A prototype interactive identification tool to fragmentary wood from eastern central Australia, and its application to Aboriginal Australian ethnographic artefacts

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Declaration

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Abstract

Wood identification can serve a role wherever wood has been separated from other diagnostic plant structures as a result of cultural or taphonomic processing. In disciplines that study material culture, such as museum anthropology and art history, it may serve to augment and verify existing knowledge, whilst in fields like palaeobotany, zoology and archaeology, wood identification may test existing paradigms of ecology and human behaviour. However, resources to aid wood identification, particularly of non-commercial species, are sorely lacking and, in Australia, there are only a handful of xylotomists, most of whom are attached to Forestry organisations. In addition, wood fragments are commonly the limit of material available for identification. They may be the physical remains of a wider matrix – as may often appear in biological, archaeological, palaeobotanical or forensic contexts – or a splinter removed from an ethnographic artefact or antique.

This research involved the development of an updateable, interactive, computer-based identification tool to the wood of 58 arid Australian species. The identification tool comprises a series of keys and sub-keys to reflect the taxonomic hierarchies and the difficulty of separating wood beyond family or genus. The central *Sub-key to Arid Australian Hardwood Taxa* is comprised of 20 angiosperm taxa which include families and single representatives of genera. The treated taxa in this key are defined by 57 separate characters. They are split into sets of like characters including four sets based upon method of examination: anatomical (scanning electron microscopy), anatomical (light microscopy), chemical observations and physical properties. These character sets follow a logical progression, in recognition of the variability in available sample size and that non-invasive techniques are often desirable, if not essential. The use of character sets also reflects that this variability in sample size can affect the range of available characters and the available method of identification, and their diagnostic potential tends to increase with the complexity of the identification method.

As part of the research, the identification tool is tested against wood fragments removed from several Aboriginal Australian artefacts from central Australia and case studies are provided.

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Chapter One. Introduction

Preamble

A renewable natural resource, wood is one of the most pervasive materials used in past and contemporary societies. As well as being used for the construction of buildings, ships, homes, flooring and fencing, it is used for the manufacture of paper, heat, furniture, tools, musical instruments and sculpture, and it is utilised by both animals and humans. The prevalence of wood is such that knowledge of wood use can provide important insights into human (and animal) behaviours. In addition, most wood comes from trees that are geographically restricted, and its presence in particular contexts may reveal patterns of trade and exchange and the movement of people. Its preservation in deep time may also indicate past environments and vegetation history. Indeed, wherever wood has been separated from other botanical structures and there is a need to find out the provenance of an object, wood identification may serve a role. Accordingly, wood identification offers a valuable tool to a variety of scientific disciplines and fields of humanities.

Despite its extensive applications, resources for wood identification are limited. Globally, there are many thousands of wood-producing trees but most wood identification resources focus on the important commercial timbers which number in the hundreds. In addition, even fewer wood identification resources account for cultural and/or taphonomic processing, particularly fragmentation. Indeed, there are many circumstances where wood fragments are the limit of material available for identification. This thesis responds to the need for wood fragment identification and involves the development of an interactive identification tool that is sensitive to the identification of wood fragments.

Identification of plant parts

Taxonomies are developed to classify organisms (and objects) based upon similar characteristics. In biology, organisms are placed into hierarchies of family, genus and species. The work of taxonomists, their research outputs and revisions, provide society with a systematic means to identify biological organisms. To distinguish between organisms, taxonomists isolate diagnostic sets of characters that describe their features. In botany, taxonomic characters may involve vegetative and reproductive parts including the fruits, flowers and leaves.

Standard plant taxonomic studies usually assume that all the relevant plant structures are present and the full suite of characters is examinable. However, often only certain plant parts may be available for identification. There are two processes that might result in the separation of plant parts – human or animal processing or environmental intervention. There are any number of cultural processes that will separate parts of a plant: for example, making a table from Red Gum (*Eucalyptus camaldulensis*[1]); fashioning sleepers for railways; burning wood for a campfire; weaving a basket of reeds; making an ornament of seeds; eating a fruit and leaving the seed; contracting a splinter from a tree; or the inadvertent deposition of pollen on clothing after brushing past a flower. The process of mastication, in animals or humans, can also separate and fragment plant parts. Environmental intervention, such as bushfires and floods, may separate botanical structures whilst in deep time, selective preservation may preserve plant parts such as wood, leaves or pollen.

There are many areas of science that require the identification of single botanical structures. For example, archaeologists learn of past human behaviour by examining refuse of fruits, seed and wood; forensic scientists may examine a splinter of wood, a single grain of pollen, a seed or a leaf to piece together the events at a crime scene; anthropologists may examine the plant materials used to construct ethnographic artefacts to learn of material culture; whilst palaeobotanists examine fossilised plant parts such as wood, fruits or leaves to learn of past environments and flora.

In the absence of the broader set of botanical structures and in recognition of the diagnostic potential of some plant parts, specialist fields have developed including the study of pollen (palynology), the study of wood (xylology) and the study of bark and seeds. Each of these fields has developed a set of specific diagnostic characters and terminologies that relate to these plant parts. Accordingly, it may be possible to identify a tree by examination of its wood, a single pollen grain, a single seed or its bark. However, these taxonomies also assume an intact specimen from which to sample and one where all diagnostic characters

[1] A list of species with authorities for the species mentioned in the text of this thesis are contained in Appendix One. Species authorities mentioned in the remaining Appendices can be obtained from the *Australian Plant Name Index* (APNI) at http://www.anbg.gov.au/win/index.html or the *International Plant Name Index* (IPNI) at www.ipni.org/index.html.

are present and examinable. Characters used in wood identification, for example, assume the presence, or ability to differentiate between, sapwood and heartwood and earlywood and latewood. Yet environmental and cultural processing can result in heavily fragmented (and modified) plant structures.

Is it possible to identify an object when only part of a diagnostic structure (and therefore only a portion of the character set) is available for analysis? What is the limit of material required for such an identification? Will a limited amount of material impede standard practises involved in identification, particularly preparation and analysis? How helpful are standard taxonomic characters that relate to the source of the fragment?

This research responds to these questions as well as the lack of identification tools sensitive to the identification of fragmentary taxonomic materials and the circumstances under which a fragment is the limit of information available. Tools for the identification of fragmentary plant – and animal – remains have a potential application to a range of disciplines including botany, zoology, forensic science, anthropology, archaeology and evolutionary biology.

Wood and wood identification: a background

The research presented in this thesis is underpinned by wood taxonomy. In order to contextualise the study, a broad introduction to wood anatomy and identification is provided. This includes a brief discussion of the difference between hardwoods and softwoods; wood structure and function; the methods used to identify wood; the salient wood surfaces; distinguishing hardwoods from softwoods; and characteristic hardwood anatomy.

Wood taxonomy: hardwoods and softwoods

Wood-producing plants occur in both broad botanical divisions of the angiosperms and gymnosperms (conifers). Angiosperms are further separated into dicotyledons and monocotyledons. Monocotyledons refer to palms and bamboos which each have a distinctive wood anatomy. Dicotyledonous wood – also referred to as hardwoods – includes common and commercial timbers such as Maple (*Acer*), Birch (*Betula*), Hickory (*Carya*), Chestnut (*Castanea*), Walnut (*Juglans*), Ash (*Fraxinus*), Beech (*Fagus*), Oak (*Quercus*), Poplar (*Populus*) and Elm (*Ulmus*) and Australian species such as Gum

(Eucalyptus) and Wattle *(Acacia)*. Gymnosperms – or softwoods – include Pine (*Pinus*), Fir (*Abies*) and Spruce (*Picea*) and the Australian Native Pine *(Callitris)*. It is with the separation of the gymnosperms from the dicotyledons that wood identification typically begins.

On a global scale, extant gymnosperms are few, representing less than 0.5% of the number of extant angiosperm species (Hill 1998: 505). This amounts to less than 1000 extant gymnosperm species, about 600 of which are the economically-important, timber-producing conifers (Hill 1998: 509). Of the conifers, less than 50 species are native to Australia and only a few of these are distributed in arid Australia. The predominant coniferous species in the Australian desert, *Callitris glaucophylla*, is the only gymnosperm treated in this work. The rest of the treated species are hardwoods (dicotyledons), and except where describing the separation of hardwoods from softwoods, examples and images in this thesis will usually be of hardwood species.

Wood structure and function

A typical wood-producing stem consists of several types of tissue (Figure 1). The dead cells of the outer bark provide protection for the tree and can be useful for identification purposes (although bark anatomy is a specialist science in itself). Beneath this is the inner bark (or phloem), living plant tissue involved in the transport of nutrients from the leaves to the stem and roots. Under the phloem is the living cambium tissue; through cell division within the cambium growth rings are created and the tree's girth is increased, as new phloem and xylem cells are formed. Xylem is the correct term for wood.

Predominantly consisting of non-living cells, the xylem is involved in the transport of nutrients and water from the roots to the leaves. As it makes up the majority of a mature stem, the xylem also provides important structural support for the tree. Typically, the xylem is characterised by both sapwood and heartwood. Sapwood is situated between the cambium and the heartwood; consisting of living and non-living cells, its main purpose is the storage of food and the conduction of water and sap. Heartwood refers to the innermost part of the wood, excluding the pith, where all cells are non-living and inactive. The heartwood provides important structural support to the tree, and is often distinguished from the sapwood by the presence of extractives, extraneous substances that have been

collected by the tree. Extractives stored in the heartwood often stain it a characteristic colour and can make it resistant to decay and repellent to wood-boring insects and fungi.

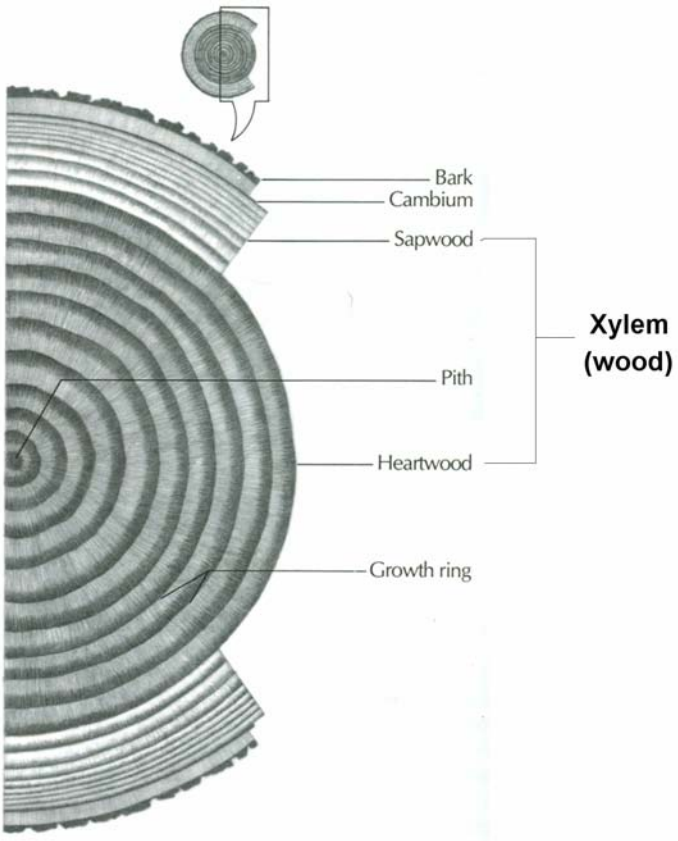

Figure 1 Illustrating the structure of wood as viewed on the endgrain. Diagram reproduced and modified from Hoadley (1990: 8)

Wood identification

Wood identification (or xylology) is, therefore, the study of xylem properties. This may include its physical and chemical characteristics as well as anatomical features. Wood enthusiasts, for example, can often identify wood by examining basic physical properties of grain and figure – produced by characteristic cell arrangement and cell densities – and/or simple chemical characteristics such as colour and odour that are produced by extractives. On the other hand, wood identification can involve more specialist analyses such as the study of wood chemistry utilising chemotaxonomic procedures. Typically, however, wood identification involves examination of wood anatomy.

The three surfaces of wood

In wood identification it is desirable that anatomical features are examined as they appear on surfaces that have been exposed along the transverse, tangential and radial planes (Figure 2). All wood identification texts refer to features as they appear on these surfaces and surfaces that are oblique to these planes produce confused results.

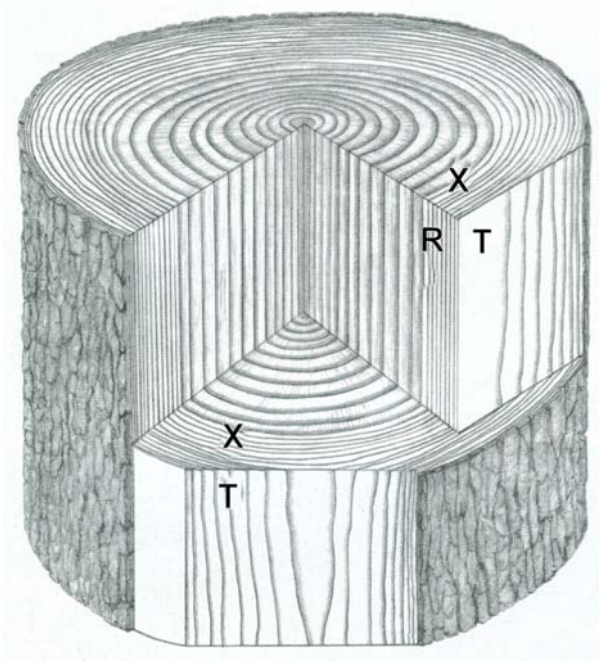

Figure 2 Illustrating the three surfaces of wood: Transverse (X), Tangential (T) and Radial (R). Diagram reproduced and modified from Hoadley (1990: 12).

Transverse (X)

The transverse plane (or cross-section) occurs across the grain and perpendicularly to the long axis of the tree. This surface exposes concentric growth rings. Depending on their size, vessels that punctuate the surface (if the specimen is a hardwood) may be visible to the naked eye. Rays that permeate in lines from the pith of the stem to the cambium may also be observed.

Tangential (T or TLS)

One of two longitudinal planes, the tangential surface occurs perpendicularly to the rays and roughly parallel to the growth rings.

Radial (R or RLS)

The radial surface refers to the surface exposed by bisecting the centre of the tree. Like the tangential surface, it occurs parallel with the longitudinal grain direction.

Examination of wood anatomy

Identification of wood by examination of its anatomy can be conducted using several methods; an image exemplifying each of the methods is provided in Figure 3. In its simplest form, the endgrain (also known as the cross-section or transverse surface) is exposed and polished with a razor blade and the surface examined with a hand-lens or low-powered dissecting light microscope (up to 50x). Often, however, it can be helpful to observe wood features as they appear in thin section and under transmitted light microscope (up to 100x); typically thin sections are produced with a microtome but they may also be removed with a razor blade. More recently, scanning electron microscopy (SEM) has offered a valuable opportunity to observe small, polished blocks of wood (up to 1 cm^3) at high magnifications (typically up to 10,000x) and in three dimensions. To establish identifications using any of these methods requires comparison with contemporary collections of reference wood specimens or the use of publications or identification tools containing descriptions and images.

Distinguishing hardwoods from softwoods

One of the more rudimentary requirements in wood identification is to distinguish dicotyledons (hardwoods) from gymnosperms (softwoods)[2]. Generally hardwoods and softwoods are easy to separate with the gymnosperm wood lacking the specialist structures of the more recently evolved dicotyledons. The most conspicuous difference is that the vessels that characterise dicotyledons are absent in gymnosperms, whilst gymnosperms are typified by row upon row of tracheids. Softwoods and hardwoods are usually easily separated by examination of the transverse surface with a hand-lens, light microscope or scanning electron microscope (Figure 4).

[2] The terms “softwood” and “hardwood” are actually misnomers, having nothing to do with the relative hardness of the woods.

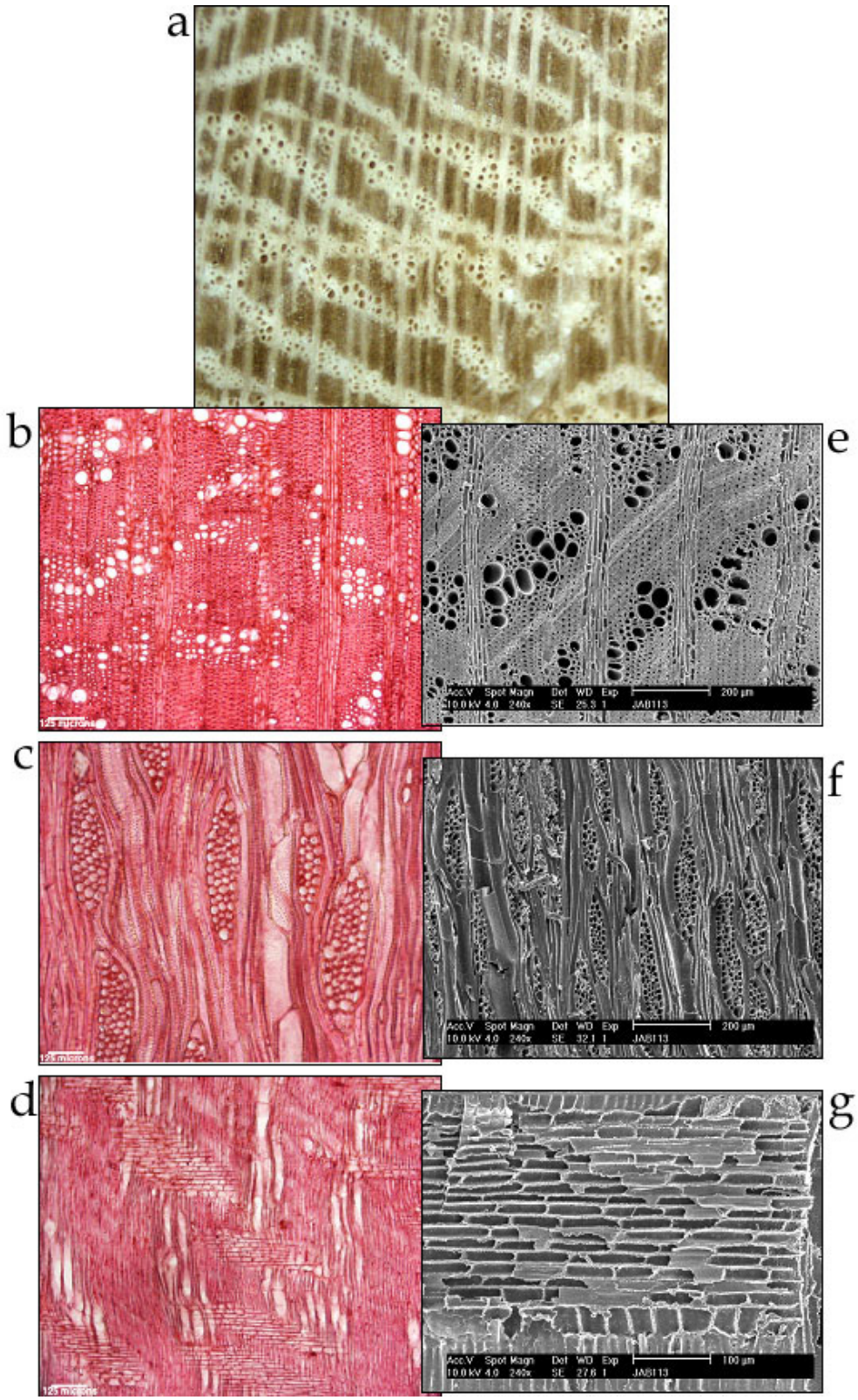

Figure 3 Methods of examining wood anatomy as illustrated by *Pittosporum angustifolium.* A: Endgrain image of JAB113 with light microscope (scale = 500 µm); B, C, D: Transverse, tangential and radial thin section images of unvouchered specimen ED8.1 (scale = 125 µm); E, F, G: Transverse, tangential and radial SEM images of JAB113 (Scale = 200 µm; 200 µm; 100 µm).

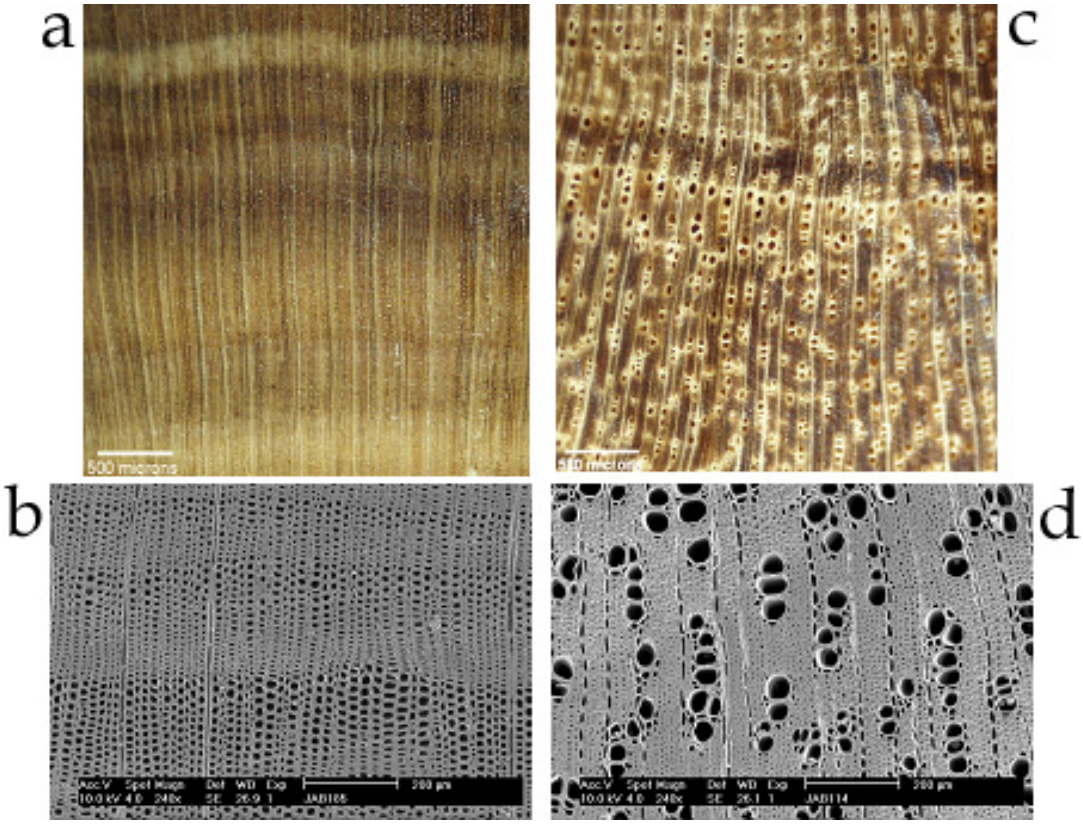

Figure 4 The difference between softwood anatomy and hardwood anatomy as observed on the transverse surface. A & B: JAB185 *Callitris glaucophylla* (softwood) without vessels and with rows of tracheids; scale = 500 µm & 200 µm. C & D JAB114 *Eremophila longifolia* (hardwood) with vessels, parenchyma, and fibres; scale = 500 µm & 200 µm.

Distinguishing between hardwoods: hardwood anatomy

Hardwoods are characterised by four major cell types (Figure 5).

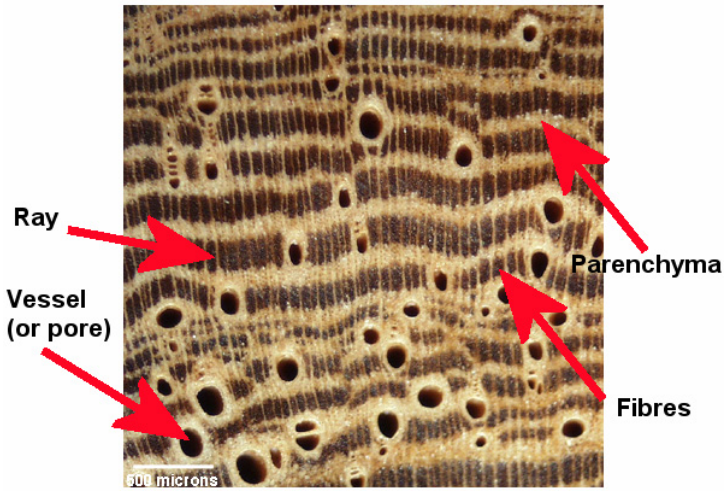

Figure 5 JAB138 *Bauhina gilva.* Endgrain (X) image showing salient hardwood features: vessels are either solitary and occur in radial multiples; parenchyma are in pale horizontal bands (in horizontal bands); rays are narrow, vertical lines; fibres form darker background mass; scale = 500 µm.

It is by assessing various qualitative and quantitative diagnostic characteristics of these cells – such as those presented in Figure 6 – that hardwood species are separated.

Vessels

Occurring parallel to the longitudinal axis of the tree, vessels are the conduits that transport water and sap from the roots of the tree to its leaves. They are usually the easiest cell type to recognise and, on a polished endgrain surface, they are typically visible with a hand-lens and sometimes with the naked eye. Vessels are also commonly referred to as pores, particularly where they occur on the transverse face. On true tangential and radial surfaces the longitudinal axis of vessels is exposed. A single vessel is actually comprised of a series of vessel elements which share perforated end walls known as perforation plates. The common, lateral wall of two vessel elements is usually punctuated by pits; these vessel to vessel pits (or inter-vessel pits) allow the transport of nutrients between vessels. Inner vessel walls may also be characterised by helical thickenings. Various substances may clog vessels including gum or mineral deposits such as silica or calcium carbonate; this is especially so of vessels that occur in the heartwood. Heartwood vessels in some species are characterised by balloon or bubble-like structures called tyloses.

Rays

Unlike the other three cell types, ray cells are elongated transversely with the longest axis perpendicular to the stem of the tree. Rays provide an important passage for the transport of substances from the centre of the tree to the outside of the tree, or from the pith to the cambium. On the transverse surface rays occur perpendicularly to the growth rings and permeate from the pith. The tangential surface of a hardwood is characterised by the end walls of the rays whilst their lateral axis is exposed on a true radial surface. Rays vary considerably between species in width, height and number but will usually be visible on a polished endgrain and occasionally with the naked eye. Pits that occur on contiguous walls of rays and vessels – ray-vessel pits – allow the exchange of substances between the cells.

Rays may also be referred to as ray parenchyma or medullary rays.

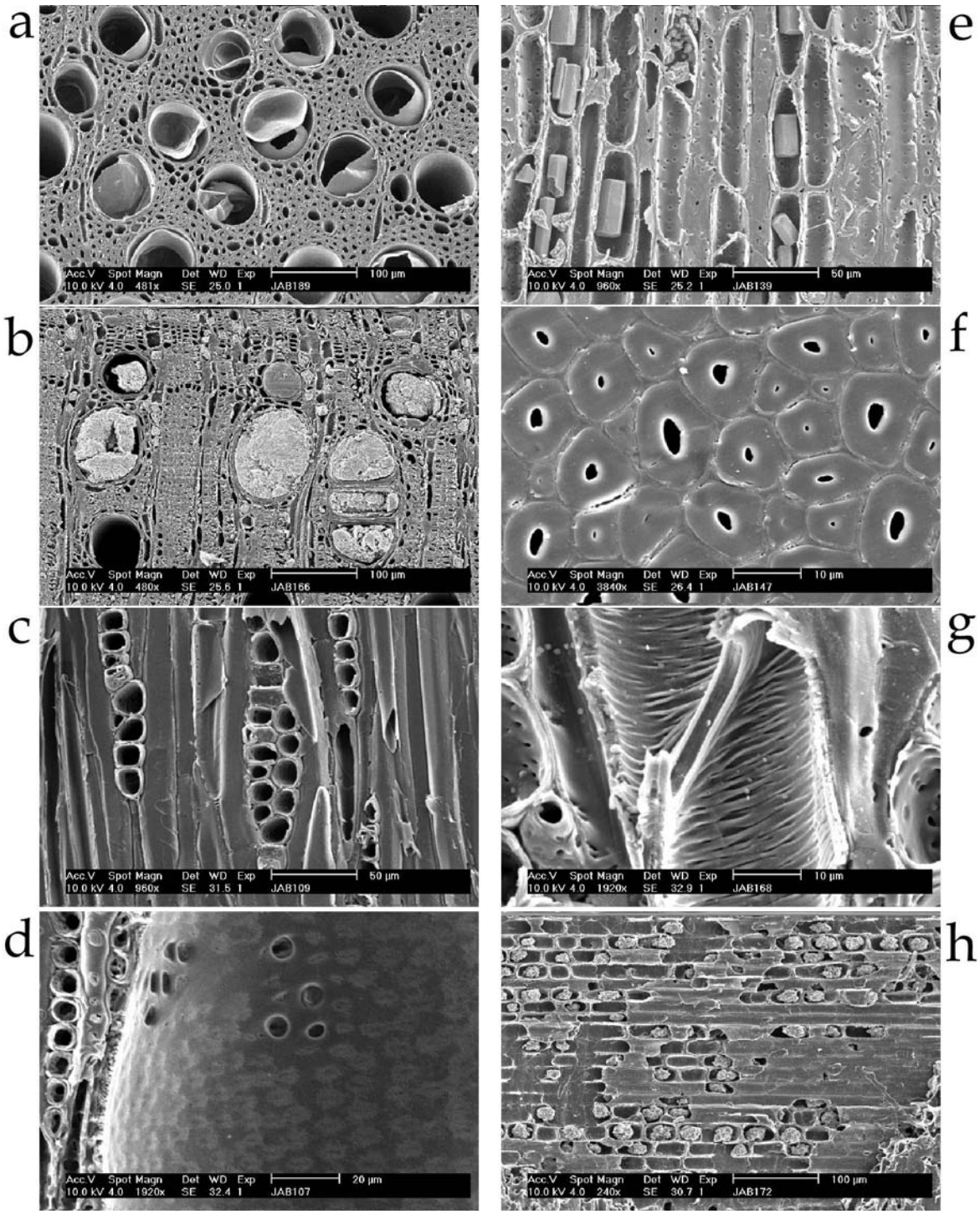

Figure 6 SEM images showing salient hardwood features. A: JAB189 *Melaleuca glomerata* Tyloses in solitary vessels (X) (Scale = 100 µm) B: JAB166 *Ventilago viminalis* Gum and white deposits in vessels; vessels in radial multiples (X) (Scale = 100 µm) C: JAB109 *Acacia salicina* Ray ends (TLS) (Scale = 50 µm) D: JAB107 *Eucalyptus coolabah* Ray-vessel pits and vestured vessel to vessel pits (TLS) (Scale = 20 µm) E: JAB139 *Hakea eyreana* Elongated crystals in multiseriate ray cells (X) (Scale = 50 µm) F: JAB147 *Grevillea juncifolia* Fibre cells (X) (Scale = 10 µm) G: JAB168 *Eremophila longifolia* Simple perforation plate with prominent rim separates two vessel elements; helical thickenings are present (X) (Scale = 10 µm) H: JAB172 *Capparis loranthifolia* Procumbent and upright ray cells with silica inclusions (RLS) (Scale = 100 µm).

Parenchyma

Parenchyma are largely involved in the storage of nutrients in both the heartwood and sapwood. Where they occur in the sapwood, they are the only living cells in wood. Parenchyma are small and short; they are usually thin-celled and vary in density and in their arrangement and association with vessels. At high magnifications their thin walls often contrast with the thicker-walled and densely packed fibres, and viewed en masse at low magnification there is often a distinct colour contrast between parenchyma and fibres as observed on a polished endgrain.

Parenchyma are also known as axial parenchyma (as distinct from ray parenchyma) or soft tissue.

Fibres and tracheids[3]

Fibres are small and elongated cells that largely contribute to the strength of wood; they are often densely packed with thick cell walls. At low magnifications, individual cells are indistinguishable and the fibres usually form a dark background mass on the transverse surface. For this reason, they are also known as ground tissue. Under higher magnifications, fibre cells may be distinguished from parenchyma on the longitudinal surfaces by their tapering ends. Fibres may have simple or bordered pits.

Tracheids are cells with closed (or imperforate) end walls. There are two recognised types of tracheids in hardwoods. Even at high magnification, vascular tracheids are indistinguishable from small vessels on the transverse surface; however, the absence of perforation plates distinguishes them from vessels on the longitudinal surfaces. Vasicentric tracheids are small, thin-walled cells with rounded ends. They usually occur in association with vessels and mixed with parenchyma. Heavily pitted and elongated they are distinguishable from parenchyma on the longitudinal surface.

[3] This research largely avoids distinguishing between fibres and tracheids as they are difficult to tell apart and there is some confusion in the wood anatomical literature as to their definitions in hardwoods (Wheeler, Baas *et al.* 1989: 264). For example, *Eucalyptus* and *Melaleuca* species contain numerous, conspicuous bordered pits that are both called fibre tracheids (Dadswell 1972: 21) and vasicentric tracheids (Wheeler, Baas *et al.* 1989: 262).

Extent of wood identification

Definitive wood identification to species level is often difficult and frequently impossible. Wood may not be sufficiently variable within a genus to enable identification to species level; conversely, there may be significant variation within a species which can prohibit identification beyond family or genus. The website (Centre for Wood Anatomy Research 2005) of professional xylologists Regis B. Miller and Alex Wiedenhoeft (*USDA Forest Products Laboratory*, Wisconsin), for example, cautions:

> *Identifications based on wood anatomy are generally accurate only to genus (e.g. a species of spruce) or, in some cases, to a subgeneric grouping (e.g. white oak group) but rarely to the exact species.*

This statement is echoed by the *CSIRO Forestry & Forest Products* website (CSIRO 2005), home to Australia's foremost wood identification expert, Jugo Ilic:

> *Wood specimens can usually be identified to genus level and sometimes to species level. Eucalyptus can usually be identified to a particular group e.g. ash, gum, ironbark etc and occasionally to species level.*

And on the website (Alden Identification Services 2005) of xylologist Harry A. Alden (*Smithsonian Centre for Materials Research and Education*, Maryland):

> *The microscopical* (sic) *determination of wood to the species level is usually not possible…* [because of] *the evolutionary conservative nature of wood.* [However,] *identification of wood to the genus level is usually very accurate.*

It is for this reason that supplementary knowledge relating to the provenance of a wood specimen is an important resource for a xylologist. The geographically restricted nature of many plants is such that where a wood specimen is identifiable only to genus, the likely species may be extrapolated if other sources can shed light on its provenance. For example, it may be assumed that a fossilised or carbonised wood specimen removed from a palaeobotanical or archaeological context was from a tree that grew in the region; the typology of a wooden table may be characteristic of a certain manufacturer and documentary evidence may indicate the wood preferred for it's construction; or oral histories may be attached to a wooden object which may indicate its provenance. The

nature of wood is such that wood identification using morphological features may often not progress beyond family or genus without this extra information.

The presented thesis: an overview

This study sought to develop an interactive identification tool to arid Australian wood. It attempted to separate more than 50 species of wood using standard wood identification characters, including anatomical, physical and chemical markers, whilst conducting limited testing for intra-specific variation. In recognition of the range of scientific disciplines that require wood identification, particularly of fragmented wood, the developed tool was applied to three wooden Aboriginal artefacts in an attempt to identify the wood used in their construction whilst preserving the integrity of the objects. Satisfying this objective also required determination of a method of effectively and efficiently softening the arid Australian wood, amongst the densest wood in the world. This section outlines the research aims, the location of the research and provides a broad overview of the structure of the thesis.

Research aims

- To develop a technique of wood identification, combining non-invasive and invasive methods, that can distinguish between Australian arid lands species, particularly those belonging to the same genera.

- Using contemporary reference wood samples, to compare and account for any differences in cellular, physical and possibly chemical attributes that may occur within the same species e.g. as a result of different growth regimes or as a result of anatomical variation among the wood of different plant parts e.g. roots, juvenile wood, branches etc.

- To assemble this information into an interactive identification tool (using *Lucid* software) that can be applied to ethnographic artefacts from arid Australia, enabling a definitive determination of the wood species used to construct the artefact, whilst preserving the integrity of the object.

- To determine a method of efficiently softening high density, arid Australian wood in order to sufficiently prepare it for standard anatomical microscopy and examination

Scope and location of research

This study treated 58 wood species that occur in north-east South Australia, south-west Queensland and far western New South Wales; for a list of the collected species see Table 1 and for a map of the location of the research see Figure 7. However, many of the treated species are distributed in other areas of arid Australia providing the developed identification tool with an expanded geographic application (see distribution maps for treated species in Appendix Two). This area was chosen due to the restricted number of wood-producing species occurring in the region and because of their limited treatment in existing identification keys that largely deal with commercial timbers. In addition, the project aims were considered more achievable if the study was confined to a region where the resource base available to Aboriginal people includes a limited diversity of plant species.

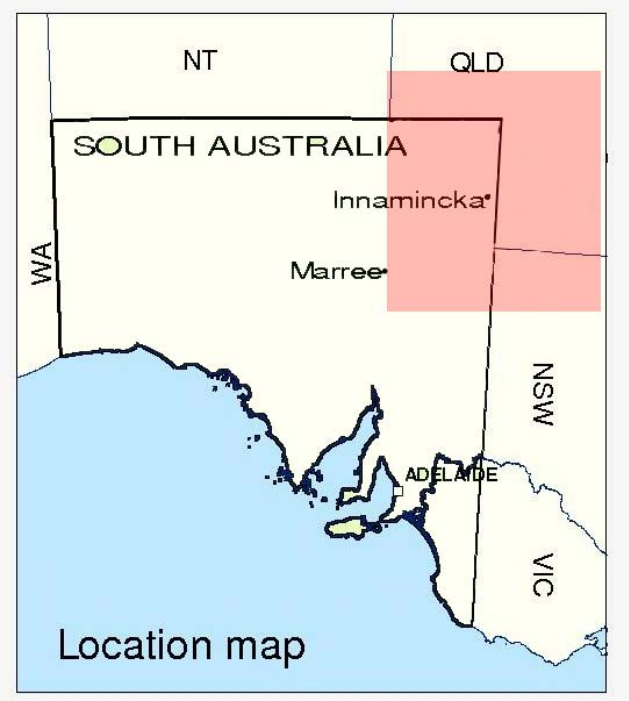

Figure 7 Map highlighting (in pink) the location of the 58 wood species treated in this research.

Table 1 List of collected wood specimens. The identifications of the associated voucher specimens were made by staff of the *State Herbarium of South Australia*.

FAMILY	Genus	Species	Collection number (s) (JAB XXX)	Common names
ANACARDIACEAE	*Schinus*	*molle*	190	Pepper-Tree
CAESALPINIACEAE	*Bauhinia*	*gilva*	138	Beantree
	Senna	*artemisioides* ssp. *filifolia*	183	Silver Cassia
CAPPARACEAE	*Capparis*	*loranthifolia*	162, 172	Narrowleaf Bumble
	Capparis	*mitchellii*	132	Native Orange, Wild Orange, Bumble, Native Pomegranate
CASUARINACEAE	*Casuarina*	*pauper*	179, 187	Black Oak, Belah
CUPPRESACEAE	*Callitris*	*glaucophylla*	185	White Cypress Pine, White Pine, Native Pine
LEGUMINOSAE	?*Acacia*	*aneura* var. *intermedia*	177	Mulga
	Acacia	*aneura* var. *aneura*	121, 171	Mulga
	Acacia	*cambagei*	169	Gidgee, Gidgea, Stinking Wattle
	Acacia	*cana*	178, 180	Broad-leaved Nealie, Cabbage-tree Wattle, Boree
	Acacia	*cyperophylla* var. *cyperophylla*	136	Red Mulga, Mineritchie
	Acacia	*farnesiana*	130	Sweet Acacia, Cassie, Mimosa Bush
	Acacia	*ligulata*	109	Umbrella Bush, Small Cooba, Sandhill Wattle, Dune Wattle
	Acacia	*ligulata* ?intergrade with *A. bivenosa*	150	
	Acacia	*murrayana*	165, 186	Murray's Wattle, Sandplain Wattle
	Acacia	*oswaldii*	111	Umbrella Wattle, Miljee
	Acacia	*petraea*	164	Lancewood
	Acacia	*peuce*	126	Waddy, Waddi, Waddy-wood, Birdsville Wattle
	Acacia	*pickardii*	122	
	Acacia	*salicina*	117	Broughton Willow, Native Willow, Willow Wattle, Cooba
	Acacia	*stenophylla*	102, 105	River Cooba, Eumong
	Acacia	*stowardii*	151, 158	Bastard Mulga
	Acacia	*tetragonophylla*	108, 128	Dead Finish, Kurara
	Acacia	*victoriae* ssp. *arida*	118	Elegant Wattle, Bramble Wattle, Prickly Wattle
	Acacia	*victoriae* ssp. *victoriae*	135	Elegant Wattle, Bramble Wattle, Prickly Wattle
MELIACEAE	*Owenia*	*acidula*	125	Emu Plum, Sour Plum, Sour Apple, Gooya, Gruie, Colane
MYOPORACEAE	*Eremophila*	*bignoniiflora*	129	Bignonia Emu-bush, Gooramurra, Eurah, Creek Wilga
	Eremophila	*duttonii*	175	Budda, Harlequin Fuchsia-bush
	Eremophila	*freelingii*	152	Limestone Fuchsia, Rock Fuchsia-bush
	Eremophila	*longifolia*	106, 114	Weeping Emu-bush, Berrigan, Long-leaved Eremophila
	Eremophila	*macgillivrayi*	140	Dog-bush

	Eremophila	*mitchellii*	167	Sandalwood, False Sandalwood, Bastard Sandalwood, Sandalbox, Rosewood Balvory, Buddah, Budtha, New South Wales Sandalwood, Native Sandalwood
	Eremophila	*polyclada*	181	Flowering Lignum, Twiggy Emu-bush
	Eremophila	*sturtii*	168	
	Myoporum	*montanum*	101	Native Myrtle, Western Boobialla, Waterbush
MYRTACEAE	*Corymbia*	*aparerrinja*	157	Ghost gum
	Corymbia	*terminalis*	143, 156, 160	Long-fruited Bloodwood, Western Bloodwood, Inland Bloodwood, Pale Bloodwood
	Eucalyptus	*camaldulensis* var. *obtusa*	146, 182, 191	(River) Red Gum
	Eucalyptus	*coolabah*	100, 107, 133, 137	Coolabah
	Eucalyptus	*ochrophloia*	161	Black Butt, Napunyah, Lapunyah, Yapunyah, Yellow Jacket.
	Eucalyptus	*populnea*	159, 170	
	Eucalyptus	*thozetiana*	163	Mountain Yapunyah, Napunyah, Thozets Box, Thozets Ironbox, Lapunyah
	Melaleuca	*glomerata*	176, 189	White Tea-tree, Desert Paperbark
	Melaleuca	*trichostachya*	144	Narrow-leaved Honey Myrtle
PITTOSPORACEAE	*Pittosporum*	*angustifolium*	113	Native Apricot, Weeping Pittosporum, Native Willow, Poisonberry Tree, Apricot Tree, Berigan, Butterbush, Meemeei
PROTEACEAE	*Grevillea*	*juncifolia* ssp. *juncifolia*	147, 149	Honeysuckle Spider-Flower
	Grevillea	*striata*	124	Beefwood
	Hakea	*eyreana*	139, 142	Corkbark, Corktree, Corkwood, Straggly Corkbark
	Hakea	*leucoptera* ssp. *leucoptera*	110, 112	Needle bush, (Silver) Needlewood, Needle Hakea, Pin Bush, Water Tree, Kulua
RHAMNACEAE	*Ventilago*	*viminalis*	166	Barndaragu, Supplejack, Thandorah, Vinetree
RUBIACEAE	*Psydrax*	*latifolia*	153	Native currant, Wild Currant
RUTACEAE	*Flindersia*	*maculosa*	155	Leopardwood, Leopard Tree
SANTALACEAE	*Anthobolus*	*leptomerioides*	174	
	Santalum	*lanceolatum*	123	Plumbush, Native Plumbush, Cherry Bush, Northern Sandalwood, Sandalwood
SAPINDACEAE	*Atalaya*	*hemiglauca*	127	Whitewood
	Dodonaea	*viscosa* ssp. *angustissima*	119, 184	Sticky Hop-bush, Akeake
TAMARICACEAE	*Tamarix*	*aphylla*	115	Athel Pine, Athel Tamarix, Athel Tree

Thesis structure

This section briefly outlines the arrangement of the thesis and summarises the research methodology.

Review of literature

The project commenced with a review of the relevant existing literature on the identification of wood and wood fragments. Chapter Two discusses the various disciplines and professional fields which require wood identification, including anthropology, archaeology, palaeobotany, zoology, art history, forensics and quarantine. Chapter Three provides a survey of current resources available for wood identification whilst Chapter Four discusses the importance of basing wood identification on specimens that are represented by voucher specimens. Finally, Chapter Five examines future molecular directions for wood identification and recent advances in the extraction of DNA from wood.

Collection of contemporary wood specimens

Chapter Six discusses the assemblage of a contemporary wood reference collection upon which to build the identification tool. Initially unvouchered wood specimens – those without associated botanical specimens – were collected to trial standard wood identification techniques and technologies. These trials informed the procedure later applied to the vouchered wood specimens collected from north-east South Australia, south-west Queensland and far western New South Wales. Botanical specimens associated with this vouchered collection were deposited in the *State Herbarium of South Australia* where they were identified by botanists. Contemporary vouchered wood samples were fashioned into rectangular reference samples to form both a "working" collection – one from which samples could be removed and tests applied – and an intact reference collection. Discs of wood removed from the end of crude reference samples were lodged in the *State Herbarium of South Australia*.

Preparation and analysis of contemporary wood specimens

Chapter Seven discusses the data collection phase and the process employed to prepare the wood specimens for analysis, including the use of hydrofluoric acid to successfully soften the samples. Up to a dozen 1 cm^3 blocks were removed from the "working" reference

collection specimens. These were softened and prepared for a series of anatomical, physical and chemical observations and assessments. This included exposure of the transverse surface (or endgrain) of the wood for light microscope examination and preparation of the transverse, tangential and radial surfaces for scanning electron microscope (SEM) analysis.

The analysis of the contemporary wood specimens involved an examination of characters largely adapted from the *International Association of Wood Anatomists* (IAWA) standard list of characters for hardwood identification (Wheeler, Baas *et al.* 1989). The cellular features of the sectioned wood were analysed using scanning electron microscopy. This involved examining, photographing and recording the cellular features of the three surfaces evident upon each wood section. The endgrain of the wood was also examined and photographed using a light dissecting microscope. A number of physical features of the reference wood blocks were documented and a series of simple chemical observations were also made. Numerical data for vessel diameter (in µm), vessel number per mm^2, ray height (in µm), ray number per mm and ray width (number of cells) were collected from SEM images using *analySIS* software.

Creation of interactive identification tool

The construction of a prototype, interactive identification tool to the wood of 58 arid Australian taxa – *Key to a Selection of Arid Australian Hardwoods & Softwoods* – is discussed in Chapter Eight. The tool contains the data obtained from the analysis of the contemporary reference specimens and is well supported by images pertaining to the timber properties of each species as well as descriptions of characters and taxa. It contains a set of eight hierarchical keys that increase in the complexity of method, invasiveness and the potential level of taxonomic identification. This structure provides users of the identification tool with optimised control of the identification process, something that is particularly important when faced with invasive analysis of precious cultural objects and/or wood fragments.

Testing the identification tool

The results of two tests of the identification tool are provided in Chapter Nine:

To determine its accuracy, the tool was tested by applying it to 10 contemporary vouchered wood specimens. These specimens were reserved for this purpose on return from the field trip, as field identifications indicated that examples of these species had previously been collected. The actual identification of these specimens – conducted by botanists and based on the herbarium vouchers – remained unknown throughout the test and the field identifications had been long forgotten by the time the test took place. Data from the 10 specimens were added to the identification tool after this test.

To test the operation, accessibility and functionality of the identification tool a second trial was performed using the 10 specimens. This test investigated whether a plant taxonomist with advanced knowledge of *Lucid* software but limited knowledge of wood anatomy could elicit correct identifications using the identification tool.

Statistical analyses of numerical characters

One of the issues that confront wood taxonomy and identification is that variation can occur in wood within a species. Conversely, wood may lack variability within a genus or family making identification difficult if not impossible. To attempt to determine the significance of any intra-specific variation occurring within the treated species, this research incorporated a series of statistical tests of the data collected for the numerical characters vessel diameter (in µm), vessel number per mm^2, ray height (in µm), ray number per mm and ray width (number of cells). The results of these statistical analyses are provided in Chapter Ten.

Application of the identification tool to Aboriginal Australian artefacts

Chapter Eleven discusses the application of the identification tool to samples of wood removed from three Aboriginal ethnographic artefacts, purportedly from central Australia. Photographic documentation recording the appearance of the objects before and after sampling was retained. Data collected from the removed wood samples by microscopic analyses were used to navigate through the identification tool in an attempt to identify the wood used to construct each artefact. Conclusions were drawn regarding the value of the identification tool for this purpose.

Discussion

Chapter Twelve summarises the important outcomes of the research presented in this thesis and how they have addressed the major issues that confront contemporary methods of wood identification. The thesis ends with recommendations for the future direction of wood identification.

Conclusions

This chapter has highlighted the circumstances in which complete sets of botanical structures are unavailable for identification purposes and the need for resources to aid the identification of fragmentary taxonomic materials from a variety of cultural and environmental contexts. It is in response to the paucity of identification tools to wood fragments that this research developed. The chapter has also introduced wood identification and anatomy and some of the salient concepts and features as well as outlining the research objectives and structure of the ensuing thesis. With the use of case studies and an emphasis on wood fragments, the next chapter examines in greater detail the applications of wood identification to a range of disciplines.

Chapter Two. Applications of wood and wood fragment identification

Introduction

The pervasiveness of wood in society means that the identification of wood fragments is a requirement of a number of scientific disciplines as well as some fields of humanities. In this chapter, a more detailed review of the applications of wood identification is provided, where possible elucidating its significance with case studies – although much of this research probably remains unpublished. A distinction is drawn between the different circumstances that mean that fragments are the limit of material available for identification, and there is a strong bent towards the identification of historical wood as it is against Australian Aboriginal artefacts that the developed identification tool will be applied (see Chapter Eleven). Several case studies expose the limitations of historical documentation and oral history, and serve as a warning for over-reliance on these resources for species identification. A common thread will develop which highlights the lack of suitable reference collections, the lack of treatment of non-commercial wood species and the difficulty in identifying wood to the species level.

Background

There are two circumstances in which wood fragments may be the limit of material available for identification:

1. Where the fragments are samples removed from a precious object such as an antique or anthropological artefact. Wood identification methods must be sympathetic and preserve the integrity of the object. Depending on the effects of cultural processing, the wider wood matrix may also be available for non-invasive examination, particularly of physical features.

2. Where the fragments are the physical remains of a wider wood matrix, as may often appear in biological, archaeological, palaeobotanical or forensic contexts. Separation from a wider matrix may be the result of human or environmental processes. In the absence of the wider wood matrix, there may be fewer characters available for identification, but examples may be more common (and less precious) allowing more liberal sampling.

Whilst each of these circumstances may be usual to particular disciplines, the two possibilities are not discipline dependent and either circumstance can occur within a discipline. For example, forensic scientists may identify wood fragments (trace evidence) which have been separated from an object, but sometimes much larger samples may be available. In addition, it is likely that those involved in wood identification for forensic purposes will have access to as much of the available wood as is required for definitive identification for, in this field, conviction or acquittal may rest upon the outcome of the wood identification. In archaeology, wood will often be recovered in a fragmented condition, but sometimes much larger pieces can survive as well as intact wooden archaeological objects. No attempt is made to distinguish between the two circumstances in this chapter but readers should be aware of the different conditions under which fragments are available and the restrictions on sampling procedures and available features.

For the purposes of this literature review, research involving wood identification in the area of science and humanities has been categorised into disciplines. However, these are loose containments for much of wood identification is inter-disciplinary. For example, conservation studies that employ wood identification may examine anthropological artefacts or objects of art history; plant analyses of Stick-Nest Rat middens are as much indicators of Stick-Nest Rat ecology (zoology) as they are indicators of past environments (palaeobotany); and identification of carbonised wood may provide insights into both human behaviour (archaeology) and vegetation history and change (palaeobotany).

Finally, studies that utilise wood identification in the following disciplines are scarce, some more so than others. Whilst it may be logical to conclude from this that there is not a need for wood analysis, the experiences of eminent xylologists as related in popular publications (Bird 2003; CSIRO 2000; Layton 2002; Milius 2002) and elsewhere (Hoadley 1990; Keenan 1987; Stern 1976) suggest otherwise. Instead it is suggested that where wood identification is not practised it is a direct reflection of the lack of resources and the specialist training required for xylology. In addition, the inter-disciplinary nature of wood identification, and the common need to outsource the work to an expert xylologist, has probably led to much of the research that is conducted remaining unpublished. That there are beneficial outcomes from wood identification for a variety of disciplines is demonstrated in the ensuing review with several case studies. However, in the absence of

cases of wood identification within fields such as zoology and quarantine, the projected benefits are largely inferred.

Museum Anthropology/Ethnography

> *When one looks at the Australian museum scene one is struck by the work undertaken in past decades by curators such as Tindale, McCarthy and Edwards. Their research publications together form a most respectable contribution to our study of Aboriginal material culture. But what of now, of the past decade? With the exception of the Anthropology Museum of the University of Queensland, the ethnological research production of museums across the country has been negligible.*
>
> (Reynolds 1979: 10)

In the two decades since the aforementioned quote was published, research into artefacts held in ethnographic collections in Australia remains poorly developed. A perusal of Australian museum and anthropology publications revealed few studies involving material culture whilst the international anthropological literature seems equally sparse with respect to artefact materials identification (see exceptions Dechamps 1970; Dechamps 1971). It has been suggested that this dearth in material culture studies is largely the result of decreasing funds and declining staff numbers in museums, the need to prioritise collection management over research (Furst 1989; Reynolds 1979; Reynolds 1989) and the split between museum anthropology and university anthropology that occurred in many western countries early in the 20th century, when university interests steered away from material culture and towards social anthropology (Bouquet 1999: 7; Reynolds 1979; Reynolds 1989: 112). Despite the lack of material culture research output in recent decades, a few pilot studies involving wood identification of ethnographic artefacts were conducted by Queensland institutions during the late 1970s and early 1980s.

Case study: wood identification of Aboriginal Australian spearthrowers

An important and successful precedent to this project is a study identifying the wood species used in the construction of a selection of *Queensland Museum* spearthrowers (Robins 1980). The spearthrower collection was selected due to the strength of the

accompanying ethnographic documentation and because this literature indicated that most of the spearthrowers had been constructed from heartwood (Robins 1980: 50). In addition, the majority of the 511 items held in the collection were considered suitable for sampling; this was largely decided on the basis of conservation needs, the rarity of the object and the existence of a suitable area from which to remove a sample for microscopic analysis (Robins 1980: 51).

The microscopic analyses of the wood samples were conducted by the *Queensland Department of Primary Industries (Forestry)*. Ninety per cent of the 452 objects sampled were identified to at least family level (Robins 1980: 51). Forty-seven genera or species were identified as well as 23 species that had not been documented in the literature (Robins 1980: 51). Following this, three examples were provided that relate to the results of the analysis of the spearthrowers collected by Joseph Campbell (agriculturalist), Reverend Hey (Superintendent, Mapoon Mission) and W.E. Roth (anthropologist) in the late 1890s to early 1900s. In each example discrepancies exist between the species identified as a result of the microscopic analysis and the species documented in the collectors' literature. These examples are used to demonstrate the inadequacy of the ethnographic documentation. (A more specific example of the outcomes of this particular study in terms of exposing collector biases is given in Chapter Eleven.)

A second, earlier paper (Buhmann, Robins *et al.* 1976) indicates that the spearthrower study was part of an ambitious "wood identification project [that] aims to gain plant species information for all wooden artefacts in the *Queensland Museum*." It is unfortunate that this project was never completed (Robins 2001: *pers. comm.*) given the tremendous research potential of such a study. However, Robins' paper and the themes outlined provide the background and validation for this project, particularly the application of the developed wood identification tool to a set of Aboriginal Australian ethnographic objects (see Chapter Eleven.)

Case study: wood identification of Aboriginal Australian swords

Another relevant anthropological study involved the identification of wood used in the construction of swords from the *James Cook University Material Culture Unit* and the *Queensland Museum*. The results of this analysis are reproduced in the endnotes of Cosgrove (1980). Identification of the wood used to construct 45 swords was conducted

by Forestry Departments in Atherton and Brisbane (Cosgrove 1980: 16) and merely indicated that the swords were made of five very hard and dense wood species (Cosgrove 1980: 17). No indication of the species or further information has been located.

Art History

Another field where wood identification can be of value is art history. Broadly speaking art history may include antiques, particularly furniture, but also wooden items such as sculptures and other visual arts, and utilitarian items such as bowls and utensils. It may also include musical instruments. For the purposes of this discussion art history has also been defined as pertaining to items of the last four or five centuries where good historical records are still retained. Again, there are few published studies that discuss the wood identification of items of art history and presumably much of this work is unpublished. For example, only one reference was uncovered to a study that involved the microscopic wood identification of furniture (Montgomery 1966).

The study of antiques and *objet d'art* generally has the luxury of an historical context and documentation. Wood identification may often be used to test and augment what is already known through written resources. As one researcher stated in relation to the identification of wood used to construct musical instruments:

> *"One does not usually need to identify the woods to learn where the instrument was made."*
>
> (Koster 1995: 2)

For example, much will be known from historical records about changing preferences in the wood used to construct particular items of furniture, which manufacturers worked with which timbers, and which wood was coveted and which was inexpensive. Similarly, the same historical records will yield information on changing preferences in furniture types, which manufacturers made which particular items of furniture and which pieces were mass-produced as opposed to rare pieces. More can be learned about an item of furniture by examining its structure and how it has been put together; given knowledge of the invention of particular tools and technologies the method by which an item has been constructed can provide a useful indication of its age. Furthermore, when it comes to the

international market in antiques, there are usually a limited number of commercial timbers represented, and many art historians and antique experts have the experience to distinguish these by their grain and figure, and without invasive analyses. In addition, the global market in timbers means that any indication of provenance of an item through wood identification must often be treated with caution (Koster 1995: 2).

Whilst wood identification of *objet d'art* and antiques will not always be necessary to determine the identity or value of an object it can contribute to knowledge of the provenance of an item, the period of its manufacture and its manufacturer. For example, art galleries may require identification of the wood used in the frame for a painting (Gare 2005: *pers. comm.*), particularly where the painting is unsigned and its country of origin is unknown. There may also be times where the wood species used to construct an object is a very important indication of value, especially where an item has been constructed using a rare wood-producing species, or a timber seldom used in its construction. For example, xylologist Alex Wiedenhoeft's (*United States Department of Agriculture (USDA), Forest Products Laboratory*, Wisconsin) identification of samples removed from a table determined that it was an early American example of Eastern White Pine[4] furniture, rather than a European piece. As a result, the value of the table increased from the US$15,000 paid at auction to US$100,000 (Milius 2002).

Wood identification can also be used to assess authenticity by determining whether an item may be a fake or whether it has been modified or repaired. Identification of interior woods, particularly in the case of furniture, may provide a better indication of provenance since these were often local species whilst the exterior surfaces were made of imported timbers (USDA Forest Service 2005). Finally, as the following case studies attest, wood identification can provide a useful test of theories of provenance, age and manufacture developed from historical documents, oral histories and expert experience.

[4] This article referred to the wood only by its common name but according to Bishop (1999: 208) Eastern White Pine is *Pinus strobus*.

Case study: wood identification of American keyboards

One United States study involved the identification of the wood from historical keyboards including pianos and harpsichords housed in various US museums (Koster 1995). The author maintained that wood identification is necessary "if only to describe them accurately in museum catalogues and other sources of data intended for scholarly or professional use" (Koster 1995: 2). Furthermore, since keyboards tend to be made of many timber species (Koster 1995: 1), knowledge of the wood species used for different keyboard parts may be of interest to contemporary keyboard makers who may be looking for a species that imparts a particular sound and resonance.

The study involved the microscopic analysis of over 1000 samples from keyboards held in the *Museum of Fine Arts* in Boston (Koster 1995: 2). From these analyses, Koster felt some confidence in stating that certain species were frequently, infrequently or never used in the construction of keyboards from particular countries (Koster 1995: 2). Koster also knew that during the 18th and 19th centuries, there were two major keyboard manufacturers in the United States: one working in the English-style in New England and New York, and the other working in the German-style in Pennsylvania. With this knowledge, Koster set out to determine the origin of five keyboards of unknown origin. We will use the second case study to serve as an example since it serves a warning for accepting oral accounts and histories.

One of the five examined keyboards was an 18th century German-style square piano housed in the *Metropolitan Museum of Art*, New York. The former owner's knowledge of the family history, and the fact they were of German ancestry, led them to believe the piano had come from Germany. However, this was contradicted by the results of the analysis of the wooden parts used to construct the keyboard. The bottom of the piano and the soundboard were both made of Eastern White Pine[5], and the key levers of Yellow Poplar[6], both unknown timber species in Germany in the 18th century. Koster determined

[5] This article referred to the wood only by its common name but according to Bishop (1999: 208) Eastern White Pine is *Pinus strobus*.

[6] This article referred to the wood only by its common name but according to Bishop (1999: 166) Yellow Poplar is *Liriodendron tulipifera*.

that the piano was in fact American and, due to the family's Pennsylvanian and German history, it was probably made by the Pennsylvanian manufacturer.

In a discussion of practical and ethical considerations, Koster acknowledges that wood identification is often not possible beyond genus and that, without knowledge extracted from historical resources, origin of an instrument's manufacture can not be reliably determined using wood analysis alone. Whilst admitting to being "contra-conservational" in promoting and using invasive analyses for wood identification, Koster argues that much of conservation work is cosmetic and not necessary for preservation – certainly in the case of *objet d'art* and antiques he may be right – but that museums should be ethically bound to advance knowledge of their collections through materials identification using careful analytical techniques that are sensitive to the object's integrity.

Case study: wood analysis of Italian violins

A study that did not involve wood identification but did involve wood fragment analysis was conducted on 16th - 18th century Italian violins made of spruce (Barlow and Woodhouse 1990). The research was devised to assess the validity of claims that the spruce wood may have been soaked in water for a significant period of time before being used to construct the violins. The reasons a manufacturer might have used "ponded" spruce to make violins are unknown but there is some suggestion that it may have been used to increase the wood strength and permeability to preservatives (Barlow and Woodhouse 1990: 203).

The study involved the examination of 13 violins of known provenance, manufacturer and estimable age. Whilst the violins were undergoing restorative work, fragments were removed for analysis using various methods including fracture, a knife or a plane (Barlow and Woodhouse 1990: 206). In what was another example of the capacity of wood analysis to test the veracity of existing knowledge and hypotheses, the study determined that there was no evidence of the spruce wood being soaked before construction; this is because the membranes of the bordered pits did not show the signs of bacterial degradation that might be expected after a period immersed in water (Barlow and Woodhouse 1990: 210).

Materials conservation

To appropriately conserve and repair objects it may be helpful to know the identification of the materials used in their construction. However, in the area of object conservation, only two New Zealand studies were located that involved wood identification of artefacts using scientific methods (Wallace 1982; Wallace 1989). It has been suggested that this is largely because much of the identification work conducted by conservators remains uncollated and unpublished (Gott 2001: *pers. comm.*; Johns 2001: *pers. comm.*; Sease 2001: *pers. comm.*). Furthermore, there can be logistical constraints and, for a variety of reasons, very few conservators attempt to determine the scientific names of unprovenanced and unknown pieces of plant (or animal) material that comprise an artefact:

- Conservators often lack training in scientific disciplines of botany and zoology;
- Identification to species or genus is often not necessary to determine appropriate conservation strategies;
- Comprehensive comparative reference collections comprising plant and animal parts are not available or easily accessible;
- The time and money necessary to reliably identify materials could be spent on more pressing conservation issues pertinent to the larger collection, such as storage and pest management. For example, a single artefact may comprise a range of plant (and animal) parts and fibres which can complicate and intensify the identification process.

(Norton 2001: *pers. comm.*)

There is also likely to be resistance by some conservators who see the practise of wood identification through invasive analyses as counter to the objectives of their discipline. Where wood identification is required, conservators may prefer to use non-scientific and non-invasive methods of identification that may include consulting historical documentation and oral and written histories attached to the objects.

In Australia, where the state museums struggle beneath the weight of housing the majority of the nation's moveable heritage, many of the collections are in dire need of conservation

(Commonwealth of Australia 1995: 7). Whilst entire collections are being inadequately conserved and under-resourced it is difficult to imagine materials identification of single objects becoming a priority in the near future. South Australia's major conservation organisation *ArtLab Australia* tend not to conduct invasive analyses for the purpose of wood identification, preferring to send objects where definitive identifications have been requested to xylologist Jugo Ilic (*CSIRO Forestry and Forest Products*, Victoria). *ArtLab* does employ a wooden objects conservator with a background in carpentry and joinery who has had limited professional training in wood identification; he may attempt to identify more common species of Australian timber without invasive analyses (Gare 2005: *pers. comm.*). Whilst probably often accurate, this method of identification does not replace the level of certainty that may be attached to identification through invasive analyses and may serve to create misconceptions about the artefact.

Some conservators who do carry out identification work fail to identify the source of their identification (Norton 2001: *pers. comm.*). For example, a study examining dance crests from New Britain and Papua New Guinea involved the identification of their botanical (non-wood) parts to determine their condition and to establish an appropriate approach to their conservation (Daly 2000). Daly listed the plant materials used in the construction of the dance crests, some to genus and species level, but did not reveal the basis for her conclusions. This is a dangerous practice as it may manifest the perception in the reader that the identifications are correct and based on definitive and acceptable sources.

General texts on materials conservation

Despite the logistical impediments, there are occasions where scientific methods of identification, including wood identification, have been conducted for conservation purposes. Sandy (1997) discusses the application and value to conservation studies of a range of botanical resources that may be used for the identification of plant material, including plant morphology, anatomy, ultrastructure, biochemistry and ethnobotany (Sandy 1997: 78). A book produced by the *Getty Conservation Institute*, Los Angeles and relating to the conservation of artefacts made of plant material (Florian, Kronkright *et al.* 1990) provides a useful discussion of plant anatomy and its use in identification, as well as outlining techniques for sampling and microscopic analysis of different plant parts. A chapter is also devoted to recognising the impact of cultural processing and construction

processes, and the effects of physical, chemical, biological and mechanical deterioration on the conservation needs of artefacts made of plant material. Whilst recognising that identification of ethnographic artefact material can be problematic, the authors suggest that materials identification can be an important consideration when determining the conservation needs of an artefact. This is in contrast to another publication on the conservation of wooden artefacts (Unger, Schniewind *et al.* 2001) which provides comprehensive detail on recognising, diagnosing and treating the various biological threats to wood stability, but – despite a chapter on wood structure and properties – completely neglects the subject of wood identification.

Case study: wood identification of Maori artefacts, New Zealand

Like the study on the Queensland spearthrowers, research conducted in New Zealand demonstrated the risk of accepting identifications from ethnographic literature. The study identified the wood used in prehistoric Maori artefacts (Wallace 1982) and developed into a doctorate thesis on the preservation of waterlogged wood (Wallace 1985). One of the aims of the research was to compile a list of wood-producing species used by pre-European Maori communities. The earlier project examined the wooden hafts and sockets of 56 wooden Maori adzes collected from waterlogged sites (and dry caves) from a variety of regions and deposited in various New Zealand museums (Wallace 1982: 179). Despite the poor condition of the wood, Wallace was able to successfully identify the adze hafts and sockets by extracting small fragments of wood for thin section microscopic analysis; the resources used to make the determinations are not mentioned. Most identifications were made to species level, although the similarity in cell anatomy within and between certain genera precluded identification beyond genus for some artefacts (Wallace 1982: 182). In the study, ethnographic documentation is used to describe the physical appearance of the adze hafts, as well as to provide evidence of their construction and distribution; it was also indicated that identifications were made in the ethnographic literature, but unfortunately the list of species was not recorded in the paper. However, in a very brief discussion, it is noted that the identifications determined as part of the microscopic analyses did not generally accord with those given in the ethnographic literature, with only two species appearing on both lists (Wallace 1982: 183).

A second publication emanating from this doctorate involved the identification of the wood used in 762 wooden Maori artefacts recovered from swamps (Wallace 1989). The analysis encompassed a wide geographical area and a broad range of artefacts including house timbers, bowls, carved panels, fern root beaters, tapa beaters, mauls (hammers), paddles, weapons, eel clubs, *kaheru* (spades) *ketu* (weeding tools), *ko* (digging sticks), *teka* (footrest lashed to *ko*), *hoto* (spade-like tool), spinning tops, *wakahuia* (treasure chests) and *heru* (hair combs). Samples of wood were extracted from artefacts, softened in hot water and the cellular structure of thin sections was analysed under a transmission light microscope. Identifications were conducted at *Waikato University*, Hamilton and with the aid of a series of publications on wood anatomy but it is not clear who made the identifications. In most cases identifications were determined to species level. In total, 37 wood species were used to construct the 21 artefact types. Results were examined for each artefact group; the type of wood used (e.g. hardwoods or softwoods), and whether a correlation existed between particular woods and particular artefact types, was noted. It was concluded that a majority of artefact types were made from a short-list of preferred woods, but recommended that the project be extended to include artefacts from museum collections and archaeological excavation sites that retain information regarding provenance and dating. This would provide a valuable spatial and temporal context of Maori wood use.

Archaeology

Given the existence of favourable preservation conditions, plant parts such as seeds, fruits, leaves and wood may survive in archaeological deposits. Where plant remains have not preserved in a carbonised state they will often be fragmented, waterlogged or desiccated, if they are to preserve at all, and most international archaeological studies relating to botanical material refer to remains in these conditions (Alves, Rieth *et al.*; Alves, Rieth *et al.*; Asouti 2003; Bamford and Henderson 2003; Bernabei and Romagnoli 2001; February 1996; Goren-Inbar, Werker *et al.* 2002; Lev-Yadun, Artzy *et al.* 1996; Pendleton and Warnock 1990; Smith, Vellen *et al.* 1995; Smith, Vellen *et al.* 1998; Wasylikowa 1997; Watters and Miller 2000). In Australia most plant remains have been recovered from desiccated sites (Ladd 1988: 12).

As with other disciplines that require wood identification, comprehensive reference collections and keys to macroscopic plant remains – including wood – are lacking in

archaeology[7]. Furthermore, in Australia, macroscopic plant recovery and analysis has been minimal (Beck, Clarke *et al.* 1989; but see exceptions Clarke 1985; Clarke 1989; McConnell and O'Connor 1997) despite the common recovery of carbonised wood from Aboriginal hearth sites. The accepted explanation is that the Australian environment is not conducive to macroscopic plant preservation. However, some argue that the systematic procedures to promote their extraction are not in place (Clarke 1989: 56). In particular, the technique of flotation – a water-based method of plant recovery which works on the principle that organic material will float in water – is not readily practised on Australian excavation sites (Clarke 1989: 56). However, since its development in the 1960s (Struever 1968), flotation has revolutionised macroscopic plant recovery in the United States and Europe where it is employed on most archaeological sites; in addition, most of the larger European and US excavations employ an archaeobotanist specialising in plant recovery and analysis (e.g. Asouti 2003).

Papers pertaining to the botanical identification of archaeological material are more prevalent than those referring to the botanical identification of ethnographic artefacts in anthropological studies. Perhaps one of the reasons for this is that archaeologists often lack the accompanying documentation upon which anthropologists so rely when interpreting and ascribing meaning to objects. Wood identification is an aspect of archaeology that is difficult to ignore given the importance of wood-use in cultures across the world and the prevalence of carbonised wood in archaeological sites. Wood has been extracted from maritime, historical and prehistoric archaeological sites; the following section provides case studies where wood identification has been employed in each of these areas.

Maritime archaeology

Maritime archaeology refers to the archaeological investigation of all things nautical. In particular, it involves the underwater survey and analysis of shipwreck sites and their cargo, but also includes the archaeological investigation of harbours and jetties. It provides valuable knowledge on international trade, sea-faring and ship building.

[7] A precursor to this doctorate was the development of an interactive identification tool to plant disseminules (seeds and fruits) from archaeological deposits in northern Australia (Barker 2000).

Wood identification can play an important role in maritime archaeology, particularly in identifying the wrecks of famous ships. For example, xylologist Jugo Ilic (*CSIRO Forestry & Forest Products*, Victoria) has identified timber samples recovered from a shipwreck off Rhode Island to help determine if it was Captain Cook's *Endeavour* (Layton 2002). The wood samples were analysed for indications of Australian wood species that were used in the ship's repair whilst it was stranded on the Great Barrier Reef off Queensland. Unfortunately, analysis of the wood, stone ballast and coal indicated that the ship was not the *Endeavour (Australian Government 1999).* However, *Australian National Maritime Museum* (Sydney) staff are confident that the ship is one of twelve other eighteenth century shipwrecks scuttled off Rhode Island (Australian Government 1999).

Ilic has also identified wood from the site of the legendary Mahogany Ship, a Portuguese or Spanish vessel thought to have been lost beneath shifting sands at Warrnambool, Victoria (Layton 2002); its discovery would push back Australia's date of European arrival by 250 years. Ilic identified the timber as *Quercus* spp. (White Oak), a common shipbuilding timber of the northern hemisphere. While lending support to the possibility that it was from the Mahogany Ship, *Heritage Victoria* cautioned that other ships of northern hemisphere origin had been wrecked along this stretch of coast (Heritage Victoria 2005).

Finally, in the United States, xylologist Alex Wiedenhoeft (*USDA Forest Products Laboratory*, Wisconsin) has identified White Oak[8] recovered from the remains of a ship thought to have been used by the pirate Blackbeard (Milius 2002).

Case study: a 14th century wooden diptych recovered off the coast of Turkey

It is not only ship timbers that may be identified but also the wooden cargo they may contain. In 1986, a wooden diptych[9] was recovered during an excavation of a 14th century shipwreck off the coast of Turkey; the wood was identified from 1-2 mm fragments (reserved during reconstruction of the diptych) using scanning electron microscopy (SEM)

[8] This article referred to the wood only by its common name but according to Bishop (1999: 124) White Oak (as distinct from Red Oak) refers to a group of North American *Quercus* species.

[9] A diptych is an ancient "notebook" consisting of two panels made of wood, ivory, bone or metal connected by a hinge.

(Pendleton and Warnock 1990). Fragments were placed in heated, distilled water before they were immersed in xylene and amyl acetate solutions. Upon drying, the fragments were split to expose the desired planes and prepared for SEM. By using several wood identification texts, databases, comparative reference specimens and GUESS (a computer-based wood identification tool) the wood was identified as *Buxus* sp. (Boxwood), a species commonly associated with the construction of small, wooden items of antiquity.

Historical archaeology

Historical archaeology refers to the study of the material culture and behaviours of people who retained a contemporary written record. At the same time, it can provide a valuable supplement to historical documentation, particularly of historically marginalised people – poor, female or non-white – whose experiences may be absent or misrepresented in the written record.

Case study: wood identification of coffins from colonial South Africa

In one historical archaeology study, wood identification was used to analyse coffins excavated from a South African cemetery outside Vredendal (February 1996). The research was conducted to expand existing knowledge of colonial South African burials that had largely been gleaned from analysis of skeletal remains. The cemetery was probably operational from 1837 until about 1920 but, whilst locals knew of its presence, no historical documentation relating to the burials – including its occupants and the dates of their burials – was retained. However, graves were marked with a headstone and footstone.

Due to termite activity, of 45 burials, only 11 retained wood sufficiently preserved to allow examination. In six of these cases only fragments were available for identification. To prepare the wood for analysis, samples were boiled in water and thin sections were removed with a microtome and mounted on slides. The sections were compared to modern reference material and it was determined that all of the represented wood specimens were from Pine (*Pinus* spp.) wood. The use of the most common commercially available timber in South Africa during the colonial period, the recycling of timbers from fruit crates, and the absence of timbers associated with high status burials, indicated that the people buried in the cemetery were poor.

Case study: identification of timbers from colonial-age buildings in the island of Barbuda

Another study, co-authored by xylologist Regis Miller (*USDA Forest Products Laboratory,* Wisconsin), examined wood from colonial buildings (post 17th century) in Barbuda, an island in the Caribbean (Watters and Miller 2000). Splinters of wood were removed from beams and structural timbers from three buildings and thin sections were created using a hand-held microtome knife and examined under a light microscope. The sections were identified with the aid of comparative wood specimens, thin section slides, and various wood identification texts and computer-based and paper-based keys. The study determined that three timber species were present – *Chlorocardium rodiei* (Greenheart), *Pinus* sp. (from the White Pine group) and *Quercus* sp. (from the White Oak group) – none of which are native to Barbuda. This corroborated historical records of the importation of timber into the colonial British West Indies. The geographical restrictions of these species, and documented records of the trade in timbers, also allowed some inference as to the source of the timber. For example, the authors surmised that *Chlorocardium rodiei* (Greenheart) was likely to be from South America and the White Pine species from North America.

Prehistoric/indigenous archaeology

Prehistoric or indigenous archaeology refers to the study of human remains and behaviours in the absence of a written record. Except where cultures are extant – as is the case with Aboriginal Australians and many other indigenous populations around the world where a rich oral history often survives – the archaeology is based entirely on the remains of material culture. More often than not material recovered from prehistoric/Aboriginal archaeological sites is fragmented and/or carbonised, the by-product of cultural or taphonomic processing. Such material is not always easily attributed to human use. Sometimes, however, archaeologists do recover the remains of relatively intact artefacts during excavation, or as the result of surface collection, particularly stone tools, but sometimes wooden artefacts. An example of this is the boomerangs recovered from Wyrie Swamp in south-east South Australia; these were identified as being manufactured from *Casuarina stricta*[10], a local timber (Ladd 1988; Luebbers 1975). Wooden tools were also

[10] Now *Allocasuarina verticillata* (Jessop and Toelken 1986: 112).

recovered from Anbangbang 1, a rock-shelter in Kakadu National Park, Northern Territory of Australia (Clarke 1985), an unmistakeable indication of human occupation, whilst, in 1995, a possible digging stick was found protruding from the base of a cliff in south-east Australia (Argue 1995)[11].

Case study: wooden artefacts from melting ice patches of southern Yukon, Canada

In 1997, melting alpine ice patches in southern Yukon, Canada revealed large amounts of well-preserved organic archaeological material amongst thick layers of caribou dung. The study described here (Hare, Greer *et al.* 2004) involved the analysis of over 146 objects – mostly related to caribou hunting – recovered from the area. The bow-and-arrows and throwing-darts were made of organic material including antler, bone, wood and stone. Radiocarbon dates of the dung and artefacts spanned from 8360 BP to 90 BP indicating that the site had seen continuous use by First Nation people – the indigenous people of Canada – throughout the Holocene when the area had been home to large herds of caribou. Radiocarbon dates of the objects supported North American evidence that the bow-and-arrow technology was widely in use between 1500 and 1200 BP. Microscopic examination of the wood of the throwing-dart shafts indicated that 70% were made of *Betula* sp. (Birch), which supported the ethnographic documentation, whilst *Picea* sp. (Spruce) was the dominant wood used to construct the arrow shafts. This indicated that the transition to bow-and-arrow technology might also have resulted in an adjustment to plant use and preferences.

Carbonised wood

In archaeology, the presence of carbonised wood – particularly where it is part of a hearth and/or appears with signs of human occupation such as stone tools, bone or other macroscopic plant parts – is usually seen as a source of datable material (Donoghue 1989: 90). A limited number of publications actually attempt to identify the wood (Asouti 2003; Bernabei and Romagnoli 2001; see for example February 1992). An example of carbonised wood identification from an archaeological excavation of a central Australian

[11] The precise location was not disclosed due to cultural sensitivities.

rock-shelter (Smith, Vellen *et al.* 1995) is provided in the following section that deals with palaeobotanical studies.

Palaeobotany

Palaeobotany, the study of the plant fossil record, attempts to explain the origin and evolution of flora; it also provides insight into climate change and plant adaptation. Given the right conditions, plant fossils (both microscopic and macroscopic) may preserve over many millennia. In general, preservation requires an anaerobic, waterlogged environment, such as occurs in swamps and bogs, and depends on the ability of different plant structures to survive (Martin 1982). This selective preservation biases the plant fossil record towards high-rainfall distributed species with plant structures suitable for fossilisation. Accordingly plant fossils are uncommon in the last two million years (Quaternary), where Australia has experienced increased aridity (Hope 1994: 379), and the palaeobotanical record is largely reconstructed from palynological studies in the wetter, coastal climes. In turn, the palynological record may be biased towards wind-pollinated species, where pollen is produced in abundance (Martin 1982: 638; Martin 1994: 105) .

Wood that preserves in the palaeobotanical record survives through petrification (wood is gradually replaced by minerals), carbonisation, or waterlogging and these processes can often preserve the structure well enough to enable identification. Fossil wood can contribute to knowledge of climate – evidence of seasonal variation may be observed in annual growth rings – as well as plant evolution and systematics. For example, a recent taxonomic re-evaluation of the fossil *Nothofagoxylon* wood record provided an extra dimension to palynological insights into the origin of the extant genus *Nothofagus* (Poole 2002), a genus considered key to understanding plant evolution and distribution in the southern hemisphere (Hill 1994). Finally, in a region where the pollen record is poor, examples of fossilised wood within Stick-Nest Rat middens, and carbonised wood in central Australia, provide a rare insight into arid Australian vegetation history in the Quaternary period.

Papers on fossil wood recovery in Australia – carbonised, petrified or otherwise – are rare and only a few were located. This is in contrast to North America where papers on fossil wood are quite commonplace. For example, one paper refers to the abundance of fossil wood in the south-eastern United States (Blackwell 1982: 395) but fossil wood has been

collected from most parts of the US and examples date from the Quaternary to the Cretaceous (Blackwell 1982; Blackwell 1983; Boeshore and Gray 1936; Boeshore and Jump 1938; Cahoon 1972; Daugherty 1934; Knowlton 1896; Manchester 1979; Manchester 1980; Manchester 1983; Page 1967; Page 1968; Prakash, Barghoorn *et al.* 1962; Spackman Jr 1948; Wheeler 1977; Wheeler 1991; Wheeler, Lehman *et al.* 1994). The reasons for the dearth in papers relating to fossil wood recovered from Australian palaeobotanical sites is largely related to the lack of suitable reference wood collections, identification keys and experts in wood identification in Australia (Hill 2005: *pers. comm.*).

Mineralised wood

One early Australian account of mineralised wood refers to the discovery of mineralised wood recovered from a road cutting near Brisbane (Shirley 1902). Slides of the transverse, tangential and radial surfaces were prepared and identification attempted. Two of the specimens were identified as a coniferous (softwood) species *Taxoxylon philpii* whilst three were possibly attributed to *Araucarioxylon*. Two other specimens did not retain sufficient anatomical structure to enable identification.

A second paper describes the transverse, tangential and radial surfaces of a specimen of well-preserved silicified, dicotyledonous wood from near Ulladulla on the eastern Australian coast, south of Sydney (Barnard 1927). The 8 by 4 cm specimen was tentatively identified as belonging to the Saxifragaceae family. Reference was also made to two other publications that examined fossil wood; Sahni (1920) identified two fossil wood specimens from Queensland as *Petaloxylon*[12] *scalariforme* and *P. porosum* whiles Nobes (1922) concluded that a South Australian wood specimen was too poorly preserved for identification (Barnard 1927: 113).

