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THE 1ST MILLENNIUM AD MEDITERRANEAN SHIPBUILDING TRANSITION AT DOR/TANTURA LAGOON, ISRAEL: DATING THE DOR 2001/1 SHIPWRECK

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ABSTRACT. During the 1st millennium AD, a fundamental set of changes in ship design, building methods, and sequence of construction took place in the Mediterranean. This process is known as the "Transition in Construction." Before the Transition, ship hull design was based longitudinally on the ship's strakes ("shell-first"). By about the mid-1st millennium AD, the concept and construction of ship hulls had changed and were based on the ship's frames ("frame-based"). The Transition was a complex, nonlinear evolution. High-precision dating of the construction and service period of ships built during the 1st millennium is essential for elucidating the Transition process. Such dating precision is possible using radiocarbon wiggle-matching and Bayesian analysis techniques. The following study uses these techniques to determine the construction, launch, and final voyage (wrecking) dates of Dor 2001/1, a Byzantine shipwreck from northern Israel that was built based on frames. The results indicate that Dor 2001/1 was likely constructed and launched in the first third of the 6th century AD and was wrecked no later than AD 540. This is one of the earliest frame-based ships found in the Mediterranean so far. Dor 2001/1 is therefore an important shipwreck in understanding the Transition, since it provides evidence that frame-based hulls were already being built by the mid-1st millennium AD, about 500 yr earlier than has been commonly accepted.

INTRODUCTION

The 1st millennium AD was a key period of change in shipbuilding in the Mediterranean and northern Europe. This process is known as the "Transition in Construction" (Pomey et al. 2012). It involved basic changes in ship design, building methods, and construction sequence. Previously, ship hulls were based on strips of planking ("strakes") oriented lengthwise. Ship planks (the "shell") were constructed before frames, which were installed later and connected to the pre-existing shell. Hull strength was based on mortise-and-tenon edge-jointed planking ("shell-first"). After the Transition, hull design was transversely oriented and based on frames ("frame-based"). Frames were installed before planks, which were nailed to the frames, and hull strength was based on frames nailed to the ship keel (Pomey et al. 2012).

Frame-based hulls were generally smaller, wasted less wood, used lower-quality wood and metal fasteners, and required less labor than earlier shell-first hulls. Consequently, frame-based hulls were cheaper to build, and easier to construct and to repair and maintain. However frame-based hulls were less strong and durable than shell-first hulls, so their development also represented deterioration in ship construction quality. Nevertheless, frame-based ships could carry cargoes efficiently and apparently were profitable. This move towards less costly construction methods may possibly be explained by social and mainly economic stresses. These resulted from the complex political, economic, and social changes around the Mediterranean and Europe in the mid-late 1st millennium AD, including the end of Roman supremacy, Byzantine economic decline, Islamic conquests, and possibly also the influences of invaders to the western Mediterranean (van Doornick 1972:134, 139; 1976:130; 1982:139–40; Kreutz 1976; Casson 1990; Steffy 1995; McCormick 2001).

Until recently, it was commonly accepted that the earliest known frame-based ship to have been constructed was the Serçe Limanı "Glass Wreck" from the 11th century AD (Steffy 1982; 1994:83–91; 2004:155–62; McGrail 2008:624). However, the recent excavation and analysis of several new

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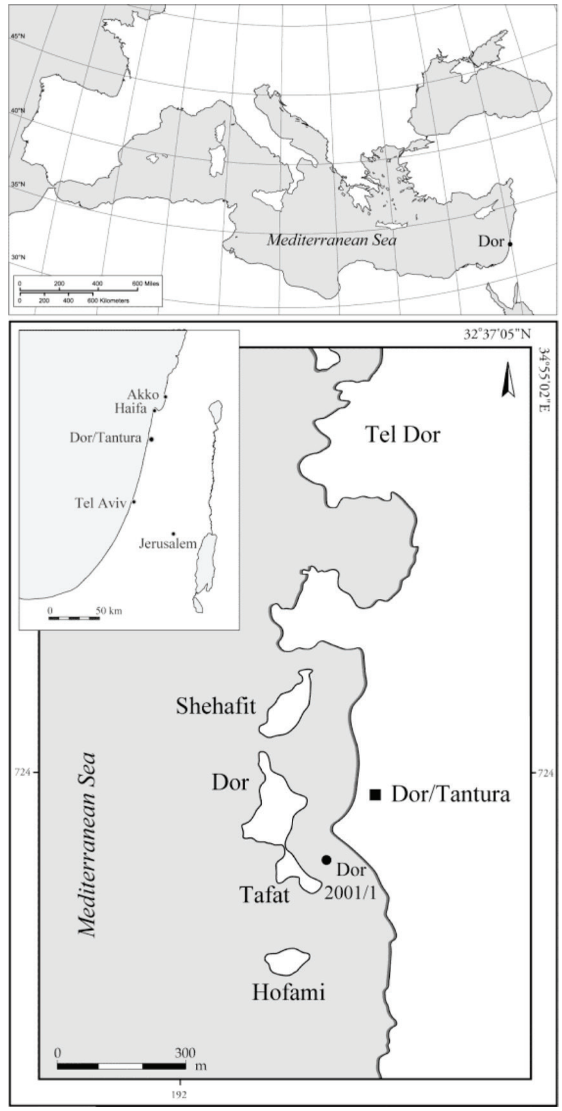

Figure 1 Map showing Dor/Tantura Lagoon's location in the eastern Mediterranean and along Israel's northern coast, and the Dor 2001/1 shipwreck's location in the lagoon (map: N Yoselevich, H Itzcovich).

