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Ancient Monuments Laboratory
Report 47/93

DOVER BRONZE-AGE BOAT: ASSESSMENT FOR CONSERVATION

Jacqui Watson

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Summary

Report on the condition of the boat timbers based on their water content, specific gravity, pore volume, mineral content and cellular structure, with contributions by Dr M. Jones. On the basis of this information two conservation regimes are put forward, freeze-drying and PEG replacement, along with recommendations for the display environment. 25 pages including plan of boat with the location of samples, table of water contents, and micrographs of wood structures.

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Dover Bronze-Age Boat: Assessment for Conservation

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The Bronze-Age boat was found well preserved in peat, still assembled with tool marks clearly visible in the wood surface. The boat is in fact made up of many elements. In some places there are six oak planks lashed together with yew withies, and all the joints have been reinforced with a thin lath of oak over moss caulking. The two central planks are joined by a slightly different arrangement, integral to the base plank are 3 or 4 large cleats and the central edge has a continous ridge (inverted T-shaped section) c.17cm thick. Cross braces wedged between the cleats and through the ridge join the two planks together, and the area between the two ridges is also sealed with moss and a covering lath. The whole boat has been fashioned in such a way that most of the vessel's surface has a tangential or oblique radial surface.

Preliminary examination of the boat timbers indicated that the condition of the wood varied over the length of the boat and among the different elements. In order to make recommendations on suitable conservation treatments the condition of the wood has to first of all be assessed. During early December 36 samples were taken of the boat timbers to look at the water content and residual cellular structure. Because of the grain orientation of the timbers it was difficult to take auger samples as originally intended. Instead sections were cut back from the sawn edges to minimise damage to the boat. The work and information on specific gravity, pore volume and microscopic study were provided by Dr. Mark Jones of the Mary Rose Trust, Portsmouth.

The boat was removed in sections from the excavation, so that despite its overall size methods involving freeze-drying or replacement with polyethylene glycol (PEG) can be attempted. At the moment it is preferable to use PEG as it contains no hazardous components, and we have more idea of its predicted performance than the new polymers currently being investigated for waterlogged wood conservation. Also the museum would like to have some of the material on display while undergoing treatment.

After the individual timbers have been conserved, the boat will need to be reconstructed for permanent display in a conditioned gallery.

1. Condition of timbers

For most conservation purposes the condition of wood is normally expressed in relation to its water content. This can be based on either the oven dry weight (Umax) or the saturated wet weight, although the former is more commonly used. Based on the weight of the dried samples it has also been possible to calculate their specific gravity and estimated pore volume. As these numerical expressions can only serve as a guide to the condition of a structure as large as the boat, a microscopic study of the residual cellular structure has also been undertaken. The possible presence of iron salts was also considered.

Water Content

The calibration of both water contents was undertaken as follows (Hoffman, 1981):

all the samples were twice saturated under vacuum, they were removed from the water only just before weighing and then the excess water on the surface was blotted off. After weighing the samples were first cured for around 6 hours at 60°C, then completely dried by heating for 14 hours at 104°C. The samples are weighed again when oven dried.

The water contents are then calculated using these two formula -

i. $$\text{Umax} = \frac{\text{wet wt} - \text{dry wt}}{\text{dry wt}} \times 100\%$$

ii. $$\text{saturated wet weight} = \frac{\text{wet wt} - \text{dry wt}}{\text{wet wt}} \times 100\%$$

The location and water content of all the samples are presented in appendices 1 and 2, but different elements of the boat have the following range of water contents (Umax):

220-350% withies
200-550% central keel boards
400-650% side boards
400-850% lathes and cross braces

Generally the southern end of the boat appears to be in better condition than the north. This cannot be shown numerically as the "swallowtail" section did not have any suitable breaks or sawn edges to take samples from. By inserting a pin into this end, it was quite clearly in better condition than the rest of the boat. It was also possible to profile the water contents across some sections, and as expected the outer layers are more degraded than the core. As far as conservation is concerned both sound and very degraded wood are present in the boat, and these would normally be treated using different ratios of mixed PEGs in both freeze-drying and PEG replacement methods.

Using Umax any slight operator errors give wildly variable results, as can be seen from the table of water contents, and this is further amplified when comparing the results of different laboratories. It is certainly a good idea to only use water content in conjunction with microscopic examination as a basis for conservation evaluation.

Specific gravity

Specific gravity was worked out for a small group of samples which included the most diverse elements of the boat, and are as follows:

	1 oak	3 oak	4a oak	15 yew	fresh oak
specific gravity	0.26	0.13	0.14	0.32	0.55-64

These results can be compared with fresh oak and waterlogged wood of known specific gravity to get an idea of the projected shrinkage rates on air drying. No comparative material was available for the yew withies, so it has not been possible to suggest their likely shrinkage rates.

	1 oak	3 oak	4a oak	fresh oak
estimated shrinkage%				
longitudinal	10	15	14	0.4
radial	14	16	15	5
tangential	44	60	58	11

From the projected shrinkage rates it is quite clear that the dover boat timbers would not be suitable for controlled air drying. Most of the boat surface has a tangential section, which has the most extreme shrinkage rates and this would probably result in huge cracks along the grain.

