Selecting and Sampling Shipwreck Timbers for Dendrochronological Research: practical guidance

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In this article, we provide practical and straightforward guidance for the selection and sampling of shipwreck timbers for dendrochronological research. We outline sampling strategies and present informative figures that illustrate how to proceed in a variety of scenarios that archaeologists regularly encounter. However, in order to fully exploit the potential of tree-ring research on these objects, we would urge archaeologists to involve dendrochronologists during the project planning phase to carefully plan and conduct adequate sampling of shipwreck assemblages.

Key words: shipwrecks, guidelines, timber sampling, wood provenance, dendrochronology, best practice.

Determining the construction period and place of a ship is paramount for nautical archaeologists studying shipwrecks and ship timbers (Farrell and Baillie, 1976). Dendrochronology is a powerful tool that can provide clues to elucidate those questions. Once the date and provenance of timber used for ship construction, and indeed timbers and wooden artefacts found in the ship's cargo, are established, it is possible to infer information about the construction period of the ship and the timber resources used, as well as the length of its working life, and even the route it sailed. Even if an absolute date for construction cannot be established, the tree-ring patterns of the examined surviving timbers can produce valuable information on the craftsmanship of the ships' builders, wood conversion processes, and the timber assemblage, such as forest management practices, selection of different species, preferred growth rates for specific timber elements, number of trees employed, and so on. The possibilities for applications of tree-ring research in nautical archaeology have been illustrated in recent years through the study of different types of shipwreck assemblages (Loewen and Delhaye, 2006; Daly, 2007; Daly and Nymoen, 2008; Dobbs and Bridge, 2008; Domínguez-Delmás *et al.*, 2013; Haneca and Daly, 2014; Martín-Benito *et al.*, 2014; Nayling and Susperregi, 2014; Daly and Belasus, 2016).

However, the range of research questions that can be answered by dendrochronology is directly linked to the chosen sampling strategy, and archaeologists are often confronted with the question of how to select and sample timbers for dendrochronological research. Existing literature provides general guidelines for sampling timber elements from archaeological sites and historical buildings (Morgan, 1975; Nayling, 1991; Historic England, 1998; Miles, 2006), and although most of these guidelines are applicable to the research of shipwrecks, they are mostly biased towards the selection of samples with numerous rings because these are more likely to provide a date. Intrinsic to research on shipwrecks, there are two additional factors that increase the complexity of the inspection, selection, and sampling of timbers, and which therefore warrant further consideration apart from previously published guidelines: first, the environment in which the selection and sampling of timbers has to be carried out, often under water, with limitations including visibility, tools and time; second, ships could be built with wood from different species supplied from different, sometimes distant, geographical areas, and they may also contain reused or refitted timbers. Consequently, wood from different species, periods, and source areas could be present in the same shipwreck.

These peculiarities make shipwrecks a most challenging research object, requiring adequate planning and a specific sampling strategy, as all shipwreck timbers contain valuable cultural information (Rich *et al.*, 2018). A well-conducted timber selection and sampling programme can assist retrieving that cultural information, opening a window to past craftsmanship, cultural contacts, and human-environment interactions. This paper aims to provide practical and straightforward guidelines for the selection and sampling of shipwreck timbers for dendrochronological research in order to fully exploit the scientific potential of tree-ring research in nautical archaeology. These guidelines are the result of the authors' accumulated experience researching shipwreck assemblages, and different situations and scenarios are considered to account for the various circumstances in which one might be sampling a shipwreck: under water, on land, in the intertidal zone, or in a museum or conservation setting. Timbers being sampled may be in a variety of conditions, so we consider waterlogged timbers, as well as those about to undergo conservation treatment and those that have already been treated for long-term preservation and public display because, fundamentally, 'large quantities of conserved timber can have little intrinsic value if no identifications or analyses may be carried out' (Morgan, 1975: 229).

Key concepts in dendrochronology

To establish an adequate sampling strategy that is both efficient and ethically sound, some basic knowledge about tree growth and wood anatomy is required.

Identification of wood species

The identification of the wood species used in the construction of a ship entails the examination of a significant number of timbers. The results may assist in more closely defining the potential construction area (Guibal and Pomey, 2003; Pulak and Liphschitz, 2007/2008; Allevato *et al.*, 2010; Liphschitz, 2012). Also, taxa identification of the ship timbers and of wood cargo may provide valuable information about the trade of timber for the ship's construction, or the route it sailed. For instance, a majority of structural elements made of Mediterranean tree species will point towards a shipyard in the Mediterranean region (for example Giachi *et al.*, 2003). The scattered presence of elements made from tropical wood on a ship otherwise suggestive of a European origin might indicate repairs at a shipyard where such wood was available, whereas a predominance of tropical wood in structural timbers would imply a construction site in, for example the Caribbean, north-east South America, Africa, India, or Southeast Asia, depending on the species identified.

