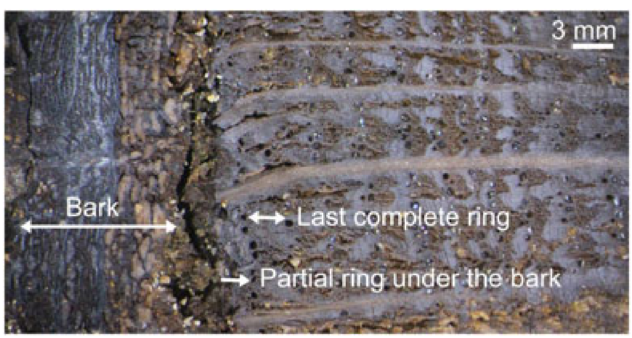

FIGURE 7 The last partially grown ring under the bark of sample YMT 1194 [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Periods of posts in Docks K3, K 5–6–7–8, and K 17 and position of disconformities formed by in-placement of these posts

Docks	K3		K 5–6–7–8		K 17	
Periods	Date	Disconformity	Date	Disconformity	Date	Disconformity
6			778 AD	Probably in Unit 7		
5			690–770 AD[a]	In Unit 6 5 cm below Unit 7		
4	640 AD	After Unit 5			639 AD+0–7 years	After Unit 5
3					594 AD	In Unit 4 13 cm below Unit 5
2	583 AD	In Unit 5a 10 cm below Unit 5				
1			528 AD	In Unit 4 20 cm below Unit 5		

[a]Dendrochronological data were not available. Dates are based on C14 data of Algan et al. (2011) and relative stratigraphy.

could be used to suggest that this period relates to date between 690 and 770 AD (Table 2). At each of the other two docks, two time periods are dated with strong dendrochronological matches (Figure 8). The respective periods are 583 AD and 640 AD in Dock K3, and 594 AD and 639 ± 8 AD in Dock K17 (Figure 8 and Table 2).

It is obvious that the periods at 640 AD and 639 ± 8 AD should be considered as one period. These six dated periods and the position of the disconformities which have been formed by the related posts are shown in Figure 8.

4.2 | Construction, repair, extension of the docks, and other activities in the harbor

Results of this study enabled an interpretation of some construction and repair activities in the harbor and led to some statements about the geoarchaeological implications. The investigated docks are constructed almost perpendicular to the shoreline, that is to the main quay of the harbor (Kuniholm et al., 2014, 2015; Pearson et al., 2012). Considering that the harbor was established at the end of the 4th century, it can be assumed that after approximately 130 years the existing docks along the main quay were insufficient to satisfy the growing demands of the flourishing new capital of the Eastern Roman Empire and additional docks were required. In 528 AD the construction of Dock K 5–6–7–8 was initiated. It seems that this dock met the growing demand for another approximately 50 to 60 years until the end of the 6th century. In 582 AD (Dock K3) and soon after in 594 AD (Dock K17), posts were cut for their construction. So, at the end of the 6th century in this part of the harbor at least three parallel docks were in use. The next period of posts is dated to after 640 AD, when it seems likely that both in Dock 3 and 17 repairs were made related to severe destruction induced by a tsunami or flood event, which was also responsible for the deposition of chaotic Unit 5. The fact that Unit 5 also covers some of the destroyed posts suggests that the respective docks were seriously damaged and put out of use. When exactly this event happened cannot be answered precisely. The archaeological objects found in this unit are from the 5th, 6th, and 7th centuries (Kızıltan, 2010, 2014). This implies that the event must have happened in the 7th century or later. Algan et al. (2011) reported radiocarbon dates based on *Cerastoderma glaucum* and *Paphia aurea* shells from this sedimentary unit as AD 70–350, AD 250–550, AD 260–580, and AD 400–650 (68% certainty). The respective dates at 95% certainty are AD 100–490, AD 100–660, AD 90–700, and AD 230–740, again the youngest materials representing the 7th century. Perinçek (2010b) presented a C14 date based on a piece of wood from this unit as calibrated years AD 420–570 (95% certainty). He also argued that this chaotic unit represents the impact of a tsunami caused by the famous earthquake dated to AD 557. However, our data, dated by a systematic study of sediment deformation in combination with dendrochronology indicates that this proposed date is too early, in agreement with the more recent radiocarbon evidence (Algan et al., 2011). The geological and dendrochronological investigations conducted in this study allow us to narrow down the possible dates for Unit 5. Namely, the uppermost part of the underlying Unit 4 (10 cm below the boundary with Unit 5), is dated to AD 594 by dendrochronology. Accordingly, deposition of Unit 4 must have ended later, most probably during the first one or two decades of the 7th century. Considering that the uppermost part of Unit 4 was also eroded by the event, the respective depositional period would have been even longer. Furthermore, posts of docks K3 and K17 rammed in after the deposition of Unit 5 is dated to soon after AD 640. In K17 the repair phase is dated to sometime after 639 AD, with the outer edge of the sample missing, but 23 sapwood rings allow us to estimate a felling date for the repair of 639 AD or slightly later. Considering that the deposition of Unit 4 may have continued until 610 or 620 AD and the date of the posts that have been used for the repair of the docks is 640 AD as a terminus post quem, the date of the tsunami or flood event can be narrowed down to a period between 620 and 639 (or fewer) years AD.