Pore Volume

The pore volume of the samples has been calculated using the following formula:

$$P = \frac{154 \text{ x } U}{(U \text{ x } 154) + 100}$$

P - pore volume
U - Umax or water content based on dry weight

The pore volume of the samples is as follows:

	1 oak	3 oak	4a oak	15 yew
pore volume %	0.83	0.92	0.91	0.79

The value of calculating the pore volume is that it can be used to work out the theoretical weight of PEG needed for complete impregnation. This is given by the following formula:

$$Tw = \frac{V \text{ x } P}{d}$$

Tw - theoretical weight of PEG
V - wood volume
d - density of relevant PEG grade

It is especially important if using the PEG replacement method, although in this case there would be a difficulty in accurately estimating the volume of the wood involved.

Cellular Structure

The four samples analysed above were also examined microscopically, using both scanning (SEM) and transmitted (TEM) electron microscopes. With these methods it was possible to see that the yew withies were still in good condition, but the oak had examples of all three types - good, transitional and highly degraded, see appendix 3. In all the oak samples the tyloses were still intact, which means that the ingress of PEG and egress of water will have to be mainly through the tangential and radial surfaces.

Mineral Content

When first excavated the boat timbers were a pale brown colour, but over a period of hours they darkened to brown/black. This probably indicates the presence of iron, and was confirmed by X-ray flouresence analysis. It is common for iron salts accumulate in the wood structure as a result of bacterial activity during burial. The levels are probably not high as there are as yet no signs of the formation of reddish brown iron oxides on the wood surface.

2. Conservation options
a. Supports

Both methods will require some type of support for the individual blocks during their treatment. It may also be possible to use the same supports in the display.

Ideally all pieces need to be reconstructed upside down - possibly on polyurethane foam - then the underside cleaned so that polyester resin mounts can be made. An assessment for this process is being produced separately by A.Tribe and P.Bennett.

It should be pointed out that both polyurethane foam and polyester resin are made from hazardous chemical components, and they should only be used by staff wearing the necessary protective clothing and under the supervision of trained personnel. If the work has to be carried out in the present warehouse, staff not involved in the production of the supports should not be working in the same area. A Health and Safety assessment for this stage should be undertaken.

b. Freeze-drying

The condition of the wood means that it will have to be impregnated with mixed PEG solution prior to freeze-drying. A liquid grade PEG is used to compensate for the effects of freezing on the cellular structure (Ambrose, 1990), and it also bonds to the wood making it less susceptible to rapid changes in relatively humidity during storage or display (Grattan 1981). The solid grade consolidates the structure by coating the cell walls (Watson, 1981).

The concentrations required will probably be in the region of 10% PEG 400 with 20-25% PEG 4000, with the concentration of the solution including the volume of the timber. This means that the real concentration will in fact be higher than this, probably in the region of 13% PEG 400 and 30% PEG 4000. Initially the wood is immersed in the low grade PEG for around 6-8 weeks, then 2.5% of the high grade PEG is added every fortnight till the final concentration is reached. The wood should be left at the final concentration for at least a further 6 months. The total time for impregnation should be about a year. Then sections of the boat can be removed for freeze-drying in batches, which will probably take around 2 months each to dry. The whole process could probably be accomplished within 2-3 years.

It is presumed that the pretreatment stage will be done in Dover, and where possible will use the existing tanks. In order to do this one will need the following:

i. The tanks will need covers for the early stages to cut down on bacterial activity.

ii. Requires a circulating pump not liable to corrosion by PEG, ie. stainless steel; and be able to cope with a solution having a viscosity in the region of 50 mm2/s.

iii. Will require some form of heating system for the winter months so that the bath temperature does not fall below 20°C.

iv. Additional help when the tanks are filled, and when batches are removed for freeze-drying.

v. Using the current holding tanks, the following amount of PEG would be required:-

2 tanks - 3x4m, 4x5m, which would hold a total of 16m3 of solution

1.6 tonnes PEG 400	at £730.00* per tonne	..........£1095.00
3.5 tonnes PEG 4000	at £1194.00* per tonne	..........£3582.00
		total..........£4677.00

*prices from BP, but PEG is also available from ICI and Union Carbide.

Due to the size of the individual sections, the freeze-drying stage will have to be done either at York or Portsmouth, as there are no other installations available in the UK which have the necessary capacity. The two groups are providing separate tenders for this stage.

c. PEG replacement

To conserve the boat timbers a twin PEG replacement regime would be required. This involves replacing nearly all the water in the waterlogged wood with 2 grades of PEG, using PEG 600 to replace all the the interstatial water and PEG 4000 to replace the free water in the cells (Hoffman, 1984). Initially the wood is soaked in a bath of 10% PEG 600, which is increased by small increments to around 50%. When the wood is fully impregnated with this grade, it is removed and put into a bath of 50% PEG 4000. The concentration of this second bath is then gradually increased to around 80%.