A more recent study relates to the identification of silicified wood retrieved from the upper Lachlan valley in New South Wales (Bishop and Bamber 1985). The fossils were recovered from basaltic lavas of early Miocene age and, using petrographic thin sections,

[12] Further information relating to the genus *Petaloxylon* may be found in Suzuki, Joshi & Noshiro (1991: n.v.)

three well-preserved examples were identified as *Acacia*, *Nothofagus* and Myrtaceae (aff. *Eucalyptus* B[13]). It is not clear what reference material was used to assist with the identifications. The *Nothofagus* specimen was the first example of a macrofossil belonging to this genus recovered from mainland south-eastern Australia, whilst the *Acacia* specimen represented one of the earliest macrofossil records of the genus.

Carbonised wood

Another area of palaeobotanical analysis that can yield information on vegetation history and change is the identification (and radiocarbon dating) of carbonised wood. This is an area of palaeobotanical analysis that is not commonly studied in Australia but may represent a valuable alternative to studies of vegetation change in arid regions where conditions are not conducive for pollen survival (Smith, Vellen *et al.* 1995). Whilst some shrinkage and distortion can occur, wood withstands the carbonisation process quite well, often preserving its anatomical structure well enough to allow identification (Donoghue 1989: 95; Hoadley 1990: 191; Smith, Vellen *et al.* 1995: 173).

Two major Australian studies – one in central Australia and one located in north Queensland – have involved the anatomical identification of carbonised wood; the outcomes of the research are discussed in terms of vegetation change (Hopkins, Ash *et al.* 1993; Smith, Vellen *et al.* 1995). The central Australian study appears to be the only published study to have involved an anatomical treatment of arid Australian wood to this time. Outcomes from both studies are briefly discussed here to demonstrate the potential contribution that carbonised wood identification can provide to our understanding of palaeo-environments.

Case study: identification of carbonised wood from northern Queensland

In the north Queensland study, carbonised wood was recovered from soil profiles beneath an extant rainforest; radiocarbon dating and identification of the wood indicated that much of the tropical rainforest was penetrated by sclerophyll *Eucalyptus* forest and fires during the late Pleistocene (Hopkins, Ash *et al.* 1993: 368). This supported previous palynological and sedimentary evidence that indicated sclerophyll forest and *Eucalyptus*-dominated

[13] Affinity *Eucalyptus* B refers to the genus *Corymbia*.

woodlands had occupied the region until approximately 8000 years BP when they started to be replaced by rainforest species (Hopkins, Ash *et al.* 1993: 368).

Case study: identification of carbonised wood from central Australia

In the central Australian study, fragmented carbonised wood, commonly around 0.5 cm length, was recovered from Putjarra rock-shelter, an Aboriginal occupation site located in the Cleland Hills, west of Uluru. The site contained evidence of human occupation from the present to 27,000 years BP. Ostensibly an archaeological study – the carbonised wood was not found in archaeologically sterile layers but amongst other material indicators of human occupation – the authors also recognised its usefulness as a source of palaeobotanical evidence for the late Quaternary. The authors conclude that whilst the wood recovered from the site would have been skewed towards those species preferred for fuel production, the identifications are representative of extant wood-producing species located around the rock-shelter. Comparisons are made between the species composition before, during and after the last glacial maximum (approximately 20,000 years BP) and it is observed that notable extant species such as *Acacia aneura* and *Eucalyptus camaldulensis* were not represented in any large quantities until after 13,000 year BP, and that *Callitris glaucophylla* representation declined after this time.

Subsequent papers pertaining to both the north Queensland and central Australian studies have also been published in a volume intended as a resource for future comparative analyses of carbonised material from the regions (Hope 1998).

Stick-Nest Rat middens

An area of palaeobotanical study where wood identification, particularly of fragments, has an obvious role is the analysis of fossil rodent middens. Rodent middens may contain both macroscopic and microscopic material including twigs, leaves, pollen, insect parts, small amounts of bone, faeces, rocks and sand (Pearson 1999). Nests are cemented together by crystallised urine. As a result, the nests may survive several thousand years and radiocarbon dates can be obtained from the stratigraphic layers. In the United States, studies of Packrat (*Neotoma* spp.) middens are well advanced and have provided important insights into environmental change (temporal and spatial) in arid and semi-arid America,

particularly through analysis of plant macrofossils (Pearson 1999: 39; Pearson and Betancourt 2002: 499).

In Australia, where research in this area is not as advanced, several studies have involved the identification of material in middens constructed by Stick-Nest Rats (*Leporillus apicalis* and *L. conditor*) with a view to gaining valuable insights into vegetation change and faunal distribution in arid central Australia (Allen, Head *et al.* 2000; Berry 1991; Pearson 1999; Pearson, Baynes *et al.* 2001). Stick-Nest Rats are extinct on the Australian mainland and most of their surviving nests date to the late Holocene, although older middens have been recorded (Pearson and Betancourt 2002: 504). Research has largely concentrated on pollen recovery and analysis, despite the US experience that warns against palynological analysis occurring at the expense of plant macrofossil investigation (Pearson and Betancourt 2002: 502). In the absence of suitable reference collections, wood identification, in particular, seems to be a neglected area of macrobotanical analysis of rodent middens. The authors of one New South Wales study that conducted plant macrofossil analysis remarked that middens were mainly composed of sticks, twigs and other fibrous material, but identifications were limited to leaves, phyllodes, burrs and seeds (Allen, Head *et al.* 2000: 336). Another study of two middens from around Alice Springs recovered numerous sticks (the largest measuring 7.5 cm by 5 cm) but identification of many of the plant macrofossils and fragments was not possible because of the lack of suitable reference collections (Berry 1991: 308).

Forensic Science & Law

The existence of taxonomic systems that describe individual biological species, and the restricted geographic distribution of many plants and animals, has meant that biology can play an important role in legal cases. Wood identification has served a role in both criminal and civil cases and xylologists have been required as expert witnesses.

Criminal law

Probably the most sensational area in which biological evidence has played a role is forensics. Palynology, in particular, has featured in cases before the court as pollen is widespread, microscopic and highly diagnostic. However, fragments of other plant parts – leaves, seeds, burrs, grasses and fragments of wood – can also settle or catch on a person,

their clothing or possessions and the geographically restricted nature of most plants may assist in tying them to a crime scene. Unfortunately, in forensics, much of this work remains unpublished even though many of the cases would make good technical notes (Pearman 2005: *pers. comm.*).

Xylologists have assisted in a number of coronial and criminal investigations. For example, Bruce Hoadley identified a fragment of wood lodged in a car that had been involved in an accident which killed the occupants (Hoadley 1990: 181). The identification of the wood fragment enabled investigators to determine that the car had hit a cherry tree, causing the driver to lose control and swerve off the highway (Hoadley 1990). In another case, Alex Wiedenhoeft (*USDA Forest Products Laboratory*, Wisconsin) matched wood from a murder weapon – a pool cue – to slivers recovered from a suspect's car (Milius 2002). In Australia, wood identification is often outsourced to the Botany Group within Victoria State Forensics who work closely with xylologist Jugo Ilic (*CSIRO Forestry & Forest Products*, Victoria) (Pearman 2005: *pers. comm.*). In one case of criminal law, Ilic provided crucial evidence in linking a splinter of wood from a murder victim's head with a baseball bat made of cheap Malaysian timber (Bird 2003).

Nowadays, forensic science is increasingly replacing conventional methods of identification using morphological markers with molecular tools where identification work is more precise and less time consuming (Pearman 2005: *pers. comm.*). Whilst extraction of DNA from most botanical plant parts has become fairly routine, the identification of wood by molecular means is not straightforward, largely as a result of its degradation within what is mainly dead tissue. Furthermore, the use of non-human molecular evidence in legal cases remains a contentious issue. Recent efforts to extract DNA from wood and the issues that confront this research are further explored in Chapter Five. In the meantime, traditional wood taxonomy using anatomical markers will be of value to forensic science for some years to come.

Case study: the South Australian Royal Commission into the conviction of Edward Charles Splatt

A sensational criminal case that occurred in South Australia which involved wood identification was the 1977 murder of Rosa Simper and the subsequent conviction of Edward Charles Splatt. The prosecution's case was based almost entirely on forensic

evidence – one of the first of its kind – and their success relied on the jury accepting this evidence and the evidence of the expert scientific witnesses who examined the trace (microscopic) materials (South Australian Government 1984: 9). Aside from particles of wood, the forensic evidence included paint, foam and metal particles, seed endosperm, hair and fibres (South Australian Government 1984: 15-20).

Wood particles were retrieved from the victim's bedsheet, the painted window sill of the bedroom where it was believed that the perpetrator had gained access to the home, and Splatt's coat. The expert witness for the prosecution, Rex Kuchel (a botanist and former Assistant Director of the *Adelaide Botanic Gardens*, South Australia) identified wood particles from all three items as Jarrah[14] (South Australian Government 1984: 18). Furthermore, he maintained that cells within the wood were blocked with a substance he attributed to the leaching of an oil-based paint. The prosecution relied heavily upon the evidence of Kuchel that the wood from Splatt's coat and from the painted window sill were both Jarrah; in their closing remarks they described the wood from Splatt's coat as "perhaps the most conspicuous item of cross-transference" (South Australian Government 1984: 112).

In 1984, six years into Splatt's imprisonment, a Royal Commission was mounted into his conviction amid continuing questions as to the validity of the scientific evidence and the jury's ability to understand it. In regard to the wood particle evidence, the inquiry concentrated on the testimony of Kuchel and his identification of certain wood particles as Jarrah (South Australian Government 1984: 113). During the trial and the Royal Commission, expert witnesses for the defence maintained that there were not sufficient differences between the wood from the window sill, coat and bedsheet to determine whether the fragments were of *Eucalyptus*, let alone Jarrah (South Australian Government 1984: 115, 117). Indeed, it was argued that Jarrah could not be distinguished from Karri[15] or Red Gum[16] microscopically. One expert witness for the defence introduced a CSIRO

[14] The scientific names of the wood were not given in the examined excerpts of the Royal Commission report but Jarrah usually refers to *Eucalyptus marginata*.

[15] Karri usually refers to *Eucalyptus diversicolor*.

[16] Red Gum usually refers to *Eucalyptus camaldulensis.*

key for the identification of wood and explained that wood splinters or particles may not carry enough diagnostic information to allow identification at the species level; indeed, he was unable to identify the control sample as Jarrah using the key (South Australian Government 1984: 117). Having viewed the three slides containing the wood particles, this same witness stated that the particles were not inconsistent with Jarrah – or inconsistent in comparison with one another – but that they could be one of many hardwood species (South Australian Government 1984: 117). The defence's witnesses also maintained that blocking of lumens with resinous material was a natural phenomenon and not, as Kuchel maintained, evidence that the wood particles had come from wood that had been painted (South Australian Government 1984: 116, 118-119).

The inquiry heard evidence from further expert witnesses which cast sufficient doubt upon the jury's decision. With respect to the wood evidence, the Royal Commission upheld most of the defence witnesses' findings and found that the identification of the wood particles as Jarrah had been "inadequate and unscientific" (South Australian Government 1984: 134). Indeed, under cross-examination Kuchel effectively conceded that the wood might not be of Jarrah. Ultimately the findings of the inquiry resulted in Splatt's pardon and a $300,000 compensation payout from the state government of South Australia (Haran 1990: 7).

Case study: the Lindbergh kidnapping, New Jersey

The most famous case in which forensic evidence was obtained from wood, and assisted in the apprehension and conviction of a criminal, was the Lindbergh kidnapping, the 1932 abduction and murder of the infant son of aviator Charles Lindbergh from his New Jersey home (Stern 1988b: 6). In what was to be the first case in which botanical evidence was submitted to a US court, xylologist Arthur Koehler, of the US Forest Product Laboratory, Wisconsin, examined a crucial piece of evidence – a crude, homemade ladder – that had been left at the scene. Koehler's examination of the rungs, rails and dowels revealed the ladder was made of four types of wood – Ponderosa Pine, Douglas Fir, North Carolina Pine and Birch[17] (Palenik 1983: 6). This helped investigators locate where the wood had

[17] The scientific names given by Koehler were not listed in this paper but they were probably *Pinus ponderosa* (Ponderosa Pine), *Pseudotsuga menziesii* (Douglas Fir), *Pinus taeda* (North Carolina Pine) and *Betula* sp. (Birch).

been purchased – a mill in the Bronx, New York City. (Palenik 1983: 8). In 1934, a suspect, Bruno Richard Hauptmann of the Bronx, New York City, was apprehended on other evidence and Koehler was able to make positive comparisons with micrographs of Hauptmann's hand plane, markings on a homemade shelf, and markings on the ladder rungs (Palenik 1983: 10). Police investigation of Hauptmann's home also revealed that a board had been sawn from the attic floor; the placement and spacing of nail holes in the wooden floor joists and one of the ladder rails matched, whilst examination of the wood figure and annual rings indicated that the rail and the remaining section of the board were once a single piece (Stern 1988b: 8). Hauptmann was later convicted and executed.

Civil law

In addition to criminal cases, wood identification has been used to assist in the resolution of civil disputes. In fact, xylologist Alex Wiedenhoeft (*USDA Forest Products Laboratory*, Wisconsin) has remarked that much of his work comes from this field (Milius 2002). For example, lawyers for a company that produced kitty litter asked Wiedenhoeft to determine if a rival company was using the same wood in their kitty litter production; the case was to decide whether the second company was in contravention of a patent belonging to the first company for the wood being used for this purpose (Milius 2002).

Often civil law cases involve exposing manufacturers or suppliers of lumber or wooden products, who may attempt to substitute desirable timber with cheaper imitations. One xylologist appeared as an expert witness in a case where a fence, supposedly of Cedar wood, had collapsed three years after purchase (Hoadley 1990: 181). In another case where a window cleaner fell from a ladder, the ladder wood was found to be of a Fir[18], a wood not listed in the ladder code (Hoadley 1990: 181). In a third case, wood chips used for a horse's bedding were identified as Black Walnut[19]; a toxic chemical that is released by the wood of this species was thought to be absorbed into the horse's skin, causing it to develop a debilitating disease, and potentially leaving the bedding supplier liable (Keenan

[18] This article referred to the wood only by its common name but according to Bishop (1999: 172) Fir may refer to several taxa: *Abies* spp. produce "true" firs but the name may also be applied to *Pseudotsuga menziesii*, *Tsuga heterophylla* and *Pinus sylvestris*.

[19] This article referred to the wood only by its common name but according to Bishop (1999: 172) Black Walnut refers to *Juglans nigra*.

1987: 47). In a more serious civil suit in Florida, a wooden decking collapsed and killed several people; the contractor escaped liability when it was determined that the Cypress wood used in the decking's construction met the building specifications (Keenan 1987: 47). Unfortunately, the specifications made no distinction between sapwood and the more decay resistant heartwood (Keenan 1987: 47).

Zoology

References that relate to the use of wood identification in zoological studies are difficult to locate but there is evidence of its relevance. US xylologist Bruce Hoadley has identified wood from racoon stomachs, discovered softwood fibres from a paper mill clogging fish gills, and investigated the wood used to create the paper nests of hornets (Hoadley 1980: 180). There are other areas of zoology where wood identification can play a role, particularly in cases where animal behaviour has resulted in the separation of wood from other botanical features. In some cases the separation of wood from a plant may be observed in the field and the wood may be identified from botanical parts from the tree of origin; however, one can imagine circumstances where field observations may not always be available.

Beaver wood use

An animal that relies heavily on wood for shelter and food is the beaver (*Castor* spp.). They use wood to construct dams and they eat the inner bark (cambium), twigs and roots. Beavers occur in several continents including Asia, Europe and North America. Several US studies have demonstrated that beavers significantly alter their environment with their preference for some trees over others (see references cited in Haemig 2005). In one Wisconsin study a population of beavers showed a predilection for Salicaceae wood – Willows (*Salix* spp.) and Aspens, Cottonwoods and Poplars (all common names for *Populus* spp.) – over Black Ash (*Fraxinus nigra*) and Tag Alder (*Alnus rugosa*). This resulted in an increased density of the latter species (Johnston & Naiman in Haemig 2005: 1). Whilst these studies presumably used botanical features to identify the species, it does serve to highlight the significance of wood to the beavers and the potential of wood identification, particularly given that processing by beavers will result in the separation of the wood from the rest of the botanical features. Whilst studies have not been located to this end, it is not difficult to imagine the circumstances where analysis of the wood used to

construct beaver dams and analysis of the contents of beaver stomachs may assist understanding of their ecology.

Bird nests

Another area of zoology where wood identification might have a role is ornithology where knowledge of the botanical composition of bird nests may provide important indicators of changing environments and bird adaptation. No studies have been found; plant uses that are related in ornithological references refer to nesting choice (e.g. Woods 1993) or feeding preferences (Paton 2005: *pers. comm.*).

Quarantine & Customs

As a large island continent Australia's quarantine systems play an important role in protecting local environments and industries from exotic pests and diseases. Whilst few references to the application of wood identification in quarantine have been located, there are some areas where quarantine scientists might find wood identification desirable. However, in practise wood identification may play a smaller role than one might expect. Two botanists employed by the *Australian Quarantine and Inspection Service* (AQIS) confess to no experience in wood identification (Mitchell 2005: *pers. comm.*; Waterhouse 2005: *pers. comm.*). In addition, they know of no cases that have required wood identification within AQIS (Mitchell 2005: *pers. comm.*; Waterhouse 2005: *pers. comm.*); this suggests that it is a service that would need to be outsourced to an expert in xylology if cases should arise.

This research has identified three areas in which wood identification may serve a role:

AQIS Import Conditions Database (ICON)

At the time of writing, the AQIS import conditions database (ICON) revealed that imports of *Eucalyptus* spp. timber from the Americas have been suspended or restricted after a consignment was found to be infected by *Puccinia psiddii* (Guava Rust) (AQIS 2005). A quarantine alert is also current for *Phytophthora ramorum* (Sudden Oak Death). *Phytophthora* is a microscopic, soil-borne organism that infects the roots and stems of plants and eventually results in death (dieback). In California, USA, thousands of *Lithocarpus densiflorus* trees and *Quercus* (Oak) species have been lost to *Phytophthora ramorum* (Forestry Commission 2005) Similarly, in Australia *Phytophthora* (particularly

P. cinnamomi) dieback affects native and introduced species causing concerns for entire ecological communities (Phytophthora Technical Group 2003). Accordingly, the current quarantine alert places strict restrictions on the import of timber produced by host plants from the USA and Europe (AQIS 2005). The list includes well-known commercial hardwoods and softwoods including eight *Quercus* sp. (Oak), *Pseudotsuga menziesii* (Douglas Fir), *Fagus sylvatica* (European Beech), *Sequoia sempervirens* (Redwood), and *Abies grandis* (Grand Fir) (AQIS 2005). The correct identification of these timbers is important to ensure that AQIS meets the conditions of its own database and to protect against restricted timbers entering the country under non-listed names.

Identification of CITES-listed timbers

Finally, Australia, along with 167 other countries, is a signatory of CITES (Convention on International Trade in Endangered Species of Wild Flora and Fauna), an international agreement that controls global trade in endangered plants and animal (CITES 2005). In the CITES listing are numerous wood-producing species – such as *Swietenia macrophylla* (Bigleaf Mahogany), *Dalbergia nigra* (Brazilian Rosewood), *Gonystylus* spp. (Ramin) and *Cedrela odorata* (Barbados Cedar) – many of them of Central and South American origin. To effectively uphold the agreement, Australian customs and quarantine officers must be able to recognise listed timber-producing species – and separating them from non-listed species, particularly those that occur within the same genus, can be a difficult task (Gasson and White 2004). Xylologists in Britain have worked with customs officers to help them recognise the CITES-listed timbers (Gasson and White 2004), whilst in the US xylologist Alex Wiedenhoeft (*USDA Forest Products Laboratory*, Wisconsin) was involved in resolving a case where a company was attempting to sell timber and veneer wood that they claimed was made of African Mahogany[20], but customs officers claimed was a CITES-listed mahogany from South America (Milius 2002). The correct identification of these timbers is important to ensure that AQIS meets the CITES regulations and to protect against restricted timbers entering the country under non-listed names.

[20] The common name for several species belonging to the African genus *Khaya*.

Identification of exotic wood-boring insects

Despite some of the toughest quarantine laws in the world, occasionally exotic pests, particularly insects, make it past Australia's borders. In 2004 a European House Borer was found in a Perth house; the beetle commonly infests untreated seasoned softwood timbers (Western Australian Government 2004). Previously, in 2002, wooden frames on a consignment of paintings destined for the Italian Masters Exhibition at the *National Gallery of Australia*, Canberra indicated fresh attack by exotic wood-boring insects (Australian Government 2002). Given the threat to Australian timber, as well as the gallery's own collection, the consignment was quickly contained and fumigated by Australian quarantine authorities before the exhibition went ahead (Australian Government 2002). Even the Australian wine industry is not immune to quarantine restrictions with French oak barrels undergoing inspection for wood borers before they can be dispatched to the wineries (Anon. 2003) whilst, when entering the country, any wooden objects or furniture must be declared by international travellers. Monitoring of wooden objects and timber might be assisted if AQIS officers were able to identify wood prone to insect infestation.

Conclusions

These studies have shown that wood identification has significant applications to an extensive range of academic disciplines and professional fields. Indeed, wood identification can serve a role wherever wood has been separated from other diagnostic plant structures as a result of cultural or taphonomic processing. In disciplines that study material culture, such as museum anthropology, archaeology, art history and materials conservation it may serve to augment or validate existing knowledge or enhance knowledge of an object for which no other data exists. More specifically, wood identification can increase our understanding of cultural heritage by:

- Determining the provenance of an object;
- Increasing knowledge of human exploitation of the environment;
- Revealing misconceptions or validating in historical documentation;
- Providing insights into the conservation needs of an object;

- Establishing the rarity of an object;
- Establishing the authenticity of an object;
- Establishing the presence of repairs/modifications;
- Assessing the monetary value of an object;
- Identifying the manufacturer of an object;
- Establishing a date for an object's construction;
- Assisting with repatriation efforts (e.g. to Aboriginal communities);
- Recapturing and returning lost knowledge (e.g. to Aboriginal communities).

Wood identification may contribute to palaeobotany by:

- Furthering understanding with respect to vegetation change, particularly in arid regions where pollen does not usually survive;
- Furthering understanding with respect to climate change;
- Enhancing knowledge of plant evolution and systematics.

In law, wood identification may impart invaluable evidence in civil, criminal and coronial cases by:

- Assisting in establishing the cause of accidents;
- Assisting in the apprehension and conviction of suspects in criminal cases;
- Establishing where desirable timbers have been substituted for cheaper imitations;
- Determining where timbers have not met various regulations or codes (e.g. building).

Wood identification may contribute to zoological research by:

- Testing existing paradigms of ecology and animal behaviour;
- Providing an important indicator of animal adaptations to changing environments;
- Increasing knowledge of animal/plant relationships.

Finally, in quarantine, wood identification may assist the protection of Australia's native flora and its export dollars by:

- Assisting in identifying wood that is prone to insect infestation;
- Assisting in identifying timbers listed as restricted by ICON or CITES.

In the absence of a centralised and updateable reference bank of wood and keys accessible to a range of disciplines and species – particularly to non-commercial wood – studies remain patchy and lacking in consistent methods. As a result, wood identification fails to be systematically employed in any single discipline. The next chapter surveys a selection of the wood identification resources that are presently available.

Chapter Three. Existing morphological resources for wood identification

Introduction

As the previous chapter revealed, despite the unquestionable value of wood identification to a range of scientific disciplines and fields of humanities, there are some common problems: the lack of suitable reference collections, the lack of treatment of non-commercial plant species, or of woody parts other than trunkwood, and the difficulty of discerning between plants to the species level, a factor that can greatly enhance knowledge based upon the restricted geographic range of certain plant species. This chapter will review the resources available for wood identification based on morphological markers, including books, reference collections, atlases and computer-based tools.

Existing international resources for wood identification

This is not an exhaustive literature review but a survey of important and influential texts and other resources. Many other references are cited in the ensuing chapters.

Xylologists and professional organisations

Whilst one is careful to point out that there is more to wood anatomy than wood identification, the leading professional association to which xylologists belong is the *International Association of Wood Anatomists* (IAWA). The IAWA has approximately 550 members from about 55 countries. The countries with the four largest memberships – the USA, Japan, Germany and The Netherlands – comprise almost half of the entire membership. Members are largely attached to Forestry and Wood Science institutions but member addresses also indicate affiliations with departments of botany/plant science, palaeobotany/palaeontology, anthropology/archaeology, geology, geography, civil engineering and conservation (information taken from *International Association of Wood Anatomists* 2003).

Journals and treatments

In addition to annual meetings, the IAWA produces a quarterly, refereed journal – the *IAWA Journal* (formerly the *IAWA Bulletin*) – which occasionally contains papers that involve wood identification (e.g. Avella, Dechamps *et al.* 1988; Del Fueyo, Taylor *et al.*

1995; Dyer 1988; Pendleton and Warnock 1990; Wilkes 1988). The only other international journal of note is *Wood Science and Technology* where papers involving wood identification may also be published (e.g. Pandey, Upreti *et al.* 1998). The *International Wood Collectors Society* (IWCS), a non-academic organisation, also retains a number of members interested in wood identification, and many maintain personal reference wood collections; articles on wood identification are often published in their monthly magazine *World of Wood* which is not refereed.

Whilst their development would be very welcome, with the exception of the website "Inside Wood" (2004) (see later this chapter), to my knowledge there are no dedicated publications – the equivalents of *Floras* and *Faunas* – in which wood species are systematically described and revised. Wood treatments – and dichotomous keys – do exist but these are scattered through various publications and journals, including those of a botanical nature – such as *Annals of the Missouri Botanical Garden*, *American Journal of Botany*, *Australian Journal of Botany* or the *Botanical Journal of the Linnaean Society* – and forest research journals – such as *New Zealand Journal of Forestry Science*, *CSIRO Research Bulletin* and *USDA Forest Service Research Papers;* for further examples, see wood identification and wood anatomy bibliographies (Gregory 1980; Gregory 1994; Smithsonian Centre for Materials Research and Education 2005). Whilst recommendations on the layout and arrangement of wood anatomical descriptions have been made (see for example Carlquist 2001), treatments do not appear to be standardised. This is something that could be simply addressed by the IAWA in subsequent editions of the standard lists of softwood and hardwood characters (see Richter, Grosser *et al.* 2004; Wheeler, Baas *et al.* 1989).

Standard lists of characters in wood identification

Two of the most important wood identification publications are the *IAWA List of Microscopic Features for Hardwood Identification* (Wheeler, Baas *et al.* 1989) and the *IAWA List of Microscopic Features for Softwood Identification* (Richter, Grosser *et al.* 2004). Developed by IAWA member committees with the purpose of standardising wood identification treatments, these publications provide lists and descriptions of diagnostic features for separating angiosperm woods (hardwoods) and for separating gymnosperm woods (softwoods).

Hardwood identification

The *IAWA List of Microscopic Features for Hardwood Identification* (Wheeler, Baas *et al.* 1989) isolates 163 independently numbered, diagnostic anatomical features (or states), each representing the range of variation that can occur within a species. Like features are placed in broader categories so that, for example, there are features that describe variation in vessel porosity, vessel arrangement, vessel perforation plates, vessel helical thickenings, vessel-vessel pits, ray width, ray height, and ray composition. Categories are also used to describe variation in fibres, tracheids and parenchyma, mineral inclusions, crystals, druses, silica, oil cells, intercellular canals, tubes/tubules and cambial variants. On approximately every second page, features are exemplified by black and white micrographs of thin sections from representative hardwood species. Descriptions are clear and concise. Qualitative features are defined both with descriptions and examples of representative taxa, whilst quantitative features tend to be self-explanatory. Text under "Comments", "Procedure" and "Cautions" provide any further information including recommended methods for the assessment of features as well as any caveats and qualifications. For example, in the "comments" section for the category "Vessels per square millimetre", it is noted that vessel number is not recorded for ring-porous wood; this warns the user against using this category if feature 3 – "wood ring-porous" – is present (Wheeler, Baas *et al.* 1989: 259). Useful cautions are also given where a feature may not be applicable or easily assessed on fossil or archaeological specimens as a result of taphonomic or cultural processing (e.g. Wheeler, Baas *et al.* 1989: 324). An Appendix contains a further 58 miscellaneous features which include some simple observations on physical and chemical properties. These features fall within broad categories of geographical origin, habit (of plant), specific gravity, heartwood colour, odour, heartwood fluorescence, ethanol and water extract fluorescence, ethanol and water extract colour, Chrome azurol-S test, burning splinter test, and froth test. The publication is fully referenced and indicates where further information on particular features may be obtained.

Softwood identification

The *IAWA List of Microscopic Features for Softwood Identification* (Richter, Grosser *et al.* 2004) is set out in the same manner as its hardwood equivalent. However, anatomical features are reduced by about half to 84 which reflects the less-specialised gymnosperm

wood anatomy. A further 40 features relate to the geographical origin and physical properties of softwoods.

International xylaria

The most recent comprehensive survey of international xylaria – *Index Xylariorum* – examined 134 wood collections (Stern 1988a). It revealed that, excluding Antarctica, all the continents are represented by xylaria and many countries – e.g. Australia, Brazil and the United States – are represented by several xylaria. Xylaria are largely housed by forestry or wood technology research institutes. The oldest collection is in Saint Petersburg, Russia (Lew)[21] and was founded in 1823 (Stern 1967). Several other collections were established in the 19th century – including xylaria in Queensland (BRIw), New South Wales (SFCw), India (DDw), South Africa (PFPw), Europe and the United States– but the majority were founded in the early to mid 20th century. Most of the xylaria specialise in regional wood-producing species but the larger xylaria often incorporate specimens from an extended area and include commercial timbers, particularly those from Asia or Central and South America (Stern 1988a). Large xylaria (> 15,000 specimens) occur in Europe, the United States, Australia, Russia, South America, China, Japan, India and Indonesia (Stern 1988a). Around 1970, two of these collections – the *Samuel James Record Memorial Wood Collection* (SJRw) from *Yale University* in New Haven, Connecticut and the wood collection at the *Field Museum* in Chicago, Illinois (Fw) – were incorporated into the xylarium housed by the *USDA Forest Products Laboratory*, Wisconsin (MADw) (Miller 1999; Stern 1976). With a combined collection of approximately 125,000 specimens this is probably the largest xylarium in the world.

Wood identification using scanning electron microscopy

Reference books on wood anatomy that illustrate the structures of wood with scanning electron microscope (SEM) images are few. SEM is still a relatively recent application to wood anatomy and whilst it has been increasingly used in the discipline in the last twenty years, it has not replaced thin sections, the traditional means of analysing and identifying wood. Moreover, the two wood identification standards for hardwood and softwood

[21] Where specific xylaria are mentioned in the text they are followed by their unique abbreviations as per *Index Xylariorum* (Stern 1967).

identification continue to use thin section images to illustrate the list of characters used in hardwood identification (Richter, Grosser *et al.* 2004; Wheeler, Baas *et al.* 1989). Whilst SEM technology does have some advantages over thin sections, the latter is by no means an obsolete method of wood identification and its persistence in contemporary research may be partly attributed to the collections of prepared thin section slides that are often associated with xylaria.

Several books have been produced that display wood in its three-dimensions. First published in 1972, one seminal publication – *Three Dimensional Structure of Wood* – is now available in a number of incarnations, each of which has involved major revisions and updates; a second edition of the book was published in 1980, followed by a dual Hungarian-English language edition and a dual Korean-English edition. The Korean version (Butterfield, Meylan *et al.* 2000) is largely comprised of SEM image plates and captions of representative species; these provide an exceptional illustration of the wood features described in the text. The first chapter introduces the general structure of wood and is followed by chapters on the structure of softwoods, hardwoods and palmwoods. Each chapter begins with several pages devoted to a description of salient wood anatomical features.

A similar publication with equally superb SEM images – *Wood Micromorphology: An Atlas of Scanning Electron Micrographs* (Ohtani 2000) – describes the timber from 25 softwoods and 18 hardwoods growing in Japan. The anatomy of each species is given in a description followed by several pages of representative SEM images.

Two other publications illustrated with SEM include a book on New Zealand woods (Butterfield and Meylan 1978) and another on the major wood-producing species in China (Xishen 1988: n.v.). For the preparation of wood for scanning electron microscopy (SEM) there are several useful papers (Exley, Meylan *et al.* 1977; Heady 2000; Jansen, Kitin *et al.* 1998; Kucera 1986).

Sources of wood used in identification

Publications dealing with wood invariably treat limbwood or trunkwood. Rootwood may vary considerably from wood from other parts of a tree, and standard reference collections that contain trunkwood or limbwood are of limited application for root identification. In

response to these limitations, the Jodrell Laboratory in Kew, England developed a collection of thin section slides from authenticated rootwood (Cutler, Rudall *et al.* 1987: 1). This collection has since been used to identify the source of roots that are damaging buildings (Cutler, Rudall *et al.* 1987: 1). To make the collection more accessible a companion book – *Root Identification Manual of Trees and Shrubs* (Cutler, Rudall *et al.* 1987) – was produced which describes, both with thin section images and text, the diagnostic properties of 250 northern European hardwood and softwood species that are common to many parts of the world. There are two other publications on rootwood anatomy and identification (Cutler 1976; Hather 1993) whilst books on general plant and wood anatomy also commonly include general explanations of rootwood morphology (e.g. Metcalfe and Chalk 1989).

In terms of trunkwood and limbwood, publications often do not make clear which of these parts is being examined and this information may not be retained with individual specimens in xylaria. Whilst many xylaria are attached to Forestry, it is feasible that much of the material is trunkwood; however, where specimens were collected from a living tree, it is probable that sampling occurred from limbs so as to preserve the tree.

Computer-based resources

The benefits of providing computer-based access to wood collections, including electronic wood identification keys, have been recognised for several decades (Ilic 1993; Ilic and Miller 1996; *International Association of Wood Anatomists* 1981; Kuroda 1987; Quirk 1983; Wheeler, Pearson *et al.* 1987a; Wheeler, Pearson *et al.* 1987b) and, particularly since the introduction of web-based technologies, they are increasingly becoming the preferred option for databasing species and hosting identification tools. Whilst paper-based dichotomous keys, descriptions and atlases (Dadswell and Eckersley 1935; Ilic 1991; Klaassen 1999; Schweingruber 1990a; Westra and Koek-Noorman 2004) to wood do exist, they have limited application and accessibility and are difficult to update.

Online databases

The following section reviews some of the existing computerised databases relating to wood. Most of the online databases are "works in progress" and so not all of the intended assets and features may be available.

"Inside Wood" database of wood descriptions and identification tool

Collection: over 5200 wood taxa descriptions

Recently an ambitious, web-based project – "Inside Wood" (2004) – was launched. It aims to produce a centralised database that integrates all existing anatomical data for modern wood[22]; in September 2005, the website included 5773 wood descriptions and 21,892 images. The database is still under development and is maintained as part of the *North Carolina State University* (NCSU) Library electronic collections and supported by a US National Science Foundation research grant. It is a collaborative effort between the NCSU Library and three major partner institutions – National *Herbarium of The Netherlands*, Leiden; *Jodrell Laboratory*, Kew, England; and *CSIRO Forestry & Forest Products*, Victoria, Melbourne. The initiative involves well-known xylologists Elisabeth Wheeler, Pieter Baas, Peter Gasson and Jugo Ilic of these institutions.

To utilise the database requires access to the IAWA standard list of hardwood characters – softwood species do not seem to be treated in the website at this stage – although permission has recently been granted to reproduce the definitions of the features on the site. Species descriptions are presently defined by the relevant feature numbers. For example, *Acacia aneura* is described by feature numbers 1, 4, 12?, 13, 22, 23?, 25?, 26?, 27?, 29, 30 etc. (Features with question marks represent uncertainty over the presence of particular features).

"Inside Wood" maintains a practical search engine which enables four simple means of querying the data. Users may search by family, genus, species, common name or the author of publications that contain the original descriptions. Alternatively, they may browse alphabetically ordered lists of descriptions by family or genus. Essentially operating like simple multiple-entry keys, there are also two search engines that allow isolation of species which present with certain features. These operate with feature numbers in association with a key – P (present), A (absent), R (required present), E (required absent) – where A and E features *must* be present or absent regardless of the

[22] A similar database of fossil wood descriptions is expected to be available on the website shortly.

number of mismatches allowed. Mismatches account for variability in wood and users may choose between 0 to 10 mismatches, so that allowing for two mismatches will generate a list of species where all but two of the chosen features match the unknown specimen.

Searchable databases of xylaria holdings

On-line databases are maintained for several major xylaria:

- Forestry and Forest Products Research Institute (TWTw) Tsukuba, Japan (20,500 wood specimens) (http://f030091.ffpri.affrc.go.jp/index-E.html)
- Tervuren Xylarium (Tw) Wood Database, *Royal Museum of Central Africa*, Belgium (57,165 wood specimens representing 13,600 species) (http://www.metafro.be/xylarium/wood_collection)
- Database of the wood collection of the *USDA Forest Products Laboratory*, Wisconsin (MADw) (49,322 wood specimens) (http://www2.fpl.fs.fed.us/WoodColl/MADwCollectionSearch.html)
- Database of the *National Herbarium of The Netherlands* (incorporating xylaria Lw, Uw, WAGw), The Netherlands (35,000 wood specimens) (http://www.nationaalherbarium.nl/virtual/content.htm#Wood)
- Database of the *United States National Herbarium* (incorporating xylarium USw), Washington, US (42,500 wood specimens) (http://ravenel.si.edu/botany/wood/)
- Database of the Oxford University Herbaria (incorporating xylarium FHOw), England (24,255 wood specimens representing 9155 species) (http://herbaria.plants.ox.ac.uk/)

These databases vary in their level of sophistication and content but all provide search facilities that allow the collections to be queried. Delimiters include family, genus, species, collector, habit of plant, country, herbarium voucher number and location and wood specimen number (amongst others). None of the databases provide descriptions of the wood although the Japanese collection (TWTw) is supported by a simple, multiple

entry key. Image support – or provision for image support – is provided by MADw, TWTw, FHOw and the Dutch database supports thin section images from over 3000 species (also available on the "Inside Wood" (2004) database). Some of the databases also support photographs of associated herbarium vouchers and surface images of the wood (longitudinal and cross-section).

Identification tools

Apart from traditional paper-based dichotomous versions, there are other alternatives for the development of keys, including those that utilise purpose-built computer software packages (as is the case with this research). Two of the keys reviewed here use the computer program *Intkey* (a DELTA – DEscription Language for Taxonomy – product[23]). *Intkey* provides the foundation for the development of interactive, computer-based identification keys to any set of organisms or objects. Much like the *Lucid* software used in this research, the system is operated by navigating through a list of characters and selecting the states (or features) that best describe an unknown specimen (Figure 8). As states are selected, taxa are eliminated. Keys may be supported by images and notes. These can be used to define characters as well as taxa. This section provides a brief description of two keys to wood developed using *Intkey* and two other web-based keys.

Commercial timbers: descriptions, illustrations, identification, and information retrieval (an *Intkey* product)

Collection: 350 wood taxa

By H.G. Richter (xylologist) & M.J. Dallwitz

[23] Further information on DELTA software can be located at http://freedelta.impa.gov.br/

This comprehensive tool (Richter and Dallwitz 2005) provides a key to 350 of the major hardwood timbers that are traded internationally. It uses 117 characters, mostly aligned with the IAWA standard for hardwoods (Wheeler, Baas *et al.* 1989) and, in many cases, reproduces its feature definitions from this publication. There is provision to show sets of related characters – e.g. vessels, axial parenchyma, rays, mineral inclusions etc. – which breaks up the long list of characters and makes navigation easier. However, it is impossible to isolate only the IAWA features from the wider list of characters.

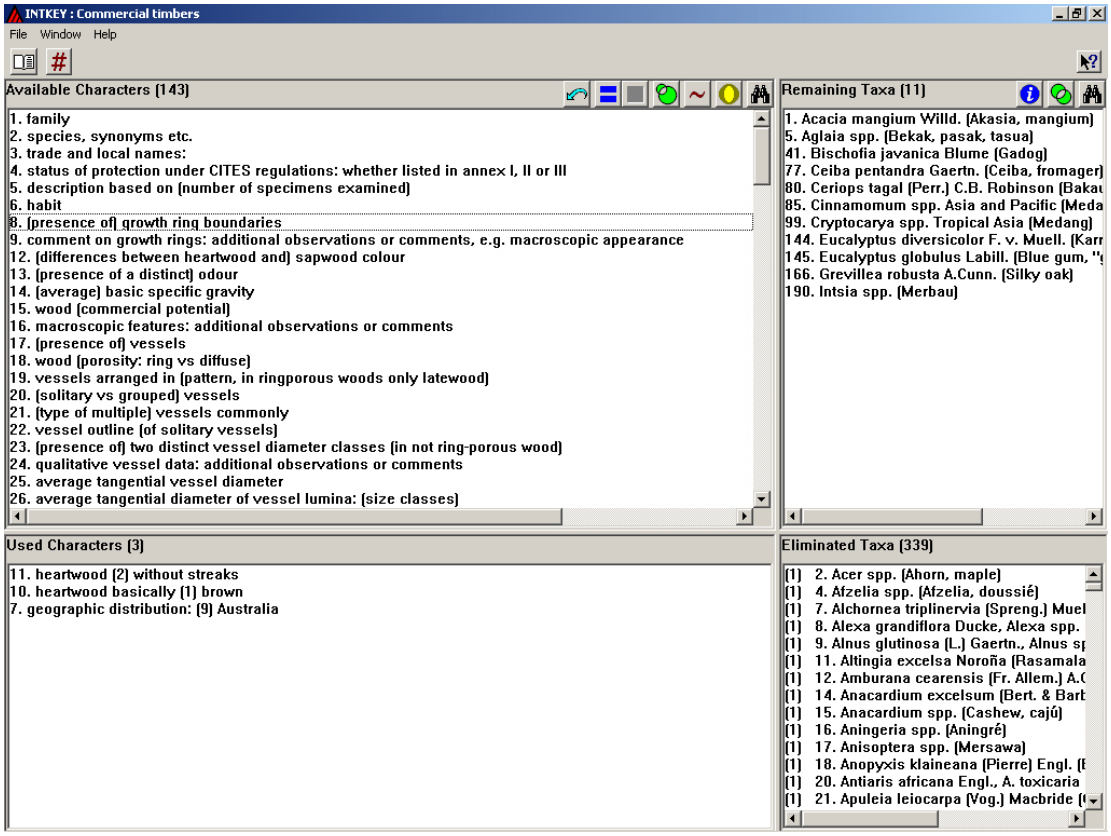

Figure 8 The interface of an *Intkey* identification tool

Images depicting certain features have not yet been attached to the character list but photographs of the wood surface and thin sections of the transverse, tangential and radial planes are present. These, and a full description of the wood, only seem to be accessible if one is connected to the Internet. However, notes on nomenclature and other distinctive attributes are available offline as is the diagnostic description.

None of the species descriptions refer to a specimen number or herbarium voucher and it is unclear how many samples contributed to the treatment of each taxon.

Anatomy of European and North American woods (an *Intkey* product)

Collection: 426 wood taxa

By Andreas G. Heiss

This tool provides a key to the common, non-commercial wood species from Europe and North America (Heiss April 2005). It includes 325 hardwood species and 101 softwood species (native and introduced). It has been created from wood descriptions appearing in wood identification publications as well as through the author's own research. In total, there are 145 characters and 15 sets. An extra feature of the tool is two sets which isolate the states (or features) that are applicable to the identification of modified wood and carbonised wood from palaeobotanical contexts. A useful feature – which the key to commercial timbers lacks – is a set that isolates the characters that were taken from the IAWA standards. However, it would have been useful if these had been categorised further – e.g. vessels, rays, parenchyma, chemical observations – as it still leaves a long list of 114 characters.

At this stage, the tool is supported by limited images and notes, and identification is apparently only possible to genus in most cases, but there are plans for expansion. Neither notes nor illustrations are attached to the characters which increases subjectivity and the chances of error. To effectively operate the IAWA characters – which comprise the majority of the characters – would depend on experience of the feature definitions and access to the published feature list and definitions. Two descriptions are attached to each taxon – one describing taxa using the IAWA features – and one that describes the species using the added characters. The purpose of the diagnostic description is not entirely clear but it appears to list a set of salient features that, if chosen, will separate the species from the largest number of taxa. None of the species descriptions refer to a specimen number or herbarium voucher and it is unclear how many specimens contributed to the treatment of each taxon.

<u>Wood anatomy of central European species (web-based)</u>

Collection: approximately 130 wood taxa

This website (Schoch, Heller *et al.* 2004) represents a revised version of the book *Microscopic wood anatomy: structural variability of stems and twigs in recent and subfossil woods from central Europe* (Schweingruber 1990b). The identification key is essentially a paper-based, synoptic key to coniferous and dicotyledonous species reproduced with a few hyperlinks to assist navigation. It utilises a few characteristic microscopic features to assist identification to genus (Figure 9). For example, for ring-porous dicotyledonous wood, key characters are ray width, the type of perforation plate, and the presence or absence of spiral thickenings. For coniferous wood, the key characters relate to the size of the ray pits, the presence or absence of resin canals and spiral thickenings in the tracheid walls. Once the correct genus has been identified, it is selected and information and images of the treated species are obtained.

Dicotyledon wood — Wood with vessels (pores)

Ring-porous wood

Ray width	Perforation plates	Spiral thickenings	Species	Key characteristics
uniseriate	simple	absent	Castanea	Latewood with dendritic pore arrangement, rarely biseriate rays.
bi- to triseriate	simple	absent	Fraxinus	Latewood pores solitary or in small radial groups, thickwalled.
		present	Hippophaë	Ring-porous, sometimes semi-ring-porous, rays generally storied.
3- to 5-seriate	simple	present	Ulmus	Pores, vascular tracheids and parenchyma in latewood in tangential to slightly oblique bands.
			Robinia	Pores, vascular tracheids and parenchyma in latewood in clusters to short bands, conspicuous tyloses.
>5-seriate	simple	absent	Vitis	In the narrow latewood pores in radial files and small groups. Rays very wide. Vessels with scalariform pits.
		present	Clematis	Latewood generally narrow, growth ring boundaries festoonlike, large rays.
			Berberis	Ring-porous to semi-ring-porous, latewood pores and vascular tracheids in clusters with a tangential to diagonal or dentritic orientation.
			Laburnum	Growth ring boundaries festoonlike, rays often over 5 cells wide, gum deposits in the heartwood vessels.
			Ailanthus	Often slightly oblique to tangential parenchyma bands, often indistinct ring-porous, variable.
uni- and multiseriate	simple	absent	Quercus	Dendritic pore groups in the latewood, uniseriate and very broad rays.
		present	Rosa	Broad rays often over 10 mm high.

Figure 9 Extract from the synoptic key on the "Wood anatomy of central European species" website. This section shows the treated dicotyledonous species that are ring-porous.

Species may also be browsed by family or genus using A to Z listings or by separately browsing by genus the dicotyledonous species or the coniferous species. Individual species are described by brief summaries of features on the transverse, radial and tangential surface. Each of these summaries is supported by several superb thin section images. Key diagnostic features are also noted whilst a "remarks" section indicates where certain taxa may be indistinguishable e.g. *Pinus silvestris* cannot be separated from *P. mugo* or *P. nigra*.

A section on "Macroscopic characters" briefly describes the basic structure of wood as observed with the naked eye or at 5x to 20x magnification. This is supplemented by diagrammatic representations of the structure of wood and low-magnification micrographs that illustrate the difference between coniferous, dicotyledonous (ring-porous) and dicotyledonous (semi-ring-porous) woods. For fossil and carbonised wood, where many macroscopic features such as colour, odour and weight have been lost or modified, it is explained that this is usually the limit of macroscopic differentiation. Another section entitled "Microscopic characters" lists salient structures in coniferous and dicotyledonous wood and describes and illustrates with thin sections the range of variation that can occur in these structures. For example, within "vessels", thin section micrographs and brief descriptions are provided for ring-porous, semi-ring-porous, and diffuse porous vessels, as well as solitary, clustered and radial vessel files and oblique, radial and tangentially oriented vessels. The value of each diagnostic feature is measured using a key where H is high, ME is medium, and M is modest.

Finally, a section on preparation of specimens explains how to soften and section wood for the creation of thin sections as well as the preparation and examination of fossil and carbonised wood specimens.

Microscopic identification of Japanese Woods (web-based)

The on-line database of the Forestry and Forest Products Research Institute (TWTw) Tsukuba, Japan supports a simple, multiple entry key to 776 wood species based on the IAWA standard list of characters (Wheeler, Baas *et al.* 1989). On a single page, all of the IAWA features are listed next to a check box and users seeking an identification may select as many or as few features as they please by checking the relevant boxes. Species with the chosen features are listed, some with thin section images attached. There are no further descriptions of the species. There are no explanations of features on the site and so access to the IAWA standard is assumed. Additionally, the key is lacking a browse function that allows one to browse lists of species by feature(s).

Hard copy publications

Several other publications are worth mentioning. A popular text that introduces wood anatomy and wood identification is *Identifying wood: accurate results with simple tools*

(Hoadley 1990). Written for a novice audience, this is a US-based publication and is largely based on North American timber species and other commercial timbers. Explanations are clear and it is well illustrated with colour endgrain images and black and white micrographs of thin sections. In addition to discussing hardwood and softwood anatomy, the preparation of specimens for endgrain and thin section analysis and the identification of tropical timbers, it includes advice on how to remove samples from historical objects and advice on the development of wood reference collections.

More advanced explanations of wood properties and structure are provided in *Wood Structure and Composition* (Lewin and Goldstein 1991). Chapters examine wood chemistry, wood formation and morphology, cellulose, lignin, hemicellulose, bark, and techniques for chemical analysis. For a more detailed description of wood anatomy *Comparative Wood Anatomy* (Carlquist 2001) devotes individual chapters to growth rings, vessels, rays, parenchyma, fibres and tracheids, cell contents, the cambium, methods for anatomical analysis and examination, and wood evolution.

For the preparation of thin sections, an excellent guide has recently become available (Ives 2001). Written and published by Ernie Ives, a member of the *International Wood Collectors Society* (IWCS), and an enthusiastic microtomist, the book has been written for the amateur enthusiast who may be on a budget and lack access to equipment; it contains some fairly ingenious inventions and adaptations that evolved through trial and error. Ives discusses the production of thin sections using razor blades, planes, and sledge and sliding microtomes. In addition, he includes important chapters on the sharpening of microtome knives and cutting sections with microtomes – for further instructions on this subject see Ilic (1985). The rest of the book is devoted to a comprehensive description of the production of thin sections, from preparing, softening and storing initial small blocks from which to section, to wax-embedding low-density wood, and staining, clearing and mounting sections.

Finally there are a number of publications that are largely directed at those who process wood for construction, furniture-making and *objet d'art*. One such publication (Bishop 1999) provides a double-page spread of 100 popular commercial timber species. The species occur in alphabetical order based on their common or trade names. Text is limited to physical descriptions and important wood working characteristics including weight,

durability, "bendability", hardness, sawing and usability, splitting, and gluing. Each species is illustrated with a distribution map, and colour photographs of the longitudinal surfaces, as well as a low-magnification image of the endgrain.

Existing Australian resources for wood identification

Despite the thousands of wood-producing species in Australia, with the exception of a few notable contributions, there is a paucity of literature pertaining to Australian timbers. There are no Australian journals or societies devoted to wood anatomy, and only a handful of xylologists; according to the 2003 membership records, only twelve members of the *International Association of Wood Anatomists* (IAWA) reside in Australia and they are not all involved in wood identification in a professional capacity. This section briefly examines the resources available in each state followed by relevant and seminal Australian publications that aid wood identification.

State & territory based survey of wood identification services and xylaria

This section briefly summarises the major state and territory-based wood identification services and xylaria in Australia.

Queensland

The *Queensland Department of Primary Industries (Forestry)*, Indooroopilly offers a wood identification service (for which they charge about $110/hour) although it is not expected to be offered for much longer (Hopewell 2005: *pers. comm.*). The associated xylarium (CQTw) was established in 1922 (Stern 1988a: 210) and contains approximately 10,000 wood specimens including the important collection of Queensland Colonial Botanist, F.M. Bailey. Herbarium vouchers are no longer retained (Hopewell 2005: *pers. comm.*). Since an increase in the price of the service, the number of wood identifications conducted has decreased from 1000 per year to 300 per year. Samples for identification are received from within Australia as well as Asia, the Pacific and the United Kingdom (Hopewell 2005: *pers. comm.*). Apart from the xylarium, consulted publications include the computer-based identification key *CSIROID*, and out-of-print publications and card-sorting keys. Identifications are conducted by examining the endgrain, sometimes in combination with simple chemical observations such as the burning splinter and froth test (Hopewell 2005:

pers. comm.). The constraints of time usually prohibit the production of thin sections but a collection of thin section slides of commercial timbers is held.

The collection at the *Queensland Herbarium* in Brisbane (BRIw) has approximately 2600 vouchered wood specimens and approximately 500 unvouchered specimens (Bolin 2005: *pers. comm.*). The collection was founded in 1880 and specialises in timber from Queensland and New Guinea (Stern 1988a: 210). No wood identification service or expertise is offered by the herbarium (Bolin 2005: *pers. comm.*).

A former employee of *Queensland Department of Primary Industries (Forestry)*, Myron Cause, also works as a private consultant in Brisbane (Hopewell 2005: *pers. comm.*), whilst *Timber Queensland* conducts wood identification of structural timbers used in homes (White 2005: *pers. comm.*).

Australian Capital Territory

A wood identification service is offered by *Timber Technology Services*, a consulting arm of *Australian National University* (ANU) *Forestry*, Canberra (ANUTECH Pty. Ltd. 2005). These identifications are carried out by Roger Heady who also teaches a university subject on wood identification. Philip Evans (adjunct Professor at ANU and *British Columbia University*, Canada) may also maintain some involvement in wood identification at ANU.

New South Wales

At *Forests New South Wales*, there is a large historical wood collection (SFCw) assembled over 120 years by foresters and botanists including J.H. Maiden, one of Australia's foremost botanists (Woodford 2004). After the *Queensland Herbarium* collection (BRIw), it is the oldest wood collection in Australia and is comprised of an estimated 30,000 specimens including a large collection of *Acacia* and a comprehensive set of thin section slides (Eldridge 2005: *pers. comm.*; Joe 2005: *pers. comm.*; Stern 1988a: 207)[24]. As much as 75% of the collection may retain botanical vouchers (Stern 1988a). Former curator of the collection, R.K. Bamber, conducted wood identification but is now retired and resides

[24] *Index Xylariorum* records that the collection includes 8000 thin section slides (Stern 1988a: 207).

in Tasmania. John Ford, presently a private consultant, but formerly curator of the collection, also offers a wood identification service (Ford 2005).

Forests NSW no longer has adequate storage for the SFCw collection or the facilities for its curation and they are seeking to relinquish the collection to another repository; at this time, negotiations are being made with the *Royal Botanic Gardens* in Sydney (Eldridge 2005; Woodford 2004: *pers. comm.*).

Western Australia

In Western Australia, Graeme Siemon conducts wood identification for the Forest Products Commission. To assist identifications, the WA Forest Products Commission has a small collection of approximately 700 specimens of wood located at Riverdale, Perth (Siemon 2005: *pers. comm.*). The macro key (hand-lens) component of *CSIROID* – a computer-based wood identification tool – is also consulted (Siemon 2005). The wood collection is not authenticated by herbarium vouchers (Siemon 2005).

Ian Godfrey, Head of *Materials Conservation* at the *Western Australian Maritime Museum* has identified wood – largely various wooden cargo items and structural timbers – from numerous Australian shipwreck sites (e.g. see Richards 2001) as well as from Sri Lankan and Indonesian sites (Godfrey 2005: *pers. comm.*). He has a comparative reference collection comprised of mainly Australian specimens as well as some commercial overseas timbers and tropical woods; he does not indicate the number of specimens this collection comprises and the collection seems not to be vouchered. Identifications are conducted using *CSIROID* and by consultation with various publications (e.g. Hoadley 1990; Ilic 1987; Ilic 1990; Ilic 1991) (Godfrey 2005: *pers. comm.*).

Northern Territory

Formerly belonging to NT Forestry, a small wood collection of approximately 200 – 300 specimens is retained by the *Department of Business Industry and Research Development* (DBIRD) (Reilly 2005: *pers. comm.*). Located at *Berrimah Research Farm*, the collection includes timbers from Australia, Indonesia and Papua New Guinea; it is not associated with herbarium vouchers or thin section slides. Beau Robertson (DBIRD) also has a personal collection of Northern Territory native timbers; he and colleague Don Reilly have limited wood identification skills which are largely based on physical observations and do

not extend to the cellular level (Reilly 2005: *pers. comm.*). There are no xylologists working in the Northern Territory.

Tasmania

When contacted, *Forestry Tasmania* did not know of any wood identification experts in the state (Wood 2005: *pers. comm.*).

South Australia

The wood collection of *Forestry SA* (WFw) has been in storage at a facility in Murray Bridge since the 1980's. The collection is believed to comprise over 4000 specimens from Australia and New Guinea (Richardson 2005: *pers. comm.*). According to *Index Xylariorum* vouchers are restricted to 96 species of South Australian *Eucalyptus* which were transferred to the *State Herbarium of South Australia* in 1986 (Stern 1988a: 205). There are plans to recover the collection from Murray Bridge and find a suitable repository (Richardson 2005: *pers. comm.*).

There are no experts in wood identification in South Australia but several members of the local branch of the *International Wood Collectors Society* (IWCS) maintain an interest in wood identification.

Victoria

As the previous chapter attested, much of the wood identification work in Australia is conducted by a single xylologist who curates and utilises the *Australian Wood Collection* (FPAw) housed at the *CSIRO Forestry and Forest Products*, Victoria. Jugo Ilic also conducts the CSIRO's wood identification service where specimens may be identified for AU$275 each or AU$385 for roots (CSIRO Forestry and Forest Products 2005).

With over 47,000 blocks of wood and approximately 8700 thin section slides, the *Australian Wood Collection* is one of the largest in the world. It is comprised of some 13,000 species represented by approximately 270 families (Ilic 1991: 1; Stern 1988a). Incorporated within the *Australian Wood Collection*, and making up the bulk of the material, is the *H.E. Dadswell Memorial Wood Collection*. H.E. (Eric) Dadswell was a prolific collector who, through exchange and a network of field collectors – including forestry units posted with Australian armies in the Pacific (AAS 2005) – established the

wood collection in the 1920s and oversaw the acquisitions until 1964 (Day, Hewson *et al.* 2004: 5).

CSIRO publications

Several important publications have emerged from *CSIRO Forestry and Forest Products*, Victoria, particularly those authored by H.E. Dadswell and Jugo Ilic. This section provides a brief review of some selected publications.

Card-sorting identification system

One of the most important outputs of the CSIRO in terms of wood identification was H.E. Dadswell's multiple-entry, card-sorting system introduced to the CSIRO in 1935 and modified by S.H. Clarke in 1938 (Ilic 1987: 3). Based on the increasing wood collection, each taxon (or group of related taxa) was represented by a single card. Upon each card was recorded a uniform set of characteristics that defined a set of species. Each of the characteristics was connected with a perforated hole at the edge of the card. To describe a taxon, the holes corresponding with the relevant features were clipped. To use the system as a key to identify an unknown specimen, the cards were combined and a needle was inserted through the hole corresponding with the relevant characteristics. After each selection, the taxa that shared this feature were shaken out, removed and used to select the next feature. Eventually, this would result in a single taxon or, where the list of characteristics had been exhausted, a number of potential possibilities.

Selected H.E. Dadswell publications

Aside from introducing the card-sorting system to the CSIRO, Dadswell also published several papers on the wood anatomy of Australian timbers (Dadswell 1972; Dadswell and Burnell 1932; Dadswell and Eckersley 1935). In particular, Dadswell was interested in the Australian *Eucalyptus* genus and his work culminated in the anatomical examination of 108 species; his treatment was published posthumously after his sudden death in 1964 (Dadswell 1972). The paper begins with general descriptions of the key anatomical characteristics and variations within the *Eucalyptus* genus, followed by a list of common

names, trade names and synonymy. Finally, each of the *Eucalyptus* species is described in tabulated form[25].

In another, early publication Dadswell describes the properties of 96 commercially-important Australian timbers other than *Eucalyptus* (Dadswell and Eckersley 1935). Between two and eighteen samples were examined per species. After first providing a general explanation of the various wood characters, descriptions of individual species are given including common names, distribution, general macroscopic wood properties – including heartwood colour, density, grain and texture – vessel size, number and arrangement, parenchyma arrangement, ray size and number per mm, and any important microscopic features – e.g. type of perforation plate, vessel pitting, presence of crystals etc. – where these are required for identification. At the end of the paper are 56 plates of endgrain images at 10x or 35x magnification as well as a dichotomous key to the treated species.

Selected publications by Jugo Ilic

In an effort to make the collection more accessible, Jugo Ilic has published several seminal, companion publications to the *Australian Wood Collection.* Each of the publications is underpinned by the work of H.E. Dadswell in overseeing the development and expansion of the wood collection, creating thin section slides and pioneering a set of multiple-entry, card-based keys. An atlas of micrographs and two paper-based keys to Australian hardwoods have been published (Ilic 1987; Ilic 1990). Both of the keys were developed as companion resources for use with their computer-based counterpart *CSIROID*. Contrary to their titles, they will not operate as keys independently of these computerised systems. Rather, they operate in much the same way as the IAWA standard lists of characters in providing lists of independently numbered features for hardwood identification.

Atlas of Hardwoods

[25] Dadswell's research lends support to the recent segregation of the genus *Corymbia* from the genus Eucalyptus. It was noted that Eucalyptus species listed under Corymbosae (Peltatae and non-Peltatae) (after Blakely 1955) – equivalent to *Corymbia* - had distinctly different vessel arrangements from the rest of Eucalyptus: Eucalyptus vessels were found to be largely solitary whilst *Corymbia* vessels were in short vessel multiples or clusters. *Corymbia* wood anatomy was also very similar to that of the genus Angophora. The debate about the limits of these genera continues (e.g. Brooker 2000; Steane, Nicolle *et al.* 2002).

The *CSIRO Atlas of Hardwoods* (Ilic 1991) covers almost 2000 major Australian and overseas hardwood timber species and covers approximately 150 families. It includes common timbers from Australia, Papua New Guinea, the USA and Europe, and includes some commercially important tropical timbers. Approximately 320 of the treated species are from Australia. A beautifully presented book, it contains approximately 500 pages of black and white micrographs of the three salient surfaces of wood (per species) mainly photographed at 25x using transmitted light microscopy. A 6.5x colour endgrain (transverse) image is also provided. There are no descriptions of the wood and only a brief introduction to the book. Navigation is alphabetical, initially by family and then genus and species. Whilst the atlas covers a large number of species it is obviously not exhaustive and only ten of the 50-odd species treated in this research are illustrated in the endgrain images and only nine in the thin section images[26]. Specimen numbers that allow reconnection with the wood from which the images are taken are not provided.

CSIRO Macro Key for Hardwood Identification

The *CSIRO Macro Key for Hardwood Identification* (Ilic 1987) is largely based on simple characters for examination of the endgrain anatomy with a 10x hand-lens. It includes "categories" that describe vessel number, size, arrangement, and contents, parenchyma arrangement and bandwidth in relation to vessels, and ray width. It also attempts to define the colour of the wood on the tangential surface, the presence of an odour, the density, the presence of ripple marks, distinctness of growth rings, the presence of other features such as crystals, and the geographic origin of the wood. Based on these characteristics, Ilic defines the features (or states): the range of variation that can occur within a category. Each of the 60 features are independently numbered and illustrated by endgrain plates from four representative species. A written description also accompanies each category and feature. The feature numbers are designed for entry into *CSIROID* – the companion, computer-based key to assist separation of species. An Appendix also describes all 1100

[26] Species common to this research include *Eucalyptus camaldulensis*, *Grevillea striata*, *Hakea leucoptera*, *Acacia aneura*, *Acacia cambagei*, *Acacia salicina*, *Flindersia maculosa*, *Santalum lanceolatum*, *Dodonaea viscosa* and *Tamarix aphylla*. *A. aneura*, *D. viscosa*, *H. leucoptera* and *E. camaldulensis* are not assigned to their relevant sub-species or varieties (as these revisions occurred post-publication); recourse would need to be made to the voucher specimens to determine their assignations. *G. striata* is not illustrated by thin section images.

of the treated hardwood timbers by listing their appropriate feature numbers. Specimen numbers that allow reconnection with the wood used to extract these descriptions are not provided – nor does there seem to be an easy way to reconnect to the herbarium specimen vouchers (Ilic 2005: *pers. comm.*).

CSIRO Family Key for Hardwood Identification

The *CSIRO Family Key for Hardwood Identification* (Ilic 1990) has a very similar approach and layout to the macro key. However, the family key is based on microscopic features as observed on thin sections of the transverse, tangential and radial surfaces using transmitted light microscopy. The categories examine vessel arrangement and tangential diameter, vessel pitting, perforation plates, parenchyma arrangement, ray width and shape, vessel-ray pits, vertical canals, crystal and silica type and location, geographic origin of the wood, and several miscellaneous features. The categories are defined by 99 features (or states), each independently numbered and with written explanations and four representative thin section images. Unlike the macro key, the 152 treated hardwood families are not individually described by listing their appropriate feature numbers.

CSIROID (computer-based identification tool)

From Ilic's initial forays into computer-based wood identification in the early 1980s, and the databasing of the multiple entry, card-sorting keys pioneered by Dadswell, a Windows-based key called *CSIROID* evolved. However, in recent years CSIRO has become increasingly corporatised, and *CSIROID* is no longer publicly available; instead it is used in-house for their wood identification service (Ilic 2002b: *pers. comm.*). Accordingly, the key is difficult to review although published information is available from a few sources (CSIRO; CSIRO; Ilic 1993; Ilic 2002a).

Other publications

There are several publications that refer to Australian woods in terms of their physical and mechanical features (Boas 1947; Bolza and Kloot 1961; Mann 1921). A more recent publication of this nature is *Wood in Australia: Types, Properties and Uses* (Bootle 1983) by a former employee of the Forestry Commission of New South Wales. A scholastic and comprehensive text, the book is divided into two parts. The first part is written with the forestry industry in mind – although it will no doubt be of interest to all woodworkers –

and discusses the properties of wood. Chapters include: "The nature of wood", "Colour changes in wood", "Mechanical properties of timber", "Drying of wood", "Plywood", "Pulp and paper" and "Bending of wood". The second section of the book provides species descriptions for the commercial Australian species as well as those Australian wood-producing species of "general interest". Nine characteristics are described for each species: "Size of tree and type of forest", Description of wood" – usually limited to heartwood colour, grain and figure – "Density", "Drying and shrinkage characteristics", "Workability", "Durability", "Strength grouping", "Use" and "Availability". It has a limited application to wood identification.

Finally, in a review of Australian woods, one cannot ignore the superb publications of forester Richard T. Baker, particularly *The Hardwoods of Australia and their Economics* (Baker 1919) and *Cabinet Timbers of Australia* (Baker 1913). Whilst these books may be dated, it is their age, combined with the number of treated species and their presentation – including colour plates – that makes these books important historical resources. The books provides insights into the Australian forestry industry of the early 20th century when only 200 species of *Eucalyptus* had been described, and Australia, despite its vast size, was believed to have less wood-producing species than North America (Baker 1919: xi). The commercial potential of Australia's vast *Eucalyptus* forests was being recognised and already there were calls for reafforestation (Baker 1919: xi). These books provide a wealth of information on the physical properties of timber as well as their uses in architecture, engineering and other endeavours. Individual timber descriptions and uses are illustrated with colour plates showing the longitudinal grain and figure, and occasionally with black and white thin section images of the transverse, tangential and radial surfaces.

Conclusions

This survey of wood identification resources has shown that there are large collections of wood specimens housed on almost every continent. They are usually attached to forestry departments and often have a xylologist attached. Electronic databases and computer-based keys to wood are being developed but they are usually restricted to commercial species including the only Australian-produced identification tool *CSIROID*. Unfortunately, this survey has also revealed that the full scientific potential of xylaria (and their associated resources and research) is not being realised as, in many cases, voucher

specimens remain disconnected with the wood specimens. The following chapter explores in more detail the importance of basing wood identification research and resources on voucher specimens.

Chapter Four. The importance of retaining herbarium vouchers in wood identification

Introduction

One of the most common and concerning threads that emerged from the review of resources for wood identification was the extent to which wood specimens are unvouchered. More alarming, however, was the extent to which "authenticated" wood specimens have become disconnected from herbarium vouchers. It is imperative that herbarium vouchers underpin all wood identification descriptions, tools and treatments since they allow the botanical material to be revisited, and the research updated in the wake of any taxonomic name changes. However, this research has revealed dangerous misconceptions about what is meant by "authenticated" or "vouchered" wood collections and the importance of the continued association and *reconnection* of wood with vouchers. This chapter first examines the significance of vouchers in wood identification and exposes some common misconceptions. This is followed by a case study where the vouchers for a group of wood specimens collected in 1967 are revisited to update any changes to taxonomy.

What is meant by an "authenticated" wood collection?

In wood identification and wood anatomical texts one often reads that research is based on "authenticated" specimens. This simply means that when each wood specimen was collected, a branch with leaves, fruits and/or flowers was also reserved for professional identification by botanists or taxonomists and deposition in an herbarium or other appropriate repository. This branch is also called a "voucher" or "herbarium voucher". Vouchers are the foundation for all scientific research – in zoology, entomology, ecology and botany– and some scientific journals will not accept papers unless they are based on vouchered specimens (see, for example, *Australian Systematic Botany, Annals of the Missouri Botanical Gardens, Novon, Systematic Botany* and *Kew Bulletin*). Ideally this would be the expectation of all biological science journals including the *IAWA Journal*. The importance of vouchers to taxonomic research is further discussed in Huber (1998).

Most xylologists will understand the requirement for collecting wood that has been authenticated with a voucher specimen, for they know that wood may not be sufficiently

variable to elicit reliable identifications to species level. Alternatively, it may be too intra-specifically variable to allow identification from the wood alone. Plant taxonomists, however, have several reproductive and vegetative parts available for identification, and it is by examination of the variation in these features that identifications (and revisions) of species are made. However, beyond this purpose, the importance of voucher specimens seems often to be misunderstood. Once a wood specimen has been identified by its botanical features its role in research is not complete, yet there are many examples in technical and popular scientific literature where vouchers are discarded upon identification, if they are collected at all (e.g. Hosking, Sainty *et al.* 1996; Moore 2005; Smith, Vellen *et al.* 1998).

Why are vouchers necessary?

> …[Kukachka's] *philosophy was to keep only samples that were well-authenticated with herbarium material. Consequently, he discarded many undocumented samples that had been accessioned from previous identifications.*
>
> Comment on the methods of a former curator of the MADw collection
> (Miller 1999: 245)

The names of plants are constantly changing. However, it is a common misconception that, in the wake of taxonomic revisions, new plant names can simply replace old plant names. Sometimes name changes can be straightforward. For example, a group of *Eucalyptus* species known as the Bloodwoods are now commonly referred to as *Corymbia* (Hill and Johnson 1995; Nicolle 1997) although this is not accepted by all taxonomists (see Brooker, Slee *et al.* 2002; Brooker 2000). Other name changes can be geographically based. For example, *Acacia ligulata* was separated into two species so that in southern Australia it is now recognised as *Acacia cupularis* (Maslin 2001). If an *A. ligulata* wood specimen that pre-dates the name change was collected far enough north it may be inferred that it is *A. ligulata.* However, if it was collected from southern Australia where the two species overlap it will be impossible to determine the correct identification unless a voucher specimen exists (Figure 10). Moreover, there is no protection against future revisions of *Acacia ligulata* that may not be so straightforward.

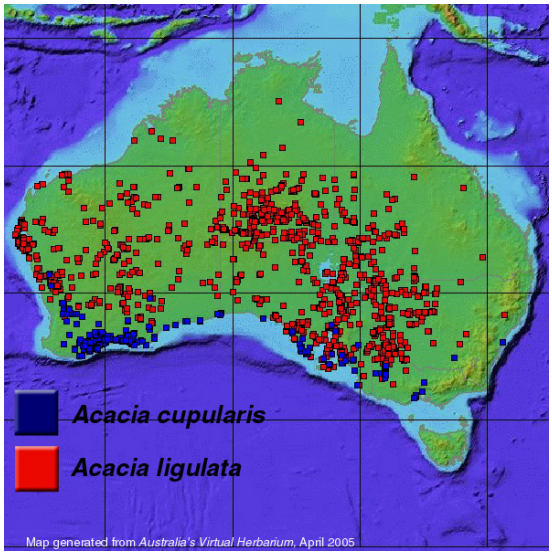

Figure 10 Distribution map generated from *Australia's Virtual Herbarium* (CHAH April 2005). The map shows herbaria collections of Acacia cupularis (in red) and Acacia ligulata (in blue). Wood specimens from the area in which the two species overlap would be virtually impossible to identify without an herbarium voucher specimen.

Accordingly, without voucher specimens, the veracity of scientific research cannot be tested and, whilst identifications may often be correct, there is no way of establishing this without recourse to a voucher specimen. In addition, without a voucher there is no allowance for future name changes. It is because of the possibility of future name changes that professional botanical identifications in the field will not negate the need for an herbarium voucher and nor will identification of botanical material using botanical publications, regardless of whether they are new or out-of-date.

In Chapter Two, the outcomes of the identification of carbonised wood from the Puritjarra rock-shelter, central Australia, as well as the identification of carbonised wood from north Queensland rainforests, were briefly discussed in terms of vegetation change (Hopkins, Ash *et al.* 1993; Smith, Vellen *et al.* 1995). In a separate volume (Hope 1998), two subsequent papers describe the methodology used to prepare the comparative reference collections of carbonised wood for each study and include a set of scanning electron microscope (SEM) images depicting the salient wood anatomical surfaces and features (Hopkins, Graham *et al.* 1998; Smith, Vellen *et al.* 1998). In what is a major shortcoming of the study, the reference wood specimens were identified by botanists but voucher specimens containing samples of the fruits, flowers and leaves were not retained for herbarium deposition (Smith, Vellen *et al.* 1998: 5). That the research was not based on vouchered reference collections was not even acknowledged in the initial paper that discussed the outcomes of the identifications in terms of vegetation change (Smith, Vellen

et al. 1995). Without recourse to a voucher specimen, the specimen names cannot be reliably updated in the event of name changes and the future value of the research is compromised. That vouchering is essential is acknowledged in the second paper on north Queensland carbonised wood where the reference collection of over 840 species was authenticated with herbarium specimens "to allow incorporation of future changes in nomenclature" (Hopkins, Graham *et al.* 1998: 67).

Finally, botanists can make mistakes – both in the field and when conducting identifications in the herbarium. Indeed, in this research, the Australian expert on Myoporaceae originally identified both JAB167 and JAB168 as *Eremophila sturtii*; when the associated wood samples indicated some variation in qualitative anatomical characteristics, it was only by revisiting the vouchers that the mistake was discovered. JAB167 was re-identified as *E. mitchellii*, a taxon that can be difficult to separate from *E. sturtii* using botanical specimens.

How often do plant names change?

Many researchers do not realise just how frequently plant name changes occur. To demonstrate how often they are revised, in the twelve years from 1988 to 2000, a further 300 *Eucalyptus* species were recognised (Brooker 2000; Chippendale 1988), whilst in an eighteen year period between 1982 and 2001, the number of *Acacia* species recognised by systematists increased by 250 to 955 species (Elliot and Jones 1981; Orchard and Wilson 2001a). Many of these species were new, the result of splitting a previously recognised single species into more than one species, sub-species or variety to recognise different levels of variation. Divisions may even occur at the genus or family level (see, for example, the recent taxonomic debate in Australia over the classification of the *Eucalyptus* and *Acacia* genera (Brooker 2000; Hill and Johnson 1995; Maslin 2004) where the same species may be referred to under different names depending on which classification system is adopted). Without recourse to voucher specimens, the use of old or alternate names may eventually lead to confusion as to the identity of the specimen. It can be quicker to check the identity of a voucher than try and follow changes in name through a synonymy provided by a botanist, particularly as many botanical treatments have not provided exhaustive synonymies in latter years (Barker 2005: *pers. comm.*).

Misconceptions about the importance of voucher specimens

Underestimation of the importance of voucher specimens stems from a limited understanding of taxonomy and name changes. For example, the reference collection used to conduct wood identifications at *Queensland Department of Primary Industries (Forestry)* is apparently 95% authenticated (Hopewell 2005: *pers. comm.*). However, the botanical vouchers associated with the collection were removed in 2004 and may have been discarded or given away (Hopewell 2005: *pers. comm.*). Furthermore, specimens obtained from other institutions are assumed to be authenticated and their botanical identification is accepted (Hopewell 2005: *pers. comm.*). For identification purposes various publications are consulted including out-of-print publications, card-sorting keys and the computer-based key *CSIROID* (which is based on disconnected wood from the *Australian Wood Collection* (FPAw)) (Hopewell 2005: *pers. comm.*). In Western Australia, Principal Research Scientist for the *Forest Products Commission*, Graeme Siemon utilises an unvouchered wood collection, as well as *CSIROID* (Siemon 2005: *pers. comm.*), whilst at CSIRO *Forestry and Forest Products*, Victoria, Jugo Ilic utilises disconnected wood from the *Australian Wood Collection* (FPAw) for his publications – which include *CSIROID* – and wood identification work (Ilic 2002b: *pers. comm.*).

The identification of wood using out-of-date tools and publications and reference collections that have not been reconnected with herbarium vouchers seems to be an international problem. It is presumably for reasons of limited understanding of taxonomy and name changes that xylologists may persistently repeat the following errors and omissions. These seriously compromise their research and others who may use it.

Failing to periodically revisit vouchers and their identifications

According to *Index Xylariorum* many xylaria with vouchered wood specimens do not retain the associated herbarium voucher specimens. For example, the online *US National Herbarium* (USw) database states that 60% of their wood collection is vouchered but that, whilst most vouchers are in the *US National Herbarium* (US), a significant number are in other herbaria (United States National Herbarium 2005). Similarly, whilst 85% of the *Australian Wood Collection* (FPAw) held at *CSIRO Forestry and Forest Products*, Victoria is said to be authenticated with herbarium specimens, the associated vouchers are

deposited in various Australian herbaria (Ilic 2002b: *pers. comm.*; Stern 1967: 27). Wood specimens have not been reconnected with their corresponding voucher specimens (Ilic 2002b: *pers. comm.*) so as to reflect any changes to taxonomy or to correct misidentifications of the original material.

Using wood specimens separated from vouchers in descriptions

Any descriptions or identifications that are based on wood that has been separated from its associated herbarium voucher are subject to error. Furthermore, anyone who uses this research, applies descriptions, or accepts identifications based on this work seriously jeopardises their own research. The situation is compounded by the tendency for publications to maintain that their work is based on "authenticated" material. Whilst this may be ostensibly true, it may have been years since the vouchers have been revisited. Where vouchers have not been revisited it is extremely misleading to claim – without qualification – that research, descriptions or treatments have been based on vouchered material and much confusion – not to mention misidentifications – can be perpetuated. Unfortunately, such a claim was made in the *CSIRO Atlas of Hardwoods* (Ilic 1991: 1) which is based on specimens from the *Australian Wood Collection* (FPAw) in Melbourne. Whilst out-of-date name in the atlas are inevitable as taxonomic revisions continue, more serious are the divisions that have occurred since publication that do not represent straightforward name changes. For example, there are ten varieties and potentially five species recognised within the species complex *Acacia aneura* (Mulga) whilst *Acacia aulacocarpa* (Salwood) is now divided into eight species (Maslin 2001); see Figure 11. Without reconnection of the *A. aneura* and *A. aulacocarpa* specimens with their herbarium vouchers it is impossible for any subsequent editions of the *CSIRO Atlas of Hardwoods* to be properly updated.

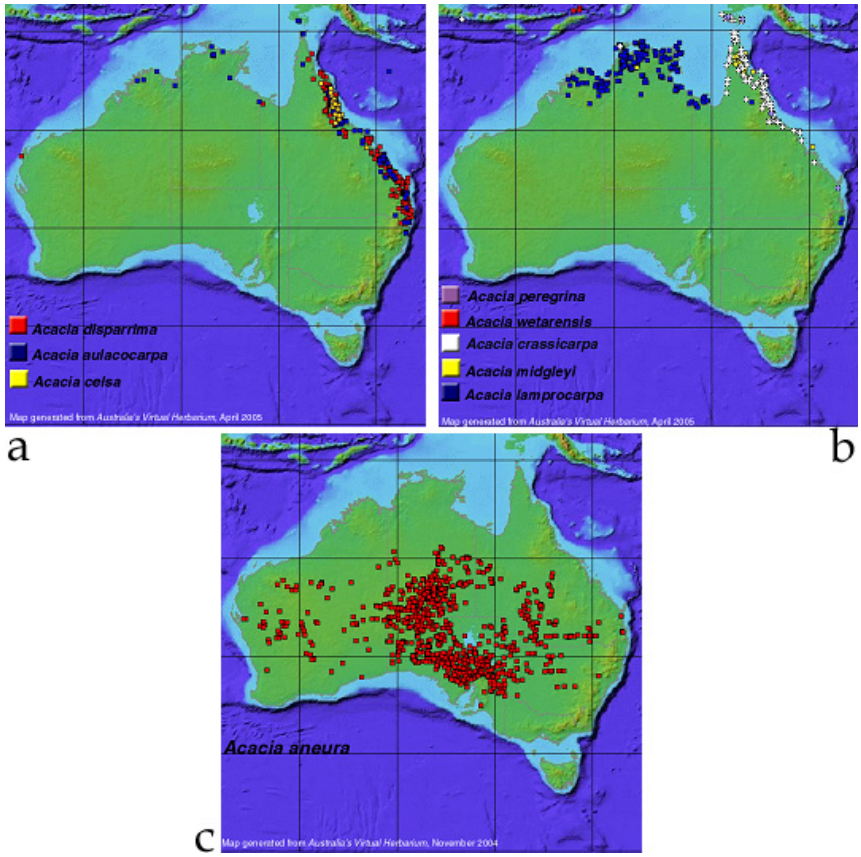

Figure 11 Distribution maps generated from *Australia's Virtual Herbarium* (CHAH April 2005). A & B: Distribution of the eight *Acacia* species all formerly known as *Acacia aulacocarpa*. Any wood specimens that retain the *A. aulacocarpa* name and are without a voucher would be impossible to identify using this new taxonomy. C: Distribution of *Acacia aneura*, a species complex now with ten varieties and potentially five species. The correct identification could not be determined without access to a voucher specimen.

Failing to record specimen numbers in publications

Another common oversight observed in the survey of wood identification resources was the failure to retain both the wood specimen numbers and locations, and the voucher specimen numbers and locations (if different), in publications. This information was lacking in all the consulted identification keys (e.g. Heiss April 2005; Richter and Dallwitz 2005). The "Inside Wood" (2004) website seems to integrate information from various sources for a single species. For example, at the time of review, the description of the wood of *Eucalyptus microtheca* was taken from a paper by H.E. Dadswell (1972) – where connections with the wood specimen numbers that contributed to the descriptions do not seem to be retained – whilst the images are attributed to wood specimen FPAw 1736. Voucher specimen numbers and locations – for either images or descriptions – do not seem to be provided at all in the database. This is concerning since users expect the information

to be reliable and revisitable particularly if they are to pin their own research on identifications gleaned from resources such as “Inside Wood”.