1st millennium AD shipwrecks—including a group of wrecks from Dor/Tantura Lagoon in northern Israel—demonstrates that the Mediterranean shipbuilding Transition took place at an earlier date (Kahanov 2011a,b; Pomey et al. 2012). Pomey et al.'s (2012) detailed analysis of 1st millennium AD shipwrecks and their construction further suggests that the Transition in the Mediterranean was not a linear evolution. Instead, the Transition was a more complex process, which occurred at different rates throughout different locations in the Mediterranean, and multiple shipbuilding traditions were occasionally used side-by-side.

A precise chronological framework detailing when 1st millennium AD shipwrecks were built and used is essential for understanding fully the timing, process, and (consequently) causes of the Transition. Radiocarbon wiggle-matching and Bayesian chronological modeling offer a means of determining when ships were constructed and used more precisely than either single accelerator mass spectrometry (AMS) ^{14}C dates or typological dates derived from cargo, equipment, or finds. We present here the results of a study in which we use ^{14}C wiggle-matching and a Bayesian analytical model to estimate the dates of construction, launch, last voyage/wrecking, and service period of the Dor 2001/1 shipwreck from Dor/Tantura Lagoon. Our results provide some of the first high-precision dates for the construction and service period of an East Mediterranean shipwreck dating to the 1st millennium AD. This work is the first in a series of studies in which we are using a combination of dendrochronology, ^{14}C wiggle-matching, and Bayesian analytical methods to date 1st millennium shipwrecks from Dor/Tantura and elsewhere in the East Mediterranean, in order to improve our knowledge of the development of ship construction during this dynamic period.

THE DOR 2001/1 SHIPWRECK

The Dor 2001/1 shipwreck is located ~70 m offshore in the Dor/Tantura Lagoon, next to the lagoon's navigation channel, under 1.5 m of water and 1.5 m of sand (Figure 1). It was excavated over five seasons from 2002–2006 by the Leon Recanati Institute for Maritime Studies at the University of Haifa. The shipwreck was oriented roughly northwest/southeast; the total length of the find was 11.5 m, and its maximum width was 4.5 m (Figure 2). Dor 2001/1 was likely a Byzantine coaster, about 16.9 m long and 5.4 m maximum width. The hull of Dor 2001/1 was a frame-based construction. This is clearly demonstrated by several of the ship's construction features: frames nailed to the keel; planks nailed to the frames by small iron nails; garboards not connected to the keel; plank butt joints attached with nails at frame stations; seam caulking; and no planking edge-fasteners (Pomey et al. 2012; Kahanov and Mor 2014). The 96 building stones found as part of the cargo in the shipwreck suggest that Dor 2001/1 was transporting the material for a construction project somewhere along the coast. A complete description of the ship components and finds is given elsewhere (Kahanov and Mor 2014).

The shipwreck site lacked ceramic assemblages from a secure context or finds (such as coins) that might estimate the date of the ship's construction and period of use (Kahanov and Mor 2014). Preliminary single-sample ^{14}C dates of wood fragments and organic materials from the shipwreck indicated that the ship was built during the early to mid-1st millennium AD (about AD 250–610) (Mor and Kahanov 2006). Since Dor 2001/1 was potentially one of the earliest frame-based shipwrecks found in the Mediterranean and therefore a critical vessel for understanding the timing of the Transition, it was chosen as the first shipwreck from Dor/Tantura Lagoon to be analyzed using high-precision ^{14}C wiggle-matching and Bayesian analytical dating methods.

