INVITED REVIEW

The principles, procedures and pitfalls in identifying archaeological and historical wood samples

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BACKGROUND

The science of wood anatomy has evolved in recent decades to add archaeological and historical wood to its repertoire of documenting and characterizing modern and fossil woods. The increasing use of online wood anatomy databases and atlases has fostered the adoption of an international consensus regarding terminology, largely through the work of the International Association of Wood Anatomists (IAWA).

SCOPE AND CONCLUSIONS

This review presents an overview for the general reader of the current state of principles and procedures involved in the study of the wood anatomy of archaeological and historical specimens, some of which may be preserved through charring, waterlogging, desiccation or mineral replacement. By means of selected case studies, the review evaluates to what extent varying preservation of wood anatomical characteristics limits the level of identification to taxon. It assesses the role played by increasingly accessible scanning electron microscopes and complex optical microscopes, and whether these, on the one hand, provide exceptional opportunities for high-quality imaging and analysis of difficult samples, but, on the other hand, might be misleading the novice into thinking that advanced technology can be a substitute for specialized botanical training in wood anatomy.

Key words: Wood anatomy, charcoal, scanning electron microscopy, light microscopy, thin sectioning, archaeological wood, historical wood.

INTRODUCTION

The microscopic recognition of detailed cellular features that form the structure of woody trees and shrubs is an integral part of the identification and classification process comprising the scientific discipline of wood anatomy. For many decades, wood anatomy has focused primarily on the differentiation of fresh specimens. To ensure that wood anatomists around the world adopt a uniform protocol for recognizing and describing features, the International Association of Wood Anatomists (IAWA) has created and (regularly updates) catalogues of microscopic anatomical features through its publications (e.g. Wheeler et al., 1989; Richter and Dallwitz, 2000), the IAWA Bulletin (1976–1979), the IAWA Bulletin New Series (1980–1992) and the IAWA Journal (1993 onwards), and the IAWA website (http://www.iawa-website.org/index.html). The InsideWood Project under the leadership of Elisabeth Wheeler (http://insidewood.lib.ncsu.edu/welcome; Wheeler 2011; https://www.facebook.com/pages/InsideWood/368062966397) provides an unparalleled online searchable resource that integrates descriptions and images of modern and fossil hardwoods (dicots) from >200 plant families. At the time of writing, the InsideWood database had 6821 modern wood descriptions and 41 022 modern wood images (in addition to 1785 fossil wood descriptions and 2405 fossil wood images). Other online xylarium databases, wood atlases and publications (such as Schweingruber, 1990; Neumann et al., 2001; Richter et al., 2004; Schoch et al., 2004; Cartwright, 2001; see also http://insidewood.lib.ncsu.edu/links) provide key data on hardwoods and softwoods to the student and professional specialist alike.

It is self-evident that for the reliable utilization of any wood anatomy atlas, database or text, whether it is in hard copy or online, specialist knowledge of botanical structures is essential. Without being able to recognize anatomical structures accurately, these resources cannot function in the manner for which they were designed. For example, searching in InsideWood (http://insidewood.lib.ncsu.edu/search/) for key characteristics such as helical thickenings, when what are actually present are vestiges of scalariform perforation plates, could fatally flaw the whole procedure (even if a number of feature mismatches are permitted). InsideWood is incomparable in the value of its usefulness, but it cannot, and is not intended to provide an entirely global substitute for reference collection specimens and thin sections of wood. Nor can it create ‘instant’ wood anatomists of those lacking the requisite botanical training.

AIMS

By means of selected case studies, this review article aims to illustrate how the discipline of wood anatomy has expanded over the past 30 years to encompass the identification to taxon (at the level of family, genus or species) of archaeological and historical wood specimens. This expansion has accelerated rapidly in the last decade when it has become easier than ever before to access and routinely use sophisticated optical microscopes and scanning electron microscopes. Whilst the basic principles of
wood anatomy remain constant, new technologies and equipment offer the conscientious professional enhanced opportunities for identification and imaging of poorly preserved or very ancient specimens of wood and charcoal. However, such opportunities are not without pitfalls, both in terms of limits of discernment of anatomical features (as will be seen in selected case studies to follow) and also in respect of the requisite protocols and methods adopted. There are many ways in which secure identifications may be jeopardized, and only some examples are presented here. Unreliable identifications may occur when attempted under adverse working conditions by insufficiently trained or supervised individuals, by inadequate reference specimens being available for consultation, by individuals taking 'short-cuts' and only examining transverse sections (see below) at low magnifications on inappropriate equipment, or by sole reliance on comparisons with photographs in books and not adopting the rigorous IAWA protocols involving a sequential feature-by-feature examination.