Only very few timbers used for shipbuilding can be identified to the species level through microscopic examination of their wood anatomical features. In most cases, only a botanical identification up to genus level is possible. Some genera have a very wide spatial distribution, so their identification does not help to identify the likely growth location of the trees. For instance, whereas a predominance of *Q. pyrenaica and Q. faginea* in a shipwreck would point towards a construction area in the Iberian Peninsula because these species are endemic to this territory alone, the fact that they cannot be distinguished by their wood anatomical features from *Q. robur/petraea*, which have a wide geographical distribution across Europe (Crivellaro and Schweingruber, 2015) would prevent attributing the ship to a construction area in Iberia. Therefore, not only must the taxonomic identification of these oak samples be limited to the widespread category of deciduous oak, such as *Quercus* subg. *Quercus*, but moreover, they cannot be used to assign a likely construction area (Domínguez-Delmás *et al.*, 2013: 120–121).

Oak was the most widely used species group along the Atlantic seaboard and the rest of coastal northern Europe for the construction of ships. Even with the naked eye, basic wood anatomical observations can identify oak during the inspection of ship timbers because the wood is characterized by large earlywood vessels placed in a ring-porous disposition, and large multiseriate rays clearly visible in the transverse section (Fig. 1). This combination of anatomical features is unique to the oak group. Sweet chestnut (*Castanea sativa*), for instance, is very similar to the group of deciduous oaks, but it lacks the very wide multiseriate rays; therefore, it can easily be distinguished from oak. Tropical species, however, are much more difficult to identify and require the microscopic examination of thin sections (Fig. 1), along with wood anatomical databases and identification keys. Even then taxonomic identification might be restricted to the family or genus level (see Wheeler, 2011). Likewise, all non-deciduous oak timbers can only formally be identified through microscopic examination of their wood anatomy by making thin sections for microscopic observations and using authenticated reference collections of thin sections and/or illustrated identification keys (Schoch *et al.*, 2004).

Tree-rings

Most tree species that grow in temperate and continental climate zones produce a growth ring every year directly under the bark. Trees of the same species growing at the same time in the same area will have similar growth responses to the same annual variations in climatic factors, such as temperature and precipitation, making it possible to cross-match their individual ring-width sequences to produce reference chronologies. For example, broadleaf species native to the northern hemisphere such as deciduous oaks (*Quercus* subg. *Quercus*) and beech (*Fagus sylvatica*), and conifers such as pines (*Pinus sylvestris*, *P. nigra*, etc.), fir (*Abies* sp.), spruce (*Picea abies*), and larch (*Larix* sp.), have distinct annual growth rings that have enabled researchers to develop ring-width reference chronologies that can be used to date historic timbers converted from these tree species. However, the response of specific individual trees to natural or anthropogenic disturbances including coppicing and pollarding, may hamper their suitability for dendrochronological dating. This is the case of species such as walnut (*Juglans regia*) or poplar (*Populus* sp.): while producing growth rings with annual resolution, their short lifespan and long history of management for timber or fruit production hinder crossdating and the development of reference chronologies that permit dating. Additionally, many trees growing in tropical climates produce growth rings (Worbes and Fichtler, 2011), but they often lack annual resolution, which is a crucial feature needed to apply dendrochronology as an absolute chronometric dating technique. Although samples of such tree species may not be useful for dating, they are nevertheless relevant for wood species identification, which provides insight into decision-making processes that occurred in the shipyard.

Sapwood

The sapwood consists of the living (physiologically active) wood tissues that transport the sap from the roots to the leaves. It is located along the outermost part of stems and branches (Fig. 2). In some species, such as the group of deciduous oaks, chestnut, larch (*Larix decidua*), and most pines for example, sapwood can be distinguished by its lighter colour. In other species, however, such as beech or fir, there is no clear distinction between heartwood and sapwood, and the felling date may only be established if the bark, or the waney edge, is present in the sample. The sapwood is more prone to biological degradation than the more durable heartwood, situated towards the centre of a tree (Fig. 2). Shipwrights were aware of the perishable character of sapwood, so it was often removed during the process of timber conversion; however, in most instances partial sapwood will be present in some parts of framing timbers and planks.

Oak samples taken from timbers with sapwood but which lack waney edge (Fig. 2C) may still provide the opportunity to determine the felling date range of the parent tree. For oak trees growing in specific regions, the minimum and maximum number of sapwood rings is fairly consistent. This means that a statistically sound estimate can be made of the expected number of missing sapwood rings when only partial sapwood survives (Hughes *et al.*, 1981; Hillam *et al.*, 1987; Wazny and Eckstein, 1991; Miles, 2006; Rybnicek *et al.*, 2006; Haneca *et al.*, 2009; Sohar *et al.*, 2012). Such an estimate allows for the determination of an interval of some years during which the actual felling date of a tree occurred. When the felling date ranges for the parent trees of dated timbers with sapwood have been established, it is possible to infer the probable construction date of the vessel (Domínguez-Delmás *et al.*, 2013). Therefore, when selecting timbers for sampling for dating purposes, priority should be given to those retaining at least some sapwood (Fig. 2).

Bark or waney edge

Dendrochronological dates are precise to a specific calendar year and may even permit dating of the felling season of the parent trees from which ship timbers were derived. However, this requires that the analysed sample retains the complete outermost ring. While the bark is usually missing, the outermost tree-ring under the bark is often present in framing elements made of oak, and very occasionally in some parts of radial planks. In these cases, the surface of the timber appears continuous and smooth (Fig. 2D). This area, known as the 'waney edge', may cover a large portion of the timber, but more often will only survive along one corner of the framing element or in a small section of a radial plank. If present, the sample removal location needs to be chosen with care in order to include both the waney edge and the longest possible sequence of tree-rings. In some cases, it may be necessary to take multiple samples from the same timber to meet both these objectives.