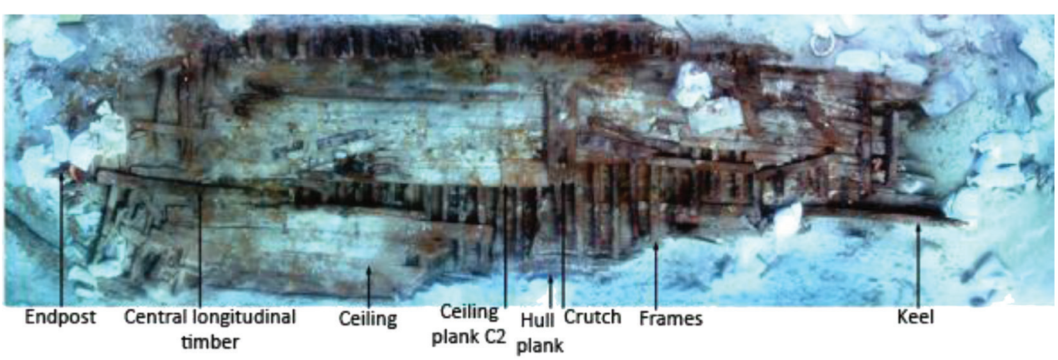

Figure 2 Top view of the hull remains of Dor 2001/1 after the ship's cargo was removed. The hull components, including ceiling plank C2 (which was sampled for the ^{14}C wiggle-match), are labeled (photo: S Breitstein).

SAMPLING AND METHODS

We used a Bayesian analytical model in OxCal v 4.2.3 (Bronk Ramsey 1995, 2009a), in order to estimate the date ranges of the ship's construction, initial voyage (launch date), final voyage (wrecking date), and service period. This model incorporates the following two data sets: (i) a set of ^{14}C dates on wood samples from the ship timbers; and (ii) a set of ^{14}C dates on short-lived sample materials (rope and matting) that were part of the ship cargo or equipment and in use on Dor 2001/1 at the time of its wrecking (Table 1). The model compares all available ^{14}C data against the IntCal13 ^{14}C calibration curve (Reimer et al. 2013) with curve resolution set at 5 yr. Bronk Ramsey's (2009b) General Outlier model is used to evaluate ^{14}C data agreement within the model.

Table 1 Samples and ^{14}C data employed in this study. The sequence of timber samples used in the ^{14}C wiggle-match is recorded in terms of an arbitrary relative sequence beginning with ring 1001.

Lab ID	Sample name	Sample material	Start ring	End ring	$\delta^{13}C$ (‰)	^{14}C age (yr BP)	SD
OxA-19435	DTL-7	Wood	1007	1016	−23.57	1695	28
OxA-19469	DTL-7	Wood	1017	1026	−23.91	1642	23
OxA-19470	DTL-7	Wood	1047	1056	−23.42	1567	27
OxA-19471	DTL-7	Wood	1067	1076	−22.92	1616	24
OxA-19472	DTL-7	Wood	1087	1096	−23.10	1626	25
OxA-19436	DTL-7	Wood	1107	1116	−23.43	1591	28
OxA-19710	DTL-7	Wood	1117	1126	−23.06	1638	28
RT-4254	Initial survey	Wood			−27.8	1680	60
RT-4255	Initial survey	Wood			−23.7	1620	50
RT-4256	Initial survey	Wood			−26.5	1650	60
RT-4610	G74-2002/1000	Wood			−24.8	1520	35
ETH-25381	Initial survey	Wood			−25.8	1680	50
ETH-28109	G48-2003/2011	Bark			−28.3	1590	45
ETH-31268	G55-2005/4006	Bark			−23.8	1590	45
ETH-26367	G74-2002/1006	Matting			−17.7	1625	45
ETH-28110	G48-2003/2010a	Rope			−14.6	1665	40
ETH-29913	G64-2004/3015	Rope			−26.7	1450	40
OxA-28737	G64-2004/3015	Rope			−26.6	1606	28
OxA-28834	G64-2004/3015	Rope			−26.4	1592	24

Modeling the Ship Construction and Launch Dates

The Dor 2001/1 ship timbers were first analyzed for potential dendrochronological dating to provide a precise *terminus post quem* for the ship's construction and estimated launch date. Unfortunately, many of the timbers are species that are unsuitable for dendrochronology or have short tree-ring sequences (<50–100 rings) that cannot be dendrochronologically crossdated securely. Additionally, many of the ship timbers are either *Pinus halepensis* Mill. or *Pinus brutia* Ten. (these two species cannot be differentiated by wood anatomy alone) (Schweingruber 1990; Lev-Yadun 2000), and East Mediterranean dendrochronological reference chronologies for these species currently do not extend back to the 1st millennium AD. Since the timbers could not be dated dendrochronologically, the ship's construction and launch dates were estimated using ^{14}C dates from (i) ^{14}C wiggle-matching of a tree-ring sequence from one of the ship timbers; (ii) a set of ^{14}C dates on fragments of other ship timbers; and (iii) two ^{14}C dates on bark samples that had been preserved on the ship timbers (Table 1).

A ceiling plank (plank C2 in the excavations; labeled DTL-7 here) was selected for ^{14}C wiggle-matching (Bayliss and Tyers 2004; Bronk Ramsey et al. 2001; Galimberti et al. 2004). This sample is of *Pinus halepensis*/*brutia* and is the longest tree-ring sequence (131 rings) of the analyzed ship timbers. Seven decadal-length segments, whose relative position to one another on the sample is known from exact ring counts, were dissected. Decadal, rather than subdecadal, sections were chosen for wiggle-matching, because the timber was cut from a slow-growing tree with narrow ring growth. Thus, taking decadal sections allowed sufficient amounts of wood to be sampled for dating while gaining adequate dating precision against a calibration curve that was also developed largely from ^{14}C measurements of decadal tree-ring sections and then modeled at 5-yr intervals (Reimer et al. 2013).

