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FULL PAPER

A RE-EVALUATION OF THE USE OF MAXIMUM MOISTURE CONTENT DATA FOR ASSESSING THE CONDITION OF WATERLOGGED ARCHAEOLOGICAL WOOD

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Maximum moisture content (U_{max}) "profiles" were produced throughout cut cross-sections of waterlogged archaeological oak, poplar and pine timbers, and the distribution of values compared to visible degradation patterns. Attempts were then made to classify the degree of degradation in each timber. Where appropriate, comparisons were made with the established classification scheme of de Jong (1977), for waterlogged archaeological oak. Numerical classification schemes were investigated after statistically analysing U_{max} data ranges for each of the three species.

Moisture content profiles from all timber sections reflected visible degradation patterns, supporting the use of U_{max} data as an indicator of preservation state. Incorporating numerical data in to a classification system presented potential problems, as large ranges of values were common within individual timbers. Numerical schemes were suggested however, by incorporating two ranges of U_{max} values, which separate well preserved and degraded regions respectively. U_{max} ranges were unique to the individual species studied and a generalised scheme was not possible. A generic classification system based on visual appearance or physical examination is proposed, by modifying de Jong's scheme for European oak, which compares relative proportions of well preserved versus degraded material. Collectively, results provide reference data for assessing similar timbers, where large destructive samples cannot be taken.

1 Introduction

The design of an appropriate conservation treatment for a waterlogged archaeological wooden object will be dictated largely by its state of preservation. An accurate condition assessment is a crucial first step for conservators, who may employ a number of analytical techniques. Chemical analyses,[1-3] examination of wood microstructure[4,5] and measurement of physical and mechanical properties[3,6-10] have all

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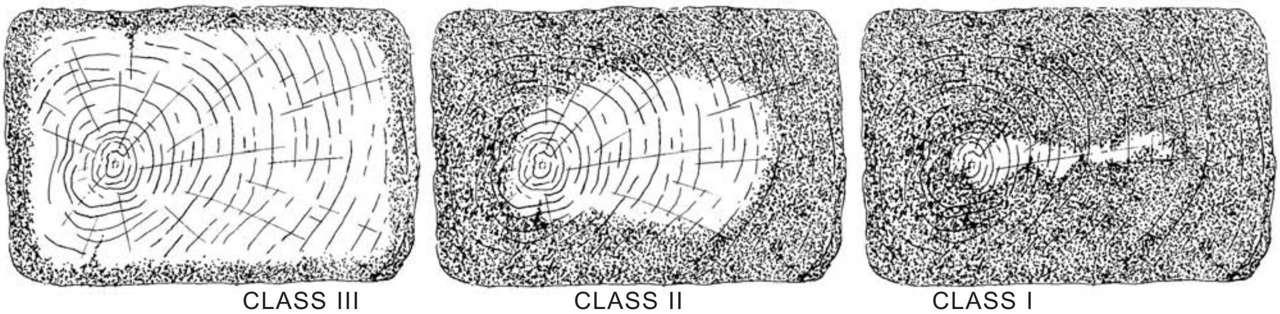


Figure 1: De Jong's classification for the degree of degradation of European oak. Adapted from ref. 18. CLASS III - "Wood containing <185% water". Sound core beneath a thin deteriorated layer. CLASS II – "Wood containing 185 - 400% water". Comparatively small core present. CLASS I – "Wood containing >400% water". Highly degraded wood predominates.

been shown to be useful indicators of the preservation state of waterlogged wooden objects.

One simple and routinely employed technique is the determination of moisture content. Values rise in line with increases in the porosity of the wood cell wall, resulting from microbiological degradation[11-13] and to a lesser extent from physicochemical processes[14-16] before and / or during burial. Hoffmann[1] stressed the importance of using maximum, rather than actual moisture content measurements. By initially placing submerged samples cyclically under partial vacuum, any trapped air is expelled. This ensures a maximum moisture content reading is obtained, that reflects the full extent of the voids that have resulted from degradation.