Crossdating

Crossdating is the basic concept of dendrochronology (Fritts, 1976: 20). This procedure consists of synchronizing or cross-matching individual tree-ring series based on their comparable patterns of wide and narrow rings. Crossdating can be performed on tree-ring series of samples from the same tree, as well as on series from different samples collected from different timbers originating from trees that grew under similar conditions. A group of crossdated tree-ring series from shipwreck timbers can be averaged into a mean series or object chronology representing the average growth pattern of those trees (Fig. 3). By comparing the object chronology with dated reference chronologies of the same species from different sites and regions, crossdating can be achieved and the absolute calendar date for each growth ring is identified. Additionally, the provenance of the wood might be revealed when outstanding statistical results are found with chronologies specific to a certain region; such a statistical match could indicate the area from which the trees for the ship originated (see Daly and Nymoen, 2008; Domínguez-Delmás *et al.*, 2013; Haneca and Daly, 2014; Rich *et al.*, 2018).

Sampling strategy and rules

The dendrochronological research should be determined during the planning phase before excavation or recovery of the vessel, so that the sampling strategy can be established in accordance with the research questions outlined in the project design. These questions may include:

When was the ship built?

What is the geographical origin of the wood used in its construction?

Was the ship built of timber from a single or from multiple sources?

When and where were repairs or later adjustments to the original design made?

Were timbers from the same tree used at different positions in the ship?

What type of forest did the ship timbers originate from: for example dense-canopy forest, or open landscape?

Were different timber elements, such as hull planks and framing timbers, made from the same genus, geographical origin, or types of trees?

If the construction period of a ship is the key question, sampling should prioritize timbers with sapwood and, if possible, waney edge. Framing elements, through-beams, and hull-planking elements are likely to belong to the original structure and should therefore be targeted. Timbers that may have been replaced or that may have been reused may be disregarded. However, such timbers should be considered if the goal is to gain information about the working life of the ship or the route sailed. Although the sampling strategy can quickly become a complex consideration (Rich *et al.*, 2018), we propose five easy-to-remember sampling rules that apply in all cases.

Rule 1. Record, label, sample

Before any sample is taken, the position of the timber in the ship and, when possible, the timber itself must be adequately labelled and recorded, through drawings, photographs, or any other means according to the possibilities of the site. This is a crucial step in the process that allows the results to be placed in the exact context of the shipwreck. During the sampling of *in situ* shipwrecks prior to any excavation, detailed recording of the timbers from which the samples are taken is not likely to be possible as they will mostly be partially buried. In this situation, the location of each sample combined with a photograph of each sample location should suffice as part of an evaluation of the site. This is commonly undertaken to assess the significance of the wreck-site and assist identification of shipwrecks found largely buried in the intertidal zone or on the seabed. Under other circumstances, where the ship's timbers have been mostly exposed or recovered for post-excavation documentation, then sampling should only take place once the timber record has been completed. The location of any sample, whether a core, wedge, or full cross-section slice, should be added to this timber record. Often the taking of a full cross-section slice means that a single timber will become three separate pieces that can be described as the parent, orphan, and sample. Here, the parent is defined as that part of the timber that retains the original timber label, and the orphan is that part that has become separated and is in danger of losing its identity. Each needs to be labelled and appropriate entries made in the timber register to ensure that the three can be re-united (for example after conservation) and the contextual information of the sample is secure. When only macro-photographs of the transverse section of a timber are taken to extract ring-width data, this process should also be meticulously recorded.

Rule 2. Sample timbers in context

When sampling shipwrecks *in situ,* as tempting as it may be to sample opportunistically by selecting loose timbers lying on top of or close to the wreckage, this is to be avoided because their exact position in the ship and relative chronology can seldom be established with certainty. Loose fragments of wood may belong to the cargo or may not belong to the ship at all. Therefore, a careful and deliberate selection of timbers should be made from different parts of the intact shipwreck assemblage. Samples of structural timbers from all preserved areas of the vessel (stern, bow, starboard and port) will ensure that the retrieved tree-ring sequences are interpreted within the context of the ship.

Rule 3. Size does not matter

To select the best sample for dendrochronological research, the growth rate of the wood (that is the average width of the tree-rings) and the type of timber conversion (for example, radially split vs tangentially sawn) are more important than the size of the timber. Dendrochronology typically requires tree-ring series with more than 80 annual growth rings to generate a reliable and statistically sound match with reference chronologies. However, one cannot assume that massive portions of timbers, or timbers with large diameters, will contain more tree rings than timbers with a small diameter or section. In fact, sometimes, thick framing elements have been processed from fast-grown oak trees that have very wide tree rings and were only a few decades old when felled (Fig. 4). Shipwrights knew that young, fast-grown oak trees produce much denser wood, that is heavier per volume, and therefore more suited to resist specific forces, with better mechanical properties, such as higher bending strength and stiffness, than slow-growing oaks. Such properties were appreciated for framing elements in a ship; however, fast-grown trees were not always necessarily selected for those elements, and we have also found framing timbers derived from old slow-grown trees, such as those made of French oak in the Arade 1 shipwreck (Domínguez-Delmás *et al.*, 2013: 127), or the Southern Baltic oak frames in the Bøle ship (Daly and Nymoen, 2008: 160). Dendrochronological research on shipwreck assemblages from northern Europe has shown that during medieval times and up to the 15th century, thin hull planks were often processed from slow-grown oak trees by radial splitting of the trunks (see for example Daly, 2007; Daly and Nymoen, 2008; Soberón Rodríguez *et al.*, 2012; Nayling and Jones, 2014). Those planks often contain numerous tree-rings, as slow-grown oak trees are much easier to split than fast-grown ones. From the late 14th century onwards, however, planks were increasingly processed with saws in a tangential fashion, and the selection of slow-grown trees became less relevant. Additionally, different wood species have different properties whether they are fast or slow-grown. Slow-grown pine is denser than fast-grown, quite the opposite to oak, where slow-grown wood is less dense. Consequently, timbers of all sizes should initially be considered, and a careful inspection should be carried out prior to sampling in order to select the best-suited timbers for further dendrochronological analysis.