This treatment regime will require the construction of tanks that can incorporate heating elements, as in the later stages the PEG solution will need to be kept at a constant 60°C. The tanks will also need to have close fitting covers and be well insulated. Heavy duty pumps are required to circulate the PEG solution, with filters to keep the solution clean.

Once impregnated with PEG the timbers have to be cleaned and conditioned. Excess PEG is removed from the surface with hot water and hot air dryers and is a time consuming process. Conditioning of the timbers involves their slow drying by gradually reducing the relative humidity (RH) of the surrounding air. The best way to do this stage, is to construct a large polythene tent in which the air can be conditioned with dehumidifiers. Will also need some specialist advice on the control of microorganisms.

The treatment time could easily be between 5-10 years, depending on the rate of diffusion of PEG into the wood. In addition to this the conditioning phase could take another 1-2 years.

This treatment not only takes longer than the pretreatment phase of the freeze-drying process, but it also requires more monitoring. For this reason it would be necessary to employ someone to oversee the whole process. The tanks need constant monitoring and maintenance, PEG has to be added at regular intervals, and cores have to be taken from the timbers to observe the diffusion rate of PEG into the wood. After impregnation the timbers have to be cleaned of excess PEG and the conditioning phase has to be closely regulated. It would be worthwhile setting up a formal conservation advisory panel to discuss progress and make reccommendations on any adjustments to the treatment regime and programme if necessary.

To undertake this treatment regime, the following would be required:-

i. Construction of a tank of similar volume to the holding tanks, c.30m3 to hold 16m3 of wood and PEG solution. The tank needs to have covers and to be well insulated.

ii. Heating elements, able to heat solution to 60°C, and if these are to be inserted into the solution, they should be able to withstand the corrosive effects of PEG.

iii. Circulation pump and the necessary pipework. The pump will need to be able to cope with a solution of viscosity in the region of 100 000 mm2/s.

iv. PEG:

6 tonnes PEG 600 at £730.00 per tonne £4380.00
11 tonnes PEG 4000 at £1194.00 per tonne................£12134.00
total...............£16514.00

v. Polythene tent and dehumidifier for the conditioning stage.

vi. Salary for someone to monitor progress of treatment and maintain equipment.

d. Choice of treatment

As far as finished results are concerned, there is little to choose between freeze-drying and PEG replacement for these boat timbers. But both treatment regimes need to be closely monitored in order to get good results.

PEG replacement will take much longer than freeze-drying, this could be over 10 years, and will overall be more expensive. However, the whole process could be undertaken in Dover under the direct control of the museum.

Freeze-drying on the other hand, will take around 3 years to completely process all sections of the boat for display. The pretreatment phase can still be done in Dover, and if necessary using the existing holding tanks. The pretreated sections will have to be transferred to facilities, such as York or Portsmouth, for freeze-drying.

e. Display treatment tank

This is based on the display treatment tank in the Mary Rose Museum and the following information was supplied by the Trust. This tank contains about 1m3 of wood and PEG solution. It is made of heavy guage steel protected from corrosion by PEG using marine anti-fouling paint. The front observation panel has to be made from toughened glass sealed to the sides with silicone rubber. It is essential to have a circulation pump with filters to keep the PEG solution clear. Heating is also required if using PEG replacement treatment.

This particular tank originally cost the Mary Rose Trust around £20 000.00, including special discounts from local suppliers for some of the equipment.

It is difficult to give accurate costings for the equipment and materials needed for the conservation of the Dover boat as the Museum can undoubtably arrange to have them donated or buy them at special discount prices from local suppliers.

3. Coordination of Sampling for Dendrochronology

The assessment report for dendrochronological analysis indicates that samples will have to be taken as 5cm slices that will need freezing prior to ring measurement. If these samples are to be conserved and reinstated with the displayed timber, the stage at which the samples can be taken must be coordinated with conservation.

If freeze-drying is adopted to conserve the boat, it is very important that samples for dendrochronology are taken after the timbers are impregnated with PEG and prior to freeze-drying.

Using the twin PEG replacement treatment, the samples can be taken either before immersion in PEG, or preferably after partial impregnation with PEG 600.

4. Reconstruction and display

Once treated the boat sections need to be placed on a permanent support, possibly incorporating the polyester mounts used during their conservation.

To prevent the wood from deteriorating while on display it will be necessary to keep it in an air-conditioned case, or the gallery needs to be air-conditioned so that the RH is maintained in the region of 45-65% (Watson, 1987), preferably with only slight fluctuations. If the wood becomes too dry, there is a danger that large cracks will appear along the grain. These will be more noticeable if the boat has been freeze-dried, and they are non-reversible.

Lighting should also be carefully considered so that there are no hot spotlights directed onto the boat. Most of these conditions are included in the designers assessment and costings for the gallery.

Acknowledgments

Jo Dillon helped with the sampling of the timbers, keeping their concordance and assisting with the water content analysis. Dr Mark Jones of the Mary Rose Trust, undertook the microscopic study of small group of samples along with calibrating their specific gravity and pore volume. He also provided the information on the projected shrinkage rates.