Waterlogged archaeological timbers often display visibly distinct regions of differently degraded material in cross-section. In decayed, high moisture content areas, wood is physically softer and appears darker, with less distinct surface details. Conversely, well preserved areas are physically sound, usually lighter in colour and macrostructures such as growth rings remain clearly visible. The distribution of differently degraded regions was used by Christensen[17] to develop a classification system, based on the oak timbers of a Viking wreck from Roskilde Fjord, Denmark. De Jong[18] later developed this scheme for European oak (Figure 1), which has become widely adopted by conservators. Valuable archaeological material can rarely be destructively sampled to reveal internal degradation patterns. Instead, conservators typically assess timbers by extracting small diameter core samples, probing with needles and measuring the moisture content of fragments.

In this study, several oak timbers from the Tudor warship *Mary Rose*[19,20] are destructively sampled to reveal their internal degradation patterns in cross-section. These are described and visually compared to measured U_{max} distributions throughout each cut timber slice. Statistical distributions of U_{max} values are also examined, in an attempt to provide a numerical classification scheme that relates to a visual or physical assessment of degradation patterns. Similar data is examined for a selection of poplar and pine timbers from the *Mary Rose*, to assess how degradation patterns, U_{max} ranges and potential classification schemes might vary for timbers of other species. The aim is to produce reference data describing typical degradation patterns and U_{max} ranges for the three species, which can then be used to aid the assessment of similar timbers, where destructive sampling is not possible.

Timber description	Ref. Code	Visual appearance of timber cross-section
Oak "Deck Beam"	Oak 1	Very thin decayed outer layer and large sound core
Oak "Half-Beam"	Oak 2	Thin decayed outer layer and large sound core
Oak "Half-beam"	Oak 3	Very thin decayed outer layer and large sound core
Poplar "Half-Beam"	Poplar 1	Sound pockets surrounded by highly degraded area
Poplar "Half-Beam"	Poplar 2	Small sound pockets, large highly degraded areas
Poplar "Half-Beam"	Poplar 3	Thin decayed outer layer surrounding large sound core
Pine "Half-Beam"	Pine 1	Thin decayed outer layer and large sound core
Pine "Half-Beam"	Pine 2	Thin decayed outer layer and a large sound core
Pine "Half-Beam"	Pine 3	Very thin decayed outer layer and large sound core

Table 1: Timbers used as source material.

2 Materials and Methods

Source material for investigations comprised oak (*Quercus robur* L. or *Quercus petraea* (Matt.) Liebl.), poplar (*Populus tremula* L. or *Populus nigra* L.) and Scots pine (*Pinus sylvestris* L.) timbers from the Tudor warship *Mary Rose*. Species identifications were confirmed microscopically using the keys of Schweingruber[21] and Hather.[22]

Initial tests compared actual moisture content values to maximum (U_{max}) values. Six, 2cm × 2cm × 2cm samples were cut from homogeneously degraded regions of each source timber (Table 1), three of which were immersed in water and placed cyclically under partial vacuum to expel any trapped air. The moisture content of all six samples was then determined by the oven dry method as described below. Negligible differences were found between actual and maximum moisture content values, indicating timbers were fully waterlogged. All subsequent measurements were therefore made without first placing samples under vacuum and all figures given should be considered maximum values.

To illustrate U_{max} distributions throughout individual timbers, profiles were produced from one centimeter thick "slices", cut transversely from timbers using a band saw. Each slice was further cut to produce approximate 1cm × 1cm × 1cm cubes (Figure 2). For each of these, a note was made of its visible physical state (well preserved or degraded) and its maximum moisture content determined.

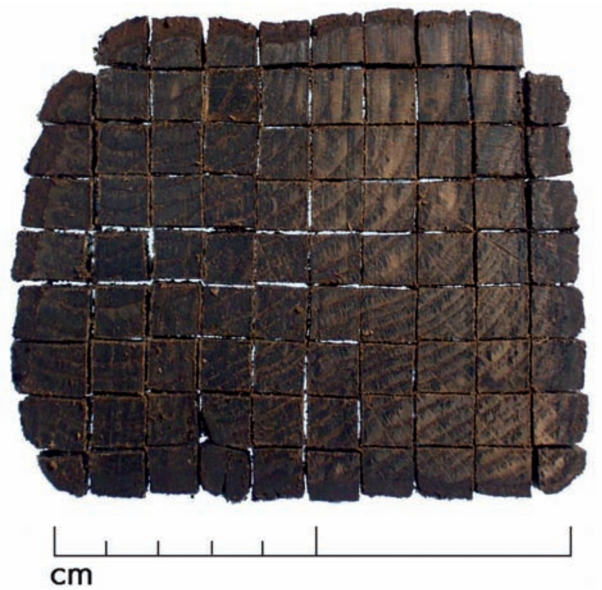


Figure 2: Timber section after cutting to produce individual 1 cm cubes.