Rule 4. Try to avoid wood borers

Although dendrochronologists can often find their way around samples severely affected by *Teredo navalis* or other wood borers (Fig. 5), the chances of retrieving a long, continuous tree-ring sequence from such samples are low. There are many other bio- geo- and anthropogenic agents that damage exposed ship timbers as well. While the most superficial timbers of a shipwreck assemblage are usually the most damaged, the parts that have remained buried for a longer time are often in a considerably better state of preservation (Björdal and Gregory, 2011; Palma and Santhakumaran, 2014). Consequently, to avoid unnecessary damage to the shipwreck assemblage by removing samples that cannot be used, timbers in good condition should be targeted preferentially, which may require excavation to reach those parts of the vessel that have been protected by stratigraphy.

Rule 5. More is more

As a rule of thumb, the more samples taken, the more information gained; however, this requires that samples are taken from different parts of the shipwreck assemblage. As stated in Rule 2, timber elements that belong to the structural context of the ship and that are located in different positions across the ship should be sampled because a good balance of samples from different parts of the ship structure will yield the most valuable results (Orton, 2000). Additionally, it is necessary to take multiple samples from all parts of the shipwreck to enhance the possibility of creating object chronologies for those different groups of timber. This will increase the chances of dating the samples and, by extension, of determining the geographical origin of the wood. However, while more is typically better, particularly when dealing with ships that might have been built of timber from different sources, a compromise will have to be made between the number of timbers that can be sampled (for example financial constraints, potential damage to a shipwreck to be publicly displayed, and so on), the quality of the samples that will be obtained for tree-ring analyses, and the research questions to be answered. Clearly, it is better to have few high-quality samples than dozens of low-quality ones. The total number of required samples depends on the vessel, the timber quality in terms of growth rate and conversion method, and again, the research questions being asked. A highly generalizing rule of thumb would suggest that 20–50 samples should be removed from an archaeological ship-timber assemblage, each from a different structural timber group with the entire assemblage being represented.

When the goal is to study the use of timbers from the same tree in the ship, for example if one wants to check the assumed symmetrical layout of planks from the same parent tree in the hull of a ship (see Haneca and Daly, 2014: 98), more samples should be taken in addition to the standard dendrochronological sampling strategy. Elements originating from the same parent tree will (usually) display a conspicuously high correlation between their tree-ring patterns.

Sampling methods in varied circumstances

Under water

In many cases, shipwreck sampling campaigns will be conducted under water, in conditions that could vary from crystal-clear seas to muddy rivers. When sampling under water, it is often most convenient to remove cross-sections from exposed ends of timbers, although these exposed areas are also often the most deteriorated (see sampling Rule 4). If the wood is not too badly damaged, remove the end using a wood saw (Fig. 6A, B). If there is too much damage, or if the transverse end of the timber is not visible, or not accessible (for example if the ends are overlain by other wreckage or joined to other timbers, or they are buried beneath a great deal of sediment), samples may be removed from the centre of a timber (Fig. 6C); however, this requires making two cuts under water, meaning that the labour and time needed for sampling is doubled. Another possibility is to remove a wedge sample (Fig. 6D). To take a wedge sample, the saw is positioned at an acute angle to the length of the timber. After cutting some centimetres into the timber, the saw is removed and then placed 4–5cm further down the timber at an opposite angle so that the cuts join some centimetres into the timber, and a wedge-shaped piece of wood can be removed. If the dendrochronological potential seems promising, in that there is sapwood and/or the annual growth rings are narrow indicating an older longer-lived parent tree, it may be worthwhile to dedicate a whole dive, or more, to removing a full cross-section from this timber. Sampling from the middle of timbers is more likely to compromise the structural integrity of the assemblage, so it should be considered a last resort.

Clearly, the safety of the divers is more important than removing that last cross-section. Sawing large timbers under water requires a great deal of physical exertion, and divers should be prepared to extend their usual air consumption rate by two or three times. There are also associated dangers of using saws under water, where lacerations can easily occur without the diver even being aware of them. Chainsaw sampling under water should only be undertaken by surface-supplied divers wearing a hard helmet (Fig. 7). In this case the diver should be an experienced, competent and qualified chainsaw user. It is normally prudent for no other divers to be close by at the time. Using increment borers under water is not an option because the diver has limited to zero leverage; even if the diver successfully manages to insert the borer, the presence of cavities covered by shells from shipworms, such as *Teredo navalis,* would destroy the drill bit, the core sample could be mangled beyond use, and any sapwood could be destroyed. In our experience, Stanley® FatMax® handsaws with BladeArmor® coating have proven the most effective instruments for removing cross-sections under water due to an effective tooth pattern that maximizes sawing efficiency, along with a coating that resists oxidation in the marine environment (Rich *et al.*, 2018: 22).