Basing contemporary descriptions on outdated wood descriptions

A number of the consulted resources utilised previous research to provide, or augment, wood descriptions. This is perfectly acceptable if the wood specimens used to conduct the original research have been retained to allow their revisitation. In addition, the wood specimens must have been vouchered, and both the wood specimen numbers and herbarium voucher numbers recorded in both the original research and any publications that utilise this research.

In 1994, *E. microtheca* was divided into two species and over much of its previous distribution it is now known as *E. coolabah* (Hill and Johnson 1994) (Figure 12). In the previous example from the “Inside Wood” website, the description of the *Eucalyptus microtheca* specimen originated from an H.E. Dadswell (1972) paper.

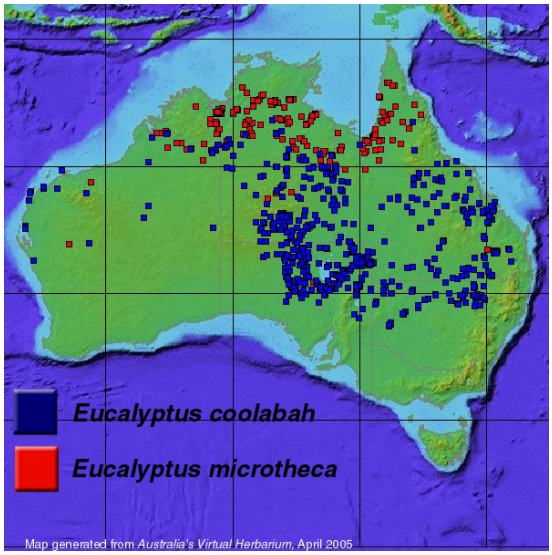

Figure 12 Distribution map generated from *Australia’s Virtual Herbarium* (CHAH April 2005). The map shows herbaria collections of *Eucalyptus microtheca* (in red) and *Eucalyptus coolabah* (in blue). Wood specimens from the area in which the two species overlap would be virtually impossible to identify without an herbarium voucher specimen.

This particular publication does not retain any apparent connections with the wood specimen numbers and multiple examples of each species contributed to the treatments. In addition, despite the fact that the original wood specimens may have been authenticated

with herbarium vouchers – as much of Dadswell's collection was – there is no record of its number or location retained in Dadswell's paper[27]. Accordingly, there seems to be little possibility of revisiting the specimen upon which the *E. microtheca* descriptions were based (to test the veracity of the descriptions) much less any associated herbarium vouchers (to determine the correct identification).

Reconnecting wood specimens and associated herbarium vouchers

The separation of wood from associated botanical material can be explained by several reasons. To begin with, many xylaria will not have the facilities to store herbarium specimens as well as wood, particularly as they are largely attached to Forestry departments who do not traditionally examine botanical material other than wood. Secondly, wood specimens were often collected by botanists who *were* interested in the botanical material and deposited the associated vouchers in the herbaria to which they were attached. For example, a search of the USw database revealed that vouchers for several hundred Papua New Guinean wood specimens collected by Canberra-based botanists Richard Schodde and Lyn Craven are in the *Australian National Herbarium* (CANB) and in the *United States National Herbarium* (US).

There are other reasons why wood may become disconnected from herbarium vouchers. Wood specimens are often exchanged between institutions and they may be collected in duplicate and deposited in several xylaria. For example, a search for the Australian collector H.E. Dadswell on the electronic database that incorporates the FHOw collection revealed two wood specimens in Oxford: both specimens were collected in Australia in 1936 and both herbarium voucher specimens are in Melbourne. Thus, the Oxford specimens may have been duplicates or the product of an exchange. The disconnectedness of the *Australian Wood Collection* (FPAw) is largely because the H.E. Dadswell collection – which comprises much of the xylarium – was supplemented by a network of collectors.

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[27] In Dadswell's paper, the "Blakely no." referred to in the species lists and tables do not refer to herbarium vouchers, as was initially assumed. They are cross-references to the independent numbers given to each species by Blakely in his key and descriptions to *Eucalyptus* (Blakely 1955). Accordingly, they are of no value in updating taxonomies.

Index Xylariorum does record that many of the xylaria maintain a record of where vouchers have been deposited. This is commendable for it means vouchers can be revisited, but one suspects that most of these vouchers will not have been re-examined since their initial identification. Accordingly, to reconnect xylaria with their voucher specimens and update taxonomic names would be a very useful undertaking. Until such time, many wood descriptions, treatments and keys in some otherwise excellent publications cannot be confidently accepted.

Case study: revisiting vouchers from a small collection of wood specimens from the State Herbarium of South Australia

To demonstrate the importance of voucher specimens, vouchers associated with a small assemblage of wood samples housed in the *State Herbarium of South Australia* were revisited. The wood, along with the herbarium vouchers, was collected in 1967 from around Koonalda (far western South Australia) by plant taxonomist David Symon. Each wood specimen was labelled with Symon's collection number, location details and the original identifications (established using the botanical vouchers). The collection numbers were cross-referenced against the electronic ADHERB database where currently accepted names (based on the voucher specimens) are provided. The results, shown in Table 2, indicated that of the 20 wood specimens collected in 1967, six have undergone changes in their taxonomy. Two of these were straightforward name changes: the name *Acacia sowdenii* was completely replaced by *A. papyrocarpa* (Maslin 1980), whilst the genus *Kochia* was renamed *Maireana* in Australia when a revision of the genus *Kochia* determined that it largely occurs in the northern hemisphere (Wilson 1975). *Pittosporum angustifolium* should also be a fairly straightforward replacement since the distribution of *P. phylliraeoides* is limited to the far west coast of Australia (Cayzer, Crisp *et al.* 2000) (Figure 13). South Australian specimens previously recognised as *Arthrocnemum* are now divided into three genera including *Sclerostegia*; without access to the voucher specimen, it would have been impossible to update the name of the wood to *S. disarticulata*.

Table 2 List of wood specimens collected near Koonalda, South Australia by plant taxonomist David Symon in 1967. Collection numbers (first column) were cross-referenced against the *State Herbarium of South Australia's* ADHERB database to determine if the orginal identifications of the voucher specimens (second column) had been retained. Where names have changed, presently accepted taxonomies are given (third column).

Collection number	Wood specimen label identification	Current herbarium voucher identification (if changed)
4538	*Myoporum platycarpum*	
4578	*Eucalyptus gracilis*	
4603	*Myoporum platycarpum*	
4604	*Acacia sowdenii*	*Acacia papyrocarpa*
4605	*Acacia sowdenii*	*Acacia papyrocarpa*
4606	*Acacia oswaldii*	
4620	*Acacia oswaldii*	
4621	*Santalum acuminatum*	
4622	*Santalum spicatum*	
4674	*Santalum acuminatum*	
4676	*Melaleuca lanceolata*	
4677	*Eucalyptus oleosa* var. *angustifolia*	*Eucalyptus oleosa* ssp. *ampliata*
4678	*Atriplex nummularia*	
4679	*Pittosporum phylliraeoides*	*Pittosporum angustifolium*
4680	*Cratystylis conocephala*	
4681	*Exocarpos aphyllus*	
4688	*Lycium australe*	
4689	*Atriplex vesicaria*	
4690	*Kochia sedifolia*	*Maireana sedifolia*
4691	*Arthrocnemum* sp.	*Sclerostegia disarticulata*

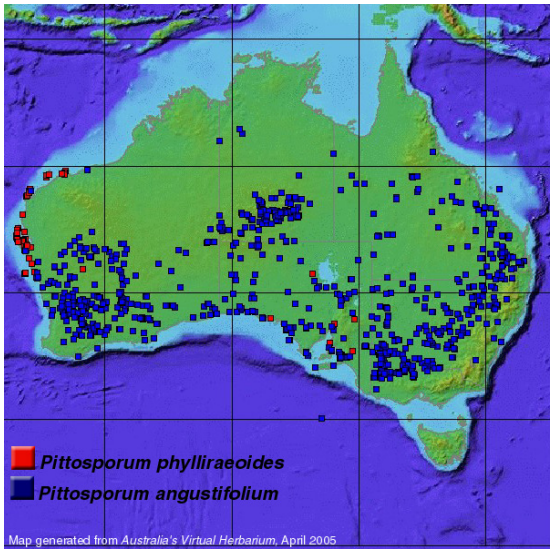


Figure 13 Distribution map generated from *Australia's Virtual Herbarium* (CHAH April 2005). The map shows Australian herbaria collections of *Pittosporum phylliraeoides* (in red) and *Pittosoporum angustifolium* (in blue). All records were previously named *P. phylliraeoides* but the current taxonomic revision indicates that this species is largely limited to the far western Australian coast.

With respect to the *Eucalyptus oleosa* specimen, its original identification – *Eucalyptus oleosa* var. *angustifolia* – is no longer recognised. Contemporary taxonomists recognise three sub-species: *Eucalyptus oleosa* ssp. *ampliata*, *E. oleosa* ssp. *oleosa* and *E. oleosa* ssp. *repleta* (Brooker, Slee *et al.* 2002). Distribution maps that plot herbarium records indicate that all three sub-species occur near Koonalda (Figure 14). Without recourse to the herbarium voucher the wood specimen could not have been reliably identified.

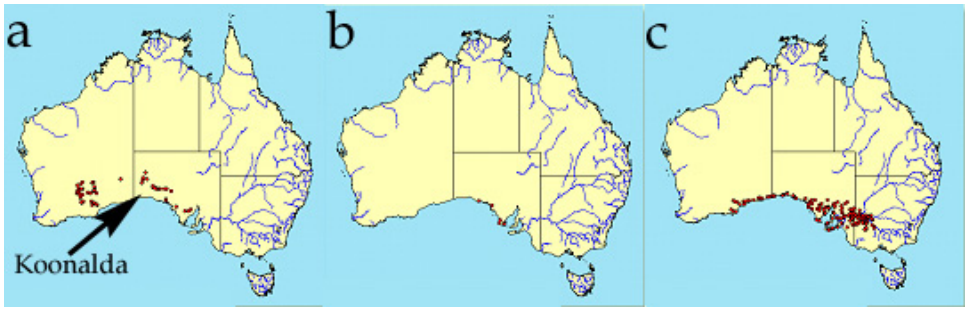


Figure 14 Distribution maps reproduced from EuclID (Brooker, Slee *et al.* 2002) for the three presently recognised sub-species within *Eucalyptus oleosa*. A: *E. oleosa* ssp. *repleta*; B: *E. oleosa* ssp. *ampliata*; C: *E. oleosa* ssp. *oleosa*.

This case study demonstrates that updating taxonomies for an unvouchered specimen, or a wood specimen that has not been reconnected to its voucher, can be a straightforward process. In the case of the Eucalyptus oleosa specimen, the sub-species determination required access to the associated herbarium voucher whilst the wood specimen originally identified as Arthrocnemum sp. could not have been updated to Sclerostegia diarticulata without revisiting the voucher. Making straightforward name replacements still relies on the assumption that the original identification was correct; and without a voucher specimen this cannot be verified. Additionally, unvouchered or disconnected wood specimens are not protected against future name changes that are not so straightforward.

Conclusion

This chapter has revealed the importance of founding all wood identification research, reference collections, identification tools and descriptions on vouchered specimens. It has also explained why it is not adequate to base research on wood specimens which have associated herbarium vouchers if the two specimens have never been reconnected. Without the reconnection of wood specimens with herbarium vouchers, the value of any research – including excellent initiatives such as the "Inside Wood" (2004) website – is seriously compromised. At the very least, where research is based on "authenticated" material that has not been revisited, the failure to do so must be disclosed.

Chapter Five. Future, molecular directions for the identification of wood and wood fragments

Introduction

The case studies in Chapter Two revealed the circumstances in which specimens for wood identification may be limited to fragments. In addition, the survey of existing wood identification resources in Chapter Three highlighted the need for reference collections of comparative material that allow identification of fragmented wood whilst, if necessary, remaining sympathetic to the integrity of the object. However, extracting samples for wood identification using morphological characters can be technically problematic, particularly where fragments are the limit of material available for analysis. Furthermore, to physically section a fragment requires that it is an intact sample, at least the diameter of a toothpick, and not a collection of shavings. In view of these impediments, and because the extent of necessary damage can be a serious consideration when it comes to wood identification, this chapter begins with an overview of DNA taxonomy and explores the possibilities that DNA analysis might offer as a tool for the identification of wood and wood fragments. There is an overview of recent successes in the extraction of DNA from as little as 100 milligrams of wood shavings and the following questions are posed: what we can realistically expect to learn if DNA can be successfully isolated from fragments? What are the limitations of the method? How does DNA taxonomy compare to identification using morphological markers?

Background

> *Unfortunately, to the dismay of people seeking an immediate panacea, the molecular identification of species is fraught with the same constraints and inconsistencies that plague morphological judgements of species boundaries. The exception is that most morphologically knowledgeable workers have a suite of complex morphological characters upon which to base their conclusions, rather than relying on part of a single gene.*
>
> (Will and Rubinoff 2004)

DNA taxonomy refers to the use of DNA sequences to identify and classify living species. Proponents of DNA taxonomy support the development of a reference collection of "DNA

barcodes" (Hebert, Cywinska *et al.* 2003); these barcodes are short sequences of DNA from uniform localities on the genome that are used to identify a species (Anon. 2004). As DNA barcodes are isolated, they are linked to named collections of specimens identified through traditional taxonomic means (Consortium for the Barcode of Life 2003).

The promises of DNA taxonomy are many. Those listed by the Consortium for the Barcode of Life (2003) include the ability to identify a plant or animal at any stage in its development; removing subjectivity in the identification process by reducing the reliance on ambiguous morphological descriptors; separating species of plant or animal that are morphologically similar and difficult to separate using traditional taxonomy; and, of most note to this research, it promises fragment identification, where species are identified using a fraction of the material usually required for morphological analyses. In the future, it is envisaged that hand-held barcoders will eventually be available to identify species (Consortium for the Barcode of Life 2003) revolutionising the cataloguing of life, putting identification in the reach of many (not just traditional taxonomists) and encouraging the rapid identification (and revision) of greater numbers of new (and existing) species. In the words of one of the leading advocates of DNA taxonomy:

> *Single gene reads will deliver an unambiguous species identification in more than 95% of* [animal] *cases within a decade.*
>
> (Paul Hebert in Atkinson 2004)

To this end, recent breakthroughs using mitochondrial DNA include the isolation of unique barcodes from 260 North American bird species resulting in the identification of four possible new species (Hebert, Stoeckle *et al.* 2004), and the identification of the Costa Rican butterfly *Astraptes fulgerator* as a species complex of at least 10 species (Hebert, Penton *et al.* 2004).

Traditional taxonomists accept the potential of DNA taxonomy but are sceptical as to whether it can realistically deliver on its promises. Most believe DNA can play a central role in identification as long as it is underpinned by classical systematics (Tautz, Arctander *et al.* 2003: 70). In the same way that traditional morphological identification requires a collection of reference or voucher specimens at its foundation, DNA taxonomy requires a library of reference or voucher DNA; this DNA must necessarily come from

morphologically identified voucher specimens (Stoeckle 2003: 796). Some taxonomists also consider that a DNA sequence, whilst useful in making broad-scale comparisons at the family and generic level between plant and animal taxa (Seberg, Humphries *et al.* 2003: 64) is but a single character; in a discipline where a range of morphological markers are employed, taxonomists warn against using a single character to identify a species, particularly where it is subject to the same intra- and inter- specific variation as morphological characters (Lipscomb, Platnick *et al.* 2003: 65; Mallet and Willmott 2003: 57; Moritz and Cicero 2004: 1529; Seberg, Humphries *et al.* 2003: 64; Will and Rubinoff 2004: 48). Closely related species may yield identical or near-identical DNA sequences whilst variation in sequences may occur in individuals belonging to a single species (Mallet and Willmott 2003: 57; Stoeckle 2003: 796). Accordingly, how does one decide whether variation between DNA sequences is "biologically relevant"?; that is, that it denotes a separate species and is not a result of intra-specific variation (Blaxter 2004: 673). As one researcher has expressed:

> *…it will take sampling across the full range of each species to establish the credibility of DNA barcodes, one species at a time…*
>
> (Sperling 2005: 3)

Whether or not DNA taxonomy can deliver on its promises, it seems clear that there are several issues to be resolved – and that vigorous debate may continue for some time; see the most recent article on the subject (Barrett and Hebert 2005) and associated correspondence (2005; Hebert 2005; Prendini 2005) in the *Canadian Journal of Zoology*. However, sampling of variation and the importance of vouchers collections will continue to be important considerations in this new field just as they are for the more traditional taxonomic approaches based on morphological markers.

Removal of DNA from wood

DNA can be extracted from most living plant parts with relative ease. However, it has not been as straightforward to extract it from wood, and efforts to this end have enjoyed only recent success. Whilst it can be expected that the use of wood by society will continue to advance research in this area, there are some obstacles peculiar to wood that researchers

must overcome. This section outlines some of the issues followed by a brief review of the recent studies that have successfully isolated DNA from wood.

The issues

The most important difficulty in isolating DNA from wood is that even in a living tree DNA in wood fragments or degrades. Most wood cells lose their protoplasm shortly after development (Hoadley 1990: 7) so that, apart from parenchyma cells in the sapwood, much of the wood structure is composed of non-living cells involved in passive structural and functional processes. The extent of DNA degradation varies depending upon the area of wood sampled. In wood fresh from a living tree, DNA fragmentation may be expected in increasing levels from the living cambium, through to the sapwood (some living cells), through to the heartwood (the oldest part of the tree). Once wood is felled (loosely termed "dry wood") the DNA continues to degrade so that the older the piece of wood the more deteriorated the DNA.

The environmental conditions that the wood is exposed to may further damage DNA, particularly exposure to water (Cano 1996: 164; Deguilloux, Pemonge *et al.* 2002: 1044), and potentially the pH of the environment, oxidisation and exposure to UV light (Cano 1996: 165). As is the case with fossil DNA (Cano 1996), specimens that have undergone rapid dehydration, such as those stored indoors, are believed to have the best chance of optimal DNA preservation (Deguilloux, Pemonge *et al.* 2002: 1044). Surface wood is at risk of contamination by animals (particularly insect or human), pollen grains, sawdust and other debris, especially if the wood is porous, or cracks or splits are present (Deguilloux, Pemonge *et al.* 2002: 1044)

Recent successes in the isolation of degraded, low-quality DNA from wood used polymerase chain reaction (PCR) amplification. PCR is an analytical tool that makes possible the extraction of badly fragmented DNA; the method has seen particular success with the isolation of ancient DNA[28] (Cano 1996: 162). As with ancient DNA, the fragmented nature of DNA in wood requires special laboratory conditions to optimise the

[28] Ancient DNA, the genetic materials of fossil plants and animals, is providing a useful indication of how life has evolved by isolation from specimens up to several hundred thousand years old (Willerslev and Cooper 2004: 6).

PCR amplification and avoid contamination. It has been recorded, however, that certain compounds sometimes present in wood can obstruct PCR amplification (Cano 1996: 166; Petit and Deguilloux 2001: 2).

Recent successes

Despite these impediments, in recent years there have been a handful of encouraging publications that describe the successful isolation of DNA sequences from both fresh and dried wood. A broad overview is provided.

In one of the earliest studies, samples from a cross-section of the bark, transition zone, sapwood and heartwood were removed from freshly cut wood of *Robinia pseudoacacia*; DNA fragmentation was found to increase with the age of the wood with PCR amplification significantly less in heartwood than in sapwood (De Fillipis and Magel 1998).

In the first study on dry wood, fragments of DNA were removed from oak wood specimens aged up to 600 years (Dumolin-Lapegue, Pemonge *et al.* 1999). Meanwhile, in Japan, genomic DNA was successfully isolated from heartwood blocks from post-glacial, buried fossil trees of *Cryptomeria japonica* (Tani, Tusumura *et al.* 2003); this was the first study to successfully isolate DNA from fossil wood.

Other successful attempts at extracting DNA from wood have been motivated by the desire for a means of certifying the geographical origin of wood. Most of these studies have used microsatellite markers (or short tandem repeats (STRs); these are short stretches of DNA consisting of repeated sequences of nucleotides (i.e. adenosine (A), guanine (G), cytosine (C) and thiamine (T)). A method that allows wood to be traced to its origins has implications for industry, science and art in providing certification for lumber, furniture, artefacts and wine barrels. French cooperages, for example, guarantee that their barrels are made only from high-quality French oak wood[29] (Deguilloux, Pemonge *et al.* 2003: 1631).

[29] The authors concede, however, that geographic variation in oak forests does not conform to European political boundaries (Deguilloux, Pemonge *et al.* 2003: 1631) so that presumably wood sourced from oak forests that span France and a neighbouring country could not conclusively be certified as of French origin using this method.

To this end, in 2000, a European Union collaborative effort produced a set of microsatellite markers for oak forests. Using chloroplast DNA, obtained from living (non-wood) tissue, a comprehensive record of 2600 European oak forest fingerprints was developed, based on the genetic variability of geographically separate forests (INRA December 2000). Using this record, researchers can theoretically trace any part of an oak tree – e.g. a leaf or acorn – to the forest from which it originally came. In the wake of the initial success at amplification of DNA from oak wood (Dumolin-Lapegue, Pemonge *et al.* 1999) and with the development of an oak forest reference map several more French studies described attempts to extract DNA from oak wood. The first study obtained DNA from *Quercus petraea* (Sessile Oak), examining variables of region, environmental conditions (stored indoors or outdoors after felling) and time since felling (Deguilloux, Pemonge *et al.* 2002). The second study extracted DNA from the wood of *Quercus petraea* (Sessile Oak) and *Quercus robur* (Pedunculate Oak), two economically-important European species (Deguilloux, Pemonge *et al.* 2003).

Using knowledge of the genetic identity of regional European oak forests, the potential of using DNA to trace the geographic origin of oak wood from wine barrels was recently tested (Deguilloux, Pemonge *et al.* 2004a). DNA was removed from 131 wooden staves of *Q. robur* and *Q. petraea*. Samples were from green oak wood staves that had been seasoned outdoors for less than a year, staves from wood that had been air-drying in the open for more than two years, and staves from finished barrels which had undergone "toasting"; DNA from the green wood staves was less fragmented. The study revealed several inconsistencies between the provenance of oak wood, as indicated by the DNA, and the origin of the oak, as understood by the cooperages. For example, some eastern European oak wood was being passed off as French, whilst several samples believed to be from one of the famous French oak forests were not (Deguilloux, Pemonge *et al.* 2004a). More recently, another paper based on this research has been published (Deguilloux, Pemonge *et al.* 2004b).

In another wood certification study, forestry and law enforcement agencies in British Columbia, Canada, are developing a reference collection of unique microsatellite markers (from living (non-wood) tissue) for *Thuja plicata* (Western Red Cedar), a tree frequently illegally harvested from British Columbian forests (White, Hunter *et al.* 2000: 923). DNA

extracted from the wood of *Thuja plicata* cross-referenced to the microsatellite markers will allow authorities to connect lumber that is suspected stolen to the stumps of illegally harvested trees (White, Hunter *et al.* 2000).

In wood certification of a different kind, a recent study describes the identification of a foreign gene in the wood of genetically modified trees of transgenic hybrid Aspen (*Populus tremula* x *P. tremuloides*) (Fladung, Nowitzki *et al.* 2004). Whilst concerns remain about cross-contamination of native populations by genes from genetically modified trees, the detection of the transgenic gene may assist labelling, identifying, and regulating trade in genetically modified wood. The researchers successfully extracted DNA from fresh wood, air-dried and cold-stored woods; the bark and cambium produced the most DNA with the greatest DNA yield coming from the fresh wood (Fladung, Nowitzki *et al.* 2004).

Identifying wood from fragments using DNA analyses

Given the right conditions, it is possible to extract DNA sequences from wood. With a particular emphasis on cultural objects, the next section briefly discusses some of the technical constraints that might frustrate attempts at isolating DNA from wood fragments and, assuming these impediments are surmountable, the potential of identifying wood using DNA barcodes. It is important to make clear that the successful isolation of DNA from wood and the potential for using this DNA for identification purposes are two separate issues.

Extracting DNA from fragments

The studies conducted to date on DNA isolation from wood have generally required only small amounts of wood shavings ground to a fine powder – 100 mg (De Fillipis and Magel 1998: 378), 200 mg (Deguilloux, Pemonge *et al.* 2003: 1630; Deguilloux, Pemonge *et al.* 2002: 1040), 400 mg (Dumolin-Lapegue, Pemonge *et al.* 1999: 2137; Tani, Tusumura *et al.* 2003: 860), 1-2 grams (Fladung, Nowitzki *et al.* 2004: 207) and 10-15 grams (White, Hunter *et al.* 2000: 923)[30]. These limited requisite sample sizes alone encourage

[30] The authors of the latter paper concede that minimum required sample sizes would be lower than used in this study (White, Hunter *et al.* 2000: 926).

exploration of the potential of using DNA analysis to identify fragmentary wood. Fragmented wood can be difficult to identify using morphological means and this technology offers the best possibilities of a result. Unlike morphological analyses, the technique offers a much less invasive sampling procedure since the sample may be limited to shavings. Moreover, sectioning to expose the tangential, transverse and radial faces will no longer be required, increasing the flexibility over the chosen sample area, and simplifying the techniques used to extract the sample. Were a drill to be used to remove shavings, for example, this would result in a discreet but uniform treatment that could be carefully applied to the most precious cultural objects. Surface contamination, however, might necessitate deeper sampling.

Whilst sampling techniques for DNA analysis may be more favourable than methods for morphological analysis, there are some obstacles that may obstruct DNA amplification, particularly from cultural objects. Any one or a combination of these factors may result in amplified DNA that is so badly fragmented that sequences are too short to make any meaningful comparisons with reference data.

Ostensibly the most serious impediment will be the age of the wood, for one may expect that the older the wood the poorer the DNA quality. However, the extent to which wood fragments have been exposed to environmental conditions such as water, oxidisation and UV light may also influence amplification. This is of particular concern for wood from archaeological or palaeobotanical contexts, as well as cultural objects which often have a utilitarian use. Storage conditions, however, would also be a factor so that, all other variables being equal, one may expect to amplify DNA from a fragment of wood from an antique chair more successfully than a fragment from an Aboriginal Australian adze.

The part of the tree used to manufacture the object may also affect DNA quality with heartwood likely to result in the least amplification. The durability of heartwood is such that it is often preferred for cultural processing; moreover, the increased resistance of heartwood to decay may mean that it is more greatly represented than sapwood in archaeological or palaeobotanical contexts.

The presence of preservatives, decorative substances and other surface contaminants may also influence attempts to amplify DNA from fragments. In the case of Aboriginal

Australian artefacts, for example, the addition of ochre, blood, grease or resins or contamination by insects, pollen or other debris may all potentially interfere with the process of DNA amplification.

Identifying wood fragments

Assuming these obstacles are surmountable, and DNA can be successfully isolated from cultural objects, what can we realistically expect to learn? Can we identify wood using DNA reference sets and how does the method compare to the identification of wood using morphological markers, particularly in terms of its application to cultural objects? Can the wood be identified to species level, or even beyond this – to different geographic populations, as is being attempted with *Thuja plicata* (Western Red Cedar) and the European *Quercus* sp. (Oak)?

The promises

If the proponents of DNA taxonomy are to be believed, and their promises extrapolated to wood, DNA taxonomy offers great potential to wood identification. The work would be underpinned by a reference collection of DNA sequences from taxonomically identified specimens but this DNA need not be from wood – it may be from fresh, living plant material or herbarium specimens making it easier to collect DNA and resulting in less destruction to living plants. Morphological variation that can occur in the wood from different plant parts would be negated by a uniform DNA sequence. This would be particularly valuable in the identification of Aboriginal Australian artefacts where ethnographic and historical documentation records the use of rootwood, trunkwood, limbwood and probably juvenile wood.

Finally, identification might be possible to specific geographic populations, if the intra-specific variability could be quantified to this level. Certification of cultural objects to a fairly specific geographic location would increase their historical value and may yield important information on trade, exchange and the movement of people. It could also be used to authenticate the provenance of wooden antiques and modern-day art and tourist items and provide certification for wood from commercial lumber yards.

The challenges

The issues that confront wood identification using DNA barcoding are very similar to those that confront traditional systematics using morphological markers – and the same as confronted by the author of this thesis: a reference set is crucial to the outcomes of any research of a taxonomic nature. There are thousands of wood-producing species in Australia and every wood-producing plant species would need to be sampled for a DNA reference set to establish a barcode. The biggest obstacle, however, is that a single DNA sequence is unlikely to uniquely identify a species. In much the same way as statistical analyses have been utilised in this research (see Chapter Ten), there is a need to account for the variation that may occur in DNA sequences within and between species. As with standard taxonomy based on morphological characters, inter- and intra- specific intergradation can obfuscate the identification process; numerous replicates must be tested and any variation must be measured in order to know when differences in DNA sequences are taxonomically relevant. Intra-specific variation in DNA sequences as a result of different growth regimes, whilst useful if the sequences remain uniform within different geographic populations, must also be measurable.

Sceptical researchers claim that because of the issues of intra- and inter-specific variability, DNA barcodes are "useful in all except the kind of identifications that matter most" (Sperling 2005; Will and Rubinoff 2004: 54) – that of separating closely related species. Wood identification is no different: using morphological characters classification may often only be possible to genus or even family level as some wood lacks variability beyond these ranks or it exhibits high levels of intra-specific variation so as to inhibit separation. However, if DNA analyses can not resolve identifications at the species level there seems to be little value in expending the effort and expense of DNA analyses to determine genus and family where routine morphological analyses are simpler, cheaper and quicker to use (Will and Rubinoff 2004: 54). Furthermore, there may also be occasions where DNA amplification is not possible and morphological characters are all that is available. That DNA has not preserved in sufficient quantities is a distinct possibility with wood, but particularly wood that is aged or exposed to adverse environmental conditions. In the case of carbonised wood, which can retain a sufficient morphological structure to elicit positive identification, the carbonisation process will often have resulted in the loss of DNA.

Conclusions

In the wake of limited resources for wood identification based on morphological markers, this chapter has briefly examined the potential of DNA barcoding for the identification of wood fragments from a variety of contexts. It has shown that whilst the promises of DNA taxonomy are exciting, they are ambitious, and beset by the same issues as any other systematic study. In addition, whilst recent studies have involved the successful isolation of DNA from wood, the peculiarities of wood are such that the DNA is fragmented and requires special laboratory conditions to increase amplification. Whilst these studies are undeniably encouraging, the infancy of the efforts suggest that morphological markers will be required for some time to come. Indeed, a reference set to wood DNA could probably never completely replace traditional systematics based on morphology; this is particularly the case for aged wood, burnt wood or wood stored in adverse environmental conditions since these may not retain sufficient DNA for comparison with reference specimens.

Chapter Six. Initial trials on unvouchered wood and collection of vouchered wood

Introduction

This chapter outlines the methods used to collect the data for the compilation of a wood identification tool to a selection of arid Australian hardwoods and softwoods developed as part of this research. It includes a brief discussion of initial trials on unvouchered wood samples, followed by a discussion of the objective and collecting policy used to define a field trip to arid Australia to collect vouchered wood specimens. Particular attention is given to the requirement to account for intra-specific variation in wood. Finally, there is a discussion of the outcomes of the field trip and whether the objectives were met.

Initial trials on unvouchered wood

The first step in this research was to conduct trials on unvouchered wood; that is, wood specimens which do not carry botanically authenticated identifications. Wood samples were obtained during a field trip to Alice Springs, Northern Territory as well as from the region around Roxby Downs, South Australia and from *Xylo-Australis*™, a Victorian business that sells arid Australian timbers. Most of the samples were of arid Australian limbwood, although some trunkwood was represented. Appendix Three lists the unvouchered wood specimens used in these trials.

Trials on unvouchered wood offered an opportunity to become familiar with wood anatomy (particularly of hardwoods), preparation for wood anatomical analysis (including for endgrain, thin section and SEM analysis), and to trial recently emerged technologies (see Appendix Four). To this end, a visit to CSIRO *Forestry & Forest Products*, Victoria, and use of the facilities at *Adelaide Microscopy*, a consulting arm of *Adelaide University*, proved useful. Experimenting with unvouchered wood also provided an opportunity to reconcile the extremely high density of the arid Australian wood with standard wood anatomy processes (generally developed with lesser density American and European woods in mind); this was especially necessary in finding an appropriate method to soften the wood (see Appendix Five and Chapter Seven).

Field trip

In late October 2003, a field trip to north-east South Australia, south-west Queensland and far western New South Wales was undertaken for the purpose of collecting wood samples and voucher specimens. The field trip took place in the company of Dr Frank Badman, an Adelaide-based consultant botanist with a good knowledge of the flora of the arid zone, particularly north-east South Australia, and an experienced traveller in the region. Michael Barker also attended to photograph the habit and major botanical features of the collected plants and to assist in general duties.

Objective. Collection of vouchered wood samples

The prevailing objective of the field trip was the collection of wood samples with associated voucher specimens. The collection of vouchered wood samples ensured that the research was based on scientifically robust data; this provides for an important application of the developed identification tool to research in scientific disciplines such as forestry, plant taxonomy, anthropology, archaeology and forensics.

Collection of vouchered wood samples was approved by application to the relevant state authorities.

Collection policy rationale

With this objective in mind, the rationale for the field trip was kept simple with the adoption of a broad and flexible collecting policy not confined to the species lists compiled for the three regions (see Appendix Six). Instead, the brief was to collect vouchered samples from any shrub or tree species that produces wood suitable for the construction of robust objects. Robust artefacts have been loosely defined as large, sturdy objects that generally require a reasonable amount and thickness of wood to construct e.g. fence posts, fence rails, bowls and Aboriginal artefacts such as clubs, spears, boomerangs, shields, adzes, digging sticks and carrying vessels (pitchis) etc.

The reasons behind the adoption of a flexible collection policy included:

- To ease pressure on field identification skills;
- To limit biases or errors that might exist in a species list as a result of misinformation or confusion over species names. For example, most historical

sources that document Aboriginal and non-Aboriginal wood use would be based on unvouchered specimens and observations;

- To account for any oversights in the species lists compiled from botanical data;
- To prevent collection that is so rigid and prescriptive in keeping to a species list that it occurs at the expense of other suitable species;
- To collect only the major wood-producing species to ensure the applicability of the tool to all the disciplines which have a requirement for wood identification.

The route for the field trip was developed so that it traversed different vegetation types (e.g. along watercourses, dune systems, salt pans etc.) to ensure a thorough and extensive collection.

Accounting for intra-specific variation

Intra-specific variation in wood can occur as a result of two major factors:

- Within-tree variation that occurs as a result of age and different plant parts (e.g. burls, rootwood, trunkwood, limbwood);
- Between-tree variation that occurs in separate trees of a single species as a result of regional differences in growth regimes.

In standard wood anatomy it is usual to collect five to ten specimens of wood from separate individuals to account for within-species variation. Generally foresters (from whom standard wood anatomical practises have usually developed) will remove a core from the trunkwood using an increment borer. However, an increment borer would not have penetrated the high density arid Australian wood (Hill 2005: *pers. comm.*). Collecting trunkwood from arid Australian species would be very difficult without the use of a chainsaw and this would cause unsightly damage to the tree or ultimately cause its death. For these reasons, collections were restricted to limbwood. The variability in limbwood, however, does increase the necessity for intra-specific testing and it was advised that at least five samples per individual should be collected to account for any diversity (Ilic 2002b: *pers. comm.*).

Despite knowledge of best practice and the very real problem of wood variability for identification purposes, collection of specimens from separate individuals was limited from the outset of the project. With time constraints, the repetitious data collection and processing involved in accounting for intra-specific variation would ultimately and significantly reduce the number of treated species. Furthermore, storage of the wood and time in the field were both logistical concerns. Despite limiting the level of intra-specific analysis, this would not necessarily preclude the opportunistic collection of wood from subsequent individuals for future treatment.

Outcomes of field trip

The field trip to arid Australia resulted in the collection of limbwood from 58 species of the more robust trees and shrubs in the region (species are listed in Table 1). The trip traversed the major vegetation types that distinguish the region with collection often taking place along watercourses but also on dune systems, spinifex plains, stony flats and rises, near salt pans and flood plains, and in the timber country of south-west Queensland where the vegetation is dominated by large and extensive stands of *Acacia cambagei* and *Acacia aneura* (Figure 15). All wood specimens were vouchered and ascribed a unique number (including samples from the same species but separate individuals) with the prefix JAB[31]. On return from the field, the collected vouchers were lodged in the *State Herbarium of South Australia* where they were identified by staff. Identifications were not obtained until after the data from the specimens was collected and the identification tool had been developed.

[31] Occasionally, the prefix of specimen numbers may be JB rather than JAB.

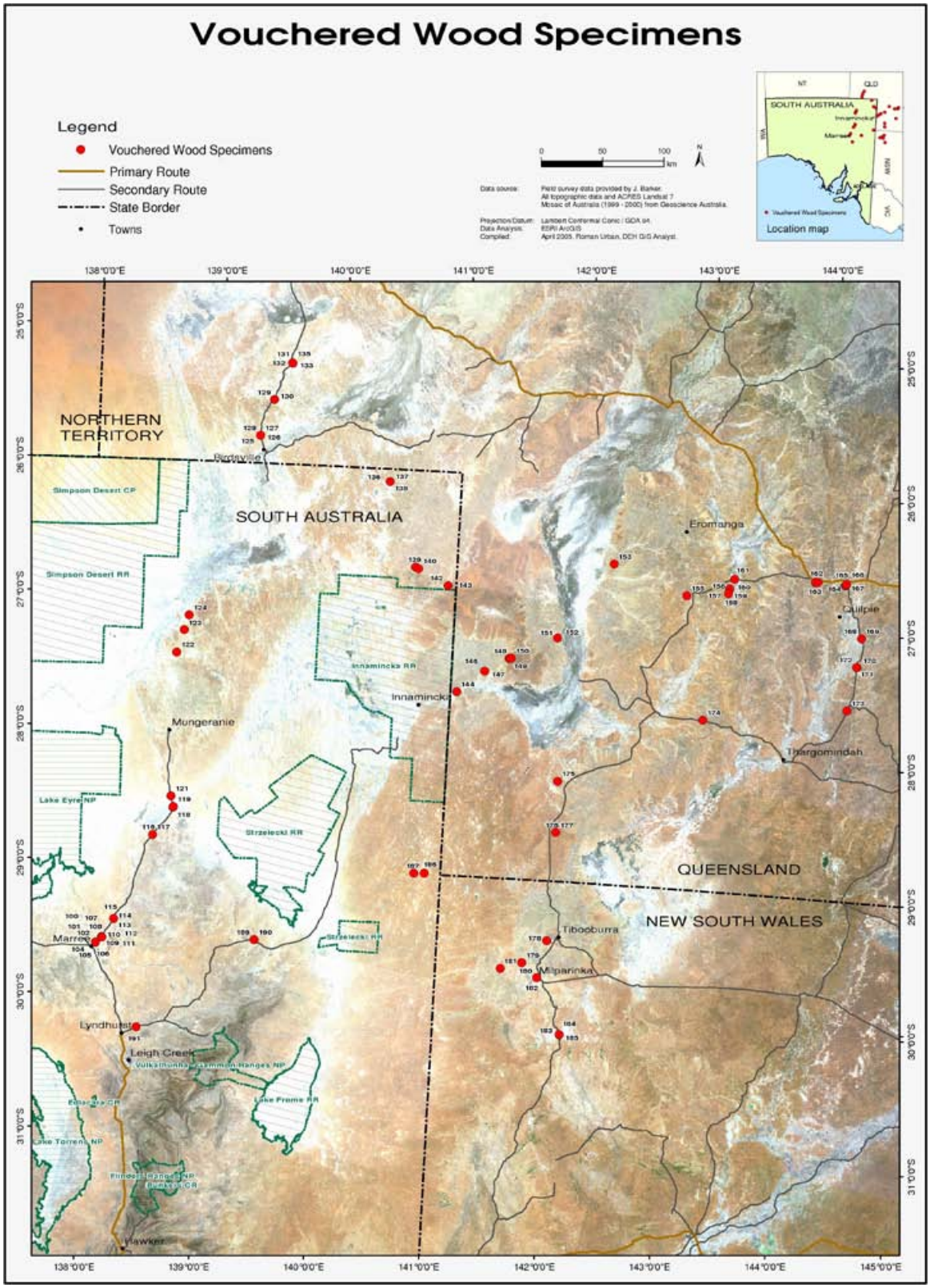


Figure 15 Map showing location of vouchered wood specimens collected in north-east South Australia, south-west Queensland and far western New South Wales. A single red dot may represent a collection from more than one species.

For 10 species more than one wood specimen (from separate trees) was collected; these are indicated in Table 3.

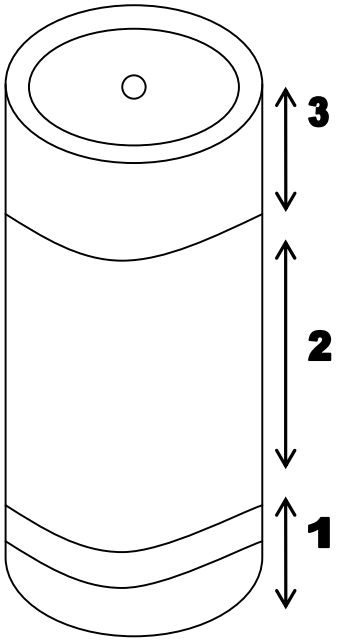
Table 3 Ten species for which more than one specimen (from separate trees) was collected.

Species	JAB specimen number
Acacia cana	JAB178, JAB180
Acacia murrayana	JAB165, JAB186
Acacia stowardii	JAB151, JAB158
Capparis loranthifolia	JAB162, JAB172
Corymbia terminalis	JAB143, JAB156, JAB160
Dodonaea viscosa ssp. *angustissima*	JAB119, JAB184
Eremophila longifolia	JAB106, JAB114
Eucalyptus coolabah	JAB100, JAB107, JAB133, JAB137
Eucalyptus populnea	JAB159, JAB170
Hakea eyreana	JAB139, JAB142

A further 10 specimens were opportunistic collections where field identification suggested that they were examples of species previously collected: JAB171, JAB179, JAB176, JAB118, JAB102, JAB146, JAB182, JAB149, JAB110 and JAB108. These specimens were left aside during the initial treatment of species for the identification tool and used to form a test of the tool. This is further discussed in Chapter Nine. Statistical analyses that test for intra-specific variation using data from the collected specimens are provided in Chapter Ten.

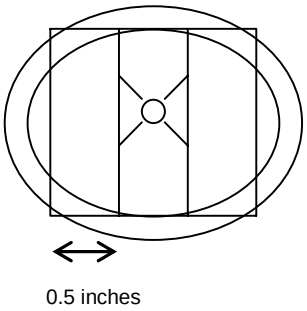
Initial preparation of reference wood samples

On return from the field, the wood was placed in a freezer to kill any wood-boring insects that may have been present. No preservatives or agents to prevent moisture loss had been added in the field. Following this, the wood was cut down to rough rectangles usually about 15 cm length (along the longitudinal grain) by 1.5 cm depth; the width and number of samples depended on the diameter of the original limb and varied accordingly. In addition, two 2.5 cm discs cut transversely were reserved for lodgement with the botanical voucher specimens in the *State Herbarium of South Australia*. Any wood that remained in reserve after this processing was retained as an offcut. A diagram of this process is illustrated (Figure 16).



Initial processing

1. Two one inch disks for lodgement with herbarium voucher specimens – can be roughly cut. Leave bark intact.
2. Six inches for cutting *reference samples*.
3. Offcut. (Any excess wood after 8 inches length removed for herbarium voucher specimens and reference samples.) Reserve.



Reference samples

- Cut to regular-sized pieces.
- Any dimensions allowable will be fine as long as the samples are equal-sided (for measuring density.)
- Most samples should allow 6 inches length (15.42 cm) by 0.5 inch (1.27 cm) depth.
- Width will vary depending on the diameter of the wood and can be adjusted accordingly.
- These dimensions should produce at least two regular-sized reference samples, even with the smallest diameter wood.
- Don't avoid the pith.
- Reserve offcuts (with bark intact).

Figure 16 Diagrammatic representation and instructions for procedure followed to prepare rectangular reference specimens from crude wood specimens. The top diagram shows wood from a longitudinal perspective whilst the bottom digram illustrates an aerial view of the endgrain.

For each separate collection, one of the rectangular blocks was reserved to act as an intact reference specimen. A second rectangular block was reserved for microscopic, anatomical analysis.

Conclusions

The wood collected during the field trip to north-east South Australia, south-west Queensland and far western New South Wales forms the basis of the developed identification tool. The collection of associated herbarium vouchers and their lodgement in the *State Herbarium of South Australia* ensures that this research can be repeated and revisited if any question arises as to the identification of any of the species or if any of the species changes their names. However, the limited testing for intra-specific variation must be borne in mind.

Chapter Seven. Preparation and analysis of vouchered wood

Introduction

Once the crude voucher specimens collected in the field had been fashioned into rectangular reference samples and discs, the wood was prepared for microscopic analysis. The original trials conducted on the unvouchered wood informed the processes that were eventually followed for the vouchered wood. This chapter details how the wood was sampled, softened and polished to present a suitable endgrain surface for optical and scanning electron microscopy (SEM). This is followed by an outline of the process used to fracture the sampled wood blocks to expose their radial and tangential surfaces for the scanning electron microscope. A discussion of the endgrain and SEM image collection and analysis, as well as an outline of the initial statistical analyses, follows. The final section discusses the treatment of the wood for a series of chemical observations and an assessment of a selection of physical properties.

Throughout all processing and analysis specimens retained their unique collection number (JAB XXX).

The density of arid Australian woods

> *The difficulties encountered in the preparation of microtome sections of wood are fully appreciated by wood anatomists, particularly when the wood being sectioned is in a higher density class and contains silica…*
>
> (Kukachka 1978: 301)

Arid Australian wood is renowned for its hardness and unusually high density. It is common for many species to record densities of greater than 1000 kg/m^3 and some as much as 1400 kg/m^3. This is considerably higher than that of most commercial European and American woods, on which standard wood anatomy practises have been based. Variously recorded at between 1100 kg/m^3 and 1250 kg/m^3, Lignum Vitae, the name given to the wood of several South American and Central American species of the genus *Guaiacum*, is commonly recognised as the highest density commercial timber available (Bishop 1999: 96). Greenheart (*Ocotea rodiei*) and Cocobolo (*Dalbergia retusa*) – at 1050 kg/m^3 to 1250 kg/m^3 and 1120 kg/m^3 respectively – also from the American tropics, are

examples of other hard and dense commercial timbers (Bishop 1999: 56, 74) However, amongst commercial woods these examples are very much exceptions to the rule for, at less than 1000 kg/m^3 (the density of water), the vast majority of the commercially available wood species would not sink in water.

In an American publication on wood identification techniques a table provides the specific gravities – an alternative expression of density – for approximately 170 softwood and hardwood species mentioned in the text; only two species measure 1000 kg/m^3 or greater, both are from the tropics and one is Lignum Vitae (Hoadley 1990: 49 - 51). Indeed, in their list of characters for hardwood identification, the *International Association of Wood Anatomists* (IAWA) do not provide a separate category for wood with a density greater than 1000 kg/m^3, classifying density in the following manner:

- Density low, ≤ 400 kg/m^3
- Density medium, 400 – 750 kg/m^3
- Density high, ≥ 750 kg/m^3

(Wheeler, Baas *et al.* 1989: 322)[32]

Given that these two well-known wood identification texts do not commonly treat wood with densities greater than 1000 kg/m^3, the challenge in this research was to find a method of treating the very dense arid Australian wood, either from the literature or through trial and error. At least 20 of the treated species in this research would sink in water whilst only a handful of species had densities of less than 800 kg/m^3 (e.g. *Acacia salicina*, *Schinus molle*[33]), usually considered the upper limit of normal density wood.

Problems with the extreme density of the treated wood permeated much of this research and influenced the techniques adopted, particularly the decision to use scanning electron microscopy (SEM) in favour of the more conventional analysis of thin sections. For use in

[32] In their list of character states the IAWA actually express density in terms of specific gravity but, for consistency, these have been converted to density measurements of kg/m^3.

[33] *Schinus molle* is an introduced species to Australia.

the SEM, wood could be quickly fractured to expose longitudinal faces and microtome knives could be spared the ravages of insufficiently softened wood. However, a method to adequately soften high density wood was required for sectioning and polishing the endgrain. Whilst some of the softening methods trialled on unvouchered wood (see Appendix Five) were moderately successful, they were extremely time consuming and it took some time to discover the efficient and effective softening capacity of hydrofluoric acid. This softening process was so successful that it is anticipated that good quality thin sections (previously of poor quality because of inadequate softening methods for the densest of wood) would be achievable with the use of a razor blade or microtome.

Preparation of reference blocks for microscopic analyses

From one end of one of the rectangular reference specimens previously prepared, between six and twelve 1 cm^3 blocks were sawn and reserved for microscopic, anatomical analysis. Of these small blocks, about half were placed in a solution of 50:50 glycerine to ethanol for storage and initial softening. The remaining blocks were reserved in sealed plastic bags for future analyses if they become necessary.

Measuring density

A very useful, though not essential, practice at this time is to measure the density of the wood. Doing so can inform subsequent procedures, particularly the method required to soften the wood and/or the selected method of polishing, sectioning and analysis. Density was measured in kilograms per cubic metre (kg/m^3) using the rectangular reference specimens from the intact reference collection[34]. To ensure a constant moisture content – and since wood is hygroscopic – the specimens remained in the laboratory for some weeks so that they might equilibrate with the environment. However, as these specimens were not cut precisely to size, and were consequently somewhat irregular, the volume, and therefore the final density reading, may be slightly erroneous and can only be used as an estimate. Rough density measurements are sufficient to inform the subsequent procedure followed for softening the wood and, in the light of a preponderance of wood with a

[34] The rectangular reference specimens are a more appropriate size for measuring density than the $1cm^3$ blocks, where the small volume and weight of the blocks is likely to result in greater errors.

density greater than 1000 kg/m^3, to expose any wood with a lighter density amongst the collection.

Softening

A chemical that proved a very successful and efficient softening agent was hydrofluoric acid. The method was adapted from Dadswell & Burnell (1932) but references to the use of the chemical for very dense species have since been discovered elsewhere (Ives 2001; Jansen, Kitin *et al.* 1998; O'Brien and McCully 1981; Radford, Dickison *et al.* 1974). In fact, one publication claims that it is the oldest known method of softening wood with references to its use in the early 1900s (Plowman 1904 cited in O'Brien and McCully 1981: 4.10). The extreme toxicity of hydrofluoric acid, and the possibility of death upon inhalation, ingestion or exposure to skin, necessitates strict adherence to the recommendations for use and safety outlined in the *Material Safety Data Sheet*[35].

For each species, several of the 1 cm^3 wood blocks were removed from the glycerine/ethanol storage solution, deposited in labelled plastic vials and stored in a test tube rack for added stability. Working within a fume cupboard, and with the appropriate protective clothing, 50% hydrofluoric acid[36] was dispensed into the vials until the blocks were immersed. Figure 17 shows the wood soaking in vials of the acid under the fume cupboard. After up to 30 hours, and following the same safety protocols, the hydrofluoric acid was diluted by filling the vials with water. The solution was then decanted, taking care not to dispose of the wood blocks at the same time. The vials were then refilled with water and decanted. The test tube rack, along with the vials it stored, was removed from the fume cupboard. To avoid exposure to residual hydrofluoric acid, forceps were used to carefully transfer the wood blocks from the plastic vials to labelled glass vials. The glass vials were filled with water and placed on a hot plate. To avoid inhaling residual hydrofluoric acid it was necessary to ensure the area was adequately ventilated. After boiling for up to 6.5 hours, the blocks were immediately removed with forceps into a storage solution of 50:50 glycerine to ethanol. Glass and plastic vials were soaked in water and thoroughly washed.

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[35] A web-based *Material Safety Data Sheet* for hydrofluoric acid is located at http://msds.ehs.cornell.edu/msds/msdsdod/a59/m29196.htm.

[36] Ives uses a solution of approximately 30% hydrofluoric acid, immersing wood blocks for one week (Ives 2001: 57).

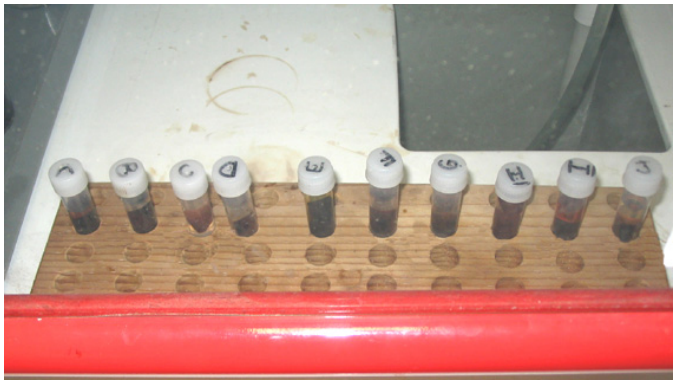

Figure 17 Plastic vials containing wood soaking in hydrofluoric acid. The vials are kept in the fume cupboard and kept stable in a test tube rack.

Some modifications were made to the method depending on wood densities. Lower density species – generally those with a density of 1000 kg/m^3 or less – were immersed in the acid for 24 hours and boiled for 2.5 hours. Approximately a dozen of the densest samples – with densities around 1100 kg/m^3 to 1300 kg/m^3 – proved stubborn and were subjected to both treatments; that is, 54 hours in hydrofluoric acid and 9 hours boiling.

Endgrain preparation for optical and SEM microscopy

The endgrain (transverse) surface of wood contains useful diagnostic information when polished and observed using optical microscopy and scanning electron microscopy. This section details how the wood endgrain is prepared, polished and photographed in readiness for both types of analysis.

Pre-softened blocks were removed from the glycerine/ethanol storage solution and the endgrain of the wood, usually punctuated by vessels[37], was located under a dissecting microscope. Polishing was conducted with a single-edge razor blade[38]. Used razor blades were used to make the initial cuts on the endgrain but final cuts were made with a new blade. Once polished, the blocks were soaked in a 25% solution of sodium hypochlorite (bleach) for up to 30 minutes to remove debris (Ohtani 2000; Wheeler, Baas *et al.* 1989: 252), rinsed under distilled water and left to dry overnight in the fume cupboard.

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[37] Coniferous woods (softwoods) do not contain vessels; only angiosperms (hardwoods) are characterised by vessels and these are most heavily represented in the treated species.

[38] A microtome can also be used to polish the endgrain but only if the wood has been adequately softened. Very dense wood will require softening with hydrofluoric acid to protect the microtome knives. Trials with disposable knives were unsuccessful with these proving far too flimsy for the dense wood. A razor blade can produce a good polished endgrain without the fuss that use of a microtome can entail.

Images of the polished endgrain were collected using an Olympus DP11 digital camera attached to a Zeiss Stemi 2000 dissecting microscope. Given that one square millimetre of the endgrain is often all that is required for wood identification purposes, a 25x image, which produces approximately a 4.5 mm x 5.5 mm frame provided a good balance between field of view and magnification; this magnification was suitable for data collection and analysis and for accounting for variation in the anatomy that may occur on the endgrain.

Once photography was complete, the polished endgrain block was split in halves with a chisel and mallet. A dissecting microscope was used to locate the radial and tangential direction on the endgrain surface and to determine the most suitable direction of the split. The half block depicting the most endgrain clarity (as observed under a dissecting microscope) was reserved for scanning electron microscope (SEM) analysis. It was mounted onto a stub using double-sided sticky tape and the exposed areas of the stub and the sides of the block were painted liberally with carbon paint, taking care to avoid the polished endgrain surface; the specimens were coated in carbon and gold. Meanwhile, the second half of the original endgrain block was reserved as a permanent record of the endgrain and stored in a 50:50 glycerine to ethanol solution. Both halves of the endgrain block will be available for future optical or SEM analyses should these be required.

Preparation of longitudinal surfaces for SEM analysis

During trials on unvouchered wood specimens it was determined that the two longitudinal surfaces were most efficiently prepared for scanning electron microscopy if they were fractured. Fracturing of the longitudinal surfaces is also ideal for very dense wood and can be conducted without the requirement for softening[39]. In fact, it is likely that the density of the wood, particularly on straight-grained timbers, assists the production of a clean fracture.

The procedure followed was informed by a variety of publications that detail methods for preparing wood for SEM analysis (including Exley, Meylan *et al.* 1977; Heady 2000; Jansen, Kitin *et al.* 1998). Most of these publications deal with cutting samples (that is,

[39] This is not so for the transverse surface where fracturing is not possible because it would need to occur against the predominant cell direction in wood. For this reason, softening is a necessity to adequately expose the transverse surface.

polishing and surfacing the three faces with a blade) rather than preparing longitudinal surfaces through fracture. The use of fracture has, however, been efficiently and effectively applied to carbonised wood largely in archaeological (e.g. Donoghue 1989; Hope 1998; Smith, Vellen *et al.* 1995) and palaeobotanical studies (e.g. Hopkins, Ash *et al.* 1993; Hopkins, Graham *et al.* 1990).

In standard wood anatomical studies which deal with normal density wood, fracturing is not generally practised as the surfaces produced tend to be rougher than those that are polished with a razor blade or microtome. Moreover, outer cell walls may be left intact so that examination of the inner vessel wall or inner ray wall is restricted to areas of exposure; this limiting characteristic of the fracturing process was observed in this research and has been noted elsewhere (Jansen, Kitin *et al.* 1998). Nevertheless, coupled with SEM analysis, the process provides an efficient and effective means of dealing with very dense wood with simple tools and without the requirement for softening.

Using a pre-prepared 1 cm^3 unsoftened block, the endgrain was given a cursory polish with a razor blade so that the tangential direction could be located under a dissecting microscope and delineated with a pencil. The block was split along the tangential direction using a chisel and mallet. A second split was made along the tangential surface so that a sample with a flat top and bottom, less than 0.5 cm thick, was created. Most of the tangential specimens had much larger dimensions than were required with some up to 1 cm in length and width. Longitudinal faces were observed under a dissecting microscope to check for adequate vessel exposure. For small, awkward or irregular blocks that could not be easily split with a chisel, samples were pressed into a lump of "blue tac" and a razor blade was pushed through the block along the tangential plane to create a flat underside[40]. Once prepared, samples were placed in a 25% solution of sodium hypochlorite (bleach) for up to 30 minutes to remove debris, whereupon they were removed from the solution, rinsed in distilled water, and left to dry overnight in the fume cupboard. Specimens were mounted for SEM using the same procedure outlined for the transverse surface (Figure 18).

[40] Flat undersides are desirable for SEM analysis so that the specimen rests with its underside flush to the stub; this reduces the prospect of the specimen charging (retaining energy from the electrons).

Figure 18 Preparation of specimens for SEM analysis. The tangential surface has been exposed by fracture and is facing upwards on the stubs.

The radial surface was prepared in the same way as the tangential surface. However, usually an offcut created during fracturing of the tangential surface was used. From the endgrain of this offcut, the radial surface was located and exposed by fracture. Both the tangential and radial specimens used for SEM analysis can be revisited for future examination.

Endgrain analysis

Polished endgrain blocks (and images) were revisited for an assessment of a set of qualitative characters commonly used in wood identification. A clear area of the transverse surface was observed with a dissecting light microscope. Observations occurred at at least 25x magnification and no more than 50x magnification and the examined features were dictated by several wood identification publications (Hoadley 1990; Ilic 1987; Ilic 1990; Wheeler, Baas *et al.* 1989). The recorded characteristics can be broadly defined under the following descriptions:

- Vessel arrangement
- Parenchyma arrangement
- Ray width (in relation to one another)
- Ray width (in relation to vessels)

- Presence of inclusions/tyloses in vessels

Commonly numerical information on the tangential diameter of vessels (in µm) and the number of vessels per square millimetre are also collected from the endgrain. Unfortunately the constraints of time meant that these analyses were sacrificed for collection of similar numerical data from SEM images. The greater magnification and clarity of SEM images means that the data are not necessarily compatible or comparable with similar data collected from the endgrain.

Further information on the breakdown of the characters is provided in the following chapter.

SEM analysis

Transverse, tangential and radial surfaces were observed using a Philips XL-20 scanning electron microscope housed at *Adelaide Microscopy, Adelaide University* (Figure 19). For each surface, on what were essentially very large specimens, a broad reconnaissance of the sample was conducted, dictated by typical quantitative and qualitative diagnostic features used in wood identification. As a general rule, images were collected at relatively low magnifications, albeit much higher than those afforded by light microscopy. Magnifications of 120x or 240x were usual but occasionally images were also collected at higher magnifications of between 3000x and 10,000x; for example, these magnifications were usually necessary for the imaging of pits. To optimise the accuracy of the statistical analyses of the numerical data and for comparative purposes, every attempt was made to standardise selected magnifications across the taxa; however, the magnifications that would provide a balance with field of view varied among species and depended on the feature being examined. To standardise analysis within taxa, and to account for any local variation within the wood of a single sample, particularly where data was to be collected for numerical analyses, up to ten images were made from each surface at the same magnification and from widely separated areas of the specimen.

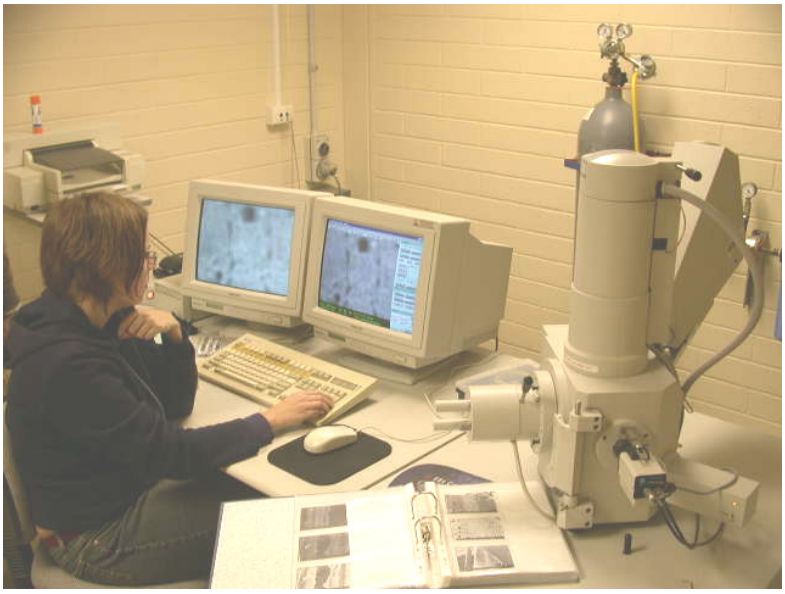

Figure 19 Using a Philips XL-20 SEM to collect images from the transverse, tangential and radial surfaces.

The features sought during examination with the SEM can be broadly placed in the categories given in Table 4.

Table 4 Features sought on the transverse, tangential and radial surface during SEM examination. Characters followed by an (N) refer to numerical features.

Transverse surface	Tangential surface	Radial surface
Vessel number per square millimetre (**N**)	Ray height (in µm) (**N**)	Ray cell shape
Vessel diameter (in µm) (**N**)	Ray width (number of cells wide) (**N**)	Pits (e.g. vessel-vessel, ray-vessel, fibres, vestured, bordered)
Vessel arrangement	Ray number per millimetre (**N**)	Helical thickenings
Parenchyma arrangement	Ray arrangement	Perforation plates
Ray width (in relation to one another)	Inclusions in vessels (or other wood cells)	Chambered axial parenchyma
Ray width (in relation to vessels)	Perforation plates	Inclusions/tyloses in vessels (or other wood cells)
Inclusions/tyloses in vessels (or other wood cells)	Helical thickenings	
	Chambered axial parenchyma	
	Pits (e.g. vessel-vessel, ray-vessel, fibres, vestured, bordered)	

The reconnaissance and data collection was largely informed by the standard list of characters for hardwood identification (Wheeler, Baas *et al.* 1989). This publication contains applicable characters to SEM analysis but it is illustrated by images of thin sections. To overcome difficulties with interpreting the same structure from the different image outputs produced by the two techniques, references containing compendia of SEM images were used to assist the identification of diagnostic microstructures (Butterfield and Meylan 1980; Butterfield, Meylan *et al.* 2000; Ohtani 2000). However, with SEM still a

relatively recent application to wood anatomy and identification, there is a paucity of comprehensive reference books that illustrate the characters used in hardwood identification[41].

Further information on the breakdown of the characters is provided in the following chapter.

SEM image analysis for numerical characters

The digital image analysis software *analySIS*, a *Soft Imaging Systems* product is an efficient method of generating large amounts of numerical data on particles. In this research it was employed to generate standard numerical data from wood cells contained in scanning electron microscope images. The software was previously tested on 19 unvouchered wood samples from nine genera (including *Acacia*, *Eremophila*, *Hakea* and *Grevillea*), particularly to assess vessel diameter and vessel number per square millimetre. Collection of numerical data is a tedious process, whether more traditional techniques are employed or computer-assisted methods. The advantages of the *analySIS* software are its speed and ability to process large amounts of data. The accuracy of the technique is improved by the reduced subjectivity inherent in the process and the ability to generate large amounts of numerical data that should statistically reduce the margin for error. This section discusses the process used to capture the relevant data using the *analySIS* software so that the procedure may be replicated. Experienced limitations of *analySIS* are given in Chapter Ten

Vessel diameter and vessel number per square millimetre

Low magnification SEM images of the transverse surface were used to assess vessel diameter and vessel number per square millimetre. Magnification varied depending on the species but the selected images were generally either 120x, 240x or 480x – for very small vessels such as in Myoporaceae; these magnifications usually provided the best balance with field of view.

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[41] Another reference (Xishen 1988) could not be obtained through inter-library loan or by contacting the Chinese publishing house.

Data on vessel diameter and vessel number were collected simultaneously. For vessel diameter, the IAWA states that the "tangential diameter of the vessel lumina, excluding the wall, is measured at the widest part of the opening" (Wheeler, Baas *et al.* 1989: 258). The *analySIS* software contains numerous interpretations for calculating diameter and it was determined that its definition of "Proj X Diameter"[42] was the most suitable. For vessel number, the individual vessels that comprise vessel multiples were counted separately and parameters were set so that only 50% of vessels in partial view within a frame were included in the analysis; this is in accordance with the IAWA standard (Wheeler, Baas *et al.* 1989: 259).

An SEM image taken at the appropriate magnification was opened in *analySIS* and delineated with a 644 x 422 pixel frame that encapsulated the entire area above the SEM data bar. This frame defined the area of data collection. Thresholds were adjusted to capture the vessels by dragging left and right sliders along a histogram outputting the image intensities until a suitable balance was found. If too great a threshold is selected, areas of the image other than the vessels were included in the analysis but if the threshold is set too low some of the smaller vessels were not captured. Where cells or cell masses other than vessels were captured, they were eliminated from the image by setting and adjusting parameters. For example, elongated ray cells could often be removed by using the filter to remove any cells with an aspect ratio of 2:1 or, in some cases, 3:1. Parenchyma cells could sometimes be removed by adjusting the minimum Proj X Diameter; for example, the Proj X Diameter minimum could be adjusted to eliminate from the captured data any cells that were less than 20 µm diameter. An SEM image with captured vessels is shown in Figure 20.

[42] Defined in *analySIS* as: "The maximum distance of all boundary points in the horizontal direction projected onto the X axis." Further numerical data such as vessel area or aspect ratio can be generated but their diagnostic potential is not known.

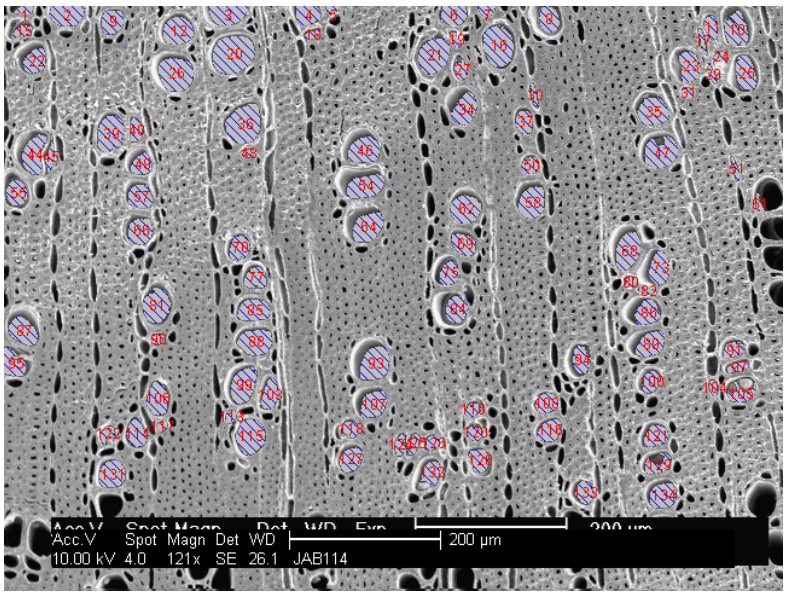


Figure 20 Using *analySIS* software to measure vessel diameter (in µm) and vessel number per mm^2 on the transverse surface. In this image of JAB114 *Eremophila longifolia* the vessels have been captured and numbered for analysis. (Scale = 200 µm)

Unwanted particles could also be manually deleted from the image and previously uncaptured vessels appended by freehand drawing. Too much manual removal and addition of particles is time consuming and it may upset the statistical balance. However, many of the treated species were characterised by vessels with inclusions which were not captured appropriately using the threshold and parameter adjustment. Consequently, there were many occasions where manually appending large numbers of vessels was necessary.

Once the vessels had been suitably captured, and each vessel had been automatically ascribed a unique number, the numerical data were generated. This created an .xls (Microsoft Excel) spreadsheet containing the diameters (in µm) of each of the captured vessels. The number of vessels observed provided the data for vessel number per square millimetre.

Data were collected in this manner for each species with each SEM image representing a sampled area. A minimum of two SEM images and a maximum of 10 SEM images were examined per species, with the average species sampled from four SEM images. This average falls short of the IAWA recommendation of sampling from "at least five (and preferably ten) fields of appropriate size" for vessel number per square millimetre (Wheeler, Baas *et al.* 1989: 259). However, the data collection for vessel diameter satisfied the IAWA recommendation of measuring at least 25 vessels (Wheeler, Baas *et al.*

1989: 258); a minimum of 41 vessels and a maximum of 977 vessels were measured with an average number of 167 vessels per species. Within each species, data were collected from images of the same magnification.

Ray width

Ray width was measured on the tangential surface, perpendicular to the ray axis using low magnification SEM images. As with vessel diameter and number, the optimum magnification varied between species but analysis of 120x or 240x images was usual; 60x magnification was required for some species with very wide multiseriate rays, particularly Proteaceae. Using the *analySIS* software, ray cells were counted by selecting each of the cells that occurred across the widest part of each ray (Figure 21). In keeping with IAWA recommendations, where rays were of two distinct widths, as with Proteaceae, only the larger class was measured (Wheeler, Baas *et al.* 1989: 282).

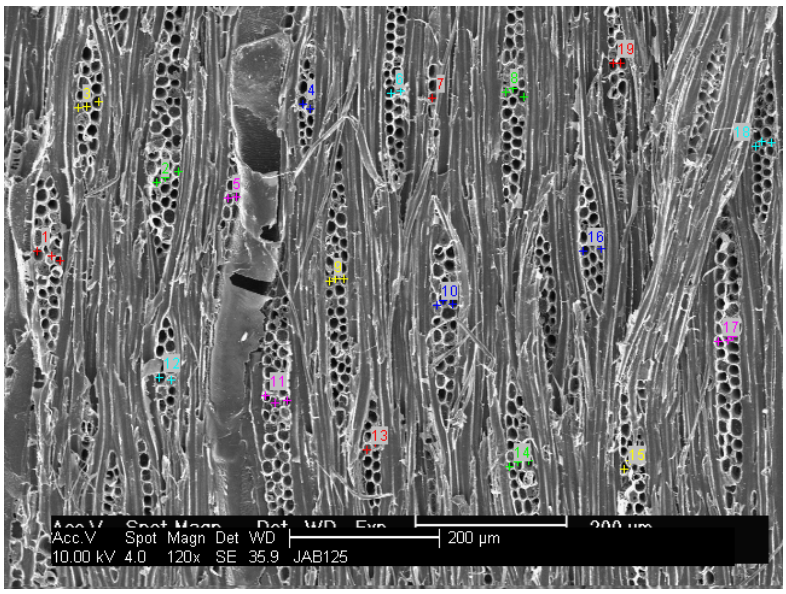


Figure 21 Using the *analySIS* software to determine ray width, counts were made of the number of cells that occurred across the widest part of each ray on the tangential surface. The image shown is JAB125 *Owenia acidula*. (Scale = 200 µm)

Data collection for ray width continued for each species with a minimum of three and a maximum of 18 sampled areas; the average species was sampled from seven SEM images. The minimum number of rays measured per species was 13, the maximum was 214 rays and the average number was 96 rays. An Excel spreadsheet containing the number of cells that made up each ray was generated.

Ray height

Ray height was measured on the tangential surface, parallel to the ray axis. Magnifications were usually 120x or 240x, except for species with very large multiseriate rays where ray height was often measured at 60x. Unfortunately, at 60x magnification image clarity was reduced and measurements may be erroneous; this is discussed in Chapter Ten. Individual ray heights were measured by dragging a line from the top of a ray to the bottom of a ray (Figure 22).

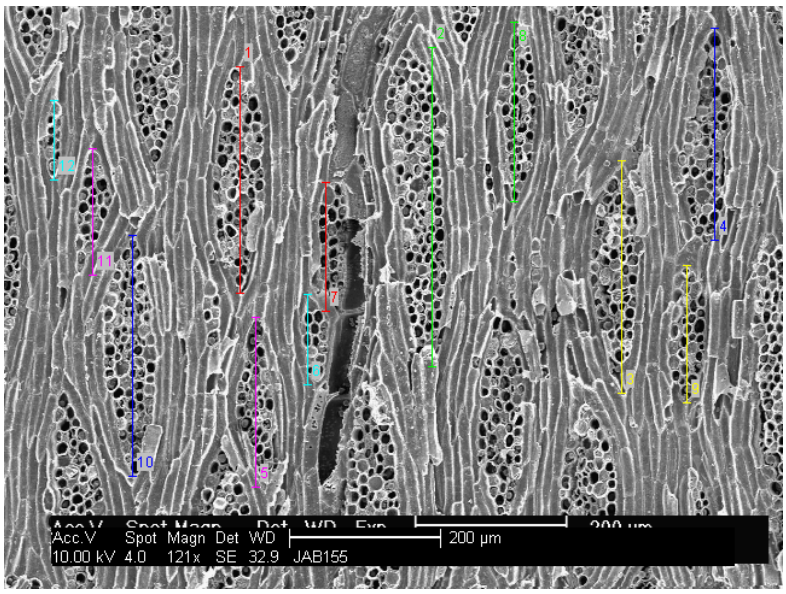


Figure 22 Using the *analySIS* software to measure ray height (in µm) on the tangential surface. The image depicted is of JAB155 *Flindersia maculosa*. (Scale = 200 µm)

Data collection for ray height continued for each species with a minimum of three and a maximum of 12 sampled areas per species; the average species was sampled from six SEM images. The minimum number of rays measured per species for ray height was 30; the maximum was 242 rays and the average was 78 rays. An Excel spreadsheet containing the height (in µm) of each ray was generated.

Rays per millimetre

Rays per millimetre was measured on the tangential surface, along an arbitrary line perpendicular to the ray axis. To ensure a standardised method of measurement, the arbitrary line was positioned at 211 pixels. The line was dragged from the middle of the left-most, bisecting ray to the middle of the right-most, bisecting ray. Each ray that bisected the line was counted. The bisecting line and counted rays are shown in Figure 23.

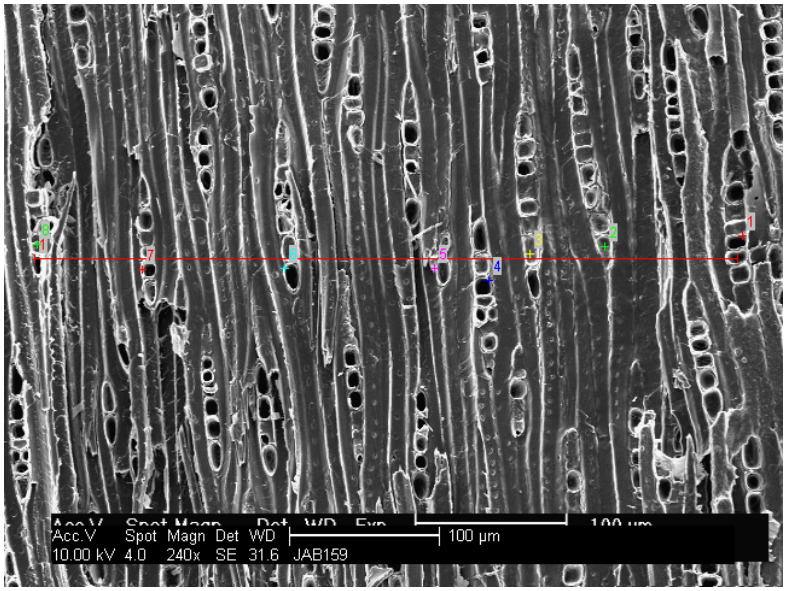


Figure 23 Using the *analySIS* software to measure ray number per mm on the tangential surface. A line of known length extends from the leftmost ray to the rightmost ray; each ray that bisects the line is counted. The image depicted is JAB159 *Eucalyptus populnea*. (Scale = 100 µm)

Data collection for rays per millimetre continued for each species with a minimum of three and a maximum of 15 sampled areas per species; the average species was sampled from seven SEM images. An Excel spreadsheet containing the number of rays that bisected the arbitrary line was generated.

Following from the numerical data collection, data in the resultant spreadsheets was statistically analysed. All the files created as a result of the numerical data collection, including the modified SEM images and separate spreadsheets, were retained so that they may be revisited in future.

Initial statistical analyses

According to the IAWA standard list of characters for hardwood identification, basic standard statistics collected from wood include the mean, the standard deviation, the range and the number of observations (Wheeler, Baas *et al.* 1989). However, in an article on numerical values in wood identification, Ilic & Miller (1996) make some recommendations on how to create meaning from numerical data on cell dimensions when it is based on only a single sample. In accordance with the IAWA, the article suggests that mean, standard deviation and number of observations should be recorded but in a description, not in an identification key. Whilst they believe that standard deviation is important for limited samples, because it provides an indication of variability, they question the usefulness of a

mean when it is generated from limited data from a single sample (Ilic and Miller 1996: 85). They point out that in wood identification it is not so important that two different samples contain small vessels of 30 µm; diagnostic differences are dependent on whether the largest vessels in one sample are greater than the largest vessels in another, or whether one sample has a denser distribution of the small 30 µm vessels than the other (Ilic and Miller 1996: 85). Accordingly, for single samples they suggest that the mean may not adequately reveal variability and recommend the use of the range instead; that is, the minimum numerical value in the data set and the maximum numerical value in the data set. These recommendations were adopted in this study.

Using the two publications (Ilic and Miller 1996; Wheeler, Baas *et al.* 1989) as a guide and the numerical data generated during the image analysis, statistical information was generated for vessel diameter, vessel number per square millimetre, ray height, ray width and ray number per millimetre. This section provides further details and compendia for each of these characters is presented in Appendix Seven.

Vessel diameter

Ilic & Miller (1996) suggest that a description for vessel diameter include the average maximum calculated by randomly selecting 50 values from a data set and taking the average of the largest 20% of the values. They propose that with further research this feature may prove to be of greater diagnostic value than the mean as the average maximum indicated how large vessels can become. With this in mind, statistical information calculated from the numerical data on vessel diameter included the mean, standard deviation, range, average maximum and number of observations.

Vessel number per square millimetre

Before any statistical analysis took place, the vessel number per square millimetre was calculated from the numerical data. Following this, the mean, standard deviation, range and number of observations were evaluated.

Ray height & ray width

As with vessel diameter, the mean, standard deviation, range and number of observations were calculated.

Ray number per millimetre

Before the statistical analysis commenced, the number of rays that occurred per millimetre was calculated from the numerical data generated for each specimen. The mean, standard deviation, range and number of observations were computed.

Physical analyses

Most publications or descriptions on the properties of wood will include information on physical properties such as density, grain and figure; yet the physical characteristics of wood are largely ignored in identification tools, probably as a result of the variability that can occur in these properties within a single species. However, many wood enthusiasts and collectors use these properties to assess and identify wood. Years of experience has meant that often they are able to identify wood correctly to genus and sometimes to species level. The IAWA includes information on specific gravity (another expression of density), heartwood colour and odour in their standard list of characters for hardwood identification (Wheeler, Baas *et al.* 1989). This indicates that despite the variation in physical properties that can exist within a species, they do have some diagnostic value and, if they are applied with caution, can be useful. Of course, this scale of identification necessitates a relatively large and unmodified sample and the assessment of certain characters might also require some processing of specimens.

With the exception of assessment of wood density, which was discussed earlier in this chapter, this section details the physical assessment of the vouchered reference samples.

Heartwood/sapwood colour

Many species produce wood with a visual colour contrast between the outer sapwood and the inner heartwood, the contrast the result of extractives stored in the heartwood (Figure 24). Usually the heartwood is darker than the sapwood as, for example, with *Acacia*. In other species, however, there is no visible contrast between the heartwood and sapwood and it is difficult, if not impossible, to discern with the naked eye where the sapwood ends and the heartwood begins. Where wood has no visual distinction the wood is usually uniformly pale as, for example, with *Atalaya hemiglauca* or *Pittosporum angustifolium*. However, caution must be exercised in assessing uniformly pale wood specimens as these may represent specimens where heartwood has not developed; this can complicate the

assessment of characters that are heartwood-dependent and this is further discussed in the following chapter.

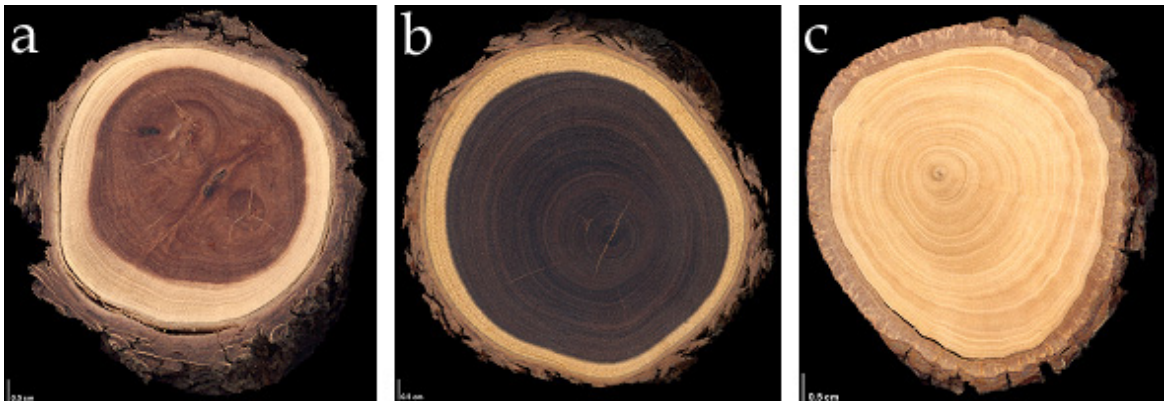


Figure 24 Heartwood and sapwood colour. A: JAB125 *Owenia acidula*; B: JAB169 *Acacia cambagei*; C: JAB123 *Santalum lanceolatum.* In *Santalum lanceolatum* heartwood is not distinguishable from sapwood with the naked eye. (Scale = 0.5 cm).