Docks K17 and K3 appear to have been seriously damaged by this event and repairs were necessary within five or fewer years of 640 AD.

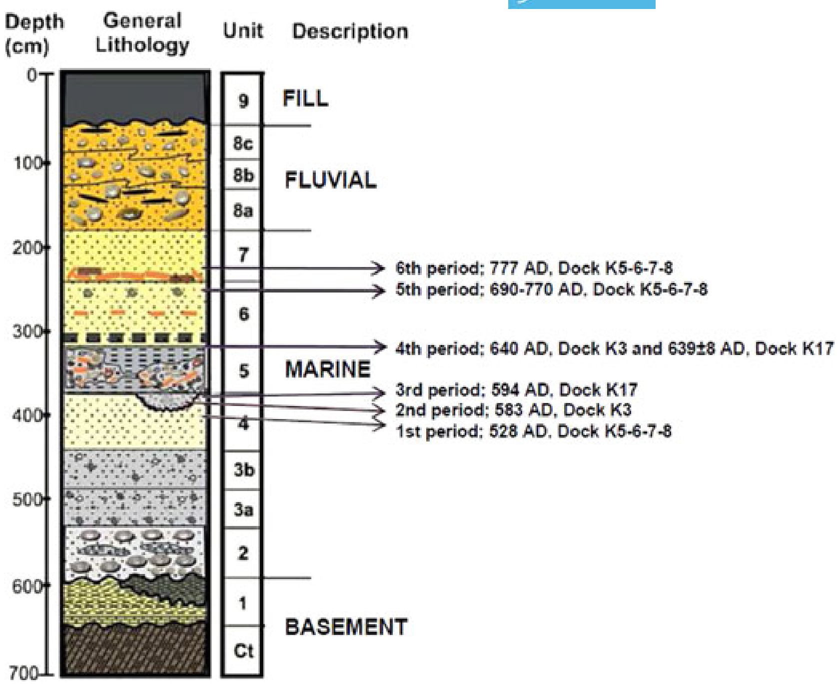

FIGURE 8 Position of equivalent stratigraphic intervals of six periods according to the results of dendrochronology. The positions of periods 4 and 6 are not indicated by a disconformity because the respective units had already been excavated before this study [Color figure can be viewed at wileyonlinelibrary.com]

At Dock K 5–6-7–8 we do not find evidence for repairs at this date. However, this repair phase might be represented by the currently undatable *Castanea* sp. samples. The next repair period here is dated to not earlier than 690 AD. A final repair activity is observed in Dock K 5–6-7–8 indicated by posts provisionally dated to after 778 AD.