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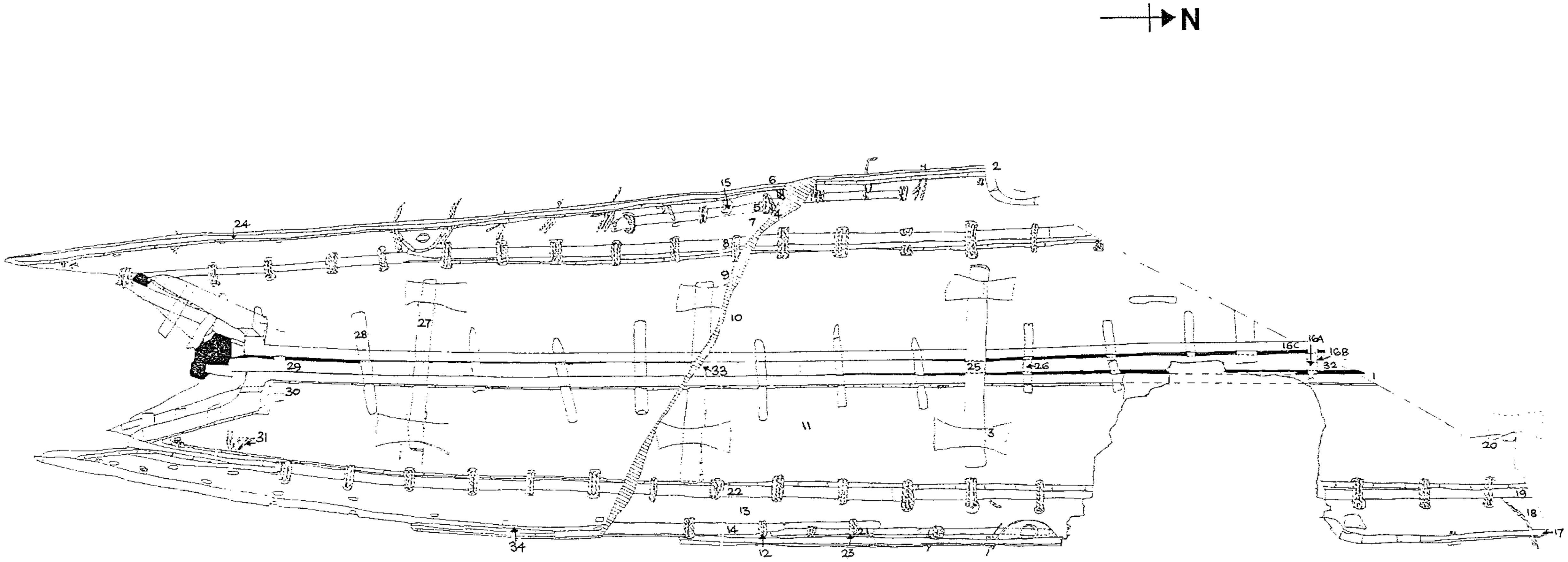
Appendix 1

Plan of boat with location of samples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Appendix 2

Table with concordance of samples and their water contents

sample	section	timber	location	%wc.dw	%wc.ww	average
1a	Aiii	1	East keel board, diagonal cut piece from under piling	1314.7	92.9	
1b				332.5	76.9	
1c				318.6	76.1	
2	I	45?	Upper west side board, north side of cleat	491.4	83.1	
3	C		Cleat C, top surface only	664.2	86.9	
4a	V	50	Lower west side plank, east of upper lath 166/159, cut	568.4	85.0	595.3
4b			by piling	694.5	87.4	
4c				515.0	83.7	
4d				603.4	85.8	
5	V	166	West edge of upper lath, possible repair	490.6	83.1	
6a	V	45?	Outer edge of upper west side board, above cut withy 112	461.6	82.2	542.1
6b				547.1	84.5	
6c				617.5	86.1	
7a	V	111	Lower west side board, immediately south of piling	655.3	86.8	604.8
7b				645.3	86.6	
7c				538.8	84.3	
7d				579.9	85.3	
8	V	170	West lower lath south of withy 174	580.5	85.3	
9a	V	137	West keel board, west of cleat D, immediately south of	602.2	85.8	525.5
9b			piling	470.2	82.5	
9c				487.6	83.0	
9d				542.2	84.4	
10a	Jii	17	West keel board, west of transverse peg 42	416.4	80.6	520.3
10b				525.3	84.0	
10c				522.8	83.9	
10d				616.8	86.0	