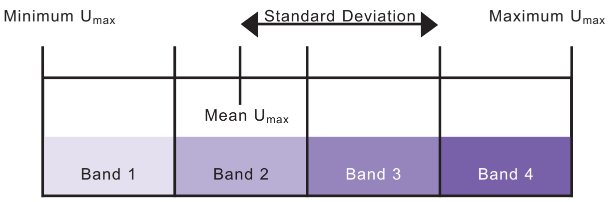


Figure 3: Arbitrary method used to divide the total range of moisture content values for each species into four "bands".

Cubes were numbered and weighed in the waterlogged state using a digital balance accurate to 0.001 g, then placed in an oven at 103 ± 2 °C for 48 h and reweighed. Maximum moisture content values were calculated using the following equation:[23]

$$U_{max}\% = ((W_{wet} - W_{dry}) / W_{dry})\ 100\%$$

where, W_{wet} = weight of fully waterlogged sample and W_{dry} = weight of sample after complete desiccation.

Calculated U_{max} values were plotted on a two-dimensional representation of each slice to illustrate their distribution. Collective data ranges for all three timber slices of each species were arbitrarily divided into four bands (Figure 3), which were used to colour-code the profiles.

Average maximum moisture content values were also calculated for six 2cm × 2cm × 2cm replicates of modern samples of oak (*Quercus robur* L.), poplar (*Populus alba* L.) and pine (*Pinus sylvestris* L.) heartwood, which were artificially waterlogged under vacuum, to allow direct comparisons.

3 Results and Discussion

3.1 Oak

All oak timber sections showed degradation patterns corresponding to class III of de Jong's scheme (Figure 1), in general agreement with previous studies of the hull's timbers.[8,24,25] Values within the inner cores were close to that obtained for modern waterlogged oak (Table 2). High moisture content values were concentrated in outer, visibly degraded regions, as reflected in the moisture content profiles of each slice (Table 3).

Application of de Jong's classification using maximum moisture content values highlighted a potential problem. Using mean data for each slice (Table 2), as de Jong would have intended, did give classifications consistent with the visual aspect of his scheme (Class III, <185% moisture content). The success of this method however, relies on the use of just one, average moisture content value, for the whole timber slice or sample. Contradictory results might be seen where only small samples are available for destructive testing, as is often the case. This is evident in the ranges of individual values for the oak slices reported here (Table 2), which cover two of the classes defined by de Jong's scheme (Figure 1). An improved numerical scheme would ideally incorporate two different moisture content ranges, representing well preserved and degraded areas of timbers respectively. By studying the statistical distribution of values within the slices studied here, it might be possible to identify ranges of data that can be used to form such a scheme.

	Oak 1 U_{max}	Oak 2 U_{max}	Oak 3 U_{max}	Combined data
Minimum	74	72	77	72
Maximum	209	365	303	365
Mean	97	118	127	108
S.D.	26	49	39	38
Variance	658	2434	1513	1416
Moisture content profile "bands" calculated from combined data and Fig. 3				
Band 1	<96			
Band 2	96 - 121			
Band 3	122 - 146			
Band 4	>146			

Table 2: Statistical data and moisture content profile bands for oak slices. U_{max} obtained for modern waterlogged European oak (*Quercus robur* L.) = 102%. S.D. = standard deviation.

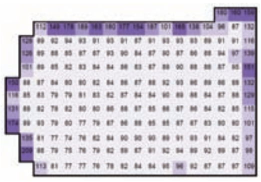
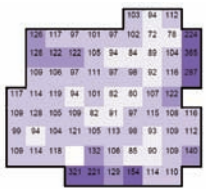
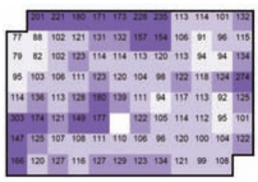
	Timber section	Moisture content profile
Oak 1		
Oak 2		
Oak 3		

Table 3: Oak timber slices and their corresponding moisture content profiles.