In order to illustrate more fully what may and may not be possible with regard to the levels of identification of the wood anatomy of archaeological and historical specimens, and to provide a framework of understanding for the selected case studies that follow, it is important to summarize the types of wood preservation that may be encountered. Charring or burning is by far the most common form of preservation of wood on archaeological sites around the world. Charcoal may be found as a result of different forms of deliberate human activities, including selection of fuel-wood for hearths, domestic fires, ovens and kilns, as well as fuel for burial ceremonies and social rituals. It may also be present on archaeological sites as a consequence of accidental conflagrations of timber components within houses, villages or towns, or through natural lightning strikes affecting woody vegetation in the site's environs.

Waterlogging may preserve wood in both archaeological and historical contexts – in freshwater, brackish or marine environments, and in moist peat deposits. Waterlogged contexts will tend to preserve large quantities of plant and other organic material. These may include woody and non-woody taxa that reflect the surrounding natural environment, in addition to artefacts made by people. A contrasting set of ecological and geographical parameters may preserve archaeological and historical wood through desiccation. Extreme desiccation of wood may ultimately result in mineral replacement, for example by silica or calcium carbonate from the surrounding soil. Mineral replacement or mineral preservation of wood can also occur, particularly in archaeological contexts, when the wood is in very close association with bronze or iron metal objects. Within the bronze or iron corrosion products on the internal or external surfaces of the artefacts, remnant traces or negative impressions may survive of the anatomical features of the associated wood. While such traces can be evidence of the wooden component(s) of a composite object, this type of mineral-replaced or mineral-preserved wood could equally well represent vegetation growing adjacent to the final resting place of the artefact – thus having no functional or technological significance.

In addition to all these parameters, mention must be made of the important subject of the variability of wood anatomical structure linked to growth, soils, wounding or frost (amongst other ecological factors); such variability (e.g. Schweingruber, 1990; Carlquist, 2001; Schoch et al., 2004) introduces further complexities for the analytical and identification process.

METHODS

In the relevant publications cited, the reader can find full details of procedures adopted for each case study. In order to draw attention to the particular set of demands associated with the determination of the wood anatomy for these case studies, here follows a summary of the methods and protocols adopted.

Irrespective of the type of preservation of wood encountered – whether charred, waterlogged, desiccated, mineral-preserved or simply old – it is imperative to prepare and examine the three sections needed for the determination of the wood anatomy of each specimen: transverse section (frequently abbreviated to TS), radial longitudinal section (RLS) and tangential longitudinal section (TLS). For modern/fresh wood, including reference specimens, short lengths or cubes of wood from botanically vouchered (or accredited) woody trees and shrubs may be boiled in a beaker of water on a hotplate for an appropriate length of time until sufficiently soft to be sectioned using a microtome. Following standard procedures, the resultant TS, RLS and TLS sections are dehydrated first in an alcohol (ethanol) series before they are cleared in xylene or Histoclear, stained (e.g. with Safranin or haematoxylin) for better cellular visibility under the microscope, mounted onto microscope slides and covered by a cover-slip, ready for light microscopy or polarized light microscopy examination using an optical (also known as light) microscope in transmitted light (Fig. 1). Although the preparation and examination of the wood anatomy revealed in TS, RLS and TLS remains a constant for all types of archaeological and historical samples, techniques of sample preparation will vary to cope with issues caused by variable states of preservation. For archaeological and historical woods that have undergone shrinkage, distortion, alteration or fungal/insect attack, caution and discretion will be needed regarding quantitative IAWA descriptors on InsideWood’s Modern Wood Data Sheet (http://insidewood.lib.ncsu.edu/files/insidewood/ModernWoodDataSheet.xls). It would be misleading, for example, to measure the mean tangential diameter of vessels (feature numbers 40–43) in specimens of archaeological charcoal whose vessel dimensions had been altered by the temperature involved in the burning of the wood (Fig. 2), or indeed in specimens of waterlogged wood whose vessels size and shape (along with parenchyma and fibres) had been severely distorted after rapid drying out following removal from the host marine environment (Fig. 3). Thin sections of archaeological and historical wood samples are made following the above protocol where possible (e.g. Harrison, 2008), although a freezing stage attached to the microtome may be required for sectioning some poorly preserved specimens.