Making judgement calls under water, where cognitive faculties are stunted by the environmental effects of submersion on the human body, is an extraordinarily difficult task and important decisions should be made on land for this reason. Along with increased time, expense, and risk, this too is an unavoidable aspect of working in this unique environment and one that archaeologists should factor into their diving and sampling plans (for more on underwater sampling strategies and methods, see Rich *et al.*, 2018).

On-land and intertidal

Considerations on where and how samples should be taken from wrecks excavated on land or in the intertidal zone are similar to those under water, but here the working conditions are less restrictive. Sawing cross-sections is still the method that will produce the most intact samples, especially to preserve any remains of the soft sapwood or waney edge. Obtaining cross-sections with a chainsaw by a licensed user is the fastest method, but the choice of saw should be considered in relation to possible later conservation of the shipwreck and/or its timber assemblage. A chainsaw removes more wood when cutting than a narrower kerfed hand-saw; hence the latter is to be used when the intention is to put the fragments together after conservation.

Again, a cross-section should be taken from timbers in context (Rule 2) to avoid analysis of material that does not belong to the original vessel. Examine the timber for any remains of the outer, lighter-coloured, soft sapwood, and sample across these locations. Sample the timber where it is not damaged by erosion, drying out, dredging etc. Observe whether the timber has large knots in the wood. The sample should not be taken across knotty wood, as sawing is much more difficult at the knotted grain, and more importantly, the tree rings are distorted, hampering possibilities to obtain a representative tree-ring pattern. A slice of the timber does not need to be thicker than 3–5cm.

Taking cores from waterlogged wood for dendrochronological analysis is only seldom successful. Several coring tools exist and can be divided into dry-wood and fresh-wood models (Fig. 8). The fresh-wood borers are designed for coring living trees. Waterlogged timbers in a shipwreck should be very well preserved for a borer of this type to work. Very solidly preserved oaks will invariably have a very soft outer surface, especially where sapwood is preserved. This soft wood will not remain intact using the borer, and vital outer rings will be thus missing from the sample. A combination of wedge sampling of the outermost rings and increment coring of the heartwood can be productive.

If the timbers are going to be retained for later conservation, more samples could be taken later on if necessary.

Before or after conservation treatment

Ship timbers that have already been excavated are often the subject of dendrochronological analysis either before or after conservation. The condition of these timbers varies greatly. Some elements may have been allowed to dry out, or may have only superficially been treated with preserving products. Others may have been kept submerged so that they remain waterlogged. Still others may have been through full conservation treatment, most often with polyethylene glycol (PEG), or a combination of PEG and freeze-drying. The condition of these timbers in combination with their value as heritage objects will dictate to a large extent how sampling for dendrochronology is best carried out. Those timbers that are still waterlogged should be sampled in the same way as those during excavation, taking slices using a saw (Fig. 9A). Timbers that have been dried after PEG impregnation can be cored with a dry-wood borer (Fig. 9B). This is best done by a dendrochronologist so that the best sample, with maximum possible tree-rings, is achieved. Observation of the grain of the timber and remains of sapwood, bark, or waney edge is made in order to choose the best sampling position in the timber. According to the type of dry-wood borer used, a hole of 12mm (Berlin-type borer) up to 23mm (Pressler borer) will be visible on the timber after sampling, hence the position where the samples are taken should be thoroughly recorded (sampling Rule 1).

If end-grain is accessible on timbers, either because the timbers were already sawn after excavation, or if the shaping of timbers in antiquity exposed the timber cross-section, the section can be cleaned with razorblades and macro-photographs can be taken including a measuring scale

(Fig. 9C). The tree-ring pattern is subsequently measured on the calibrated images. This whole procedure should be executed by a dendrochronologist.

Non-invasive analysis is also possible in certain circumstances. Dried-out timber (and probably certain conserved wood with a very low moisture content) can be analysed using micro-focus CT scanning but, currently, there are limits to this technique regarding the size of the object that can be scanned in this way (Bill *et al.,* 2012; Van den Bulcke *et al.*, 2014; Daly and Streeton, 2017).

Sampling for wood identification

The sampling of timbers for species identification can be achieved simultaneously with the inspection and selection of timbers for tree-ring research. Species identification of timbers selected for dendrochronological research will be carried out on the same sample; however, for timbers that will not be sampled for dendrochronology, a small piece of wood of at least $1cm^3$ (preferably 2–$3cm^3$) can be retrieved with a utility knife or sharp chisel. Such a sample allows the specialist to identify its taxonomical classification by observing wood anatomical features on thin sections through detailed microscopic examination.