The ditch feature uncovered during archaeological excavations in the area of dock K3 can also be further investigated using our approach. This ditch was dug out perpendicular to the dock, and its long axis, heading E-W, was approximately 6 m long. Its other axis is much shorter. The ditch is within Unit 4 and was dug out probably shortly before the deposition of Unit 5. It is filled with well-bedded, gray colored silt and sand, which appears from the shape of the fill which mimics the geometry of the ditch (Figure 5c), to have been deposited rapidly. The first time period represented for this dock is a disconformity within the ditch-fill, 5 cm below the boundary of Unit 5. The respective posts are dated dendrochronologically to 583 AD. Hence, the ditch definitely predates 583 AD. Considering that Unit 4 is represented almost in its original thickness at both margins of the ditch, we can assume that it was dug relatively close to this date. The question of why cannot be answered with certainty, but dredging to remove excess silt is likely. However, as also indicated by another smaller older ditch to the east of this ditch (Figure 5c), such depressions were filled very rapidly and this approach at this time was less than successful.

5 | SEDIMENTATION RATES

It was possible to date certain stratigraphic layers very precisely during this study, presenting opportunities to calculate more specific rates of sedimentation. For two levels of Unit 4, with a 7 cm space between them, ages of AD 528 and 594 have been determined. Hence, during c.66 years a 7 cm thick sand layer was deposited (assuming no removal by erosion). This corresponds to a sedimentation rate of 0.11 cm/year. This is a relatively high rate compared with rates of deposition in a coastal environment (Hong et al., 1997; Zuo, Eisma, & Berger, 1991; Zuo, Eisma, Gieles, & Beks, 1997). As these two dates mark the construction periods of docks K 5–6-7–8 and K 17, it can be inferred that siltation of the harbor had already started at that time, because material transported from the Lykos River was preferably deposited in the harbor which was protected by a breakwater (Kızıltan, 2014).

For the level of Unit 7 just above the interval consisting of coarse sands, broken ceramics, rock and marble pebbles, and shells an age of after AD 778 is indicated by dendrochronology. For the upper parts of Unit 4 an age of AD 528, was determined. Considering an average thickness of two meters for the interval between these levels a sedimentation rate of 0.8 cm/year can be roughly calculated. This very high rate can be explained by the very intensive use of the harbor during this period, by the increasing amount of anthropogenic and natural material transported by the Lykos River and particularly by sand, which was brought into the harbor by storm waves.

Enhanced sedimentation rates during the Greco-Roman and Byzantine periods have also been reported from many other Mediterranean ancient ports. For example, rates such as 1.0 cm/yr in Tyre (Marriner & Morhange, 2006), 2.2 cm/yr in Marseilles (Morhange et al., 2003), 1.0–4.0 cm/yr in Ostia (Rome) (Goiran et al., 2010), and 1.0 cm/yr in Sidon (Marriner, Morhange, & Doumet-Serhal, 2006; Marriner, Morhange, Doumet-Serhal, & Carbonel, 2006) are in accordance with the rate of 0.8 cm/yr calculated for a 2 m thick interval, deposited during a period from 528 to 778 AD in the Theodosian harbor.

6 | CONCLUSIONS

The results obtained in this multidisciplinary study in the ancient Theodosian harbor in Istanbul and their interpretations have led to the following conclusions:

- A novel approach has been developed to establish a high-resolution stratigraphy for Holocene sequences in complex sedimentary environments such as harbors, where suitable and sufficient wooden posts are available for dendrochronological dating.
- This approach can be used to also provide high-resolution reconstructions of sedimentation history in coastal terrains.
- Sedimentary evidence of historical events and/or processes can be reconstructed with an unusually high dating accuracy offering better defined periods in which to search written records for evidence of anthropogenic activities such as dredging or natural events, such as earthquakes, tsunamis, storms, or floods.
- Dendrochronology in combination with sedimentary interpretation has enabled the definition of the construction, repair, and extension periods of three docks in the Theodosian Harbor of Yenikapı-İstanbul. The docks were constructed c. AD 528, 582 and 594. All of these docks were repaired and/or extended at some time after AD 639, 778 and again at a time between 690 and 770 AD, which could not be determined dendrochronologically.
- Periods of construction, repair, and extension coincide with the 6th to 8th century time frame during which the harbor is known to have flourished.

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