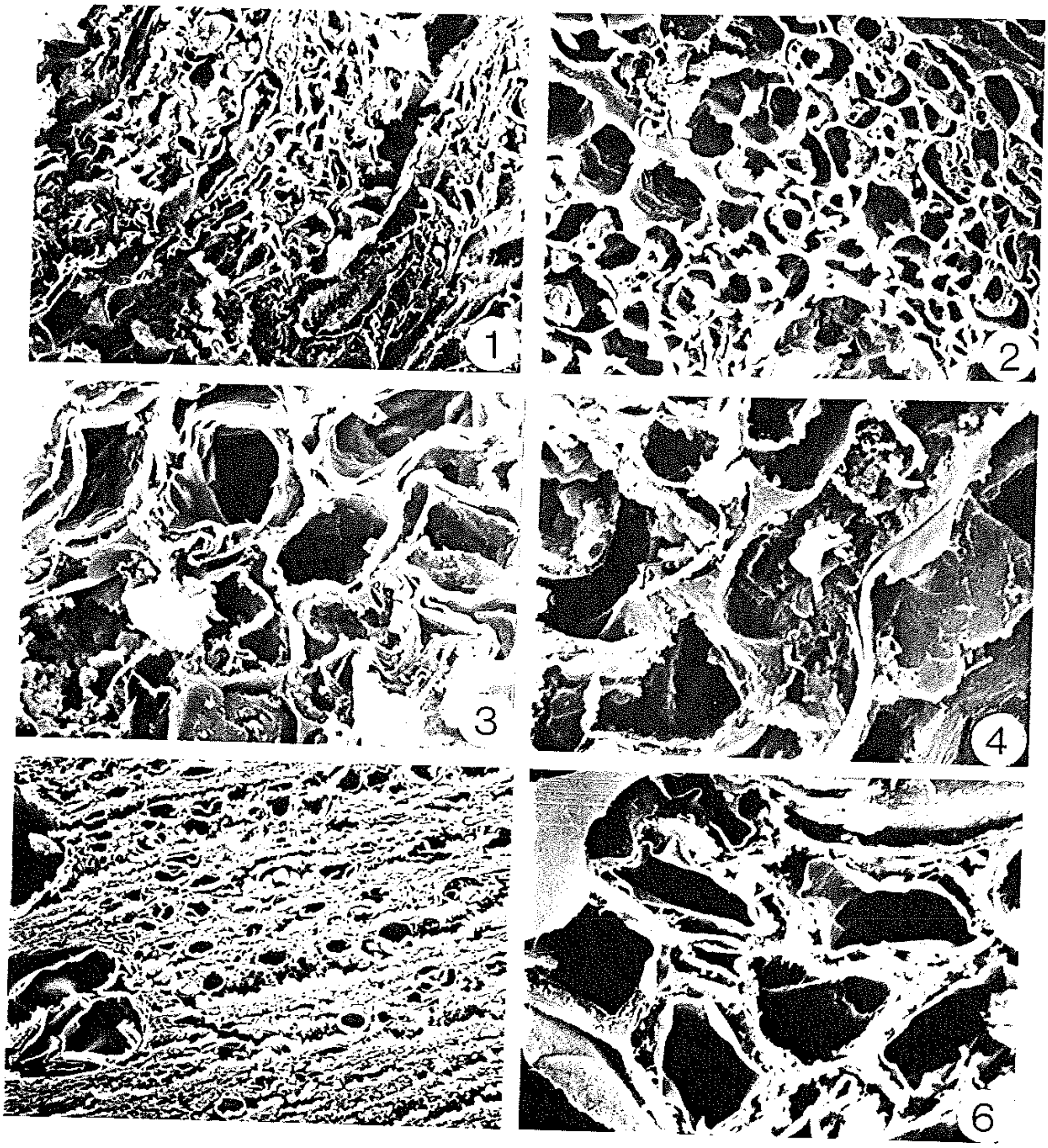
sample	section	timber	location	%wc.dw	%wc.ww	average
11a	C	40	East keel board, north of cleat E	412.8	80.5	418.8
11b				424.9	80.9	
12	B(s)	32	Withy, immediately south of lath 36	349.0	77.7	
13a	B(s)	38	Lower east side board, south end, east of lower lath 63	302.4	75.2	346.7
13b				390.9	79.6	
14	B(s)	34	East upper lath	358.5	78.2	
15	V	108	Cut withy from upper west side board	227.5	69.5	
16A	Aiii	13	Transverse centre peg	608.2	85.9	
16B	Aiii	14	Centre lath, cut by piling	573.9	85.2	
16Ca	Aiii	17	Inverted T-piece from west keel board, cut by piling	425.0	81.0	345.0
16Cb				295.9	74.7	
16Cc				323.8	76.4	
16Cd				329.9	76.7	
16Ce				336.8	77.1	
16Cf				358.6	78.2	
17a	Aiv	2	Upper east side board, cut by piling	621.8	86.1	565.8
17b				511.9	83.7	
17c				563.8	84.9	
18a	Aiv	2	Lower east side board, cut by piling	351.9	77.9	405.5
18b				444.4	81.6	
18c				420.2	80.8	
19	Aiv	3	East lower lath, close to piling	533.6	84.2	

