Article

Forest Wood through the Eyes of a Cultural Conservator

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Abstract: If prehistoric and historical time were placed into the time span of the existence of our universe, then the act of archaeology could be defined as the act of digging up what was only buried yesterday. So, conservation is about preserving a moment that has just become past time, yet significant. It is a moment of human creativity and ingenuity. It is not strange that forest wood has become the material to convey such moments. Forest wood is a living, everlasting source growing without human intervention, within reach, easy to use and shape thinking both great and small. It does not have to be a wooden ship; it can be a mere piece of charcoal. For it is what surrounded humans in the past which archaeologists seek and use to weave human history, and what conservators bring back to context by reviving it. This work presents forest wood as an artefact and its preservation challenges as such. It touches on its natural degradation processes through burial, compromised properties and eventual conservation. Both dry and waterlogged wood are included. The overarching aim of this paper is to pay tribute, preserve and inspire the long-standing, open dialog and fruitful collaboration between cultural conservators and forest and wood scientists.

Keywords: historical wood; archaeological wood; wood degradation; artefact; heritage; conservation; cultural conservator

1. Introduction

The purpose of this paper is to present basic concepts of wood structure and its physicochemical and mechanical properties from the point of view of a cultural conservator assigned with the task of preserving wooden artefacts and the practical as well as ethical problems involved when doing so. The intention is to avoid providing specific solutions to specific problems, and rather offer to the reader a way of critical thinking when challenged with the study and preservation of a piece of historical wood regardless of the burial environment it was found in. As it is not feasible to include all aspects of wood, let alone degraded wood, it is also a wish to communicate to wood scientists those wood terms and issues with an immediate interest to conservators brought together with the societal role of the latter. Last, it is hoped that the paper will be a useful introduction to those conservators new to the field of wood conservation.

Here, both archaeological and historical wood are referred to as 'historical wood', meaning generally wood of historical as well as cultural value. Besides, historical time becomes irrelevant with regard to wood degradation. Wood degradation and severity of degradation is partially about the wood species and deterioration already present at the moment of 'discard' and, more importantly, the burial process and type and duration of subsequent prevailing environmental conditions to which wood is exposed. Even so, it would be advisable for the reader to keep in mind throughout the text that the word 'historical' wood will also imply some meaning of degradation apart from its value.

2. Why Wood?

The answer to this question emerges plainly in Perlin's introductory line of his book *A Forest Journey: The role of wood in the development of civilization*—'Ancient writers observed that forests always recede as civilizations develop and grow' [1] (p. 25). The connection

between human evolution and forests is inextricably tied. For when wood was critically limited, humans engineered ways of acquiring iron from copper slag, carelessly marking the beginning of a new historical era [1] (p. 17).

In an ancient world already covered with trees for hundreds of millions of years, humans picked up wood and started building it around them. It warmed them, housed them, carried them, protected them, and its beauty even filled them with awe. Wood still lies out there to speak to us of life during the Mesolithic time in the Western Solent, UK [2]. It has helped us reconstruct a Mycenaean shipwright's toolkit from the Late Bronze Age, Greece [3]. It has also taught us about pioneering maritime engineering and stuns us with the scale of wooden constructions humans were capable of building, a case in point being the emergence of the harbour of King Herod of Judea Caesarea Palaestinae (ca. 23–15 BCE) out in the open sea (Figure 1) [4]. For a resourceful collection of references to Greek and Roman wood technology, including entries on energy conversion, fire and fuels, the research by Humphrey et al. is certainly worth a glance [5].
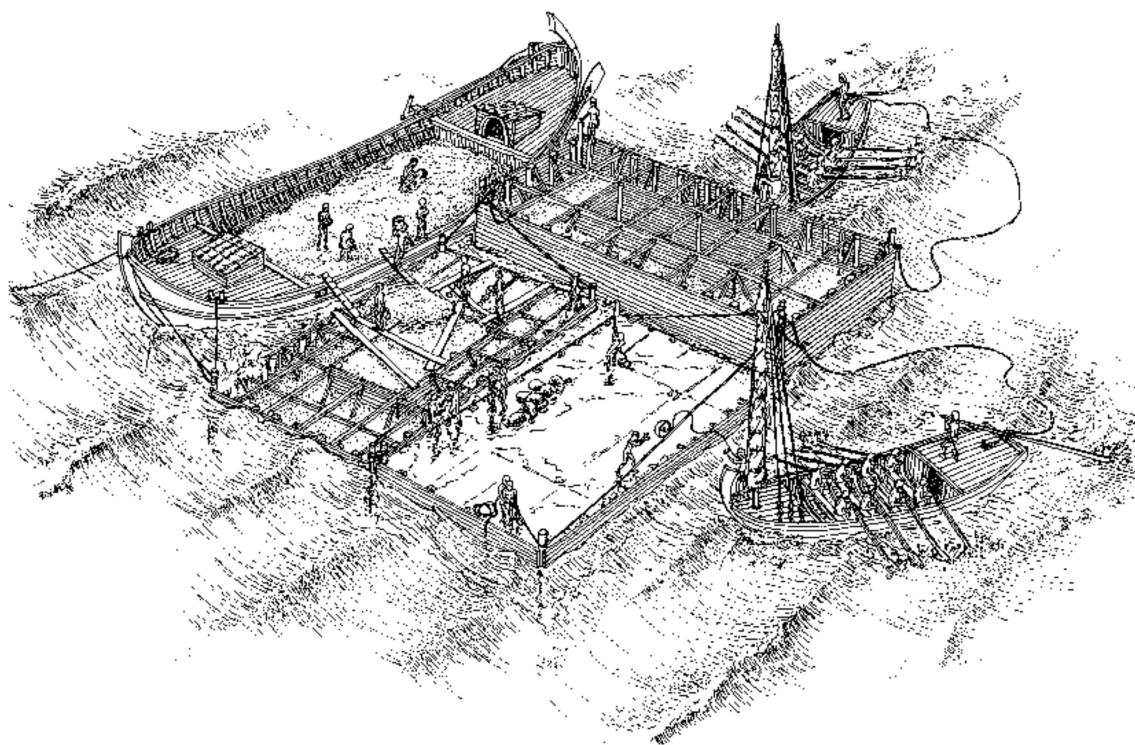
Figure 1. Reconstruction of prefabricated caissons being positioned and loaded with concrete at Area K at the northern end of the main enclosing mole at Caesarea [4] (p. 213). Drawing: C.J. Brandon; used with kind permission.

An artificial harbour on a far smaller scale is now being unravelled at Lechaion in Corinth, Greece, with much of the wooden infrastructure still preserved in situ [6]. Along with its value in understanding the role of the city and port of Ancient Corinth during the Roman and Byzantine (Late Antiquity) period, its excavation gives us a unique opportunity to access yet another source of information—tree-rings. It is hoped that it will be possible to expand tree-ring chronological sequences in the Aegean [7], and so, add fixed points for archaeologists for dating finds based on dendrochronology [8]. It will also enhance our knowledge of forestry practices in ancient times. Reconstruction of the paleoclimate and evaluation of climate model simulations constitutes yet another dynamic aspect offered by tree-rings [9,10].

Faced closely with something made in the past, the role of a conservator is to preserve the find and therefore, preserve history for today's humans to reflect on before handing it down to a later time. Humbly drawn from our short cosmic lives, the perception of

our personal role as individuals is that of rather small significance for the continuation of history, yet history fully resonates within us. It only takes a visit to a museum to make even an unwitting soul aware of their part in this abiding history, intertwined, no matter the distance, with the events that generated what we today admire as artefacts in displays. The museum that truthfully brings about this self-consciousness to its visitor has fulfilled its purpose. History becomes essential reference points for perpetual evolution of life. It imparts confidence and provides comfort: '[. . .] but even unfinished wood, as it darkens and the grain grows more subtle with the years, acquires an inexplicable power to calm and soothe.' [11] (p. 12).