Degree of Degradation	U_{max}
Well preserved	≤150%
Degraded	>150%

Table 4: Proposed classification scheme for oak.

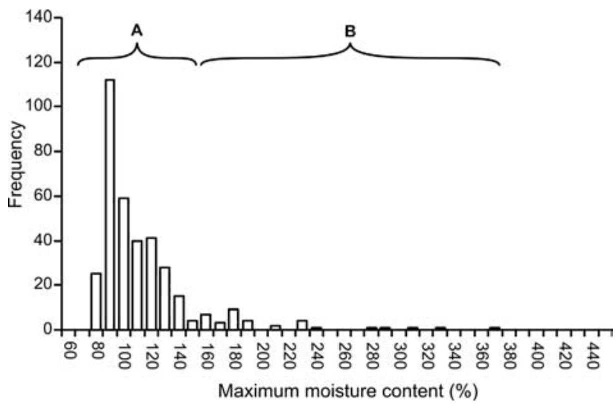


Figure 4: Histogram showing distribution of collective maximum moisture content data for all oak timber slices studied.

Collective moisture content data from all three oak timber slices are presented as a histogram in Figure 4. Most values fall within a narrow range (70% to 150%), and were derived from the large sound cores of the sections (Band A). A second, less well defined population with higher range (151% to 365%), is made up of data from degraded outer layers (Band B). A potential classification scheme based on these data ranges is given in Table 4.

3.2 Poplar

Mary Rose poplar timber slices (Table 1) revealed considerable variation in their moisture content values (Table 5) and visible degradation patterns (Table 6). Timber "Poplar 3" was best preserved, with a large sound core where U_{max} values were generally close to that obtained for modern waterlogged poplar (Table 5).Timbers "Poplar 1" and "Poplar 2" both showed small irregular pockets of well preserved material, surrounded by larger, highly degraded areas. Again, visible degradation patterns of all slices were reflected in their moisture content profiles (Table 6).

Clearly a different classification scheme is required for these timbers, though de Jong's system provides a convenient basis for this. His system is easily modified to compare relative proportions of well preserved material versus highly degraded, as given below :

Class A – Well preserved material dominates.
Class B – Roughly equal proportions of well preserved and highly degraded material.
Class C – Highly degraded material dominates.

This would classify timber "Poplar 3" as class A and timbers "Poplar 1" and "Poplar 2" as Class C (Table 6). Squirrell and Clarke [8] present data for a core sample taken from timber "Poplar 2" (*Mary*

Rose timber number MR81T353) in general agreement with this assessment.

Collective moisture content data are presented as a histogram in Figure 5. Even in well preserved areas, values are dramatically higher than seen for denser oak timbers, and clearly a separate classification system is required based on these data. Though less distinct than was seen for oak, two broad data groups are visible that might be used to form a basic classification scheme, as given in Table 7.

	Poplar 1 U_{max}	Poplar 2 U_{max}	Poplar 3 U_{max}	Combined data
Minimum	378	170	100	100
Maximum	988	1162	817	1162
Mean	777	689	304	563
S.D.	137	263	161	258
Variance	18799	69026	25853	66712
Moisture content profile "bands" calculated from combined data and Fig. 3				
Band 1	<477			
Band 2	447 - 648			
Band 3	649 - 821			
Band 4	>821			

Table 5: Statistical data and moisture content profile bands for poplar slices. U_{max} obtained for modern waterlogged poplar (*Populus alba* L.) = 254%. S.D. = standard deviation.

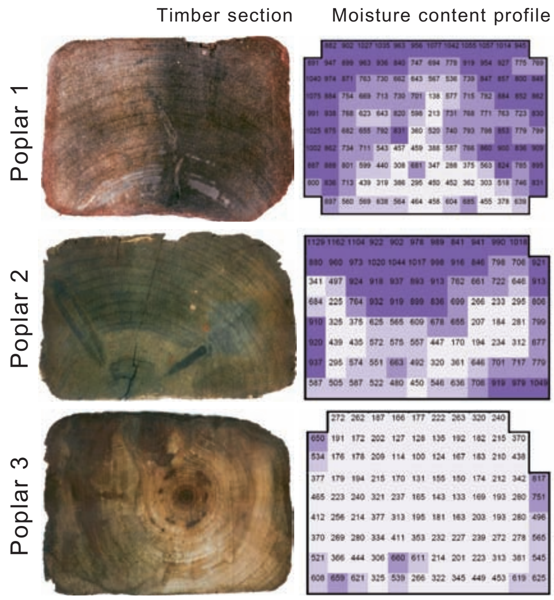


Table 6: Poplar timber slices and their corresponding moisture content profiles.