sample	section	timber	location	%wc.dw	%wc.ww	average
20a	Ai	1	East keel board, next to cleat A, cut by piling. Not a complete section.	566.7	85.0	440.9
20b				590.0	85.5	
20c				418.6	80.7	
20d				188.2	65.3	
21	B(s)	36	East upper lath, possibly repair, under withy 30	721.4	87.8	
22	B(s)	63	East lower lath, north of withy 22	427.2	81.0	
23	B(s)	30	Withy, possible repair, binding laths 35 & 36	221.8	68.9	
24a	L		Upper west side board, north of stitch 111/B	507.9	83.6	537.8
24b				511.9	83.7	
24c				583.5	85.4	
24d				548.0	84.6	
25a	E	39	Transverse brace, through cleats B & C.	416.5	80.6	511.8
25b				562.6	84.9	
25c				556.4	84.8	
26	E	20	Transverse peg, north of transverse brace 39	328.2	76.6	
27a	S	159	Transverse brace passing through cleats F & G, west side	377.2	79.0	344.7
27b				312.2	75.7	
28a	T	125	Transverse peg, west end, south of transverse brace 159	608.8	85.9	506.9
28b				540.5	84.4	
28c				371.3	78.8	
29	T	177	Central lath between T-pieces, north of peg 126	205.6	67.3	
30	T	101	East keel board, east of T-piece, north of peg 126	317.4	76.0	

sample	section	timber	location	%wc.dw	%wc.ww	average
31	R(E)	132	Cut withy, east keel board	286.1	74.1	
32	Aiii	14	Central lath between T-pieces, near piling	486.4	82.9	
33	Jii	14	Central lath, next to piling, below brace 122	857.4	89.6	
34	O	?100	Upper east side strake, centre, west of stitch 100/Q	504.2	83.4	

Appendix 3

Electron micrographs of the wood structure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Figures 1-4. Scanning electron micrographs of transverse section of oak sample 1, part of keelboard.

1. Section taken 1mm below the surface, showing extensive cell wall degradation causing the cells of this region to collapse. Best preserved cell wall layer is the middle lamella (highly lignified). x800

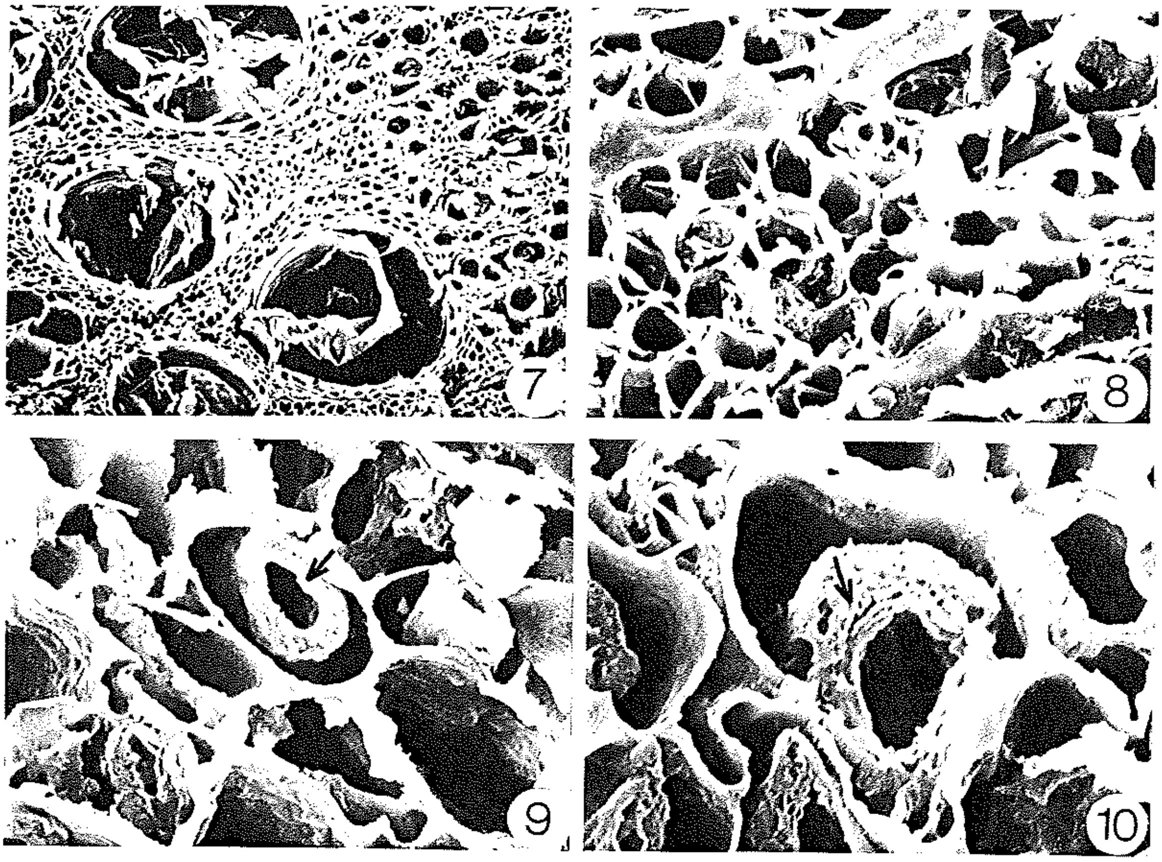
2. Section taken 2mm below the surface, showing fibre cell walls. The secondary wall layers of some cells are completely degraded, whereas others exhibit a highly porous and detached secondary wall layer. x1200

3, 4. Sections taken 1mm below surface showing extensive cell wall degradation and collapse. x2400 and x5600

Figures 5 and 6. Scanning electron micrographs of transverse sections of an oak sample 3, top of cleat C.