Assessment of heartwood colour was conducted by a visual examination of the one inch discs created during the initial processing of the vouchered wood. Examination of the discs ensured that the entire circumference of the wood was observable. Heartwood colour assessment is a non-destructive process if wood is freshly cut but ageing, certain treatments and decay may necessitate the preparation of a freshly cut surface. The major characteristic that was noted was whether the heartwood colour was darker than the sapwood colour. As this could only be accurately surmised from specimens where there was a distinct colour difference between the sapwood and heartwood, pale wood and specimens where uncertainty existed were also noted. The different colours that occurred in the heartwood were noted and an attempt was made to categorise the variation. Any distinctive and characteristic heartwood colours were also recorded (e.g. the purple heartwood of *Acacia peuce*) (Figure 25).[43]

[43] Using this character alone *Acacia peuce* may still be confused with *Acacia carneorum*, an arid Australian *Acacia* with purple heartwood.

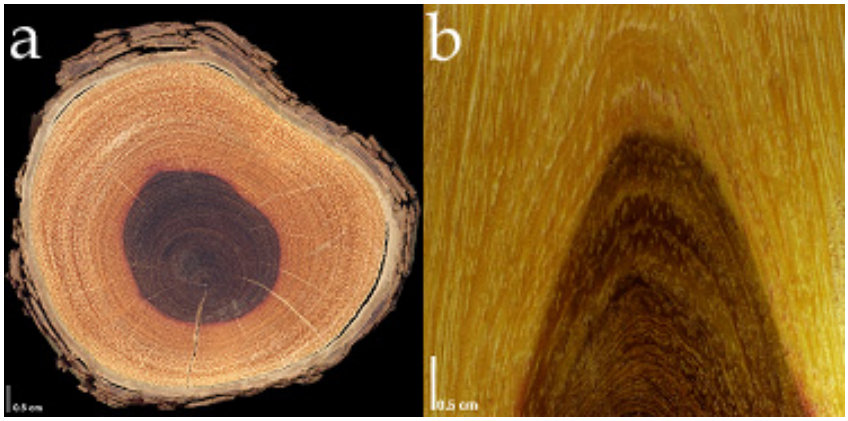


Figure 25 Seen here in cross-section (A) and longitudinally (B), the heartwood of JAB126 *Acacia peuce* is characterised by a purple tinge that becomes more evident with age. (Scale = 0.5 cm)

Heartwood fluorescence

Another heartwood-dependent feature, fluorescence occurs when certain materials deposited in the heartwood fluoresce when exposed to ultra-violet light (Figure 26); the fluorescence varies in intensity and colour with yellow and green shades common (Wheeler, Baas *et al.* 1989: 325). This fluorescence is not detectable under normal light conditions. Several studies have assessed the diagnostic potential of the character (Avella, Dechamps *et al.* 1988; Dyer 1988; Pandey, Upreti *et al.* 1998) and the IAWA notes that the absence of heartwood fluorescence is important in some families, including Leguminosae (Wheeler, Baas *et al.* 1989).

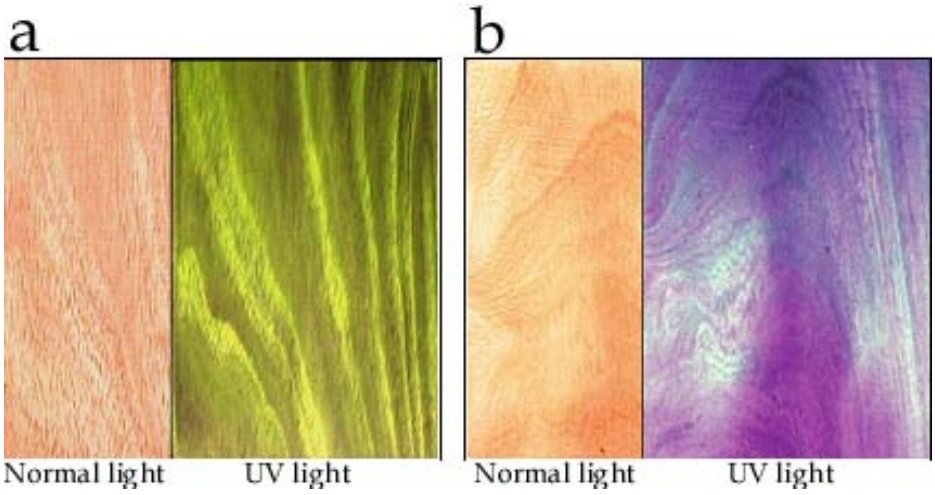


Figure 26 Examples of fluorescent wood of *Acacia melanoxylon* (A) and *Acacia sutherlandii* (B). Wood under normal light is at the left of each image; wood under UV light shows fluorescence and is at the right of each image. These images were modified from originals and reproduced from *The Wood Explorer* website (2003); neither of the species are treated in this research.

Examination for the presence of heartwood fluorescence is a non-destructive process if the wood assessed is fresh and without additives or decay (which may also emit associated

fluorescence). To test this character, the rectangular wood samples, previously prepared from the voucher specimens to act as intact reference specimens, were placed in front of a UV lamp in a darkroom. Specimens that presented clearly defined heartwood and sapwood were relatively straightforward to assess; the colour and intensity of the heartwood fluorescence was noted. Intensity varied with some samples exhibiting weak, but positive, fluorescence. For wood without visually discernable heartwood, the colour and intensity of any fluorescence was also recorded; the majority of these pale woods did not fluoresce but this may have been due to the absence of heartwood. Care needed to be taken not to confuse reflections from the UV light that can occur in some wood with fluorescence (Wheeler, Baas *et al.* 1989: 325).

Odour

Certain wood species emit an odour, the result of deposited extraneous oils and other substances. For example, the green wood of native pine JAB185 *Callitris glaucophylla* was laden with a visible, sticky resin that produced the familiar pine odour. Several of the treated Myoporaceae produced lemon-scented heartwood. JAB123 *Santalum lanceolatum*, northern sandalwood, also produced an odour when freshly cut, presumably not as fragrant as the commercially harvested sandalwood, *Santalum spicatum*. In the field, the green wood of JAB130 *Acacia farnesiana* emitted a very strong and disagreeable odour which had disappeared several weeks later when it was cut into reference blocks.

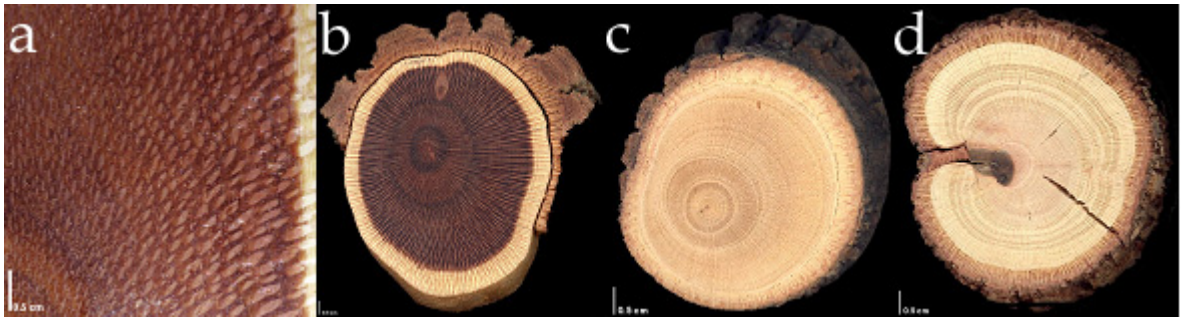
Generally, the presence of an odour was assessed when the rectangular reference wood specimens were hand sawn into smaller blocks. This is a good time to assess the character as aromas will often be emitted during and immediately after wood has been freshly sawn[44]. Along with the wood, assessment was often assisted by smelling the blade of the saw immediately after sawing to ascertain the presence of an odour; however, care needed to be taken not to mistake the smell of the heat generated from the saw for scented wood. Faint odours were recorded as well as distinctly strong smells and it was very important to note whether the odour is heartwood-specific, indicating that the smell comes from the extractives present in the wood (Hoadley 1980: 47).

[44] The IAWA also suggest an alternative method of adding moisture to the wood to draw out any odour (Wheeler, Baas *et al.* 1989: 325).

Other distinguishing physical characteristics

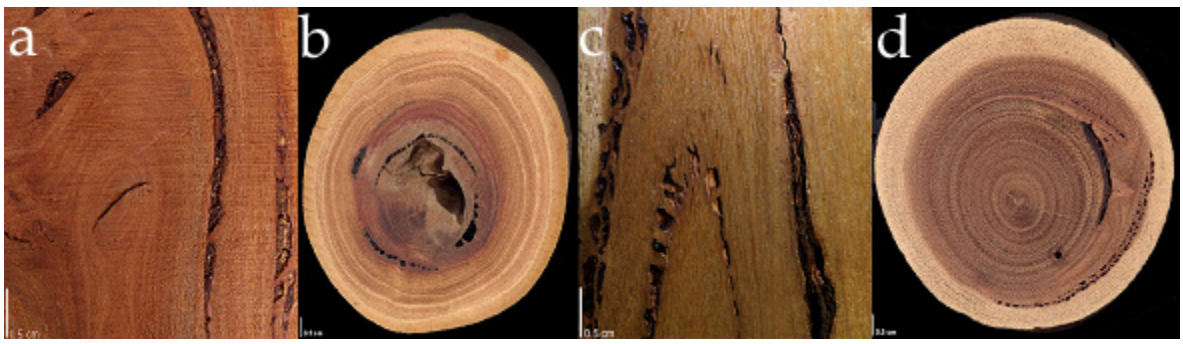
There are other visual attributes that may be characteristic of certain families, genera or species. As noted earlier, purple heartwood may indicate *Acacia peuce*. The longitudinal surfaces of Proteaceae (and some Casuarinaceae) are characterised by ray fleck; these are most striking on the radial surface where the wood is cut parallel to the long axis of the large multiseriate rays. Multiseriate rays may also be visible to the naked eye on a cross-section (Figure 27).

Figure 27 Wide multiseriate rays create ray fleck on the longitudinal surface (A) of *Grevillea striata* whilst rays are visible to the naked eye on the cross-section (B). The cross-sections of *Capparis loranthifolia* (C) and *Tamarix aphylla* (D) also present with rays visible on the cross-section. (Scale = 0.5 cm)



Corymbia ssp. can often be distinguished by gum or kino veins, produced in response to injury (Bootle 1983: 32); this is why the *Corymbia* species are colloquially known as Bloodwoods, although kino veins were also evident in JAB191 *Eucalyptus camaldulensis* (Figure 28).

Figure 28 Kino or gum in longitudinal (A) and cross-section (B) of JAB191 *Eucalyptus camaldulensis* and in longitudinal (C) and cross-section (D) of JAB156 *Corymbia terminalis*. (Scale = 0.5 cm)



In the course of this research, a distinctive blue ring around a number of Myoporaceae specimens was observed although its cause and diagnostic potential require investigation (Figure 29).

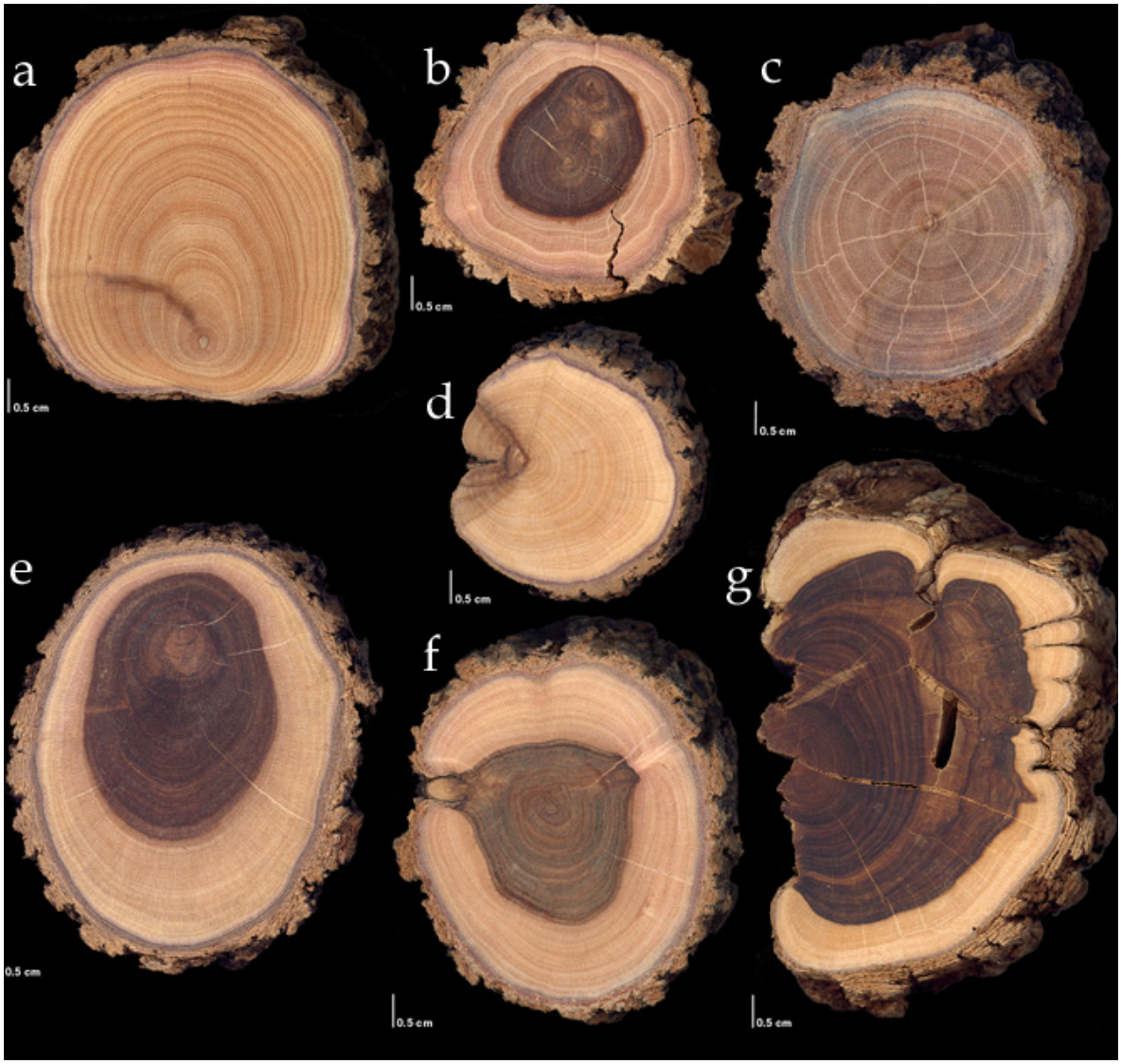


Figure 29 Sanded, transverse discs of a selection of treated Myoporaceae species each characterised by a distinctive, blue ring at the xylem perimeter. A: JAB181 *Eremophila polyclada*; B: JAB101 *Myoporum montanum*; C: JAB106 *E. longifolia*; D: JAB168 *E. sturtii*; E: JAB167 *E. mitchelliii*; F: JAB129 *E. bignoniiflora*; G: JAB152 *E. freelingii*. (Scale = 0.5 cm)

Chemical analyses

The chemistry of wood offers an entirely different approach to wood identification; it is a discipline in itself. For example, classification of the extractives contained in heartwood can be diagnostic at the genus or species level (Lewin and Goldstein 1991: 5) but their

huge variety makes this process complex (Harlow 1970: 73; Lewin and Goldstein 1991: 5). Groups of compounds that occur in the heartwood may include:

> *…volatile oils, terpenes (turpentines, resin acids, sterols), fatty acids and their esters, waxes, polyhydric alcohols, mono- and polysaccharides, alkaloids, and aromatic compounds (acids, aldehydes, alcohols, phenylpropane dimers, stilbenes, flavonoids, tannins and quinones).*
>
> (Lewin and Goldstein 1991: 5)

Phytochemical studies have been conducted on wood, including the Australian *Acacia* species (Tindale and Roux 1969; Tindale and Roux 1974). Using chromatography, the studies examined chemical variations in the flavonoids occurring in the heartwood of several hundred native Australian *Acacia* species (Tindale and Roux 1969: 1713). Their research placed *Acacia* into four broad chemical sub-divisions. Whilst these did not exactly concur with the accepted morphological divisions within *Acacia* at the time (Bentham 1875), there was some correlative suggestion. According to Pedley (1987), several other studies on the chemistry of Australian *Acacia* also supported the broad subdivisions (Clarke-Lewis and Dainis 1967; Clarke-Lewis and Porter 1972). Other chemical analyses of Australian *Acacia* include several on gum exudates (Anderson 1978; Anderson, Bell *et al.* 1971; Anderson, Farquhar *et al.* 1984).

Time constraints and the complexities of the science meant that efforts at separating the treated wood species by examination of their chemistry could not be further explored; however, some simple chemical tests, borrowed from the IAWA (Wheeler, Baas *et al.* 1989), were included in this research. The methods used to treat the vouchered wood are outlined. As most of the chemical tests require access to heartwood, for species where heartwood was not present, or not readily distinguishable from the sapwood, this was noted, along with the results of the tests.

Initial preparation for froth test and ethanol and water extract tests

Following is an outline of the initial procedure used to prepare for five of the chemical tests: the froth test; the water extract test: fluorescence and colour; and the ethanol extract test: fluorescence and colour.

Using a Stanley knife and funnel, enough heartwood shavings were removed from the rectangular reference samples (previously used to prepare for the microscopy analyses) to generously cover the bottom of labelled 5 cm x 1 cm glass vials. For each species, two sets of glass vials were made to satisfy the five tests. The glass vials had previously been sterilised in boiling water. Two "control" vials were prepared (without shavings), one containing 5 millilitres of distilled water (pH 6.86) – buffered with phosphate buffer solution – and the other containing 5 millilitres of 100% ethanol.

Froth test

The froth test provides an indication of the presence of saponins in wood. Saponins are plant products that produce a lather when mixed with water; they are used commercially in detergents and soaps.

Shavings were covered with 5 millilitres of the buffered distilled water, covered and vigorously shaken. After allowing the vial to stand for one minute, the presence or absence of froth was recorded (Figure 30). If the froth test was positive, froth still completely covered the surface; if it was weakly positive, the froth formed a ring around the vial; and if the test was negative, the froth had completely disappeared.

Figure 30 Vials containing heartwood shavings and buffered distilled water immediately after being tested for the presence of saponins. If the froth remains in the three vials on the left after one minute these specimens are positive; if only a ring of froth remains around the edge of the vial they are weakly positive. The three vials on the right without froth scored negatively for the froth test.

Water extract: fluorescence

Some plant species produce heartwood containing extractives that are soluble when immersed in water, causing the extractives to stain the solution. Furthermore, in certain species the extract produced may fluoresce when observed under ultra-violet light. Fluorescence is usually observed in shades of blue and green of variable intensities (Wheeler, Baas *et al.* 1989: 326)

This test was conducted immediately after the froth test. Having been left to stand for approximately two minutes, the vials containing the heartwood shavings were placed in front of a UV lamp (in a darkened room) and assessed for fluorescence. When placed next to the vials containing the shavings, the "control" vial (containing only distilled water) was helpful in indicating fluorescence, particularly where it was weak.

Water extract: colour

Heartwood extractives present in some species are soluble when immersed in water, causing the extractives to stain the solution. Stains usually occur in shades of brown, red or yellow – occasionally black, orange or purple – and in varying intensities (Wheeler, Baas *et al.* 1989: 326).

Approximately 4.5 hours had passed since the shavings had been immersed in water for the froth test. The vials were placed on a hotplate and the solution brought to the boil. The colour of the extract was assessed – holding the vials against a white sheet of paper and the "control" vial assisted assessment (Figure 31).

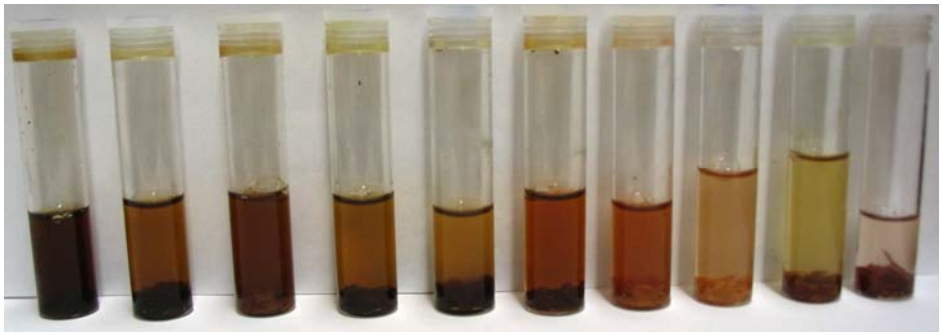


Figure 31 Vials containing heartwood shavings and buffered distilled water are held against a white sheet of paper after being brought to the boil. All these specimens test positively for discolouration of the water extract.

Ethanol extract: fluorescence

Heartwood extractives that are soluble in ethanol may also fluoresce when observed under ultra-violet light. Fluorescence is usually observed in shades of blue and green of variable intensities (Wheeler, Baas *et al.* 1989: 326).

Shavings in the second prepared vials were covered with 5 millilitres of 100% ethanol, covered and vigorously shaken. The vials were left to stand for approximately two minutes whereupon they were placed before a UV lamp (in a darkened room) and assessed

for fluorescence. When placed next to the vials containing the shavings, the "control" vial (containing only 100% ethanol) was helpful in indicating fluorescence, particularly where it was weak (Figure 32).

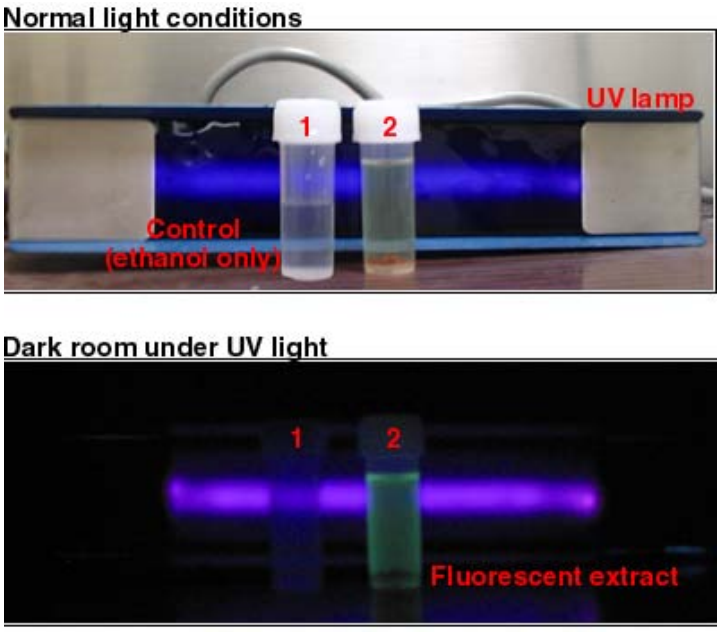


Figure 32 Testing for fluorescence in an ethanol extract. The top image shows – under normal light conditions – the control vial (1) which contains only ethanol; a vial containing heartwood shavings in ethanol (2); and an operating UV lamp. The bottom image depicts the same scene in a dark room; the ethanol extract in vial 2 is fluorescent.

Ethanol extract: colour

Some plant species produce heartwood containing extractives that are soluble when immersed in ethanol, causing the extractives to stain the solution. Stains usually occur in shades of brown, red or yellow – occasionally black, orange or purple – and in varying intensities (Wheeler, Baas *et al.* 1989: 326).

Approximately 3 hours after testing for fluorescence in the ethanol extract, the vials were placed on a hotplate and the solution brought to the boil. The colour of the extract was assessed by holding the vials against a white sheet of paper and comparing them with the "control" vial (Figure 33).

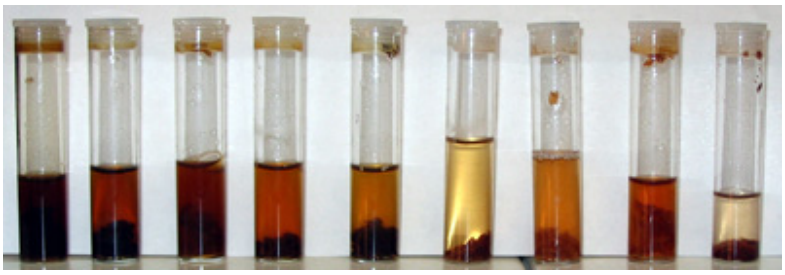


Figure 33 Vials containing heartwood shavings and ethanol are held against a white sheet of paper after being brought to the boil on a hotplate. All these specimens test positively for discolouration of the ethanol extract.

Chrome Azurol-S test

Chrome azurol-S is used as an indicator for the presence of aluminium in both sapwood and heartwood. It has been adopted by the IAWA as a character for hardwood identification (Wheeler, Baas *et al.* 1989). According to Kukachka & Miller (1980) wood with aluminium present will produce a bright blue colour upon addition of a few drops of chrome azurol-S to a freshly exposed area of the endgrain.

Following the IAWA guidelines, a 0.5% solution of chrome azurol-S reagent was prepared by dissolving 5 grams of sodium acetate and 0.5 grams of chrome azurol-S in 80 millilitres of distilled water. Once dissolved, an extra 20 millilitres of distilled water was added to the solution to make 100 millilitres of reagent. Using a teat pipette, several drops of the reagent were added to the endgrain of the rectangular reference blocks (previously used to remove samples for microscopy)(Figure 34). The colour was monitored over a 72 hour period.

Conclusions

This chapter has summarised the means by which the vouchered wood specimens were prepared for anatomical examination – using light microscopy and SEM – and for physical and chemical observations. The procedure and the characters assessed were largely adopted (and adapted) from contemporary anatomical texts and the IAWA standard list of hardwood characters. The results of the character assessment for individual taxa are presented in the descriptions attached to the taxa in the identification tool, whilst the method by which the data were recorded in the keys is discussed in the following chapter.

Figure 34 Rectangular reference specimens after treatment with chrome azurol-S reagent. After 72 hours none of these specimens had reacted positively with the affected area indicating blue.

Chapter Eight. Building the wood identification tool: its structure and content

Introduction

The interactive identification tool – *Key to a Selection of Arid Australian Hardwoods & Softwoods* – developed in this research was created with *Lucid*, a software package designed to aid in the construction of identification tools to any set of organisms or objects. This chapter briefly introduces the *Lucid* software and discusses the construction and organisation of the identification tool, the selection of the characters and the addition of data. Further information on the use of the identification tool and detailed descriptions of characters and taxa can be obtained from the tool itself.

Background to Lucid

Developed by the *Centre for Pest Information Technology and Transfer, University of Queensland*, *Lucid* is just one example of a suite of recently available, computer-based, diagnostic software packages that have been adopted by a range of disciplines including entomology, botany, zoology, quarantine, dentistry and mineralogy for the construction of identification tools[45]. With the benefit of multiple-entry keys and the ability to attach multimedia and factsheets to illustrate terms, characters and taxa, *Lucid* provides a powerful alternative to traditional, paper-based dichotomous keys and taxonomic revisions such as Floras and Faunas.

Lucid is comprised of two components – a Builder and a Player. The Player is like the front-end of a database, providing the platform for the completed identification tool; once distributed with the Player, users may apply the tool to a similar set of unidentified organisms. The backend of the database – the Builder – is used to compile data for a given set of taxa against a given set of characters. A character is a taxonomic term that refers to a feature of an organism. Characters are selected on the basis that they best describe (and distinguish) the treated taxa, and variability within a character is defined by the states or

[45] Previous research involved the development of a prototype identification tool to macroscopic plant remains (specifically plant disseminules – seeds and fruits) from archaeological deposits (Barker 2000) using the *Lucid* software. Further information on *Lucid* can be obtained from www.lucidcentral.com.

character states. For example, the character "Vessels, solitary or not" is defined by two character states "Vessels, solitary" and "Vessels, not solitary"; each taxon is scored against the relevant character state. Within the Builder, keys can be augmented with the addition of explanatory notes and diagrams, and independently-operable sub-keys can be linked to the tool.

This chapter is primarily concerned with the Builder as it describes the construction and structure of the developed identification tool.

Hierarchical key structure

Rather than combining all the treated species in a single tool, the developed identification tool comprises a series of keys and sub-keys to reflect the taxonomic hierarchies. This section provides a breakdown and rationale of the identification tool structure. An organisation chart shows the rudimentary structure of the tool (Figure 35).

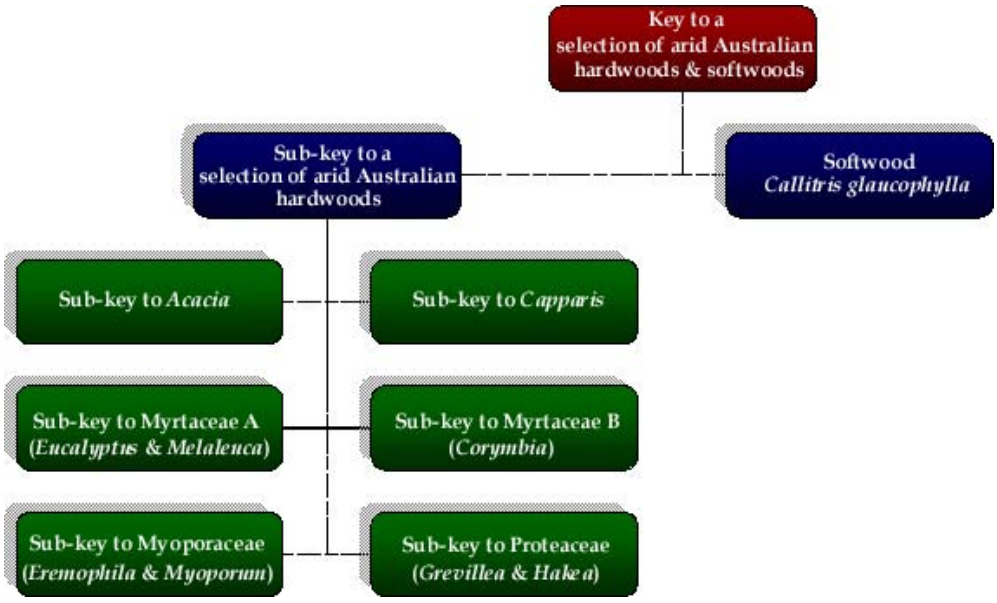


Figure 35 Diagram of hierarchical tool structure showing nested identification keys

Key to a Selection of Arid Australian Hardwoods & Softwoods

At the foundation of the identification tool is a simple key that will separate *Callitris glaucophylla* – the single softwood species treated in this identification tool and the predominant coniferous species in the Australian desert – from 57 arid Australian hardwood taxa. It utilises a single character "With vessels (hardwood) or not (softwood)" to separate the taxa. The character states "With vessels (hardwood)" and "Without vessels

(softwood)" are described in attached factsheets and illustrated with examples. A factsheet that describes and illustrates the wood of *Callitris glaucophylla* is also attached. Examples of a character state factsheet and a taxa factsheet are provided later in this chapter.

Whilst remaining an important component for novice users, this first key may often be superfluous to user requirements as users with even a cursory knowledge of wood identification will likely be able to distinguish between angiosperm and gymnosperm wood without the use of a key. The predominance of Australian hardwoods means that most users will progress to the sub-key attached to the "Arid Australian hardwoods" taxa.

Sub-key to a Selection of Arid Australian Hardwoods: the central key

The central component of the tool is the *Sub-key to a Selection of Arid Australian Hardwoods*. Primarily a key to genera, this sub-key can be operated independently of all other keys, or used in conjunction with six attached sub-keys that assist further separation at the genus or species level (see next section: *Sub-keys to species*). The structure of all the sub-keys to Australian hardwood taxa is outlined in Table 5.

The following section outlines the selection of the taxa and characters for the central *Sub-key to a Selection of Arid Australian Hardwoods*.

Selection of taxa

The *Sub-key to a Selection of Arid Australian Hardwoods* is comprised of 20 angiosperm taxa which include families and genera (Figure 36). The creation of a key at this taxonomic level recognises the difficulty of separating wood beyond family or genus and the limited testing for intra-specific variation. The divisions used in this key are such that separation at the family or generic level should occur predominantly on qualitative characters, and that further separation within a genus may be more reliant on numerical characters where testing for intra-specific variation is even more vital.

Some families indicate variation between genera. *Corymbia* exhibits a conspicuously different vessel and parenchyma arrangement to *Eucalyptus* and *Melaleuca*. Given this, the family Myrtaceae was split into Myrtaceae A (containing *Eucalyptus* and *Melaleuca*) and Myrtaceae B (containing *Corymbia*). However, families such as Proteaceae (*Grevillea*

Table 5 Table showing the structure of the hierarchical sub-keys to a selection of arid Australian hardwoods. 1 – 7: refers to the set-up of the interactive keys with Myrtaceae A, Myrtaceae B, Proteaceae, Myoporaceae, Acacia, Capparis and all single representatives of genera forming the central Sub-key to a Selection of Arid Australian Hardwoods. Sub-keys are available to Myrtaceae A, Myrtaceae B, Proteaceae, Myoporaceae, Acacia and Capparis to assist further separation of taxa at the genus or species level.

FAMILY	Genus	Species	Collection number(s)	Sub-keys
1 MYRTACEAE A	*Eucalyptus*	*camaldulensis* var. *obtusa*	191	
		coolabah	100, 107, 133, 137	
		ochrophloia	161	Sub-key to Myrtaceae A
		populnea	159, 170	
		thozetiana	163	
	Melaleuca	*glomerata*	189	
		trichostachya	144	
2 MYRTACEAE B	*Corymbia*	*aparerrinja*	157	Sub-key to Myrtaceae B
		terminalis	143, 156, 160	
3 MYOPORACEAE	*Eremophila*	*duttonii*	175	
		freelingii	152	
		longifolia	106, 114	
		bignoniiflora	129	
		macgillivrayi	140	Sub-key to Myoporaceae
		mitchellii	167	
		polyclada	181	
		sturtii	168	
	Myoporum	*montanum*	101	
4 PROTEACEAE	*Grevillea*	*striata*	124	
		juncifolia	147	Sub-key to Proteaceae
	Hakea	*eyreana*	139, 142	
		leucoptera ssp. *leucoptera*	112	
LEGUMINOSAE	**5 *Acacia***	*aneura* var. *aneura*	121	
		?aneura. var. *intermedia*	177	
		cambagei	169	
		cana	178, 180	
		cyperophylla var. *cyperophylla*	136	
		farnesiana	130	
		ligulata	109	
		ligulata ?intergrade with *A. bivenosa*	150	
		murrayana	165, 186	Sub-key to *Acacia*
		oswaldii	111	
		petraea	164	
		peuce	126	
		pickardii	122	
		salicina	117	
		stenophylla	105	
		tetragonophylla	128	
		victoriae ssp. *victoriae*	135	
		stowardii	151, 158	
CAPPARACEAE	**6 *Capparis***	*loranthifolia*	162, 172	Sub-key to *Capparis*
		mitchellii	132	
		7 Single representatives of genera		
SANTALACEAE	*Anthobolus*	*leptomerioides*	174	
SANTALACEAE	*Santalum*	*lanceolatum*	123	
SAPINDACEAE	*Atalaya*	*hemiglauca*	127	
SAPINDACEAE	*Dodonaea*	*viscosa* ssp. *angustissima*	119, 184	
CAESALPINIACEAE	*Bauhinia*	*gilva*	138	
CAESALPINIACEAE	*Senna*	*artemisioides* ssp. *filifolia*	183	Sub-key to a Selection of Arid Australian Hardwood
CASUARINACEAE	*Casuarina*	*pauper*	187	
RUTACEAE	*Flindersia*	*maculosa*	155	
MELIACEAE	*Owenia*	*acidula*	125	
PITTOSPORACEAE	*Pittosporum*	*angustifolium*	113	
RUBIACEAE	*Psydrax*	*latifolia*	153	
ANACARDIACEAE	*Schinus*	*molle*	190	
TAMARICACEAE	*Tamarix*	*aphylla*	115	
RHAMNACEAE	*Ventilago*	*viminalis*	166	

and *Hakea*) and Myoporaceae (*Eremophila* and *Myoporum*) did not produce significant variation in qualitative features to assist inter-generic separation. Further separation at this level can be attempted in the attached sub-keys to Proteaceae or Myoporaceae.

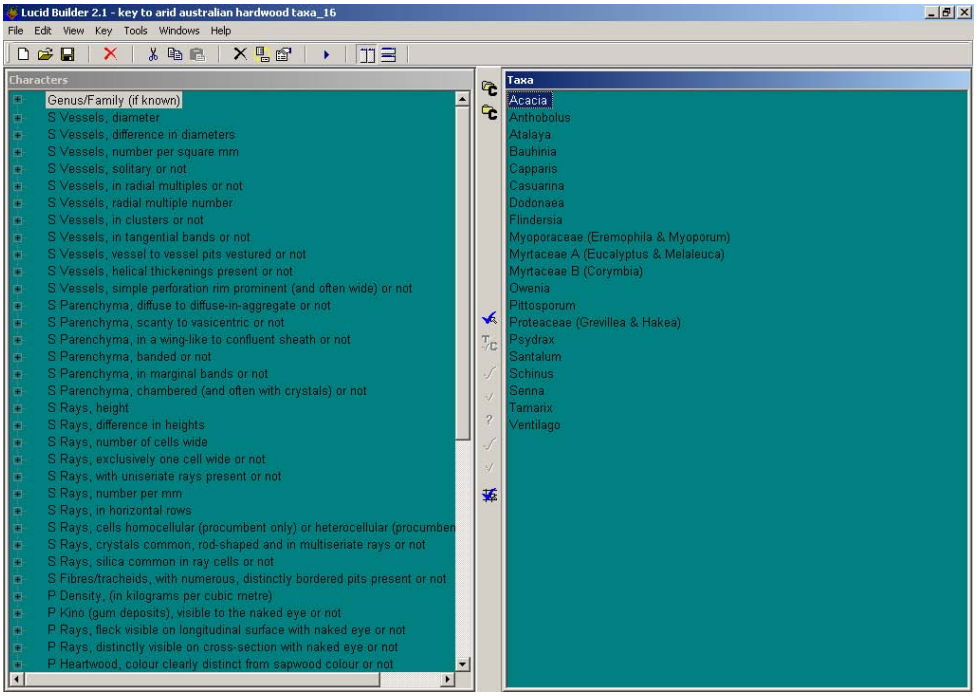


Figure 36 Interface of *Lucid* Builder showing the Sub-*key to a Selection of Arid Australian Hardwoods*. A selection of the characters are shown in the left window; the 20 hardwood taxa are listed in the right window.

Selection of character sets

A total of 56 characters largely borrowed and/or adapted from the *International Association of Wood Anatomists* standard list of hardwood characters (Wheeler, Baas *et al.* 1989) have been used to define the treated taxa in this key. These characters have been broadly defined and placed into applicable "character sets" – groups of related characters that promote efficient navigation through a key. Nine character sets have been adopted in this key and characters may be shared between sets. Four of the sets relate to the available identification method:

- Anatomical: scanning electron microscopy (31 characters)
- Anatomical: endgrain (light microscopy) (15 characters)
- Chemical observations (5 characters)

- Physical properties (8 characters)

Table 6 shows the characters in the *Sub-key to a Selection of Arid Australian Hardwoods* arranged by identification method. Each of the characters is also prefaced by a letter (or a combination of two letters) which also serve to retain the link between the character and the relevant identification method(s): P: physical properties; C: chemical properties; E: endgrain; or S: Scanning electron microscope.

Table 6 Table showing list of characters and states within each of the four character sets relating to available identification method. Characters with single states are those where taxa is separated on the basis of quantitative data rather than qualitative data. Some characters are shared between sets.

Character	States
PHYSICAL PROPERTIES	
P Rays, distinctly visible on cross-section with naked eye or not	Rays, distinctly visible on cross-section with naked eye
	Rays, not distinctly visible on cross-section with naked eye
P Rays, fleck visible on longitudinal surface with naked eye or not	Rays, fleck visible on longitudinal surface with naked eye
	Rays, fleck not visible on longitudinal surface with naked eye
P Kino (gum deposits), visible to the naked eye or not	Kino (gum deposits), visible to the naked eye
	Kino (gum deposits), not visible to the naked eye
P Density, (in kilograms per cubic metre)	Density, very dense > 1000 kg/m^3
	Density, dense to light < less than 1000 kg/m^3
P Heartwood, colour clearly distinct from sapwood colour or not	Heartwood, colour clearly distinct from sapwood colour
	Heartwood, colour not clearly distinct from sapwood colour
P Heartwood, colour purple or becoming purple or not	Heartwood, colour purple or becoming purple
	Heartwood, colour not purple
P Heartwood, odour distinctly evident from freshly cut wood or not	Heartwood, odour distinctly evident from freshly cut wood
	Heartwood, odour not distinctly evident from freshly cut wood
PC Heartwood, fluorescent or not	Heartwood, fluorescent
	Heartwood, not fluorescent
CHEMICAL OBSERVATIONS	
C Heartwood, froth test positive or negative	Heartwood, froth test positive
	Heartwood, froth test negative
C Heartwood, ethanol extract fluorescent or not	Heartwood, ethanol extract fluorescent
	Heartwood, ethanol extract not fluorescent
C Heartwood, water extract colourless or discoloured	Heartwood, water extract colourless
	Heartwood, water extract discoloured
C Heartwood, ethanol extract colourless or discoloured	Heartwood, ethanol extract colourless
	Heartwood, ethanol extract discoloured
PC Heartwood, fluorescent or not	Heartwood, fluorescent
	Heartwood, not fluorescent
ANATOMICAL: ENDGRAIN (LIGHT MICROSCOPY)	
E Vessels, solitary or not	Vessels, solitary
	Vessels, not solitary
E Vessels, in radial multiples or not	Vessels, in radial multiples
	Vessels, not in radial multiples
E Vessels, radial multiple number	Vessels, in radial multiples of 4 or more
	Vessels, not in radial multiples of 4 or more
E Vessels, in clusters or not	Vessels, in clusters

	Vessels, not in clusters
E Vessels, in tangential bands or not	Vessels, in tangential bands
	Vessels, not in tangential bands
E Parenchyma, in a wing-like to confluent sheath or not	Parenchyma, in a wing-like to confluent sheath (paratracheal)
	Parenchyma, not in a wing-like to confluent sheath
E Parenchyma, in marginal bands or not	Parenchyma, in marginal bands
	Parenchyma, not in marginal bands
E Parenchyma, banded or not	Parenchyma, banded
	Parenchyma, not banded
E Banded parenchyma, broken or unbroken	Banded parenchyma, broken
	Banded parenchyma, unbroken
E Banded parenchyma, with a bandwidth commonly larger than ray width or not	Banded parenchyma, with a bandwidth commonly larger than ray width
	Banded parenchyma, with a bandwidth not commonly larger than ray width
E Banded parenchyma, in bands commonly further apart than rays or not	Banded parenchyma, in bands commonly further apart than rays
	Banded parenchyma, in bands not commonly further apart than rays
E Banded parenchyma, in bands narrower than vessels or not	Banded parenchyma, in bands narrower than vessels
	Banded parenchyma, in bands not narrower than vessels
SE Rays, distinctly wider than vessels or not	Rays, distinctly wider than vessels
	Rays, not distinctly wider than vessels
SE Rays, of two distinct widths or not	Rays, of two distinct widths
	Rays, not of two distinct widths
SE Heartwood, vessels commonly with tyloses or not	Heartwood, vessels commonly with tyloses
	Heartwood, vessels not commonly with tyloses
ANATOMICAL: SCANNING ELECTRON MICROSCOPY	
S Vessels, diameter	Vessels, diameter (minimum and maximum vessel diameters)
S Vessels, difference in diameters	Vessels, difference in diameters (maximum minus minimum vessel diameters)
S Vessels, number per square mm	Vessels, < 50 per square mm
	Vessels, 50-100 per square mm
	Vessels, >100 per square mm
S Vessels, solitary or not	Vessels, solitary
	Vessels, not solitary
S Vessels, in radial multiples or not	Vessels, in radial multiples
	Vessels, not in radial multiples
S Vessels, radial multiple number	Vessels, in radial multiples of 4 or more
	Vessels, not in radial multiples of 4 or more
S Vessels, in clusters or not	Vessels, in clusters
	Vessels, not in clusters
S Vessels, in tangential bands or not	Vessels, in tangential bands
	Vessels, not in tangential bands
S Vessels, vessel to vessel pits vestured or not	Vessels, vessel to vessel pits vestured
	Vessels, vessel to vessel pits not vestured
S Vessels, helical thickenings present or not	Vessels, helical thickenings present
	Vessels, helical thickenings absent
S Vessels, simple perforation rim prominent (and often wide) or not	Vessels, simple perforation rim prominent (and often wide)
	Vessels, simple perforation rim not prominent
S Parenchyma, diffuse to diffuse-in-aggregate or not	Parenchyma, diffuse to diffuse-in-aggregate (apotracheal)
	Parenchyma, not diffuse to diffuse-in-aggregate
S Parenchyma, scanty to vasicentric or not	Parenchyma, scanty to vasicentric (paratracheal)
	Parenchyma, not scanty to vasicentric
S Parenchyma, in a wing-like to confluent sheath or not	Parenchyma, in a wing-like to confluent sheath (paratracheal)
	Parenchyma, not in a wing-like to confluent sheath
S Parenchyma, in marginal bands or not	Parenchyma, in marginal bands
	Parenchyma, not in marginal bands
S Parenchyma, banded or not	Parenchyma, banded
	Parenchyma, not banded

S Parenchyma, chambered (and often with crystals) or not	Parenchyma, chambered (and often with crystals)
	Parenchyma, not chambered
S Rays, height	Rays, height (minimum and maximum ray heights)
S Rays, difference in heights	Rays, difference in heights (maximum minus minimum ray heights)
S Rays, number of cells wide	Rays, number of cells wide
S Rays, exclusively one cell wide or not	Rays, exclusively one cell wide (uniseriate)
	Rays, not exclusively one cell wide
S Rays, with uniseriate rays present or not	Rays, with uniseriate rays present
	Rays, with uniseriate rays absent
S Rays, number per mm	Rays, <4 per mm
	Rays, 4 - 12 per mm
	Rays, >12 per mm
S Rays, in horizontal rows	Rays, in horizontal rows (storied)
	Rays, not in horizontal rows
S Rays, cells homocellular (procumbent only) or heterocellular (procumbent and upright)	Rays, cells homocellular (procumbent only)
	Rays, cells heterocellular (procumbent and upright)
S Rays, crystals common, rod-shaped and in multiseriate rays or not	Rays, crystals common, rod-shaped and in multiseriate rays
	Rays, crystals not common, rod-shaped and in multiseriate rays
S Rays, silica common in ray cells or not	Rays, silica common in ray cells
	Rays, silica not common in ray cells
SE Rays, distinctly wider than vessels or not	Rays, distinctly wider than vessels
	Rays, not distinctly wider than vessels
SE Rays, of two distinct widths or not	Rays, of two distinct widths
	Rays, not of two distinct widths
SE Heartwood, vessels commonly with tyloses or not	Heartwood, vessels commonly with tyloses
	Heartwood, vessels not commonly with tyloses
S Fibres/tracheids, with numerous, distinctly bordered pits present or not	Fibres/tracheids, with numerous, distinctly bordered pits present
	Fibres/tracheids, with numerous, distinctly bordered pits not present

In addition to the character sets relating to the available identification method, many of the characters listed in Table 6 are also sorted into one of four sets relating to diagnostic feature:

- Vessels (16 characters)
- Rays (14 characters)
- Parenchyma (13 characters)
- Fibres/tracheids (1 character)

These characters are prefaced by the relevant diagnostic feature e.g. “S Vessels,…”, “S Rays,…” and “E Parenchyma,…”

Finally, characters that require heartwood to be present in order to make a proper assessment of the states have also been grouped into a single set:

- Heartwood-dependent characters (9 characters)

These characters begin with "P Heartwood,…" or "C Heartwood,…".

As Table 6 indicates, characters are shared between sets. For example, most of the the characters in the physical or chemical observations sets are also heartwood-dependent. In the case of the character "PC Heartwood, fluorescent or not", this may be considered a chemical or physical observation so it is placed in both sets as the prefix "PC" indicates. The characters "SE Heartwood, vessels commonly with tyloses or not", "SE Rays, distinctly wider than vessels or not" and "SE Rays, of two distinct widths or not" are assessable on the transverse surface using SEM or light microscopy. As the results seem to be consistent within a species, and between the two methods of observation, these characters are retained in both the SEM and endgrain anatomy sets.

During data collection, use of endgrain and SEM analyses to assess the same character did occasionally produce inconsistent results within a single specimen. Compared to the assessment of the transverse surface under a light microscope, the SEM provides extra clarity, higher magnification and a black and white image output; these factors can combine to produce subtle differences in how a single specimen is scored against a single character. For example, four or more vessels arranged in radial multiples can be more apparent on an SEM image than an endgrain image. To protect against these inconsistencies, separate characters describing vessel arrangement and parenchyma arrangement have been constructed for each set e.g. "S Vessels, solitary or not" for analysis of the transverse surface with an SEM and "E Vessels, solitary or not" for assessment of the transverse surface using a light microscope.

The character sets that relate to identification method follow a logical progression in recognition of the variability in available sample size, and that non-invasive techniques are often desirable, if not essential. The provision of a heartwood-dependent character set also recognises that it can be difficult to determine whether heartwood is present – either as a result of a limited sample size or because, in some species, heartwood is not visually discernible from sapwood. The use of character sets also reflects that this variability in

sample size can affect the range of available characters and the available method of identification. For example, where a splinter is the limit of material available the most applicable method of identification will be an examination of the wood anatomy using scanning electron microscopy. In this case it is unlikely that any of the heartwood-dependent characters, or the physical and chemical observations, will be applicable. However, if the object from which the splinter was removed was also available for examination, characters from these sets, along with those from the endgrain set, may be applicable.

The diagnostic potential of each of the character sets tends to depend upon the complexity of the identification method(s) they employ. However, time constraints have meant that there is room for expansion of all the sets to include further characters. There is particularly room for expansion of the endgrain set where the inclusion of numerical characters would drastically increase the efficacy of this method of identification. Whilst there is still scope for the expansion of the SEM set, attention was largely focused on this set given that it contains the only characters applicable to fragmentary wood.

The ability to pick and choose applicable characters from within and between sets provides users with the utmost flexibility and control of the identification process. Take, for example, the identification of the wood used to construct a boomerang. The user would need to polish a small area of the endgrain of the artefact for anatomical analysis using a dissecting microscope. Where the resultant shavings were of heartwood these would be reserved for chemical observations. Using a combination of characters from the endgrain anatomy and chemical observations sets a user might well identify a specimen as *Acacia* (Leguminosae). With damage restricted to a tiny area of up to several square millimetres, and using relatively straightforward standard wood identification procedures, the boomerang has been identified to genus[46]. For some researchers this level of identification might be sufficient but users may decide whether to progress to the more complex procedure of extracting a splinter for examination of the anatomy using scanning electron microscopy. Whilst the procedure is more invasive, use of this character set and the

[46] With expansion of the chemical, physical and endgrain sets to include more characters - particularly the addition of the numerical characters vessel number per square millimetre and vessel diameter to the endgrain set - identification may be possible to a single taxon.

attached *Acacia* sub-key may elicit identification to species level or, at least, narrow the possibilities.

The six sub-keys to genera/species

To assist further separation at the genus or species level there are six available sub-keys:

- Sub-key to *Acacia* (Leguminosae) (19 taxa)
- Sub-key to *Capparis* (Capparaceae) (2 taxa)
- Sub-key to Myoporaceae (*Eremophila* & *Myoporum*) (9 taxa)
- Sub-key to Myrtaceae A (*Eucalyptus* & *Melaleuca*) (7 taxa)
- Sub-key to Myrtaceae B (*Corymbia*) (2 taxa)
- Sub-key to Proteaceae (*Grevillea* & *Hakea*) (4 taxa)

Each of these keys is independently-operable so that they can be separately accessed if identification is already known to these taxonomic levels.

Selection of taxa

The taxa that comprise the six sub-keys were selected on the basis that they were represented by at least two species belonging to the same genus (or two genera belonging to the same family) that are not easily separable, particularly using qualitative data. These taxa are most likely to separate individually, or in groups, using the numerical characters attached to the SEM character set; however, any indications of *inter*-species variation should be cautiously received given the limited testing for *intra*-specific variation. Indications of similarities and differences can be observed in the images and descriptions attached to the taxa factsheets that comprise each sub-key. An example of a taxa factsheets is provided later in this chapter.

Selection of characters

No attempt has been made to separate characters between the central *Sub-key to a Selection of Arid Australian Hardwoods* and its attached sub-keys, so those that are most useful for family or genus identification, and those that are useful at the species level, are not defined.

Instead the full suite of characters is available in each key, excluding any *redundant characters* in the six sub-keys. Redundant characters are those with states that either apply to all of the taxa in a given sub-key or none of the taxa; in other words, they will not result in any separation of taxa so their presence in the key is superfluous. To simplify the sub-key structure, any redundant characters have been removed. In some of the sub-keys this has meant that the representative characters have been cropped by up to half. In addition, in the developed identification tool, the chosen characters in the *Sub-key to a Selection of Arid Australian Hardwoods* can be cross-checked against the characters in the appended sub-keys to genera/species so that further elimination of taxa may occur immediately upon opening the sub-key. Users may then attempt to use any of the remaining characters.

Scoring the key

The data collected from the physical, chemical, endgrain and SEM observations are used to score the key. Scoring involves selecting against each of the characters so that each of the taxa is described by the relevant states. Lucid provides flexible scoring options for both quantitative and qualitative characters (Figure 37.

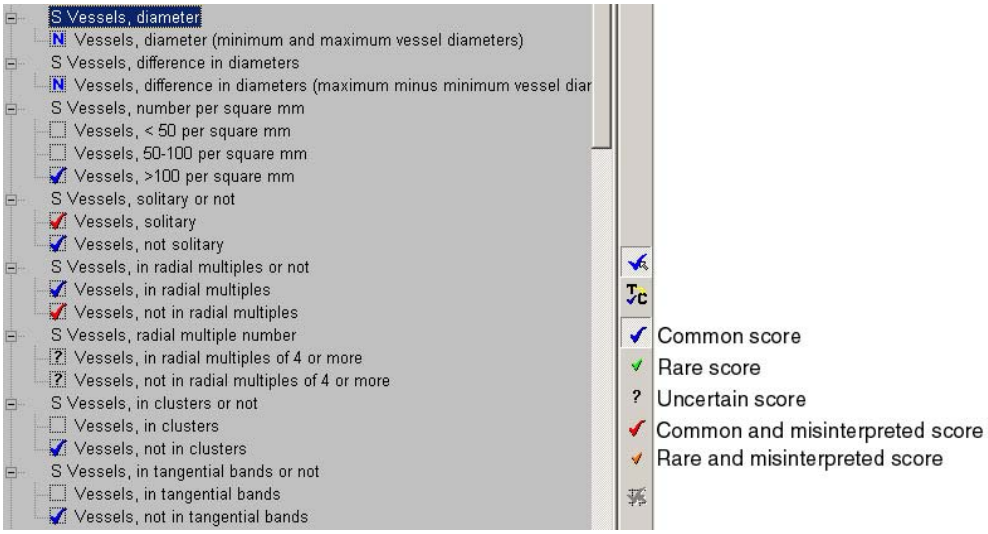


Figure 37 A section of the Lucid Builder exemplifying the different scoring options.

Common and rare scores

The standard means of scoring a qualitative character is to use the *common score*; this is used when a state is commonly present. However, Lucid also allows for states that are rarely present. For example, for the character "S Rays, number per mm", six of seven observations of *Tamarix aphylla* (JAB115) fell within the state "Rays, < 4 per mm"; this

state was given a common score. However, one observation recorded 4 rays per mm; as this sat on the cusp of two states the state "Rays, 4 – 12 per mm" was given a *rare score*.

Allowing for user and builder uncertainty

Where the builder is unsure as to the presence of a state, the state may be given an *uncertain score*. For example, assessing the numeric character "S Rays, height" for the Proteaceae family was problematic because the height of the rays (often over 1 mm) was such that, in their entirety, they would fit into the field of view of only very low magnification SEM images (approximately 30x or 60x); however, at these magnifications clarity was reduced and there was a potential bias against smaller size rays. As a result the numerical state was scored uncertain. Where a taxon does not quite fit the description of any of the states within a character, scoring each state as commonly present provides for potential uncertainty on the part of the user of the identification tool. The uncertain score was also a means of treating heartwood-dependent characters and specimens where heartwood development was indiscernible; this is discussed further shortly.

Allowing for user misinterpretation

Finally, a state may be scored as *commonly misinterpreted* if it is felt that a user may score the character incorrectly because of a wrong interpretation. For example, pale bands on the transverse surface of *Capparis* spp. wood may be easily mistaken for regular bands of parenchyma when they are in fact thin-walled fibres contrasting against thicker-walled fibres (Figure 38). To protect against this misconception, for the character "S Parenchyma, banded or not" and "E Parenchyma, banded or not" the positive state was scored as commonly misinterpreted whilst the negative state was scored as commonly present. If the character was considered only occasionally open to misinterpretation the positive state may have been scored as *rarely misinterpreted*.

Numeric characters

Five numeric characters are employed in the keys and all belong to the SEM character set: "S Vessels, diameter", "S Vessels, number per square mm", "S Rays, height", "S Rays, number per mm" and "S Rays, number of cells wide". The data for these characters were obtained using the *analySIS* software; its collection was described in the previous chapter whilst the compiled data for each species is given in Appendix Seven.

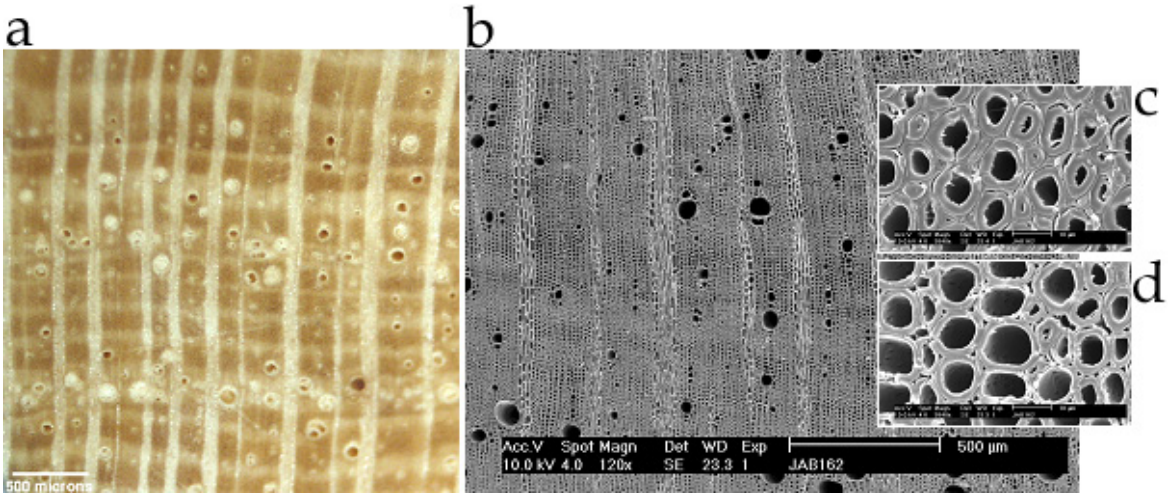


Figure 38 A: JAB132 *Capparis mitchellii* Endgrain image showing pale bands of thin-walled fibres that may be mistaken for regularly-spaced bands of parenchyma (Scale = 500 µm). B: JAB162 *Capparis loranthifolia* SEM image showing bands of thin-walled fibres (scale bar is 500 µm) and (C) thick-walled fibres (scale bar is 10 µm) and (D) thin-walled fibres (Scale = 10 µm).

Numeric characters are dealt with in one of two ways in the key. Where they consist of a single state, each taxon has been scored using a range of measurements; that is, a minimum value and a maximum value. In the case of the character "S Vessels, diameter" the entered range was the smallest diameter vessel (in µm) and the largest diameter vessel (in µm) in all the observations for a given taxon. For "S Rays, number of cells wide", the range was measured by the number of cells that occur across the widest part of a ray, and the smallest and largest values per species were entered.

Another approach to numeric characters is to construct arbitrary ranges to fit the data. For example, for the character "S Rays, number per mm", the states provided are "Rays, < 4 per mm", "Rays, 4-12 per mm" and "Rays, > 12 rays per mm". These arbitrary states are scored in the same manner as qualitative features with the most common state given a common score.

Use of explanatory factsheets

Lucid encourages explanation of characters and descriptions of taxa by supporting the attachment of images and the production of web pages (using HyperText Markup Language or HTML). In this identification tool, HTML factsheets were produced and attached to both the character states and the taxa. An example of each is shown in Figure 39.

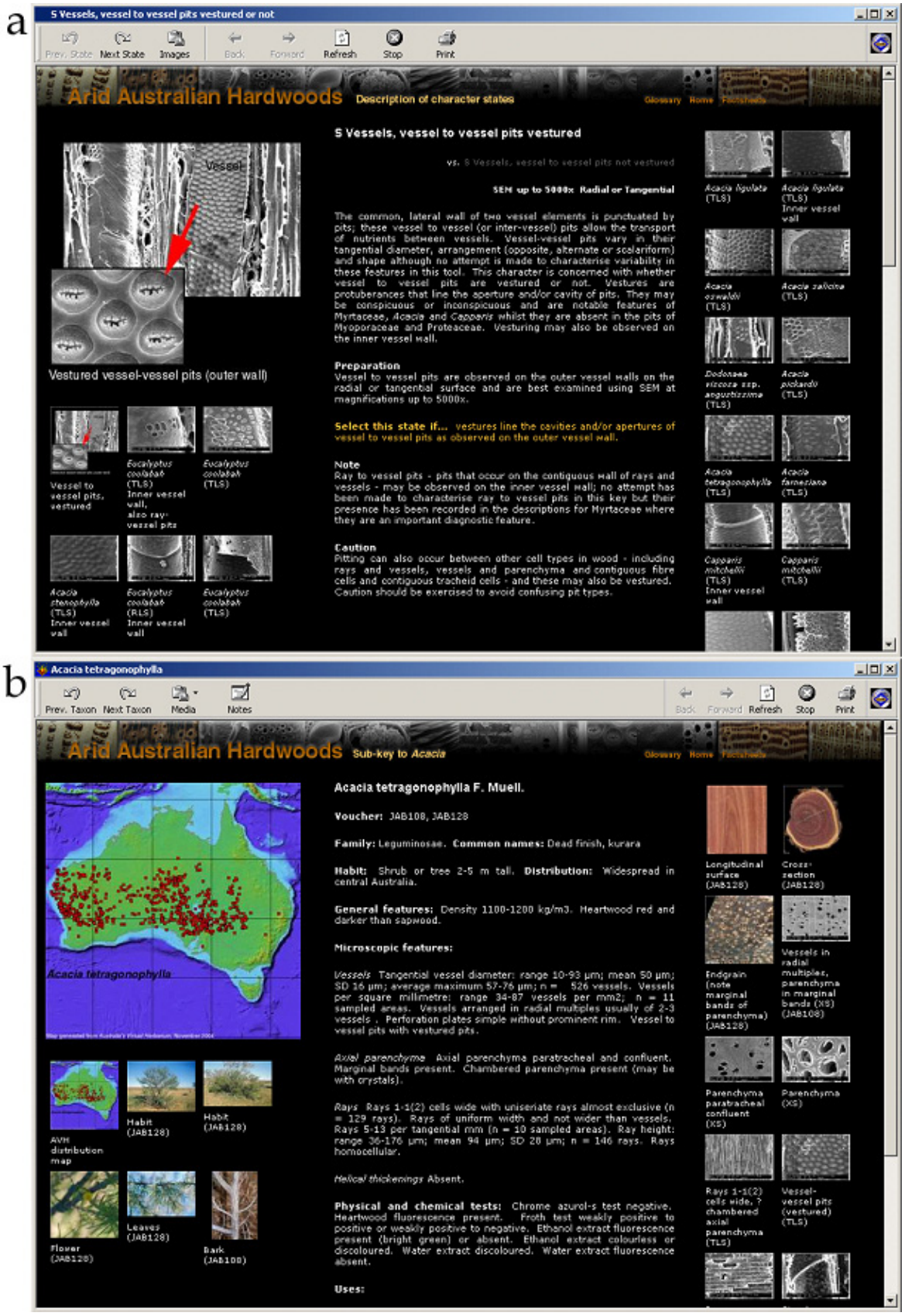


Figure 39 A: The explanatory factsheet for the character state "S Vessels, vessel to vessel pits vestured". B: The explanatory factsheet for *Acacia tetragonophylla*.

Character state factsheets

Character state factsheets provide information that defines what is meant by each character state with the use of both notes and images or diagrams. They are designed to guide the choice of character states so that they replicate as closely as possible the methods used to make the observations that built the identification tool. This explanatory information can reduce the subjectivity inherent in the identification process.Character state factsheets are comprised of thumbnail images which exemplify a particular character state; for example, anatomical characters that require SEM analysis are illustrated with SEM images, whilst characters assessed on the endgrain are illustrated with images of the polished endgrain. These thumbnail images can be projected at increased dimensions in the main image window, or by hyperlinking to the original size image. In addition to a description of the character state, the method of analysis, magnification and the surface of the wood required for assessment of each character are recommended e.g. “SEM Up to 5000x Radial or Tangential”. The alternative character state(s) has been hyperlinked so that states can be switched between.

Taxa factsheets

Taxa factsheets describe the taxa using notes and images or diagrams. Images include sanded cross-sections, photographs of the sanded longitudinal surface, endgrain and SEM micrographs of the wood surface that illustrate important diagnostic characters, and photographs of the plant habit and major botanical features. A distribution map from *Australia’s Virtual Herbarium* (CHAH November 2004)is also included. Each of these images is produced as a thumbnail image which may be projected to a larger size in the main image window. Alternatively, each of the thumbnails is hyperlinked so that an even larger image can be examined. The description includes details of the taxonomic features that characterise the wood as well as other information such as the voucher specimen/wood specimen number(s) from which data were collected, family name, common names, habit, distribution and European and Aboriginal uses of the wood (where applicable).

Introducing two new numerical characters for wood identification

Two numerical characters – “S Vessels, difference in diameters” and “S Rays, difference in heights” – were introduced to the identification tool. To my knowledge, these characters have not been used previously as an aid in wood identification. Both characters were

introduced in an attempt to resolve an inherent weakness in the numerical characters "S Vessels, diameter" and "S Rays, height" which use the range – the minimum and maximum vessel diameter (or ray height) – to select against the tool. Unfortunately, however, most of the treated wood species' vessel diameters (and ray heights) overlap which reduces the ability of the key to truly reflect variation in the characters between species. The following example comes from the *Sub-key to a Selection of Arid Australian Hardwoods*; it uses vessel diameter data but it is equally applicable to data collected for ray height.

Taxa	**Vessels, diameter (minimum & maximum)**
Myoporaceae (*Eremophila* & *Myoporum*)	10-66 µm
Acacia	10-171 µm
Myrtaceae B (*Corymbia*)	20-141 µm

This example indicates some diversity in vessel diameter amongst the three taxa. The Myoporaceae taxa are the least variable in size whilst the *Acacia* taxa cover the widest range of vessel diameters. The smallest vessel size in Myrtaceae B is 10 µm larger than either *Acacia* or Myoporaceae and the diameters are less variable than *Acacia* but more variable than Myoporaceae. All the taxa incorporate vessels in the range of 20-66 µm. Indeed, many wood taxa present with vessels of these diameters. As a result, and despite the indication of diversity in vessel diameter, the three taxa will not separate if a range is entered that incorporates a minimum and/or maximum value that falls within the 20-66 µm range. In fact, when this range is entered into the developed identification tool none of the 20 taxa are separated. For example, at 13-32 µm, *Psydrax latifolia* has the smallest range of vessel diameters, yet if this range is entered into the tool none of the taxa will separate as it falls within a range shared by all the taxa; this action will not even result in the separation of *Acacia*, which has the widest range of vessel diameters.

To counter the weakness in "S Vessels, diameter", the character "S Vessels, difference in vessel diameters" was introduced. Rather than measuring the minimum and maximum size to which vessels develop within a taxon, this character provides a relative measure between taxa of the range of variability in tangential vessel diameter. For example, if the minimum vessel diameter of *Psydrax latifolia* is subtracted from the maximum vessel diameter, the

result is 19 µm. This indicates that the range of vessel diameter variation is low; for example, *Acacia* vessels vary by 146 µm. If this result is selected against the character "S Vessels, difference diameters", all taxa are eliminated except for Myoporaceae and *Anthobolus leptomerioides*, which also exhibit little variation in vessel diameter.

The character "S Vessels, difference in diameters" represents a powerful (and simple) adjunct to the character "S Vessels, diameter" and it has been similarly introduced as an added dimension to the measurement of ray height where conventional methods of adding a range do not adequately reflect the range of variation in ray height between taxa. In the case of ray height and vessel diameter, the two related characters utilise the same data – that is, the adjunct character has not required extra data collection – and users of the identification tool have been advised to use both characters for optimum performance and increased separation of species.

Discussion

In an identification tool that can best be described as a prototype, or proof of concept, it is reasonable to expect that there will be some caveats and limitations. This section discusses some of the issues confronted during the development of the identification tool. In particular, it raises the important question of how to treat in a key characters that are heartwood-dependent in the absence of heartwood, or where heartwood is not visually distinguishable from sapwood; the omission of certain characters; the degree to which intra-specific variation was addressed; and the extent to which the characters conform to the IAWA standard list of hardwood characters (Wheeler, Baas *et al.* 1989).

Assessing heartwood-dependent features

Some characters used in wood identification are assessed by examination of the heartwood. For this reason, a character set containing all the heartwood-dependent features was developed (Table 7).

To use heartwood-dependent characters one must be certain that heartwood is present and assessable. However, except where heartwood is stained a contrasting colour by stored extractives, it is not always possible to distinguish heartwood from sapwood or to determine its presence. Where a specimen presents with uniformly pale wood, unless one is familiar with the pale wood species, it is not possible to discount the possibility that

heartwood has not yet formed. When used for diagnostic purposes, the lack of distinction that can occur between heartwood and sapwood can complicate the treatment of the pale woods for heartwood-dependent characters: one must either confirm the lack of colour contrast or determine that heartwood has not yet developed. Ideally, this confirmation would be obtained by reference to other collections of the species or descriptions. However, this is not always possible and it would require the identification of the wood to be known. In addition, in the case of fragmented wood, the presence of heartwood or sapwood will usually be impossible to determine.

Table 7 Table showing list of characters and states within the set "Heartwood-dependent characters". Each of these characters also appears in the sets relating to diagnostic feature and identification method.

Character	States
SE Heartwood, vessels commonly with tyloses or not	Heartwood, vessels commonly with tyloses
	Heartwood, vessels not commonly with tyloses
P Heartwood, colour clearly distinct from sapwood colour or not	Heartwood, colour clearly distinct from sapwood colour
	Heartwood, colour not clearly distinct from sapwood colour
P Heartwood, odour distinctly evident from freshly cut wood or not	Heartwood, odour distinctly evident from freshly cut wood
	Heartwood, odour not distinctly evident from freshly cut wood
P Heartwood, colour purple or becoming purple or not	Heartwood, colour purple or becoming purple
	Heartwood, colour not purple
C Heartwood, froth test positive or negative	Heartwood, froth test positive
	Heartwood, froth test negative
C Heartwood, ethanol extract fluorescent or not	Heartwood, ethanol extract fluorescent
	Heartwood, ethanol extract not fluorescent
C Heartwood, water extract colourless or discoloured	Heartwood, water extract colourless
	Heartwood, water extract discoloured
C Heartwood, ethanol extract colourless or discoloured	Heartwood, ethanol extract colourless
	Heartwood, ethanol extract discoloured
PC Heartwood, fluorescent or not	Heartwood, fluorescent
	Heartwood, not fluorescent

Table 8 lists the specimens treated in this project with respect to whether heartwood is distinguishable from sapwood, indistinguishable from sapwood or where its development is uncertain. It is known from experience and other wood descriptions that a number of the pale wood species have uniformly coloured sapwood and heartwood; this includes *Flindersia* (JAB155), *Santalum* (JAB123), *Atalaya* (JAB127) and *Pittosporum* (JAB113) (Figure 40). It is also known that many species produce visibly distinguishable sapwood

and heartwood (Figure 41). However, there are several species with indeterminate heartwood development; these are presented in Figure 42. Whilst it is suspected that

Table 8 List of treated specimens indicating where heartwood is distinguishable from sapwood; where heartwood development is unclear; and where heartwood is indistinguishable from sapwood. Representative images are presented in Figures 40 - 42.

Heartwood distinguishable from sapwood	Specimens where heartwood development and distinction from sapwood is uncertain	Uniformly pale wood specimens where heartwood is indistinguishable from sapwood
Eucalyptus camaldulensis var. *obtusa*, JAB191	*Eremophila duttonii* JAB175	*Pittosporum angustifolium* JAB113
Eucalyptus coolabah, JAB100, 107, 133, 137	*Eremophila macgillivrayi* JAB140	*Santalum lanceolatum* JAB123
Eucalyptus ochrophloia, JAB161	*Eremophila polyclada* JAB181	*Atalaya hemiglauca* JAB127
Eucalyptus populnea, JAB159, 170	*Eremophila longifolia*, JAB106, 114	*Flindersia maculosa* JAB155
Eucalyptus thozetiana, JAB163	*Hakea eyreana* JAB139, 142	
Melaleuca glomerata, JAB189	*Capparis loranthifolia* JAB162, 172	
Melaleuca trichostachya, JAB144	*Capparis mitchellii* JAB132	
Corymbia aparerrinja, JAB157	*Psydrax latifolia* JAB153	
Corymbia terminalis, JAB143, 156, 160	*Schinus molle* JAB190	
Eremophila freelingii, JAB152	*Tamarix aphylla* JAB115	
Eremophila bignoniiflora, JAB129	*Anthobolus leptomerioides* JAB174	
Eremophila mitchellii JAB167	*Bauhinia gilva* JAB138	
Eremophila sturtii JAB168	*Casuarina pauper* JAB187	
Myoporum montanum, JAB101		
Grevillea striata, JAB124		
Grevillea juncifolia, JAB147		
Hakea leucoptera ssp. *leucoptera*, JAB112		
Acacia aneura var. *aneura* JAB121		
Acacia ?*aneura*. var. *intermedia* JAB177		
Acacia cambagei JAB169		
Acacia cana JAB178, 180		
Acacia cyperophylla var. *cyperophylla*, JAB136		
Acacia farnesiana, JAB130		
Acacia ligulata, JAB109		
Acacia ligulata ?intergrade with *A. bivenosa*, JAB150		
Acacia murrayana, JAB165, 186		
Acacia oswaldii, JAB111		
Acacia petraea, JAB164		
Acacia peuce, JAB126		
Acacia pickardii, JAB122		
Acacia salicina, JAB117		
Acacia stenophylla, JAB105		
Acacia tetragonophylla, JAB128		
Acacia victoriae ssp. *victoriae*, JAB135		
Acacia stowardii, JAB151, 158		
Ventilago viminalis JAB166		
Owenia acidula JAB125		
Dodonaea viscosa ssp. *angustissima* JAB119, JAB184		
Senna artemisioides ssp. *filifolia* JAB183		

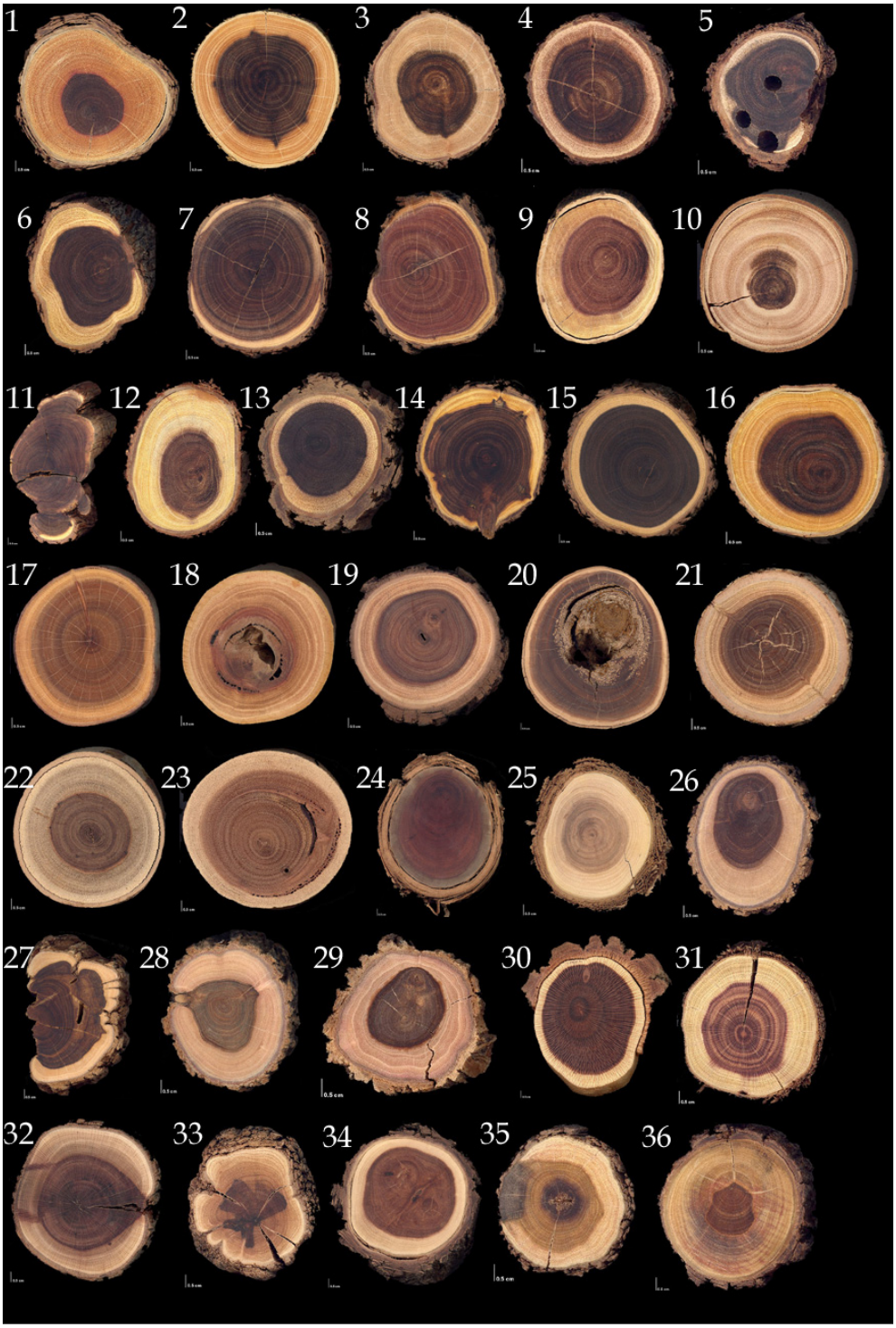


Figure 40 Treated specimens where heartwood is visibly distinguishable from sapwood. 1. JAB126 *Acacia peuce*; 2. JAB136 A. *cyperophylla*; 3. JAB135 A. *victoriae* ssp. *victoriae*; 4. JAB109 A. *ligulata*; 5. JAB111 A. *oswaldii*; 6. JAB122 A. *pickardii*; 7. JAB121 A. *aneura*; 8. JAB128 A. *tetragonophylla*; 9. JAB136 A. *farnesiana*; 10. JAB117 A. *salicina*; 11. JAB151 A. *stowardii*; 12. JAB105 A. *stenophylla*; 13. JAB180 A. *cana*; 14. JAB164 A. *petraea*; 15. JAB169 A. *cambagei*; 16. JAB186 A. *murrayana*; 17. JAB163 *Eucalyptus thozetiana*; 18. JAB191 *Eucalyptus camaldulensis*; 19. JAB137 E. *coolabah*; 20. JAB161 E. *ochrophloia*; (cont. over)

… 21. JAB170 E. *populnea*; 22. JAB157 *Corymbia apparerinja*; 23. JAB156 C. *terminalis*; 24. JAB144 *Melaleuca trichostachya*; 25. JAB189 M. *glomerata*; 26. JAB167 *Eremophila sturtii*; 27. JAB152 E. *freelingii*; 28. JAB129 E. *bignoniiflora*; 29. JAB101 *Myoporum montanum*; 30. JAB124 *Grevillea striata*; 31. JAB147 G. *juncifolia*; 32. JAB112 *Hakea leucoptera* ssp. *leucoptera*; 33. JAB119 *Dodonaea viscosa* ssp. *angustissima*; 34. JAB125 *Owenia acidula*; 35. JAB183 *Senna artemisioides* ssp. *artemisioides*; 36. JAB166 *Ventilago viminalis*. Scale is 0.5 cm.

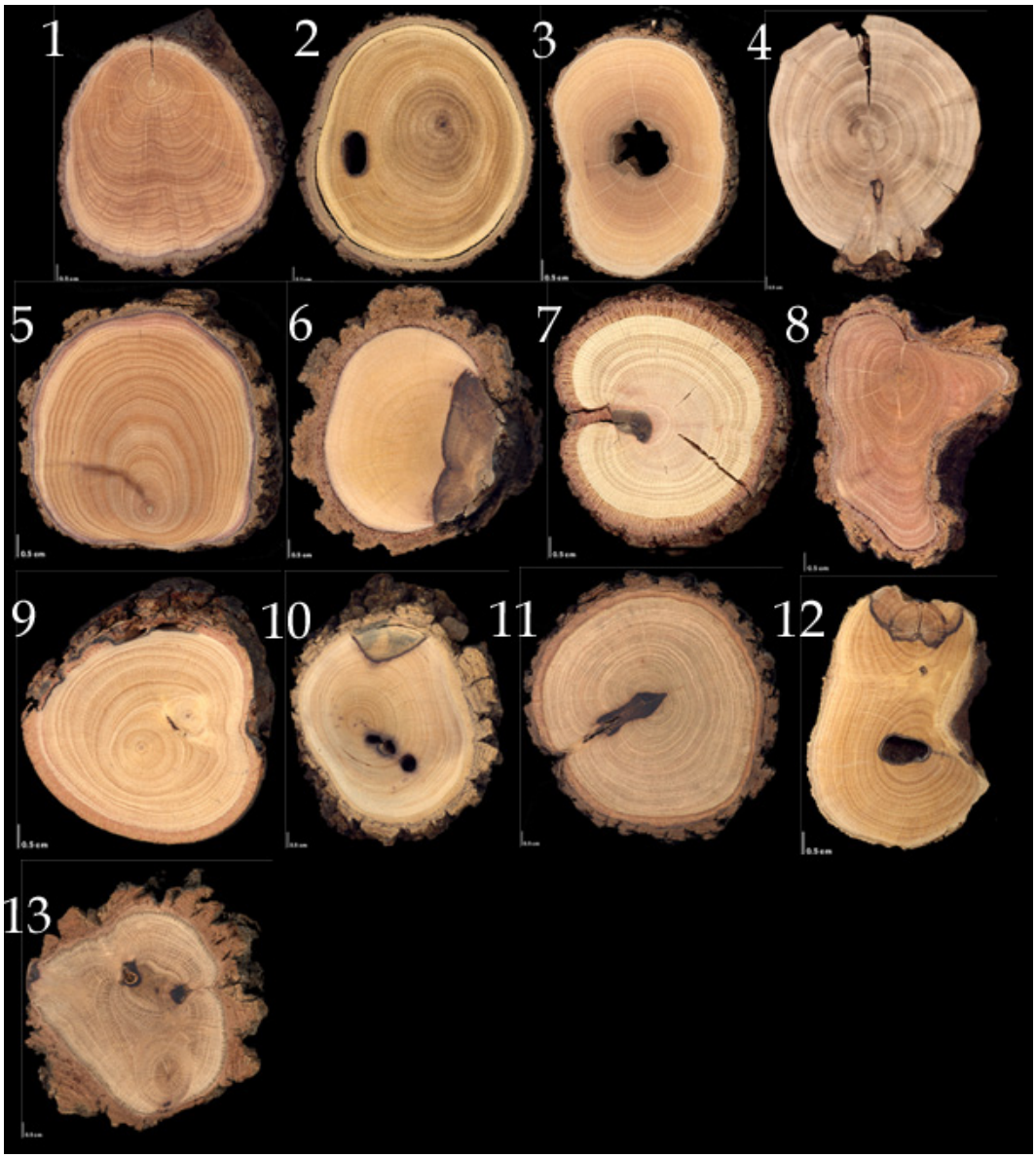


Figure 41 Specimens with pale wood where heartwood development is indiscernible. 1. JAB153 *Psydrax latifolia*; 2. JAB187 *Casuarina pauper*; 3. JAB140 *Eremophila macgillivrayi*; 4. JAB190 *Schinus molle*; 5. JAB181 E. *polyclada*; 6. JAB175 E. *duttonii*; 7. JAB115 *Tamarix aphylla*; 8. JAB106/114 *Eremophila longifolia*; 9. JAB162 *Capparis loranthifolia*; 10. JAB132 C. *mitchellii*; 11. JAB138 *Bauhinia* gilvum; 12. JAB174 *Anthobolus leptomerioides*; 13. JAB139 *Hakea eyreana*. (Scale is 0.5 cm).