Conservation of wood of historical and cultural value goes hand-in-hand with wood science. They are both built around the theory of wood as raw material, its structure and properties. Conservation consults wood science and adopts ways of studying wood within the ethics that now define it as an artefact. For in the majority of cases, particularly in the Western world, historical wood can no longer serve its original purpose especially if that was functional. An artefact is unique and now destined for study and appreciation and interventions, therefore, have to be minimal and well justified to serve its longevity. The reader is greatly encouraged to refer to the work by Muñoz Viñas 'Contemporary Theory of Conservation' which discusses intervention with great deliberation, reflecting on the way to adhere to the authenticity of an object [12]. A fine use of both 'science conservation', which seeks the truth of the object, as well as 'contemporary conservation theory' which values the object for the immaterial matters it represents such as art, meaning and feeling, is to this author, central. So, in a way, both worlds are reflected in the word 'artefact'.

Meanwhile, historical wood deteriorates as any piece of wood. Expertise knowledge of the structure and properties of wood helps the conservator assess its current state of preservation by knowing what to look for and how, in order to understand what care it needs and how best to give it. Many decades of collaboration with forest and wood experts have advanced the conservation of wood by establishing solutions both simple and sophisticated to be utilized reasonably. It is true that even after so much progress it is still difficult to predict how a conserved piece of historic wood will fair in time, regardless of the time and most conscientious efforts spent on this. Having said that, we can assume that if it is in existence today, it will be so in the future, for responsible care is underway.

3. Basic Wood Structure and Properties concerning Conservation

Hort in his translation of Theophrastus (ca. 370-285 BCE) *Enquiry into Plants* (Greek: Περὶ φυτῶν ἱστορία, Latin: *Historia Plantarum*), remarks Theophrastus's continuous wonder as to which essential characteristics distinguish one plant from another [13] (p. xxii). It is notable that the first systematic botanist based his ratiocination on direct comparisons with the other division of Aristotle's kingdoms of life, that of the animals: 'Fibre and veins (Hort note: 'muscles and veins') have no special names in relation to plants, but, because of the resemblance, borrow the names of the corresponding parts of animals.' [13] (p. 19). Theophrastus's work builds on that of his contemporary mentor Aristotle in *History of Animals* (Τῶν περὶ τὰ ζῷα ἱστοριῶν or *Historia Animalium*): 'However, since it is by the help of the better known that we must pursue the unknown [. . .] it is clear that it is right to speak of these things in the way indicated' [13] (p. 19); a core science lesson still holding true today.

A long history past these cornerstones, Linnaeus carries this inner need to understand and rationalise an apparent chaotic plant diversity and submits it in his *Systema Naturae* (1735). Linnaeus's early work in the classification of flowers seemed to work well for the then known plants, but there was a problem (solved by Swedish botanist, Florin in the 1950s) when trying to fit the first, in evolutionary terms, order of trees—the Coniferales [14]. It is well known that gymnosperms—of which conifers are a group—are the primitive state and that the angiosperms are the derivative, an evolution taking place sometime in the mid-Mesozoic and certainly by the end of it, at the Lower Cretaceous [14]. Setting aside for a moment the thriving diversity of angiosperms, Farjon shows his respect for conifers,

these ancient living and intelligent organisms, with a life that covers more than 300 million years of existence and evolution, and whimsically notes: in contrast to the much-admired dinosaurs, conifers did not become extinct at the end of the Cretaceous. That the internal structure of conifer wood remained virtually unchanged for millions of years, efficient in its simplicity and homogeneity and capable of adapting to a wide range of climates from the very cold to the very dry, has allowed conifers to continue to prosper on Earth.

A rich fossil plant record informs us that during the Late Cretaceous angiosperms became an important component of the vegetation in the warm subtropical climates of Antarctica [15]. Although heading into the Pleistocene deep-freeze this vegetation disappeared from the continent, angiosperms managed to succeed and even force out conifers from the lowland tropical rainforests, which instead resided in mountains, on coasts, in high deserts, and in cold climates [14]. Today angiosperms account for about 300,000 species, whereas conifers a mere 630 species.

Angiosperms produce what is called hardwood whereas conifers produce softwood. The terms are based on the hardness of wood and its weight, or density, although names do not necessarily correspond to the actual wood properties even today [16]. Theophrastus already excludes hardwood lime wood for it is especially soft and easy to work [13] (p. 445).

3.1. Macroscopic Structural Characteristics

Softwood and hardwood artefacts are equally stored in museum collections or found still standing in the open air or submerged in the seas and lakes. A quick guide to distinguishing between the two is the presence or absence of wood rays in its cross-section, easily noticed with the naked eye. While wide and conspicuous in hardwoods like oak, beech and sycamore, rays are difficult to distinguish in softwoods like pine and spruce, even with a hand lens. A second feature of hardwoods only, more often than not visible to the naked eye, but certainly with the use of a hand lens, is the presence of pores, the small openings within growth rings. These openings correspond to the cell lumina of the vessel members, a cell type unique to hardwoods only. Depending on their arrangement in relation to the rings, hardwood is classified as ring-porous, semi-ring-porous or diffuse porous. Equally, some softwoods like those of the Pineceae family also have small openings in their cross-section. However, these openings are not cells, but intercellular spaces corresponding to axial resin canals (traumatic canals included). They are found scattered on the cross-section mainly as solitary openings or in pairs, or in small groups aligned with the rings.

Furthermore, looking at the cross-section of both types of woods, one can easily identify an inner dark wood portion expanding outwards from the central part of the tree trunk (pith), called heartwood which is surrounded by a lighter and narrower in width wood portion called sapwood (Figure 2). Heartwood is the result of the progressive transformation of the living sapwood into dead tissue. As such, heartwood does not participate in the translocation and storage of food, solely run by sapwood, but provides mechanical support to the tree. The formation of heartwood is a natural aging process and associated with bordered pits aspiration, formation of tyloses and deposition of extractives, all of which protect the wood from decay by occluding pathways.

With this initial distinction between hardwood and softwood, the conservator can assume from the outset that penetration depth of a conservation material will be difficult in hardwood like oak because its heartwood is rich with tyloses; similarly, it will be difficult in the prominent by pit-aspiration heartwood of softwoods. That conservators are more likely holding in their hands such wood, is a valid probability as, unless restricted by supply, local availability and the time allowed to grow, heartwood was chiefly used for its superior mechanical properties and resistance to attack by microorganisms, attributes ancient people were very well aware of [17] (p. 28).

Woodworking is also of importance when it comes to the impregnation of wood with conservation agents (Figure 2). Standing trees or dead wood generally absorb fluids along the main growth axis, the longitudinal. Flow follows naturally along the open pathways

formed by stacked cell lumina of myriad wood cells aligned with their long axis almost in parallel to the tree trunk [18]. Impregnation drops for the transverse directions by a factor of 10^4. Therefore, permeability, or else, penetration depth, of a conservation agent depends additionally on this wood structural characteristic. It is not surprising that techniques as deep incising, radial drilling and through-boring are utilised to substantially improve penetration depth of preservatives in service wood poles today [19]. Certainly, one cannot so light-heartedly perforate wood of historical value, but can surely mimic the idea behind the procedure starting by using existing lateral entry points, usually pre-existing cracks or openings. Instances might still rise when such drastic interventions are a one-way street, but for reasons other than rushing through conservation treatments.
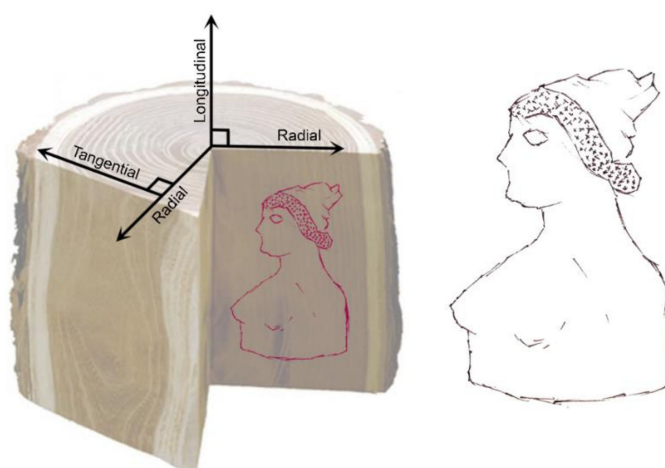
Figure 2. Artefact orientation inside a tree-trunk. Artistic interpretation of a female wooden figurine found in waterlogged condition at the excavations of the Temple of Artemis in Brauron, Greece (2500 years old) [20]. Image from a sector of coniferous wood stem adopted from http://www.woodanatomy.ch/macro.html (accessed on 8 May 2015). In ref. [21]. Image of figurine from https://www.tovima.gr/2011/10/03/culture/ksylino-eidwlio-kai-soles-papoytsiwn-ilikias-2500-etwn/ (accessed on 11 June 2021). Drawing: A. Zisi.