The scanning electron microscope (SEM) may be used for desiccated, fragile or damaged samples of archaeological/historical wood where permanent or temporary thin sectioning is not feasible, on account of either the condition or the small size of the samples (e.g. Attenbrow and Cartwright, 2014). A razor blade may be used to prepare TS, RLS and TLS for examination, either uncoated in a variable pressure SEM (VP SEM) – particularly when the samples are to be submitted
uncontaminated for radiocarbon examination (e.g. Ostapkowicz et al., 2013) – or in a field emission SEM (FE SEM) where the enhanced imaging and magnification capabilities may require the samples to be gold/platinum coated to augment their conducting capabilities in the electron beam (Cartwright et al., 2012b). A cold stage may be used in the VP SEM for moist, but not fully waterlogged specimens (Fig. 4). Both the VP SEM (Fig. 5) and FE SEM can be used for determining the wood anatomy of charcoal (Fig. 6) particularly when high-quality imaging is required (e.g. Leme et al., 2010; Cartwright et al., 2012a), However, given that most archaeological sites produce large quantities of charcoal, routine identification of such material is likely to be carried out using a light microscope (LM) in reflected (also known as incident) light mode on TS, RLS and TLS of each charcoal fragment at magnifications from ×50 to ×1000.

SELECTED CASE STUDIES
Charred wood and charcoal
Composite artefacts that have both organic and metal components preserved are rarely found in archaeological sites dating to the European Bronze and Iron Ages. Usually some particular form of preservation is needed for their survival. One such example relates to the specific technological manufacturing requirements of Iron Age neck-rings or torcs. Iron Age torcs from Snettisham in Britain have shown evidence for a flexible branch of coppiced wood being bent to form a support around which the torc wires had been twisted (Cartwright et al., 2012b). The heating process involved in manipulating the torc wires charred the wooden branch that remained within the core of the torc, thus preserving it in situ, only to be revealed after the torc had become broken over time. The branch was not already in the
form of charred wood or charcoal before becoming the core of the finished torc as charcoal would not have provided the necessary flexible support for the desired shape. Having been preserved in situ and protected by the enclosing metal wires of the torcs (Fig. 7), the charred cores displayed good preservation of their wood anatomical features when examined in the VP SEM, although exposing the requisite TS, RLS and TLS sections was not always straightforward. From a technological viewpoint, it

Fig. 2. Variable pressure scanning electron microscope image of a transverse section of *Olea europaea* subsp. *africana* (African wild olive) charcoal from the archaeological site of Diepkloof Rock Shelter (South Africa), showing that the vessel outlines have been altered by the temperature involved in the burning of the wood. Image: C. R. Cartwright.

Fig. 3. Variable pressure scanning electron microscope image of a transverse section of *Quercus* sp. (oak) waterlogged wood from a 17th century shipwreck in Salcombe Bay (Devon, UK) whose vessel sizes and shapes (along with parenchyma and fibres) have been severely distorted after rapid drying out following removal from the marine environment. Image: C. R. Cartwright, © The Trustees of the British Museum.
was important to try to establish the temperature at which the torc metal wires had charred the wooden cores so thoroughly.

Relevant to this study is the fact that wood retains most of its qualitative features when charred or converted to charcoal, but temperature-dependent anatomical changes occur. These changes vary from one species to another, but experimental charring under laboratory conditions of the identified woods (willow, *Salix* sp.; alder, *Alnus glutinosa*; hazel, *Corylus avellana*; dogwood, *Cornus sanguinea*; elder, *Sambucus nigra*; and field maple, *Acer campestre*) yielded accurate and useful comparative information on temperature-related anatomical alterations (Cartwright *et al.*, 2012b). Such comparative charring...
experiments had already been undertaken by the author to produce highly informative data (including observing the degradation of calcium oxalate crystals in axial parenchyma cells; Fig. 8) relating to temperature-related anatomical changes in kiln-produced and reference specimens of *Mimosa ophthalmocentra* and *M. tenuiflora* charcoal in Pernambuco, Brazil (Leme et al., 2010; Cartwright et al., 2012a).