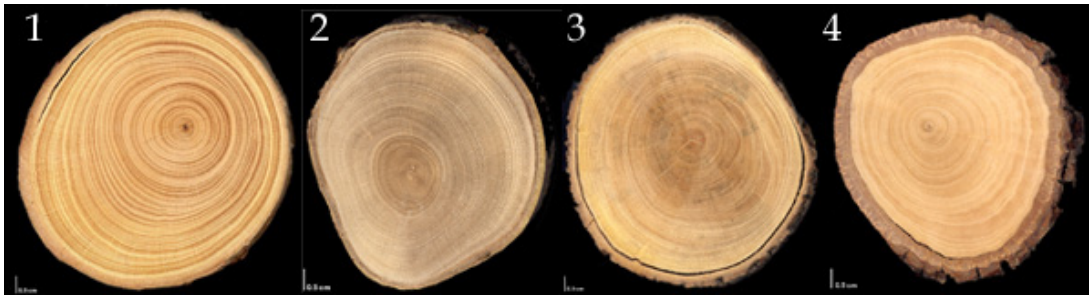


Figure 42 Specimens with uniformly coloured heartwood and sapwood. These specimens are known to produce a visually indiscernible heartwood. 1. JAB155 *Flindersia maculosa*; 2. JAB113 *Pittosporum angustifolium*; 3. JAB127 *Atalaya hemiglauca*; 4. JAB123 *Santalum lanceolatum*. (Scale is 0.5 cm).

Capparis (JAB162/JAB172, JAB132), S*chinus* (JAB190) and *Tamarix* (JAB115) have uniformly pale wood this was not corroborated; conversely, several *Eremophila* species (JAB175, JAB140, JAB181, JAB114/JAB106) and *Hakea eyreana* (JAB139/JAB140) presented with pale wood when it is likely that they had not developed the darker heartwood characteristic of other *Eremophila* and Proteaceae species. As a result, along with *Psydrax* (JAB153), *Casuarina* (JAB187), *Bauhinia* (JAB138) and *Anthobolus* (JAB174), where uncertainty as to heartwood development existed, each of these taxa needed to be treated carefully when scoring for heartwood-dependent features.

For the taxa where heartwood development was indiscernible all heartwood-dependent character states for each of the heartwood-dependent characters were given an uncertain score. Unfortunately, the necessary caution employed in the scoring of heartwood-dependent features in the *Sub-key to a Selection of Arid Australian Hardwoods*[47] has greatly reduced the effectiveness of the identification tool: the uncertain taxa will be retained regardless of which states are chosen. For example, only seven of the taxa genuinely presented with distinct heartwood. However, only the four genuinely pale wood species will be eliminated if the user selects the state "Heartwood, colour clearly distinct from sapwood colour", reducing the taxa from 20 to 16. If the negative state is chosen – and users are advised to select this state with caution – 13 taxa remain. Similarly, the efficacy of the tool is reduced in separating *Acacia* based on its fluorescent heartwood, Myrtaceae (*Eucalyptus, Melaleuca* and *Corymbia*) on the basis of tyloses present in its

[47] Many of the heartwood-dependent characters were redundant in the six sub-keys attached to *Sub-key to a Selection of Arid Australian Hardwoods* – that is, all the character states applied to none of the taxa or all of the taxa.

heartwood and Myoporaceae (*Eremophila* and *Myoporum*) with its distinctly lemon-scented heartwood.

Recording extra data in descriptions

Rather than devising characters for the key, several characteristics were recorded in the factsheets attached to the taxa. As the ensuing discussion reveals, this was generally employed as a cautionary approach and a means of describing features that may be subjective.

Heartwood colour

Heartwood colour could only be accurately surmised from specimens where there was a distinct colour difference between the sapwood and heartwood. Where heartwood was apparent, the common heartwood shades of red and brown (two of the categories used by the IAWA to differentiate heartwood colour (Wheeler, Baas *et al.* 1989: 323)) can be difficult to clearly differentiate. The subjective nature of attempts to categorise heartwood colour are compounded by the potential for intra-specific variation. Accordingly, heartwood colour shades are only included in the taxa descriptions, whilst any distinctive and characteristic heartwood colours were recorded (e.g. the purple heartwood of *Acacia peuce*) for inclusion as a separate character in the key.[48]

Heartwood odour

The subjectivity and unreliability of the human olfactory sense (Wheeler, Baas *et al.* 1989: 325) meant that classifications of scents were not appropriate for inclusion as characters in the identification tool. For this reason, attempts to classify scent were recorded only in the descriptions.

Gums and mineral inclusions in heartwood vessels

Like tyloses, the presence of deposits such as gum and mineral inclusions is assessed on the heartwood. A combination of time constraints, lack of knowledge of the deposit

[48] Using this character alone *Acacia peuce* may still be confused with *Acacia carneorum*, another arid Australian *Acacia* with purple heartwood (not treated in this research).

compositions, and the difficulty of assessing specimens where heartwood development was unclear meant that their presence was recorded in the descriptions attached to the taxa.

Density measurements

In the previous chapter it was recorded that the densities of the rectangular vouchered wood samples were roughly measured to inform the subsequent methods used to process the wood for anatomical examination. This implies variability in wood density that may be useful as a diagnostic tool. Globally, wood densities range from 160 kg/m^3 when dry, as with the lightweight, South American hardwood Balsa (*Ochroma pyramidale*), up to 1000-1400 kg/m^3 when dry, as with many arid Australian species. With some exceptions, particularly amongst the tropical woods, most common and commercial woods of the world fall within a density range of 300 kg/m^3 to 900 kg/m^3 when dry. In this research, the wood is generally much heavier with wide density parameters of between approximately 800 kg/m^3 and 1400 kg/m^3 when dry.

Unfortunately, however, the density of wood of a single species can also vary within a tree, between trees and between environments. Density measurements within temperate wood species may fluctuate around +/- 50 kg/m^3, a small enough margin for the character to provide some diagnostic use – although tropical woods can be more variable (Hoadley 1990: 47). In arid Australia, where growing and climatic conditions lack the stability of temperate zones, it is likely that density might also fluctuate widely. Accordingly, whilst density can remain reasonably constant within a given species, fluctuations that may occur reduce the reliability of density as a diagnostic tool. Without further testing for *intra*-specific variation, relying on density for *inter*-specific separation is not recommended, except where the genus includes species with highly divergent density readings. Such diversity is more likely to occur at the family or generic level, so the reliability of density as a diagnostic character may be improved at these taxonomic levels. For this reason, the rough estimations of density described earlier in the chapter were retained and adapted into two broad character states that separate very heavy wood from very light wood: "P Density, very dense > 1000 kg/m^3" "P Density, dense to light < 1000 kg/m^3". The use of 1000 kg/m^3 as the delimiter – the density of water – also provides users with an alternative measure of density for larger specimens: if a specimen sinks in water it is greater than 1000 kg/m^3 and if it floats its density is less than 1000 kg/m^3.

Omitted characters

Whilst the identification tool is supported by 56 characters covering a variety of physical, chemical and anatomical attributes, it is not exhaustive. A few characters were assessed but removed after it was determined that they provided limited value for separating the treated taxa, whilst other well-known wood features were not assessed as a result of time constraints. The depth of knowledge of wood identification required to completely satisfy all the characters in the IAWA standard (Wheeler, Baas *et al.* 1989) was not possible to acquire in this space of time. Nevertheless, there are some notable omissions.

Porosity

In most wood identification tools for hardwoods a character pertaining to the porosity of growth rings is present. This is a character that may be assessed at low magnification by examination of the polished endgrain. It compares vessel size and arrangement in the earlywood and latewood. Wood that is diffuse-porous refers to vessels of a similar size that are dispersed evenly across the earlywood and latewood; ring-porous wood refers to wood which produces large vessels in the heartwood and small vessels in the latewood; whilst vessels in semi-ring porous wood gradually decline in size from the earlywood to the latewood (Wheeler, Baas *et al.* 1989: 236).

Earlywood and latewood are terms usually reserved for northern hemisphere species which experience a distinct wet season and dry season which is reflected in their growth rings. Most arid Australian species are slow-growing and yearly rainfall is minimal and sporadic; as a result growth rings tend to be narrow and earlywood and latewood do not tend to be distinguishable in wood from this region. For this reason the character was omitted from the identification tool as attempts to categorise vessel porosity across the treated taxa proved difficult. There are circumstances where vessel arrangement is notably different. However, these particular characteristics are not typically dealt with by characters pertaining to porosity. For example, both *Capparis* spp. and *Bauhinia* present vessels with two different diameter classes although their proximity within the growth ring indicates that they are not ring-porous. Another characteristic that may be seen as an indicator of wood porosity is the presence of tangential bands; this is characteristic of Proteaceae and is dealt with in the characters pertaining to vessel arrangement. In the standard list of

hardwood characters for identification (Wheeler, Baas *et al.* 1989) both features are treated separately from wood porosity and this has been adopted in the identification tool.

Perforation plates

Perforation plates occur at the end walls of two contiguous vessel elements and allow the vertical transport of substances through the xylem. The type of perforation – simple, scalariform, or reticulate – can be diagnostic (Wheeler, Baas *et al.* 1989: 246). However, amongst the treated taxa only simple perforation plates were present. The same findings were made in previous research on central Australian wood (Smith, Vellen *et al.* 1998: 10). Indeed, over 80% of the world's woods possess a simple perforation plate (Wheeler, Baas *et al.* 1989: 249). Nevertheless, it was discovered that the prominence of the simple perforation plate rim was strongly variable between taxa and a character reflecting this difference – "Vessels, simple perforation rim prominent (and often wide) or not" – was added to the SEM character set of the identification tool.

Chrome azurol-S test

A positive result from the chrome azurol-S test – or the test for the presence of aluminium in wood – is said to be the production of a "bright blue" colour at the point where the reagent contacts the wood (Kukachka and Miller 1980; Wheeler, Baas *et al.* 1989: 328). Highly positive wood – wood with high concentrations of aluminium – will react in minutes whilst others may take time to absorb and react to the reagent, particularly where only low concentrations of aluminium are present (Kukachka and Miller 1980: 328; Wheeler, Baas *et al.* 1989). It is further maintained that the test is consistent within genera, and that where inconsistencies within genera do occur they are the result of contamination by dirt or fungi (Kukachka and Miller 1980). In addition, previous research has indicated that positive results are limited to a small number of families and genera (Dyer 1988; Kukachka and Miller 1980); in one study of the wood of 179 native South African trees only one species tested positive (Dyer 1988).

Inadequate descriptions of positive specimens and what is meant by "bright blue" have meant that it was difficult to conclude with certainty that none of the treated taxa tested positive to the presence of aluminium. Nevertheless, the results of the South African study (Dyer 1988) and the assertion that the character is present in a limited amount of taxa, lend

support to the findings of this test as negative for the woods treated in this study. It remains unclear, however, why specimens from the supposedly positive family Proteaceae (Kukachka and Miller 1980) did not produce positive results. For these reasons the character was omitted from the identification tool; however, notes were added to the taxa descriptions.

Water extract fluorescence

Whilst the test was conducted, a character pertaining to the fluorescence of the water extract produced from heartwood shavings (presence or absence) was not added to the identification tool. The results of the test indicated that the diagnostic potential of this character in separating the treated species was almost nil with only very weak fluorescence possibly produced by *Senna* (JAB183) and *Atalaya* (JAB127). Several specimens that may have displayed a weak fluorescence had unclear heartwood development – *Hakea eyreana* (JAB142), *Psydrax* (JAB153), *Eremophila longifolia* (JAB114) and *Capparis mitchellii* (JAB132) – and, had the character been added to the identification tool, these would have been scored uncertain. Furthermore, in all cases the fluorescence was so weak that it was difficult to be sure of its presence, even compared to the control vial containing only water.

Burning splinter test

The burning splinter test is a simple observation that involves the assessment of the ash produced by a splinter that has been ignited with a match. According to the IAWA, assessment involves whether the splinter burns to charcoal, a partial ash or a full ash. If it burns to a full ash, then its colour may be assessed: the alternative states suggested are bright white, yellow-brown or any other colour. Apart from its use in CSIRO keys, use of the character has been limited and some previous research has indicated that it may be of limited value (Wheeler, Baas *et al.* 1989: 329).

Pits

Only two characters pertain to pits in the identification tool. Pits occur between contiguous wood cells to allow the passage of substances. Vessel to vessel pits (or inter-vessel pits) occur on the lateral walls of vessels allowing the lateral transport of substances between the cells (Figures 43 - 46). Ray-vessel pits are located on adjoining walls of ray cells and vessel elements and are often conspicuous in Myrtaceae (Figure 47). Vessel-

vessel pits may be alternate, opposite or elongated (scalariform). The size of alternate or opposite pits may also be diagnostic and may range from less than 4 µm to greater than 10 µm diameter (Wheeler, Baas *et al.* 1989: 250). Vessel-vessel pits may be vestured, a feature characteristic of several of the taxa treated in this research and dealt with in the character "S Vessels, vessel to vessel pits vestured or not" (Figure 48). Finally, fibres may also be characterised by pits along their radial or tangential walls and these may be bordered or simple pits. Myrtaceae fibres/tracheids, for example, are typified by conspicuous bordered pits (Figure 49); the character "S Fibres/tracheids, with numerous, distinctly bordered pits or not" was included in the tool largely to separate Myrtaceae from other taxa. The future addition to the identification tool of a character pertaining to vessel-vessel pit size would provide another valuable numeric character whilst qualitative characters pertaining to vessel-vessel pit arrangement and the presence or absence of ray-vessel pits would also be useful additions.

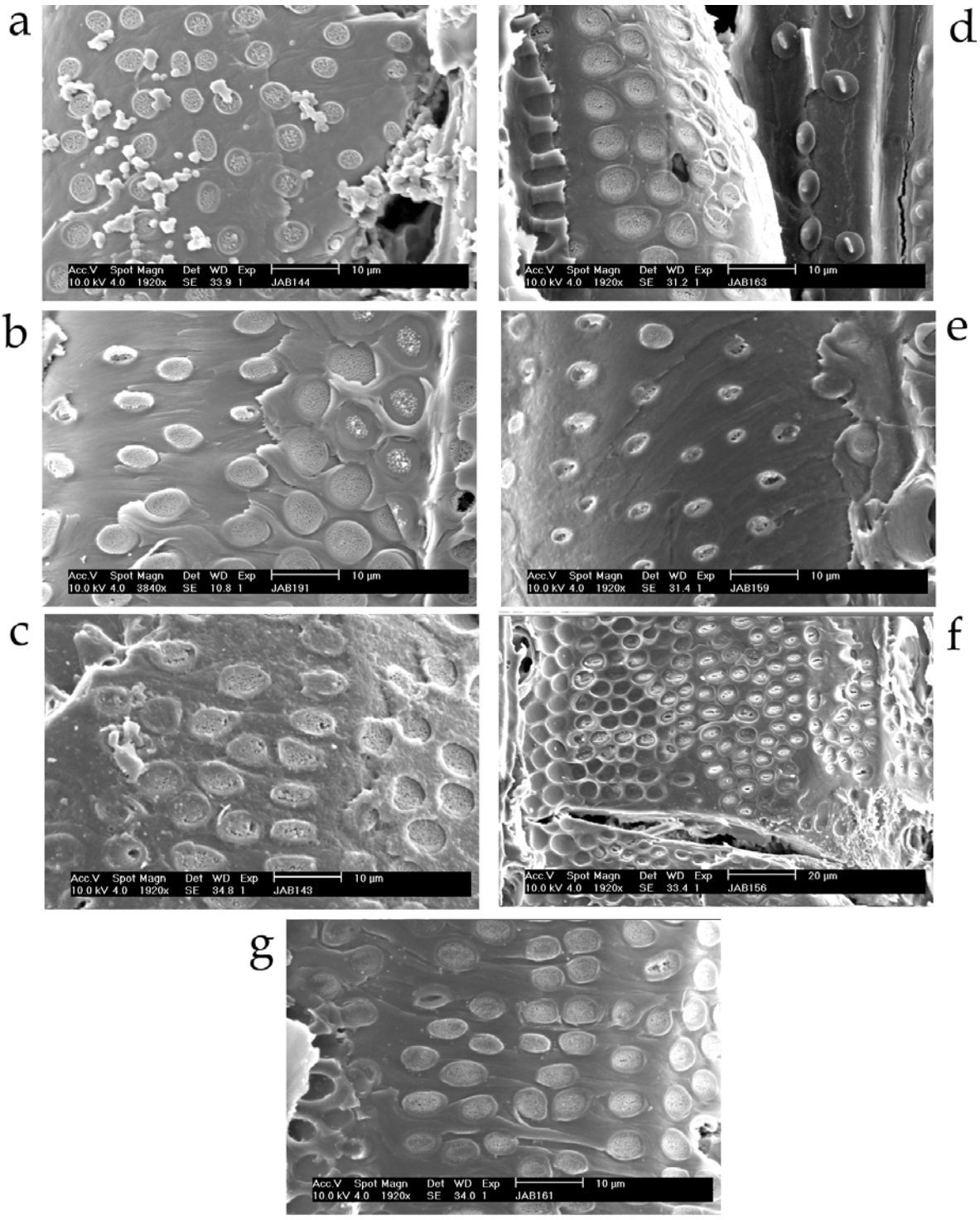


Figure 43 Vessel-vessel pits. Myrtaceae. TLS surface. A. JAB144 *Melaleuca trichostachya* (Scale = 10 µm); B JAB191 *Eucalyptus camaldulensis* (Scale = 10 µm); C: JAB143 *Corymbia terminalis* (Scale = 10 µm); D. JAB163 *Eucalyptus thozetiana* (Scale = 10 µm); E JAB159 *Eucalyptus populnea* (Scale = 10 µm); F:JAB156 *Corymbia terminalis* (Scale = 20 µm); G. JAB161 *Eucalyptus ochrophloia* (Scale = 10 µm).

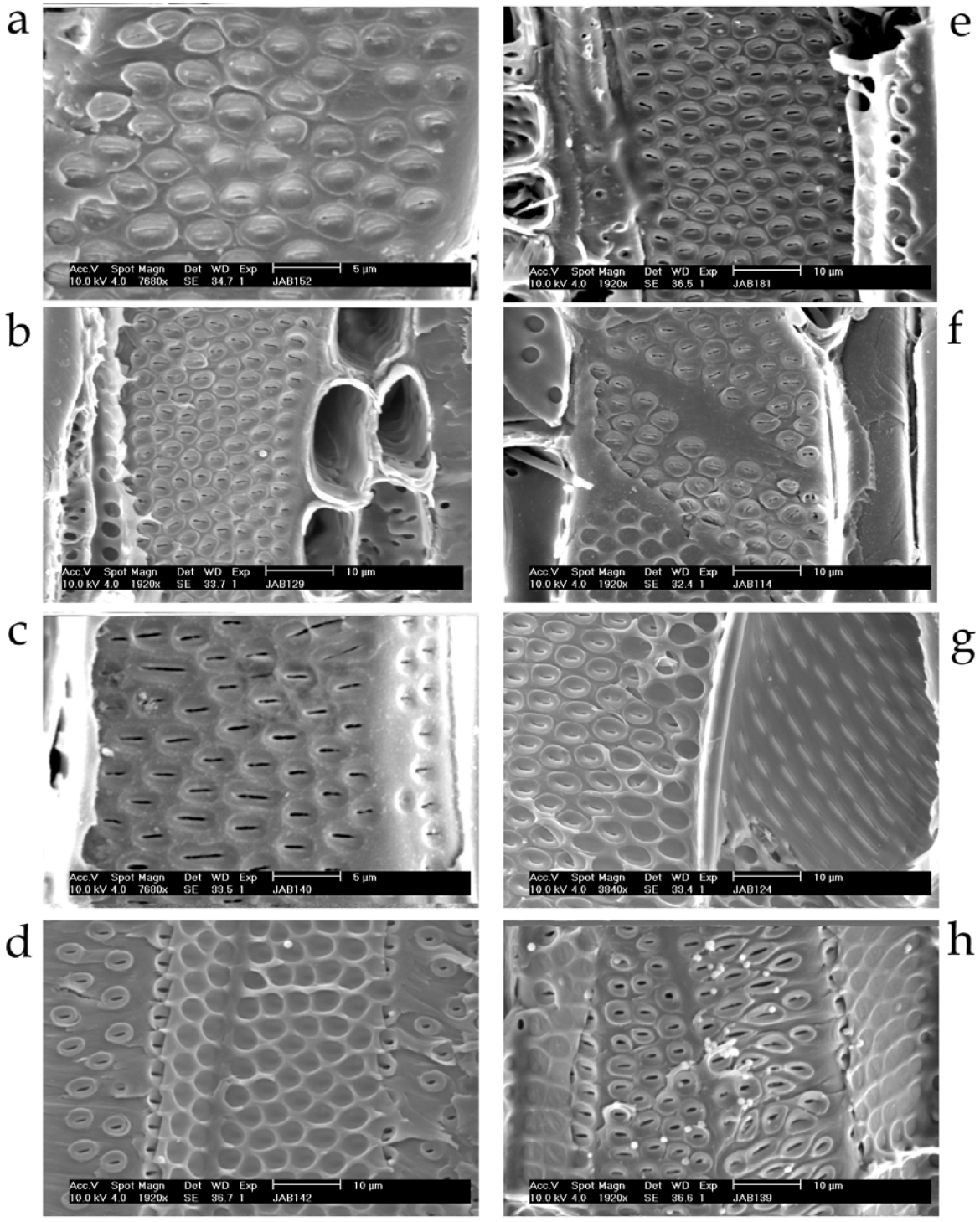


Figure 44 Vessel-vessel pits. Myoporaceae and Proteaceae. TLS surface. A. JAB152 *Eremophila freelingii* (Scale = 5 µm); B. JAB129 *E. bignoniiflora* (Scale = 10 µm); C. JAB140 *E. macgillivrayi* (Scale = 5 µm); D. JAB142 *Hakea eyreana* (Scale = 10 µm); E. JAB181 *E. polyclada* (Scale = 10 µm); F. JAB114 *E. longifolia* (Scale = 10 µm); G. JAB124 *Grevillea striata* (Scale = 10 µm); H. JAB139 *H.eyreana* (Scale = 10 µm).

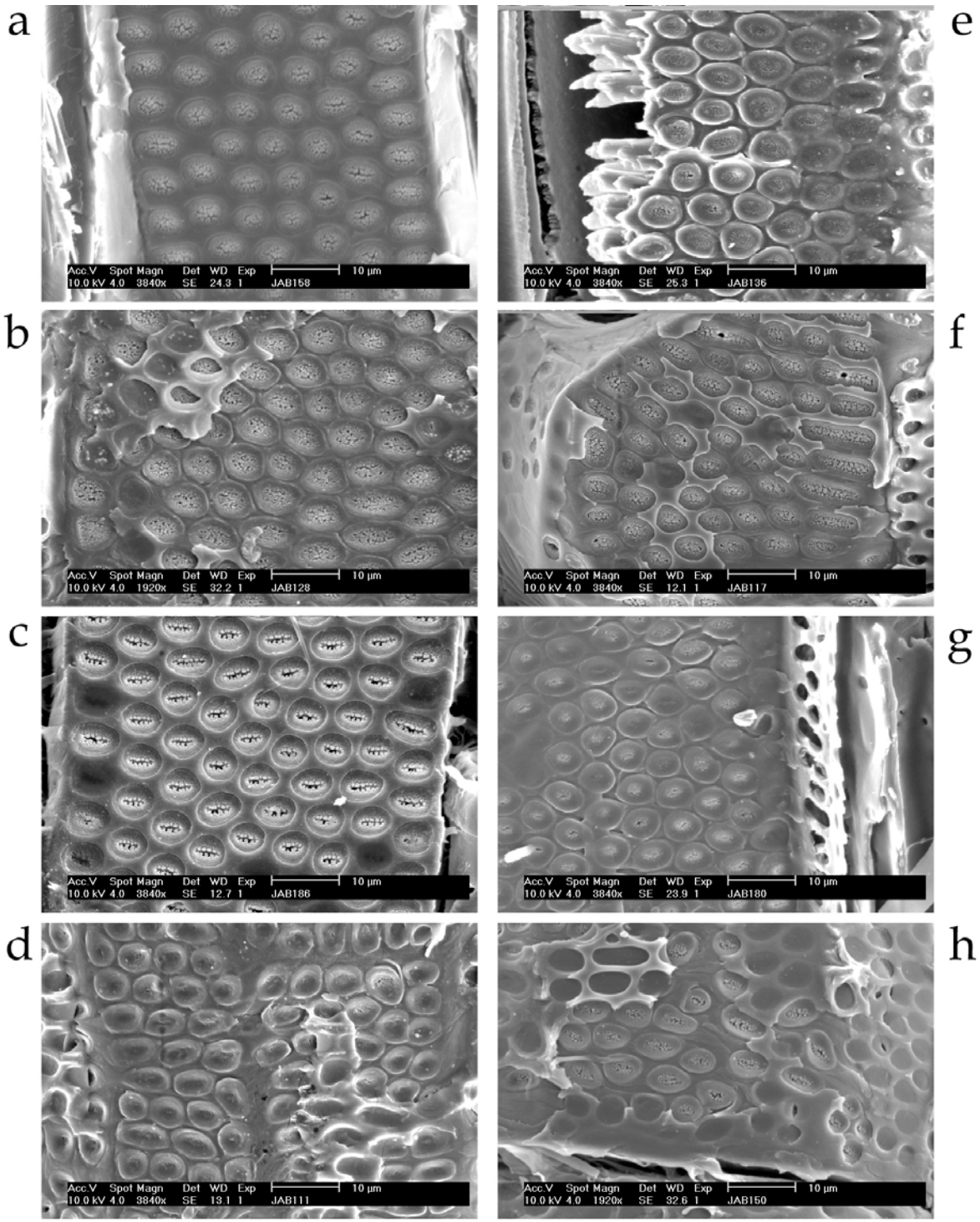


Figure 45 Vessel to vessel pits. *Acacia*. TLS surface. A. JAB158 *A. stowardii*; B. JAB128 *A. tetragonophylla*; C. JAB186 *A. murrayana*; D. JAB111 *A. oswaldii*; E. JAB136 *A. cyperophylla*; F. JAB117 *A. salicina*; G. JAB180 *A. cana*; H. JAB150 *A. ligulata* ?intergrade with *A. bivenosa.* (Scales = 10 µm)

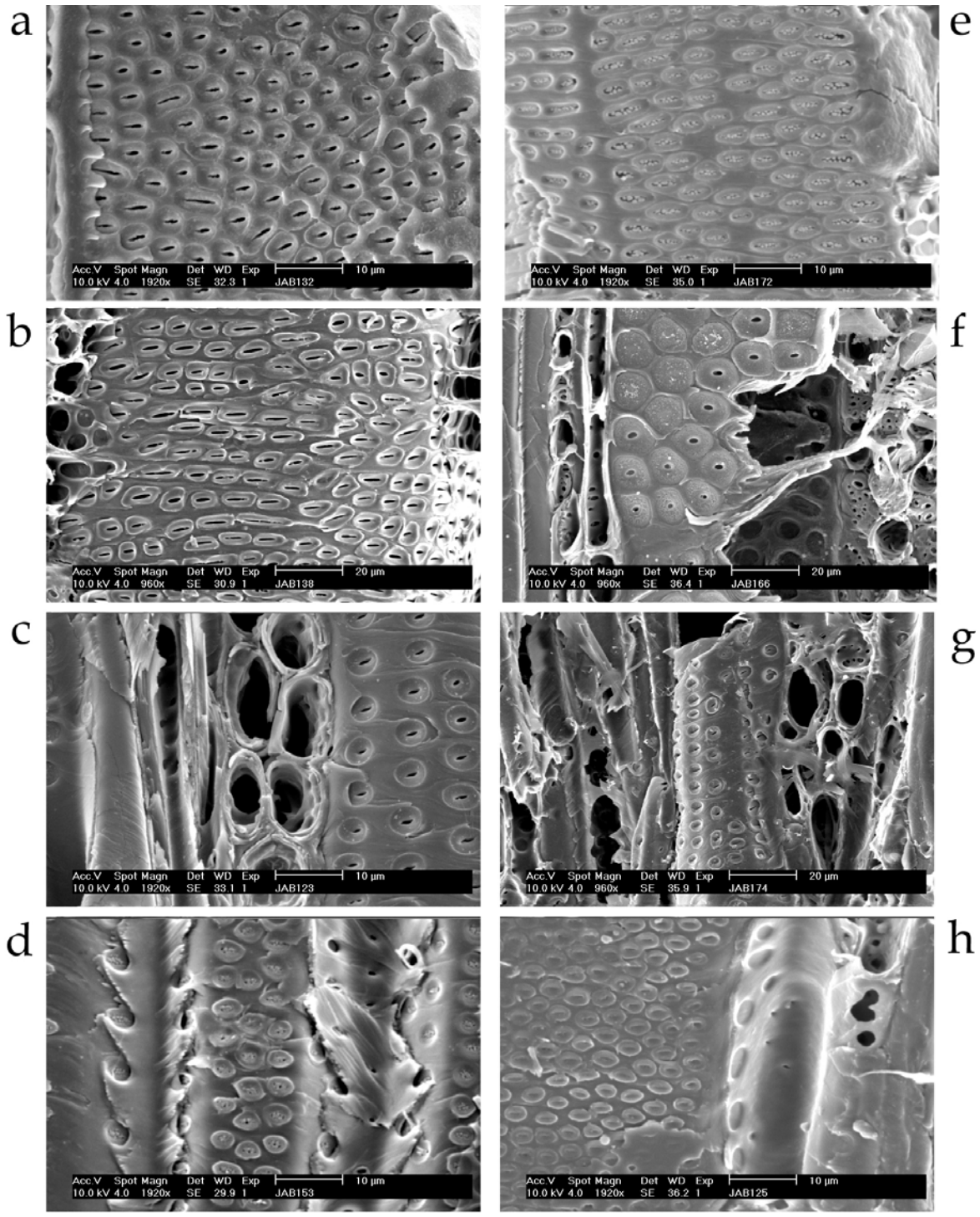


Figure 46 Vessel-vessel pits. TLS surface. A. JAB132 *Capparis mitchellii* (Scale = 10 µm); B. JAB138 *Bauhinia* gilvum (Scale = 20 µm); C. JAB123 *Santalum lanceolatum* (Scale = 10 µm); D. JAB153 *Psydrax latifolia* (Scale = 10 µm); E. JAB172 *Capparis loranthifolia* (Scale = 10 µm); F. JAB166 *Ventilago viminalis* (Scale = 20 µm); G. JAB174 *Anthobolus leptomerioides* (Scale = 20 µm); H. JAB125 *Owenia acidula* (Scale = 10 µm).

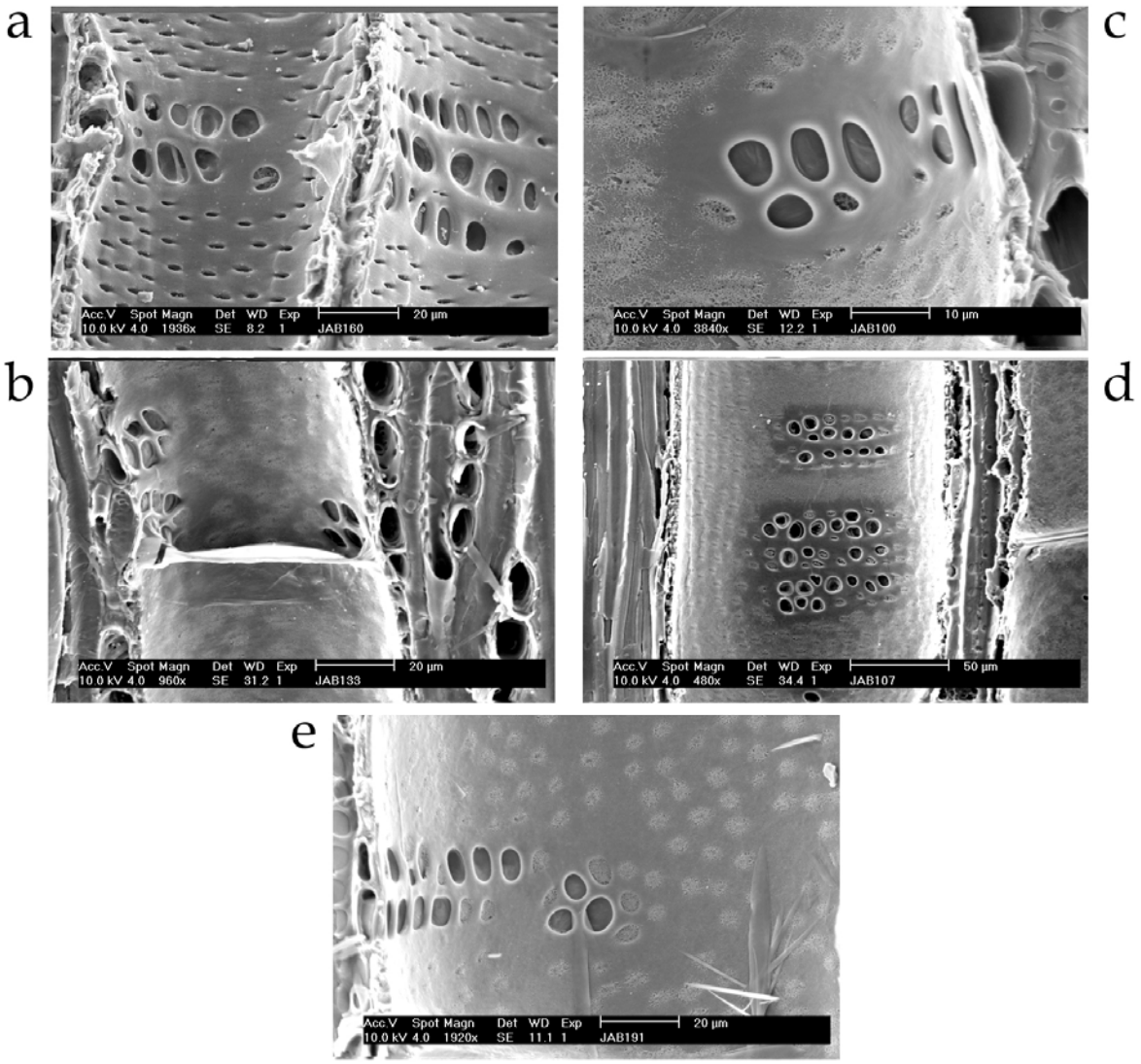


Figure 47 Ray-vessel pits. TLS surface. A. JAB160 *Corymbia terminalis* (Scale = 20 µm); B. JAB133 *Eucalyptus coolabah* (Scale = 20 µm); C. JAB100 *E. coolabah* (Scale = 10 µm); D. JAB107 E. *coolabah* (RLS) (Scale = 50 µm); E. JAB191 *E.s camaldulensis* (Scale = 20 µm).

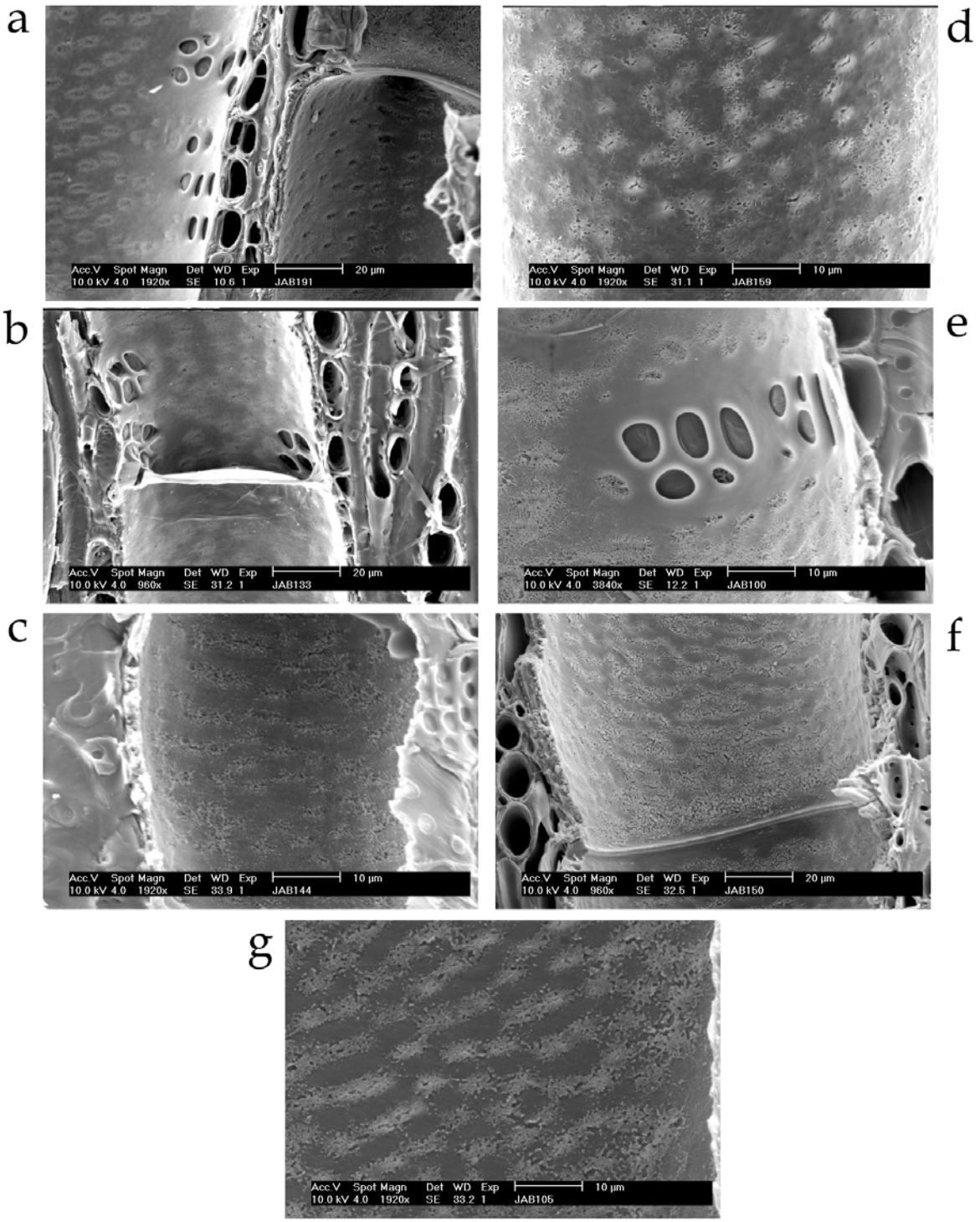


Figure 48 Vestured pits on vessel walls. TLS surface. A. JAB191 *Eucalyptus camaldulensis* (Scale = 20 µm); B. JAB133 *E. coolabah* (Scale = 20 µm); C. JAB144 *Melaleuca trichostachya* (Scale = 10 µm); D. JAB159 E. *populnea* (Scale = 10 µm); E. JAB100 E. *coolabah* (Scale = 10 µm); F. JAB150 *Acacia ligulata* ?intergrade with A. *bivenosa* (Scale = 20 µm); G. JAB105 A. *stenophylla* (Scale = 100 µm). (Note also the ray-vessel pits in A, B and E.)

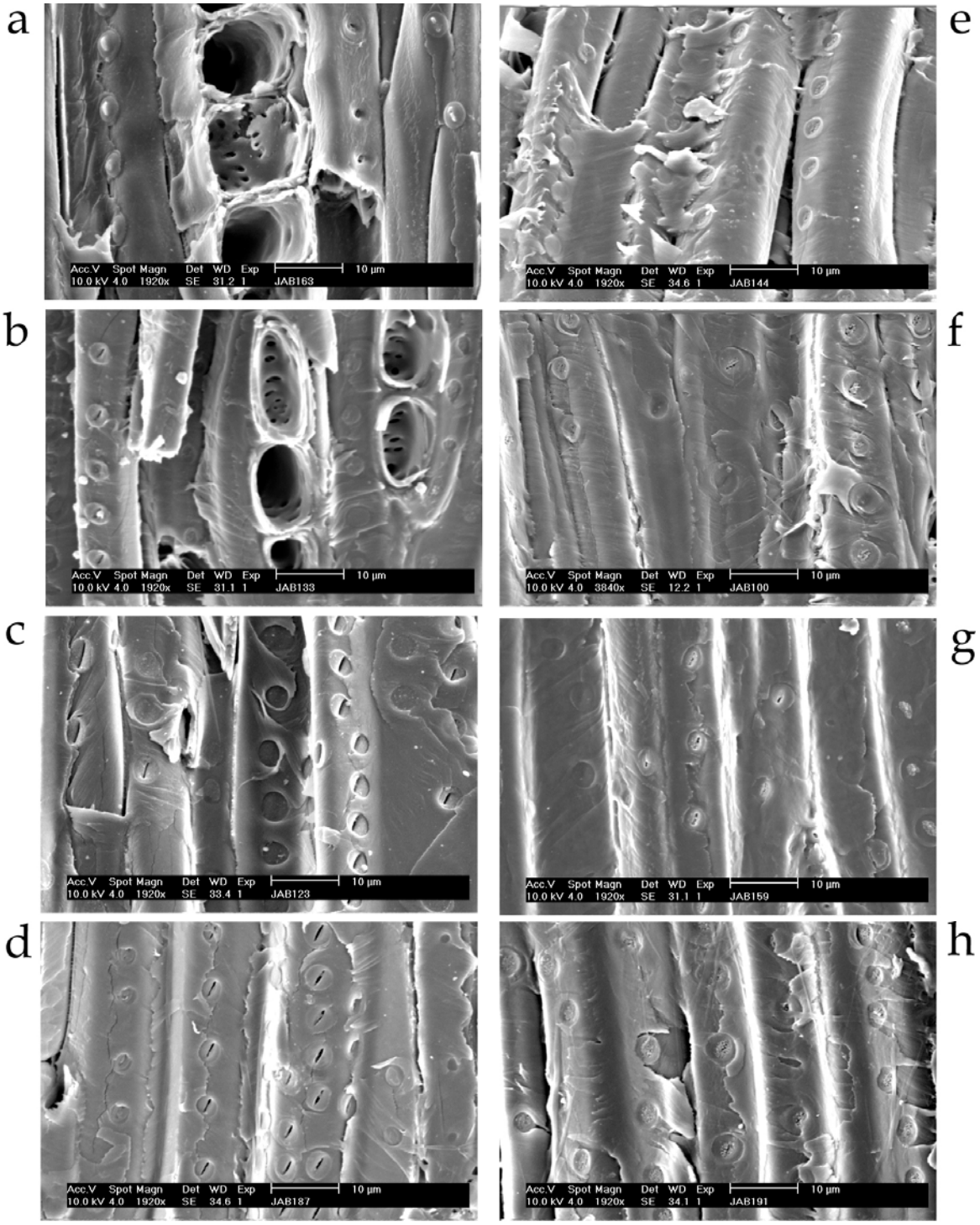


Figure 49 Bordered pits on fibre tracheids. TLS surface. A. JAB163 *Eucalyptus thozetiana*; B. JAB133 *E. coolabah*; C: JAB123 *Santalum lanceolatum*; D. JAB187 *Casuarina pauper* (RLS surface); E. JAB144 *Melaleuca trichostachya* (RLS surface); F. JAB100 *E. coolabah*; G. JAB159 *E. populnea*; H. JAB191 *E. camaldulensis* (RLS surface). (Scales = 10 µm)

Accounting for intra-specific variation

The extent to which an identification key accounts for intra-specific variation is an important indicator of its veracity. However, where research is confined by time restrictions, adequately accounting for intra-specific variation – with the treatment of several specimens per taxon – may result in the treatment of fewer species. This research has attempted to address this issue by striking a balance between these two considerations. As a result, the majority of species in the key are represented by a single specimen. However, 10 species were represented by between two and four specimens collected from separate trees: *Acacia cana* (JAB178, JAB180), *Acacia murrayana* (JAB165, JAB186), *Acacia stowardii* (JAB151, JAB158), *Capparis loranthifolia* (JAB162, JAB172), *Corymbia terminalis* (JAB143, JAB156, JAB160), *Dodonaea viscosa* ssp. *angustissima* (JAB119, JAB184), *Eremophila longifolia* (JAB106, JAB114), *Eucalyptus coolabah* (JAB100, JAB107, JAB133, JAB137), *Eucalyptus populnea* (JAB159, JAB170) and *Hakea eyreana* (JAB139, JAB142). Scoring of these species was based on data collected from each specimen, and indications of inter- and intra-specific variation in terms of the treated numerical characters are given in Chapter Ten. However, the testing of limited samples has meant that it is important that future expansion of the identification tool includes the treatment of additional specimens for each species. In addition, whilst the identification tool is presently based only on limbwood, it may be expanded to include the wood from different plant parts (e.g. rootwood and trunkwood). Until each taxon is represented by a sufficient number of specimens, the keys must be used with caution. Nevertheless, the study provides a powerful prototype database system upon which to add additional data and develop future research.

Conformity of characters with IAWA standard list of hardwood characters

The characters employed in the identification tool were adapted from several publications, including the IAWA standard list of characters for hardwood identification (Hoadley 1990; Ilic 1987; Ilic 1990; Wheeler, Baas *et al.* 1989). With only minor adaptations and the addition of a couple of extra characters, all the chemical and physical observations – including those that were heartwood-dependent – were adopted from the standard. The SEM and endgrain characters have not always retained the structure or wording of the IAWA standard but they are easily substituted. For example, in the standard, variation in

ray height is limited to whether rays are greater than 1 mm or not (Wheeler, Baas *et al.* 1989: 284); in this research, the ray height characters are considerably more powerful with the measurement and input of the minimum and maximum ray heights for each taxon.

Conclusions

This chapter has outlined the construction of a prototype identification tool to a selection of arid Australian wood taxa and introduced the Lucid software. The identification tool is comprised of a set of hierarchical keys; at its foundation is a key to the separation of hardwoods and softwoods whilst attached sub-keys reflect taxonomic levels of family, genus and species. Character sets reflect the fact that the amount of material available for wood identification, as well as the available methods, can be variable. In this way, the tool has been developed so that it is sympathetic to the identification of fragmented wood. However, it also recognises that sophisticated, microscopic analyses which require the removal of a splinter from a wider matrix may not always be possible or, indeed, desirable. For this reason, the provision of a set of endgrain characters is invaluable since this method of wood identification is relatively simple and accessible and damage can be limited to a small polished section of the endgrain. In addition, the transverse surface is highly diagnostic and identification may often be possible to genus.

Chapter Nine. Testing the Key to a Selection of Arid Australian Hardwoods & Softwoods

Introduction

This chapter presents the outcomes of tests of the *Key to a Selection of Arid Australian Hardwoods & Softwoods.* It is divided into two sections. To test the robustness of the data set upon which the tool is presently based, and the ability to elicit correct identifications at each level of the hierarchical key, tests were conducted using 10 unknown wood specimens from the region of study. To test the operation, accessibility and functionality of the identification tool, the trial was repeated by a plant taxonomist with limited knowledge of wood anatomy. For both tests, the limited data set upon which the tool is presently based and the potential for its future expansion should be borne in mind.

Test of identification tool using 10 unknown specimens

The identification tool was applied to 10 wood specimens of unknown identification collected during the field trip to north-east South Australia, south-west Queensland and far western New South Wales. The purpose of the test was to investigate if the wood could be correctly identified using the nested keys that comprise the tool and what level of identification could be achieved using each of the character sets independently. This would provide a measure of confidence for each of the hierarchical levels of the tool and each of the methods of identification. Of particular interest was to establish if the correct identification could be achieved at the species level as this would provide an important indicator of the extent of intra-specific variation within the treated wood species.

Methods

The following section outlines the preparations for this trial; the processes used to initially prepare the wood specimens for the collection of data; and the application of these data to the identification tool.

Selection of specimens

The 10 vouchered wood specimens tested against the identification tool were JAB171, JAB182, JAB179, JAB146, JAB176, JAB149, JAB118, JAB110, JAB102 and JAB108. These specimens were reserved at the time of collection, when field identifications

indicated that they may be from species for which there was at least one other collected specimen; associated herbarium vouchers were lodged in the *State Herbarium of South Australia* and identifications of this material were obtained only after the test of the wood was completed. Field data was deliberately avoided for these specimens so that their field identifications were long forgotten by the time these trials took place. Consequently, whilst it was known that any of the 10 specimens may have belonged to species already represented in the identification tool this was by no means certain.

Initial preparation of specimens

A colleague covered with masking tape the unique JAB specimen numbers marked upon each of the ten rectangular reference specimens. The masking tape was then relabelled with a letter from A to J. From one end of one of the rectangular reference specimens, a 1 cm^3 block was sawn and reserved for softening and microscopic, anatomical analysis. Each block was softened in 50% hydrofluoric acid for 24 hours followed by 3.5 hours in boiling water. After attempting to polish each of the endgrains it was determined that specimens A, B, D, E, F, I and J required further softening; these were returned to 50% hydrofluoric acid for a further 24 hours after which they were boiled in water for 2.5 hours.

Collection of data

The methods followed to prepare the wood for the collection of data from the endgrain and using scanning electron microscopy; for the collection of information on the physical and chemical properties of the wood; and for analysis of the numerical data using the software *analySIS* were the same as those employed for the specimens that comprise the identification tool (see Chapter Seven).

Application to the identification tool

Vessels were present in the wood of each of the 10 specimens – indicating all were hardwood species - so the identification process began with the major key: *Sub-key to a Selection of Arid Australian Hardwoods.* The four character sets relating to identification method – physical properties, chemical observations, endgrain and scanning electron microscopy (SEM) – were independently applied to the 10 specimens; between them, these character sets incorporate all of the characters treated in the identification tool. Character states that could not be answered with confidence were not selected.

Acquisition of herbarium identifications

Identification of botanical voucher specimens collected with the 10 wood specimens was conducted by plant taxonomists at the *State Herbarium of South Australia*. These identifications – and whether they matched the 10 wood identifications - were used to test the veracity of the tool.

Results

The results of the test of the identification tool are given in Appendix Eight. This includes plates of SEM and endgrain images depicting some of the salient wood anatomical features of each of the unknown specimens. Tabulated results of the application of the qualitative and quantitative data collected from specimens A to J to the identification tool are also presented. Each table lists the remaining taxa/taxon and includes lists of the selected character states after data from each specimen was independently tested against each of the character sets. Initially the major key - *Sub-Key to a Selection of Arid Australian Hardwoods* – which comprises 20 taxa, was used in an attempt to identify the specimens to family/genus. Where a single taxon resulted and a sub-key to species was attached this key was also trialled. Three sub-keys to species were tested as a result of these trials:

- Sub-key to Myrtaceae A (*Eucalyptus* & *Corymbia*): 7 taxa
- Sub-key to *Acacia*: 18 taxa[49]
- Sub-key to Proteaceae (*Grevillea* & *Hakea*): 4 taxa

Finally, the entire process was repeated with the selection of all the relevant character states from all the relevant character sets.

Discussion

Table 9 shows the professional identifications of the botanical voucher specimens associated with the wood samples A to J and the identifications obtained using the key. T The herbarium identifications indicate that nine of the specimens are examples of species

[49] There were 18 taxa represented within the *Sub-key to Acacia* at the time of the test; the 19th taxon was added to this key as a result of these analyses.

treated in the identification tool whilst the tenth – Acacia victoriae ssp. arida – is closely related to treated taxon Acacia victoriae ssp. victoriae. The results are discussed in terms of what they reveal about the usefulness of the four character sets/methods of identification and the capacity of the tool to successfully identify wood to family/genus and to species. A "successful" identification is one where a single remaining taxon in a key matches the voucher specimen identification.

Testing the major key - Sub-key to a Selection of Arid Australian Hardwoods - *by character set*

The application of specimens A to J to the Sub-key to a Selection of Arid Australian Hardwoods resulted in the successful identification to family/genus for each of the ten specimens. Whilst the future addition of new taxa and data to the identification tool will improve its accuracy, these results indicate that identifications to family/genus that draw from the existing data can be accepted with a reasonably high degree of confidence.

Using the physical and chemical character sets only

As expected, the efficacy of the character sets based upon chemical and physical observations was reduced by the treatment in the identification tool of specimens where heartwood is absent or indistinguishable from the sapwood - Anthobolus, Bauhinia, Capparis, Casuarina, Psydrax, Schinus and Tamarix. In the chemical observations set, where all of the characters are heartwood-dependent, these seven taxa were always retained amongst the remaining taxa. In the physical properties set, where half of the characters are heartwood-dependent, between two and six taxa were retained for each application. These results indicate that in the future, when the appearance of heartwood in these taxa can be established, the potential of these character sets will be increased.

Using the endgrain character set only

Applications to the endgrain set returned mixed results with between one and 15 taxa remaining. However, in all of the applications to the character sets where more than one taxon remained, the correct taxon was always retained. Specimens F and H were successfully identified as Proteaceae (Grevillea & Hakea) using the endgrain character set. Larger numbers of remaining taxa tended to occur where parenchyma or vessel arrangement was difficult to reliably assess e.g. specimens A, B and E.

Table 9 The identifications of the botanical voucher specimens associated with the wood samples A to J and the identifications obtained using the key.

ID	Family	Genus	Species	JAB specimen number	Example(s) originally treated in ID tool	Identification in key to family/genus using all character sets (remaining taxon)	Identification in key to species using all character sets (remaining taxon/taxa)
A	LEGUMINOSAE	*Acacia*	*aneura* var. *aneura*	171	121	*Acacia*	No remaining taxa
B	MYRTACEAE	*Eucalyptus*	*camaldulensis* var. *obtusa*	182	191	Myrtaceae A (*Eucalyptus* or *Melaleuca*)	*E. coolabah* *E. populnea*
C	CASUARINACEAE	*Casuarina*	*pauper*	179	187	*Casuarina*	na
D	MYRTACEAE	*Eucalyptus*	*camaldulensis* var. *obtusa*	146	191	Myrtaceae A (*Eucalyptus* or *Melaleuca*)	*E. coolabah* *E. populnea* *E. thozetiana*
E	MYRTACEAE	*Melaleuca*	*glomerata*	176	189	Myrtaceae A (*Eucalyptus* or *Melaleuca*)	Myrtaceae A (*Eucalyptus* or *Melaleuca*)
F	PROTEACEAE	*Grevillea*	*juncifolia*	149	147	Proteaceae (*Grevillea* & *Hakea*)	*Hakea eyreana*
G	LEGUMINOSAE	*Acacia*	*victoriae* ssp. *arida*	118		*Acacia*	No remaining taxa
H	PROTEACEAE	*Hakea*	*leucoptera* ssp. *leucoptera*	110	112	Proteaceae (*Grevillea* & *Hakea*)	G. *juncifolia* ssp. *juncifolia* G. *striata* *H. eyreana* *H. leucoptera* ssp. *leucoptera*
I	LEGUMINOSAE	*Acacia*	*stenophylla*	102	105	*Acacia*	?*A. aneura* var. *intermedia* *A. cana* *A. pickardii* *A. salcina*
J	LEGUMINOSAE	*Acacia*	*tetragonophylla*	108	128	*Acacia*	No remaining taxa

These results obscure the potential of the character set for where the vessel and parenchyma arrangements were assessable – e.g. specimens C, D, F, G, H and I - over three-quarters of the original taxa were eliminated. The addition of numerical characters for the assessment of vessel diameter and vessel number per square millimetre would further improve the efficacy of this character set.

Using the SEM character set only

The application of the data collected from specimen A to J to the SEM character set proved most useful, with each of the specimens successfully identified to family/genus. This provides a good measure of confidence in the qualitative and quantitative characters that make up this set and its capacity to return a single, correct taxon.

Using all the character sets

With the selection of all the relevant character states from each of the four sets, each of the 10 specimens keyed out to a single, correct taxon. This completed a wholly successful test of the *Sub-key to a Selection of Arid Australian Hardwoods* and established its potential to elicit correct identifications to the family/genus.

Testing the sub-keys to species by character set

With all of the specimens keying out to a single taxon in the *Sub-key to a Selection of Arid Australian Hardwoods*, there were nine opportunities to test the sub-keys to species[50]. This section discusses the outcomes of the identifications to species level and the application of the three tested sub-keys to species: Sub-key to Myrtaceae A (*Eucalyptus* & *Melaleuca*), Sub-key to *Acacia* and the Sub-key to Proteaceae (*Grevillea* & *Hakea*). The outcomes are first discussed in terms of the independent application of the endgrain and SEM character set. This is followed by a summary of the identifications obtained by selecting character states from all the character sets.

[50] The identification of specimen C as *Casuarina pauper* was merely an extrapolation from the Sub-key to a Selection of Arid Australian Hardwoods since this was the only species treated in *Casuarina*; this identification agreed with the herbarium voucher determination but it could easily have been *C. cristata* since this also occurs in northern New South Wales (where specimen C was collected); *C. cristata* was not treated in the identification tool.

Using the endgrain character set only

In the previous test specimens F and H – *Grevillea juncifolia* and *Hakea leucoptera* ssp. *leucoptera* - had been identified to Proteaceae (*Grevillea* & *Hakea*) using the endgrain set of the *Sub-key to a Selection of Arid Australian Hardwoods.* Accordingly, data collected from the endgrain of the two specimens were applied to the endgrain set of the *Sub-key to Proteaceae (Grevillea & Hakea).* However, most of the endgrain characters were redundant in this sub-key to species; that is, they describe all or none of the four treated taxa. As a result, and until such time as numerical characters are added to the endgrain set, the value of this character set to this sub-key is severely limited and the identification of the specimens was not advanced any further.

Using the SEM character set only

In the previous test, specimens A, B, D, E, F, G, H, I and J were identified to a single taxon using the SEM character set of the *Sub-key to a Selection of Arid Australian Hardwoods*. Each taxon that resulted was supported by a sub-key to species. In this test, selected SEM character states were applied to the SEM character set of the relevant sub-keys to species. The results are discussed here.

Whilst none of the wood specimens was accurately identified to a single species, in five cases – specimens B, D, F, H and J – the correct identifications were retained amongst the remaining taxa. The SEM character set also did not fare well in separating the Proteaceae taxa with only *Grevillea striata* eliminated for specimen F and none of the taxa eliminated for specimen H. This may be an indication of limited inter-generic diversity within Proteaceae wood.

In the case of specimens A, I and E – all correctly identified to family/genus in the *Sub-key to a Selection of Arid Australian Hardwoods* – the correct taxon was not retained amongst the remaining taxa in the applied sub-keys to species. These results are indicative of the limitations of these six sub-keys and the need to bolster the numerical characters with the treatment of more representatives from each species.

Specimen G was identified from the botanical voucher specimen as *Acacia victoriae* ssp. *arida*; this constituted the only taxon represented amongst specimens A-J that was not already included in the identification tool - although the closely related sub-species *Acacia*

victoriae ssp. *victoriae* is represented. Using the SEM character set of the *Sub-key to Acacia,* the specimen retained 12 of the 18 taxa treated in the tool including *Acacia victoriae* ssp. *victoriae.*

Using all the character sets

As Table 9 indicated, eight of the nine specimens tested against a sub-key to species belong to species represented in the tool. However, none of these specimens was successfully identified – that is, isolated to a single correct taxon – to the species level. Using the character states selected from all the character sets, specimens A and J did not fit any of the taxa in the *Sub-key to Acacia* whilst data collected from specimen I matched that of four incorrect *Acacia* species. For specimen G – the only taxon not represented in the tool - the *Sub-key to Acacia* eliminated all of the treated taxa. No taxa remained when specimen E was tested against the *Sub-key to Myrtaceae A (Eucalyptus & Melaleuca)* whilst specimens B and D were incorrectly identified as *Eucalyptus coolabah*, *E. populnea* or *E. thozetiana.* Using the *Sub-key to Proteaceae*, specimen F was identified as *Hakea eyreana* when it is in fact *Grevillea juncifolia* ssp. *juncifolia* whilst, for specimen H, none of the treated taxa was eliminated which meant the correct taxon – *Hakea leucoptera* ssp. *leucoptera* – was retained. Whilst these results indicate that the sub-keys to species are presently unreliable, the future augmentation of the data set upon which the keys are based may increase their accuracy and potential to elicit correct identifications.

Repeat of test by a novice user

The second half of this chapter reports on the outcomes of a test of the identification tool by a novice user - a plant taxonomist well acquainted with the production and use of *Lucid* tools but with only a very rudimentary knowledge of wood anatomy. This test utilised the same A-J specimens discussed in the first half of this chapter. The only important difference was that data collected from the 10 previously unknown specimens as a result of the initial test were added to the identification tool before the second test took place. This resulted in the addition of a single new taxon - *Acacia victoriae* ssp. *arida* – and an augmented data set for the nine species already represented in the identification tool. The descriptions contained within the factsheets attached to each taxon were also updated to incorporate the new data. With the addition of the new data, the taxonomist could potentially correctly identify all of

the specimens – to species level as well as to family/genus - or at least have the correct taxon present amongst the remaining taxa.

Methods

The user was asked to familiarise herself with the key structure and wood identification terminology using the electronic slide presentation attached to the identification tool. She was then asked to independently utilise the physical, chemical, endgrain and SEM character sets and, finally, to select all the relevant character states from each of the four character sets against the tool.

To avoid the re-collection of data, the endgrain and SEM character sets were tested using the same images previously collected from specimens A to J; all of the collected images were at the user's disposal and SEM images were separated into radial, tangential and transverse folders. For the numerical states, measurements were made directly from the SEM images using the scale bar and a ruler. The taxonomist also had the rectangular reference specimens available to her for the examination of physical characters and heartwood fluorescence and vials of heartwood shavings were prepared for testing the chemical characters. Density was assessed by placing the rectangular reference specimens in a sink of water and noting those that immediately sank to the bottom. These specimens were scored the state "Density, > 1000 kg/m^3".

Owing to the specialist nature of the identification tool, some training is required to instil in a novice user the confidence to correctly score the characters. In the early stages a great deal of use was made of the explanatory character state factsheets but with familiarity this use virtually ceased. On the whole, however, the test was conducted independently particularly as the test progressed and the user's confidence and ability to identify salient wood anatomical features increased.

Results

Tabulated results of the test of the identification tool by a novice user are given in Appendix Nine. The results are presented in the same manner as those from the initial test discussed in the first half of this chapter.

Discussion

Table 10 shows the professional identifications of the botanical voucher specimens associated with the wood samples A to J and the identifications obtained by the plant taxonomist using the tool. In addition, where the correct taxon was eliminated, the table records the chosen character state(s) that resulted in its removal. These results are briefly summarised here.

Testing the major key - Sub-key to a Selection of Arid Australian Hardwoods - *by character set*

This section discusses the application of specimens A to J to the *Sub-key to a Selection of Arid Australian Hardwoods*. It begins with a summary of the results returned by each character set followed by the results returned using all of the selected character states from each of the four character sets.

Using the physical character set only

On all ten occasions the physical character set was appropriately scored so that the correct taxon was preserved amongst the remaining taxa. Between three and 17 taxa remained in this character set. These results are reflective of those obtained during the initial test and the high values represent the presently limited potential of the character set to isolate taxa. The three remaining taxa for specimen F and H confirm the value of physical characters in isolating specimens belonging to Proteaceae.

Using the chemical character set only

On nine of 10 occasions the chemical character set was appropriately scored so that the correct taxon was preserved amongst the remaining taxa. Between 11 and 13 taxa remained in this character set. For specimen I, the user scored the character state "Heartwood, fluorescence negative" which resulted in the elimination of the correct taxon – Acacia. This indicates an interpretive difference and the error could be avoided if the tool is modified so that Acacia is scored for both "Heartwood, fluorescence negative" and Heartwood, fluorescence positive".

Table 10 Identifications of the botanical voucher specimens associated with the wood samples A to J and the identifications obtained by the plant taxonomist using the tool. Where the correct taxon was discarded, the final column lists the selected character state that resulted in its elimination.

ID	Family	Genera	Species	Identification in key to family/genus using all character sets (remaining taxon)	Identification in key to species using all character sets (remaining taxon/taxa)	Selected character states that resulted in elimination of correct taxon (if applicable)
A	LEGUMINOSAE	*Acacia*	*aneura* var. *aneura*	*Acacia*	*Acacia* sp.	Parenchyma, not in marginal bands S Vessels, difference in diameters: #:35 µm S Rays, difference in heights: #:20 µm S Vessels, solitary
B	MYRTACEAE	*Eucalyptus*	*camaldulensis* var. *obtusa*	Myrtaceae A (*Eucalyptus* or *Melaleuca*)	*E. coolabah* *E. populnea* *E. thozetiana*	Kino (gum deposits), not visible to the naked eye
C	CASUARINACEAE	*Casuarina*	*pauper*	No remaining taxa	na	E Parenchyma, not banded
D	MYRTACEAE	*Eucalyptus*	*camaldulensis* var. *obtusa*	Myrtaceae A (*Eucalyptus* or *Melaleuca*)	*E. camaldulensis* var. *obtusa*	
E	MYRTACEAE	*Melaleuca*	*glomerata*	Myrtaceae A (*Eucalyptus* or *Melaleuca*)	*M. glomerata*	
F	PROTEACEAE	*Grevillea*	*juncifolia*	Proteaceae (*Grevillea* & *Hakea*)	*H. eyreana* *H. leucoptera* ssp. *leucoptera*	Heartwood, froth test negative
G	LEGUMINOSAE	*Acacia*	*victoriae* ssp. *arida*	*Acacia*	*Acacia* sp.	Heartwood, ethanol extract discoloured S Rays, <4 per mm
H	PROTEACEAE	*Hakea*	*leucoptera* ssp. *leucoptera*	Proteaceae (*Grevillea* & *Hakea*)	*H. eyreana*	Vessels, helical thickenings absent
I	LEGUMINOSAE	*Acacia*	*stenophylla*	Myrtaceae B	No remaining taxa	Heartwood, not fluorescent
J	LEGUMINOSAE	*Acacia*	*tetragonophylla*	*Acacia*	No remaining taxa	Heartwood, ethanol extract not fluorescent E Vessels, in radial multiples of 4 or more

Using the endgrain character set only

On nine of 10 occasions the endgrain character set was appropriately scored so that the correct taxon was preserved amongst the remaining taxa. Between one and 10 taxa remained for this character set with specimens F and H (both Proteaceae species) successfully identified to family level. For specimen C, the correct taxon (*Casuarina*) was eliminated because the character state "Parenchyma, not banded" was selected. Rather than reflecting an interpretive problem with the character, this was more indicative of the quality of the endgrain image that the user consulted and the fact that there is no colour contrast between the parenchyma bands and fibres. Indeed, the user easily identified the parenchyma bands on the SEM images of the transverse surface of this specimen where they were much more visible. Nevertheless, to protect against this error the tool could be updated so that *Casuarina* is scored commonly misinterpreted for the character state "Parenchyma, not banded" and commonly present for "Parenchyma, banded".

Using the SEM character set only

The taxonomist successfully utilised the SEM character set to return a single, correct taxon for each of the ten specimens. Indeed, by the time the user had progressed to the SEM character set, she had clearly gained in confidence and began to be directed by what she saw in the images rather than approach the characters in a linear fashion. For example, for specimens F, G and H the correct taxon was isolated using only two to six character states.

The taxonomist recommended a couple of minor modifications to this character set. Firstly, a user with minimal wood anatomical knowledge would be better assisted if the SEM set was split into radial, tangential and transverse characters; at present, this information is only available on the character state factsheets (Barker 2005: *pers. comm.*). In addition, it would be helpful if the characters were placed in an order where the characters that can be answered with the greatest amount of confidence were placed at the top or placed in a separate set of characters (Barker 2005: *pers. comm.*). This will assist users with a limited knowledge of wood identification who will probably approach the characters in a linear fashion.

Using all the character sets

With the selection of the relevant character states from the four character sets, the taxonomist was able to successfully identify eight of the 10 specimens to a single, correct taxon in the

main key. Unfortunately, the "Parenchyma, not banded" character state selected in the endgrain set to describe specimen C resulted in the elimination of all taxa. This is despite the fact that the user correctly identified banded parenchyma as present in the SEM character set and could have corrected her mistake on this basis. However, the elimination of all taxa immediately signals a restart of the key on the assumption that a mistake has been made. For specimen I, the user's determination that heartwood fluorescence was not present resulted in the elimination of the correct taxon – *Acacia* – and the specimen was misidentified as Myrtaceae B (*Corymbia*). This misidentification is not surprising for *Acacia* and *Corymbia* can be difficult to separate at the cellular level. Nevertheless, it is important that future modifications of the tool address this problem and ensure that both the positive and negative states are scored for *Acacia* for the character "Heartwood, fluorescent or not".

Testing the sub-keys to species by character set

This section discusses the outcomes of the identifications to species level and the application of the three tested sub-keys to species: *Sub-key to Myrtaceae A (Eucalyptus & Melaleuca)*, *Sub-key to Acacia* and the *Sub-key to Proteaceae (Grevillea & Hakea)*. A fourth sub-key – *Sub-key to Myrtaceae B (Corymbia)* – was also employed in error because of the misidentification of specimen I in the test of the *Sub-key to a Selection of Arid Australian Hardwoods*. The outcomes are first discussed in terms of the independent application of the endgrain and SEM character set. This is followed by a summary of the identifications obtained by selecting character states from all the character sets.

Using the endgrain character set only

The taxonomist successfully identified specimens F and H as Proteaceae species in the *Sub-key to a Selection of Arid Australian Hardwoods*. In the *Sub-key to Proteaceae (Grevillea & Hakea)* the correct identifications – *Grevillea juncifolia* ssp. *juncifolia* and *Hakea leucoptera* ssp. *leucoptera* – were retained amongst the remaining taxa. However, this was not surprising since this character set is not sufficiently discriminating to distinguish between *Proteaceae (Grevillea & Hakea)* species.

Using the SEM character set only

On two of the nine occasions that the sub-keys to species were tested did a single correct taxon remain; using the SEM character set, specimen D was correctly identified as

Eucalyptus camaldulensis var. *obtusa* and specimen E was correctly identified as *Melaleuca glomerata*. Nevertheless, on five other occasions – for specimens B, F, G, H and J - the correct taxon was retained with other taxa that fit the character state selections. These results indicate that the SEM character sets of the three tested sub-keys to species can elicit successful identifications but the user is more likely to attain a group of species rather than a single taxon. Future addition of more data may assist their separation from other like taxa.

For specimen E, all taxa were eliminated including the correct taxon (*Melaleuca glomerata*). This result is indicative of the limitations of these six sub-keys and the need to bolster the numerical characters with the treatment of more representatives from each species.

For specimen I, the correct taxon (*Acacia stenophylla*) was eliminated in the *Sub-key to Acacia* because the user misinterpreted the character state "Vessels, solitary". *A. stenophylla* was also removed from amongst the remaining taxa because of the score for the character "Rays, difference in heights". The 25 µm that the user entered into the tool was outside the range for *A. stenophylla* of 66-176 µm.

A very similar experience was had with specimen A. The correct taxon – *Acacia aneura* var. *aneura* – was eliminated in the *Sub-key to Acacia* because the character state "Vessels, solitary" was chosen and because the values entered into the tool for the numerical characters "Rays, difference in heights" – 20 µm - and "Vessels, difference in diameters" – 35 µm – fell outside the ranges for *Acacia aneura* var. *aneura* (31-149 µm and 43-102 µm respectively). Whilst these numerical characters – newly introduced in this research - require further testing, the data set is too small to draw any reliable conclusions on their accuracy and value and any disparities may improve with the addition of data from extra representatives of each species. Indeed, both of these characters assisted in isolating the correct taxon in the *Sub-key to a Selection of Arid Australian Hardwood Taxa* where the data set used to describe each genus/family is much larger.

Using all the character sets

In the final part of the test by the taxonomist, all of the relevant character states selected from each of the four character sets were applied to the relevant sub-keys to species. With the exception of specimen D and E– *Eucalyptus camaldulensis* var. *obtusa* and *Melaleuca glomerata* – all the specimens were misidentified. For specimens B and F, however, it

appears that the correct taxa (*Eucalyptus camaldulensis* var. *obtusa* and *Grevillea juncifolia* ssp. *juncifolia*) was eliminated because two character states - "Kino (gum deposits), not visible to the naked eye" and "Heartwood, froth test negative" - had not been scored appropriately when the tool was built.

Specimen A was not matched to any of the treated *Acacia* species with the correct taxon – *Acacia aneura* var. *aneura* - eliminated largely because of the character states selected against the SEM character set; these were discussed in the preceding section. However, the selection of the endgrain character "Parenchyma, not in marginal bands" also resulted in the elimination of *Acacia aneura* var. *aneura* which had been scored positively for this state. This disparity may have related to the clarity of the image or may indicate that this taxon is variable.

The only new taxon added to the identification tool as a result of the initial test - *Acacia victoriae* ssp. *arida* – was eliminated because the character states "Heartwood, ethanol extract discoloured" and "Rays, < 4 per mm" were selected to describe specimen G. The initial test found the ethanol extract to be colourless which suggests that any discolouration observed by the taxonomist must have been very weak whilst the low number of rays per millimetre probably arose from a single measurement taken from a single image.

Specimen H – *Hakea leucoptera* ssp. *leucoptera* – was misidentified as *Hakea eyreana* because the character state "Vessels, helical thickenings absent" was selected. However, helical thickenings in an inner vessel wall are clearly present in one of the SEM images taken of the radial surface of specimen H (Figure 76D in Appendix Eight).

As was previously discussed, specimen I was mistakenly identified in the major key - *Sub-key to a Selection of Arid Australian Hardwoods* - as a Myrtaceae B (*Corymbia*) species and the correct identification (*Acacia*) was eliminated because the taxonomist selected the character state "Heartwood, not fluorescent". The taxonomist went on to attempt to identify Specimen I to species level using the *Sub-key to Myrtaceae B (Corymbia)* but both the treated *Corymbia* taxa were eliminated.

Finally, the correct taxon for specimen J – *Acacia tetragonophylla* – was eliminated because "Heartwood, ethanol extract not fluorescent" was selected from the chemical character set and "Vessels, in radial multiples of 4 or more" was selected from the endgrain set. The

selection of both these states – when the initial test indicated that the negative states were present – may indicate differences in interpretation. In re-examining the endgrain image of specimen J, for example, it can easily be seen why the user chose the positive character state since vessels occurring in radial multiples of four or more are present.

Conclusions

The two tests of specimens A-J against the major key - *Sub-key to a Selection of Arid Australian Hardwoods* - yielded very successful results. Indeed, on each occasion that the SEM character set was independently tested against this key it returned a 100 per cent success rate in isolating the correct taxon. Moreover, where all the character sets were utilised the correct taxon was isolated on 19 of the 20 occasions. Even with its present limited data set, this indicates that the major key – *Sub-key to a Selection of Arid Australian Hardwoods* - can be successfully utilised using all of the available identification methods and that the resultant identifications to family or genus can be accepted with a relatively high degree of confidence.

With limited testing for *intra*-specific variation, confidence in any indications of *inter*-specific variation necessarily declines within the hierarchical key structure. This was borne out by the results of the tests against the sub-keys to species where a large number of misidentifications were returned. Accordingly, in their present state, any results obtained from the six sub-keys to species can not be reliably accepted. Whether the treatment of additional specimens per species and the addition of new characters will increase the possibility of obtaining successful identifications at the species level can not be predicted.

This chapter also described the testing of the identification tool against a group of unknown wood specimens by a plant taxonomist with only a basic understanding of wood anatomy. The results indicated that, with some training, a novice user can successfully navigate through the identification tool and that their confidence in isolating important wood anatomical features can increase quite rapidly; this is particularly so when presented with character state factsheets rich in representative images that can be compared to an unknown specimen. In addition, it is expected that the chances of misidentifications as a result of user-error or misinterpretation will be reduced if the novice user scores only those characters in which they feel confidence as the tool is designed to be used; testing within character sets is artificial and bears no relationship to normal use of the tool.

The tests have also revealed several modifications that should be made to the identification tool. As expected, heartwood-dependent features reduce the efficacy of the tool as a whole but particularly the physical properties and chemical observations sets. This will be remedied in the future when it can be established whether particular taxa presently represented in the tool produce heartwood that is visually distinguishable from the sapwood. Moreover, and as has previously been acknowledged in this thesis, the addition of numerical data on vessel diameter and vessel number per square millimetre would improve the value of the endgrain character set which has the potential to identify families/genera without the requirement for more invasive methods of identification. The division of the SEM character set into radial, tangential and transverse groups of characters would also benefit novice users and greater attention needs to be paid to the order of the characters in the keys. Time constraints have precluded the modification of the tool to account for these amendments but these are something that can be addressed with any expansion of the keys in the future.

The next chapter discusses the statistical analyses conducted to determine the level of variation within and between selected taxa.

Chapter Ten. Statistical analysis of numerical characters

Introduction

Studies (particularly in the area of Forestry) have shown that variation in wood characteristics within a single species may occur within trees, between trees and between environments (e.g. Lamoureux and Murakami 1992; Robbertse, Venter *et al.* 1980; Taylor c. 1972; Wilkes 1988). This variation in wood anatomical characters may hamper the identification of species. At the other extreme, wood may not be sufficiently inter-specifically variable to allow the separation of species; that is, closely related species (usually from the same genus, but sometimes family) may not produce wood with sufficient variation to permit identification. For example, *Quercus petraea* and *Quercus robur*, two major European oak species, are difficult to separate (Feuillat, Dupouey *et al.* 1997) as are the European and North American poplars (*Populus* sp.) (Bishop 1999: 140; Tennesen, Blanchette *et al.* 2002). In the case of coniferous woods (softwoods), separating species beyond genus or family level is made even more difficult by a simple cell structure that lacks the specialisation of hardwoods (e.g. Ilic 1996).

Given the variability that can occur within a species, and, conversely, the lack of variation that can occur within the wood of a genus or family, it was important for this research to make some attempt to address the issues of intra- and inter- specific variation. To determine whether significant variation occurs within and between the wood of a selection of the treated species, biometrician Kate Dowling of *BiometricsSA* was employed to conduct relevant statistical analyses using collected numerical data relating to the vessels and rays. With her permission, descriptions of the methods and tables presenting the results of the statistical analyses have been reproduced from the report compiled by *BiometricsSA*. This chapter outlines the scope and methods of the statistical analyses and provides a discussion of the results where consideration is given to the limitations of the data collection and analysis.

Collection of raw data

The raw data used for the statistical analyses described in this chapter were collected from SEM images using the image analysis software *analySIS*. The process used to collect the

data was outlined in Chapter Seven. Data was collected for the following standard wood anatomical characters:

- Vessels, diameter
- Vessels, number per square millimetre
- Rays, height
- Rays, number per mm
- Rays, number of cells wide

Scope

The statistical analyses conducted by *BiometricsSA* involved analysis of data collected for the five numerical characters to investigate intra-specific variation and inter-specific variation. In statistics these characters are referred to as "responses".

Intra-specific analyses (within species variation)

The intra-specific analyses tested for non-significant variation occurring within 18 of the treated species for which there were at least two vouchered collections. The tested specimens were:

- *Acacia cana* (JAB178, JAB180)
- *Acacia murrayana* (JAB165, JAB186)
- *Acacia stowardii* (JAB151, JAB158)
- *Acacia aneura* var. *aneura* (JAB121, JAB171)
- *Acacia stenophylla* (JAB102, JAB105)
- *Acacia tetragonophylla* (JAB108, JAB128)
- *Eremophila longifolia* (JAB106, JAB114)
- *Eucalyptus camaldulensis* var. *obtusa* (JAB146, JAB182, JAB191)

- *Eucalyptus coolabah* (JAB100, JAB107, JAB133, JAB137)
- *Eucalyptus populnea* (JAB159, JAB170)
- *Melaleuca glomerata* (JAB176, JAB189)
- *Grevillea juncifolia* (JAB147, JAB149)
- *Hakea eyreana* (JAB139, JAB142)
- *Hakea leucoptera* ssp. *leucoptera* (JAB110, JAB112)
- *Casuarina pauper* (JAB179, JAB187)
- *Capparis loranthifolia* (JAB162, JAB172)
- *Corymbia terminalis* (JAB143, JAB156, JAB160)
- *Dodonaea viscosa* ssp. *angustissima* (JAB119, JAB184)

Inter-specific analyses (between species variation)

The inter-specific analyses tested for significant variation occurring between species belonging to genera represented in this research by multiple species. This included the genera *Acacia* (19 taxa), *Capparis* (2 species) and *Corymbia* (2 species). The analyses also extended to testing for significant variation occurring between species belonging to the families Myrtaceae A (7 species from *Eucalyptus*/*Melaleuca*), Proteaceae (4 species from *Grevillea*/*Hakea*) and Myoporaceae (9 species from *Eremophila*/*Myoporum*). These related genera were grouped together for analyses as they do not easily separate using qualitative characters[51].

[51] The genus *Corymbia* was considered separately in this research as its wood differs substantially from *Eucalyptus* and *Melaleuca* in qualitative characteristics. For this reason, the family Myrtaceae was split into Myrtaceae A (*Eucalyptus* and *Melaleuca*) and Myrtaceae B (*Corymbia*).

Methods

This section outlines the different statistical methods employed to analyse for significant variance within and between a selection of the treated species using the raw data collected for the five responses.

Intra-specific analyses (within species variation)

For responses that could be regarded as continuous[52] the method of analysis was general analysis of variance (ANOVA) with randomised blocking. For discreet data (those that could not be regarded as continuous) the method of analysis was chi-squared tests.