The larger the available cross-section surface area for accessing is, the lesser time it can take a conservation agent to impregnate wood, and the less time the drying process will take afterwards. The drying rate of smaller objects is expected to be faster than for larger objects explained by the ratio of the surface area to the volume [22]. As an object becomes bigger the surface/volume ratio becomes smaller, so the drying rate depends on the available surface area. This is of significant importance for orthotropic wood where evaporation happens more readily in the cross-section than the lateral surface (radial, tangential). Therefore, large and especially long wooden objects request longer drying times than small objects. However, longer drying times favour good results regarding avoiding adverse shrinkage or shape distortions, as well as consolidant migration to the wood surface if impregnated wood is left to dry too fast [23]. Devising ways to slower and control solvent evaporation rate is advisable for any size wooden object.

Growth abnormalities in wood like, spiral grain and reaction wood, as well as natural growth characteristics as is the pith and knots, are further structural characteristics that should concern conservators and those involved in historical wood research. Their sometimes unavoidable inclusion in objects or structures can also affect data measurements or conservation results. The latter concerns, namely the reduced permeability to conservation agents in such wood and the release of tensions upon drying after immersion in either water or non-water-based consolidants. These could result in significant alterations of, for example, important carved surfaces or make it impossible to rejoin fragmented artefacts or complex structures as planks on frames of wooden hulls. Even small misalignments can

propagate the fault further away and end up distorting considerably the original shape of an object or a structure.

Meticulous study of the wood structure per case, and mapping and flagging of potential shortcomings before treatment is essential not only for conservators to design and execute conservation schemes but also for researchers to design methodological approaches tailored to the specifics of research questions with useful answers. For example, the use of *clear*, straight-grained, quarter-sawn wood from unseasoned, that is, with moisture content (MC) already over the fibre saturation point (FSP) 30% and free from drying-induced defects, oak and pine wood, allowed the acquisition of reliable and reproducible results for studying ultrasound wave propagation in historical wood whilst in a waterlogged state (in this case MC_{max}) [24]. Moreover, taking into account the directional dependency of fluid permeability in wood, the longitudinal dimension of testing specimens was set shorter than the radial and tangential dimensions. This benefitted water absorption along the grain and tried to gain time from the waterlogging procedure, as long durations could be expected given the rather large size of the specimens [25]. Additional attention was paid to introducing a gradual vacuum power into the water bath so as to avoid possible rupturing of the pit membranes and tripping the waterlogging procedure [26]. If anything, the experiments proved that with the right knowledge of the material it is possible to control for the naturally high variability in wood, by taking a few crucial decisions right at the beginning of planning.

If not for a specific need for using hardwood species, the use of softwoods for experimental material is encouraged, for its greater structural uniformity allows easier interpretations of the effect of various applications on wood, especially at the outset of a study (e.g., [27]).

3.2. Microscopic Structural Characteristics

A closer look at thin, transparent wood sections or macerated wood substance under the light microscope, reveals a variety of wood cells bundled in different ways to form the wood tissue of conifers and angiosperms [28]. Images of sections representative of the transverse, radial and tangential planes, reveal diagnostic features for wood identification. Stitching together the three wood planes enables the conservator to see beyond the wooden surface and visualise its three-dimensional structure in greater detail than the initial dichotomous question—softwood or hardwood—allows him or her to do [29,30].