Degree of Degradation	U_{max}
Well preserved	≤400%
Degraded	>400%

Table 7: Proposed classification scheme for poplar.

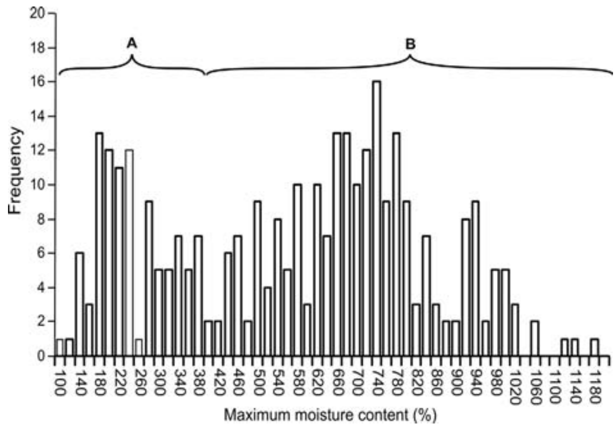


Figure 5: Histogram showing distribution of collective maximum moisture content data for all poplar timber slices studied.

Band A (160% to 400% moisture content) is made up of data from the sound "pockets" of timbers "Poplar 1" and "Poplar 2" and the sound core of "Poplar 3". Band B (401% to 1180% moisture content) was derived from highly degraded areas.

3.3 Pine

Of the three *Mary Rose* pine timbers, "Pine 3" was best preserved, with a very thin outer decayed layer and large sound core. U_{max} values were generally close to that of modern waterlogged pine (Table 8). Timbers "Pine 1" and "Pine 2" also showed large well preserved cores, though had thicker decayed outer layers (Table 9).

Use of the visual component of de Jong's classification might be attempted for these timber sections, though outer decayed layers were noticeably less uniform than given in his scheme (Figure 1). Again, visible degradation patterns throughout each slice were reflected in their moisture content profiles (Table 9).

	Pine 1 U_{max}	Pine 2 U_{max}	Pine 3 U_{max}	Combined data
Minimum	196	153	94	94
Maximum	670	485	221	670
Mean	322	262	156	244
S.D.	135	105	23	120
Variance	18358	10951	546	14470
Moisture content profile "bands" calculated from combined data and Fig. 3				
Band 1	<204			
Band 2	204 - 283			
Band 3	284 - 364			
Band 4	>364			

Table 8: Statistical data and moisture content profile bands for pine slices. U_{max} obtained for modern waterlogged pine (*Pinus silvestris* L.) = 178% . S.D. = standard deviation.

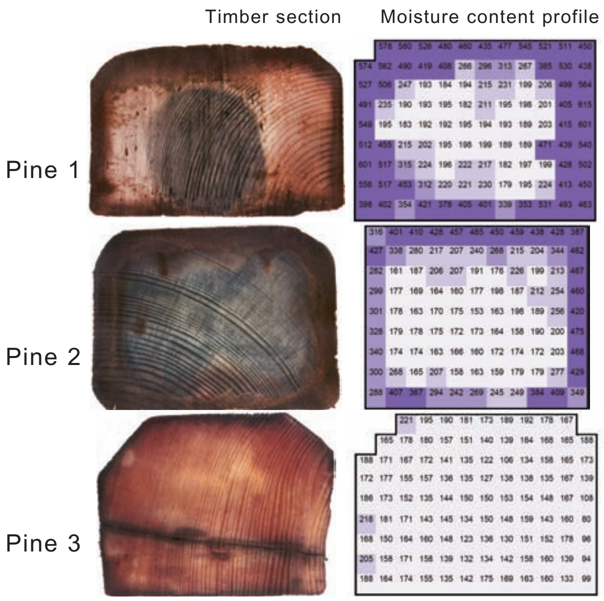


Table 9: Pine timber slices and their corresponding moisture content profiles.