The samples from DTL-7 were sent to the Oxford Radiocarbon Laboratory (OxA) for analysis. All but one of the sampled sections underwent acid-base-acid-bleach pretreatment, following the Oxford pretreatment protocol for wood and peat remains (Brock et al. 2010). Since pitch was adhered to the outer edge of the plank, sample OxA-19710 (which contained the outermost rings of the DTL-7 sequence) underwent additional solvent treatment to remove resins prior to the acid-base-acid-bleach pretreatment. The series of AMS ^{14}C dates from DTL-7 was wiggle-matched in OxCal (Bronk Ramsey 1995, 2009a; Bronk Ramsey et al. 2001) and compared against the IntCal13 calibration curve (Reimer et al. 2013). Each ^{14}C date was treated as dating the center-point of the dated rings (e.g. the date for rings 1007–1016 is treated as ring 1011.5). Since bark and vascular cambium are not preserved on sample DTL-7, the date of the sample's last extant ring from the wiggle-match provides a *terminus post quem* for when the timber was cut and for the ship's launch.

The dated fragments of wood and bark from other ship timbers were sampled during an initial survey of the shipwreck and during excavations. AMS and conventional ^{14}C dates were obtained for the samples from the Institute of Particle Physics (ETH) in Zurich and the Weizmann Institute of Science (RT) in Rehovot. Standard acid-base-acid-bleach pretreatments (similar to those used at Oxford) were used at both ETH and RT to isolate and date the cellulose portion of the wood samples. The relative sequence of tree rings from the wood fragments in relationship to one another and to the wiggle-matched DTL-7 sequence is not known, so these dates are treated as independent sequences within a Phase "All Dor 2001/Wood" in the OxCal model. These wood samples were generally taken from the outer edges of the ship timbers. While the ^{14}C data set includes some older (earlier) dates taken from wood towards the center of the tree(s), most of the sampled wood is from tree rings toward the outer edge of the tree(s), which provides younger (more recent) dates that are closer to when the timbers were cut. Therefore, the ^{14}C dates of this set of wood fragments are modeled as an exponential distribution, using a Tau_Boundary paired with a Boundary in OxCal. An alternative model, in which these dates are treated as a Uniform Phase in OxCal, was also run, and the results from both models are compared below.

The dates for the final ring of the DTL-7 wiggle-match and the Boundary "EndWood" placed after the wood fragment dates in our model both set a *terminus post quem* (Boundary "Bark TPQ") for the dates on the bark samples. Since the dates on the bark samples should be very similar (given that the ship timbers were likely cut around the same time), the two bark ^{14}C dates are combined (R_Combine in OxCal) to obtain a weighted average value for the bark date. The averaged bark date should date the felling of the ship timbers and give a very close *terminus post quem* date range for the ship's construction and launch. However, there was likely a short period of time between when the timbers were felled and the ship's launch, during which the timbers would have been seasoned (typically a period of 1–2 yr) and the vessel constructed and fitted. Therefore, our model also allows for an interval of 2 ± 1 yr (or a normal distribution of 0–4 yr at 95.4% probability) after the timber felling date determined from the bark in order to calculate Dor 2001/1's estimated launch date.

Modeling the Final Voyage/Wrecking Date and Service Period

The date of Dor 2001/1's last voyage was estimated using a set of AMS ^{14}C dates on the ship's finds (Table 1). Three dated samples (one on matting and two on rope) were obtained from ETH; all three samples underwent acid-base-acid pretreatment. The matting is made from woven broad leaves and stems in the Poaceae family (Kahanov and Mor 2014); the preservation of fibers in the matting is too poor for their exact genus or species to be identified. Dates were obtained from two pieces of rope (G48-2003/2010a and G64-2004/3015). One date each on ropes G48-2003/2010a and G64-2004/3015 was obtained from ETH, and two dates were obtained on G64-2004/3015 from OxA. The ropes are made predominantly from woven sedge fibers (*Cyperus* sp.), as well as palm leaves (*Phoenix dactylifera* L.), and bast fibers from an unknown tree species (Stephen Harris, personal communication, 2013).

Preliminary analysis of the rope and matting dates from ETH showed that there was an approximate 200-yr offset in the ^{14}C age from rope sample G64-2004/3015 and the other short-/shorter-lived materials from the ship, and that the G64-2004/3015 rope's $\delta^{13}C$ ratio (which matches the isotopic signature of a C_3 plant) differed from that of the other rope, G48-2003/2010a (whose isotopic signature matches that of a C_4 plant). Since there were concerns of sample contamination from resins on the rope, two additional samples were taken from G64-2004/3015 and submitted for botanical analysis at the Oxford University Herbaria and dating at the Oxford Radiocarbon Accelerator Unit (OxA dates). Pitch or other resins were not detected on the rope samples submitted to Oxford; therefore, both rope samples underwent acid-base-acid pretreatment (pretreatment lab code "VV" in Brock et al. 2010).