Wood under the microscope reveals that tracheid cells, which form up to 90% of the wood cell type in conifers, and fibre cells, which may contribute 50% or more of the total wood cell type in angiosperms, have tapered ends that are closed. With the ends of the tracheids closed, the transport and distribution of fluids in conifers is primarily dependent on the pitting of longitudinal tracheids. These pits conduct fluids in the tangential direction due to their positioning mainly along the radial wood surfaces (Figure 3). Although it seems that this depends on the species, as fluids in *Pinus sylvestris* L. end up filling the longitudinal tracheids having first travelled through the ray cells especially in thin and long wooden structures [31]. In the more cell type variable angiosperms, the vessel members, having large diameter cell lumen, are the actual fluid conducting cells, leaving the fibres functioning mainly as the wood strengthening cells in the living tree [32]. Vessel members form stacks of indeterminate length where fluid gets transferred through perforation plates of various typology, located at the ends of each cell—as long as there are no tyloses blocking the flow (Figures 4 and 5). From inside the vessel chamber, fluid can be transferred also in a radial manner via the intervessel pits formed on the vessel walls where a vessel member touches another one (Figure 6). Pits also exist where a vessel member meets ray cells, forming diversified vessel-ray pitting (Figure 7).
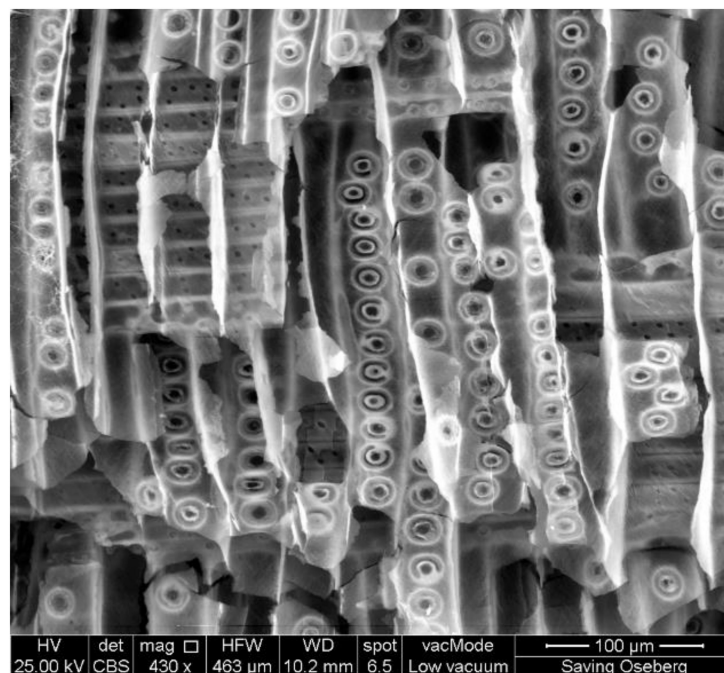
Figure 3. Scanning electron micrograph of a radial-longitudinal section from historical waterlogged *Picea abies* (L.) H.Karst. wood. Border pits in the longitudinal tracheids appear degraded whilst signs of attack by fungi are also visible along the tracheid lumen (left-hand side of image). The wood sample belongs to an assemblage of wooden stocks used for the construction of a road excavated from the medieval part of Oslo (ca. 1200–1300 CE). Image: A. Zisi, © Museum of Cultural History.
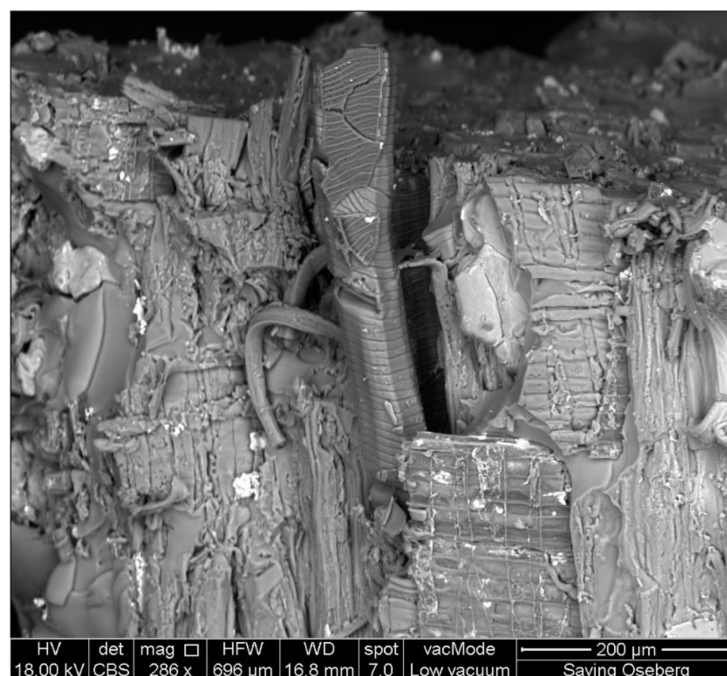
Figure 4. Scanning electron micrograph of a radial-longitudinal section from heavily degraded alum-treated wood (*Betula* spp.) from the Oseberg wooden collection. Protruding in the middle of the image is a perfect casting of the lumen of a vessel member with the bars of the scalariform perforation plate indented on its surface. Attached to the casting are pieces of the actual cell wall. The wood sample was treated with a silanol-based consolidant during re-conservation trials [33]. Image: A. Zisi, © Museum of Cultural History.
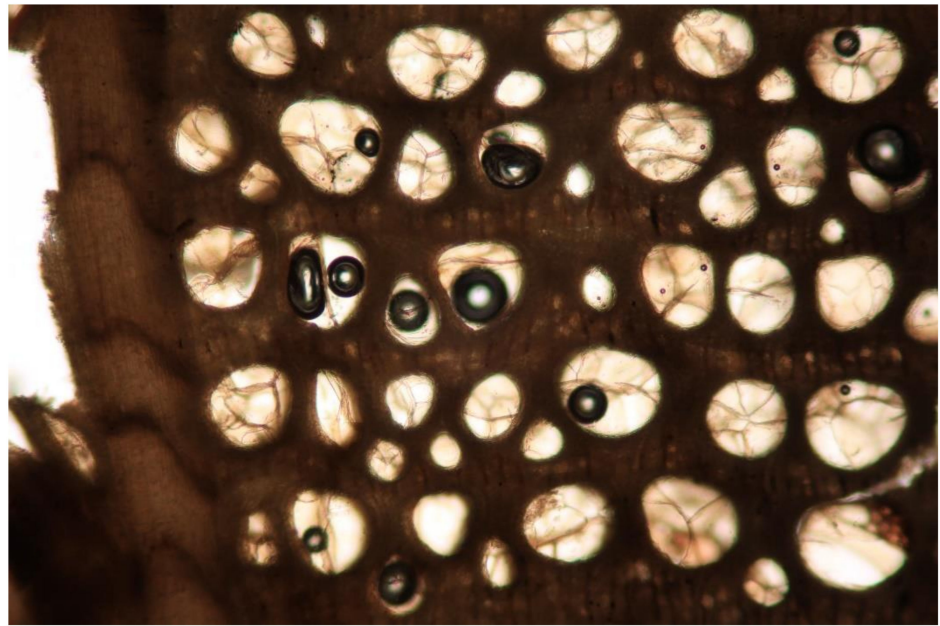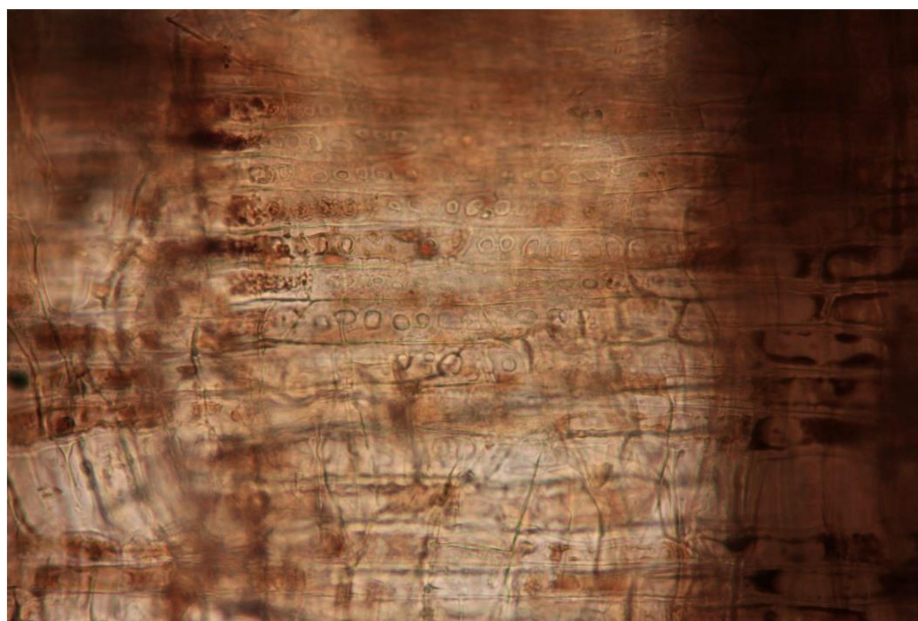
Figure 5. Light microscope image of a transverse section of a slow-grown *Quercus* spp. wood belonging to the White oak group (50×). Formation of tyloses in vessel members is prominent. The waterlogged wood sample derives from an underwater excavation site at the mouth of Ropotamo River located along the Bulgarian coast [34]. Image: A. Zisi, © Black Sea MAP.

Figure 6. Light microscope image of a tangential-longitudinal section of a *Pistacia* spp. wood (100×). Intervessel pits alternate. The waterlogged wood sample derives from an underwater excavation site at the mouth of Ropotamo River located along the Bulgarian coast [34]. Image: A. Zisi, © Black Sea MAP.

Figure 7. Light microscope image of a radial-longitudinal section of a *Quercus* spp. wood belonging to the White oak group (400×). Vessel-ray pitting with much reduced borders to apparently simple. The pits are rounded or angular. The wood sample belongs to one out of a number of piles forming a retaining wall found to the east of Lechaion's ancient harbour entrance canal during underwater excavations in Greece. Image: A. Zisi, © Lechaion Harbour Project.

Wood identification requires good knowledge of wood anatomy, training, access to reference collections, experience and continuous practice. That historical wood can be degraded, and in many cases heavily degraded, can add complexity to the process of identification and can mislead an untrained eye. Deriving a species can also prove impossible. If left unsure, the best solution is to seek advice from a wood anatomist. Besides, the first interest for the conservator is not to identify the wood type but to recognise and assess the preservation state of these wood anatomical features.

It is broadly through these pathways and the fact that in the dead wood cells the lumen is predominantly empty, on which the conservator can rely, together with any other voids and their interconnection for transferring conservation agents inside wood (Figure 8). Identifying these microstructural characteristics and their preservation state [35,36], gives valuable insight into the type of conservation agent, means of application and success of conservation treatment.