Sample handling and storage

The handling and storage of dry wood or PEG-preserved samples is quite straightforward and can be done by placing the individual samples (cross-sections) in reclosable plastic bags, and then in a box, taking the necessary measures to ensure that the sapwood will be preserved, such as wrapping the sample in the bag with bubble plastic so that it will not move when placed in a box. Samples taken with dry-wood borers should be placed in plastic or paper straws of the required diameter and once at the laboratory they can be mounted and glued in wooden supports if necessary for further handling.

Waterlogged wood (cross-sections) should be kept wet, out of direct sunlight, and, when possible, cool. To achieve this goal, samples should be placed individually inside labelled, sealed plastic bags with some fresh or salt water, and as little air as possible (see Rich *et al.*, 2018, fig. 21). Waterlogged samples should be handled with great care and sent for analysis to a dendrochronology laboratory shortly after collection. When lag time between sample removal and dendrochronological analysis cannot be prevented, samples should be kept refrigerated, or held in another dark, cool environment.

Concluding comments

A well-preserved shipwreck timber assemblage is an archive not only of historic shipbuilding and carpentry but also of climatic fluctuations, forestry practices, and international trade, which can cast light on broad socio-environmental changes. In sampling shipwreck timbers for tree-ring analysis, the information gained can include such fundamental data as exact calendar dates and provenance, but the ring-width patterns can also contribute to ongoing studies of global concern. For example, tree-ring series from ancient shipwrecks and submerged forests can help develop long-term Holocene climate records and determine how plant and human species have reacted to rapidly rising sea levels, an issue which is of concern today as we face unprecedented levels of global warming and sea-level rise.

In order to ensure that the full research potential of the material can be attained, a dendrochronologist should ideally be integrated into the project team on an archaeological investigation of a shipwreck timber assemblage, preferably from the outset during development of the project design. This specialist should undertake the timber sampling whenever possible. When the dendrochronologist cannot undertake the sampling required, for example if they do not have the relevant diving qualifications or competence to dive on a particular site, then they can provide training to the other team members. Where archaeological organizations expect to undertake recurrent investigations of ship-timber assemblages, consideration should be given to arranging training sessions on how to select and sample timbers for dendrochronological research. Individual archaeologists may be able to access training through the Nautical Archaeology Society International Education Programme (http://www.nauticalarchaeologysociety.org) or by contacting dendrochronologists directly for advice.

Although the potential data gained from sampling may be proportional to the destructive impact of removing samples, sampling strategies must always be formulated with the idea of minimizing that destructive impact (Rich *et al.*, 2018: 16). Beyond efficiency and knowledge-gain, ethics must prevail. Being able to provide answers to the all-important research questions of place and date of construction is one of the key aims of shipwreck archaeology. At the same time, UNESCO guidance on the protection of underwater cultural heritage makes clear that even scientific activities 'shall not adversely affect the underwater cultural heritage more than is necessary for the objectives of the project' (Maarleveld *et al.*, 2013: 37; sampling Rule 3). Consequently, the best way to ensure that the impact of scientific activities is proportional to the potential knowledge-gain is to follow a cautious step-by-step approach and phased decision-making; only then can knowledge acquisition and preservation of cultural heritage be reconciled and a way forward be foundmeet and find a way forward.

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References

Allevato, E., Russo Ermolli, E., Boetto, G., and Di Pasquale, G., 2010, Pollen-wood analysis at the Neapolis harbour site (1st–3rd century AD, southern Italy) and its archaeobotanical implications. *Journal of Archaeological Science* **37,** 2365–2375. DOI: 10.1016/j.jas.2010.04.010

Bill, J., Daly, A., Johnsen, O. and Dalen, K.S., 2012, DendroCT—dendrochronology without damage. *Dendrochronologia* **30**, 223–230.

Björdal, C.G., and Gregory, D. (eds), 2011, *WreckProtect: Decay and Protection of Archaeological Wooden Shipwrecks*. Oxford: Archaeopress.

Crivellaro, A., and Schweingruber, F.H., 2015, *Stem anatomical features of dicotyledons. Xylem, phloem, cortex and periderm characteristics for ecological and taxonomical analyses*. Kessel Publishing House.

Daly, A., 2007, The Karschau Ship, Schleswig-Holstein: Dendrochronological Results and Timber Provenance. *IJNA* **36.**1, 155–166.

Daly, A., and Nymoen, P., 2008, The Bøle ship, Skien, Norway—Research history, dendrochronology and provenance. *IJNA* **37**.1, 153–170.

Daly, A., and Belasus, M., 2016, The dating of Poel 11 and Hiddensee 12, Mecklenburg-West, Pomerania, Germany. *IJNA* **45**.1, 170–205.

Daly, A., and Streeton, N.L.W., 2017, Non-invasive dendrochronology of late-medieval objects in Oslo: refinement of a technique and discoveries. *Applied Physics* A **123**, 431–443.

Dobbs, C., Bridge, M.C., 2008, Construction and Refits: Tree-Ring Dating the *Mary Rose*, in P., Marsden (ed), *Your Noblest Ship. Mary Rose: anatomy of a Tudor warship*, 361–367. Portsmouth: Mary Rose Trust.

Domínguez-Delmás, M., Nayling, N., Waszny, T., Loureiro, V., and Lavier, C., 2013, Dendrochronological dating and provenancing of timbers from the Arade 1 Shipwreck, Portugal. *IJNA* **42**.1, 118–136.