5. Section taken 2mm below surface, showing highly degraded fibres and vessels. Tyloses in vessels showing selective degradation. x160

6. Porous appearance of the S2 layer of the fibre cell wall is decay due to a combination of bacteria and fungi. x3200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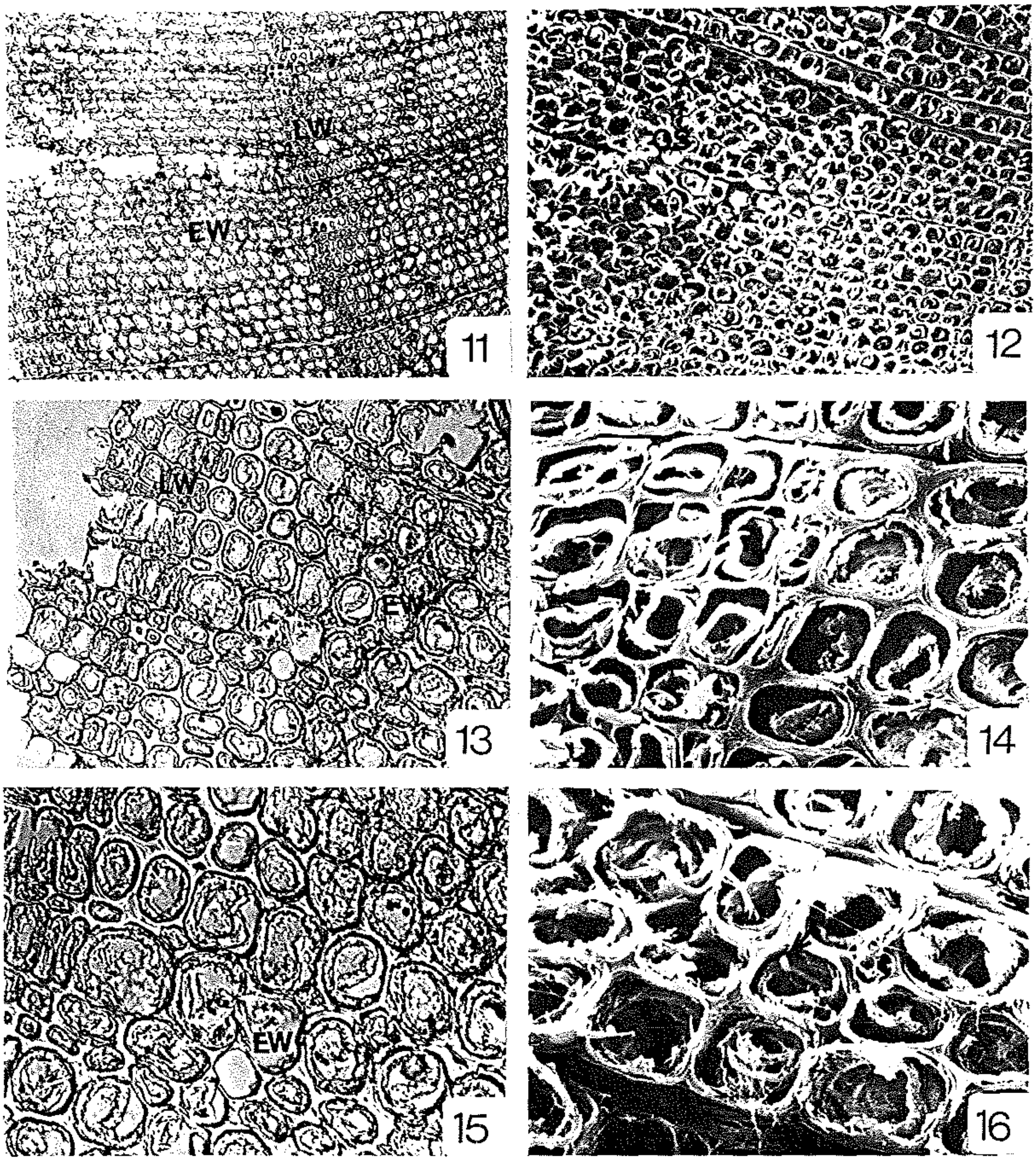
Figures 7-10. Scanning electron micrographs of transverse sections of oak sample 49, sidestrake.

7. Decayed region (outer surface) of sample showing advanced stage of decay. Tyloses in vessels showing selective degradation. x160

8. Condition of cells in the highly degraded outer surface layers - the secondary wall layers of most fibre cells are completely degraded, with only the middle lamella remaining. x1200

9, 10. Porous appearance of S2 layer (arrowed) of the fibre cell wall. Adjoining cells have lost their secondary wall layer leaving only the middle lamella intact. x3200 and x5600


LW
EW
11
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LW
EW
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EW
15
16

Figures 11-16. Light (LM) and scanning electron micrographs (SEM) of transverse sections of yew sample 15, withy 108.