Degree of Degradation	U_{max}
Well preserved	≤250%
Degraded	>250%

Table 10: Proposed scheme for Scots pine.

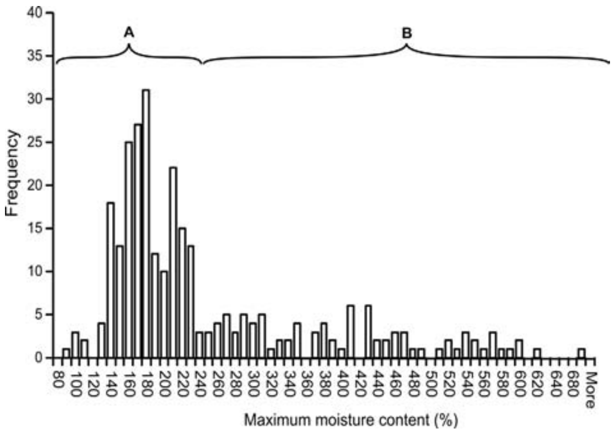


Figure 6: Histogram showing distribution of collective maximum moisture content data for all pine timber slices studied.

In Figure 6, showing collective data for the pine timber slices, the limits of populations representing well preserved and degraded regions respectively are again not as well defined as seen for oak. Two broad populations are visible however, the first derived from the sound cores (Band A, 94% to 250% moisture content) and the second from the degraded outer zones (Band B, 251% to 670% moisture content), as given in Table 10.

4 Conclusions

Moisture content profiles from all timber slices reflected visible degradation patterns, supporting the use of U_{max} data as an indicator of preservation state. Incorporating measured values in to a classification system requires care however, particularly if only small samples are available for destructive testing. The problem arises from the fact that very different states of degradation are routinely found within individual timbers. A small sample could be taken that is not in fact representative of the bulk of the timber. If a numerical classification system is to be employed, it should utilise two well defined ranges of values for "well preserved" and "highly degraded" areas respectively. Even then, this data is better treated separately from, or complimentary to, more robust classifications based on visual appearance or physical examination. U_{max} ranges will be unique to individual species and a generalised scheme suitable for all timber types is not possible. This is clearly illustrated in the differences between the three schemes proposed here for oak, poplar and pine. A common observation of potential interest however, is that the values dividing the bands for the three schemes are close to the average U_{max} values for modern material plus 50%, as shown below. Some caution is needed however, until this relationship has been tested for other timber species.

	U_{max} modern	+50%	Scheme limits
Oak	102%	153%	150%
Poplar	254%	381%	400%
Pine	178%	267%	250%

Visible degradation patterns clearly varied between the three species studied here, but this need not exclude the use of a generic visual or physical classification scheme from being used. De Jong's scheme for European oak [18] can easily be modified to compare relative proportions of well preserved versus degraded material, making it applicable to all timber species. A timber could thus be described as belonging to class A, B or C, with approximate moisture content range A (well preserved core or pockets) to B (highly decayed areas). A summarised classification scheme, combining visual and numerical aspects, is given below.

Class A - Well preserved material dominates.
Class B - Roughly equal proportions of well preserved and degraded material.
Class C - Degraded material dominates.

Where "well preserved" and "degraded" can be defined by the maximum moisture content values as follows:

	Well Preserved	Degraded
Oak	≤150%	>150%
Poplar	≤400%	>400%
Scots pine	≤250%	>250%

It is not intended that the lengthy assessment procedures described here are duplicated for other archaeological timbers. Indeed, the destructive sampling required is rarely possible for valuable archaeological material. Conservators will typically assess timbers by probing the surface with needles, extracting small diameter core samples and obtaining U_{max} measurements from fragments. Instead, it is intended that the data and classification schemes given, are used as reference material that describe typical degradation patterns and U_{max} ranges for archaeological oak, poplar and pine timbers. Data can then be used to complement and aid in the interpretation of findings obtained from less destructive sampling techniques.

It should be noted however, that data presented here are for a limited group of timbers, all of the same age and from just one burial site. A broader sampling strategy should ensure the full range of degradation states has been explored for each species, and further studies are underway at the Mary Rose Trust, assessing timbers from a wider range of burial environments. Other species, including English Ash (*Fraxinus excelsior*) and Elm (*Ulmus procera*) are also being examined.

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