Farrell, A.W. and Baillie, M.G.L., 1976, The Use of Dendrochronology in Nautical Archaeology. *Irish Archaeological Research Forum III* **2**, 45–55.

Fritts, H.C., 1976, *Tree rings and climate*. London: Academic Press.

Giachi, G., Lazzeri, S., Mariotti Lippi, M., Macchioni, N., and Paci, S., 2003, The wood of 'C' and 'F' Roman ships found in the ancient harbour of Pisa (Tuscany, Italy): the utilization of different timbers and the probable geographical area which supplied them. *Journal of Cultural Heritage* **4**, 269–283.

Guibal, F., and Pomey, P., 2003, Timber Supply and Ancient Naval Architecture, in Beltrame, C. (ed.), *Boats, Ships and Shipyards Proceedings of the Ninth International Symposium on Boat and Ship Archaeology 12/2000*, 35–48. Venice.

Haneca, K., and Daly, A., 2014, Tree-Rings, Timbers and Trees: a dendrochronological survey of the 14th-century cog, Doel 1. *IJNA* **43**.1, 87–102.

Haneca, K., Cufar, K., and Beeckman, H., 2009, Oaks, tree-rings and wooden cultural heritage: a review of the main characteristics and applications of oak dendrochronology in Europe. *Journal of Archaeological Science* **36**, 1–11.

Hillam, J., Morgan, R.A., and Tyers, I., 1987, Sapwood estimates and the dating of short ring sequences, in Ward, R.G.W. (ed.), *Applications of tree-ring studies: current research in dendrochronology and related areas*, 165–185. Oxford: BAR International Series 333.

Historic England, 1998, *Dendrochronology: Guidelines on producing and interpreting dendrochronological dates.* English Heritage. Online resource: https://content.historicengland.org.uk/images-books/publications/dendrochronology-guidelines/dendrochronology.pdf/

Hughes, M.K., Milsom, S.J., and Leggett, P.A., 1981, Sapwood estimates in the interpretation of tree-ring dates. *Journal of Archaeological Science* **8**, 381–390.

Liphschitz, N., 2012, Dendroarchaeology of Shipwrecks in Israel. *Bocconea* **24**, 95–104.

Loewen, B., and Delhaye, M., 2006, Oak growing, hull design and framing style. The Cavalaire-sur-Mer wreck, *c.*1479, in L. Blue, F. Hocker and A. Englert (eds) *Connected by Sea: Proceedings of the Tenth International Symposium on Boat and Ship Archaeology, Roskilde 2003*, 99–104. Oxford: Oxbow Books.

Maarleveld, T., Guerin, U. and Egger, B. (eds), 2013, *Manual for Activities Directed at Underwater Cultural Heritage: Guidelines to the Annex of the UNESCO 2001 Convention*. Paris: UNESCO.

Martín-Benito, D., Pederson, N., McDonald, M., Krusic, P., Fernandez, J.M., Buckley, B., Anchukaitis, K.J., D'Arrigo, R., Andreu-Hayles, L., and Cook, E., 2014, Dendrochronological dating of the World Trade Center ship, Lower Manhattan, New York City. *Tree-Ring Research* **70**, 65–77.

Miles, D., 2006, Refinements in the interpretation of tree-ring dates for oak building timbers in England and Wales. *Vernacular Architecture* **37**, 84–96.

Morgan, R.A., 1975, The selection and sampling of timber from archaeological sites for identification and tree-ring analysis. *Journal of Archaeological Science* **2**, 221–230.

Nayling, N., 1991, Tree-ring dating: sampling, analysis and results, in J.M. Coles and D.M. Goodburn (eds), *Wet Site Excavation and Survey,* 44–50. Exeter: WARP Occasional Paper No. 5.

Nayling, N. and Jones, T., 2014, The Newport Medieval Ship, Wales, United Kingdom. *IJNA* **43**.2., 239–278.

Nayling, N. and Susperregi, J., 2014, Iberian Dendrochronology and the Newport Medieval Ship. *IJNA* **43.**2, 279–291.

Orton, C., 2000, *Sampling in Archaeology*. Cambridge University Press.

Palma, P., and Santhakumaran, L.N., 2014, *Shipwrecks and Global 'Worming'*. Oxford: Archaeopress.

Pulak, C. and Liphschitz, N., 2007/2008, Wood species used in ancient shipbuilding in Turkey: Evidence from dendroarchaeological studies. *Skyllis* **8**, 74–83.

Rich, S., Nayling, N., Momber, G., and Solana, A.C., 2018, *Shipwrecks and Provenance: in-situ timber sampling protocols, with a focus on wrecks of the Iberian shipbuilding tradition*. Oxford: Archaeopress.

Rybnicek, M., Vavrik, H. and Hubeny, R., 2006, Determination of the number of sapwood annual rings in oak in the region of Southern Moravia. *Journal of Forest Science* **52**, 141–146.

Schoch, W., Heller, I., Schweingruber, F.H., and Kienast, F., 2004, *Wood anatomy of Central European species*. Online resource: www.woodanatomy.ch

Soberón Rodríguez, M., Pujol Hamelink, M., Llergo López, Y., Riera Mora, S., Juliá Brugues, R. and Domínguez Delmás, M., 2012, El Barceloneta I. Una embarcación medieval a tingladillo en Barcelona. *ITSAS Mem*. **7**, 411–422.