3.3. Physical Properties

3.3.1. Basic Density

Identifying the wood type has yet another importance for conservators. Whether dry or waterlogged, wood loses mass or else its density decreases due to deterioration. It is noted here that in contrast to the fields of timber industry and wood science, where 'dry wood' can denote oven-dried wood with 0% moisture content, in the fields of historical wood conservation and archaeology, the term 'dry wood' has been established to separate wood with moisture content in an air-dried condition from wood found in waterlogged contexts and therefore in a waterlogged condition, termed 'waterlogged wood'. As the degree of wood deterioration is a function of the amount of mass lost, knowledge of approximately the amount of wood that would be expected as in the healthy wood species counterpart, allows calculations to be made and classifications of a degradation level to be defined [37].
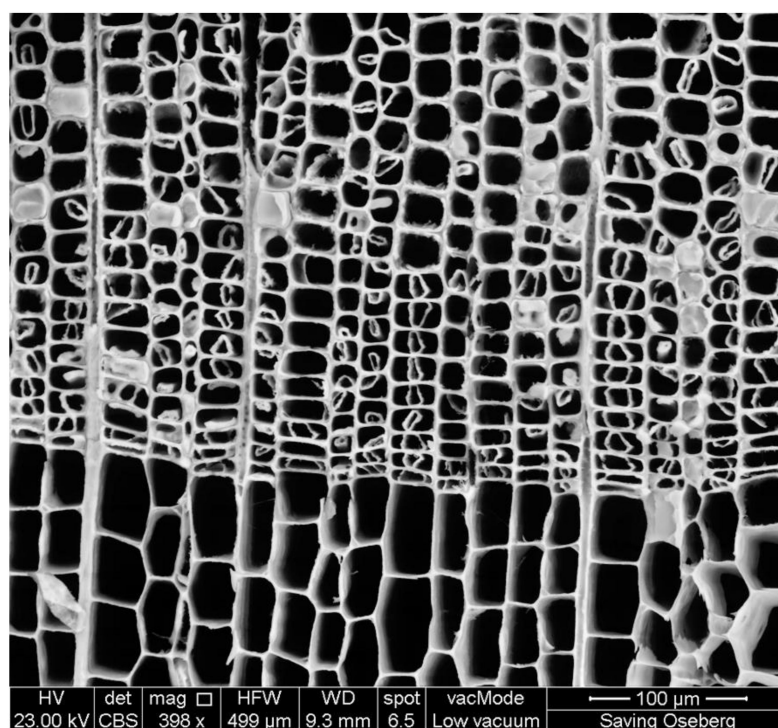
Figure 8. Scanning electron micrograph of a transverse section from historical waterlogged *Picea abies* wood. Latewood cells show severe degradation. There is pronounced secondary wall separation and collapse, with mainly parts of the primary wall and the middle lamella still in place. Seen also is the lumen of only a few latewood cells filled (or plugged) with 20% Paraloid B72 in acetone; the lumen of the earlywood cells remained empty after impregnation. The wood sample belongs to an assemblage of wooden stocks used for the construction of a road excavated from the medieval part of Oslo (ca. 1200–1300 CE). Image: A. Zisi, © Museum of Cultural History.

Basic density (based on oven-dried weight/wet or waterlogged volume) is a wood degradation benchmark for conservators. With a special note always in mind that density comparisons between that of historical wood and the average of a recent counterpart cannot be considered accurate, especially if assessed without a morphological evaluation of the wood's microstructural condition—Macchioni classifies wood samples with residual basic density (RBD%) lower than 65–70% as degraded, and with lower than 40% as heavily degraded [38]. Similarly, Jensen and Gregory suggest a density as low as 100 kg·m^{-3} to be representative of a severely degraded piece of wood, while densities around 400–500 kg·m^{-3} correspond to well-preserved wood irrespective of species [39].

Basic density is one of the first physical wood properties to be defined and can be easily performed and understood by every conservation laboratory. For wood in a waterlogged condition, density is calculated based on its oven-dried weight (at $103 \pm 2\,^{\circ}$C till constant weight is reached) and waterlogged volume. The same applies to dry wood, although, the challenge for the conservator to precisely measure the volume of dry fragile and irregularly shaped wooden artefacts would be greatly benefitted by using a low-cost device developed by Kavvouras and Fotopoulou [40].

3.3.2. Hygroscopicity

It is well known that wood absorbs and releases water vapours due to its cellular make-up. Responsible for this are the hydroxyl groups of cellulose and hemicellulose due to their good affiliation to water molecules. Lignin, the third component of the cell wall which holds things together, is comparatively less hydrophilic. Wood cell walls will thus respond to changes in the relative humidity and temperature in the air or soil it is preserved in, until it reaches an equilibrium. That is when it neither gains nor loses

moisture, a condition called equilibrium moisture content (EMC). It can be deduced that historical wood will not necessarily reach the same moisture equilibrium levels compared to sound wood under the same environmental conditions. It depends not only on the residual amount of chemicals in its cell wall and cell wall integrity, but also on the presence of any extraneous inclusions or previous treatments.

Degraded waterlogged heartwood *Pinus sylvestris* retrieved from excavations in historical Oslo with a measured density of 314 kg·m^{-3} (*o.d.*weight), that is RBD 63% compared to recent sound heartwood of the same species from Norway, reached EMC 11% after freeze-drying and conditioning at 50% ($\pm$2%) RH and 20 °C. After immersion in water for 24h, the same wood raised the MC to 63% and after another 24h under vacuum application to MC$_{max}$ 249%. Although in its dried state the moisture content of the historical wood did agree perfectly with that of its recent counterpart, the latter reached MC$_{max}$ just 101% [41]. The amount of water intake by historical wood echoes the process of wood mass loss. Empirical data reveal a very strong linear relationship between moisture content and basic density advancing wood degradation, with water now substituting the voids in historical waterlogged wood (Figure 9). For conservators woods with moisture content of more than 400% coupled with RBD less than 40% are classed as highly deteriorated. Water contents of more than 1000% for historical wood have been reported in the past [42].
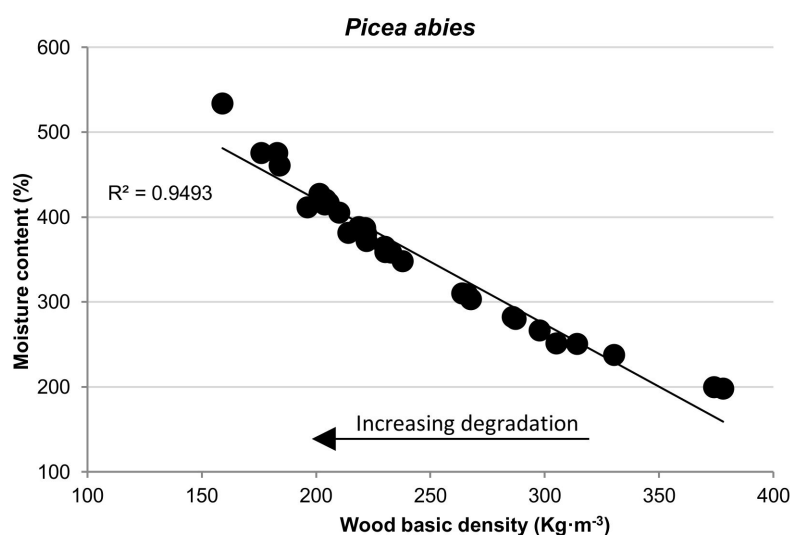
Figure 9. A strong linear relationship (r^2 = 0.949) exists between wood basic density and moisture content increasing wood degradation (*n* = 30) (author's unpublished work). A quadratic polynomial seems to better explain the relationship between the two variables (r^2 = 0.993), however, a linear is given here just for reasons of simplicity.

3.3.3. Dimensional Stability

Wood cell walls will react to changes in surrounding humidity by either swelling or shrinking. The challenge for the conservator is to minimise and control for likely dimensional changes. For dry wood, when strengthening of the cell wall is not required due to a fairly good condition of the wood, this could be accomplished passively by storing or displaying it in a controlled environment—usually 50–55% RH and 20 °C. For dry wood in need of mechanical reinforcement or for wood in a waterlogged condition, invasive methods have to be used [43].