"Rays, number of cells wide"

With the exception of *Hakea eyreana*, *Grevillea juncifolia* and *Hakea leucoptera* ssp. *leucoptera* the "Rays, number of cells wide" response was analysed using a chi-squared test. Chi-square analysis tests the hypothesis that there is no association between the row and column variables (i.e. species and "Rays, number of cells wide"). To test an association between the two categorical variables a contingency table of the observed counts is constructed and a chi-squared test applied. For instance, the contingency table for *Acacia murrayana* would be set up as follows:

Character: (Example: Rays, number of cells wide)	**Species (Example: *Acacia murrayana*)**		
	Specimen 1	Specimen 2	**TOTAL**
1	16	66	**82**
2	63	3	**66**
3	6	0	**6**
TOTAL	**85**	**69**	

The null hypothesis, that the two variables are independent and that there is no variation within a species is tested using the test statistic:

[52] Continuous responses refer to measurement data that is continuously variable. For example, between the measurements 1 and 2 µm there are a continuous range of variables from 1.0001 to 1.9999 µm. Accordingly, "Vessels, diameter" and "Rays, height" are considered continuous responses. Responses that are discreet are whole numbers such as occur with measurements based on counts, such as "Rays, number of cells wide". However, where a response is typified by a large range of counts, as was the case with "Rays, number per mm" and "Vessels, number per square millimetre", it may be treated as continuous.

$$X^2 = \sum \frac{(observed - \exp ected)^2}{\exp ected}$$

If the null hypothesis is true, X^2 has a chi-square distribution with (r minus 1) multiplied by (c minus 1) degrees of freedom, where r is the number of rows and c is the number of columns in the contingency table. For example, *Acacia murrayana* has three columns and two rows giving two degrees of freedom.

"Vessels, diameter", "Rays, height"

The method of analysis for the "Vessels, diameter" and "Rays, height" responses was ANOVA with randomised blocking. Each block in this case was a JAB specimen, with areas within each tree selected for sampling and a number of vessels/rays measured within each area. The blocking structures in the analyses of these responses were therefore JAB specimen/area/vessel and JAB specimen/area/ray (i.e. each area is nested within a tree, and a number of rays (or vessels) were measured within each area) to allow for the between tree (but within species) variation and the variation between areas within trees.

The "Rays, number of cells wide" response for *Hakea eyreana*, *Grevillea juncifolia* and *Hakea leucoptera* ssp. *leucoptera* was also analysed using ANOVA with the blocking structure JAB specimen/area/ray as it had a larger range of widths (1-9) than other species and could therefore be treated as a continuous variable.

"Vessels, number per square millimetre", "Rays, number per millimetre"

The "Vessels, number per square millimetre" and "Rays, number per millimetre" responses were also analysed using ANOVA but with a different blocking structure. As an average value for both responses was calculated for each area the blocking structure was therefore JAB specimen/area (areas nested within trees), allowing for within species variation.

In order to determine the significance of the block (JAB specimen) effect (or intra-specific variation) an F-test was performed. If the associated F probability or "p-value" of the test was equal to or less than 0.05 then it was concluded that there was significant between-species, intra-specific variation at the 5% significance level.

Diagnostic plots were used to determine if the assumptions of ANOVA (normality and constant variance) held. ANOVA assumes that data will fit a normal distribution and that

variations around the mean are constant. If these assumptions were not valid the data were transformed to meet the requirements.

Inter-specific analyses (between species variation)

Two methods of statistical analysis were employed to test for inter-specific variation: REML (Restricted Maximum Likelihood) analysis and log-linear modelling.

"Vessels, diameter", "Vessels, number per square millimetre", "Rays, height", "Rays, number per mm"

When there is a large imbalance in data REML is used rather than ANOVA. The method of analysis for the "Vessels, diameter", "Vessels, number per square millimetre", "Rays, height" and "Rays, number per millimetre" responses was REML linear mixed modelling.

REML analysis allows modelling in terms of fixed and random effects. Fixed effects correspond to treatment effects (in this case species) in the ANOVA context. The importance of each fixed effect was tested using a Wald test. If a Wald test found an effect to be statistically significant, LSD (least significant difference) tests were performed. In a LSD test pairwise comparisons are made between the means of the different levels of the significant effect. If the difference between the means was greater than the LSD value then it was concluded that the means were significantly different at the 5% level.

Random effects are the same as blocking effects in an ANOVA context. In this case, collection is the random effect.

The assumptions of REML linear mixed modelling are the same as for ANOVA – normality and constant variance – and these assumptions were checked using diagnostic plots. Responses that did not meet these assumptions were transformed.

"Rays, number of cells wide"

The method of analysis for the "Rays, number of cells wide" response (a count of the number of cells across the width of each ray) was log-linear modelling. This method is used to analyse count data and models the count of cells as a function of a number of independent (explanatory) variables $X_1, X_2, ..., X_3$. It involves transforming the mean response, μ, with the log-link function, given by $\log(\mu)$.

In this analysis there is only one explanatory variable: species. The significance of the species effect is determined using a deviance test. If the deviance test found this effect to be statistically significant, LSD tests were again performed.

Results

The results of the statistical analyses that tested for non-significant intra- and inter- species variation are given in Tables 11 and 12. These present a summary of results for the two broad analyses, as well as the tables showing the pairwise comparisons, use the following abbreviations and symbols:

NS	=	Within species variation not statistically significant at the 5% significance level
√	=	Within species variation statistically significant at the 5% significance level
~	=	No test done for this response

Intra-specific analyses (within species variation)

Table 11 shows a summary of the results for the intra-specific analyses. *Hakea eyreana*, *Grevillea juncifolia* and *Hakea leucoptera* ssp. *leucoptera were* not tested for "Rays, height" as reliable measurements could not be made (see *Limitations* section for further explanation). These species were also excluded from data collection for "Vessels, number per square millimetre" due to the presence of tangential bands (Wheeler, Baas *et al.* 1989: 259).

Table 11 Summary of results of intra-specific testing for all responses.

Responses/Taxa	Vessels, diameter	Rays, height	Rays, number per millimetre	Rays, number of cells wide	Vessels, number per square millimetre
Acacia cana	√	√	√	√	NS
Acacia murrayana	NS	NS	NS	√	√
Acacia stowardii	√	√	NS	√	NS
Acacia aneura var. *aneura*	NS	√	√	√	√
Acacia stenophylla	√	NS	NS	NS	NS
Acacia tetragonophylla	NS	√	NS	√	√
Eucalyptus coolabah	√	√	√	√	√
Eucalyptus populnea	√	NS	√	NS	NS
Eucalyptus camaldulensis var. *obtusa*	√	√	√	√	√
Melaleuca glomerata	√	√	NS	√	√
Corymbia terminalis	NS	√	NS	√	NS
Eremophila longifolia	NS	√	NS	√	NS
Grevillea juncifolia	NS	-	√	NS	-
Hakea leucoptera ssp. *leucoptera*	√	-	√	NS	-
Hakea eyreana	NS	~	NS	√	~
Capparis loranthifolia	NS	√	√	√	√
Dodonaea viscosa ssp. *angustissima*	NS	NS	√	NS	√
Casuarina pauper	√	√	√	√	√

Inter-specific analyses (between species variation)

After first presenting a summary of the results in Table 12, this section provides a breakdown of the results for inter-specific variation. The results for each genus (or related genera) are first presented with the treated taxa ranked in order of the highest predicted mean to the lowest predicted mean. Using these rankings, pairwise comparisons are presented in the second table for each response. These show whether significant statistical variation occurs between species for each response. Pairwise comparisons are not presented for *Corymbia* and *Capparis* where only two species were treated.

Table 12 Summary of results of inter-specific variation testing of selected taxa

Responses/Taxa	"Vessels, diameter"	"Vessels, number per square millimetre"	"Rays, height"	"Rays, number per millimetre"	"Rays, number of cells wide"
Acacia	√	√	√	√	√
Capparis	√	NS	NS	NS	√
Corymbia	NS	NS	NS	√	NS
Eucalyptus/*Melaleuca*	√	√	√	√	√
Eremophila/*Myoporum*	√	√	√	√	√
Grevillea/*Hakea*	√	~	~	√	√

Whether data were log-transformed (that is, transformed so the assumptions of normality and constant variance were met) is noted in the table captions. In the event that data were log transformed, the data have been back-transformed to show the means on the original scale. Means are predicted: that is, they are generated from the applied models rather than the raw data.

Acacia

Treated *Acacia* taxa showed significant statistical variation at the 5% level for each of the five responses; see Tables 13 - 22. Note that *Acacia peuce* is not represented in the responses relating to the rays; reliable data were not collected from the tangential surface for this species due to difficulties preparing a clear surface.

"Vessels, diameter"

Table 13 Rankings for predicted means for "Vessels, diameter" for *Acacia* taxa.

Rank	Species	Mean (µm)
1	*victoriae* ssp. *victoriae*	89.61
2	*pickardii*	68.60
3	*victoriae* ssp. *arida*	68.47
4	*stenophylla*	65.16
5	*ligulata*	63.72
6	*farnesiana*	62.07
7	*peuce*	60.42
8	*salicina*	58.93
9	*cambagei*	58.26
10	*oswaldii*	57.25
11	*cana*	50.91
12	*petraea*	50.74
13	*tetragonophylla*	50.62
14	*aneura* var. *intermedia*	47.52
15	*ligulata* ?intergrade with *A. bivenosa*	44.37
16	*murrayana*	41.46
17	*aneura* var. *aneura*	39.72
18	*cyperophylla* var. *cyperophylla*	38.84
19	*stowardii*	36.32

Table 14 *Acacia* taxa pairwise comparisons for "Vessels, diameter" based on predicted means. Numbers in top and left columns equate with rankings for predicted means in Table 13.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1		√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
2	√		N	N	N	N	N	√	√	√	√	√	√	√	√	√	√	√	√
3	√	N		N	N	N	N	√	√	√	√	√	√	√	√	√	√	√	√
4	√	N	N		N	N	N	N	N	N	√	√	√	√	√	√	√	√	√
5	√	N	N	N		N	N	N	N	N	√	√	√	√	√	√	√	√	√
6	√	N	N	N	N		N	N	N	N	√	√	√	√	√	√	√	√	√
7	√	N	N	N	N	N		N	N	N	√	√	√	√	√	√	√	√	√
8	√	√	√	N	N	N	N		N	N	N	N	N	√	√	√	√	√	√
9	√	√	√	N	N	N	N	N		N	N	N	N	√	√	√	√	√	√
10	√	√	√	N	N	N	N	N	N		N	N	N	√	√	√	√	√	√
11	√	√	√	√	√	√	√	N	N	N		N	N	N	N	√	√	√	√
12	√	√	√	√	√	√	√	N	N	N	N		N	N	N	√	√	√	√
13	√	√	√	√	√	√	√	N	N	N	N	N		N	N	√	√	√	√
14	√	√	√	√	√	√	√	√	√	√	N	N	N		N	N	N	√	√
15	√	√	√	√	√	√	√	√	√	√	N	N	N	N		N	N	N	N
16	√	√	√	√	√	√	√	√	√	√	√	√	√	N	N		N	N	N
17	√	√	√	√	√	√	√	√	√	√	√	√	√	N	N	N		N	N
18	√	√	√	√	√	√	√	√	√	√	√	√	√	√	N	N	N		N
19	√	√	√	√	√	√	√	√	√	√	√	√	√	√	N	N	N	N	

"Vessels, number per square millimetre"

Table 15 Rankings for back-transformed predicted means for "Vessels, number per square millimetre" for *Acacia* taxa.

Rank	Species	Mean (vessels/mm2)
1	*stowardii*	183.644
2	*aneura* var. *aneura*	149.008
3	*cyperophylla* var. *cyperophylla*	115.123
4	*aneura* var. *intermedia*	82.682
5	*murrayana*	71.450
6	*cana*	53.893
7	*tetragonophylla*	53.624
8	*petraea*	53.410
9	*oswaldii*	50.149
10	*peuce*	43.121
11	*cambagei*	40.246
12	*ligulata* ?intergrade with *A. bivenosa*	27.605
13	*stenophylla*	26.233
14	*farnesiana*	25.868
15	*ligulata*	23.500
16	*salicina*	22.488
17	*victoriae* ssp. *arida*	17.013
18	*pickardii*	15.487
19	*victoriae* ssp. *victoriae*	12.404

Table 16 *Acacia* taxa pairwise comparisons for "Vessels, number per square millimetre" based on log-transformed data. Numbers in top and left columns equate with rankings for predicted means in Table 15.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1		N	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
2	N		N	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
3	√	N		N	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
4	√	√	N		N	√	√	√	√	√	√	√	√	√	√	√	√	√	√
5	√	√	√	N		N	N	N	√	√	√	√	√	√	√	√	√	√	√
6	√	√	√	√	N		N	N	N	N	N	√	√	√	√	√	√	√	√
7	√	√	√	√	N	N		N	N	N	N	√	√	√	√	√	√	√	√
8	√	√	√	√	N	N	N		N	N	N	√	√	√	√	√	√	√	√
9	√	√	√	√	√	N	N	N		N	N	√	√	√	√	√	√	√	√
10	√	√	√	√	√	N	N	N	N		N	√	√	√	√	√	√	√	√
11	√	√	√	√	√	N	N	N	N	N		√	√	√	√	√	√	√	√
12	√	√	√	√	√	√	√	√	√	√	√		N	N	N	N	√	√	√
13	√	√	√	√	√	√	√	√	√	√	√	N		N	N	N	√	√	√
14	√	√	√	√	√	√	√	√	√	√	√	N	N		N	N	√	√	√
15	√	√	√	√	√	√	√	√	√	√	√	N	N	N		N	N	√	√
16	√	√	√	√	√	√	√	√	√	√	√	N	N	N	N		N	√	√
17	√	√	√	√	√	√	√	√	√	√	√	√	√	√	N	N		N	N
18	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	N		N
19	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	N	N	

"Rays, height"

Table 17 Rankings for back-transformed predicted means for "Rays, height" for *Acacia* taxa

Rank	Species	Mean (µm)
1	*victoriae* ssp. *arida*	179.469
2	*ligulata*	158.698
3	*victoriae* ssp. *victoriae*	152.628
4	*cambagei*	148.859
5	*cana*	136.456
6	*oswaldii*	131.368
7	*salicina*	130.712
8	*farnesiana*	121.876
9	*ligulata* ?intergrade with *A. bivenosa*	121.389
10	*pickardii*	117.801
11	*murrayana*	116.629
12	*aneura* var. *aneura*	116.396
13	*petraea*	107.770
14	*stenophylla*	101.190
15	*cyperophylla* var. *cyperophylla*	91.836
16	*tetragonophylla*	88.855
17	*aneura* var. *intermedia*	82.270
18	*stowardii*	77.246

Table 18 *Acacia* taxa pairwise comparisons for "Rays, height" based on log-transformed data. Numbers in top and left columns equate with rankings for predicted means in Table 17.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1		N	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
2	N		N	N	√	√	√	√	√	√	√	√	√	√	√	√	√	√
3	√	N		N	N	√	√	√	√	√	√	√	√	√	√	√	√	√
4	√	N	N		N	N	√	√	√	√	√	√	√	√	√	√	√	√
5	√	√	N	N		N	N	N	N	√	√	√	√	√	√	√	√	√
6	√	√	√	N	N		N	N	N	N	N	N	√	√	√	√	√	√
7	√	√	√	√	N	N		N	N	N	N	N	√	√	√	√	√	√
8	√	√	√	√	N	N	N		N	N	N	N	N	√	√	√	√	√
9	√	√	√	√	N	N	N	N		N	N	N	N	√	√	√	√	√
10	√	√	√	√	√	N	N	N	N		N	N	N	√	√	√	√	√
11	√	√	√	√	√	N	N	N	N	N		N	N	√	√	√	√	√
12	√	√	√	√	√	N	N	N	N	N	N		N	√	√	√	√	√
13	√	√	√	√	√	√	√	N	N	N	N	N		N	√	√	√	√
14	√	√	√	√	√	√	√	√	√	√	√	√	N		N	√	√	√
15	√	√	√	√	√	√	√	√	√	√	√	√	√	N		N	N	√
16	√	√	√	√	√	√	√	√	√	√	√	√	√	√	N		N	√
17	√	√	√	√	√	√	√	√	√	√	√	√	√	√	N	N		N
18	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	N	

"Rays, number per millimetre"

Table 19 Rankings for predicted means for "Rays, number per millimetre" for *Acacia* taxa

Rank	Species	Mean (rays/mm)
1	*aneura* var. *intermedia*	11.921
2	*farnesiana*	11.101
3	*petraea*	11.098
4	*victoriae* ssp. *victoriae*	10.690
5	*stenophylla*	10.428
6	*cana*	9.932
7	*ligulata*	9.806
8	*tetragonophylla*	9.334
9	*aneura* var. *aneura*	9.186
10	*victoriae* ssp. *arida*	9.146
11	*salicina*	8.677
12	*ligulata* ?intergrade with *A. bivenosa*	8.585
13	*stowardii*	8.347
14	*cambagei*	8.068
15	*murrayana*	7.805
16	*pickardii*	7.781
17	*cyperophylla* var. *cyperophylla*	6.705
18	*oswaldii*	5.830

Table 20 *Acacia* taxa pairwise comparisons for "Rays, number per millimetre" based on predicted means. Numbers in top and left columns equate with rankings for predicted means in Table 19.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1		N	N	N	N	N	N	√	√	√	√	√	√	√	√	√	√	√
2	N		N	N	N	N	N	N	N	N	√	√	√	√	√	√	√	√
3	N	N		N	N	N	N	N	N	N	√	√	√	√	√	√	√	√
4	N	N	N		N	N	N	N	N	N	N	N	N	√	√	√	√	√
5	N	N	N	N		N	N	N	N	N	N	N	N	√	√	√	√	√
6	N	N	N	N	N		N	N	N	N	N	N	N	N	N	N	√	√
7	N	N	N	N	N	N		N	N	N	N	N	N	N	N	N	√	√
8	√	N	N	N	N	N	N		N	N	N	N	N	N	N	N	√	√
9	√	N	N	N	N	N	N	N		N	N	N	N	N	N	N	√	√
10	√	N	N	N	N	N	N	N	N		N	N	N	N	N	N	√	√
11	√	√	√	N	N	N	N	N	N	N		N	N	N	N	N	N	√
12	√	√	√	N	N	N	N	N	N	N	N		N	N	N	N	N	√
13	√	√	√	N	N	N	N	N	N	N	N	N		N	N	N	N	√
14	√	√	√	√	√	N	N	N	N	N	N	N	N		N	N	N	√
15	√	√	√	√	√	N	N	N	N	N	N	N	N	N		N	N	N
16	√	√	√	√	√	N	N	N	N	N	N	N	N	N	N		N	N
17	√	√	√	√	√	√	√	√	√	√	N	N	N	N	N	N		N
18	√	√	√	√	√	√	√	√	√	√	√	√	√	√	N	N	N	

"Rays, number of cells wide"

Table 21 Rankings for predicted means for "Rays, number of cells wide" for *Acacia* taxa

Rank	Species	Mean (no. of cells)
1	*victoriae* ssp. *arida*	2.705
2	*oswaldii*	2.463
3	*cambagei*	2.069
4	*salicina*	2.030
5	*cana*	1.731
6	*victoriae* ssp. *victoriae*	1.724
7	*ligulata* ?intergrade with *A. bivenosa*	1.692
8	*stenophylla*	1.649
9	*farnesiana*	1.593
10	*murrayana*	1.507
11	*ligulata*	1.452
12	*pickardii*	1.429
13	*aneura* var. *intermedia*	1.254
14	*petraea*	1.237
15	*tetragonophylla*	1.155
16	*cyperophylla* var. *cyperophylla*	1.148
17	*stowardii*	1.064
18	*aneura* var. *aneura*	1.016

Table 22 *Acacia* taxa pairwise comparisons for "Rays, number of cells wide" based on predicted means. Numbers in top and left columns equate with rankings for predicted means in Table 21.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1		N	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
2	N		N	N	√	√	√	√	√	√	√	√	√	√	√	√	√	√
3	√	N		N	√	N	√	√	√	√	√	√	√	√	√	√	√	√
4	√	N	N		N	N	N	N	N	√	√	√	√	√	√	√	√	√
5	√	√	√	N		N	N	N	N	N	√	√	√	√	√	√	√	√
6	√	√	N	N	N		N	N	N	N	N	N	√	√	√	√	√	√
7	√	√	√	N	N	N		N	N	N	N	N	√	√	√	√	√	√
8	√	√	√	N	N	N	N		N	N	N	N	√	√	√	√	√	√
9	√	√	√	N	N	N	N	N		N	N	N	√	N	√	√	√	√
10	√	√	√	√	N	N	N	N	N		N	N	N	N	√	√	√	√
11	√	√	√	√	√	N	N	N	N	N		N	N	N	√	√	√	√
12	√	√	√	√	√	N	N	N	N	N	N		N	N	N	N	√	√
13	√	√	√	√	√	√	√	√	√	N	N	N		N	N	N	N	√
14	√	√	√	√	√	√	√	√	N	N	N	N	N		N	N	N	N
15	√	√	√	√	√	√	√	√	√	√	√	N	N	N		N	N	N
16	√	√	√	√	√	√	√	√	√	√	√	N	N	N	N		N	N
17	√	√	√	√	√	√	√	√	√	√	√	√	N	N	N	N		N
18	√	√	√	√	√	√	√	√	√	√	√	√	√	N	N	N	N	

Eucalyptus/Melaleuca

Treated *Eucalyptus/Melaleuca* species showed significant statistical variation at the 5% level for each of the five responses; see Tables 23 - 32.

"Vessels, diameter"

Table 23 Rankings for predicted means for "Vessels, diameter" for *Eucalyptus* taxa and Table 24 pairwise comparisons based on predicted means. Numbers in top and left columns equate with rankings for predicted means in Table 23.

Rank	Species	Mean (µm)
1	*ochrophloia*	70.49
2	*camaldulensis* var. *obtusa*	69.17
3	*coolabah*	62.88
4	*populnea*	61.22
5	*trichostachya*	55.54
6	*thozetiana*	53.07
7	*glomerata*	29.89

	1	2	3	4	5	6	7
1		N	N	N	√	√	√
2	N		N	N	√	√	√
3	N	N		N	N	N	√
4	N	N	N		N	N	√
5	√	√	N	N		N	√
6	√	√	N	N	N		√
7	√	√	√	√	√	√	

"Vessels, number per square millimetre"

Table 25 Rankings for back-transformed predicted means for "Vessels, number per square millimetre" for *Eucalyptus*/*Melaleuca* taxa and Table 26 pairwise comparisons based on log-transformed data. Numbers in top and left columns equate with rankings for predicted means in Table 25.

Rank	Species	Mean (vessels/mm2)
1	*glomerata*	192.32
2	*populnea*	67.31
3	*thozetiana*	65.99
4	*ochrophloia*	59.18
5	*coolabah*	42.18
6	*camaldulensis* var. *obtusa*	41.96
7	*trichostachya*	35.59

	1	2	3	4	5	6	7
1		√	√	√	√	√	√
2	√		N	N	N	N	N
3	√	N		N	N	N	N
4	√	N	N		N	N	N
5	√	N	N	N		N	N
6	√	N	N	N	N		N
7	√	N	N	N	N	N	

"Rays, height"

Table 27 Rankings for back-transformed predicted means for "Rays, height" for *Eucalyptus*/*Melaleuca* taxa and Table 28 pairwise comparisons based on log-transformed data. Numbers in top and left columns equate with rankings for predicted means in Table 27.

Rank	Species	Mean (µm)
1	*trichostachya*	231.5
2	*glomerata*	155.7
3	*camaldulensis* var. *obtusa*	149.4
4	*coolabah*	117.9
5	*ochrophloia*	90.5
6	*populnea*	85.4
7	*thozetiana*	84.6

	1	2	3	4	5	6	7
1		√	√	√	√	√	√
2	√		N	√	√	√	√
3	√	N		√	√	√	√
4	√	√	√		√	√	√
5	√	√	√	√		N	N
6	√	√	√	√	N		N
7	√	√	√	√	N	N	

"Rays, number per millimetre"

Table 29 Rankings for back-transformed predicted means for "Rays, number per millimetre" for *Eucalyptus*/*Melaleuca* taxa and Table 30 pairwise comparisons based on log-transformed data. Numbers in top and left columns equate with rankings for predicted means in Table 29.

Rank	Species	Mean (rays/mm)
1	*coolabah*	18.07
2	*thozetiana*	17.35
3	*ochrophloia*	14.70
4	*camaldulensis* var. *obtusa*	13.67
5	*populnea*	13.60
6	*trichostachya*	9.72
7	*glomerata*	6.06

	1	2	3	4	5	6	7
1		N	N	√	√	√	√
2	N		N	√	√	√	√
3	N	N		N	N	√	√
4	√	√	N		N	√	√
5	√	√	N	N		√	√
6	√	√	√	√	√		√
7	√	√	√	√	√	√	

"Rays, number of cells wide"

Table 31 Rankings for predicted means for "Rays, number of cells wide" for *Eucalyptus*/*Melaleuca* taxa and Table 32 pairwise comparisons based on predicted means. Numbers in top and left columns equate with rankings for predicted means in Table 31.

Rank	Species	Mean (no. of cells)
1	*trichostachya*	2.546
2	*glomerata*	1.934
3	*camaldulensis* var. *obtusa*	1.660
4	*thozetiana*	1.298
5	*populnea*	1.155
6	*coolabah*	1.151
7	*ochrophloia*	1.105

	1	2	3	4	5	6	7
1		√	√	√	√	√	√
2	√		√	√	√	√	√
3	√	√		√	√	√	√
4	√	√	√		N	N	N
5	√	√	√	N		N	N
6	√	√	√	N	N		N
7	√	√	√	N	N	N	

Eremophila/Myoporum

Treated *Eremophila/Myoporum* species showed significant statistical variation at the 5% level for each of the five responses; see Tables 33-42.

"Vessels, diameter"

Table 33 Rankings for predicted means for "Vessels, diameter" for *Eremophila*/*Myoporum* taxa and Table 34 pairwise comparisons based on predicted means. Numbers in top and left columns equate with rankings for predicted means in Table 33.

Rank	Species	Mean (µm)
1	*duttonii*	31.91
2	*polyclada*	28.38
3	*mitchellii*	27.21
4	*freelingii*	25.23
5	*montanum*	23.51
6	*bignoniiflora*	23.22
7	*longifolia*	22.62
8	*sturtii*	20.02
9	*macgillivrayi*	18.15

	1	2	3	4	5	6	7	8	9
1		N	√	√	√	√	√	√	√
2	N		N	N	√	√	√	√	√
3	√	N		N	N	N	N	√	√
4	√	N	N		N	N	N	√	√
5	√	√	N	N		N	N	N	√
6	√	√	N	N	N		N	N	√
7	√	√	N	N	N	N		N	N
8	√	√	√	√	N	N	N		N
9	√	√	√	√	√	√	N	N	

"Vessels, number per square millimetre"

Table 35 Rankings for back-transformed predicted means for "Vessels, number per square millimetre" for *Eremophila*/*Myoporum* taxa and Table 36 pairwise comparisons based on log-transformed data. Numbers in top and left columns equate with rankings for predicted means in Table 35.

Rank	Species	Mean (vessels/mm2)
1	*macgillivrayi*	332.620
2	*freelingii*	248.639
3	*bignoniiflora*	217.457
4	*mitchellii*	214.863
5	*polyclada*	188.105
6	*sturtii*	176.974
7	*longifolia*	151.260
8	*montanum*	124.089
9	*duttonii*	83.013

	1	2	3	4	5	6	7	8	9
1		√	√	√	√	√	√	√	√
2	√		N	N	√	√	√	√	√
3	√	N		N	N	N	√	√	√
4	√	N	N		N	N	√	√	√
5	√	√	N	N		N	√	√	√
6	√	√	N	N	N		N	√	√
7	√	√	√	√	√	N		N	√
8	√	√	√	√	√	√	N		√
9	√	√	√	√	√	√	√	√	

"Rays, height"

Table 37 Rankings for predicted means for "Rays, height" for *Eremophila*/*Myoporum* taxa and Table 38 pairwise comparisons based on predicted means. Numbers in top and left columns equate with rankings for predicted means in Table 37.

Rank	Species	Mean (µm)
1	*montanum*	239.6
2	*mitchellii*	210.2
3	*duttonii*	200.4
4	*macgillivrayi*	183.7
5	*sturtii*	161.7
6	*polyclada*	145.8
7	*longifolia*	144.4
8	*bignoniiflora*	140.4
9	*freelingii*	129.3

	1	2	3	4	5	6	7	8	9
1		√	√	√	√	√	√	√	√
2	√		N	√	√	√	√	√	√
3	√	N		N	√	√	√	√	√
4	√	√	N		√	√	√	√	√
5	√	√	√	√		N	N	√	√
6	√	√	√	√	N		N	N	N
7	√	√	√	√	N	N		N	N
8	√	√	√	√	√	N	N		N
9	√	√	√	√	√	N	N	N	

"Rays, number per millimetre"

Table 39 Rankings for predicted means for "Rays, number per millimetre" for *Eremophila*/*Myoporum* taxa and Table 40 pairwise comparisons based on predicted means. Numbers in top and left columns equate with rankings for predicted means in Table 39.

Rank	Species	Mean (rays/mm)
1	*sturtii*	14.238
2	*freelingii*	14.020
3	*duttonii*	10.726
4	*macgillivrayi*	8.986
5	*bignoniiflora*	8.163
6	*polyclada*	7.960
7	*mitchellii*	7.245
8	*longifolia*	7.217
9	*montanum*	7.129

	1	2	3	4	5	6	7	8	9
1		N	√	√	√	√	√	√	√
2	N		√	√	√	√	√	√	√
3	√	√		N	√	√	√	√	√
4	√	√	N		N	N	N	N	N
5	√	√	√	N		N	N	N	N
6	√	√	√	N	N		N	N	N
7	√	√	√	N	N	N		N	N
8	√	√	√	N	N	N	N		N
9	√	√	√	N	N	N	N	N	

"Rays, number of cells wide"

Table 41 Rankings for predicted means for "Rays, number of cells wide" for *Eremophila*/*Myoporum* taxa and Table 42 pairwise comparisons based on predicted means. Numbers in top and left columns equate with rankings for predicted means in Table 41.

Rank	Species	Mean (no. of cells)
1	*polyclada*	2.333
2	*mitchellii*	2.260
3	*bignoniiflora*	2.051
4	*montanum*	1.990
5	*longifolia*	1.669
6	*duttonii*	1.645
7	*sturtii*	1.604
8	*macgillivrayi*	1.149
9	*freelingii*	1.099

	1	2	3	4	5	6	7	8	9
1		N	N	N	√	√	√	√	√
2	N		N	N	√	√	√	√	√
3	N	N		N	N	N	√	√	√
4	N	N	N		N	N	√	√	√
5	√	√	N	N		N	N	√	√
6	√	√	N	N	N		N	√	√
7	√	√	√	√	N	N		√	√
8	√	√	√	√	√	√	√		N
9	√	√	√	√	√	√	√	N	

Grevillea/Hakea

Treated *Grevillea/Hakea* species showed significant statistical variation at the 5% level for the responses "Vessels, diameter", "Rays, number per millimetre" and "Rays, number of cells wide"; see Tables 43-48. It is not known whether the treated species show significant statistical difference for "Rays, height" as data could not be reliably collected for this response during image analysis. (see *Limitations* section for explanation.) As is the case with *Grevillea* and *Hakea*, vessels that are arranged in tangential bands are not measured for "Vessels, number per square millimetre" (Wheeler, Baas *et al.* 1989: 259); accordingly no raw data were collected for this response.

"Vessels, diameter"

Table 43 Rankings for back-transformed predicted means for "Vessels, diameter" for *Grevillea*/*Hakea* taxa and Table 44 pairwise comparisons based on log-transformed data. Numbers in top and left columns equate with rankings for predicted means in Table 43.

Rank	Species	Mean (µm)
1	*striata*	62.240
2	*eyreana*	29.874
3	*leucoptera* ssp. *leucoptera*	23.243
4	*juncifolia*	16.023

	1	2	3	4
1		√	√	√
2	√		√	√
3	√	√		√
4	√	√	√	

"Rays, number per millimetre"

Table 45 Rankings for predicted means for "Rays, number per millimetre" for *Grevillea*/*Hakea* taxa and Table 46 pairwise comparisons. Numbers in top and left columns equate with rankings for predicted means in Table 45.

Rank	Species	Mean (rays/mm)
1	*juncifolia*	3.632
2	*leucoptera* ssp. *leucoptera*	3.535
3	*eyreana*	2.364
4	*striata*	1.758

	1	2	3	4
1		N	√	√
2	N		√	√
3	√	√		√
4	√	√	√	

"Rays, number of cells wide"

Table 47 Rankings for predicted means for "Rays, number of cells wide" for *Grevillea*/*Hakea* taxa and Table 48 pairwise comparisons. Numbers in top and left columns equate with rankings for predicted means in Table 47.

Rank	Species	Mean (no. of cells)
1	*striata*	17.133
2	*eyreana*	16.692
3	*juncifolia*	10.950
4	*leucoptera* ssp. *leucoptera*	8.892

	1	2	3	4
1		N	√	√
2	N		√	√
3	√	√		√
4	√	√	√	

Capparis

"Vessels, diameter" and "Rays, number of cells wide" showed significant variation at the 5% level for the two *Capparis* species; see Tables 49-50. Pairwise comparisons are not shown since only two species were treated.

"Vessels, diameter"

Table 49 Back-transformed predicted means for "Vessels, diameter" for *Capparis* taxa. Means with different superscript letters are signficantly different. Numbers in top and left columns equate with rankings for predicted means in Table 49.

Species	Mean (µm)
mitchellii	36.929 a
loranthifolia	23.453 b

"Rays, number of cells wide"

Table 50 Back-transformed predicted means for "Rays, number of cells wide" for *Capparis* taxa. Means with different superscript letters are signficantly different. Numbers in top and left columns equate with rankings for predicted means in Table 50.

Species	Mean (no. of cells)
mitchellii	5.762a
loranthifolia	4.506b

Corymbia

The response "Rays, number per millimetre" showed significant variation at the 5% level for the two *Corymbia* species; see Table 51. Pairwise comparisons are not shown since only two species were treated.

"Rays, number per millimetre"

Table 51 Back-transformed predicted means for "Rays, number per millimetre" for *Corymbia* taxa. Means with different superscript letters are signficantly different. Numbers in top and left columns equate with rankings for predicted means in Table 51.

Species	Mean (rays/mm)
aparerrinja	13.72a
terminalis	9.34b

Discussion

The task of wood identification can be made difficult by the variation that can occur within a species and, conversely, the lack of variation that may occur between species or between related genera. Knowledge of the extent and sites of intra-specific variation can assist in providing a measure of confidence for separating closely related species. This section discusses the results of the statistical analyses at each of the tested taxonomic levels. For the largest treated genus – *Acacia* – it briefly examines whether the numerical data lends support to groupings of the genus based upon standard botanical characteristics. However, all the results must be viewed with caution given the limited specimens upon which the analyses were based.

Intra-specific analyses (within species variation)

For wood identification purposes, and, indeed, in commercial enterprises such as Forestry, it is desirable that intra-specific variation is minimal or, at least, measurable. To determine the extent of variation that can occur within a species, and the sites of this variation, can be an important requirement of wood identification. Of equal importance is to isolate and determine whether constancy in certain characters may exist within a species. Amidst other variables, these characters may provide the touchstone for the identification of the species.

In this research, the analyses conducted at the intra-specific level indicated that statistically significant levels of variation occur within all of the 18 tested species for at least one of the five responses. In the case of *Eucalyptus coolabah, Eucalyptus camaldulensis* var. *obtusa*

and *Casuarina pauper*, the tested specimens indicated significant variation for all five responses. Encouragingly, however, for one taxa (*Acacia stenophylla*) four responses did not reveal significant variation whilst a further five taxa (*Acacia murrayana*, *Eucalyptus populnea*, *Corymbia terminalis*, *Eremophila longifolia* and *Dodonaea viscosa* ssp. *angustissima*) did not reveal statistically significant variation for three responses. These results suggest that certain species may produce wood with less variability than others. To what extent this is based on similarity or differences in growth regimes requires additional testing with the analysis of further individuals.

The response that showed the greatest constancy (that is, the least occurrences of statistically significant variation) was "Vessels, diameter". On the 18 occasions the response was tested, nine non-significant results were recorded whilst "Rays, number per mm" returned eight non-significant results. "Vessels, number per square millimetre" returned non-significant results on six of the 15 occasions it was tested. The responses that showed the greatest variability were "Rays, number of cells wide" – five non-significant responses on the 18 occasions it was tested – and "Rays, height" – four non-significant results on the 15 occasions it was tested. This indicates constancy of certain characters may exist within species, and that some characters may be more reliable than others, although extra sampling is needed to test the rigorousness of this statement.

Inter-specific analyses (between species variation)

Whilst plants are separable at the genus and family level by examination of standard taxonomic features such as the fruits, flowers and leaves, this variability does not always extend to wood. This similarity is usually most apparent in the qualitative characteristics so that the wood produced from species belonging to the same genus is difficult to separate on these grounds alone. Accordingly, it is useful to determine the extent to which closely related species are separable using quantitative means and to isolate any significant variability in characters that may act as a means to separate species. The results also lend themselves to inferences on the usefulness of each character in terms of separating closely related genera – *Eucalyptus* and *Melaleuca* (Myrtaceae), *Eremophila* and *Myoporum* (Myoporaceae), and *Grevillea*/*Hakea* (Proteaceae) are difficult to separate using qualitative characters.

The results of the inter-specific testing are encouraging with all five responses indicating statistically significant variation for *Acacia*, *Eucalyptus*/*Melaleuca* and *Eremophila*/*Myoporum*. The two *Capparis* species were statistically significant for the responses "Vessels, diameter" and "Rays, number of cells wide" whilst the two *Corymbia* species were statistically significant for "Rays, number per millimetre"[2]. *Grevillea*/*Hakea* were statistically significant for all responses except "Rays, height" and "Vessels, number per square millimetre" for which data were not collected during image analysis.

"Vessels, diameter", "Rays, number of cells wide" and "Rays, number per millimetre" revealed statistically significant variability on five out of the six occasions they were tested; only *Corymbia* and *Capparis* failed to score significant results for all three responses. The least variation was shown in the responses "Vessels, number per square millimetre" and "Rays, height" (each with three of five tests statistically significant). Despite this, the following discussion of the pairwise comparisons reveals that these two responses may be important measures of variability for *Acacia*, *Eucalyptus*/*Myrtaceae* and *Eremophila*/*Myoporum*.

Acacia

The pairwise comparisons for the 19 *Acacia* taxa reveal that of the 171 available species comparisons, 134 (or 78%) are separable using the character "Vessels, number per square millimetre" and 110 (or 64%) are separable using the character "Vessels, diameter". In the absence of *Acacia peuce*, the total available species comparisons for the remaining three responses is 153, 110 (or 72%) of which are separable using the character "Rays, height"; 94 (or 61%) of which are separable using "Rays, number of cells wide"; and 51 (or 33%) of which are separable using "Rays, number per millimetre".

These results indicate that the character "Vessels, number per square millimetre" exhibits the most variability between taxa whilst "Rays, number per millimetre" presents the least variability. In other words, use of the character "Vessels, number per square millimetre" may be the best means to separate *Acacia* taxa. This concurs with cursory, qualitative judgements of this feature during microscope assessment of *Acacia* where large variations in vessel number are apparent. However, whether the extent of variability for each of the responses can be used as a reliable measure of confidence in separating species is dependent on additional testing for intra-specific variation.

In the latest *Flora of Australia* treatment, taxonomists recognise 11 distinct groupings of species within the *Acacia* genus based upon standard morphological characteristics (Maslin, George *et al.* 2001: 43); the *Acacia* species treated in this research fall within groups 4, 5, 8 and 9 whilst *Acacia farnesiana* belongs to group 1. Given the relatively large number of *Acacia* taxa examined, the results of the inter-specific analyses were compared to these morphological groups to determine if they were supported by the wood morphology. Three of the five treated Group 8 species – *A. cambagei*, *A. cana* and *A. oswaldii* – are grouped together in the rankings for "Vessels, diameter" and "Rays, height" and the three species are interrupted only by a Group 4 species – *A. salicina* – in the rankings for "Rays, number of cells wide". Three of the four treated Group 9 taxa – *Acacia cyperophylla* var. *cyperophylla*, *Acacia stowardii* and both *Acacia aneura* sub-species – are ranked together for the characters "Vessels, diameter" and "Rays, number per millimetre". For "Rays, number of cells wide" the fourth species – *Acacia petraea* – is separated from the other three species only by Group 4 species *Acacia tetragonophylla*. The numerical data did not obviously support Group 4 and Group 5 with species belonging to these groups remaining relatively isolated.

Eucalyptus/*Melaleuca*

The pairwise comparisons for *Eucalyptus* and *Melaleuca* reveal that of the 21 possible species comparisons, 17 (or 81%) are separable using "Rays, height"; 15 (or 71%) are separable using "Rays, number per millimetre" and "Rays, number of cells wide"; 10 (or 48%) are separable using "Vessels, diameter"; and for "Vessels, number per square millimetre" 6 (or 29%) were statistically significant.

Notwithstanding additional testing for intra-specific variation, these results suggest that rays exhibit more quantitative variability between taxa belonging to *Melaleuca* or *Eucalyptus* than vessels. This indicates that separating species belonging to either genus may be achieved with a greater level of confidence using numerical data obtained from rays rather than data obtained from vessels. In particular, it indicates that, of the five numerical characters, the greatest confidence can be had if separation is based on "Rays, number per millimetre".

The results also indicate that *Eucalyptus* species may be separable from *Melaleuca* species using the three numerical characters pertaining to rays. For "Rays, height" and "Rays,

number of cells wide" *Melaleuca trichostachya* and *Melaleuca glomerata* returned larger means than the *Eucalyptus* species whilst for "Rays, number per millimetre" they return the smallest means.

Eremophila/*Myoporum*

The pairwise comparisons for *Eremophila* and *Myoporum* reveal that of 36 possible species comparisons, 26 (or 72%) are separable using "Vessels, number per square millimetre" and "Rays, height"; 22 (or 61%) are separable using "Rays, number of cells wide"; 19 (or 53%) are separable using "Rays, number per millimetre"; and 18 (or 50%) are separable using "Vessels, diameter".

As with *Acacia*, and notwithstanding further testing for intra-specific variation, these results suggest that the character "Vessels, number per square millimetre" is the most reliable numerical character to separate taxa belonging to *Eremophila* or *Myoporum*. This supports expectations arising from a cursory, qualitative judgement of vessel number in the Myoporaceae family where variation seems evident. "Vessels, diameter" presents with the least significant variability between taxa and is the least useful character for separating members of *Eremophila* and *Myoporum*

The results are encouraging at the inter-generic level, with *Myoporum montanum* registering the least rays per mm and the longest rays of all the tested Myoporaceae taxa. For the remaining responses – "Vessels, number per square millimetre", "Rays, number of cells wide" and "Vessels, diameter" – *Myoporum montanum* was ranked amongst the *Eremophila* species providing little measure of difference for separating the two genera.

Grevillea/*Hakea*

The pairwise comparisons for *Grevillea* and *Hakea* show that of 6 possible species comparisons, 6 (or 100%) are separable using "Vessels, diameter" and 5 (or 83%) are separable using "Rays, number per millimetre"; and "Rays, number of cells wide". ("Vessels, number per square millimetre" and "Rays, height" were not examined).

Bearing in mind the limited data set, these results indicate that species belonging to *Grevillea* and *Hakea* show significant variation in "Vessels, diameter". The results also suggest that separating the two genera may be difficult using the tested responses with

neither *Grevillea* nor *Hakea* showing any large disparities at the generic level. This suggests Proteaceae wood may present with little inter-generic diversity.

Capparis & *Corymbia*

Corymbia showed the least statistically significant variation between the two tested species – only "Rays, number per millimetre" exhibited significant difference – whilst *Capparis* presented with significant variability for the responses "Rays, number of cells wide" and "Vessels, diameter". Whilst this may indicate that these characters are useful in separating species belonging to *Corymbia* or *Capparis* it is difficult to draw any meaningful conclusions from the data for these genera given that only two species were treated.

Limitations

Despite indicating potential trends in the data, this research has been tempered by the lack of replication for both the intra- and inter-specific analyses along with several other potential shortcomings. This section details some of these limitations.

Limited sampling

The intra-specific analyses involved testing two to four trees from 20 different species (and from different populations within the surveyed region); however, for wood identification purposes it is usual to examine specimens from up to 10 trees to account for any within-species variation. In terms of the inter-specific analyses, it is important to consider that any indications of difference in the data may be rendered artificial in the event of further intra-specific testing. Moreover, except for *Acacia*, with 19 taxa, and possibly *Eucalyptus* and *Eremophila*, the treated genera were represented by a limited number of species; nevertheless, they provide a good foundation for future inclusion and analysis of new species, and most record a common distribution in the surveyed area incorporating regions of Queensland, New South Wales and South Australia.

Within-tree variation

In examining only limbwood, a third area of variation was not considered – that which may occur within a tree in the wood from different plant parts. Studies have shown that rootwood (Cutler 1976; Cutler, Rudall *et al.* 1987), limbwood, juvenile wood and trunkwood may all show variation in wood anatomical characters. This shortcoming must be borne in mind in applying the identification tool to unknown specimens and in

comparing results with treatments that may have been based on trunkwood, as with many Forestry publications[53].

Limited number of observations per species

During data collection, the number of observations per species that were made for each character was variable. As a result, some responses tested in the statistical analyses may have produced more reliable results than others. For example, the compendia compiled for each of the characters in Appendix Seven shows that the number of observations for "Rays, height", "Rays, number of cells wide" and "Vessels, diameter" were relatively large; an average of 78 rays per tree were measured for "Rays, height" whilst an average of 184 vessels per tree were measured for "Vessels, diameter". For "Rays, number of cells wide", an average of 96 rays per tree were measured. However, for "Rays, number per millimetre" and "Vessels, number per square millimetre" the number of observations is measured by the area, not by the vessel or ray; consequently, an average of seven areas per tree were measured for "Rays, number per millimetre" whilst an average of four areas per tree were measured for "Vessels, number per square millimetre". This means interpretations based on data collected for these characters is less trustworthy since the fewer the observations the less reliable the data.

Collection of raw data using *analySIS*

The results of the statistical analyses may have been affected by the process used to collect the raw data. For "Rays, height", "Rays, number of cells wide" and "Rays, number per millimetre", the count method used to collect the data was simple and reliable and its accuracy reduced only by variability in SEM image quality and brightness and contrast. One exception was the failure to accurately measure the "Rays, height" of the treated Proteaceae taxa; the issues are described in Figure 50.

[53] However, with the exception of a few notable species, many of the treated species will not have been treated in previous research, largely because they are not utilised commercially.

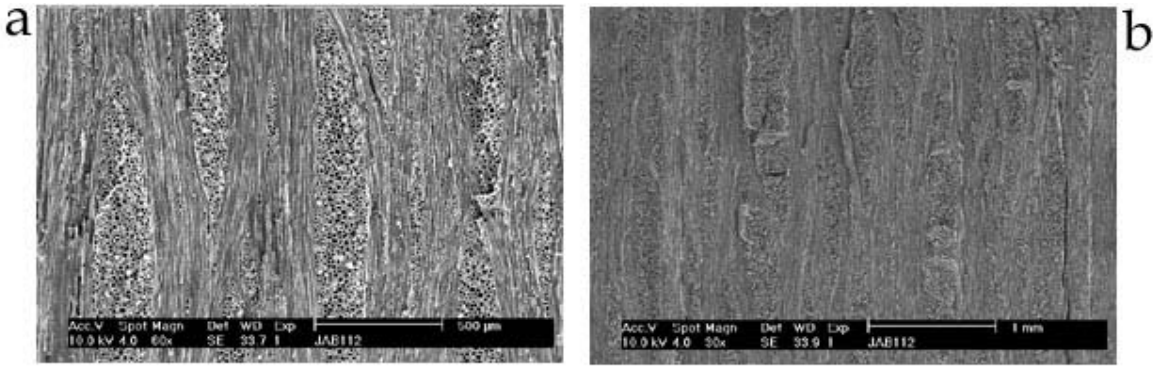


Figure 50 These tangential surface SEM images illustrate the difficulty of accurately measuring "Rays, height" in Proteacae where the largest rays measure over 1 mm. The examples are both from JAB112 *Hakea leucoptera* ssp. *leucoptera*. Image A provides the best clarity but, at this magnification, measurements would be biased towards the smaller rays in Proteaceae (Scale = 500 µm). The lower magnification image B shows some, but not all, of the larger rays in their entirety but the image clarity is considerably reduced making rays difficult to delineate (Scale = 1 mm).

The collection of data for "Vessels, diameter" and "Vessels, number per square millimetre" utilised a more subjective approach to capture (and measure) the vessels and the variability that occurs within and between species meant that some difficulties were had applying the same standards of control to every SEM image. For example, the presence of inclusions in the vessels of some species meant that vessels could not be appropriately captured using the standard technique of adjusting the thresholds (Figure 51). For these species, vessels needed to be manually appended; this was not desirable as manual intervention introduces a degree of subjectivity that reduces the ability of an automated function of *analySIS* to offset any imbalance in the data set (Self 2004: *pers. comm.*).

Depending on the species and/or the brightness and contrast of the SEM image, sometimes unwanted particles (not vessels) were captured by the thresholds. This was dealt with using one or a combination of two methods. The preferable method was to adjust the parameters that govern the particle analysis. For example, elongated ray cells could be removed by eliminating particles with ratios of greater than 2:1 or 3:1. Alternatively, the minimum Proj-X diameter could be defined so that particles with a tangential diameter of less than 30 µm were removed from the analysis; this was useful to remove unwanted parenchyma cells that had been captured by the threshold settings although it was often

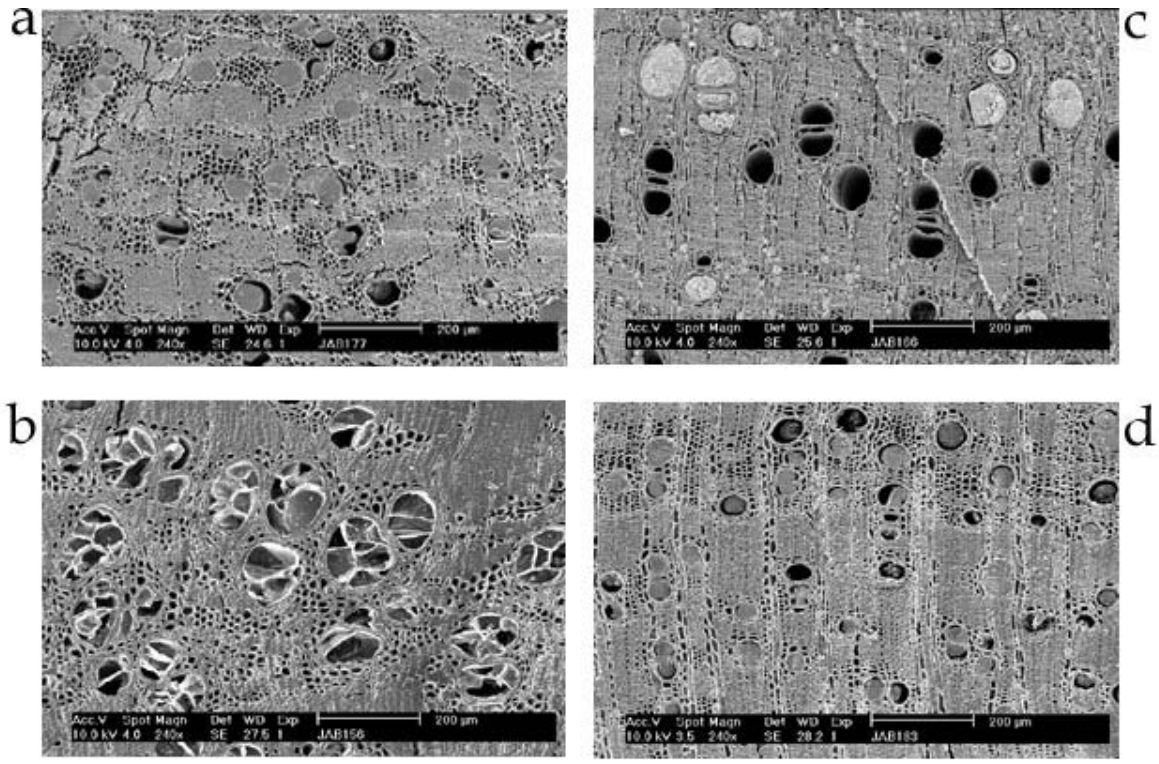


Figure 51 Vessels with inclusions required manual delineation for image analysis for "Vessels, diameter" and "Vessels, number per square millimetre". A. JAB177 ?*Acacia aneura* var. *intermedia* with resin?; B. JAB156 *Corymbia terminalis* with tyloses; C. JAB166 *Ventilago viminalis* with calcium carbonate or silica?; D. JAB183 *Senna artemisioides* ssp. *filifolia* with resin? (Scales = 200 µm)

difficult to distinguish parenchyma cells from vessels on the transverse surface, particularly where some intergradation in size occurred. The second method of removing unwanted particles from the analysis was to manually delete captured particles that were not vessels; however, of the two methods this was less desirable due to the risk of introducing subjectivity and interfering with the ability of *analySIS* to offset imbalances in the data set through automated processes.

Relativity of magnifications

In the interests of removing variables and collecting standardised data, every attempt was made to collect data at consistent magnifications. However, the variability in vessel (and ray) size was such that magnifications needed to be adjusted to provide a balance with field of view. Whilst data from separate areas of a specimen were collected at a standard magnification this magnification varied between specimens: 120x or 240x images were commonly used but occasionally data were collected at lower or higher magnifications. Just as there was variation in magnification between species there was also variation within

species; this was an unfortunate result of obtaining herbarium identifications after data collection so that, for example, data collection for "Vessels, diameter" and "Vessels, number per square millimetre" for JAB151 and JAB158 (*Acacia stowardii*) occurred at different magnifications – 241x and 121x respectively. In the case of JAB100 (60x), JAB107 (121x), JAB133 (121x), JAB137 (96x), which were all known to be *Eucalyptus coolabah* at the time of data collection, the varied magnifications were an oversight. This lack of standardisation may have affected both the intra- and inter- statistical analyses.

Replicating the process

An important consideration in producing an identification tool is that the process used to collect the data from reference specimens is transferable to unknown specimens; that is, the process should be replicable. It has been shown that the process used to collect the raw data for the numerical characters can be subjective, particularly in relation to "Vessels, diameter" and "Vessels, number per square millimetre". Moreover, variability in vessel (or ray) size between species can affect the magnification at which data are collected. Finally, variability in SEM image quality, either as a result of preparation of the specimen or imaging, can affect the accuracy of data collection. Whilst attempts have been made elsewhere to fully document the process used to collect data[54] using *analySIS*, eliminating all of these variables is impossible; accordingly, statistical analyses may be limited by the accuracy with which replication of the original process has taken place.

Conclusion

The results of the statistical analyses applied in this research provide encouraging pointers for future directions. In particular, the research has indicated that non-significant statistical variation can occur within a species and that, where qualitative characters fail, statistically significant variation in numerical characters can occur between closely related species and potentially assist the separation of species. Moreover, the analyses have revealed that certain characters may remain constant within certain species; isolating this constancy and where it exists may provide an important means of recognising intra-specific variation and

[54] See Chapter Five, where the process used to collect data using *analySIS* is described, and also the suite of identification keys, where factsheets attached to each character state contain instructions on how best to collect data.

correctly identifying a species. Bearing in mind the limited data set, the present analyses indicate the characters "Vessels, diameter" and "Rays, number per mm" are least variable within the tested species. Conversely, the analyses have reinforced the possibility that related genera that are difficult to separate using qualitative characters – such as *Melaleuca*/*Eucalyptus* and *Eremophila/Myoporum* – may be separable using certain numerical characters. The numerical data for *Grevillea*/*Hakea* revealed no variation at the generic level but future research involving further qualitative and quantitative analyses may reveal a means of separation. Encouragingly, the statistical analyses have supported expectations based on cursory qualitative judgements of numerical characters in *Acacia,* by indicating separation of species is possible.

This chapter has been strongly moderated by the need to conduct additional testing for intra-specific variation, as well as for the variation that can occur within the wood from different plant parts, so that the patterns emerging from these analyses may be tested. This will serve to instil a greater measure of confidence in the characters used to separate species, isolating the most useful and least useful characters for the process. In addition, the statistical analyses provide a helpful measure of confidence in the developed identification tools, encouraging the future incorporation of further specimens and species.

Chapter Eleven. Application of the *Key to a Selection of Arid Australian Hardwoods & Softwoods* to Aboriginal artefacts (with case studies)

Introduction

Despite the potential application of the developed identification tool to a wide range of disciplines, this study was originally developed in response to the large numbers of wooden Aboriginal artefacts held in museums across Australia and overseas. The development of a technique that allows definitive identification to species level of the wood used to construct an Aboriginal artefact can greatly enhance anthropological knowledge based upon the restricted geographic range of certain plant species. The implications of definitive identifications of cultural objects are enormous for they pave the way for a re-evaluation of existing anthropological data, reinterpretation of anthropological collections and a reinvigoration of the discipline with the development of a new set of questions based upon environmental exploitation, trade and exchange patterns, and the movement of people.

This chapter first provides a background to museum-based studies of material culture and the application of scientific methods, usually reserved for archaeology, to cultural objects. More specifically, an outline is given of the significance of definitively identifying the biological materials used to construct Aboriginal artefacts to the areas of interpretation and display, conservation, storage and repatriation. The second part of this chapter provides case studies based upon the application of the *Key to a Selection of Arid Australian Hardwoods & Softwoods* to three wooden Aboriginal artefacts purportedly from central Australia. Attempts to interpret the results in an anthropological context are limited since this was considered beyond the scope of this research; the development and wholesale use of centralised reference banks and tools dedicated to the identification of materials used in Aboriginal artefact construction would form the basis of further research projects that extend the study into these areas.

Background

In order to understand the implications of this study to the field of museum anthropology it is necessary to understand the nature of the museum collections and how they were amassed. This section provides the context for this research within an historical and contemporary framework.

The rise of the colonial museum

During the late 19th and early 20th centuries, Charles Darwin's theories of evolution and natural selection, expounded in his publication *On the Origin of Species* (Darwin 1859), were generally accepted in the Australian colonies and it had become commonplace to apply his theories to humankind. The extension of Darwinian theory to humans was referred to as Social Darwinism, an ideology used to explain why coloured races fared so badly when confronted with European invasion (Broome 1982). From Social Darwinism came the notion that Australian Aborigines represented a "dying race", a people unable to survive the evolutionary process and destined to eventually yield to the advance of "civilisation". In a country colonised by Europeans who had readily accepted much of the evolutionary and ethnocentric ideologies that preceded Darwin's theories, Social Darwinism was developed and fostered to provide scientific justification (and probably momentum) for much of the violence that occurred both within and on the frontier of Australia, as well as the racist doctrines employed by the various colonial governments of the day.

This enthusiasm for classifying nature and culture eventually gave rise to the colonial museum and by the 1860s scientific collections were open to the public in every capital city of Australia (Griffiths 1996: 18). These new museums provided a display case and storage for the "exotic" Australian plants, animals and people, all of which were fast disappearing under the advancement of Europeans. Museums embodied the imperialist principles of the Australian colonies (a label that persists into the present) and their collections of natural history specimens and ethnographic objects signified European dominance of the Australian landscape. The rise of the colonial museum was also brought about by the interest of the international, developed world in all things exotic and Australian museums participated heavily in the exchange of Aboriginal artefacts and natural history specimens and contributed specimens to the celebrated International

Exhibitions of the colonial era (see Mather 1986; Griffiths 1996: 18: Jones 1996: 55-59; Hale 1956: 21-22; Strahan 1979). The dispatch and exchange of antiquities to Europe, particularly in the early 19th century, was compounded by the lack of an Australian national identity and the strong links that were retained by colonists to their homelands (Jones 1996: 66). But even as the notion of an Australian heritage evolved in the late 19th century, the exchange in specimens of Australiana was intensifying (Jones 1996: 66). Even today, many of the early Australian ethnographic objects and plant and animal specimens are retained by European and American institutions.

The legacy of the colonial museum

The legacy of the colonial museum and its haphazard collecting policies is still evident in ethnographic collections today. Museums, particularly western institutions, have been left with immense collections comprising millions of artefacts that are, in the main, poorly documented, inadequately catalogued and under-researched (Durrans 1988: 166; Reynolds 1979: 9; Reynolds 1986: 297; Reynolds 1989: 111; Reynolds and Stott 1987: 5; Sturtevant 1969). The situation was compounded early in the 20th century with the split between museum anthropology and academic (or social) anthropology and by the middle of that century, material culture studies and research output had slumped to an all time low (Bouquet 1999; Reynolds 1979).

Since the publication of the Sturtevant (1969) report, the paucity of written records accompanying museum specimens has been generally well acknowledged and oft lamented (Durrans 1988: 166; Furst 1989: 98, 102; Nason 1987: 43; Reynolds 1979; Reynolds 1989: 111). Notations describing an object are typically limited to a brief description of the object, the collector's name and the location and date of collection. For example:

> Specimen number 32316. Club, wooden. Reuther Collection. Lake Eyre Basin. Collected 1890 – 1905.
>
> (*South Australian Museum* 2002)

Many other artefacts can not even lay claim to this level of documentation, their secrets, for the most part, remaining trapped within them.

A climate of change

Contemporary museums and museum anthropologists continue to be dogged by persistent elitist, imperial and irrelevant labels (Appleton 2001; Durrans 1988: 252; Fourmile 1989; Jenkinson 1989: 142; Mauldon 1992) but are struggling to reinvent themselves. In the last two decades, this revival has been evident in various publications based upon material culture research that have variously put forth, examined and critiqued new strategies for display, research, public access, collecting policies and the role of the curator (Cooper 1979; Crosby 1979; Koepping 1979; Lumley 1988; Pearce 1989; Reynolds 1979; Reynolds 1986; Reynolds and Stott 1987; Shelton 1992). More recently, there has also been encouraging interest, from academic and museum anthropologists alike, in increased collaboration between the two branches of anthropology in the realms of research and exhibition (Ames 1992; Bouquet 1999; Haas 1996).

Amidst this re-evaluation of the discipline, the notion of the *artefactual document* (Reynolds 1979; Reynolds 1986) emerged, a concept that seeks to view artefacts themselves as a document and to develop methods to chronicle their history and meaning, much as archaeologists have done in the absence of written records for many years (Reynolds 1979; Reynolds 1986). In fact, the notion of the *artefactual document* borrows much from archaeology with its promotion of developing laboratory techniques such as microwear analysis, dating and materials identification (Reynolds 1979) to answer fundamental questions of an otherwise silent object:

- *What is the artefact? (not always simple to answer)*
- *What is it made of?*
- *When was it made?*
- *Where was it made and used? (culturally and geographically)*
- *How was it made?*
- *What was it used for?*
- *What can it tell us about the people and their culture?*

(from Reynolds 1989: 116)

To date, and despite the advancements of archaeological techniques of analysis, few laboratory methods have been devised for application to ethnographic objects. This study seeks to examine one aspect of laboratory analysis, materials identification, in

acknowledgment of the considerable outcomes that such research can deliver in the realm of museum anthropology as well as other disciplines.

Significance

Determining the materials used in the construction of ethnographic artefacts can deliver numerous outcomes that extend across many aspects of museum anthropology. This section concentrates on the immediate benefits this study may afford to the discipline of anthropology. Whilst this research specifically deals with wood identification, the broader phrase "materials identification" is applied here in recognition of the fact that other biological materials and parts – both plant and animal – are used in the construction of cultural objects and that their identification to species level would provide similar benefits to the field of anthropology.

Conservation

Most artefacts in an ethnographic collection cannot be re-collected and are indelibly and uniquely marked by the historical context from which they came. Thus, it is important to appropriately conserve them for the appreciation of future generations. Materials identification, along with an understanding of processes of artefact construction and use, is an important requirement for conservators seeking to develop appropriate conservation strategies to increase the longevity and preserve the integrity of artefacts. Materials analysis can also be useful to conservators for restorative work and providing comprehensive documentation of the artefact as well as to establish the presence of prior repairs/modifications. Misidentification of materials can lead to the development of a conservation strategy that can seriously damage the artefacts and it is likely that misidentifications often arise by an over-reliance on identifications given in the ethnographic documentation (Norton 2001: *pers. comm.*).

Storage

A persistent issue facing museums is finding adequate storage for their vast collections. Since a large proportion of ethnographic artefacts are poorly documented, developing and applying techniques that can extract information from an object can be useful with respect to prioritising and managing collections based upon their research potential and importance.

Interpretation & Display

The collections reveal as much about the collectors as the collected…

(Jones 1996: 91)

Knowledge of the materials that comprise an artefact is an important requirement for present-day anthropology, where an over-reliance on the ethnographic documentation can result in perpetuating misconceptions pertaining to indigenous people. This misinformation can be damaging to indigenous people and our understanding of the complexities inherent in their culture. Most anthropologists will accept that the period in which an artefact was collected was not necessarily the period when the object was constructed or used, and the danger in assuming this to be so is readily understood. The same level of caution should be applied to accepting that the materials identified in ethnographic documentation are accurate. As discussed in Chapter Two, establishing the species used to construct an artefact using scientific methods can provide important validation or rejection of ethnographic documentation. In addition, materials identification may increase our understanding of the provenance of an artefact, particularly where little or no ethnographic documentation accompanies the object; increase knowledge and understanding of post-contact Aboriginal plant use and exploitation of the environment and changes over time; improve knowledge and understanding of patterns of trade and exchange between Aboriginal groups; increase insights into the mobility within and between Aboriginal groups; enhance knowledge of collector biases and misconceptions of Aboriginal Australian culture; establish the rarity, authenticity and/or monetary value of an object; and assist in determining the date of the object's manufacture.

A good example where wood identification has exposed contemporary and collector biases comes from a *Queensland Museum* study of spearthrowers (Robins 1980); this study was previously introduced in Chapter Two. Joseph Campbell was a pastoralist from Kamma, near Cairns, who employed Aboriginal labour to work on his station. In 1916 he donated 21 spearthrowers to the *Queensland Museum*. The museum register recorded each of the spearthrowers as being from the Kamma region. However, the wood analysis showed that the spearthrowers were composed of at least ten different species of wood, five of which had not been previously recorded in the ethnographic literature for that region. Robins

suggests that the discrepancy arises not from the diverse resource base of the Aborigines of the region but from the fact that Campbell probably employed Aborigines from a large area of Queensland and, presumably, a range of language groups. Had this research not been conducted staff of the museum may have continued to believe that the 21 spearthrowers were representative of Aboriginal people who traditionally belong to the Kamma region. One wonders how many other misconceptions have manifested themselves in museum registers and ethnographic documentation only to be perpetuated nearly a century later in publications and exhibitions.

Repatriation

Over the past two decades, as Aboriginal voices have become louder and the political climate has changed, there has been an increasing demand upon museums to develop policies that allow for the return of material culture to Aboriginal communities. Identifying the species used in the construction of artefacts can assist in ensuring that objects are returned to the correct communities. Such analysis would prove particularly useful for material lacking a documented provenance or where the documented provenance is proved incorrect. For artefacts of exchange, it may also establish that several communities may have valid reasons to claim the object (e.g. those that constructed the object, those that exchanged the object and those that acquired the object). In addition, where Aboriginal knowledge no longer exists, or for groups that have disappeared, materials identification of surviving artefacts can provide one of the few sources of documentary evidence pertaining to these people.

Recapturing and returning lost Aboriginal knowledge

A further outcome of materials identification is that the research can be handed back to Aboriginal communities to supplement local plant knowledge and as a teaching aid in local schools. In many Aboriginal communities in Australia there remain only a handful of people with plant knowledge and it may be useful to these communities if the knowledge could be recorded and returned in some form to the community. Consultation with community members will be important to decide the form that this information might take and that the final result is sensitive to their needs as well as their culture.

Case study: application of identification tool to three wooden Aboriginal artefacts

This section discusses the application of the three Aboriginal artefacts – a shield, a boomerang and a coolamon (carrying dish) (Figure 52) – to the *Key to a Selection of Arid Australian Hardwoods & Softwoods*. The three objects are thought to have been acquired by Walter Reichstein (father of the current owner of the artefacts, Thekla Reichstein) when he worked upon the Frew River station, south-east of Tennant Creek, Northern Territory (Figure 53). Walter Reichstein worked on the station between 1930 and 1938 and the station is believed to have used Aboriginal labour. According to maps of Aboriginal Australia the Frew River station is part of the Kaytej[55] territory (Figure 54). A table of Aboriginal wood use in central Australia based upon ethnographic references is provided in Appendix Ten.

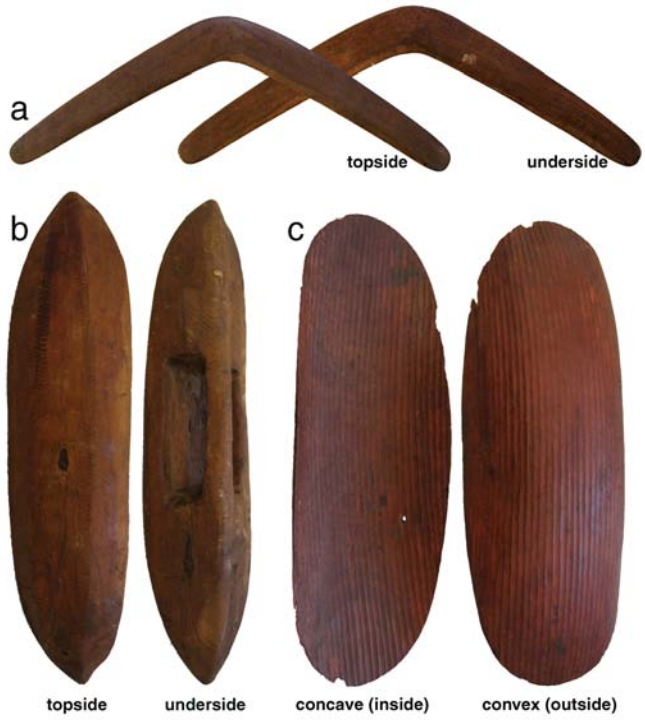


Figure 52 Three wooden Aborginal artefacts applied to the identification tool. A Boomerang; B Shield; C Coolamon.

[55] Also spelt Kaititja ((*South Australian Museum* 2005)) or Kaytetye (recognised by the *Australian Institute for Aboriginal and Torres Strait Islander Studies*.

A species list was obtained from the *Herbarium of the Northern Territory* for the region bounded by 19 by 22 degrees S and 134 by 137 degrees E (Figure 53). As Table 52 shows, at least 28 taxa are shared by the Frew River region and the identification tool. More importantly, of 20 hardwood genera represented in the identification tool, 15 are recorded for the Frew River region; *Schinus* (introduced), *Tamarix* (introduced), *Casuarina*, *Myoporum* and *Flindersia* are not recorded for this area[56].

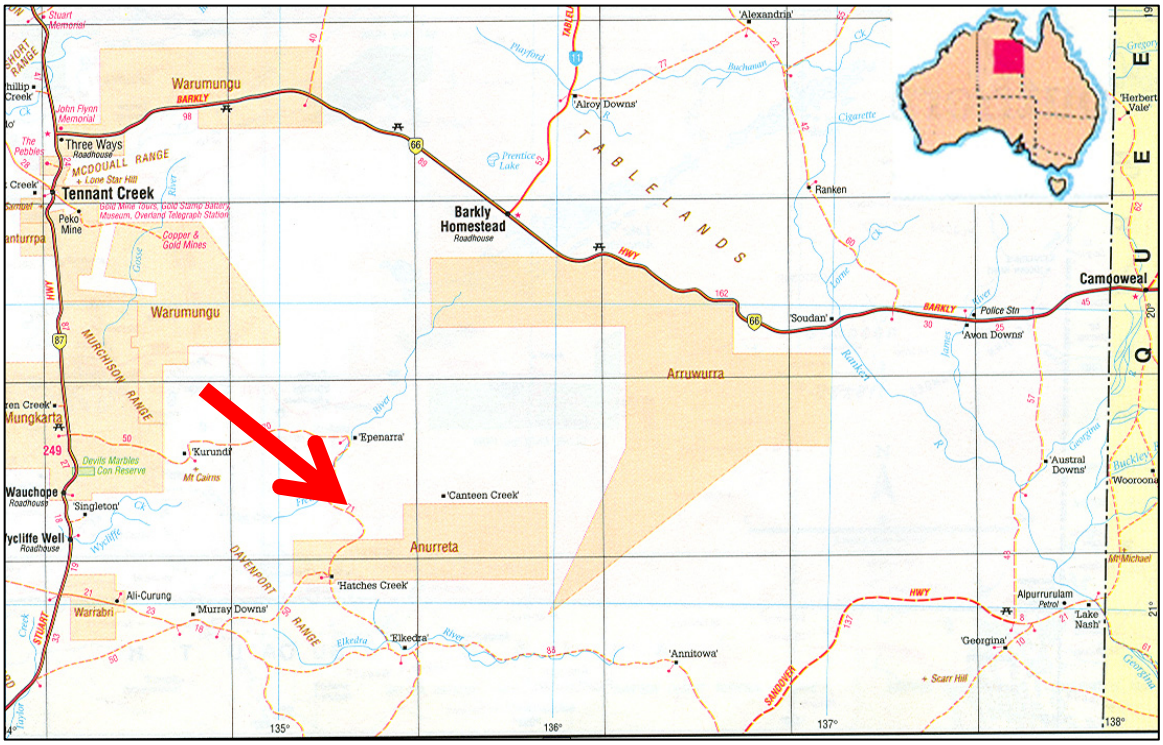


Figure 53 A list of species recorded in the Frew River region was obtained from the *Herbarium of the Northern Territory*. The map (*Queensland Department of Lands* 1995) dimensions show the approximate area for which the species are recorded; the approximate location of the Frew River homestead is indicated by the red arrow.

Methods

The following section outlines the methods by which the three artefacts were sampled, softened and sectioned for endgrain and SEM analyses. It begins, however, with a caveat about the physical and ethical challenges that sampling from Aboriginal artefacts present.

[56] *Schinus* and *Tamarix* are common introduced shade trees to homesteads so it is possible that they may also occur in the Frew River region.

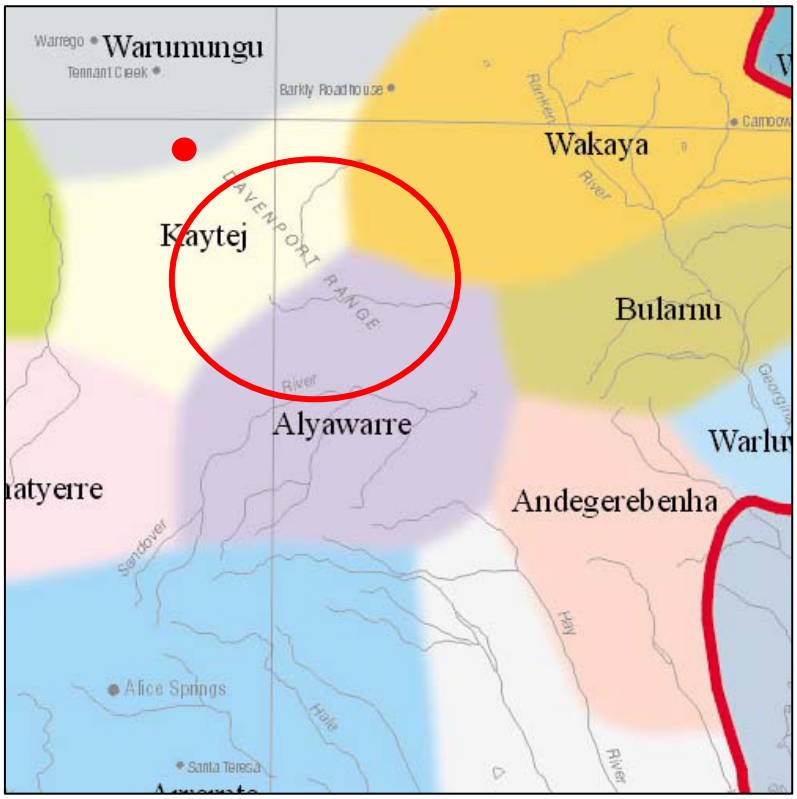


Figure 54 Section of the *Aboriginal Australia Wall Map* (Australian Institute for Aboriginal and Torres Strait Islander Studies 1994) showing the language groups of the Frew River region. Tennant Creek is indicated with a small red dot whilst the large red circle indicates the approximate location of the Frew River station.

Caveat

One of the most challenging elements of this research – both physically and ethically – is the removal of a wood sample from an Aboriginal artefact for identification purposes. Sampling must be conducted in a manner that is sensitive and preserves the artefact's integrity but the sample must also be physically large enough to section. In addition, the method of extraction may be made more difficult by the existence and extent of decoration, the density of the wood and the level of experience in removing samples for wood identification purposes. In advising people on how to sample from precious objects most xylologists recommend splitting samples from the larger object; two cuts made across the endgrain delineate the length of the sample and its depth, whilst a knife or chisel is used to

Table 52 Table listing species treated in identification tool. Highlighted species are also recorded in the Frew River region according to *Herbarium of the NorthernTerritory* data.

FAMILY	Genus	Species
ANACARDIACEAE	*Schinus*	*molle*
CAESALPINIACEAE	*Bauhinia*	*gilva*
	Senna	*artemisioides* ssp. *filifolia*
CAPPARACEAE	*Capparis*	*loranthifolia*
	Capparis	*mitchellii*
CASUARINACEAE	*Casuarina*	*pauper*
CUPPRESSACEAE	*Callitris*	*glaucophylla*
LEGUMINOSAE	?*Acacia*	*aneura* var. *intermedia*
	Acacia	*aneura* var. *aneura*
	Acacia	*cambagei*
	Acacia	*cana*
	Acacia	cf. *stowardii*
	Acacia	*cyperophylla* var. *cyperophylla*
	Acacia	*farnesiana*
	Acacia	*ligulata*
	Acacia	*ligulata* ?intergrade with *A. bivenosa*
	Acacia	*murrayana*
	Acacia	*oswaldii*
	Acacia	*petraea*
	Acacia	*peuce*
	Acacia	*pickardii*
	Acacia	*salicina*
	Acacia	*stenophylla*
	Acacia	*stenophylla*
	Acacia	*stowardii*
	Acacia	*tetragonophylla*
	Acacia	*victoriae* ssp. *arida*
	Acacia	*victoriae* ssp. *victoriae*
MELIACEAE	*Owenia*	*acidula*
MYOPORACEAE	*Eremophila*	*bignoniiflora*
	Eremophila	*duttonii*
	Eremophila	*freelingii*
	Eremophila	*longifolia*
	Eremophila	*macgillivrayi*
	Eremophila	*mitchellii*
	Eremophila	*polyclada*
	Eremophila	*sturtii*
	Myoporum	*montanum*
MYRTACEAE	*Corymbia*	*aparerrinja*
	Corymbia	*terminalis*
	Eucalyptus	*camaldulensis* var. *obtusa*
	Eucalyptus	*coolabah*
	Eucalyptus	*ochrophloia*
	Eucalyptus	*populnea*
	Eucalyptus	*thozetiana*
	Melaleuca	*glomerata*
	Melaleuca	*trichostachya*
PITTOSPORACEAE	*Pittosporum*	*angustifolium*
PROTEACEAE	*Grevillea*	*juncifolia*
	Grevillea	*striata*
	Hakea	*eyreana*
	Hakea	*leucoptera* ssp. *leucoptera*
RHAMNACEAE	*Ventilago*	*viminalis*
RUBIACEAE	*Psydrax*	*latifolia*
RUTACEAE	*Flindersia*	*maculosa*
SANTALACEAE	*Anthobolus*	*leptomerioides*
	Santalum	*lanceolatum*
SAPINDACEAE	*Atalaya*	*hemiglauca*
	Dodonaea	*viscosa* ssp. *angustissima* (Frew River is D. *viscosa* ssp. mucronata)
TAMARICACEAE	*Tamarix*	*aphylla*

prise out the sample along the longitudinal grain (Hoadley 1990: 92[57]; CSIRO 2005; Alden Identification Services 2005; Centre for Wood Anatomy Research 2005). This was essentially the method used to sample from the threeartefacts in this research; scars on the artefacts were restricted to approximately 0.3 cm width by 2 cm length. This method was also adopted in the study of wooden spearthrowers from the *Queensland Museum* where damage was limited to an average depth of 0.5 cm and average length of 2 cm (Robins 1980). However, it is clear that experience sampling from precious objects has led some xylologists to develop techniques that are much less invasive. For example, Harry A. Alden of the *Smithsonian Centre for Materials Research and Education,* Maryland, and Regis B Miller of the *USDA Forest Products Laboratory,* Wisconsin can remove radial, tangential and transverse sections directly from the artefacts with a surgical razor blade or scalpel (Alden 2003: *pers. comm.*; Miller 2003: *pers. comm.*). Alden maintains:

> *I have done this succesfully* [sic] *from many objects too small or valuable to sample the standard way. If done properly, one can not see evidence that the object was sampled. This is an advanced technique for someone with considerable experience in handling small samples & in sectioning.*
>
> (Alden 2003: *pers. comm.*)

These results are certainly impressive and suggest that, with considerable experience, precious wooden objects can be sampled with limited invasiveness. However, is not known how successfully sections could be directly removed from objects made of the high density Australian wood used in this research, particularly when a suitable method of softening the small area of wood from where the section is to be removed *in situ* would probably be required.

Ethical issues in invasively sampling Aboriginal artefacts for research purposes may be largely negated if sampling can be conducted in a sensitive manner that both preserves the integrity of the artefacts, and can be shown to contribute to furthering knowledge of Aboriginal culture. Indeed, the aforementioned study of the "Kamma" spearthrowers is

[57] A diagram of this process is given in Hoadley (1990: 92).

one example where wood identification has dispelled a damaging misconception as to the likely provenance of the artefacts and the arguments for wood identification in terms of conservation and repatriation have already been outlined in this chapter. Nevertheless, there are certain criteria that should be met for both the selection and sampling of Aboriginal artefacts.

Selection of artefacts

- Confirm that reliable comparative wood samples exist that will increase the chances of determining an identification.
- If the artefacts are from a collection, establish the frequency of similar artefacts and avoid rare and unique artefacts.
- Reject artefacts that exhibit extensive designs and/or etchings if they can not be sampled without damaging the integrity of the artefact and the designs.
- Reject artefacts that are too frail to withstand the sampling procedure.

Sampling from artefacts

- Determine the type and size of the wood sample required from the object to increase the chances of successful identification.
- Use the correct instruments for the extraction of samples.
- Sample from areas that will cause the least damage to the artefact e.g. from unfinished joints.
- Record details of all samples extracted from artefacts including information such as specimen number, the location on the artefact from which the sample was obtained and the size of the sample.
- Record details of the artefact from which the samples were extracted including provenance, if known, and a description of its appearance and texture58.
- Provide photographic documentation of the artefact before and after sampling.
- If samples have not been destroyed, deposit them back in the collection so that further analysis may be conducted and/or the identification process may be

[58] A useful template for wood identification for recording details of both the sample and the source artefact is provided in Hoadley (1990: 94).

replicated. Ensure that samples remain linked to the original artefact using the original specimen number.

- Label the artefact to record the research and any publications that have emanated from the research.

Method of sampling

In this research, sampling was conducted by Justin Gare, wooden objects conservator at *ArtLab Australia*. Whilst he had not previously removed samples for wood identification purposes from precious objects, he did practise upon several unvouchered wood specimens prior to sampling the artefacts. Samples were removed with a single-edge razor blade and a hammer. Given the density of the wood, the sharper edge of the razor blade was considered preferable to a chisel. The hardness of the wood meant that razor blades were blunted after a single use and so several were required per artefact. As Figure 55 illustrates, the artefacts were sampled by making two cuts across the grain that delineated the length of the desired sample. Following this a razor blade was carefully broken with pliers so that its length was essentially the same as that of the sample. The blade was aligned in the longitudinal direction of the sample (and between the two endgrain cuts) and struck gently with the hammer until it had reached the desired depth. This was repeated on the opposite side of the sample until the sample could be prised out. Figure 56 shows the resultant samples and photographs of the areas from which the samples were removed.