The dates on the rope and matting should provide ages from the ship's period of use and likely do not predate the approximate date of the ship's construction. The rope and matting would likely have had a short period of use on Dor 2001/1 (estimates of use spanning a few years at most are likely), so it is assumed that these samples date to a period of time close to the ship's final voyage date. The dates on the short-lived rope are not combined, even in the case of the rope sample G64-2004/3015 (from which there are three different dates), since the rope is made from several different fibers of multiple plant species. Therefore, in our model, the rope and matting dates are placed in the same phase ("Contents Ship Last Voyage") with an exponential distribution (Tau_Boundary in OxCal) towards the end of this phase.

It is conceivable that some of the rope or matting could predate the launch date boundary described above (albeit by a very short period of time), but it is unlikely that these materials predate the felling of the ship timbers and the time of the ship's construction. Thus, the initial Tau_Boundary was modeled conservatively as the modeled date for the weighted average date from the ship timber bark. The end boundary for this phase can be considered the best estimate for the date of Dor 2001/1's last voyage or wrecking date. Since the rope and matting samples were likely used for only a few years, we placed an additional time constraint on the exponential distribution of the ship's final use phase. This constraint allows a uniformly distributed period of up to 20 yr (Tau&=U(0,20)) on the time constant associated with the exponential distribution in the model (referred to here as "Model 20"). An alternative model was run employing a time constant of up to 10 yr ("Model 10"), allowing for a shorter period of use for the rope and matting.

For all models, the ship's estimated service period was calculated by subtracting the distribution of the estimated launch date (LD) from that of the estimated last voyage/wrecking date (LV), using the Difference command in OxCal.

RESULTS

The ^{14}C ages and modeled calendar placements for the wood and short-lived samples from the initial dating model ("Model 20") are shown in Figure 3 and in terms of their fit with the IntCal13 calibration curve (Reimer et al. 2013) in Figure 4. The calculated dates for the last extant ring of the DTL-7 wiggle-match, Dor 2001/1's ship construction date, estimated launch date, last voyage/wrecking date, and service period employing Model 20 and Model 10 (which has a time constant