Ideally, treatment will not amplify some possible shrinking or swelling that could be expected when invasively dealing with an object. This is most certainly true for objects with interlocking parts where possible tensions towards different directions could build up during treatment, particularly when not all parts are degraded to the same level (e.g., either repairs made whilst the object was in use [44], or later repairs). Concern rises for objects that are not in a strong enough state to be dismantled and treated separately, or when it is rather

doubtful if the separated pieces will match well after treatment. This is a fairly common phenomenon in historical wood conservation or re-conservation, with an immediate impact on the readability of the object. A good conservation agent would therefore be inert to, or even able to counteract such tensions, possibly by improving elastic properties.

Rowell and Youngs [45] calculate the antishrink efficiency (ASE) on the basis of the treated volumetric swelling coefficient which includes dimensional changes along all three wood directions, radial, tangential and longitudinal. Yet, the contribution of the longitudinal shrinkage could be omitted, as very low to negligible changes are expected along this axis and because it is chiefly influenced by the fibre organisation. A focus on the transverse shrinkage is more useful as changes across this area are mostly influenced by the density of the wood [46], upon which conservators base basic condition assessments, as already mentioned. Nonetheless, consideration should be shown to objects including juvenile wood as this part of the tree can exhibit significant longitudinal shrinkage in undegraded wood.

Grattan et al. note that the higher the transverse ASE, the better the treatment for waterlogged wood [22]. A hundred percent ASE signifies no dimensional change; equal to zero a total ineffectual treatment; and more than 75%, a reasonable result unless the wood is highly degraded, whereupon the ASE aimed at has to be very high for a treatment to be of a significant value for waterlogged wood conservation. Johns rightfully emphasises that antishrink efficiency values need to be evaluated cautiously since the comparison is made between two different populations, the untreated controls and the treated one [47]. This is important when designing experiments for testing various different conservation agents on wood, to aim for consistency among the groups being tested. For example, when experiments are run using directly historical material rather than one specially selected or engineered for the purpose, where the advantage of dealing with the authentic material outweighs the disadvantage of a loss of control over experimental variables [48]. Thus, interpretation of results would benefit from a careful distribution of the material so that any 'irregularities', that is, wood grain orientation, conversion type, especially flat-sawn, growth ring curvature, presence of reaction wood, inclusions like knots, amount and distribution of latewood bands, etc. that could affect ASE anyway, are represented in all groups and as equally as possible. Lastly, Johns raises a concern regarding ASE measurement precision when it comes to lightly degraded wood where dimensional changes might be small [47].

The amount of acceptable dimensional change is something that has to be defined by collection curators. For example, after the first conservation attempt of a wet wooden table from Gordion tumulus in Turkey in 1957, results were deemed unsatisfactory due to intense wood shrinkage, 9% tangentially and 6% radially after solvent-drying wood with ethanol and consolidating it with a solution of paraffin wax in benzene (in ref. [49]).

Similarly, this author noted tangential and radial shrinkage of 7.5% and 2.7%, respectively for degraded *Picea abies* treated via immersion in 15% Butvar B98 in 60:40 toluene/ethanol, and 6.1% and 3.5% after immersion in 20% Paraloid B72 in acetone [41]. The wood had first gone through a dehydration process from a waterlogged state (MC_{max} = 216%) via solvent exchange in successive baths, starting with 70% ethanol in water and finishing in pure acetone. Values might look reasonable for the timber industry, yet a 2.7% dimensional change could make tool marks disappear. It is suggested here that, responsible for the rather large dimensional change is a combination of extractives removal by the solvents and the subsequent use of a low resin concentration. As mentioned, extractives are deposited in cell lumina and cell walls and can be extracted by organic solvents as are alcohol and acetone. If extractives are removed from the cell wall, a definite impact on the shrinkage of wood is expected [46,50,51]. Moreover, fragments of the structural cell wall polymers could also have been removed by the solvents in this case. Therefore, the dehydration of the waterlogged wood undermined further its already compromised preservation by increasing the void volume in wood, which the low resin concentration was incompetent to support adequately. Further reduction of the initial resin concentration can be assumed due to the already solvent-wet state of the wood. Also, the solubility of wood in ethanol/benzene

(replaced by toluene as it is less carcinogenic) is an ASTM standard to measure extractive contents [52].

Recent work has shown a strong linear relationship between the weight percentage gain of water-based polyethylene glycol (PEG) by degraded wood and its transverse swelling. In a direct comparison, when non-water-based consolidants were used to treat the same experimental material, the relationship between weight gain and dimensional change (in the transverse direction) was either very weak or nonexistent, therefore, highlighting different chemical interactions taking place between the wood cell wall and aqueous- and non-aqueous-based treatments [41].

3.4. Chemical Properties

Carbon, hydrogen and oxygen combine to form the principal organic components of wood substance, namely cellulose, hemicellulose and lignin. Lignin is the cell wall component that differentiates wood from other cellulosic materials produced by nature due to its higher contribution to wood [53,54]. Moreover, extractives and ash content in wood are also relevant to conservation.

The mainly crystalline structure of cellulose makes it harder for fluid penetration. However, the fewer amorphous cellulose regions could be characterised as the polymer's weak points. The reason is that these areas account for moisture-absorbing structures in the cellulose microfibrils [55,56], which attract more water molecules by direct hydrogen bonding with them and so forth, setting-off a process of cellulose hydrolysis, although its rate seems to be significantly slowed down by the way cellulose structures water molecules above its surface [57]. In an alkaline environment, for example, submerged in the sea, cellulose swells. When the pH is too high the polymer's end units detach without further extensive depolymerisation. However, depolymerisation occurs in an acidic environment and affects the wood's mechanical strength. Hemicellulose is more readily degraded than cellulose due to side groups branching out of the main polymer axis, which prevents a tighter arrangement among chains as in cellulose [49]. Semi-crystalline hemicelluloses are attacked by strong alkalis, whereas they are easily hydrolysable in acidic environments, where extensive chain breakdown also occurs. The amorphous lignin is chemically far more stable than the other two components of the cell wall and is commonly found to be the last one to go. It imparts rigidity and dimensional stability to the cell wall. It is, however, sensitive to ultraviolet light which is a major factor for its degradation when wood is exposed to it. An example of the effect of ultraviolet light on lignin is shown in a dry Chinese fir sample from a 170-year-old wooden building in China, where 4% lesser lignin content (determined according to GB/T 744-1989) was found in the outermost wood layer exposed to the sun than the immediate middle and innermost areas [58].

Fungi and bacteria are capable of depolymerising wood for food in all types of environments—dry, wet or waterlogged. In general, deterioration by microorganisms starts from the least resistant component and moves on: hemicellulose < α-cellulose < lignin [59]. Non-biological chemical deterioration also takes place. For example, degradation of the cell wall and modification of the residual lignin that could not be ascribed to the act of microorganisms was found on wood from the high Arctic buried or frozen for 20–60 million years [60]. The proximity of wood to metal objects and metal corrosion in burial environments or in composite artefacts is another reason for chemical decomposition, as well as past conservation treatments. Thorough analyses of wood from the Oseberg collection, treated with alum more than 100 years ago, showed that the source of acidity was the alum treatment itself. With pH values even close to zero, wood is now mainly composed of lignin with up to 97% relative abundance (measured by pyrolysis-gas chromatography-mass spectrometry (Py GC-MS)) whereas, in this case, holocellulose has a 3% relative abundance [61]. For comparison, sound wood had relative abundances ranging between 21–42% for lignin and 58–78% for holocellulose [62]—the term ascribed to the total fraction of cellulose and hemicellulose.