Sohar, K., Vitas, A., and Läänelaid, A., 2012, Sapwood estimates of pedunculate oak (*Quercus robur L.*) in eastern Baltic. *Dendrochronologia* **30**, 49–56.

Van den Bulcke, J., Wernersson, E.L.G., Dierick, M., Van Loo, D., Masschaele, B., Brabant, L., Boone, M.N., Van Hoorebeke, L., Haneca, K., Brun, A., Luengo Hendriks, C.L., and Van Acker, J., 2014, 3D tree-ring analysis using helical X-ray tomography. *Dendrochronologia* **32**, 39–46.

Wazny, T., and Eckstein, D., 1991, The dendrochronological signal of oak (Quercus sp.) in Poland. *Dendrochronologia* **9**, 35–49.

Wheeler, E.A., 2011, InsideWood—a web resource for hardwood anatomy. *International Association of Wood Anatomists* Journal **32**.2, 199–211.

Worbes, M., and Fichtler, E., 2011, Wood anatomy and tree-ring structure and their importance for tropical dendrochronology, in W.J. Junk, M.T.F. Piedade, F. Wittmann, J. Schöngart, and P. Parolin (eds), *Amazonian floodplain forests. ecophysiology, biodiversity and sustainable management*, vol. 210, 329–346. Dordrecht: Springer Netherlands.

Figure captions

Figure 1. Cross-sections of timbers of different species. A: oak (*Quercus* subg. *Quercus*) framing element of the Arade 1 shipwreck in which the multiseriate rays can be perceived by the naked eye; B: chestnut (*Castanea sativa*) framing element of the Arade 1 shipwreck in which multiseriate rays are lacking; C: planks from the cargo of the Delta II shipwreck made of two different (unidentified) tropical species; C1, C2: details of the transverse section of those planks: chalk powder applied on the surface highlights the presence of numerous pores and the lack of tree-ring boundaries; D: section of a hull plank of *El Triufante* made of pine (*Pinus sylvestris/nigra*). In A and B the portions of the scale bars represent 2cm (photos: Marta Domínguez-Delmás).

Figure 2. Macroanatomy of an oak sample and types of samples depending on the portion of the wood present. A: sample containing only heartwood, arrow indicates the growth direction; B: sample reaching the heartwood/sapwood transition; C: sample with partial sapwood indicated by arrow; D: sample with complete sapwood (waney edge present, smooth area indicated by arrow). (photos: Marta Domínguez-Delmás).

Figure 3. Process of dating and provenancing ship timbers (illustrations adapted from Domínguez-Delmás *et al*., 2013). A: in yellow, oak timbers sampled for dendrochronological research; B: cross-dated tree-ring series from the oak samples are averaged into an object chronology; C: the object chronology is compared with reference chronologies and, in this case, dated with a chronology from the Loire river valley in the West of France; D: provenance plot where each dot represents a site reference chronology, and the bigger the dot, the better the statistical match with that site chronology, which allows the provenance of the wood to be identified.

Figure 4. The size of the timbers is not indicative of the number of tree rings in the wood. A: framing elements of *El Triunfante* shipwreck. Despite their large size (*c.*40 x 40cm) they contained approximately 30 to 50 tree rings and were unsuitable for dendrochronological dating (photo courtesy of Catalonian Centre for Underwater Archaeology); B and C: framing elements of the Yarmouth Roads shipwreck containing 47 (B) and 35 (C) tree rings. All these framing elements in both shipwrecks were obtained from fast-grown oak trees.

Figure 5. Wood samples severely damaged by *Teredo navalis*. A: oak sample of a framing timber from the Ribadeo shipwreck containing pith, waney edge, and 228 tree rings; B: pine sample from a

hull plank of *El Triunfante* containing pith and 117 tree rings (photos: A, Sara Rich; B, Marta Domínguez-Delmás).

Figure 6. Sampling under water. A: sawing the end portion of a hull plank of *El Triunfante* with a Japanese-type saw; B: Yarmouth Roads starboard planks labelled *in situ* and ends removed; C: *La Magdalena* pine ceiling planking sampled from centre; D: sample where a wedge had been taken before sawing to determine if the timber was suitable for dendrochronological research (photos: A, courtesy of the Catalonian Centre for Underwater Archaeology; B, Martin Davies; C, Adolfo Miguel Martins; D, Sara Rich).

Figure 7. Underwater chainsaw sampling of the 17th-century Swash Channel wreck. The surface-supplied diver is equipped with a hydraulically powered chainsaw and is wearing a hard helmet and additional personal protection equipment (photo: Jessica Berry).

Figure 8. Dry-wood borers of different diameters. They are powered by an electric drill and are typically used to sample dry wood, although the first two from the left work very efficiently on PEG-preserved wood (photo: Kristof Haneca).

Figure 9. Sampling methods before and after conservation treatment. A: removing a cross-section, hull plank of the Arade 1 shipwreck; B: coring hull planks with a dry-wood borer, Batavia shipwreck in display at the Shipwreck Galleries of the Western Australia Museum (Freemantle, Australia); C: taking macro-photographs, cross-section of a hull plank from the Doel 1 cog shipwreck (photos: A, Marta Domínguez-Delmás; B, Henrik Kiær; C, Kristof Haneca).