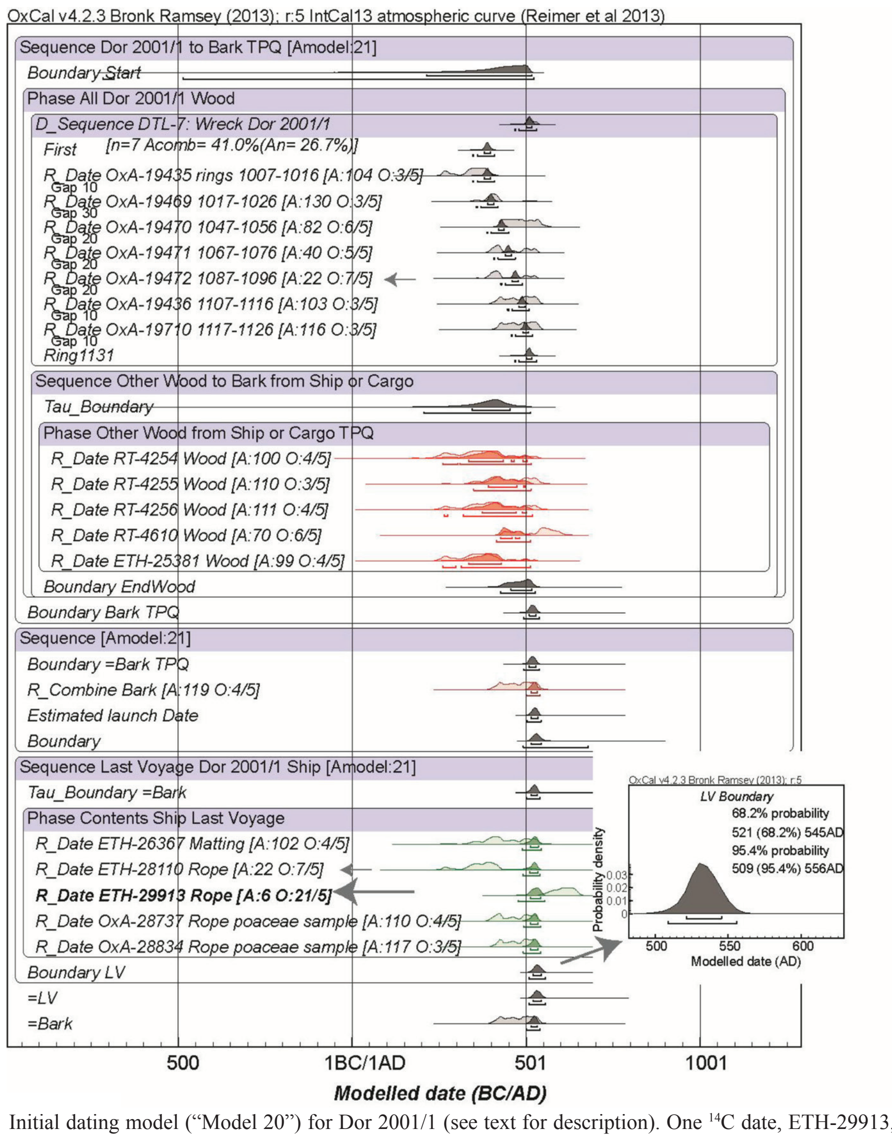

Figure 3 Initial dating model ("Model 20") for Dor 2001/1 (see text for description). One ^{14}C date, ETH-29913, is a clear outlier (indicated with large arrow) applying Bronk Ramsey's (2009b) General Outlier Model. The next two largest (but minor) outliers (OxA-19472 and ETH-28110, indicated by small arrows) are removed for Models 20b and 10b. The solid dark histograms are the modeled calendar probability distributions (with the 68.2% and 95.4% ranges indicated); the light hollow histograms show the original non-modeled calendar probabilities. The OxCal individual agreement index values (A) and the posterior/prior value for the General Outlier Model (O) are also shown. Each model run is slightly different; the results shown here are typical date ranges produced from multiple model runs. The probability distribution of the modeled Last Voyage calendar date range (inset) is also shown.

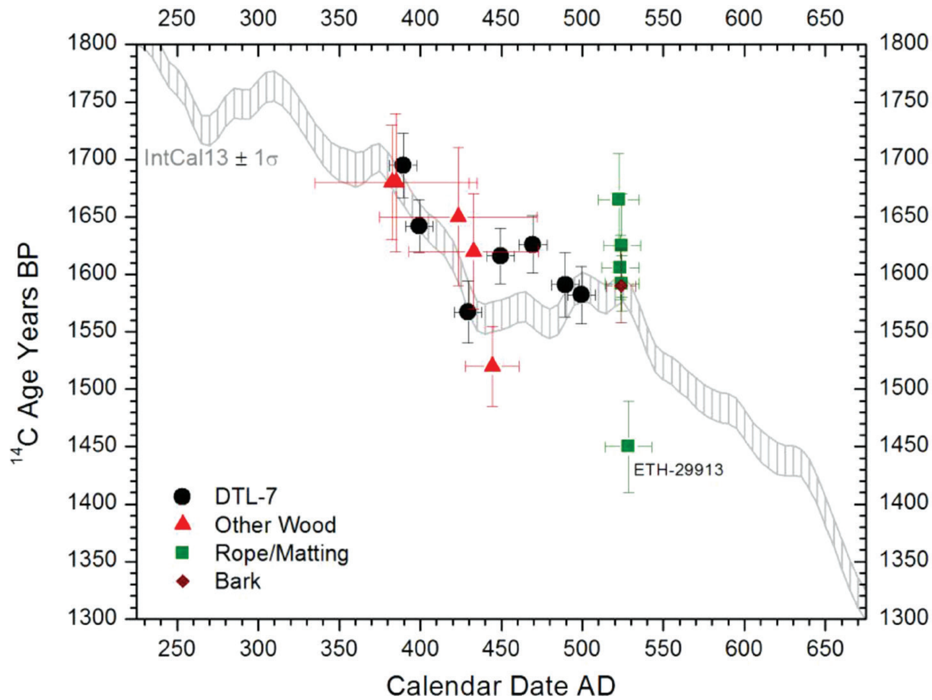

Figure 4 The initial dating model ("Model 20") for Dor 2001/1 showing the ^{14}C data from Figure 3 in terms of the IntCal13 (Reimer et al. 2013) calibration curve (see text for description and Table 1 for the non-modeled ^{14}C dates and sample descriptions). The ^{14}C data are shown as the midpoint of the modeled calibrated date ranges (± the error range at 68.2% probability, or the main part thereof if two ranges were produced) on the *x* axis (calendar years), and as the ^{14}C age BP (± the error range at 68.2% probability) on the *y* axis (^{14}C years). The data set includes one clear outlier (ETH-29913), which is a dated rope sample from the ship's rigging.

of 0–10 yr) are given in Table 2. The dates calculated employing a Uniform Phase model for the wooden fragments (i.e. those not used in the wiggle-match) are given in Table 3.

Although there is some noise or variability in the data, all of the ^{14}C dates used in the initial model fit with reasonable association against the IntCal13 curve, except for that of ETH-29913, which is one of the dates from rope G64-2004/3015. The ETH-29913 date is significantly different from the other three rope dates and is flagged as the one very clear outlier by Bronk Ramsey's (2009b) General Outlier Model in Model 20 (Figure 3), with Posterior v. Prior of 21 v. 5. The next two largest outliers by contrast are OxA-19472 and ETH-28110, which are only minor outliers with Posterior v. Prior of 7 v. 5.