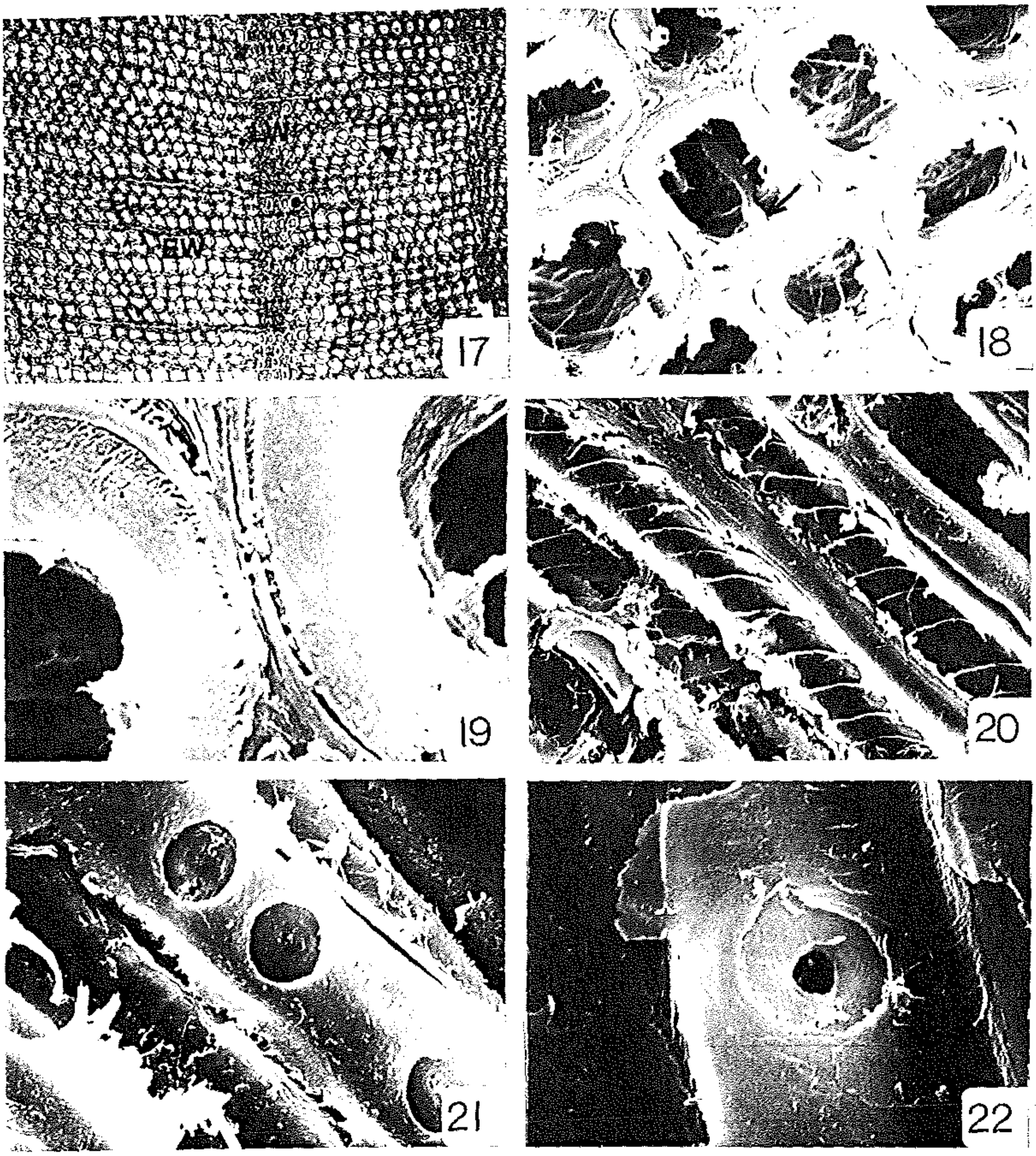
11. LM showing the gradual transition from earlywood (EW) to latewood (LW). x47

12. SEM showing the condition of cells in the outer surface (OS). x320

13, 14. Morphology of early (EW) and latewood (LW) of the outer decayed surface layers. Decay due to a combination of biological and chemical agents. x117 and x1600

15. Early and latewood tracheids showing heavy microbial attack, especially of the S2 layer in the latewood. x188

16. SEM showing extensive cell wall degradation and the presence of fungal hyphae (arrowed). x1600


EW
17
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Figures 17-22. Scanning electron micrographs of yew sample 15, withy 108.

17. Sound early (EW) and latewood (LW) with most of the cell wall still intact. x320

18. Sound earlywood tracheids. Note presence of fungal hyphae (arrowed). x3200

19. Tracheid cell wall. Note well maintained nature of the secondary wall layers. x12000

20. Longitudinal section showing spiral thickening which forms a 20-50° angle to the vertical axis. x1600

21. Longitudinal section showing the arrangement of bordered pits (single row). Pits are intact and well preserved. x3200

22. Longitudinal section showing a degraded pit. The tori has disappeared. x5600