An 8000-year-old waterlogged piece of oak wood from a Neolithic lakeside settlement in northern Greece [63], was found to contain an average of 76% lignin and 37% holocellulose (measured in accordance with ASTM D 1106-96 and ASTM D 1109-84) with values for sound wood from the literature, approximately 24% lignin and 20% holocellulose [48]. The careful reader will notice that numbers in the historical wood exceed 100%. That is because values were derived separately, using two different methods. As Florian notes, using methods for characterising and quantifying degraded wood chemicals would seem more appropriate than those designed for normal wood [64].

Lastly, regarding ash content—the inorganic content in wood. High values even up to 28% as those found in a waterlogged wood sample from the Gjellestad ship (author's unpublished work), are values that should not surprise conservators and researchers. In this case, the wood has been filtering the minerals from the soil around it like a sponge due to its severe degradation and loss in mass. Ash quantities as high as this are considerable and need to be accounted for when determining the degree of degradation—can lead, for example, to density overestimation—and when designing conservation actions and research for suitable conservation agents as wood might have lost its woody nature.

3.5. Mechanical Properties

Moisture content in wood has a very strong effect on its mechanical properties up to its fibre saturation point. Severely deteriorated wood loses its strength because of reductions of the crystal structure in the remaining cellulose. Cell walls can turn thin and weak and become prone to shrinkage and collapse. In weathered wood deterioration of earlywood cells is faster than that of the latewood cells, which show a two- to six-fold endurance to weathering; although as a whole, deterioration due to weathering is a very slow process [49]. Mass loss might occur, but not detected if replaced by minerals, typical of deteriorated waterlogged wood (or intentionally as in the conservation of the Oseberg wood). Careful study of the mechanical properties of buried historical waterlogged wood indicated a broad reduction of its compression strength parallel to the grain, static bending and stiffness [65]. Strength losses are not directly proportional to mass losses but are affected by integrity disturbances of the remaining substance. An increase in the plasticity of deteriorated cell walls [66] has been suggested as a possible explanation for the high values of impact bending strength matched with low stiffness values [65]. The comparison of Oseberg alum-treated wood to crisp-bread, retaining approximately 2–5% of the bending strength and 6–8% of the modulus of elasticity of fresh wood is representative of the challenges conservators are faced with [67]. Life becomes a bit more challenging for those involved when the artefact is furthermore a structural member of a construction such as temples, bridges, roofs [68,69] or the mothership of conserved shipwrecks, the Vasa [70].

## 4. Burial Environment and Wood Deterioration

Extreme environments [71], favour wood preservation: the dry dessert [72], sea water [73], rivers [74] and lakes, peat bogs [75], the cool and dry conditions of permafrost [76,77], any anoxic environment [78].

Shrouded in an old romantic narrative, organic wood, as indeed all types of cultural material, does not really reach an equilibrium with the surrounding environment only to be disturbed upon discovery. Wood never stops interacting with the dynamic natural environment surrounding it either passively as a source of food for organisms or energetically by the exchange of material (sediment, water, organics and inorganics), or by energy itself (sun, wind, wave, tide, currents, storm), until it reaches final disintegration [79,80]. Conservation of cultural wood has benefited from work demystifying historical wood degradation by microorganisms from dry, wet and waterlogged environments, from researchers as Blanchette [81–85] and Björdal [86–89]. Eaton and Hale [90], as well as Zabel and Morell [91], give collective background knowledge on wood microbiology and decay also for the interest of wood conservators, as is the latest extensive contribution in biodeterioration of wooden cultural heritage from both aquatic and terrestrial sites by the

conservator Pournou [92]. Below, emphasis is given to presenting wood from marine burial environments as these are usually out of sight and reach for most (probably also because of the author's bias). Although, there are no serious reasons forbidding extrapolating, to some extent, the approach in understanding the burial processes and their effects on cultural material, from the marine to the terrestrial environment.

Wooden shipwrecks on the ocean floor will first interact with it physically as would any newly introduced object to the underwater environment [93]. Over time, shipwrecks transform into fragments of the natural geological configuration and their physical effect is less significant [94]. Biochemical deterioration, however, does carry on. Even in the deep sea [78], wood will be used to its highest potential [95,96], as a whale carcass reaching the deep-sea bed [97]. Even so, the suggestion by Muckelroy that it is the composition of the seabed, rather than the depth at which a wreck lies, determines its preservation, does have basis [98]. Especially if preservation means 'existence' and not the degree of degradation, as archaeologists tend to believe. For wood that will quickly cave in on itself in a featureless bed of mud and hard clay, assisted by scouring and tides is better protected from biological and erosive actions than exposed parts. The Mary Rose ship in Portsmouth is a clear example of this. Like a clam missing one of its shells, her once-buried and so preserved half, stages today a unique glimpse into life on board a warship in the early-mid 16th century northern Europe.

By classifying marine environments based on characteristics of the biozone, as are types of seabed, seabed movement by waves and currents, levels of sunlight, water temperature and salinity fluctuations, it is easier to identify the physical, chemical, geological and biological characteristics of the environment surrounding and interacting with a site. A shipwreck lying in abyssal zones will be subjected to a different deteriorating environment compared to a wreck in the intertidal and neritic zones. Depth seems to inversely influence the variability of the deterioration of a wreck within the same zone across the geographical map, with that of the abyssal being the most constant (Figure 10) [99,100]. Although this can be challenged as new research from these remote waters is coming into light [101]. Jordan gives a thorough insight into the site characteristics affecting the survival of historical waterlogged wood [102]. Parameters such as water level, pH and evaluations of dissolved oxygen content, redox potential and concentrations of chemical elements of a site, are very useful when possible [103].
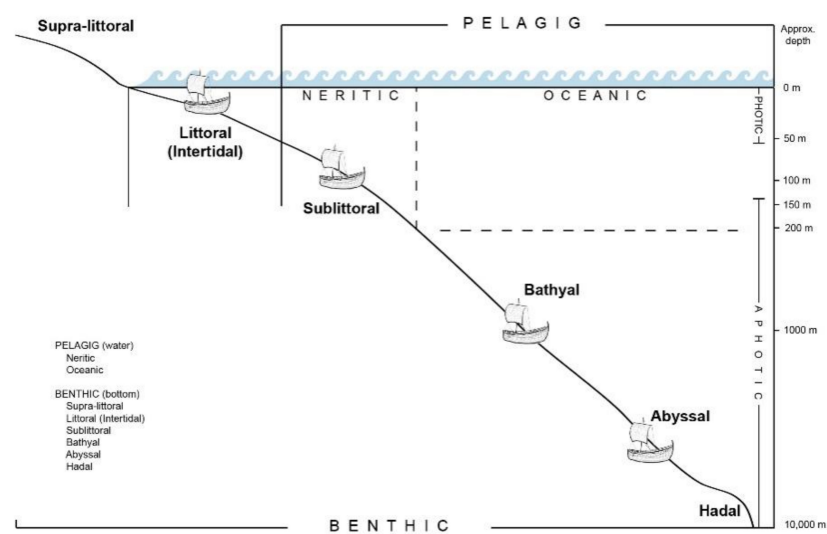
Figure 10. Classification of marine environments based on characteristics of the biozone [21] (after [99,100]). Artistic representation by A. Zisi of the Kyrenia, a 4th century BCE ancient Greek merchant ship.

The possibility of a ship's timbers being preserved and to what extend depends on the microenvironment or else the wood/marine environment interface, as this defines the speed of deterioration [89]. Two conditions play a chief role, the interface affiliation and the chemical environment [100]. Theoretically, the part of the wooden ship in contact with the sediment is preserved in good condition. It is favoured by fairly anoxic conditions promoted in close relation to sediment type and inclusions (e.g., organic matter poor), and environmental conditions. Analysis of the silt/clay sediment from around the Kolding cog shipwreck, Kolding Fjord, Denmark, for instance, showed that anoxic conditions were prevalent at a depth of only 6 mm below the sediment/water interface [104]. Jordan suggests that wood degradation from microbial activity is more likely related to the exposition of wood's end-grain surface rather than the depth of anoxia in the sediment [104].