While no pitch or resins were found on the samples of rope G64-2004/3015 dated at Oxford, it is still possible that the rope sample dated at ETH did contain such resins, resulting in the aberrant ETH-29913 date. The isotopic signatures of all of the samples from rope G64-2004/3015 (which are consistent with the $\delta^{13}C$ of a C_3 plant) differ from those of the other rope, G48-2003/2010a (whose $\delta^{13}C$ is within the range of a C_4 plant). However, the measured isotopic signatures for rope G64-2004/3015 remain consistent over multiple measurements in two different laboratories and so appear robust. Of the taxa identified in the G64-2004/3015 rope fibers, palm (*Phoenix dactylifera*) and some species in the *Cyperus* genus are C_3 plants (Bruhl and Wilson 2007), and it is possible that the fibers of the other rope (G48-2003/2010a) included different, C_4 *Cyperus* or other plant species, which would account for the differing $\delta^{13}C$ values in the rope.

Table 2 Modeled calendar dates (cal AD) for the DTL-7 wiggle-match and Dor 2001/1's estimated construction, launch date (LD), last voyage (LV), and service period at 68.2% and 95.4% probability. The ship's service period is estimated as the difference between the LV and the LD in calendar years; calculated negative numbers have been rounded up to 0. The results of the following different models are shown: Model 20 (all data with a time constant of 0–20 yr); Model 20a (excluding ETH-29913, time constant 0–20 yr) and Model 10a (excluding ETH-29913, time constant 0–10 yr); and Model 10b and Model 20b, which revise Models 10a and 20a to exclude the next two largest typical minor outliers (OxA-19742 and ETH-28110 , whose posterior v. prior values in the General Outlier Model are only 7 to 5) to produce an analysis with no outliers and A_{model} and $A_{overall}$ values >60. OxCal agreement values ("A_{model}" and "$A_{overall}$") are also listed for each model. Different model runs produce slightly different date ranges (usually varying by zero to a couple of years); the dates shown here represent typical values produced from several model runs. Our preferred model (Model 10a) is highlighted in bold.

	Model_20, A_{model} = 21 $A_{overall}$ = 25.6		Model_20a, A_{model} = 46.4 $A_{overall}$ = 49.1		Model_10a, A_{model} = 47.6 $A_{overall}$ = 49.9		Model_20b, A_{model} = 95.1 $A_{overall}$ = 96.4		Model_10b, A_{model} = 97.4 $A_{overall}$ = 98.2	
	68.2% cal AD	95.4% cal AD	68.2% cal AD	95.4% cal AD	68.2% cal AD	95.4% cal AD	68.2% cal AD	95.4% cal AD	68.2% cal AD	95.4% cal AD
DTL-7 last extant ring RY1131	501–518	468–470 (0.5%) 480–530 (94.9%)	501–517	479–526	**501–517**	**479–527**	503–519	484–527	503–519	485–528
Estimated construction	515–533	501–541	513–530	500–535	**515–530**	**500–535**	515–531	503–539	516–532	505–538
Estimated launch date (LD)	516–535	503–544	516–531	504–537	**517–532**	**504–538**	517–533	504–540	517–534	505–540
Estimated last voyage date (LV)	521–545	509–556	520–538	507–546	**519–535**	**505–540**	521–540	509–550	521–536	508–544
Approximate service period (yr)	3–6	0–19	0–11	0–18	**0–6**	**0–13**	0–11	0–18	0–6	0–13

Table 3 Modeled calendar dates (cal AD) for the DTL-7 wiggle-match and Dor 2001/1's estimated construction, launch, last voyage, and service period at 68.2% and 95.4% probability. All models consider the ^{14}C dates of the non-wiggle-matched wood fragments as part of a Uniform Phase (see text for description). The results of the following different models are shown: Model_20U (all data with a time constant of 0–20 yr); Model_20Ua (excluding ETH-29913, time constant 0–20 yr); and Model_10Ua (excluding ETH-29913, time constant 0–10 yr). OxCal agreement values ("A_{model}" and "$A_{overall}$") are also listed for each model. Different model runs produce slightly different date ranges (usually varying by zero to a couple of years); the dates shown here represent typical values produced from several model runs.