Softening of samples

Once the samples had been extracted from the artefacts and photographed they were each immersed in vials containing 50% hydrofluoric acid. After being left to soak in the acid for four hours, the samples were decanted and gently boiled in water for one hour.

Endgrain preparation for optical and SEM microscopy

The density of the wood and the lack of a technique to soften wood in situ meant that attempts to polish a small area of the endgrain directly from each artefact yielded poor results that lacked in clarity. To remedy this, immediately after the samples were removed from the boiling water, the endgrains of the samples were polished. Polishing was conducted with a razor blade and the samples were left to dry overnight. The following

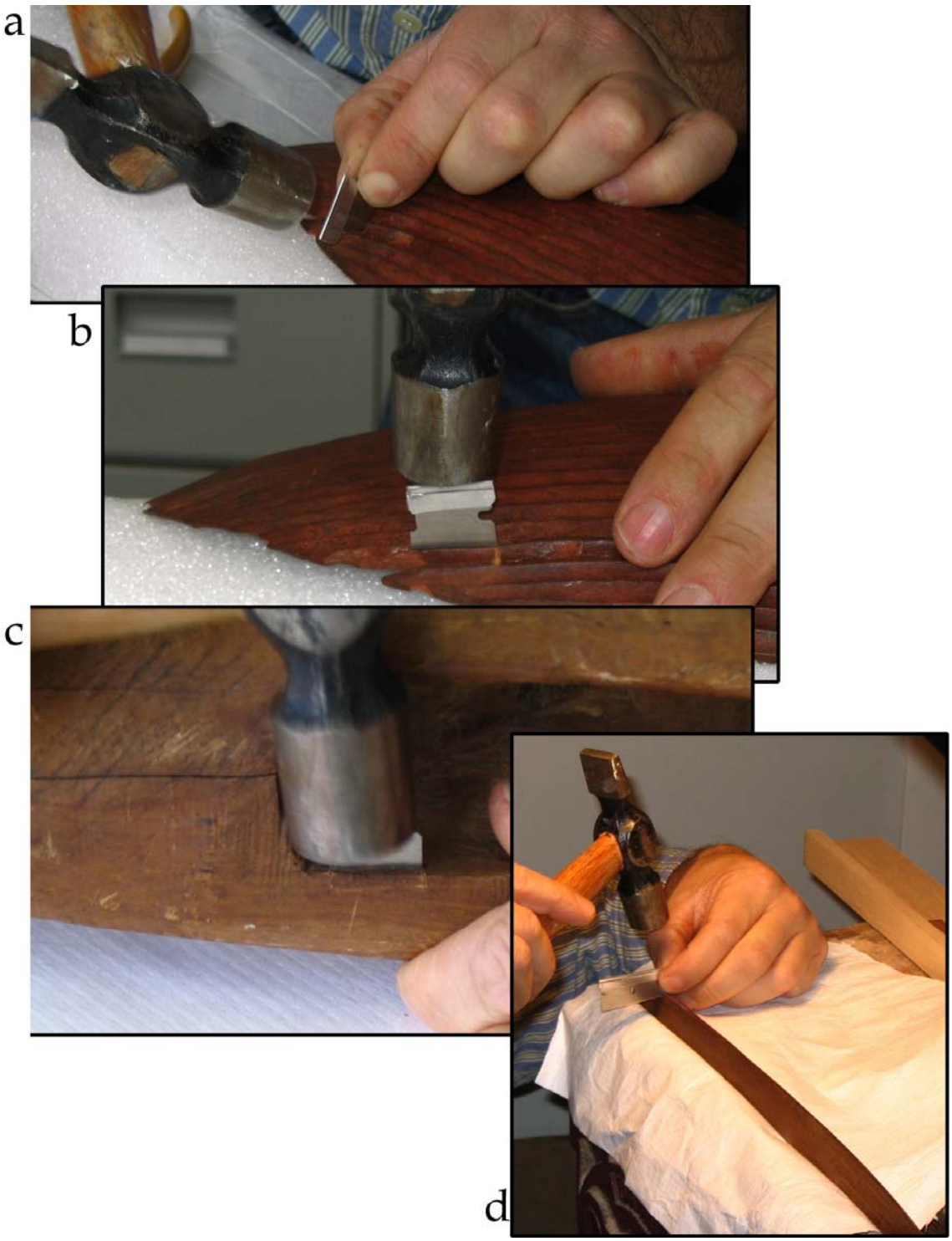


Figure 53 Removing wood samples for anatomical analyses from the artefacts. A. A cut is made with a razor blade and hammer along the endgrain of the coolamon. B. Having made a second cut along the endgrain, a cut is made along the longitudinal surface of the coolamon with a broken razor blade. C. Making the second cut along the longitudinal surface of the shield. D. Making a cut on the endgrain of the boomerang.

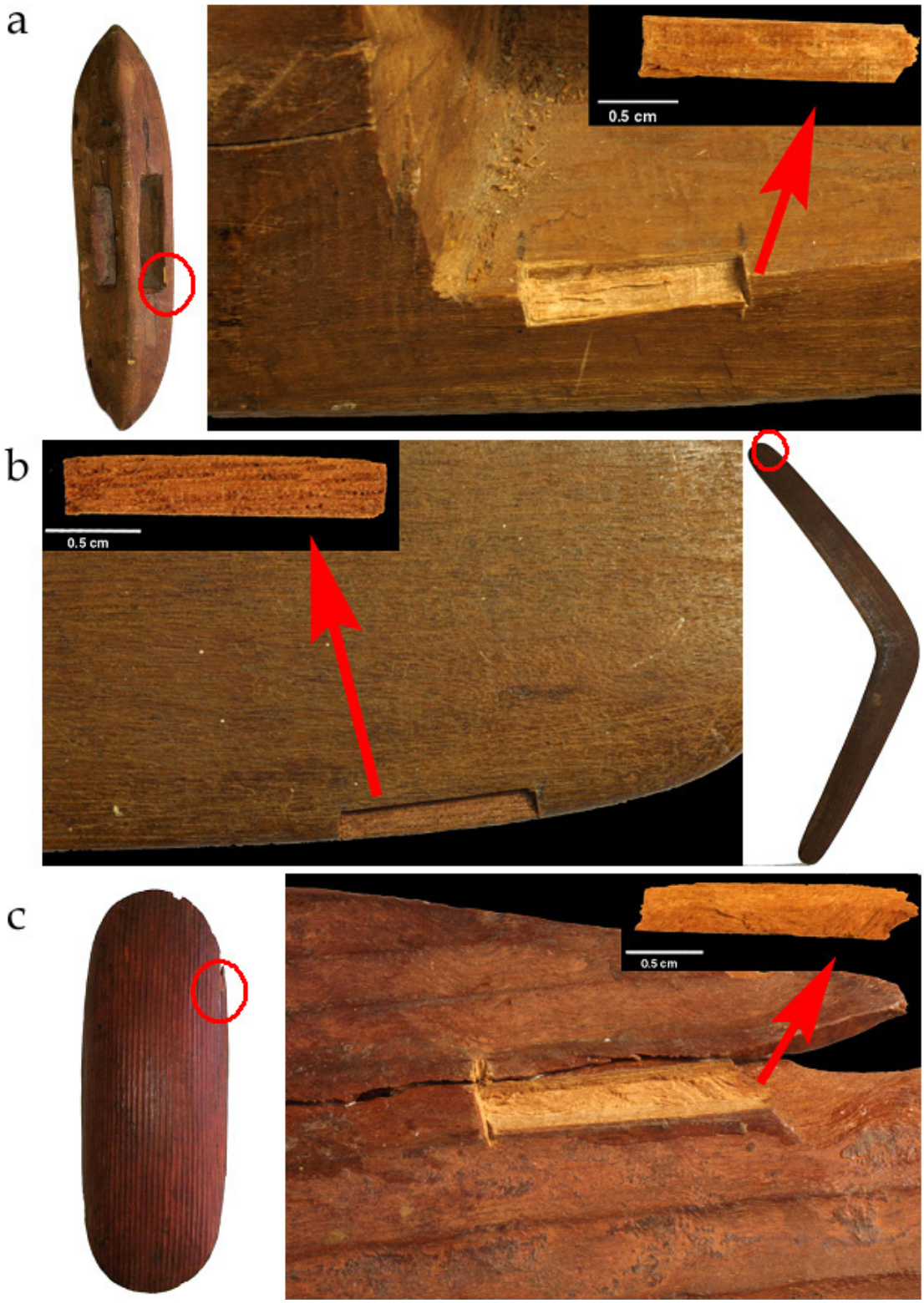


Figure 54 Images of sampled artefacts showing sample and the location on the artefacts that sampling took place. A. Shield; B. Boomerang; C. Coolamon.

day photographs of the endgrains were obtained using an Olympus DP11 digital camera attached to a Zeiss Stemi 2000 dissecting microscope. The polished endgrains were cut from the rest of the sample using a single edge razor blade and mounted face-up on separate stubs for SEM analysis. Carbon paint was liberally painted around each sample, taking care to avoid the exposed endgrain surfaces. Each of the samples was coated in carbon and gold.

Preparation of longitudinal surfaces for SEM microscopy

The radial and tangential faces were located as best as possible by examining the endgrain surfaces on what remained of the original samples with the dissecting microscope. The small size of the samples precluded fracturing them with a chisel to expose the longitudinal faces (as was the method employed for the contemporary reference wood; see Chapter Seven). Instead, a razor blade was pushed in both the radial and tangential directions so that smaller fragments were removed each with one of the longitudinal surfaces exposed. The radial and tangential fragments were mounted on separate stubs and carefully surrounded with carbon paint. Each of the samples was coated in carbon and gold.

Endgrain analysis

The polished endgrain of each of the samples was examined using the dissecting microscope, normally at around 25x magnification. Notes were made relating to vessel and parenchyma arrangement, ray width (in relation to one another), ray width (in relation to vessels), and the presence of inclusions or tyloses within the vessels.

SEM analysis

Images of the transverse, tangential and radial surfaces were obtained using a Philips XL-20 scanning electron microscope. A broad reconnaissance of each sample was conducted to observe and image qualitative features. Images were also collected from the tangential and transverse surfaces at predominantly 120x or 240x magnification to assist data collection for the numerical characters.

Image analysis

Where the clarity of the SEM images allowed, numerical data was collected for the characters “Vessels, diameter”, “Vessels, number per square mm”, “Rays, height”, “Rays,

number per mm" and "Rays, width". For "Rays, width" a survey of rays on the tangential surface during SEM imaging yielded the necessary information for this character and image analysis was not necessary. For the boomerang, "Rays, number per mm" was not possible to reliably measure due to the poor clarity of the tangential surface at lower magnifications. Data for the remaining numerical characters for each of the artefacts were collected using the software *analySIS*; the same method was employed as was used for the contemporary reference wood (see Chapter Seven).

Results & discussion

Following are wood anatomical descriptions for the boomerang, shield and coolamon and the results of the application of this data to the identification tool. Vessels were present in the wood of each of the artefacts – indicating a hardwood species – so the identification process began with the central *Sub-key to a Selection of Arid Australian Hardwoods.* The presence of heartwood could not be reliably determined for the three artefacts so the chemical and physical characters – which largely rely on heartwood being present – were not applied; only the endgrain and SEM character sets were utilised. Figures 57-59 are plates compiled for each artefact; they include an endgrain image and SEM images of the salient surfaces.

Boomerang

Description

Vessels Tangential vessel diameter: range 141-214 µm; mean 183 µm; SD 26 µm; average maximum not recorded due to limited data set; n = 6 vessels. Vessels per square millimetre: 4 vessels per mm^2; n = 1 sampled areas. Vessels very large, solitary and with inclusions, possibly tyloses. Vessel to vessel pits vestured. *Axial parenchyma* Parenchyma paratracheal, probably vasicentric. *Rays* Rays were two cells wide indicating that uniseriate rays may not be present. Rays of uniform width and not wider than vessels. Rays per tangential mm not measured. Ray height: range 197-257 µm; mean 226 µm; SD 18 µm; n = 10 rays. Rays heterocellular. *Fibres/tracheids* With large bordered pits present. Thick-walled.

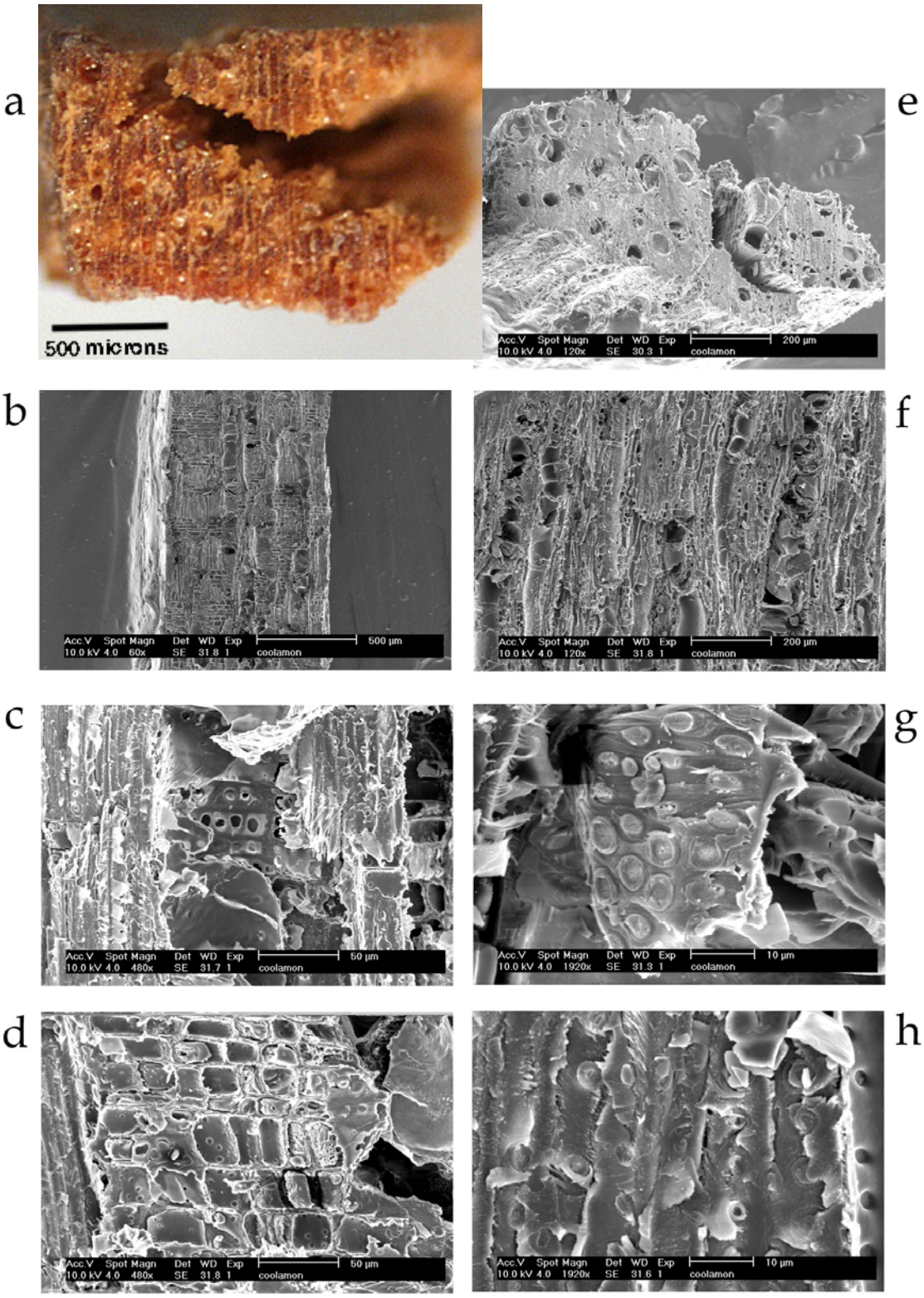


Figure 55 Image of coolamon wood. A. Endgrain (Scale = 500 µm); B. Radial surface (Scale = 500 µm); C. Possibly ray-vessel pits (Scale = 50 µm); D. Heterocellular ray cells; vessel with tyloses (Scale = 50 µm); E. SEM transverse surface (Scale = 200 µm); F. Tangential surface (Scale = 200 µm); G. Vestured vessel to vessel pits (Scale = 10 µm); H. Fibres/tracheids with large bordered pits (Scale = 10 µm).

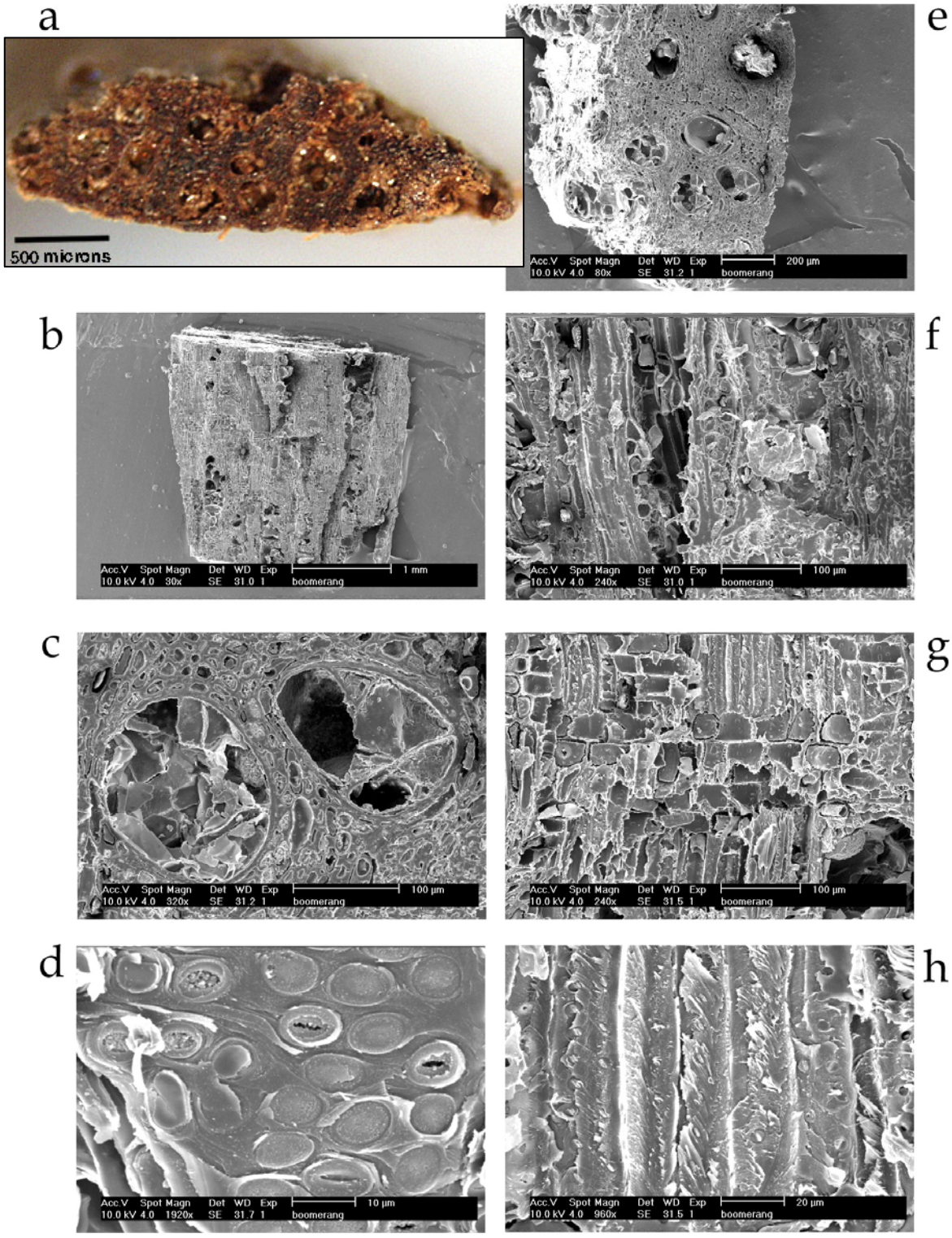


Figure 56 Images of boomerang wood. A. Endgrain (Scale = 500 µm); B. Radial surface (Scale = 1 mm); C. Large, solitary vessels, possibly with tyloses and surrounded by paratracheal parenchyma (Scale = 100 µm); D. Vestured vessel to vessel pits (Scale = 10 µm); E. SEM transverse surface (Scale = 200 µm); F. Rays 2 cells wide (Scale = 100 µm); G. Heterocellular ray cells (Scale = 100 µm); H. Fibres/tracheids with large bordered pits (Scale = 20 µm).

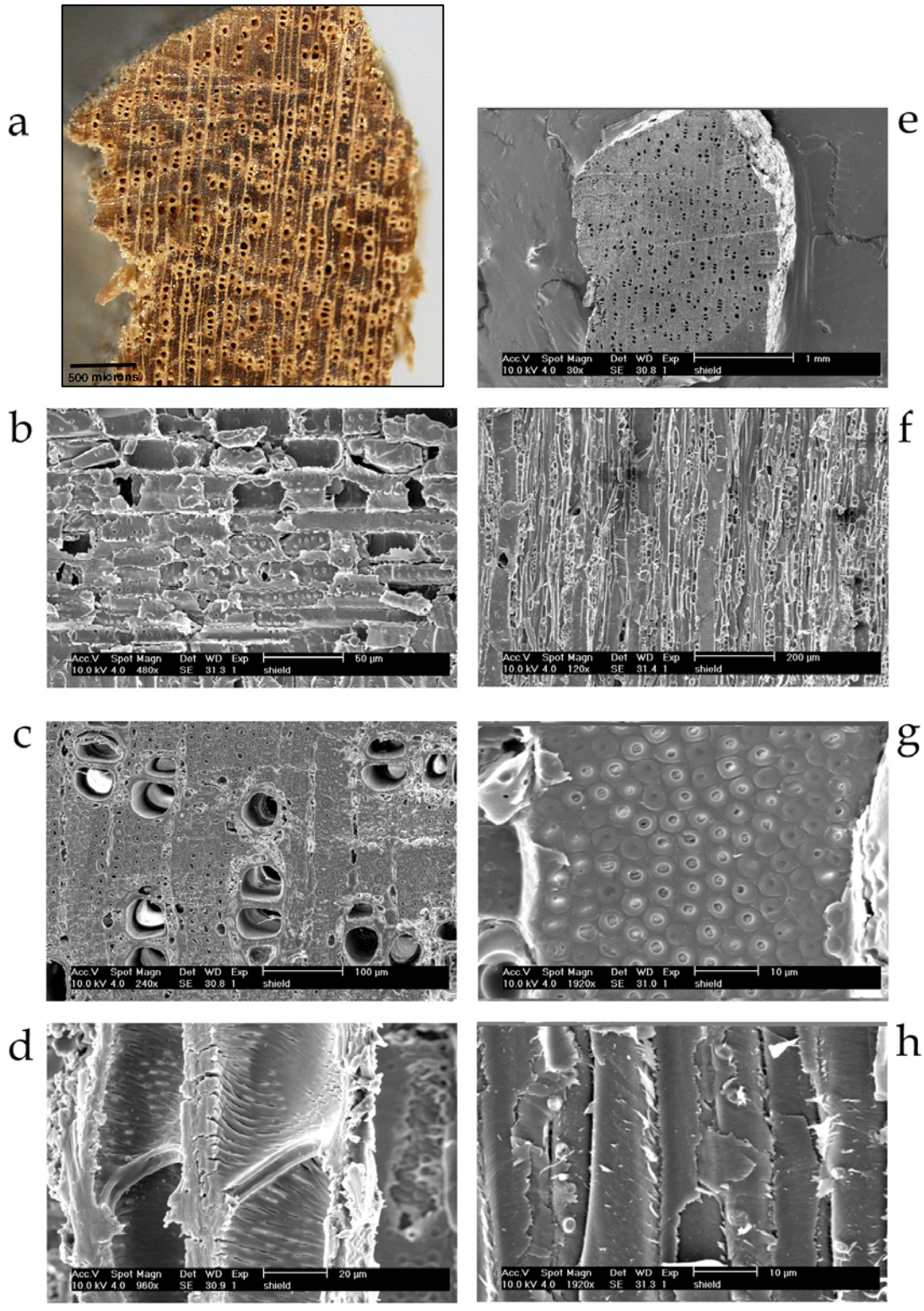


Figure 57 Images of shield wood. A. Endgrain (Scale = 500 µm); B. Radial surface (Scale = 50 µm); C. Vessels in radial multiples of 2-3 (Scale = 100 µm); D. Simple perforation plate with prominent rim (Scale = 20 µm); E. SEM transverse surface (Scale = 1 mm); F. Tangential surface (Scale = 200 µm); G. Vessel-vessel pits (Scale = 10 µm); H. Fibres/tracheids with large bordered pits (Scale = 10 µm).

Application to endgrain character set

The polished endgrain of the boomerang was very small and the vessels very large. As a result, there was some uncertainty as to whether the vessels were solitary or in radial multiples and whether vessel inclusions were tyloses. In addition, the clarity of the surface was such that parenchyma arrangement and the width of the rays in relation to one another and to the vessels could not be reliably determined. Accordingly, only a few character states could be reliably selected from the endgrain set of the *Sub-key to a Selection of Arid Australian Hardwoods*: "Vessels, not in clusters", "Vessels, not in tangential bands" and "Rays, not distinctly wider than vessels". Only two taxa were discarded: *Pittosporum* and Proteaceae (*Grevillea* & *Hakea*) leaving 18 of the 20 taxa remaining.

Application to SEM character set

Data from the transverse, tangential and radial surfaces of the boomerang sample were applied to the SEM character set of the *Sub-key to a Selection of Arid Australian Hardwoods*. The combined qualitative and quantitative features of the boomerang wood do not fit any of the taxa that presently comprise this key. On the basis of the numerical data alone the wood keys out as *Acacia.* However, conspicuous bordered pits on the fibre/tracheids, heterocellular rays, and the absence of uniseriate rays are not features of *Acacia.*

Identification

The identification of the boomerang wood is unknown, but it is unlikely to be representative of any of the taxa treated in the identification tool.

Shield

Description

Vessels Tangential vessel diameter: range 16 – 69 µm; mean 40 µm; SD 11 µm; average maximum 54.38 µm; n = 110 vessels. Vessels per square millimetre: 105 vessels per mm^2; n = 6 sampled areas. Vessels arranged in radial multiples, predominantly of two to three vessels but occasionally comprising four vessels. Most vessels are without inclusions and have a prominent perforation rim. Vessel to vessel pits are vestured but the pits are dissimilar to the vessel to vessel pits observed amongst the contemporary reference

specimens that comprise the identification tool. *Axial parenchyma* Parenchyma cells are either paratracheal scanty or apotracheal diffuse. *Rays* Rays narrow, 1-2 cells wide. Rays of uniform width and not wider than vessels. Rays 8-13 per tangential mm (n = 5 sampled areas). Ray height: range 97-221 µm; mean 156 µm; SD 27 µm; n = 83 rays. Rays may be homocellular procumbent but this was difficult to conclude with certainty. *Fibres/tracheids* With large bordered pits (not as common or conspicuous as those in *Eucalyptus* or *Melaleuca*.) Fibres arranged in a linear fashion.

Application to endgrain character set

On the basis of examination of the polished endgrain, the qualitative features of the shield wood were selected against the endgrain set of the *Sub-key to a Selection of Arid Australian Hardwoods*. The following character states were answered with confidence: "Vessels, in radial multiples", "Rays, not distinctly wider than vessels", "Rays, not of two distinct widths", "Heartwood, vessels not commonly with tyloses", "Vessels, not solitary", "Vessels, not in tangential bands", "Vessels, not in clusters". On this basis, only five taxa were discarded: *Casuarina*, Myrtaceae A (*Eucalyptus* & *Melaleuca*), *Pittosporum*, Proteaceae (*Grevillea* & *Hakea*) and *Santalum*. It could not be confidently determined if radial multiples with vessels of four or more were commonly present. However, had "Vessels, not in radial multiples of 4 or more" been chosen – which was later determined using SEM to be the correct state – only *Psydrax* would have been discarded leaving 14 of the 20 taxa remaining.

Application to SEM character set

Data from the transverse, tangential and radial surfaces of the shield sample were applied to the SEM character set of the *Sub-key to a Selection of Arid Australian Hardwoods*. The combined qualitative and quantitative features of the shield wood do not fit any of the taxa that presently comprise this key. On the basis of only the numerical features the key retains *Acacia*, Myrtaceae A (*Eucalyptus* & *Melaleuca*), *Capparis* and *Schinus*. However, the prominent perforation rim is not a feature of *Acacia* or Myrtaceae A (*Eucalyptus* & *Melaleuca*); vestured pits are not a feature of *Schinus*; large bordered pits on fibres/tracheids are not a feature of *Capparis*; and vessels in radial multiples are not a feature of Myrtaceae A (*Eucalyptus* & *Melaleuca*).

Identification

The identification of the shield wood is unknown, but it is unlikely to be representative of any of the taxa treated in the identification tool.

Coolamon

Description

Vessels Tangential vessel diameter: range 20 – 82 µm; mean 51 µm; SD 17 µm; average maximum not recorded due to limited data set; n = 25 vessels. Vessels per square millimetre: 36 vessels per mm^2; n = 1 sampled areas. Vessels solitary. Vessel to vessel pits vestured. Tyloses present and possibly also resin inclusions. *Axial parenchyma* Paratracheal scanty. *Rays* Rays narrow, 1-2 cells wide. Rays of uniform width and not wider than vessels. Rays 10-12 per tangential mm (n = 2 sampled areas). Ray height: range 89-196 µm; mean 121 µm; SD 23 µm; n = 30 rays. Rays heterocellular. *Fibres/tracheids* Possibly with large bordered pits. Fibres arranged in a linear fashion. Thick walled.

Application to endgrain character set

On the basis of examination of the polished endgrain, the qualitative features of the coolamon wood were selected against the endgrain set of the *Sub-key to a Selection of Arid Australian Hardwoods*. The following states were selected with confidence: "Rays, not distinctly wider than vessels", "Rays, not of two distinct widths", "Heartwood, vessels commonly with tyloses", "Parenchyma, not in a wing-like to confluent sheath", "Parenchyma, not banded", "Parenchyma, not in radial multiples of 4 or more" and "Parenchyma, not in tangential bands". Seven taxa remained: *Anthobolus*, *Capparis*, *Flindersia*, Myoporaceae (*Eremophila* & *Myoporum*), Myrtaceae A (*Eucalyptus* & *Melaleuca*), *Schinus* and *Tamarix*. Unfortunately, it was difficult to tell from the endgrain whether vessels were solitary or in radial multiples and these characters could not be answered with confidence. Had "Vessels, solitary" been chosen – which was later determined using SEM to be the correct state – only *Anthobolus*, Myrtaceae A (*Eucalyptus* & *Melaleuca*) and *Capparis* would have remained.

Application to SEM character set

Data from the transverse, tangential and radial surfaces of the coolamon sample were applied to the SEM character set of the *Sub-key to a Selection of Arid Australian Hardwoods*. The combined qualitative and quantitative features of the coolamon wood sample key out to Myrtaceae A (*Eucalyptus* & *Melaleuca*).

In the *Sub-key to Myrtaceae A* (*Eucalyptus* & *Melaleuca*) the eight *Eucalyptus*/*Melaleuca* taxa separated on the basis of the numerical information. (All qualitative characters were redundant as they were shared by all of the taxa.) The remaining taxa were *Eucalyptus camaldulensis* var. *obtusa*, *E. coolabah* and *E. populnea*.

Identification

The coolamon wood was identified as a *Eucalyptus* (or *Melaleuca*) species, possibly *Eucalyptus camaldulensis*, *E. coolabah* or *E. populnea*, or one of the other *Eucalyptus* or *Melaleuca* species that occur in the Frew River region but are not treated in the identification tool[59].

Discussion

The *Sub-key to a Selection of Arid Australian Hardwoods* was successfully applied to three Aboriginal artefacts purportedly of central Australian origin. The results indicated that two of the artefacts – a shield and a boomerang – are unlikely to be made from wood belonging to any of the 20 taxa represented in the key whilst the third artefact – a coolamon – was identified as a *Eucalyptus* (or *Melaleuca*) species, a determination supported by the ethnographic literature (Goddard and Kalotas 1985; Johnston and Cleland 1943; Kamminga 1988; Kamminga 2005; Kutsche and Lay 2003). With the successful test of 10 vouchered wood specimens against the identification tool, Chapter Nine showed that a high level of confidence can be had in the identification of the three artefacts at this level. In addition, whilst this study was unable to identify the species (or even genus) represented

[59] According to the *Herbarium of the Northern Territory* collections *Eucalyptus* and *Melaleuca* species occurring in the Frew River region but not treated in the identification tool include: *Eucalyptus barklyensis*, *E. chlorophylla*, *E. gamophylla*, *E. leucophloia*, *E. microtheca*, *E. normantonensis*, *E. odontocarpa*, *E. pachyphylla*, *E. pruinosa*, *E. victrix*, *Melaleuca dissitiflora*, *M. lasiandra*, *M. nervosa*, *M. viridiflora*.

by the shield or the boomerang, it can be concluded that the wood is unlikely to belong to one of the 20 taxa represented in the *Sub-key to a Selection of Arid Australian Hardwoods.* This may indicate that the artefacts were made from one of the wood-producing genera that belong to the Frew River region that were not represented in the identification tool. Alternatively, it lends support to remarks made by Dr Philip Clarke of the *South Australian Museum* that the typology of the artefacts indicates that they may both have come from further south, possibly the Flinders Ranges or the central Darling region of New South Wales (Clarke 2003: *pers. comm.*). In the case of the boomerang, he commented that it may have come from even further south (Clarke 2003: *pers. comm.*). Finally, there is a possibility that the boomerang is made of rootwood; rootwood anatomy may vary considerably from the wood from other parts of a tree (Metcalfe and Chalk 1989: 47) and the relative lightness of the wood, the large vessels and the small vessel number per square millimetre lends some support to this possibility. In addition, ethnographic records for central Australian Aboriginal wood use indicate that rootwood was utilised in the construction of artefacts (Goddard and Kalotas 1985; Johnston and Cleland 1943; Kamminga 1988; Kamminga 2005; Kutsche and Lay 2003).

The results of the tests against the identification tool (see Chapter Nine) indicated that the *Sub-key to Myrtaceae A (Eucalyptus & Melaleuca)* is limited by the restricted data set upon which it is presently based. Accordingly, the identification of the coolamon using the *Sub-key to Myrtaceae A (Eucalyptus & Melaleuca)* as either *E. populnea*, *E. coolabah* or *E. camaldulensis* can not be reliably accepted. The fact that *Eucalyptus coolabah* and *E. camaldulensis* occur in the Frew River region, and that both have been recorded in the ethnographic literature for coolamons (Goddard and Kalotas 1985; Johnston and Cleland 1943; Kamminga 1988; Kamminga 2005; Kutsche and Lay 2003), does lend some support to these identifications; however, both species are also distributed widely across Australia (see AVH distribution map, Appendix Two). In addition, whilst it is tempting to conclude that the coolamon is not likely to be made from the wood of *E. populnea* on the basis that this species does not occur in the Frew River region, this ignores the possibility that the object had come to Walter Reichstein by way of Aboriginal trade and exchange routes, or through a network of white collectors involved in the collection and exchange of Australian Aboriginal artefacts. It is also possible that the Frew River Station employed

Aboriginal labour from areas of New South Wales and Queensland where *E. populnea* does occur (see AVH distribution map, Appendix Two).

Despite these caveats, by increasing the data set for each species and expanding the *Sub-key to Myrtaceae A (Eucalyptus & Melaleuca)* to include the other *Eucalyptus* and *Melaleuca* species that occur in the Frew River region, the reliability of the identification at the species level will likely improve.

Whilst the procedure used to sample the objects was one recommended by xylologists, the invasiveness of the sampling method may be reduced if sections of the transverse, radial and tangential surface could be directly removed from the objects. Unfortunately, lack of experience in wood sampling and the high density of the wood precluded this from occurring. The high density of the wood also prohibited polishing the endgrain directly from the artefacts. This process is less invasive than removing a splinter and, by using the information from the endgrain, identifications may often be determined to generic level.

The application of the data from the endgrain to the identification tool also had positive results with respect to the coolamon with only three taxa – including Myrtaceae A (*Eucalyptus* & *Melaleuca*) – remaining. The future addition of numerical characters to the endgrain set of the *Sub-key to a Selection of Arid Australian Hardwoods* – particularly those relating to vessel diameter and vessel number per square millimetre – would increase the efficacy of this character set and the prospects of identification to family or genus without the need for removing a sample. However, to attempt to elicit identifications at the species level will still require a fragment for SEM analysis.

Finally, a small section of the samples from each of the three artefacts still remains. Along with the samples mounted for SEM these have been labelled and will remain with the three artefacts so that they may be revisited in the future. With expansion of the identification tool to include further species, larger data sets and rootwood and trunkwood, the results of a subsequent application to the identification tool may yield more definitive identifications.

Conclusions

In order to preserve a museum collection, one needs to promote the collection.

(Morris 2005: *pers. comm.*)

Traditionally, museum anthropologists have relied upon historical documentation to inform and educate and, despite some encouraging voices calling for increased adoption and adaptation of scientific methods to the discipline, this reliance on historical references has largely persisted. In addition, the last couple of decades have seen the custodial role of the anthropology curator challenged and the position accused of being antiquated and a remnant of British Imperialism. This, and the welcome increase in repatriation and communication between Aboriginal people and anthropology curator that it spawned, have rightly increased the responsibility and accountability of the curator to protect and preserve the objects for future generations of Aboriginal people. However, along with logistical impediments to adopting and adapting scientific methods to anthropological collections, the cautiousness that this philosophical change has triggered has contributed to stagnating research in the area of material culture. But any logistical constraints could probably be overcome with a change in philosophy that recognises that the benefits of artefact wood identification far outweigh the negatives in terms of furthering anthropological enquiry, increasing the value of the objects and preserving their integrity for future generations of all ethnicities. In addition, this research has shown that, with experience, and where required, sensitive sampling procedures can be developed and applied to artefacts.

In the absence of a present systematic procedure for the storage and extraction of data relating to the wood properties of ethnographic artefacts, this study represents an important step forward in establishing a storage bank that can be revisited, revised and upgraded to include new species and characters. The developed tool may be expanded to include exploited plant species from regions of Australia besides the arid zone. The methodology may also be adapted to develop tools for the identification of other botanical materials used to construct artefacts. Moreover, the tool could be expanded to include other resources used to manufacture objects such as faunal or geological material or its application extended to other disciplines, such as archaeology. This would represent a significant move towards decreasing the reliance on the often limited, biased and finite historical documentation and providing anthropology with a foundation in science and a new systematic approach to developing the research potential of museum collections.

Chapter Twelve. Conclusions

Introduction

The principal objective of this research has been successfully completed with the development of an interactive identification tool to arid Australian wood that is sympathetic to wood fragments. The importance of wood in society and the need for wood identification in a variety of professional fields including archaeology, anthropology, palaeobotany, conservation, art history, zoology, quarantine and law has been demonstrated (see Chapter Two) whilst the difficulty of identifying wood - fragmented or otherwise - to species level using morphological markers has been confirmed. A summary of the existing issues in wood identification, the major outcomes of this research and directions for the future is presented here.

Existing issues in wood identification

A number of challenges confront those involved in the discipline of wood identification. These issues – namely misconceptions as to the importance of vouchers, the limited availability of resources and keys, issues of inter- and intra-specific variability and the identification of fragments - are fundamental concerns to other areas of taxonomy and recommendations for how they can be addressed in the area of wood identification are given later in this chapter.

Limited extent of wood identification

Chapter One explained that the main issue with identifying wood to species level is anatomical variation (or lack thereof). Wood may not be sufficiently variable within a genus to enable identification to species level; conversely, there may be significant variation within a species which can prohibit identification beyond family or genus. Furthermore, wood from the roots, trunk and limbs of a single tree may be variable. These issues of inter- and intra-specific variation permeate much of this study and it was revealed that, for this reason, xylologists are often unable to identify wood to species.

Limited resources for wood identification

A survey of wood identification resources in Chapter Three revealed that there are limited comparative reference specimens and keys available, particularly to non-commercial species and to woody plant parts other than trunkwood. There are also few experts in this field, particularly in Australia but also worldwide. The only wood identification service offered by the foremost - and easily the most sought after - expert in Australia, Jugo Ilic,

costs $275 per wood sample (and $385 per root wood sample). Access to one of the few computerised identification tools to some common Australian, tropical and commercial timbers – *CSIROID* – has now been restricted to the CSIRO's internal wood identification service. In a country where thousands of plants are wood-producing, wood identification is relatively inaccessible.

Few collaborative publications on the outcomes of wood identification

There is a paucity of literature involving the applications of wood identification. Rather than being an indication of a limited need for the science it has been shown (see Chapter Two) that this is probably due to the fact that many studies remain unpublished, particularly where the work is outsourced and the significance of the identifications and the methods employed becomes lost in the inter-disciplinary divide. Even if they are published, often the papers will not include information on the techniques or limitations involved in the analyses or the resources that were used to assist identification.

Understanding the importance of vouchers

Throughout this dissertation there has been a strong emphasis on the importance of basing identifications on wood specimens that have been authenticated with botanical material (a voucher specimen). Vouchers are at the foundation of and fundamental to all taxonomic research. That wood identifications should be based on authenticated material seems to be reasonably well accepted by the xylological community and *Index Xylariorum* – a survey of worldwide xylaria – includes information for each xylarium on the percentage of wood specimens that are authenticated with voucher specimens. However, in a survey of existing wood identification resources conducted as part of this study (see Chapter Three), it was found that many publications and keys do not record voucher specimen numbers, whilst many xylaria – both in Australia and overseas – incorporate large amounts of wood specimens that remain disconnected from their associated vouchers. Consequently, it seems xylologists do not appreciate the importance of *reconnecting* "authenticated" wood specimens with their vouchers in order to update any changes to names. As was explained in Chapter Four, any description or identification that is based on wood that has been separated from its associated herbarium voucher is subject to error. Furthermore, anyone who applies descriptions or accepts identifications based upon unvouchered wood, or wood that has lost its connection with an associated voucher specimen, seriously jeopardises

their own research. This is so even if the identifications are correct at the time for it does not protect a species against future changes to nomenclature. It is not difficult to imagine potentially serious consequences if identifications obtained under these circumstances are accepted, particularly where wood identification is used in the areas of criminal and civil law.

Difficulty of identifying wood fragments

The identification of wood fragments adds a further complexity to the identification process and it was revealed - through case studies and literature review - the two circumstances under which fragmented wood is all that is available for analysis.

3. Where the fragments are samples removed from a precious object such as an antique or anthropological artefact. Wood identification methods must be sympathetic and preserve the integrity of the object. Depending on the effects of cultural processing, the wider wood matrix may also be available for non-invasive examination, particularly of physical features.

4. Where the fragments are the physical remains of a wider wood matrix, as may often appear in biological, archaeological, palaeobotanical or forensic contexts. Separation from a wider matrix may be the result of human or environmental processes. In the absence of the wider wood matrix, there may be fewer characters available for identification, but examples may be more common (and less precious) allowing more liberal sampling.

In addition, it was revealed that the requirement to physically extract a sample to expose the transverse, tangential and radial planes might result in a much larger sample (and a much greater area of damage) than is actually required for identification purposes. The need for invasive analyses (and their extent) adds a further complexity to wood identification, particularly when it comes to identifying precious cultural objects using standard morphological markers and procedures.

Outcomes of research

In response to the dearth of wood identification resources, particularly to non-commercial species and to fragments, and in the knowledge of the value of wood identification to a

variety of disciplines, the primary objective of this research was the construction of an interactive identification tool to arid Australian wood. Major challenges included finding a technique that would adequately soften the extremely dense desert woods to enable sectioning; accounting for intra-specific variation in the wood; and constructing a tool based on professionally identified, vouchered wood specimens that was sympathetic to the identification of wood fragments.

The tool

An interactive identification tool to 58 arid Australian wood species has been produced using *Lucid* software. It comprises a suite of eight nested keys and a total of 57 characters relating to physical, chemical and anatomical features that may be used to separate taxa. Most of the characters have been adapted from the *International Association of Wood Anatomists* (IAWA) standard list of characters for hardwood and softwood identification (Richter, Grosser *et al.* 2004; Wheeler 1977). Due to time restrictions, a limited number of species, each represented by a limited number of specimens, were covered in the tool. As such, the tool can only be regarded as a prototype; however, it provides a proof-of-concept as well as the platform for its expansion and for the development of similar identification tools.

Underpinned by vouchers

The wood specimens that were treated in the identification tool are all underpinned by botanical vouchers lodged in the *State Herbarium of South Australia*. Each wood specimen and voucher retains the same JABXXX number and this is recorded in the descriptions attached to each taxon in the tool. Accordingly, by revisiting the voucher specimens in the herbarium it will be possible to incorporate future name changes in the identification tool and, in the event that a wood description is challenged, it will be possible to re-examine the original specimen(s) upon which the descriptions are based.

Introduced powerful new numerical characters

> *…in comparing two woods, it is not important that they both have small vessels of a particular size, but that in one the vessels may be larger than the other…*
>
> (Ilic and Miller 1996: 85)

With the introduction to the identification tool of two new numerical characters – "Vessels, difference in diameters" and "Rays, difference in heights - this research presented a new method to increase the value and efficacy of data pertaining to the tangential diameter of vessels and the height of rays (see Chapter Eight). These characters increase the separating capacity of the vessel diameter (and ray height) data by measuring the difference between the largest and the smallest vessels in a specimen (and the longest and shortest rays). The characters present an alternative solution to the "average maximum" a calculation adopted by the CSIRO to attempt to separate wood species that share some vessels with similar diameters (Ilic and Miller 1996: 86). A limiting feature of this calculation is the fact that the "average maximum" is statistically volatile as it involves a random selection from a given set of values; in other words, the "average maximum" of a single set of values may differ each time the calculation is made. In addition, whilst the calculation is simple it is not as straightforward as the "Vessels, difference in diameter" and "Rays, difference in heights" characters where the smallest measurements are subtracted from the largest measurements.

Successful identification to family/genus

The central component of the tool – the *Sub-key to a Selection of Arid Australian Hardwoods* - comprises 20 hardwood families/genera from arid Australia. Since it is based upon a limited data set it can only be regarded as a prototype but initial testing indicated that specimens may be correctly identified to family/genus using the SEM character set. Accordingly, identifications obtained by this key may be accepted with a reasonably high degree of confidence. With the future addition of numerical characters relating to vessel diameter and vessel number per square millimetre, it is anticipated that the potential of the endgrain character set to elicit a single, correct taxon will increase.

Indications of inter-generic variation

Whilst future research involving further qualitative and quantitative analyses may reveal a means of separation, the statistical analyses have confirmed that the closely related genera *Grevillea* and *Hakea* are difficult to separate using wood anatomy alone. More encouragingly, the statistical analyses indicate that species belonging to *Melaleuca* and those belonging to *Eucalyptus* may be separable using the three numerical characters

relating to the rays. Moreover, *Myoporum* and *Eremophila* may be separable using the characters "Rays, number per millimetre" and "Rays, height".

Possibilities and limitations of identification to species

Whilst the number of collections made per species falls short of the amount recommended to adequately account for intra-specific variation, of 58 wood-producing species treated in the tool, 18 are represented by a collection of wood from at least two individual trees. However, testing with unknown specimens (see Chapter Nine) indicated that the six sub-keys to species – *Sub-key to Acacia*, *Sub-key to Capparis*, *Sub-key to Myoporaceae (Eremophila & Myoporum)*, *Sub-key to Myrtaceae A (Eucalyptus & Melaleuca)* and *Sub-key to Myrtaceae B (Corymbia)* - are presently unreliable. To what extent this is due to variation in the treated species (or lack thereof) can not be determined until the data set is increased and further tests are run.

Indications of intra-specific constancy

The results of the statistical analyses indicate that certain numerical characters may remain relatively constant (without statistically significant variation) within certain species. Isolating this constancy and the characters in which it exists may provide an important means of recognising intra-specific variation and correctly identifying a species. On the basis of the analysed data, vessel diameter was most likely to remain without statistically significant variation followed by the number of rays per millimetre and the number of vessels per square millimetre. Ray width and ray height were more likely to reveal statistically significant variation. Further sampling is required to determine whether these results are upheld.

Indications of inter-specific variation

Some numerical characters returned significant statistical variation between species, indicating that they may be useful in separating closely related species. Separation of species (or groups of closely related species) within *Acacia* and Myoporaceae (*Eremophila*/*Myoporum*) may be possible using numerical characters with the number of vessels per square millimetre returning the greatest significant statistical variation. For discriminating between *Eucalyptus* and *Melaleuca* species, numerical characters relating to ray width, ray height and the number of rays per millimetre may be useful. Vessel

diameter may be helpful in separating Proteaceae (*Grevillea*/*Hakea*) species but the results indicated that none of the numerical characters will separate the genera. Further sampling is required to determine whether these results are upheld.

Sympathetic to wood fragment identification

This research recognised the frequent requirement in wood identification to examine fragments. Whilst the identification tool is applicable to wood fragments recovered from archaeological, palaeobotanical or forensic contexts - where there are not usually cultural sensitivities attached to analyses - this study was particularly concerned with the need to sensitively identify (and sample from) the wood of precious cultural objects. The following features of the identification tool assist this process:

- The hierarchical structure of the tool reflects taxonomic levels of identification, beginning with the initial separation of hardwoods from softwoods, identification to family/genus, and finally to species.

- The provision of four methods of identification - based on physical properties, simple chemical observations, endgrain examination and SEM analysis - and the ability to pick and choose character states using multiple-entry keys, provides users with the utmost flexibility in the identification process.

- The introduction of a heartwood-dependent character set recognises that heartwood is not always present or discernible for wood identification purposes, particularly in the case of fragments.

- The provision of sets relating to physical and chemical properties reflects the possibility that diagnostic features may be assessable from the wider wooden matrix of the object.

In addition to these features, the research sought a method of wood identification that weighed the extent of invasive sampling against the likely level of identification. This addresses the difficulty that wood – fragmented or otherwise and regardless of the extent of invasive sampling - may contain too much or too little variation in morphology to allow identification to species level. With the expansion of the tool to include numerical characters for vessel diameter and vessel number per square millimetre for the endgrain, it

is anticipated that many species will be identifiable to genus simply by examining a polished endgrain with a light microscope, and utilising the central *Sub-key to a Selection of Arid Australian Hardwoods*. The level of invasiveness required for endgrain analysis is negligible, and the method is simple and one that should be accessible to a wide range of users who have been suitably trained

Having identified an unknown wooden object to family/genus by examination of the polished endgrain, identification to species will likely require more invasive analyses and involve the removal of a piece of wood and examination using scanning electron microscopy and it's associated character set. By examining the relevant sub-key to species, a user of the tool will be able to get an idea of the potential for definitive identification to species before the object is sampled. The chances of identifying an unknown specimen to species level using morphological markers will often be improved by knowledge from supplementary sources as to the likely provenance of the wood.

Results of test against Aboriginal artefacts

The tool was used to attempt to identify three Aboriginal artefacts believed to have been obtained on the Frew River Station in central Northern Territory in the 1930s. This test involved the extraction of a fragment from each artefact for application to the SEM character set. This was carried out in the knowledge that this was the only set that was likely to successfully produce an identification to family/genus. However, it should be noted that with the expansion of the tool to include numerical characters for endgrain analysis, the boomerang, coolamon and shield may have been identified to family/genus by examination of only a small area of their endgrains and without the need to remove a sample.

The results indicated that the boomerang and shield are unlikely to belong to any of the 20 taxa treated in the *Sub-key to a Selection of Arid Australian Hardwoods* whilst the coolamon is probably a *Eucalyptus* or *Melaleuca* species. Identifications obtained for the coolamon at the species level – *Eucalyptus camaldulensis, E. coolabah* or *E. populnea* - can not be reliably accepted.

Widely accessible

The variety of fields in which wood identification is needed highlights the need for accessible and user-friendly identification tools that can be operated by people with limited wood anatomical knowledge. The tool developed in this research utilises *Lucid* software, a popular choice for a variety of taxonomic keys produced in the last ten years ((e.g. Brooker, Slee *et al.* 2002; Maslin 2001). *Lucid* has powerful, in-built functions to assist the identification process and to increase the chances of a novice user successfully and accurately identifying an unknown specimen. The provision of image-rich factsheets that define character states and describe taxa, and packaging the tool with an electronic slide presentation that introduces both the identification tool and wood anatomy, increases the accessibility of the tool to a wide range of users. Indeed, with some training in the use of the tool, a plant taxonomist with very limited knowledge of wood anatomy but advanced knowledge of *Lucid* keys and their features, successfully identified eight out of 10 specimens to family/genus using the *Sub-key to a Selection of Arid Australian Hardwoods*. Without suitable training in the use of the tool, however, users may be subject to making the wrong decisions and eliciting an incorrect identification.

Unlike the card-sorting system that were traditionally used in wood identification (see Chapter Three), and the dichotomous keys more generally used in taxonomic disciplines, this identification tool is widely (and freely) accessible as it may be hosted on the Internet or published on DVD. Similar commercial identification tools that have been produced by a variety of taxonomic disciplines to suit a variety of taxonomic needs are usually available on CD or DVD at reasonable retail prices.

The techniques

Standard wood anatomical texts based upon commercial timbers use methods designed for wood with densities that generally measure less than 800 kg/m^3. The unusually high density of the wood treated in this research – largely between 1000 kg/m^3 and 1400 kg/m^3 - heavily influenced the methodology used to prepare it for anatomical analyses. Finding a method to soften the wood proved particularly difficult and this was one of the reasons for the adoption of scanning electron microscopy rather than thin sections, as SEM does not require the same level of softening for the longitudinal surfaces. Another major challenge faced by this study was the extraction of fragments from three wooden Aboriginal artefacts

for application to the identification tool. The following section provides a summary of the adopted methodologies and the manner in which these challenges were overcome.

Established a method for the softening of arid Australian wood

Several methods of softening high density arid Australian wood were explored; these included attempts to pre-soften specimens using a pressure cooker, autoclave, vacuum and various chemicals, as well as the use of direct steam during sectioning with a microtome (see Appendix Five). Ultimately, however, immersing wood blocks in vials containing 50% hydrofluoric acid proved by far the most effective and efficient means of softening the wood. The transverse surface – the most difficult surface to section as it runs perpendicular to the predominant wood cell direction – was easily polished and prepared for both light microscopy and scanning electron microscopy using a razor blade. The success of the method was such that it is anticipated that good quality thin sections could be removed from the softened wood using a microtome, possibly in combination with direct steam. Due to the constraints of time, this hypothesis will need to be tested in the future.

Use of scanning electron microscopy

Conventional wood identification usually involves the production of thin sections using a microtome and their examination using a transmission light microscope at magnifications up to 100x. In this research - and for the following reasons - wood was examined using scanning electron microscopy:

- SEM does not require the production of thin sections; blocks of wood up to 1 cm^3 are prepared to expose their tangential, radial and transverse surfaces.

- SEM does not require softening of the tangential and radial longitudinal surfaces (as is necessary for the production of good 15 - 25 µm thin sections of wood and to protect microtome knives) as the specimen can be fractured along the grain to expose (and image) these surfaces. At the time the decision was made to use SEM, an appropriate softening method for the high density wood had not been determined and the inadequately softened wood resulted in the production of sections that were of poor quality and too thick.

- SEM allows much higher magnifications that transmission light microscopy – typically up to 10,000x – and three-dimensional imaging.

A drawback of SEM use was the paucity of general wood anatomical texts that illustrate salient characters – and their various states - using the method. SEM is still a relatively recent application to wood identification; depictions of wood anatomy using thin sections probably persist in part because large collections of permanent thin section slides are housed in most major xylaria and the method of identification is still an entirely acceptable one.

Extraction of fragments from cultural objects

In the absence of a suitable and definitive non-invasive method of wood identification, this research has explored the removal of fragments from wooden objects for examination of their transverse, radial and tangential features. In Chapter Eleven it was revealed that experienced xylologists can remove sections directly from artefacts using a scalpel or razor blade with a minimum of damage. However, for those less experienced, the recommended method of fragment extraction requires the use of a small chisel (or razor blade) and hammer to prise out a fragment along the longitudinal grain that is large enough to physically section yet small enough to preserve the integrity of the object. This method was used to extract wood samples from the three Aboriginal artefacts applied to the *Key to a Selection of Arid Australian Hardwoods & Softwoods* resulting in a scar of 0.3 cm width by 2 cm length.

Criteria for the selection and sampling of precious cultural objects are discussed in Chapter Eleven. Ethical issues involved in the invasive analyses of cultural objects can largely be negated if the method can be shown to both preserve the integrity of the object and add "value" to the item in terms of increased knowledge.

Future directions for research

The wider implications of this research project are considered here. Several recommendations for expanding the identification tool are made, together with recommendations that might be considered by the international and Australian wood community. The potential for wood identification by molecular means, and the possibility of non-invasive analyses of wood using developing technologies, are considered and the

adoption of scientific practises and premises in the fields of anthropology and law are encouraged.

Expansion of identification tool

The likelihood of accurately identifying the wood to species level can only be determined after the tool has been expanded so that it treats an increased number of species, a larger data set of specimens per species, and an increased group of wood anatomical characters. Whilst variation (or lack thereof) may mean that some species may never be separable, statistical analyses and tests of the tool should continue to be run until such time that it can be determined whether accurate results can be achieved at the species level. This is particularly important for the characters based upon numerical data where further testing for intra-specific variation and statistical analyses may determine that initial indications of difference were in fact artificial.

Future expansion of the tool should address the issue of within-tree variation and incorporate data collected from rootwood, trunkwood and limbwood. Moreover, whilst wood structure tends to preserve quite well, there is a need to account for cultural and taphonomic processing if the tool is to be wholly applicable to wood that may have been modified.

As long as suitable training is provided, it is anticipated that expansion of the tool could be a collaborative exercise.

Further testing of new numerical characters

One of the species in the test was eliminated in the *Sub-key to Acacia* and the *Sub-key to Myrtaceae (Eucalyptus & Melaleuca)* on the basis of data entered into the characters "Vessels, difference in diameters" and "Rays, difference in heights". Whilst the limited data set upon which these keys are presently based means that reliable conclusions as to the efficacy of the character cannot be drawn, further analysis of both characters is required. Simply expanding the tool and increasing the data set to better account for intra-specific variability will provide an improved measure of the value of these characters.

Recommendations for the *International Association of Wood Anatomists*

This section calls for a more integrated approach to wood identification and improved awareness of standard taxonomic practises. The *International Association of Wood Anatomists* is the foremost authority for wood anatomists and the logical body to spearhead the proposals.

Base IAWA Journal *on research supported by vouchers*

Plant taxonomy journals such as *Australian Systematic Botany, Annals of the Missouri Botanical Gardens, Novon, Systematic Botany* and *Kew Bulletin* all require published morphological and molecular papers to be supported by vouchers. The *International Association of Wood Anatomists Journal* should follow suit and require that all submitted publications on wood taxonomy be underpinned by herbarium vouchers; specimen numbers and locations (for both the wood and the voucher specimen if these are separated) should be published. Recent cost-cutting/space-saving measures implemented by the *American Journal of Botany* and *Taxon*, which have seen lists of voucher specimens dropped from publications, have been vehemently protested against and it is likely that both decisions will be reversed (Funk, Hoch *et al.* 2005: 129).

Encourage the reconnection of wood specimens with wood vouchers

Wood specimens that retain links to herbarium voucher specimens need to be reconnected with the botanical material to update any changes to nomenclature. The IAWA can support this venture by educating members as to the importance of vouchered wood and insisting that papers submitted to the *IAWA Journal* be underpinned by vouchered wood specimens. An initial feasibility study should be conducted to determine the likelihood of reconnecting associated wood and voucher specimens, particularly in some of the larger xylaria. Whilst considerable funding will likely be required for this venture, it is important that the IAWA makes known examples where wood misidentified as a result of disconnected specimens has led to economic loss or other injustices.

Encourage the collection of vouchered wood specimens

Appendix Eleven presents one of the outcomes of this research - an article published in the journal of the *International Wood Collectors Society* (IWCS) which explains the importance of vouchers in wood identification. The article promotes greater links between

IWCS branches and local herbaria and encourages those members who collect in the field to collect a voucher specimen and to reserve a sample of wood - both for lodgement in herbaria. In return, IWCS members will receive professional taxonomic identifications of their wood and they may choose to retain the specimen number with any wood they trade or any items that they produce from the wood. This will mean that the correct identity of the wood (or objects made from it) can always be maintained by contacting the herbarium in which the voucher was lodged. This reciprocal relationship between herbaria and the IWCS is one that should be encouraged by the IAWA. This will result in increasing collections of vouchered wood specimens, particularly those that are not commercial and from different parts of the tree.

Release a journal dedicated to wood systematics and identification

Given its application to a broad range of disciplines the science of wood identification would benefit from a dedicated publication in terms of increased exposure and encouraging inter-disciplinary collaboration and publication. Whilst the *IAWA Journal* does publish papers on wood systematics and wood identification (and its application to fields such as archaeology and palaeobotany), many of its papers relate to research that examines wood anatomy for the improvement of commercial timbers for the Forestry industry. This is an important role for wood anatomists and it reflects their major area of employment. However, papers on wood systematics are also scattered across botanical, palaeobotanical and forestry journals. Additionally, xylologists often do not contribute to publications dealing with the outcomes of inter-disciplinary research. Their role in this area is to ensure that the analytical methods, comparative resources, voucher material and limitations of the identification are outlined in resultant papers; in addition, the certainty with which conclusions are drawn should be commensurate with the level of testing for intra-specific variation.

Finally, whilst recommendations on the layout and arrangement of wood anatomical descriptions have been made (see for example Carlquist 2001), treatments do not appear to be standardised. A single, dedicated journal that deals with wood systematics and wood identification can provide the template for future wood taxonomic descriptions. At the very least, such a template should be provided in subsequent editions of the standards lists of characters for hardwood and softwood identification.

Re-release hardwood & softwood standards with SEM images and on the Internet

Scanning electron microscopy is increasingly being employed for wood identification purposes and its three-dimensional output, and increased resolution and magnification, produces images of very different appearance to those achieved by imaging thin sections through a transmission light microscope. Whilst conventional thin section analyses are likely to persist, it would be desirable for the IAWA to release versions of their publications containing the standard lists of characters for hardwood and softwood identification with SEM images. In addition, web-based versions of both these publications would support increased illustrations and images and enhance their accessibility and value as educational tools.

Support a single, centralised resource for wood identification

There are now enough software packages on the market for the production of identification tools and databases that the IAWA could settle on a platform and support a single, centralised resource for wood identification. The web-based initiative "Inside Wood" (2004) promises to be a useful database of wood descriptions and images if it can overcome issues with vouchering. Alternatively, this research has developed the prototype for a sophisticated identification tool and database using proven taxonomic software that is user-friendly, expandable and accessible via the Lucid website (www.lucidcentral.com).

Future molecular directions for wood identification

This research has highlighted two important issues in wood identification: the difficulty of identifying wood to species level using morphological markers and the need for a method which reduces the invasiveness of sampling. To this end, this study explored the possibilities that molecular biology might offer wood identification. Chapter Five explained that whilst there have been recent successes in extracting DNA from wood it is problematic and there are still challenges to overcome:

- At present, DNA from wood must be isolated under special laboratory conditions usually reserved for amplifying ancient DNA.

- The age of the wood, exposure to water, oxidisation and UV light and storage conditions may influence DNA amplification.

- Recent research has shown that heartwood - where there are no living cells - results in less amplification than sapwood.

- Preservatives, decorative substances and exposure to other surface contaminants can contaminate DNA.

If these obstacles can be overcome, and if the promises of a DNA taxonomy are projected to wood identification, its benefits over standard morphological techniques will be considerable:

- Morphological variation within a tree (and within a species) will not be a concern because each plant species will be identified by a single, uniform genetic sequence.

- Identifications are underpinned by taxonomically identified, fresh botanical material – where amplification is straightforward - negating the need for a separate reference collection of wood DNA.

- The method is not constrained by the need for a sample that is large enough to physically section to expose radial, tangential and transverse surface. DNA has recently been extracted from 100 mg of wood shavings.

- Identification should be possible to species level and possibly to specific geographic locations.

Meanwhile, many traditional systematists have cautiously welcomed DNA but are not so sure that it can deliver on its promises. If one extends their arguments to wood identification they reason:

- DNA profiles are required for the thousands of wood-producing species.

- Variation that may occur in and between DNA sequences must be quantifiable to determine where variation is taxonomically relevant.

- There is some doubt as to whether identification can be resolved beyond family/genus.

- The method can never completely replace wood identification using morphological markers as DNA may be too fragmented to produce meaningful analyses or may not have preserved at all – as is the case with carbonised wood.

Towards non-invasive wood identification

> *The conservation and preservation of our cultural heritage is one of the main concerns…today…The increasing need for non-destructive investigations has become a major issue, as sampling is in most cases restricted in view of the value or the uniqueness of the object.*
>
> (COST 2005)

In recognition of the fact that wood identification can sometimes require invasive analyses of precious objects and in an effort to reduce the level of invasiveness required, this thesis explored several new and emerging technologies (see Appendix Four). The four investigated methods – fluorescence microscopy, confocal laser scanning microscopy, micro-CT scanning and CT-scanning - each presented possibilities but their use was limited by factors such as resolution and sample size. The most exciting aspect of these trials was the virtual cutting capability offered by the confocal laser scanning microscope, the micro-CT scanner and the medical CT-scanner. The method is more advanced in the CT-scanning technology where wood specimens can be virtually cut at any angle to expose any surface. The advantage of virtual cutting is that samples can be much smaller than those required for physical sectioning as the technology can be used to virtually locate and surface the radial, tangential and transverse surfaces. Unfortunately, however, the micro-CT scanner is restricted to specimens with a maximum size of 1.5 cm x 3 cm which precludes the examination of entire objects and necessitates the removal of a fragment. Whilst the fragment will only need to be tiny (a minimum of 1 mm^3), the present maximum resolution achievable using either technology is not sufficient for wood identification – regardless of sample size.

In the future, and with continued advancements in microscopy, CT-scanning and virtual-cutting technologies, it is expected that non-invasive wood identification of precious objects using morphological characteristics will eventually become available. Indeed, in Europe – where cultural heritage is rich and plentiful and an important source of tourism -

there is a strong awareness of the need to develop non-invasive (and portable) technologies that will both increase knowledge of European heritage and ensure its preservation. At least two consortia in Europe have been established to foster a multi-disciplinary approach to the non-invasive analyses of art historical, museum and archaeological materials (COST 2005) and inroads are being made in the fields of spectroscopy and x-ray analysis (Unger, Schniewind *et al.* 2001: 154; Vittiglio *et al.* 2004).

Future directions for museum anthropology

This dissertation repeats calls made in the early 1980s for the increased application of scientific methods to museum anthropology. This includes the identification of plant, animal and geological materials used in the construction of artefacts, knowledge of which can impart information regarding provenance based upon the restricted geographic range of plant and animal species and geological material. Suitable reference collections and keys for identification – such as those developed in this research - would need to be developed. Furthermore, greater research should be directed towards microwear and residue analysis (the identification of tools used to construct artefacts by analysis of cut-marks and the identification of microscopic residue attached to the objects to gain insights into the artefact's use) and finding a scientific method to date objects.

Unlike archaeologists who have readily embraced scientific practises to examine material culture (often in the absence of any written or oral documentation), museum anthropology continues to be trapped in the archives and material culture research has waned. Through case studies in Chapter Two, it has been shown that historical documentation can prove a useful supplement to scientific methods. Indeed, as some of the case studies demonstrated, identification to species level using morphological markers will often require knowledge from other sources as to the likely provenance of the wood. However, the application of scientific methods to artefacts may also prove a valuable test of the validity of the historical documentation and expose the danger in accepting (or extrapolating from) information acquired from a potentially biased, incorrect, incomplete or dated resource.

Ethical issues related to invasively sampling from artefacts for research purposes may be largely negated if sampling can be conducted in a sensitive manner that both preserves the integrity of the artefacts, and can be shown to contribute to cultural knowledge.

Meanwhile, the growing potential for non-invasive technologies and DNA extraction from cultural objects introduces exciting possibilities to museum anthropology in the future.

Future directions for law

Considerable time was spent (Chapter Four) in explaining the importance of underpinning wood identifications with voucher specimens and highlighting the disconnection of existing wood collections and associated botanical material. The single most important area in which wood identification plays a role is undeniably criminal and civil law and it is in this area that vouchers are critical. Indeed, any botanical material that is used as evidence in court – e.g. pollen, leaves, seeds or fruits - must be identified using comparative reference specimens that are based upon botanical material lodged in an herbarium. Through case studies, this research has revealed legal cases where the identification of the wood used to construct an item has resulted in large financial pay-outs or, even more sensationally, the apprehension and conviction of murder suspects. In the South Australian murder trial of Edward Splatt, for example, his conviction was largely based on the identification of wood particles. This was overturned in part because witnesses for the defence in the Royal Commission challenged the original wood identification on the grounds that the wood particles did not carry enough diagnostic information to allow identification at the species level – but not before Splatt had spent six years in jail and the South Australian government was forced to pay $300,000 in compensation. Whilst the issue at stake in this case was not about vouchering[60], it does drive home what may be at stake if wood is misidentified because comparative wood specimens are not reconnected with associated vouchers. If vouchers are "best practice" in taxonomy they should be mandatory in law: all taxonomic evidence submitted to courts must be based upon vouchered specimens and both the comparative wood specimen and voucher specimen should be lodged in an appropriate repository. This allows the specimens to be revisited in the future in case the original evidence is disputed or changes to nomenclature produce new evidence.

[60] From reading the relevant parts of the Royal Commission report one suspects, however, that the comparative wood material used by the expert witness for the prosecution in the Splatt case was not vouchered.

Appendices

Appendix One. Table of species mentioned in text of thesis with authorities

Note: Species authorities mentioned in the remaining Appendices can be obtained from the Australian Plant Name Index (APNI) at http://www.anbg.gov.au/win/index.html *or the* International Plant Name Index (IPNI) at www.ipni.org/index.html.

Family	Genus
PINACEAE	*Abies grandis* (Douglas)Lindley
LEGUMINOSAE	*Acacia aneura* Benth. var. *aneura*
	Acacia aneura var. *intermedia* Pedley
	Acacia aulacocarpa A.Cunn. ex Benth.
	Acacia bivenosa DC.
	Acacia cambagei F.Muell. ex R.T.Baker
	Acacia cana Maiden
	Acacia carneorum Maiden
	Acacia cupularis Domin
	Acacia cyperophylla Benth. var. *cyperophylla*
	Acacia farnesiana (L.)Willd.
	Acacia ligulata A.Cunn. ex Benth.
	Acacia melanoxylon R.Br.
	Acacia murrayana F.Muell. ex Benth.
	Acacia oswaldii F.Muell.
	Acacia papyrocarpa Benth.
	Acacia petraea Pedley
	Acacia peuce F.Muell.
	Acacia pickardii Tindale
	Acacia salicina Lindl.
	Acacia stenophylla A.Cunn. ex Benth.
	Acacia stowardii Maiden
	Acacia sutherlandii (F.Muell.)F.Muell.
	Acacia tetragonophylla F.Muell.
	Acacia victoriae Benth. subsp. *victoriae*
	Acacia victoriae subsp. *arida* Pedley
CASUARINACEAE	*Allocasuarina verticillata* (Lam.)L.A.S.Johnson
BETULACEAE	*Alnus rugosa* Sprengel
SANTALACEAE	*Anthobolus leptomerioides* F.Muell.
SAPINDACEAE	*Atalaya hemiglauca* (F.Muell.)F.Muell. ex Benth.
CHENOPODIACEAE	*Atriplex vesicaria* Heward ex Benth.
CAESALPINIACEAE	*Bauhinia gilva* (F.M.Bailey)A.S.George
CUPPRESACEAE	*Callitris glaucophylla* Joy Thomps. & L.A.S.Johnson
CAPPARACEAE	*Capparis loranthifolia* Lindl.
	Capparis mitchellii Lindl.
CASUARINACEAE	*Casuarina pauper* F.Muell. ex L.A.S.Johnson
MELIACEAE	*Cedrela odorata* L.
LAURACEAE	*Chlorocardium rodiei* (R.H.Schomb.)Rohwer, H.G.Richt. & van der Werff
MYRTACEAE	*Corymbia aparerrinja* K.D.Hill & L.A.S.Johnson

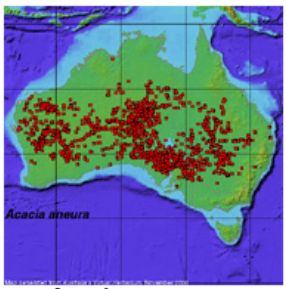
	Corymbia terminalis (F. Muell.)K.D.Hill & L.A.S.Johnson
ASTERACEAE	*Cratystylis conocephala* (F.Muell.)S.Moore
TAXODIACEAE	*Cryptomeria japonica* D.Don
LEGUMINOSAE	*Dalbergia nigra* Allem. ex Benth.
	Dalbergia retusa Hemsl.
SAPINDACEAE	*Dodonaea viscosa* ssp. *angustissima* (DC.)J.G.West
MYOPORACEAE	*Eremophila bignoniiflora* (Benth.)F.Muell.
	Eremophila duttonii F.Muell.
	Eremophila freelingii F.Muell.
	Eremophila longifolia (R.Br.)F.Muell.
	Eremophila macgillivrayi J.M.Black
	Eremophila mitchellii Benth.
	Eremophila polyclada (F.Muell.)F.Muell.
	Eremophila sturtii R.Br.
MYRTACEAE	*Eucalyptus barklyensis* L.A.S.Johnson & K.D.Hill
	Eucalyptus camaldulensis var. *obtusa* Blakely
	Eucalyptus chlorophylla Brooker & Done
	Eucalyptus coolabah Blakely & Jacobs
	Eucalyptus diversicolor F.Muell.
	Eucalyptus gamophylla F.Muell.
	Eucalyptus gracilis F.Muell.
	Eucalyptus leucophloia Brooker
	Eucalyptus marginata D.Don ex Sm.
	Eucalyptus microtheca F.Muell.
	Eucalyptus normantonensis Maiden & Cambage
	Eucalyptus ochrophloia F.Muell.
	Eucalyptus odontocarpa F.Muell.
	Eucalyptus oleosa Miq. subsp. *oleosa*
	Eucalyptus oleosa subsp. *ampliata* L.A.S.Johnson & K.D.Hill
	Eucalyptus oleosa subsp. *repleta* L.A.S. Johnson & K.D. Hill
	Eucalyptus pachyphylla F.Muell.
	Eucalyptus populnea F.Muell.
	Eucalyptus pruinosa Schauer
	Eucalyptus thozetiana F.Muell. ex R.T.Baker
	Eucalyptus victrix L.A.S.Johnson & K.D.Hill
SANTALACEAE	*Exocarpos aphyllus* R.Br.
FAGACEAE	*Fagus sylvatica* L.
RUTACEAE	*Flindersia maculosa* (Lindl.)Benth.
OLEACEAE	*Fraxinus nigra* Marshall
PROTEACEAE	*Grevillea juncifolia* Hook. subsp. *juncifolia*
	Grevillea striata R.Br.
	Hakea eyreana (S.Moore)McGill.
	Hakea leucoptera R.Br.
JUGLANDACEAE	*Juglans nigra* L.
Muridae/Rodentia	*Leporillus apicalis* (Gould, 1853): Stick Nest Rat
Muridae/Rodentia	*Leporillus conditor* (Sturt, 1848): Stick Nest Rat
MAGNOLIACEAE	*Liriodendron tulipifera* L.

FAGACEAE	*Lithocarpus densiflora* Rehder
SOLANACEAE	*Lycium australe* F.Muell.
CHENOPODIACEAE	*Maireana sedifolia* (F.Muell.)Paul G.Wilson
MYRTACEAE	*Melaleuca dissitiflora* F.Muell.
	Melaleuca glomerata F.Muell.
	Melaleuca lanceolata Otto
	Melaleuca lasiandra F.Muell.
	Melaleuca nervosa (Lindl.)Cheel
	Melaleuca trichostachya Lindl.
	Melaleuca viridiflora Sol. ex Gaertn.
MYOPORACEAE	*Myoporum montanum* R.Br.
	Myoporum platycarpum R.Br.
BOMBACACEAE	*Ochroma pyramidale* (Cav. ex Lam.)Urb.
LAURACEAE	*Ocotea rodiei* Mez.
MELIACEAE	*Owenia acidula* F.Muell.
Pythiaceae	*Phytophthora ramorum* Werres *et al.*; water mould
	Phytophthora. cinnamomi Rands; water mould
PINACEAE	*Pinus mugo* Turra
	Pinus nigra Aiton
	Pinus ponderosa Douglas
	Pinus strobes L.
	Pinus sylvestris L.
	Pinus taeda L.
PITTOSPORACEAE	*Pittosporum angustifolium* Lodd.
SALICACEAE	*Populus tremula* L.
	Populus tremuloides Michx.
PINACEAE	*Pseudotsuga menziesii* (Mirb.)Franco
RUBIACEAE	*Psydrax latifolia* F.Muell. ex Benth.
Pucciniaceae/Uredinales	*Puccinia psiddii* Wint.: fungus
FAGACEAE	*Quercus petraea* (Mattuschka)Liebl.
	Quercus robur L.
LEGUMINOSAE	*Robinia pseudoacacia* L.
SANTALACEAE	*Santalum acuminatum* (R.Br.)A.DC.
	Santalum lanceolatum R.Br.
	Santalum spicatum (R.Br.)A.DC.
ANACARDIACEAE	*Schinus molle* L.
CHENOPODIACEAE	*Sclerostegia disarticulata* Paul G.Wilson
CAESALPINIACEAE	*Senna artemisioides* (Gaudich. ex DC.)Randell ssp. *filifolia* Randell
CONIFERAE	*Sequoia sempervirens* Endl.
MELIACEAE	*Swietenia macrophylla* King
TAMARICACEAE	*Tamarix aphylla* (L.)H.Karst
TAXACEAE	*Taxoxylon philpii* J.Shirley: fossil species
CUPRESSACEAE	*Thuja plicata* Donn ex D.Don
PINACEAE	*Tsuga heterophylla* Sargent
RHAMNACEAE	*Ventilago viminalis* Hook.