In the clear blue waters of Lechaion, Greece, substantial amounts of wood remains from the infrastructure of the ancient harbour are still buried or exposed to the warm, saline and, in some cases, very shallow (50 cm deep) sea. Even with physical, chemical and micromorphological analyses to define their preservation state under way, the main challenging factor for wood preservation, and indeed existence, is their 'natural' excavation, exposure and eventual perish. Lying in a dynamic underwater environment, their documentation is a brave against nature and time.

5. Assessing Degradation State

In 1970, Christensen, conservator at the National Museum of Denmark, wrote in his book [105] (p. 9): 'We cannot standardize the artifacts and other productions of our ancestors. [...] objects passing through the hands of conservators and restorers will go on being hopelessly heterogeneous, not only typologically but also as regards materials and condition'. Fifty-one years of wood conservation progress later, this learning is a fact describing the best part of wooden artefacts across conservation laboratories worldwide. Christensen's approach to making sense of the degradation state of cultural wood by training himself so as to anticipate results remains one of the greatly motivating written resources for those new to the field, both conservators and wood scientists. For the best way to manage expectations, whether conservation attempts or research on historical wood, dry or waterlogged, one has to put this truth wholeheartedly and design actions stemming from it.

In 1981, Hoffmann [106], a wood scientist, introduced for the first time in wood conservation, a number of chemical tests by the Technical Association of the Pulp and Paper Industry (TAPPI) in an effort to standardise, insofar as possible, the characterisation of cultural wood. His aim was to give confidence to wood conservation laboratories in choosing conservation treatments for their collections based on educated decisions beyond personal experience. Jagels et al. [66] and Schniewind and Kronkright [107], most wood scientists themselves, but also one conservator, extended the assessment by adding the evaluation of the residual mechanical strength for both waterlogged and dry wood, practices borrowed from forestry and wood science sectors.

Starting from what was known to approach the unknown, today a vast selection of methods exist or have been adopted for assessing the degradation state of historical wood [108–110]. This is a result of cultural conservators receiving exponentially more scientific education and training than four decades ago and because of 'rapid developments in new instrumentation technology, computer technology, physics and chemistry, and by easier access to large scale instrumental facilities' [111]. However, it is also a response to more material coming to light that needs special care, or new problems arising from past conservation treatments as there has been time for them to age; and it is well known that with age come problems. It is the nature of conservation of cultural heritage to rely on cross-disciplinary research in finding suitable solutions to today's challenges [112]. This 'increasingly evidence-based approach' [108], '[...] is easy to foresee that [...] will continue and accelerate even more' [111].

Away from the bright lights, the bench conservator may well still find herself or himself depending on poking a piece of art wood with a humble needle to assess the degradation state. Not only because there has to be training as well as a rationalization behind using novel methods, but also, because the advantages of development are not equally shared in all parts of the world. This is unfortunate considering that the need for preserving every culture is of equal significance. This imbalance needs our attention together with our appreciation (even among conservation colleagues), combined with the fact that, more often than not, preservation of tangible and intangible culture—the raison d'être—still relies on the intuition, experience, skills and responsibility of the conservator.

6. Conservation

'A storyteller arrives, one hundred millions of years from now, to tell the tale of human species. It is an interval that will add a couple of per cent to the age of Earth and a little under one per cent to the age of the Universe.' [113] (p. 7). 'Contemporary society throws away infinitely more [...] if fossilized, might overwhelm the interpretive capacities of our far-future observers' [113] (p. 170).

In a world full of inanimate objects, the antique meaning of the word 'conservation' has rather faded away, certainly in the Western world. Resources and labour producing things in the past were too valuable to cast away compared to the present day. As this author experienced at terrestrial excavations in Corinthia in Greece, when a *pithos*—a ceramic storing vessel with a diameter of more than a meter—was broken in the past, the breakage would have been repaired by drilling holes and mounting lead staples, thus, prolonging its service life. Yet, as Dooijes and Nieuwenhuyse suggest, 'extending the social life of the object' seems additionally imprinted in ancient repairs [114]. The authors justly bring out the value of ancient repairs as fragments of the cultural biography of objects, since repairs reflect the perception and ideals of the time, even the ever-changing ones. Naturally, one cannot think through the minds of those people of the past, so as to claim they were thinking beyond their life span, millennia far into the future, to us, when doing so.

However, preserving the evidence of existence is a conscious act by the conservator of today. Conservators are here to assist, in hand with archaeologists and art historians, to not lose contact with past time; and they do it first and foremost for the people of the present. Our aim is not necessarily to force future generations to accept the values or use of heritage in the same way as past generations defined them and used them [115], but rather to allow the present generation to contemplate, question, feel, become inspired and participate in discussions, if not more. Nagmeldeen Morshed Hamza from the Conservation Center Giza in Egypt stated in his presentation during the last ICOM-CC Triennial Conference in Beijing (19 May 2021): 'Conservation is not only treatment of objects, conservation is a successful communication of interdisciplinary collaboration to conduct a meaningful and successful conservation methodology'. Today, as never before, has conservation of cultural material brought together conservators, scientists and experts from various backgrounds from all over the world, to communicate and understand each other. Perhaps that is a value past generations unknowingly handed down to us through their creations. It is the tangible as well as the intangible fruits of this communication, together with conserved heritage, which we are passing on to generations yet to come for use as they seem fit.

More than 30 years ago, Peterson perceptually remarked that 'artistic and social science definitions have a strong influence on conservation definitions' [116]. He continues: 'If we are to successfully encourage wood scientists to research areas that have application to conservation problems, scientists must be able to understand, if not appreciate, what constitutes both conservation problems and conservation solutions'. Success can be reached if conservators also make their way towards the middle ground by receiving more education on what wood and the science of wood are. Together with better dialog, 'problems of communication between disciplines will be solved' [116].

Indeed, through these past decades, far more conservators have added academic skills to their manual skills. An existing and continuously growing scientific literature of

cross-disciplinary research answering thousands of questions proves this. The disciplines of wood conservation and wood science (if not many other), and cultural heritage itself, have benefitted from significant findings and new knowledge, triggered by the challenge of dealing with wood as an artefact. This generates brilliance for future generations.

For those who have worked closely with historical finds, solutions do not always rely on numbers. Intriguingly, they rely on the experience and intuition acquired by practising conservation. Conservators are practical people 'resourceful and good technologists' [116]. They are capable of seeing the bigger picture and bridging the expectations with the reality called historical wood. Their inclusion in research projects from the very start will ensure work goes in the right direction. It is not that the efforts that do not involve conservators lack real science, but rather that the solutions offered may not become popular. At the same time, if conservators lose their manual skills and confidence, and are only focused on their academic side or other administrative work, they may not be able to offer instrumental insight to such endeavours [117].

7. Instead of Conclusions

This contribution has for the most part a Western-centred approach. Yet, conservation philosophy in the Far East, as in China and Japan, differentiates. There, it is a custom to replace deteriorated elements of, for example, wooden temples and lacquers, with new materials using the original recipes and techniques [118]. Methods and materials might be irreversible to the eye of the sometimes strongly ethical-oriented Western conservator, and difficult to use. However, the answer is that materials have been tested for so long and there is no concern as to the level of difficulty in applying them because with this philosophy it has been possible to preserve the skillset, tradition and culture uninterrupted for so long. As Jaeschke notes [118], 'the historical significance lies in the construction of the monument and the restoration process itself' and allows reuse.

In the aftermath of his translation of Tanizaki's '*In Praise of Shadows*' written in 1933, Harper notes that: '[. . .] for Tanizaki a museum piece is no cause for rejoicing. [. . .] art must live as a part of our daily lives or we had better give it up. We can admire it for what it once was, and try to understand what made it so [. . .] but to pretend that we can still participate in it is mere posturing' [11] (p. 72).

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