The size or age of fragments of archaeological charcoal may be of less significance in the discernment of diagnostic anatomical features than the condition of the material. Charcoal from...
cave sites in the south-western Cape of South Africa, for example, dating to well beyond 40 000 years old (Cartwright and Parkington, 1997; Cartwright, 2013), mostly display remarkably good surviving anatomical features despite their great antiquity (Figs 9 and 10). This is presumably attributable to the depth and protected nature of the archaeological deposits in these caves. The level of taxon identification of the charcoal that could be obtained through VP SEM and FE SEM
examination has permitted reconstructions of extraordinary sequences of changing woody vegetation through time (Cowling et al., 1999) in which the most ancient sequences with Afromontane taxa such as *Kiggelaria africana*, *Podocarpus elongatus*, *Chionanathus foveolatus* and *Celtis africana* gradually give way to mesic thicket including *Heeria argentea*, *Maytenus oleoides*, *Cassine peragua*, *Diospyros glabra* and *Dodonaea angustifolia* often coupled with proteaceous fynbos including *Protea glabra* and *Leucadendron pubescens*. The most recent sequences have evidence for the types of xeric thicket (*Euclea racemosa*, *Rhus undulata*, *Ruschia maxima* and *Zygophyllum morgsana*) and asteraceous shrubland (*Eriocephalus aromaticus*, *Aspalathus sp.*, *Passerina glomerata*, *Euryops speciosissimus*, *Chrysanthemoides sp.*, *Hymenolepis parvifolia*, *Salvia africana-lutea* and *Phylica sp.*) that are common in that region at the present day (Cartwright et al., 2014). However, three main cautions need to be highlighted in relation to this research. First, extensive collecting by collaborating botanists over two decades provided securely identified reference specimens from different ecological zones in the south-western Cape without which the research would not have been possible as no existing wood anatomy databases (online or otherwise), descriptive anatomies or atlases existed for that region. Secondly, as a consequence, characterization of the wood anatomy of the collected reference material had to be undertaken by the author before any identification of the charcoal assemblages from the cave sites could proceed (Cartwright, 2013). Thirdly, there was an initial caution over taxonomy (Cartwright and Parkington, 1997) that drew attention to the possibility that species currently unknown in the south-western Cape may have existed there >40 000 years ago. However, in an effort to reflect that caution, for example by citing sp. or cf. after the genus, it became problematic for scholars reconstructing past vegetational/climate changes to detail and model statistically the associated components of vegetational communities, so in later publications, the cf. attribution was omitted where possible. Nonetheless, no identification to taxon was taken beyond the limits of what could be observed within the surviving anatomical features, so in some instances identifications remained at genus level only (or were classified as unidentifiable). Almost invariably, TS, RLS and TLS of the charcoal fragments were obtained by fracturing the fragments manually to produce the cleanest surface for SEM or LM examination. Using a scalpel or razor blade invariably created fine charcoal dust that infilled the cellular features to be examined.

**Waterlogged wood**

Waterlogged archaeological sites in any part of the world have the potential for the survival of large quantities of organic remains including wood and other botanical material. This in itself can create problems when attempting excavations; while the rich and diverse organic preservation is a fertile source of information, it necessitates specific techniques of excavation, retrieval, short-term and long-term conservation of organic artefacts and environmental evidence alike. A good example is the Roman administrative centre at Stonea on the Cambridgeshire fens in Britain. At an early stage of the excavation of this site it was necessary to consult the wood anatomist destined to

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**Fig. 10.** Variable pressure scanning electron microscope image of a radial longitudinal section of *Celtis africana* (white stinkwood) charcoal from the site of Elands Bay Cave (South Africa). Whilst the use of the backscatter detector inevitably results in a softer focus image (compared with the sharp, crisp image produced by use of the secondary electron detector), nonetheless vital anatomical details (such as helical thickenings in narrow vessels, wide vessel tylosis, heterocellular rays, non-septate fibres, vessel-ray pits with much reduced borders to apparently simple, horizontal vessel-ray pits that are scalariform or gash-like with some that are vertical in a palisade arrangement) are clearly visible in this friable archaeological specimen that is >20 000 years old. Image: C. R. Cartwright.
identify the large quantities of wooden artefacts and other surviving plant remains in order to recommend a sampling and conservation stratagem (Cartwright, 1996). For optimal preservation of wood anatomical features, the material could not be allowed to dry out, neither could any conservation intervention be permitted (such as the application of consolidants or freeze-drying) that might obscure key cellular structure before the wood anatomy could be scrutinized and taxa identified.