	Model_20U, A_{model} = 16.2 $A_{overall}$ = 16.3		Model_20Ua, A_{model} = 36.2 $A_{overall}$ = 32.9		Model_10Ua, A_{model} = 37.1 $A_{overall}$ = 33.6	
	68.2% cal AD	95.4% cal AD	68.2% cal AD	95.4% cal AD	68.2% cal AD	95.4% cal AD
DTL-7 last extant ring	501–518	485–530	501–516	487–528	501–517	485–528
Estimated construction	514–531	500–540	512–528	501–535	512–530	500–535
Estimated launch date (LD)	514–534	504–541	513–530	504–536	515–531	503–536
Estimated last voyage date (LV)	520–544	508–554	520–537	506–545	517–535	504–540
Approximate service period (yr)	2–16	0–19	0–11	0–18	0–6	0–13

If sample ETH-29913 is excluded from the data set and Models 10 and 20 are rerun (as Models 10a and 20a), this produces the date ranges shown in Table 2. If we compare these results with those shown in Table 3 ("Models 20U, 10U, 20Ua, and 10Ua," in which the non-wiggle-matched wood fragments are modeled as a Uniform Phase), there is very little difference in the calculated date ranges. Models 20a and 10a still have OxCal A_{model} and $A_{overall}$ values less than the satisfactory level of 60. If the next two largest outliers are also removed (OxA-19472 and ETH-28110), the resulting Models 20b and 10b produce the date ranges shown in Table 2, and the sequences now have no outliers and satisfactory OxCal A_{model} and $A_{overall}$ values. The exclusion of the minor outliers makes little difference versus the original all-data model. Based on the different models employed, at 95.4% probability, construction on Dor 2001/1 may have begun as early as AD 500 or as late as AD 541. In all of the modeled scenarios (Tables 2 and 3), the ship's launch would have occurred no earlier than AD 503 and no later than AD 544 at 95.4% probability. The ship's final voyage/wrecking date likewise could be as early as AD 505, but no later than AD 556 at 95.4% probability. Dor 2001/1's estimated service time between its initial launch and wrecking date was at maximum 19 yr (95.4% probability), with its earliest wrecking date (i.e. shortest service time) on the ship's maiden voyage.

Our preferred model is Model 10a, since the model's 0–10 yr constraint on the time constant for the period of rope and matting usage is most plausible. This model also excludes the ^{14}C data set's clear outlier (ETH-29913) but includes the remaining possible outliers, which are all very minor and vary among several different model runs. Using the preferred model, Dor 2001/1 was likely constructed around AD 500–535, launched around AD 504–538, and its final voyage/wrecking occurred around AD 505–540, with a service period of 0–13 yr (all date ranges at 95.4% probability). Even if the Time Constant constraint is removed from Model 10a, the ship's calculated service period remains a relatively short 0–28 yr at 68.2% probability. (Without the Time Constant constraint, the 95.4% probability range for the ship's service period extends, of course, much later, and irrelevantly, given the exponential distribution created by the Tau_Boundary and no subsequent events in the dating model.)

DISCUSSION

The ship's construction and launch during the first third of the 6th century AD means that Dor 2001/1 is one of the two oldest frame-based shipwrecks found in the Mediterranean so far. The other early frame-based shipwreck is Tantura A (also located in the Dor/Tantura Lagoon), which dates to the late 5th to early 6th century AD, based on typological dates from the ship's ceramic assemblage and single-sample ^{14}C dates on the hull timbers (Carmi and Segal 1995:12; Wachsmann and Kahanov 1997:6; Kahanov et al. 2004:113, 124–6). Dor 2001/1 predates another frame-based shipwreck, Tantura F, by at least a century (Barkai et al. 2010). Its construction precedes that of the traditionally accepted first frame-based hull exemplified by the Serçe Limanı shipwreck by ~500 yr (Steffy 1994:83–5). Dor 2001/1 therefore establishes a construction tradition in the eastern Mediterranean of hulls built on frames, both in concept and process (Pomey et al. 2012). Its hull construction demonstrates an innovative building technique in the Mediterranean and thus warrants special attention.

Dor 2001/1 was likely in service for a relatively short period of time (0–6 yr at 68.2% probability and 0–13 yr at 95.4% probability, using our preferred model). Possible (although inconclusive) evidence of repairs to the ship's keel, endpost, and planking were identified, suggesting that the ship was not wrecked on its maiden voyage (Kahanov and Mor 2014). Thus, we estimate that the ship's service period is likely toward the higher end of the calculated distribution.

It is clear from our results that Dor 2001/1 is an important vessel in studying the Transition in Construction in shipbuilding in the Mediterranean. Dor 2001/1's hull provides evidence that Mediterranean shipbuilders were already using frame-based construction concepts, techniques, and sequences by the mid-1st millennium AD. The Bayesian dating model employed here provides more precise dates for ship construction and use than the non-modeled ^{14}C dates and ceramic typologies used previously to study other Mediterranean shipwrecks from the 1st millennium AD. Expanding on this research by using similar modeling techniques and (when possible) dendrochronology will provide a detailed chronology for comparing when 1st millennium AD Mediterranean shipwrecks were built and used. Such work will greatly enhance our understanding of the Mediterranean shipbuilding Transition and allow this process to be placed within the context of concurrent sociopolitical, economic, and paleoenvironmental changes in the region.

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