Working closely in conjunction with the excavation team, the on-site conservators and those in the laboratory, methods and techniques were agreed with the wood anatomist for stabilizing the retrieved wooden artefacts without compromising their cellular anatomy. Samples from each of the wooden artefacts were razor blade or microtome sectioned using an adapted form of the standard techniques (mentioned above) to produce temporary unstained thin sections in glycerin for LM examination and photography as part of the identification process. Common problems encountered in the examination of the wood anatomy of waterlogged wood specimens are cell wall breakdown and presence of fungal hyphae within the cells.

**Desiccated wood**

The ancient burial tombs of the Egyptian pharaohs, particularly those of the Middle Kingdom (around 2055 BC–1650 BC) provide good examples of ancient desiccated wood. The wooden coffins and associated wooden artefacts that have survived from the particular conditions within these tombs are remarkable, not least in the level of preservation of their wood anatomy (Gale and Cutler, 2000; Cartwright and Taylor, 2008).

However, although the condition of the tomb wood anatomy is excellent, macroscopically the wood may be brittle, so in the author’s experience it is preferable to fracture samples of these wooden artefacts in TS, RLS and TLS (as one would for charcoal) for SEM or LM examination, rather than thin sectioning them. In Roman period Egypt, there was a fashion for funerary portraiture that echoed Greek and Roman traditions in the Mediterranean region. The excellent condition of preservation of the wood anatomy of these mummy portraits unexpectedly revealed that the majority used European timbers such as *Tilia* sp. (Fig. 11) in preference to indigenous Egyptian woods (Cartwright, 1997; Cartwright and Middleton, 2008; Cartwright et al., 2011).

Although not matching the exact conditions of the ancient burial tombs of Egypt, desiccated wood may be preserved in other exceptional burial conditions, either in hot dry environments or occasionally in cold dry environments. The archaeological site of Jericho (in Israel), for example, displayed evidence for extensive settlement and defensive architecture from the Neolithic period (about 9600 BC) onwards, but it was the associated Bronze Age cemetery (about 1800–1700 BC) that surprised the 1950s excavation team by yielding a variety of organic remains within the tombs. Unfortunately, on excavation, this material deteriorated rapidly when exposed to light and air, and although the excavators endeavoured to cope with these special and unexpected organic assemblages, the conservation materials and techniques available at the time were inadequate. Nevertheless, despite the problems of paraffin wax being liberally applied (Fig. 12), wooden artefacts from the Bronze Age Jericho tombs have survived, mostly with sufficient diagnostic wood anatomy intact to permit identification.
In some instances, there are indications of the rapid deterioration that occurred on excavation, for example when the shapes, sizes and orientation of vessels, ray parenchyma, axial parenchyma and fibres (or tracheids and rays in the case of softwoods) have been distorted (Fig. 13) in a similar fashion to waterlogged wood that has been allowed to dry out too quickly. Similar examples can be seen in 1200 BC funerary furniture wood (Fig. 14) from the...
cemetery associated with the site at Amara West in Sudan (Cartwright, 2014).

Mineral-replaced/preserved wood

It is not uncommon to find traces of mineral-replaced/mineral-preserved wood within the corrosion products of bronze or iron artefacts dating to the European Bronze Age and Iron Age (e.g. Cartwright, 2012). This is by far the most difficult category of material in terms of discerning its wood anatomy. The main reasons are: such traces may be vestigial and incomplete, often surviving as negative or positive casts of certain features only (Fig. 15); they may only be orientated in a single plane – often just a RLS or TLS that is too thin to prepare the other two sections needed for identifications; frequently details of perforation plates, septate or non-septate fibres, vessel,
parenchyma and fibre pitting are masked by the replacement material. Consequently, on many sites, four out of every five mineral-replaced or mineral-preserved archaeological wood specimens examined may only be identified to family or genus level, not to species. This category of archaeological wood is perhaps more susceptible than others to compromised, flawed or overconfident identifications carried out by non-specialists lacking formal botanical and wood anatomy training, using inadequate microscopes.

Mineral preservation or replacement of archaeological (or historical wood) is not confined to instances in which the wood is in very close proximity to metal artefacts; it can also occur in extremely desiccated wood where the wood structure is partially or wholly replaced by silica, or by calcium carbonate as in the example in Fig. 16 from the cemetery of the site at Amara West in Sudan (about 1200 BC). Identification to taxon was possible here (Cartwright, 2014) because of the quantity of material available and the fact that specimens of the same taxon in charcoal form were available for comparison.

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LITERATURE CITED