Appendix Two. Distribution maps of species treated in identification tool

This appendix presents distribution maps obtained from *Australia's Virtual Herbarium* (CHAH November 2004). *Australia's Virtual Herbarium* is an initiative of all of the major Australian herbaria and integrates collection records from all of these institutions. The maps do not account for sub-species or varieties or reflect species abundance

Appendix Two. Distribution maps of species treated in identification tool



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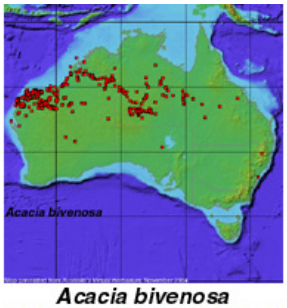

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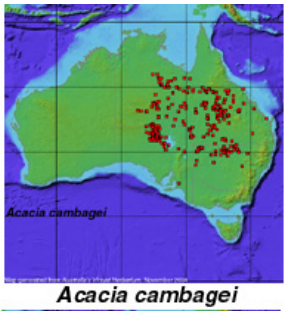

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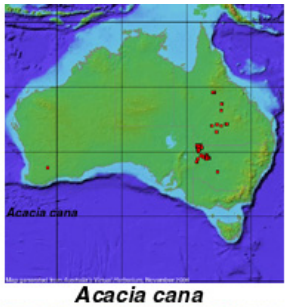

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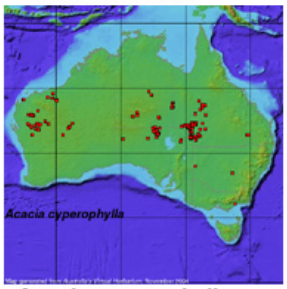
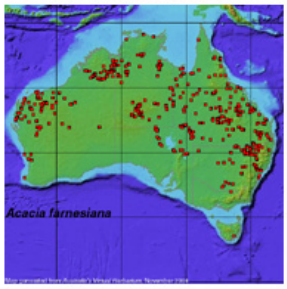


Acacia cyperophylla



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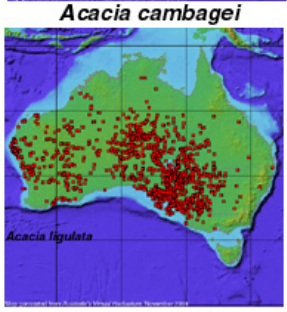
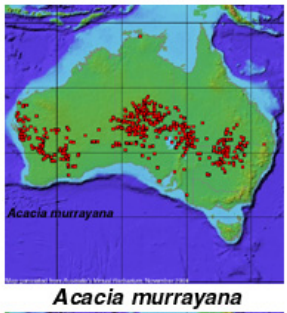


Acacia ligulata



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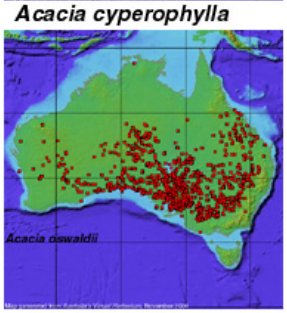
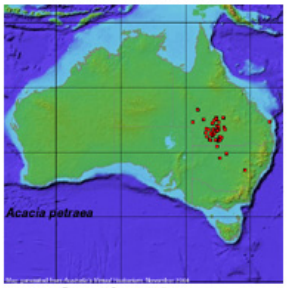


Acacia oswaldii



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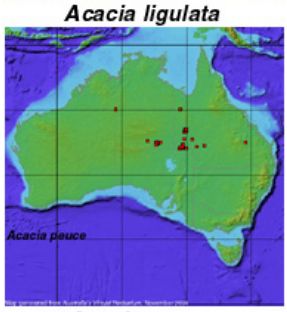
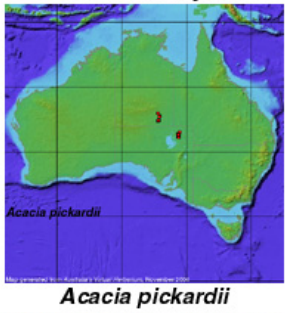
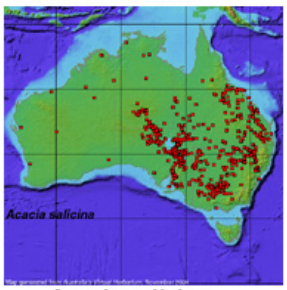


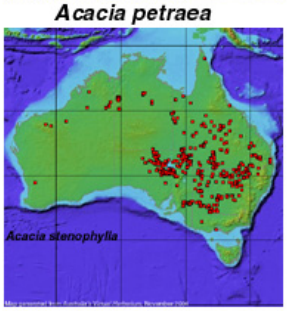
Acacia peuce



Acacia pickardii



Acacia salicina



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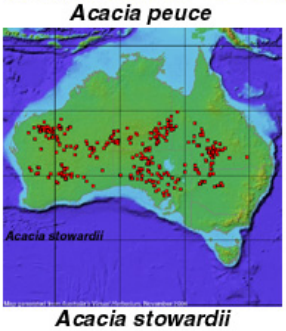

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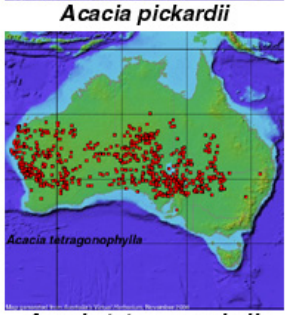

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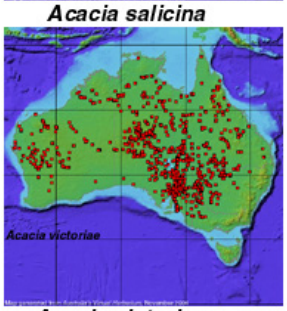
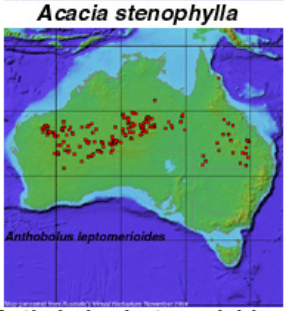
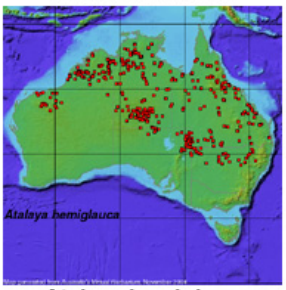


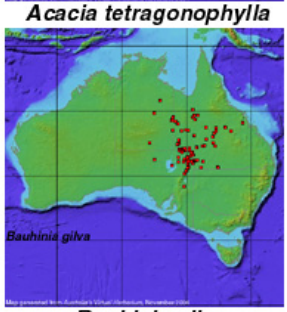
Acacia victoriae



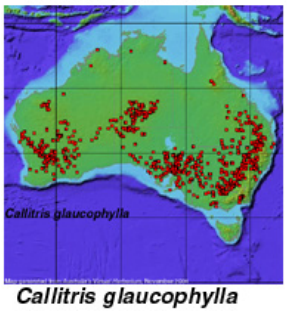
Anthobolus leptomerioides



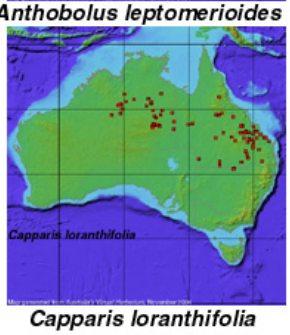
Atalaya hemiglauca



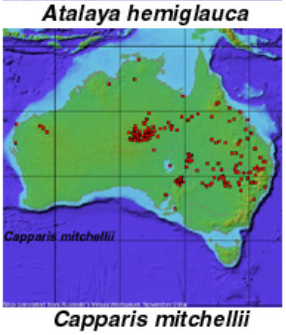
Bauhinia gilva



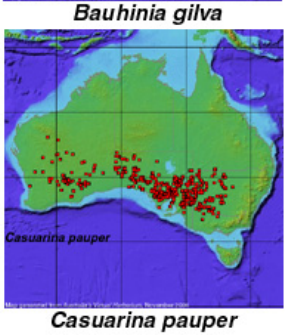
Callitris glaucophylla



Capparis loranthifolia

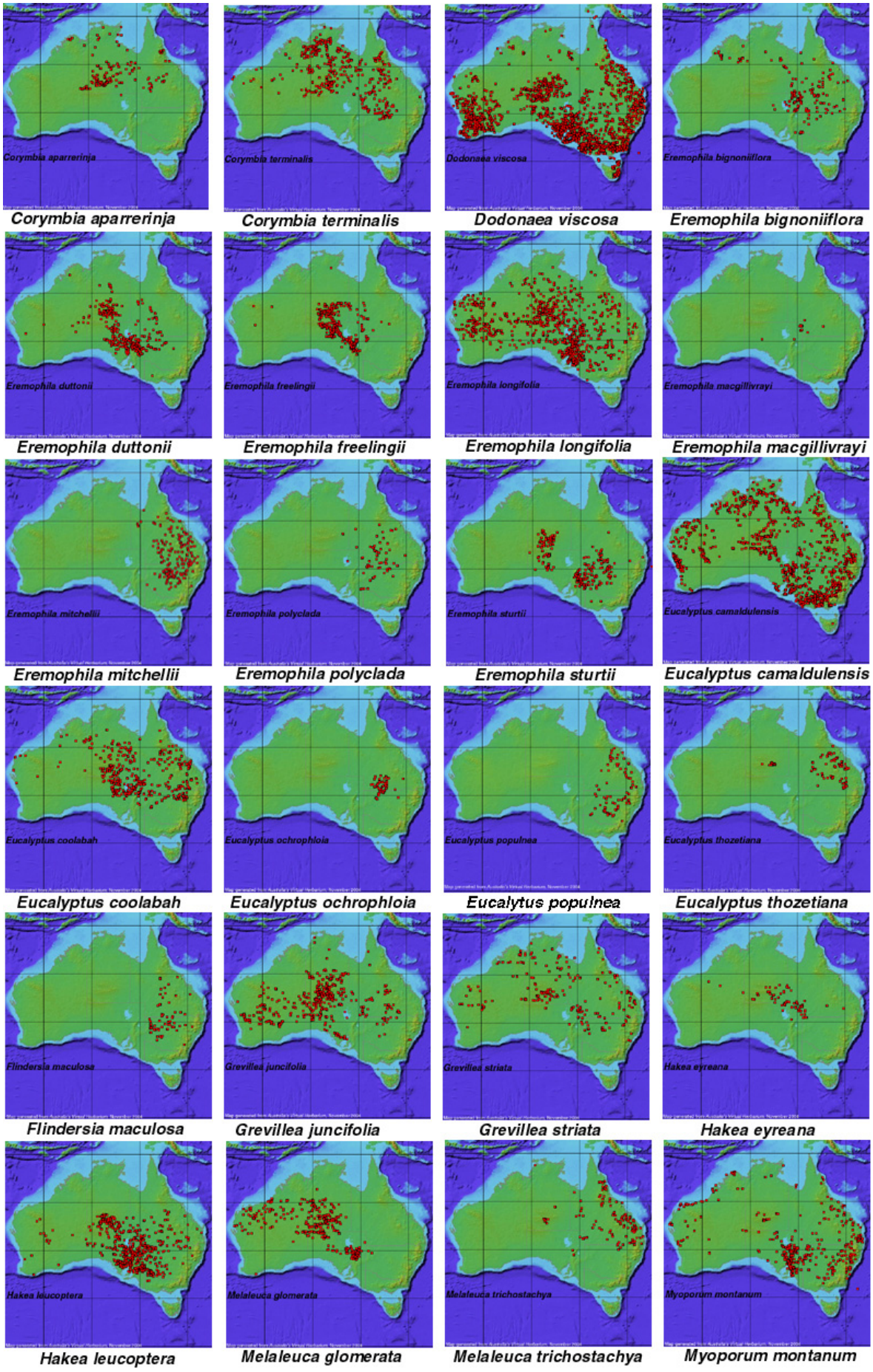


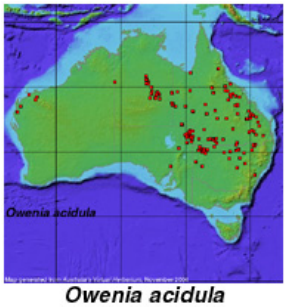
Capparis mitchellii



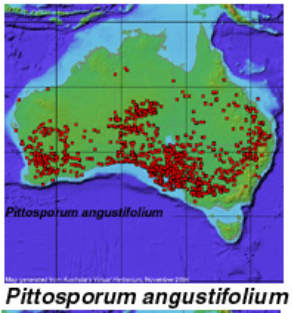
Casuarina pauper

Appendix Two. Distribution maps of species treated in identification tool

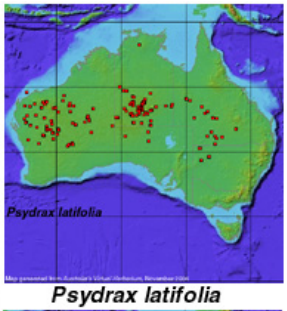




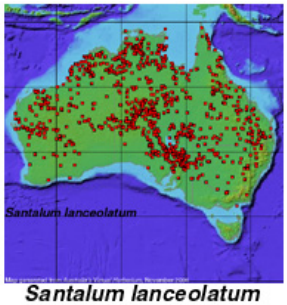
Owenia acidula



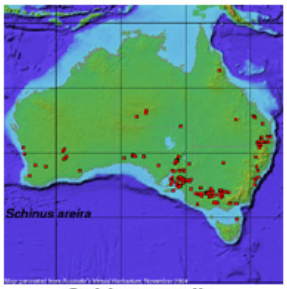
Pittosporum angustifolium



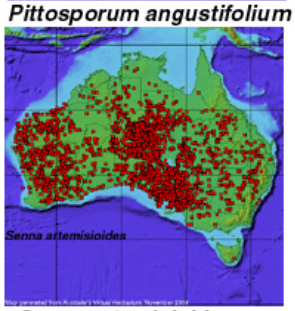
Psydrax latifolia



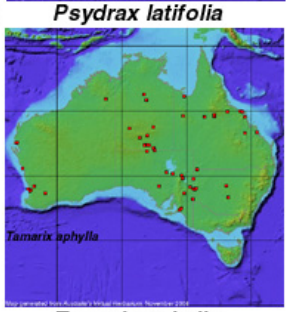
Santalum lanceolatum



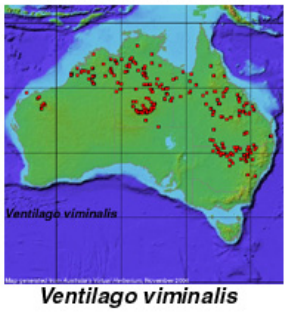
Schinus molle



Senna artemisioides



Tamarix aphylla



Ventilago viminalis

Appendix Three. Catalogue of unvouchered wood specimens

Notes on specimen numbers:

R specimens collected by John Zwar in Roxby Downs, SA region; **ABG** specimens collected from *Adelaide Botanic Gardens*; **ED** specimens obtained from Eugene Dimitriadis of *Xylo-Australis*™.; the absence of a letter before the specimen number denotes specimens collected from Alice Springs; lower case letters after the specimen numbers denote numerous samples of one species.

FAMILY	Genus	Species	Wood sample specimen number
LEGUMINOSAE	*Acacia*	*aneura*	1.1, R1.1, ABG1.1a, ABG1.1b, ABG1.1c, ED1.1
LEGUMINOSAE	*Acacia*	*coriacea*	1.2, ED1.2
LEGUMINOSAE	*Acacia*	*cowleana*	1.3a, 1.3b
LEGUMINOSAE	*Acacia*	*cyperophylla*	1.4, ABG1.4, ED1.4a, ED1.4b
LEGUMINOSAE	*Acacia*	*dictyophleba*	1.5
LEGUMINOSAE	*Acacia*	*estrophiolata*	1.6, R1.6, ED1.6
LEGUMINOSAE	*Acacia*	*georginae*	1.7, ED1.7
LEGUMINOSAE	*Acacia*	*kempeana*	1.8
LEGUMINOSAE	*Acacia*	*salicina*	1.9, ED1.9
LEGUMINOSAE	*Acacia*	*tetragonophylla*	1.10, R1.10, ED1.10a, ED1.10b
LEGUMINOSAE	*Acacia*	*victoriae*	1.11
LEGUMINOSAE	*Acacia*	*stenophylla*	R1.12, ABG1.12, ED1.12
LEGUMINOSAE	*Acacia*	*cambagei*	ED1.13a, ED1.13b
LEGUMINOSAE	*Acacia*	*peuce*	ED1.14a, ED1.14b
LEGUMINOSAE	*Acacia*	*oswaldii*	ED1.15
LEGUMINOSAE	*Acacia*	*carneorum*	ED1.16
LEGUMINOSAE	*Acacia*	*loderi*	ED1.17
LEGUMINOSAE	*Acacia*	*harpophylla*	ED1.18a, ED1.18b
LEGUMINOSAE	*Acacia*	*tephrina*	ED1.19
LEGUMINOSAE	*Acacia*	*microsperma*	ED1.20
LEGUMINOSAE	*Acacia*	*farnesiana*	
MYTRACEAE	*Eucalyptus*	*camaldulensis*	2.1a, 2.1b, R2.1a, R2.1b.
MYRTACEAE	*Eucalyptus*	*coolabah*	2.2, R2.2a, R2.2b
PROTEACEAE	*Hakea*	*divaricata*	3.1a, 3.1b
PROTEACEAE	*Hakea*	*eyreana*	
PROTEACEAE	*Hakea*	*ivoryi*	
PROTEACEAE	*Hakea*	*leucoptera*	3.2, R3.2
PROTEACEAE	*Grevillea*	*striata*	4.1a, 4.1b, 4.1c, R4.1a, R4.1b
MYRTACEAE	*Melaleuca*	*glomerata*	5.1
POLYGONACEAE	*Muehlenbeckia*	*florulenta*	6.1a, 6.1b
BIGNONIACEAE	*Pandorea*	*pandorana*	7.1
PITTOSPORACEAE	*Pittosporum*	*angustifolium*	8.1
SANTALACEAE	*Santalum*	*acuminatum*	9.1
SAPINDACEAE	*Alectryon*	*oleifolius*	10.1
SAPINDACEAE	*Atalaya*	*hemiglauca*	11.1
CUPRESSACEAE	*Callitris*	*glaucophylla*	12.1
LEGUMINOSAE	*Crotalaria*	*cunninghamii*	13.1
MYOPORACEAE	*Eremophila*	*longifolia*	14.1, ED14.1
MYOPORACEAE	*Eremophila*	*mitchellii*	ED14.2
SAPINDACEAE	*Dodonaea*	*viscosa*	ED15.1
SANTALACEAE	*Exocarpos*	*aphyllus*	ED16.1
GYROSTEMONACEAE	*Codonocarpus*	*cotinifolius*	ED17.1
GYROSTEMONACEAE	*Gyrostemon*	*ramulosus*	ED18.1
MELIACEAE	*Owenia*	*acidula*	ED19.1a, ED19.1b
CASUARINACEAE	*Casuarina*	*cristata*	ED20.1
RUTACEAE	*Flindersia*	*maculosa*	ED21.1a, ED21.1b
RHAMNACEAE	*Ventilago*	*viminalis*	ED22.1
BRASSICACEAE	*Apophyllum*	*anomalum*	ED23.1

Appendix Four. Trialled techniques for wood anatomical analysis

Introduction

> *…in the cultural heritage field, the analytical techniques should preferably be non-destructive or micro-destructive. Non-destructive techniques allow analytical information to be obtained with no damage to the sample or (in some cases) to the artefacts in question. When micro-destructive methods are used, all visible damage is avoided and the objects under examination remain aesthetically unimpaired.*
>
> (Janssens and Van Grieken 2004: 2)

There have been two major challenges in this research that have meant that the study does not comfortably conform to standard wood identification procedures. In standard practise large wood samples are often available for analysis but even samples restricted to match-stick dimensions are more than is available in this study. To identify the wood species used to construct valuable items without undermining the integrity of the objects is not a unique undertaking but the severely limited sample sizes available for analysis do impede standard practises involved in identification, particularly physical sectioning. The second challenge is the treatment of unusually dense wood most of which has a density between 1000 kg/m^3 and 1400 kg/m^3. This has severely thwarted the successful application of standard softening processes used in wood identification making the contemporary reference wood (where large samples are available) difficult to physically section. It is largely for these reasons that SEM analysis was employed in favour of thin section analysis. However, in attempting to address these issues and find suitable techniques for wooden artefact analysis and identification a number of technologies not normally employed in standard wood identification were explored. Whilst none of the techniques represented any significant improvement over standard light microscopy or SEM, they did incorporate certain technologies that could be of considerable benefit to wood identification practises.

Fluorescence Microscopy

Fluorescence microscopy is founded on the principle that some organisms and objects emit longer wavelength light (fluorescence) when they are excited by shorter wavelength radiation. Some specimens, including wood, exhibit a primary fluorescence (or auto-

fluorescence) on exposure to ultra-violet (UV) light. Other specimens can be made to fluoresce by impregnation with fluorochromes, stains that have been developed as specific markers for cellular tissues. The increase in the available range and specificity of fluorochromes in recent years has renewed interest in fluorescence microscopy. Fluorescence microscopy has traditionally been applied to biological specimens but it has also been successfully applied to inorganic materials.

Whilst diagnostic assessments are made for the presence or absence of fluorescence in heartwood by examination under a UV lamp (see for example Avella, Dechamps *et al.* 1988; Dyer 1988; Wheeler, Baas *et al.* 1989: 325), with one possible exception (seeSum, Singleton *et al.* 1991), fluorescence microscopy is not commonly utilised for wood identification purposes. Nevertheless, fluorescence microscopy has been used to examine wood and wooden objects to meet a variety of other ends. The technology has been used to examine the effects of the fungi *Ustulina deusta* on the wood of *Fagus sylcatica* (Beech) (Baum, Schwarze *et al.* 2000) and to determine the effects of increased carbon dioxide and nitrogen on the juvenile wood anatomy of three *Populus* species (Luo, Langenfeld-Heyser *et al.* 2005). Whilst not examining the wood per se, conservators have used fluorescence microscopy to examine paints, oils and other finishes on wooden objects, often with the aim of cleaning them or to restore the items to their earliest appearance (Buck 1993; Landrey 1993; Martin 1996).

Methods

Unvouchered wood (see Appendix Three) from seven species, representing six genera, was examined in this trial:

1.1 *Acacia aneura*

ED1.9 *Acacia salicina*

R2.1a *Eucalyptus camaldulensis*

R3.2 *Hakea leucoptera*

ED14.2 *Eremophila mitchellii*

12.1 *Callitris glaucophylla* (softwood)

ED20.1 *Casuarina cristata*

Endgrain blocks of approximately 1cm^3 were prepared with a microtome and placed on a cover slip. For some species, a droplet of water was placed between the cover slip and endgrain surface to test for any improvement in clarity; a droplet of oil may also be used but was not applied in this study. Examination was conducted using a Nikon Eclipse TE300 inverted microscope in fluorescence mode.

Results and discussion

Each of the endgrain wood blocks examined exhibited auto-fluorescence. Auto-fluorescence was largely evident under the blue and green UV filter and both filters produced images of the endgrain surface that exhibited subtle differences in clarity or structure. Auto-fluorescence was not evident under the red UV filter. The addition of a drop of water had variable results with some species producing better images from a dry surface. Images of *Hakea leucoptera* (Figure 60), for example, exhibited improvement in the clarity of the rays with the addition of water but the water produced cloudy rings around the vessels. The effectiveness of water might be improved if specimens are given time to absorb it.

The endgrain blocks examined in this trial were similar in appearance to traditional thin section images with many exhibiting individual ray, parenchyma and fibre cells. This represents a distinct advantage of using an inverted incident light microscope that utilises reflected UV light as it allows images of endgrain blocks at magnifications usually reserved for thin sections (in combination with transmitted light microscopes). Accordingly, for wood that may be sampled and polished to expose the transverse, tangential and radial surfaces, fluorescence microscopy may represent a non-invasive alternative to thin sections. Use of this technique will rely on the wood containing an auto-fluorescence or the impregnation of a stain that possesses an artificial fluorescence. The addition of stains to wood (and the resultant unnatural colours of the various cellular structures) is customary in thin section analysis. Consequently, this requirement need not represent a shortcoming of fluorescence examination of wood blocks at high magnifications or reduce the potential of the method as an alternative to traditional thin section analysis.

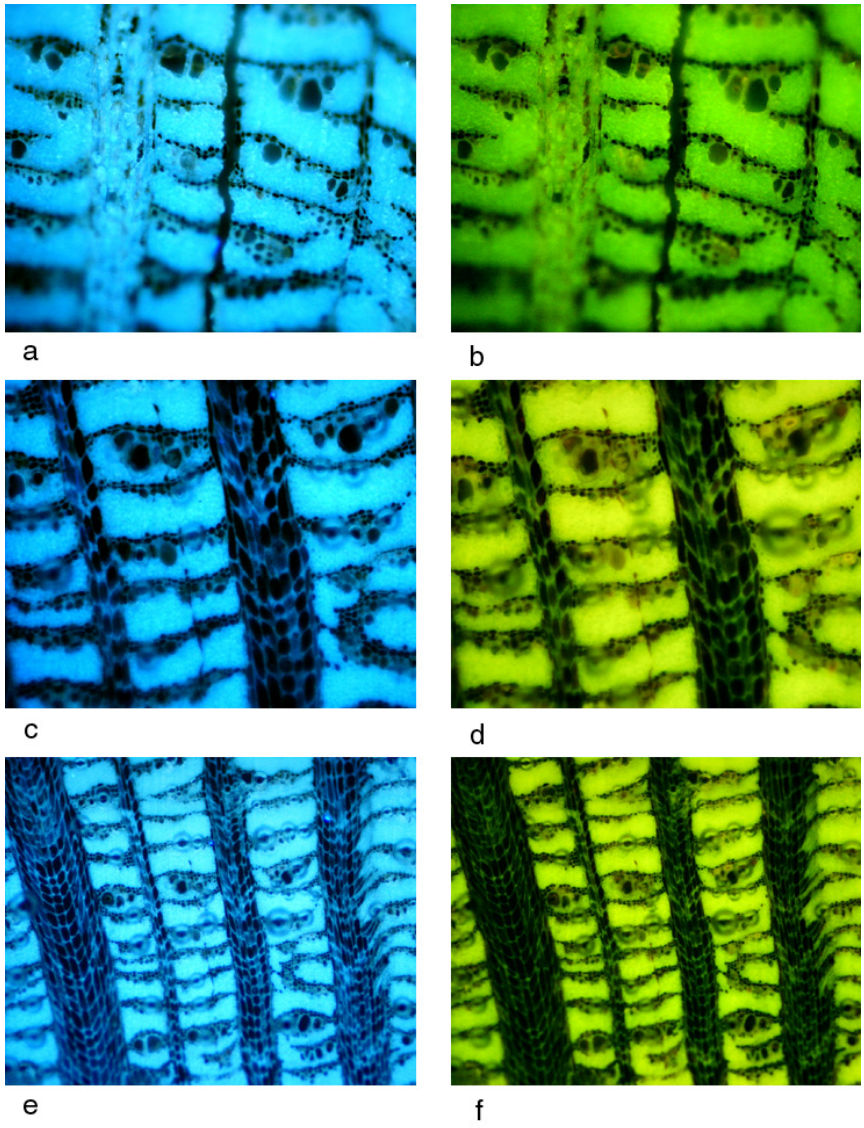


Figure 58 R3.2 *Hakea leucoptera* Endgrain block exhibiting an auto-fluorescence under both blue and green UV light on fluorescence microscope. The addition of a few drops of water between the cover slip and endgrain surface has increased the clarity in figures C, D, E and F, particularly of the ray cells which can be counted to determine the width; however, droplets of water have accumulated around the vessels. Magnifications from A-D: 20x, E-F: 10x.

A secondary advantage to the application of fluorescence microscopy to wood identification is that auto-fluorescence can be diagnostic and diagnostic tests based on fluorescence have been developed. Recently there have been advances in fluorescence microscopy with the development of acousto optical tunable filters that allow filter bandwidths to be defined. Using this technology, wood samples may be examined with filters tuned to bandwidths that will indicate (via fluorescence) the presence of particular fluorochromes that may exist within wood tissues.

Where only a limited wood sample is available, as is usually the case with artefact wood, the fluorescence microscope may be used to examine a small shaving from the endgrain of the wood or small splinters, physically sectioned to expose the two longitudinal planes. This study also exposed the advantages of Auto Montage Imaging System software where out-of-focus areas caused by undulating surfaces may be corrected with the compilation of a wholly-focused image from a series of images (Figure 61).

Despite the advantages in the application of fluorescence microscopy to wood, if the extent of identification that the method affords is no better than that of standard endgrain analysis, polishing a small area of the endgrain of the unknown wood would be a simpler and less invasive procedure than removing a sample for examination with the fluorescence microscope. Even if the higher magnifications afforded by the fluorescence microscope enabled identification beyond that provided by endgrain analysis, it would probably be less invasive (and potentially more informative) if a sample of wood was removed for examination using SEM analysis where even greater resolution and magnification can be achieved. Furthermore, in fluorescence microscopy the depth of the sample is compromised by the fluorescence intensity and a higher magnification lens may collect fluorescence too efficiently from deep tissue such as an endgrain block. In this case, thin sections or the ability to generate optical slices (as with confocal microscopy) may be required.

Confocal Microscopy

Confocal microscopy (or Confocal Laser Scanning Microscopy) refers to a light microscopy technique that utilises laser-scanning technology to generate high resolution optical section images from fluorescent biological materials to several micrometres. Importantly, only light within the focal plane is captured resulting in an image that obstructs any out-of-focus information from above or below the focal plane. In this way a series of two-dimensional optical sections taken along the Z-axis can be produced and, using specialist software, the sections can be integrated to reconstruct a focused three-dimensional image of the sample; this represents a significant advancement in the

conventional and time-consuming reconstruction method using physical sections (Gray, Kolesik *et al.* 1999). Confocal microscopy will enable the imaging of subsurface structures, an important advantage over conventional techniques including SEM (Kitin, Funada *et al.* 1999); however, the depth to which subsurface structures can be observed and the thickness of optical sections is dependent on the density of the sample.

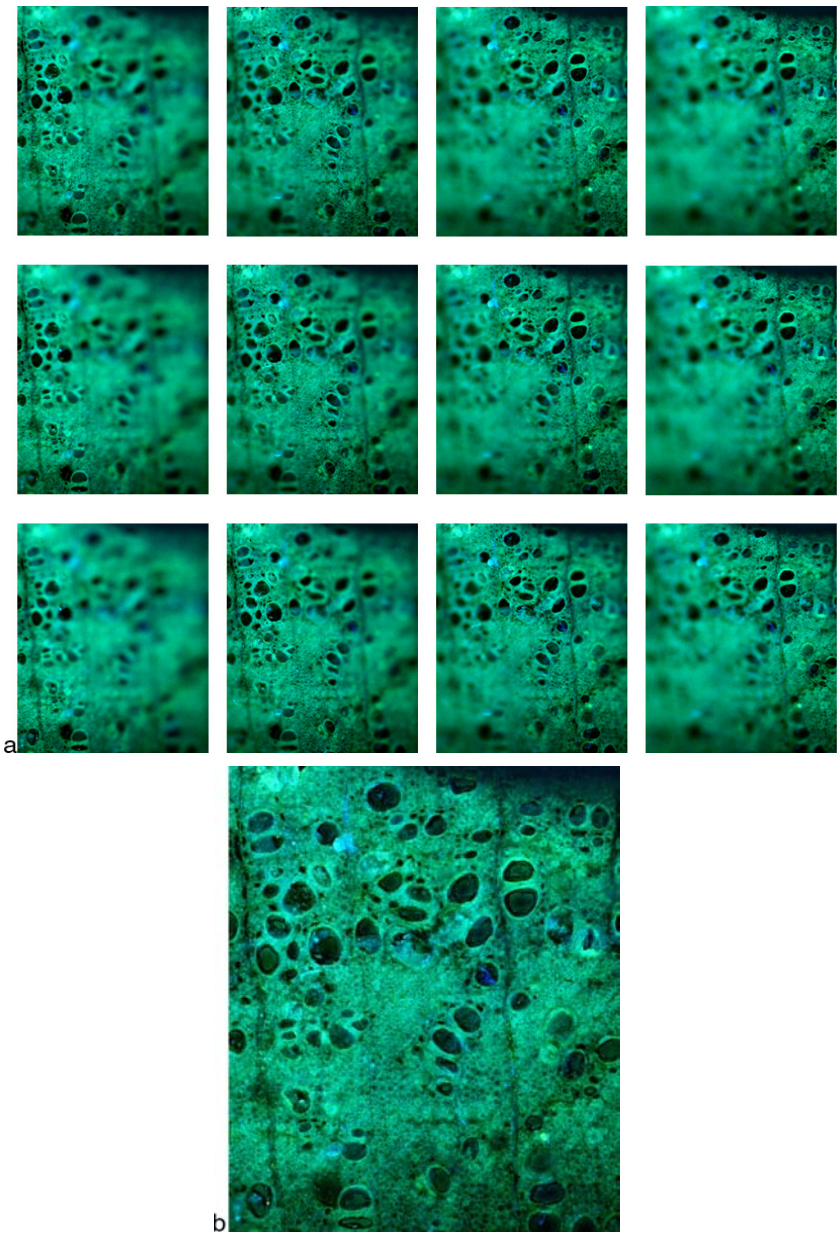


Figure 59 1.1 *Acacia aneura* A. A series of micrographs taken with the fluorescence microscope of the undulating surface of an endgrain block where the image is refocused incrementally. B. A wholly-focused image compiled from the series using Auto Montage Imaging System software.

Confocal microscopy is non-invasive in that it utilises virtual cutting technology to take optical slices from biological material, eliminating the need for physical sectioning. However, the sample size is limited to either a small sample of less than $0.5cm^3$ placed on a cover slip or to a thin section mounted on a slide. The method also relies on cellular features within the sample containing a natural or auto-fluorescence or reflective properties. In samples that do not auto-fluoresce, cellular structures can be made to artificially fluoresce with the addition of stains.

Confocal microscopy has been successfully applied to a number of recent wood anatomical studies (Donaldson and Lausberg 1998; Gray, Kolesik et al. 1999; Kitin, Funada et al. 1999; Kitin, Funada et al. 2000; Kitin, Sano et al. 2002; Kitin, Sano et al. 2003) and the importance of the technology in eliminating the need for physical sectioning has been acknowledged (Gray, Kolesik et al. 1999).

Methods

Transverse, tangential and radial thin sections as well as an endgrain block (approximately 1cm3) of ED1.9 *Acacia salicina* (density 900 kg/m3) were prepared with a microtome. One set of thin sections was stained with safranin whilst the other was left unstained to test for auto-fluorescence. The specimens were examined using a Diaphot 300 inverted microscope attached to a Bio-Rad MRC-1000UV Confocal Laser Scanning Microscope System.

Results and discussion

The confocal microscope was applied to thin sections and an endgrain block with the generation of optical slices (Figure 62). The unstained thin sections and the endgrain block exhibited autofluorescence. However, the density of the wood tissue restricted the depth of the Z-axis and the resultant loss of laser strength (attenuation) limited the collection of fluorescence from sub-surface tissues. Some unfocused areas were evident because of the thickness of the slices; slices can be thinner but it is a compromise with laser intensity and photo-bleaching can occur.

Confocal microscopy shares many of its benefits with fluorescence microscopy, particularly in terms of the ability to generate images from endgrain blocks of comparable magnification and likeness to thin sections; see Figure 62, images B and F. However, the ability to optically slice means that the confocal method will allow images of higher magnification from an endgrain block.

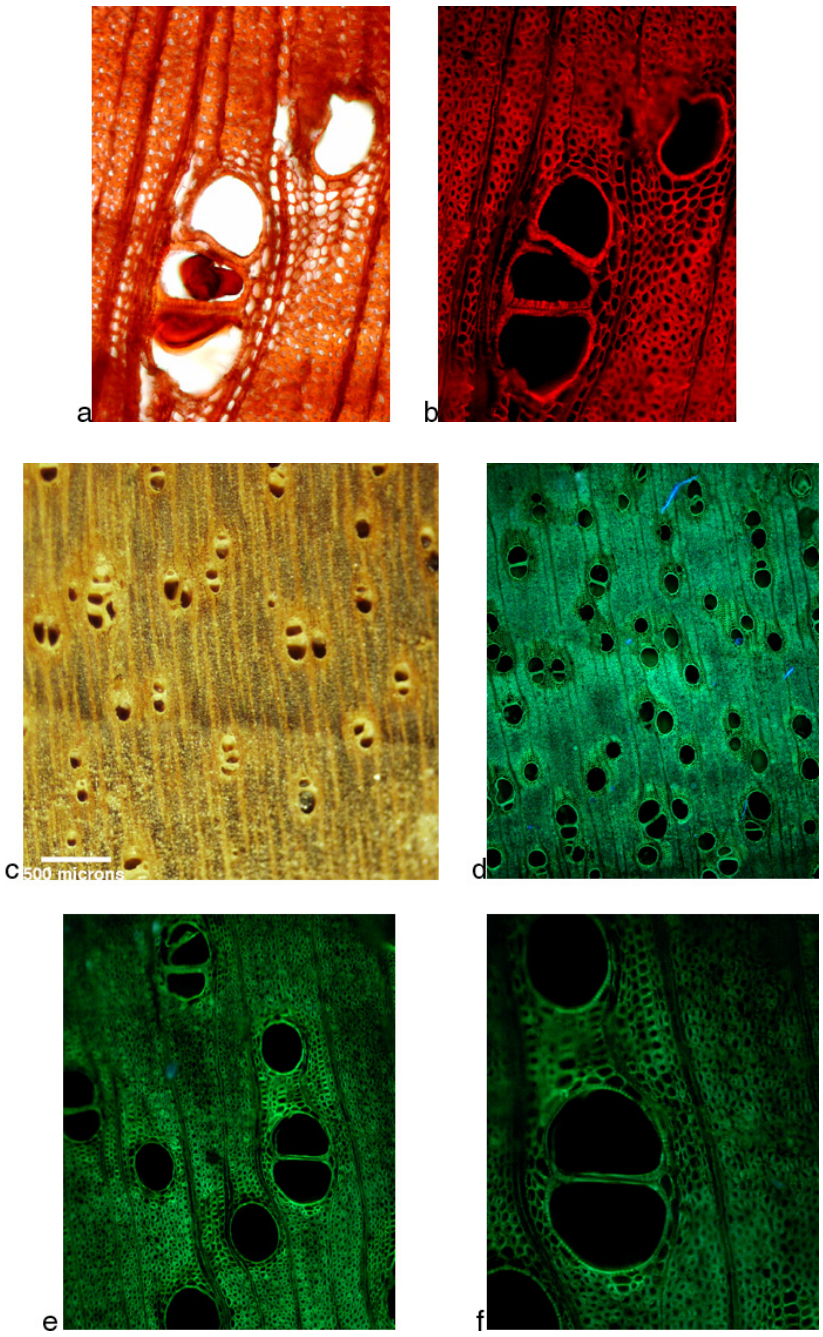


Figure 60 ED1.9 *Acacia salicina* Various images of the transverse surface taken with the confocal microscope. A. Safranin-stained thin section viewed under transmitted light; B. Safranin-stained thin section viewed under red UV light on fluorescence microscope; C. Endgrain block observed under reflected light using standard light dissecting microscope; D, E & F. Endgrain block observed under blue UV light on fluorescence microscope 4, 10 & 20x. In particular, note similarity between B (thin section) and F (endgrain block).

Since the density of a sample restricts the depth of the Z-axis, best results with the confocal microscope are achieved on wood with a lesser density. For example, a recent confocal examination of thick histological sections from the wood of *Kalopanax pictus* (density 500 kg/m^3) achieved optical sections to a depth of 30-40 µm in the cambium (Kitin, Sano *et al.* 2003: 214). Optical slices were also collected at 3 µm intervals to a depth of 144 µm in the

xylem. However, it was noted that attenuation increased in areas of higher density wood tissue, particularly at depths of greater than 30 µm (Kitin, Sano *et al.* 2003: 215)

At least 1mm^2 of information from the surface of wood is required for identification purposes. Regardless of the density of the wood, it is unlikely that depths along the Z-axis to 1 mm can be reached. Even assuming examination of wood with a confocal microscope can reach a depth of 50 µm, a virtual cut taken along a ray on the endgrain would expose only 0.05 mm of the radial surface if the image were rotated 90 degrees and twenty such slices would be required for the data to be meaningful. Whilst this limits the application of virtual cutting to within a few degrees of the exposed radial, tangential and transverse planes, it does not negate the possibility of virtually-cutting along an unsurfaced splinter to locate the radial and tangential surfaces. The Auto Montage Imaging System could then be used to fix any unfocused areas. In this regard, confocal microscopy may represent an alternative to physically sectioning small samples from valuable objects and examining them at magnifications normally reserved for conventional transmitted light examination of thin sections.

X-Ray Microtomography (Micro-CT System)

The Skyscan 1072 is a state-of-the-art micro computer-aided tomography (micro-CT) instrument developed by the Belgian-based company Skyscan. The instrument allows high resolution CT-scans of samples with a resolution of a few micrometres. This represents a marked improvement on high-resolution medical CT-scanners that achieve a resolution of 0.5 millimetres. The instrument has been applied to a range of organic and inorganic materials for observation of internal microstructure including geological and biomedical samples, plant fossils, electronics, bones and teeth, foodstuffs, metal alloys and plastics. The recommended maximum sample size is 1.5 cm diameter by 3 cm height although the smaller the diameter the greater the resolution and magnification attainable. The maximum magnification is 120x whilst on a sample measuring less than 5 mm diameter a resolution of 4 µm can be achieved.

CT scanners operate by taking a rotational series of x-ray projection images of a sample and then using standard tomographic techniques to convert these images to thin cross-section images of the sample. For the Skyscan 1072 the thickness of the cross sections is between 18 µm at minimum magnification and 3 µm at maximum magnification. The

cross-section images can be used for direct measurement of features in the sample or used to generate a three-dimensional reconstruction of the entire sample. Once scanning and three-dimensional reconstruction is complete, associated software will allow “virtual” cuts to be made of the sample at any angle and without the need for physical preparation or sectioning of the wood block. Accordingly, in the case of wood, samples can be "virtually" cut at any angle and reconstructed into a three-dimensional cube showing each of the true planes. For example, to generate the radial surface on a wood specimen, a virtual cut can be made along a ray exhibited on the endgrain and the image can be reconstructed so that it has been rotated ninety degrees to show the newly cut surface. The same principal applies for the tangential surface where a virtual cut can be made perpendicularly to the rays. Furthermore, individual cross-sections can be isolated and examined in two dimensions; with possible cross-section thickness of 18 µm or less the cross-sections are of equivalent thickness to the thin sections prepared in standard wood anatomy.

Methods

Since the micro-CT instrument is new to Adelaide Microscopy and its capabilities remain untested on a variety of materials, a small splinter (approximately 2 x 2 x 10 mm) of ED1.13a *Acacia cambagei* heartwood was sent to the Belgian developers of the machine to ensure that the optimum settings were achieved. Virtual-cutting and three-dimensional reconstruction of the resultant image was conducted by Dr Peter Self of Adelaide Microscopy. The results are shown in Figure 63.

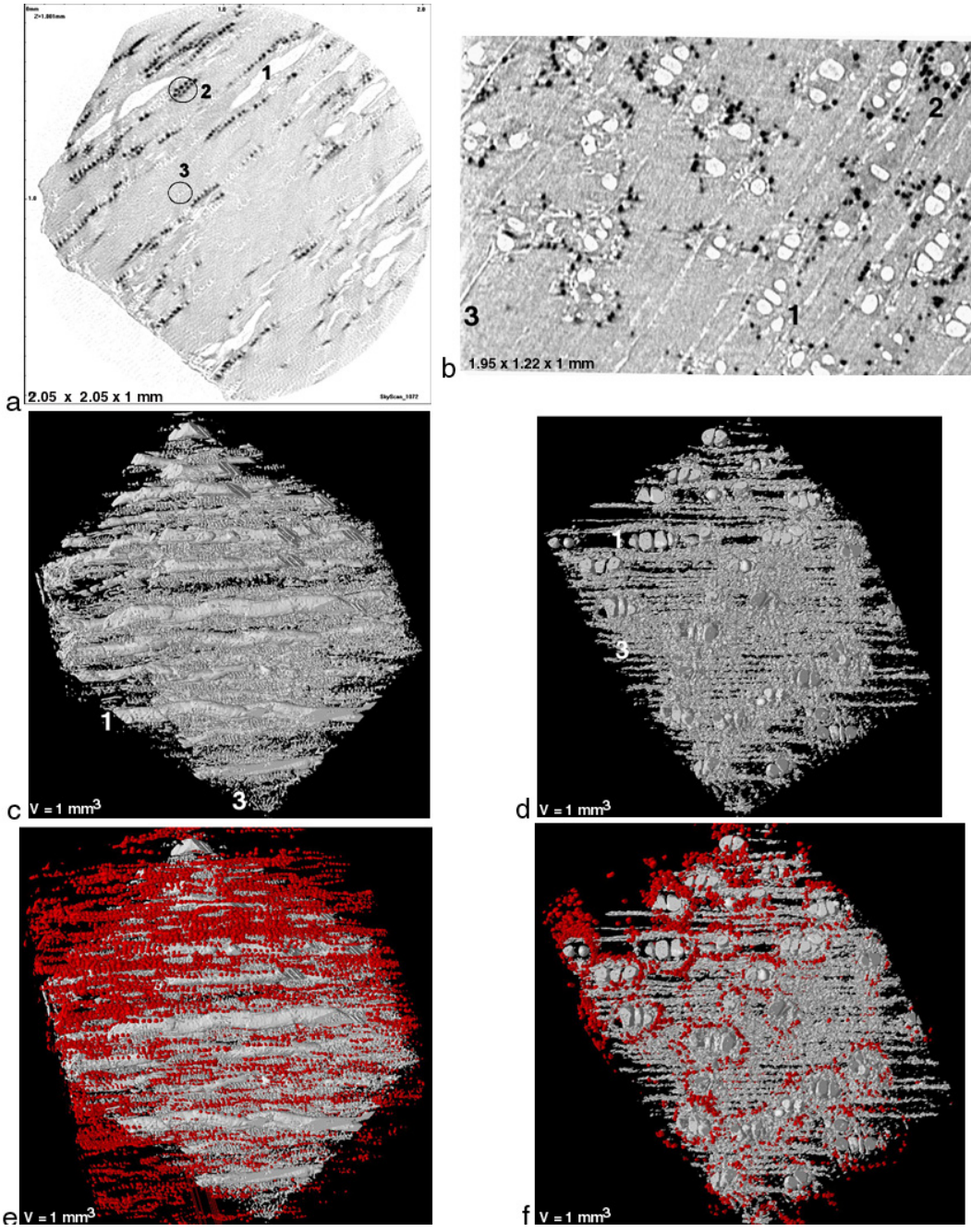


Figure 61 ED1.13a Acacia cambagei Micro-CT scanner images of wood tissues. A. An optical slice showing a longitudinal view of the wood tissues; B. An optical slice showing a transverse view of the wood tissues. The highlighted features are 1 vessels 2 resin and 3 rays. C & D. A three-dimensional reconstruction showing the vessels and rays in longitudinal and transverse views; note that in D the rays run perpendicularly to the vessels. E & F. Showing resin; note that in E the resin forms strings that run parallel to the vessels and in F that the resin clusters around the vessels; this may indicate an association with parenchyma cells.

Results and discussion

The results of the analysis were disappointing from a wood identification perspective with the production of images exhibiting poor clarity and no distinction of major wood structures apart from the vessels and rays. The resolution required to see the individual parenchyma and fibre cells appeared to be beyond the machine's capabilities. In addition, the images appear in greyscale so that, unlike light microscopy, colour variations that often discern parenchyma from fibres under low magnification are not evident (although this is also true of SEM images).

It remains to be seen whether greater distinction and contrast can be achieved between the major structures of wood to produce something of an equivalent to traditional light microscope images of the endgrain. Like many of the species treated in this research, *Acacia cambagei* wood is unusually dense (1300 kg/m^3) and it is possible that wood with lesser density may exhibit greater inter-cellular variation in this property which would possibly improve the contrast and clarity of an image. However, the results of the trial on the *Acacia cambagei* sample indicate that the extent of identification seems very unlikely to surpass or even equal that of traditional endgrain analysis. If further research on the application of the Skyscan 1072 to wood confirms this, a small area of polished endgrain analysed under a light microscope would be preferable to any method that requires the removal of a sample.

CT-Scanner

CT-scanning (otherwise known as Computed Tomography or Computed Axial Tomography (CAT) Scanning) uses x-ray technology to build a series of cross-sectional images of tissues. Like traditional x-ray machines, it works on the principle that x-rays are absorbed or attenuated (weakened) at varying levels depending on the tissues. However, with its ability to image soft tissue, CT-scanning technology is more sophisticated than conventional x-ray machines. On a CT-scan, the denser the tissue the whiter the scan. Unlike the micro-CT scanner, where resolution is available to several micrometres, conventional CT-scanners have a resolution limited to 1 to 2 mm, and even high-resolution CT-scanners are limited to 0.5 mm resolution. Given the fact that the technology is used for imaging the human body, sample size is large and would suit non-invasive analysis of many wooden artefacts and objects.

In recent years, CT-scanners, once the sole domain of medical research, have been increasingly used to examine other materials. At *Monash University*, Melbourne logs are being CT-scanned to determine the presence and extent of internal abnormalities such as fungus, decay, cracks or gum veins. The research is expected to provide foresters with the ability to grade logs and assess their suitability for products such as furniture, veneers and building materials (Monash University 1995); similar investigations have been conducted in the United States (Sarigul, Abbott *et al.* 2000; Thawornwong, Occena *et al.* 2000). Still with Forestry, a series of papers explored CT-scanning and its usefulness for measuring wood density and moisture content (Lindgren 1991a; Lindgren 1991b; Lindgren 1985; Lindgren 1992; Lindgren, Davis *et al.* 1992). In Venezuela, scientists are applying CT technology to preserve the country's cultural heritage, decimated to a great extent by the tropical climate and insect attack; not restricted to wooden objects, CT-scanning is being used to isolate areas of damage and decay in paintings, sculptures, artefacts, books, photos and written documentation, and has already assisted in stabilising the *Immaculate Creole Virgin*, a wooden statue under attack by a wood-boring beetle (Fletcher and Moscaritolo 2004). CT-scanning has also offered great potential to archaeology and the study of Egyptian mummies: in an attempt to resolve how he died, scans of the mummy of King Tutankhamen have recently determined that he was not murdered as a 1968 x-ray had suggested (Lorenzi 2005; Yapp 2005). Similarly, an archaeological team from *Macquarie University*, Sydney plan to use CT-scans and x-rays to non-destructively examine the internal structure of three well-preserved mummies excavated near Cairo (Stylianou 2005). Finally, the *Field Museum*, Chicago announced their intention to x-ray a variety of specimens from their collections; these included Egyptian mummies of gazelles, falcons and a cat (to determine if the animals are present inside), Peruvian "whistling vessels" (to determine what the whistles look like) and a female skeleton, in an attempt to resolve if it is the oldest held in any US museum (Associated Press 2004).

Whilst analysis of the *Immaculate Creole Virgin* indicated that it was made of three types of tropical wood[61] (Fletcher and Moscaritolo 2004), to my knowledge, no studies have used CT-scans or x-ray for the purpose of identifying wood. It is acknowledged that the

[61] It is not clear how the researchers knew the wood was from a tropical species or that one was of mahogany, as was stated in the article.

resolution of the technology is unlikely to show the cellular detail necessary for wood identification; however, in the absence of similar studies on Aboriginal Australian artefacts, a selection of artefacts were CT-scanned.

Methods

Four Aboriginal Australian artefacts from the Lake Eyre basin region were examined using a CT-scanner at the Lyell McEwin Hospital[62]; see Figure 64. The artefacts, each with limited accompanying documentation, were from the *South Australian Museum*'s Australian Ethnographic Collection. Invasive examination of the artefacts had not been conducted for wood identification purposes; that is, the artefact endgrains had not been polished and samples had not been removed for thin section or SEM analysis. A brief description of each of the artefacts follows:

- A31064 Fire-making apparatus consisting of a wooden base and drill. The drill is fastened to the base with wire – a post-collection strategy to keep the pieces together. The item was donated by T Vogelsang and is from the Cooper Creek region (*South Australian Museum* 2002).

- A34056 Engraver consisting of a wooden handle with stone blade bound to the handle with sinew. The artefact is probably from the Cooper Creek region and was donated by the wife of George Aiston[63] (*South Australian Museum* 2002).

[62] Staff of the hospital and museum have previously collaborated in the production of CT-scans of a Pleistocene-aged marsupial lion (*Thylacoleo carnifex*) skull excavated from the Naracoorte Caves, South Australia (Freeborn 2002). The SA Museum has also collaborated with the Royal Adelaide Hospital with the production of CT-scans from a 110 million year old ichthyosaur, a marine reptile (Pritchard 2001).

[63] George Aiston (1879-1943) was a police trooper based at Mungeranie on the Birdsville Track (1912-1924) and, in his later years, further south at Mulka (1924-1943). During his time on the Birdsville Track he maintained great interest in the Indigenous people of the region and amassed a large collection of their material culture. Much of this collection is housed in the *South Australian Museum*.

Figure 62 CT-scanned Aboriginal artefacts from the *South Australian Museum*. A. A61599 Hafted axe; B. A31064 Fire-making apparatus; C. A34056 Engraver; D. A35337 Adze.

- A35337 Adze consisting of a wooden handle with metal blade bound to the top of the handle with string and resin. The bottom of the handle is also coated in resin. The artefact is from the Diamantina region and was purchased from Miss Marshall (*South Australian Museum* 2002).

- A61599 Hafted axe consisting of a wooden handle bent around a large stone and bound together with plant fibres and resin. The artefact is of the Wonkanguru people of the Lake Eyre district; it was donated from the estate of Charles R.J. Glover (a former Lord Mayor of Adelaide) and was ex George Aiston's collection (*South Australian Museum* 2002).

Results

Data was returned from the CT-scans in the form of images (.jpg or .bmp files) containing a series of two-dimensional slices taken from each object. Longitudinal and transverse slices were both acquired. The three-dimensional reconstruction of the four artefacts took the form of image (.jpg) and movie (.avi) files of the objects in various orientations. Plates of a selection of the two-dimensional slices and three-dimensional reconstructions for each object are presented in Figures 65, 66, 67 and 68.

Confronted with a limited application to wood identification, these results discuss some of the potential of the technology in terms of informing other aspects of anthropology, including conservation and the methods used to manufacture objects.

Adze

The series of CT-scans of the endgrain of the wooden adze handle clearly indicate that the growth rings are largely incomplete over the length of the entire artefact (see Figure 65a, 65c). This illustrates that the handle must have been fashioned from a larger piece of wood (probably a limb but potentially a root) and the extent to which the growth rings are incomplete suggests that the original piece of wood had been quite heavily fashioned. This seems unusual since the use of an entire limb of suitable size would have required less energy to shape into a handle. A metal blade fastened with resin and string to one end of the artefact indicates that the artefact is post-European contact. Perhaps the blade had superior cutting abilities to traditional stone and bone and was used to fashion the wood for the handle. It is also possible that the remaining wood was used in the construction of another artefact.

Engraver

The CT-scans of the engraver illustrate the usefulness of the technology for examining parts of an object that could not normally be seen without dismantling a piece. The engraver consists of a stone blade barely visible beneath the sinew used to bind it to the wooden handle. CT-scanning allowed the engraving blade to be “virtually-cut” from the object so that it has been detached from the wood and binding sinew. This enables examination of the front, rear and side of the blade (see Figure 66e).

With respect to the wooden handle, the endgrain slices of the engraver taken with the CT-scanner are poorly resolved. However, the slices do indicate regular longitudinal gaps within the wood that run much of its length. These seem to be associated with the longitudinal ridges that characterise the handle and with the regular striations just discernable along the obscured endgrain – both observed with the naked eye. Further examination would be required to ascertain whether the longitudinal gaps are a result of tangential shrinkage along the growth rings or whether the artefact consists of longitudinal layers of wood sandwiched together. In support of shrinkage, there does appear to be a strong visual colour contrast in the wood that may denote differentiation between the earlywood and the latewood; a pronounced difference in earlywood and latewood affects cell dimensions and cell wall thickness and the earlywood, often characterised by a lesser density (Hoadley 1990: 10), may cleave more easily. Conversely, if the handle is made up of layers of wood there is no evidence of a binding agent (either on the CT-scans or with the naked eye) and the internal longitudinal gaps that run the length of the artefact do not seem to extend to the endgrain of the object.

To resolve whether the longitudinal gaps in the wood are the result of natural shrinkage or cultural construction it would be useful to polish an area of the endgrain to determine if the regular striations are growth rings rather than layers of wood. If they are found to be the growth rings, their regularity might suggest a species that is not native to arid Australia. Equally, if the handle consisted of longitudinal layers of wood the item is more likely to have been fashioned from a European object and the wood may not be native to Australia.

Finally, there is a hole in the artefact, clearly visible to the naked eye, which shows up on the longitudinal and endgrain surfaces of the CT-scan (see Figures 66a, 66c, 66d). Sinew or plant fibres may have been threaded through the hole to enable it to be worn around the neck.

Hafted axe

The CT-scans yielded little information about the hafted axe. In the series of slices of the endgrain, growth rings were visible on the ends of the piece of wood used for the handle. Growth rings were incomplete and their size suggested that the wood had been stripped from a much larger piece, perhaps the outside of a trunk or limb. Bending of the wood around the stone axe head is likely to have occurred whilst the wood was green and the

bending process may have been assisted by brandishing the wood in fire. The plant material used to bind the artefact, whilst visible in the series of endgrain slices, is poorly resolved (see Figure 67c). The density of the stone is such that it is depicted in the two-dimensional series as white (see Figure 67b).

Fire-making apparatus

Slices of the endgrain from the base piece of the fire-making apparatus clearly show wide rays permeating in a radial direction. This information limits the species used to construct the base piece of the fire-making apparatus to one with large multiseriate rays such as occurs in Proteaceae and some Casuarinaceae. However, CT-scanning was not necessary to limit the artefact identification to these taxa. The endgrain of the artefact was visible to the naked eye and not obscured by dirt and grease as can be the case with many other aged, utilitarian objects; use of a light microscope on the unpolished endgrain prior to the CT-scanning achieved the same level of identification (see Figure 68e)[64]. Even where an endgrain on an object is obscured, it would be cheaper, and likely more useful, to polish a small area with a razor blade and examine it with a light microscope than to use CT-scanning to resolve the endgrain for identification purposes.

The series of endgrain slices also indicate that the growth rings are incomplete; see Figure 68b, 68c. This confirms the visual suggestion that the wood has been split to form a flat surface upon which to drill. Figure 68c and 68d indicate a hole that extends from the inner growth rings to the bark.

Discussion

As expected, for wood identification purposes, the CT-scans of the objects are not adequately resolved[65]. The CT-scanner has clearly revealed the growth rings on the

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[64] Analysis of the endgrain using a light microscope could elicit a firmer identification if the vessel arrangement could be resolved. Whilst vessels are clearly present on the endgrain their arrangements is far too uniform and concentrated to indicate *Grevillea* or *Hakea* (Proteaceae) which usually occur in tangential bands. – check whether this could be rootwood or whether it might fit the characteristics of Casuarinaceae better.

[65] A request to resolve the images further could not be granted as the *Medical Imaging Department* of the *Lyell McEwin Hospital* did not retain the original data. Nevertheless, Ross Harper of *Medical Imaging Department* indicated that, even with the original data (or if the artifacts were rescanned), it is unlikely that much greater resolution is achievable.

transverse and longitudinal planes of the adze (see Figure 65b, 65c), and, in the transverse plane of the base piece of the fire-making apparatus (see Figure 68b, 68c) but the growth rings lack clarity on the transverse slices taken from the engraver (see Figure 66b, 66c) and the hafted axe (see Figure 67b, 67c, 67d). Beyond indicating ring-porosity, the scans of the objects provide little further information that might aid wood identification, particularly where this information (and more) can be elicited through endgrain analysis in combination with light microscopy.

Despite the limited application of CT-scanning to wood identification, and notwithstanding the present expense of the technology, these trials have shown that the technique does show some potential in terms of conservation and for shedding light on manufacturing techniques. The technology could also be used to monitor artefacts that are deteriorating, both to reduce handling and to indicate possible conservation solutions. The ability to virtually-cut objects and to examine parts of an object that would otherwise require dismantling could also benefit the conservation needs of the artefact and increase our understanding of its purpose and construction. The raw data would provide a detailed, examinable record of the internal structure of the artefacts and any area within the object could be three-dimensionally reconstructed. This would provide a useful record for posterity as well as a record of the conservation status of the object. Additionally, the data or resultant three-dimensional reconstructions, may act as a replacement for loans of objects, thereby increasing access to collections, and increasing their research potential.

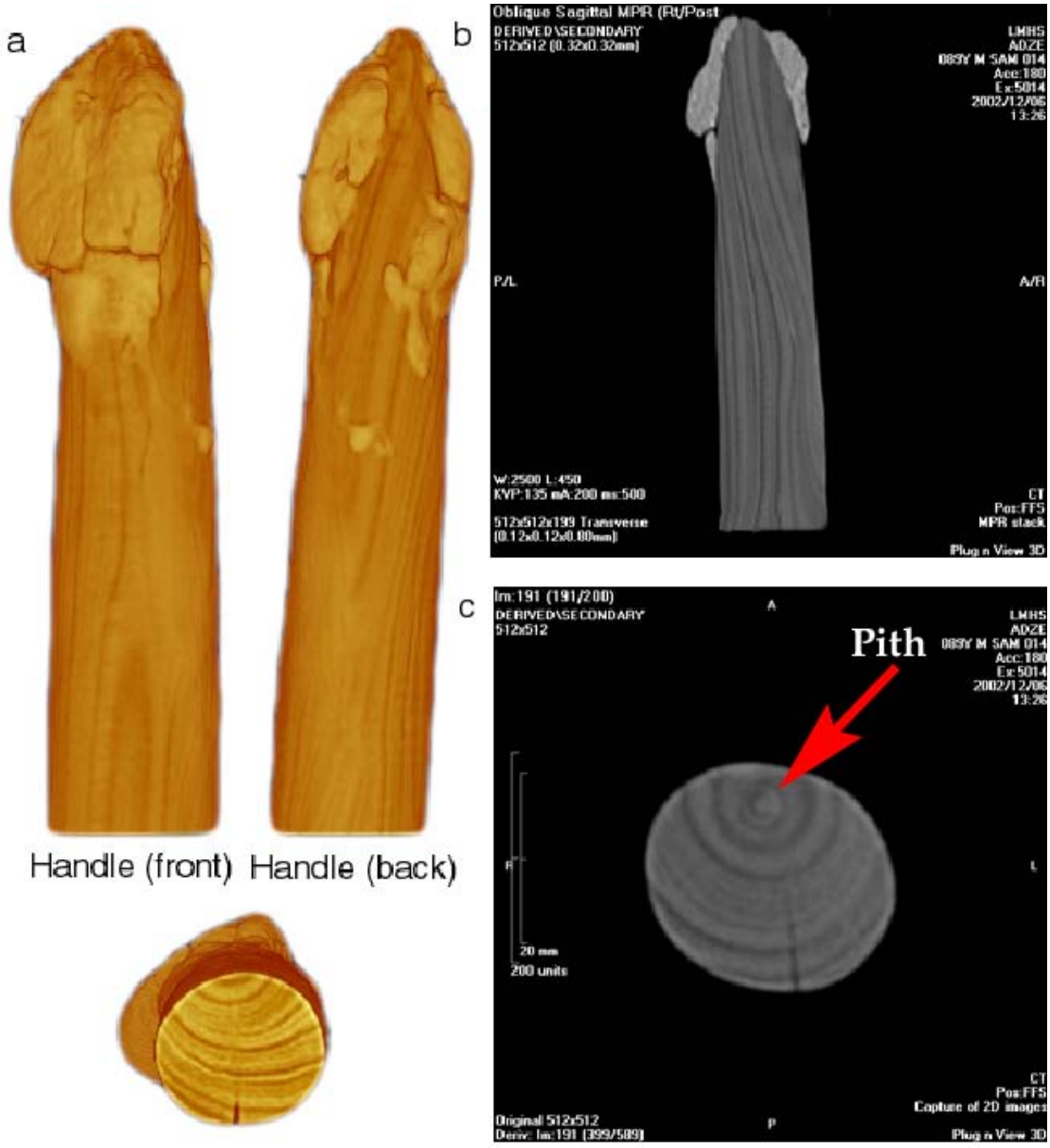

Figure 63 CT-scans of adze. A. Three-dimensional reconstruction of resin-coated handle of adze (metal blade end not depicted) – front and back – and endgrain of wood; note visibility of growth rings; B. Two-dimensional slice from longitudinal section of adze showing resin and presence of growth rings; C. Two-dimensional slice from cross-section of adze showing endgrain of wood; the arrow indicates the pith. Note most growth rings are incomplete and that the position of the growth rings in the two-dimensional slice and the three-dimensional reconstruction indicate the images are from different areas in the wood.

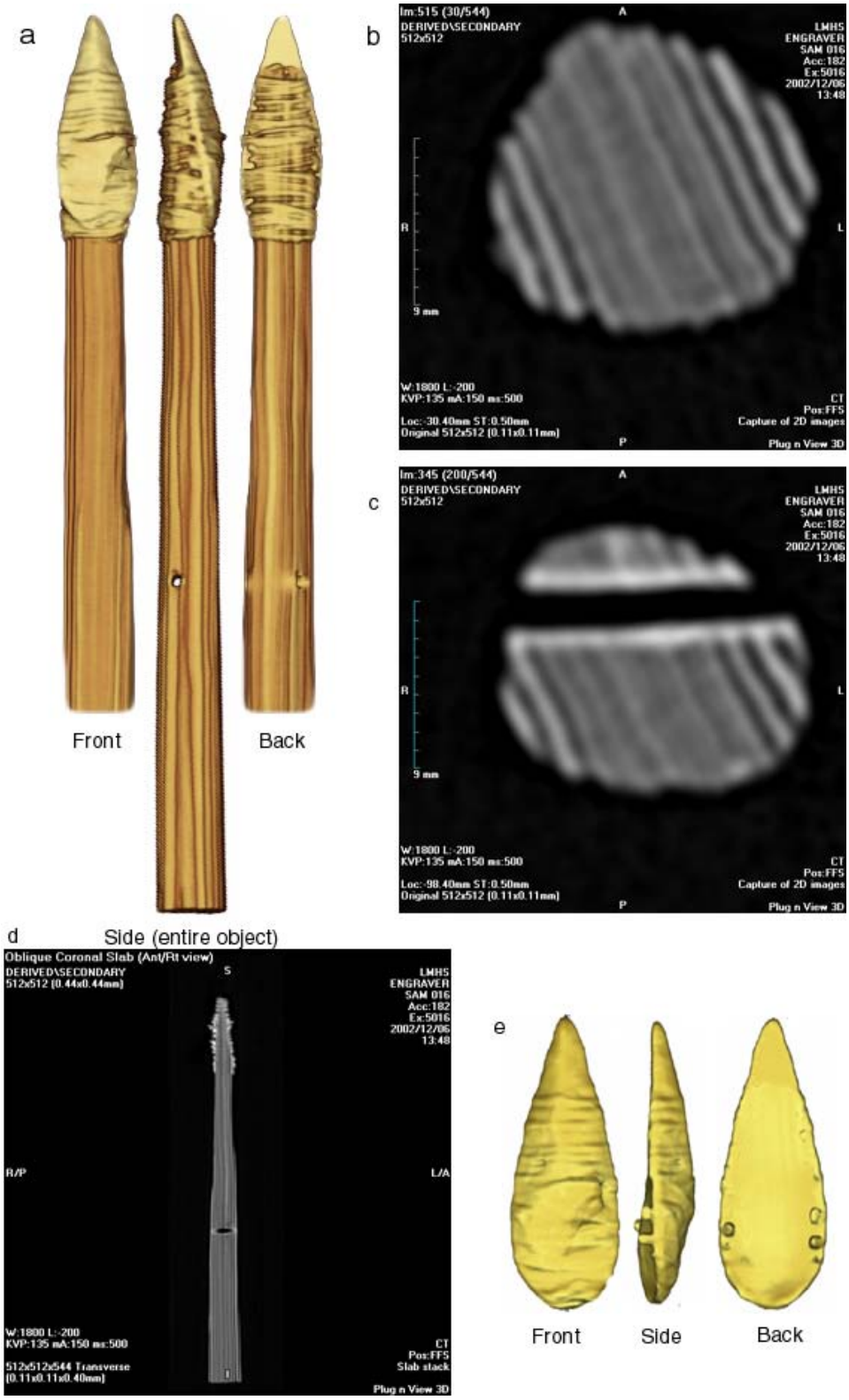

Figure 7 CT-scans of engraver. A. Three-dimensional reconstruction of engraver with engraving stone attached with sinew – front, side and back views; B. Two-dimensional slice from cross-section of engraver showing endgrain of wooden handle; C. Two-dimensional slice from cross-section of engraver showing endgrain of wooden handle where hole intersects; D. Front, side and back views of engraving stone – the blade was virtually-detached from the wood and the binding sinew.

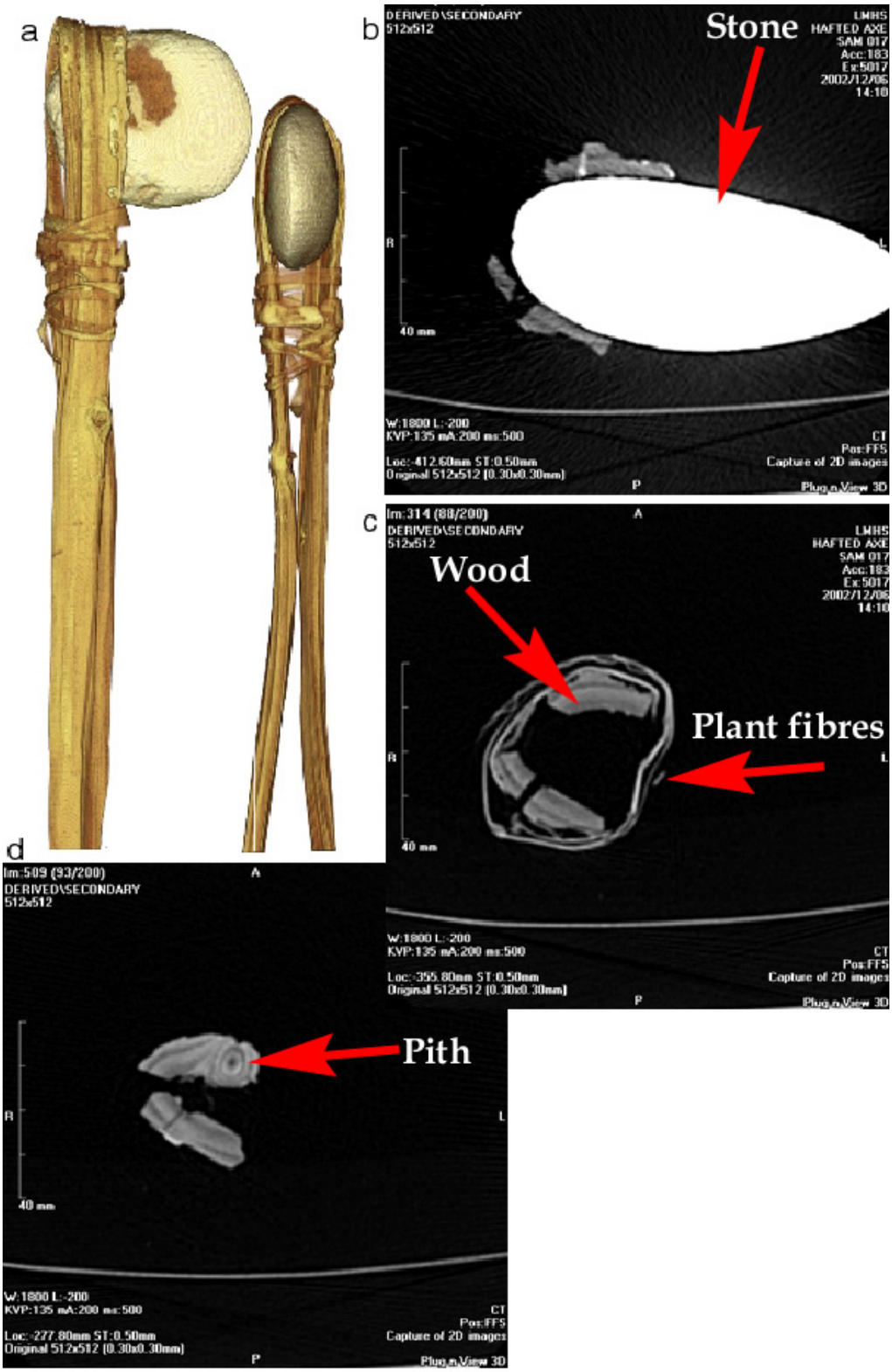

Figure 8 CT-scans of hafted axe. A. Three-dimensional reconstruction of hafted axe with stone bound to object by plant fibres; B. Two-dimensional slice from cross-section of hafted axe showing the endgrain of the stone and wood; C. Two-dimensional slice from cross-section of hafted axe showing the endgrain of the wood and plant fibres; D. Two-dimensional slice from cross-section of hafted axe showing the endgrain; the arrow indicates the pith.

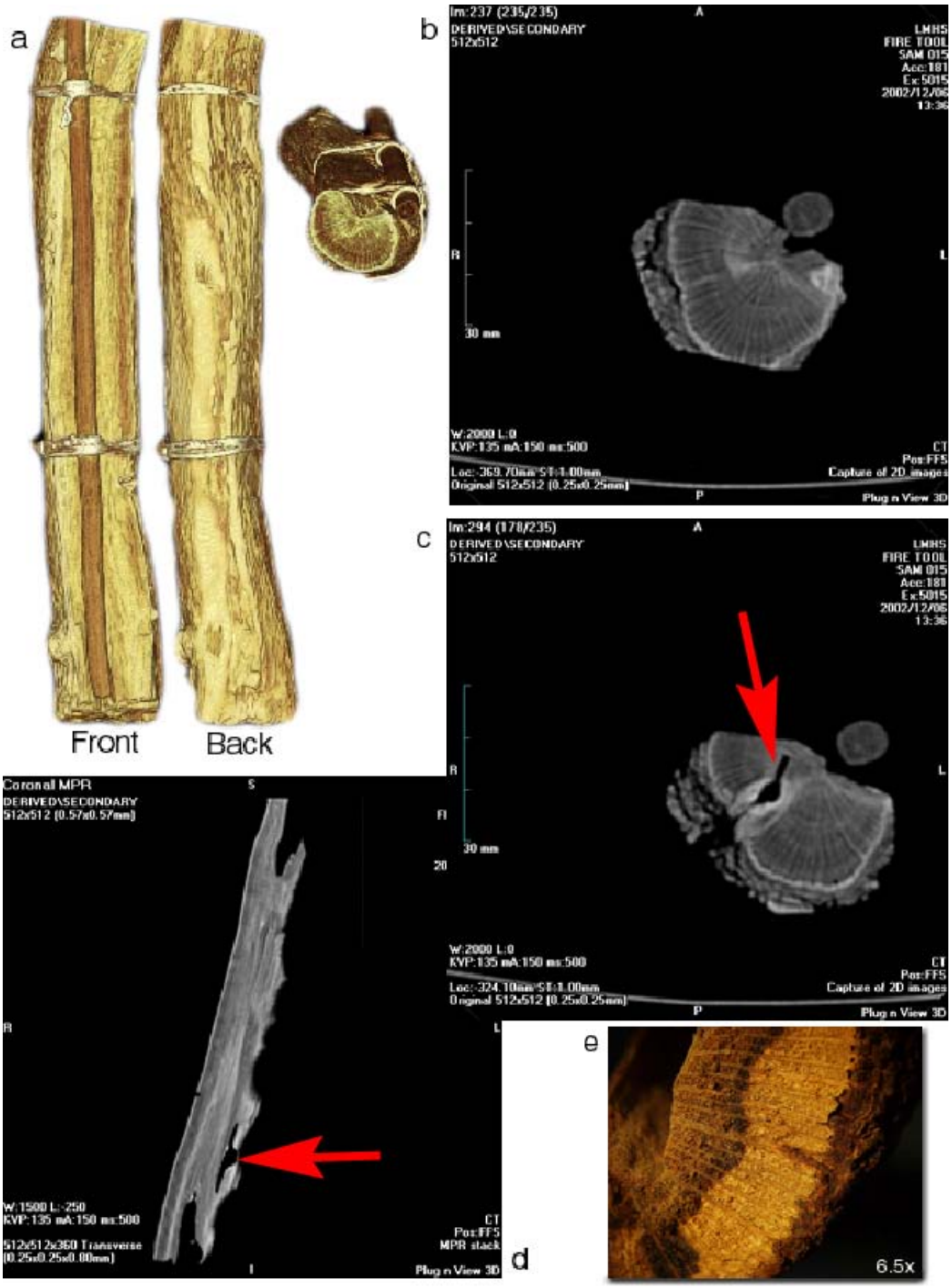

Figure 9 CT-scans of fire-making apparatus. A. Three-dimensional reconstruction of fire-making apparatus – front and back – and endgrain; note visibility of rays on endgrain; B. Two-dimensional slice from cross section of fire-making apparatus showing endgrain of base and drill piece; note the visible rays on the base piece and bark around the outside; C. Two-dimensional slice from cross-section of fire-making apparatus showing endgrain of base and drill piece; the arrow indicates a hole that permeates from the bark to the inner growth rings; D. Two dimensional slice from longitudinal section of base piece; the arrow indicates a hole within the object; E. Light microscope image of (unpolished) endgrain of base piece.

Conclusions

The four technologies trialled in this research have a limited application to wood anatomy or wood identification with few significant advantages over traditional wood identification techniques, including endgrain and SEM analysis. Nevertheless, trials conducted using fluorescence microscopy and confocal microscopy indicate that these methods may represent a non-invasive alternative to thin-section analysis where preparation time is considerably reduced with the use of small, solid samples of wood that have been physically sectioned to expose the transverse, radial and tangential planes. Once prepared, these samples may be imaged at magnifications normally reserved for thin sections (conventionally in combination with a transmitted light microscope). These trials have also demonstrated the possibilities that CT-scanning may offer for the conservation of wooden objects and for increasing knowledge of manufacturing techniques, particularly where there is limited accompanying documentation. In addition, the ability to generate fully-focused images from undulating wood surfaces using the Auto Montage Imaging System software may assist in reducing physical sectioning. This may be particularly helpful where sample sizes are limited and for preserving the integrity of valuable wooden items.

The "virtual-cutting" capabilities demonstrated in three of the technologies – confocal microscope, micro-CT scanner and CT-scanner – should be of significant interest to xylologists, particularly those who occasionally have only limited wood samples available to them for analysis. The advantage of "virtual-cutting" technology is that samples can be smaller than are usually required for physical sectioning. Theoretically this should mean that the size of a wood sample can be restricted to the limit that is required for identification purposes. In turn, this reduces the damage caused to the wood from which the sample was removed, which is particularly helpful in the case of cultural objects. Of further interest is the ability of the Skyscan 1072 to generate three-dimensional images of a wood sample at any orientation and from anywhere within the wood and to virtually reproduce two-dimensional thin slices of wood of a similar thickness to thin sections. Finally, these processes are non-invasive in that, unlike wood identification techniques that use optical microscopy or SEM, little to no preparation of samples is required. In time, and with further developments in technology, perhaps these capabilities may be adapted to traditional light microscopy and SEM; such a development would revolutionise the

methods used in standard wood anatomy and make these traditional technologies even more accessible and applicable to the discipline. Recent advances in light microscopy that have combined laser-scanning technology with "virtual-cutting" capabilities and three-dimensional reconstruction indicate that in the future such adaptations may be possible.

Further information on fluorescence and confocal microscopy and the micro-CT scanner is located at *www.adelaide.edu.au/microscopy/* or *www.skyscan.be*.

Appendix Five. Trialled techniques for softening high density, arid Australian wood

Introduction

The softening of wood fibres is necessary to achieve good 15-25 µm thin sections of wood and to protect microtome knives; it is also necessary for polishing the endgrain of wood with a high density for both light microscope and scanning electron microscope studies. A number of studies have purportedly softened wood simply by soaking blocks in distilled water for a number of days or flooding samples with water before sectioning (Exley, Meylan *et al.* 1977: 75; Heady 2000: 8; Hoadley 1990: 83). However, softening methods have generally been developed for wood with a density that falls within the normal density range; in Europe and America, for example, where most standard practises in wood identification have developed, wood species do not generally exceed 1000 kg/m^3.

The difficulty of softening wood with a density in excess of 1000 kg/m^3 is well-acknowledged and wood anatomists have proposed and developed a suite of methods for its softening. One of these, the use of hydrofluoric acid, proved an efficient and effective softening agent and, in the absence of a more powerful method, one ultimately utilised in this study for application to the vouchered wood specimens. However, hydrofluoric acid is highly dangerous and difficult to access and should be used as a last resort and in a controlled laboratory environment. It is believed that further adaptation of the four trials discussed in this Appendix may yield a suitable alternative although none are likely to be as efficient or effective.

In the softening trials conducted in this study, standard techniques, as well as methods recommended for very dense wood, were applied to unvouchered wood specimens ranging in density from 600 kg/m^3 to 1400 kg/m^3.

Vacuum

Softening wood by use of a vacuum is a method recommended by Ives (2001: 51)for wood with a density of 500 kg/m^3 to 900 kg/m^3; he conducts this method in combination with ethylene diamine (ETD). This research tested the efficacy of the vacuum method in combination with a glycerine-ethanol solution; further tests using ETD, conducted in combination with a pressure cooker, are discussed later.

Methods

Small, 1cm^3 blocks from approximately 40 species were placed in labelled glass vials containing a 50:50 glycerine-ethanol solution. The glass vials were positioned on a large petrie dish that sat within a desiccating bowl. Lids were placed loosely on the vials. A tap attached to the lid of the desiccating bowl was turned to the open position and plastic tubing connected it with a reservoir: a Buchner flask was used to prevent the backwash of oil during pumping. The reservoir was stopped with a plastic bung and connected with plastic tubing to a vacuum pump. Vacuum grease was spread over the top rim of the desiccating bowl and on the bottom of its lid to ensure a tight seal. The vacuum pump was turned on. Once all the air had been exhausted from within the desiccating chamber the pump was turned off. The timing of this was determined by the halt in production of air bubbles from the wood into the glycerine-ethanol solution. It was observed that the denser the wood the fewer and smaller the bubbles; less dense wood tended to froth more noticeably. Air bubble production had ceased from within all the vials after about ten to fifteen minutes. The tap on the desiccating chamber was turned to the closed position to retain the vacuum. The specimens were left under vacuum for 80 hours, at which time the tap was re-opened to allow air back into the chamber so that the lid could be removed.

Results and discussion

Subsequent tests of wood hardness determined that no noticeable softening had occurred using the vacuum method and that the endgrains of the densest species still proved too hard for microtome surfacing. However, this method may have been more successful if it had been conducted in combination with ETD as Ives (2001) suggested; in his method, before subjecting the specimens to a vacuum, he immerses specimens in a 4% solution of ETD for one week during which time the wood swells (Ives 2001: 51).

Boiling

Undoubtedly the simplest and most common method used to soften wood is to boil it in water (occasionally with the addition of various chemicals) until it becomes waterlogged (Hoadley 1990: 83; Ives 2001: 54; Jansen, Kitin *et al.* 1998: 43; O'Brien and McCully 1981: 4.9). This method is generally recommended for hard wood: for example, Ives uses the technique for wood with a density greater than 900 kg/m^3, sometimes in combination

with 10% glycerine or 4% ethylene diamine (ETD), boiling samples for 9 or 10 hours (Ives 2001: 55).

Methods

In this study, samples of unvouchered wood, approximately 1 cm^3 were placed in labelled glass vials. The vials were filled with water and placed in a water bath. Using a hot plate, the water was boiled for up to eight hours at a time, after which time the endgrain was tested for softening with a razor blade. Wood blocks were placed immediately afterwards in plastic vials containing a 50:50 glycerine-ethanol solution (Hoadley 1990: 83). The process was usually repeated several times, particularly for the densest species.

Results and discussion

This method did not suitably soften the wood for microtome or razor blade surfacing, particularly those species with a density greater than 1000 kg/m^3. Nor did adding a few drops of glycerine to the boiling water (Ives 2001: 55) seem to assist the process.

Whilst this common and simple method did not prove an effective softening agent in this research, further modification of the method might elicit more positive results. For example, Ives boils his samples in a reflux condenser, sometimes with the addition of 10% glycerine; for particularly stubborn samples he repeats the process or boils the specimens in a solution of 4% ETD (Ives 2001). In fact, in his experience, the use of 4% ETD in combination with the boiling method is so effective that it has been known to over-soften the wood or result in stress shakes (Ives 2002: *pers. comm.*) where wood begins to split.

Steam apparatus

Another method of softening wood is the emission of a jet of steam onto the wood surface during sectioning with a microtome (Ilic 1991; Johansen 1940; O'Brien and McCully 1981: 4.9; Radford, Dickison *et al.* 1974: 180). It is notable that this is a preferred method of Jugo Ilic (foremost Australian xylologist) for sectioning the dense tropical timbers (Ilic 2002b: *pers. comm.*). A simple apparatus was assembled for trial on the unvouchered wood; its design was informed by instructions received from Ilic (2002b: *pers. comm.*) and modified slightly for safety with the adoption of suggestions from Dr Eugene Dimitriadis (2003: *pers. comm.*). The method was trialled in combination with a Reichert™ sliding microtome and unvouchered wood. Its use is illustrated in Figure 69.

Methods

To assemble the steam apparatus a length of rubber tubing was attached at one end to the spout of a Buchner flask and at the other end to a glass pipette. For protection when handling during steam generation, the pipette end of the rubber tubing was insulated with a length of cotton wool and secured with electrical tape. Meanwhile, boiling chips were placed in the bottom of the flask, to ensure a steady boil, and water was added to approximately half-way or a little less; to reduce the build-up of pressure, filling the flask was avoided.

For safety, a pressure valve was fashioned. A hole large enough to tightly fit a glass tube was drilled into a rubber bung. A glass tube was carefully inserted into the hole and the rubber bung placed in the flask mouth to form a tight seal. The tube was wound so that it ended at the bottom of the flask. At the other end of the glass tube, a second length of rubber tubing was attached. The other end of the rubber tubing was positioned in a beaker to collect any overflow of water caused by sudden changes in pressure. Water was initially added to the beaker to prevent it from boiling dry on the hot plate.

At the pipette end, the rubber tubing was clamped to a retort stand, securing it in a position so that the pipette was about 1 cm from a wood block secured on the microtome. The tubing was also prevented from sagging where a build-up of steam could cause violent outbursts from the pressure within the flask (Goldsack 2003: *pers. comm.*). The flask and the beaker were placed on a hot plate and brought to the boil. Shortly after, a fine jet of steam was emitted from the pipette and onto the wood. The microtome knife was also exposed to the steam to keep it hot during sectioning.

Results and discussion

The use of direct steam during sectioning proved a good technique for keeping the wood fibres softened. It was most successful with wood with a density up to 1000 kg/m^3 with the production of good, thin sections and satisfactorily polished endgrains. The densest species, those measuring 1100 kg/m^3 or greater, produced better thin sections than had previously been achieved but many still seemed too hard and required a successful pre-sectioning softening treatment. Whilst later, successful trials using hydrofluoric acid to soften the densest wood, vindicated this finding, the quality of thin sections may also have

been affected by another variable: the microtome knife. At the time of sectioning, permanent and freshly-sharpened knives were used[66], but variables of the angle of knife approach and knife tilt, the extent to which the wood surface was correctly oriented to the cutting plane, and settings regulating section thickness, may have combined to affect the quality of the thin sections. Even with appropriately softened wood, knowledge of these factors, coupled with the fact that many of these settings are variable depending on the wood or surface being sectioned, render necessary considerable practise and experience in the art of microtomy if one is to produce high quality thin-sections. A modified method which ensures the steam remains hot upon exposure to the wood by passing it through heated copper coils (Crowell 1930 in O'Brien and McCully 1981: 4.10) might also be trialled.

[66] Microtome knives were professionally sharpened by *Proscitech*, Queensland. They were the only company located who undertake such a service. Initial attempts at sharpening microtome knives by a domestic knife sharpening firm were tolerable but not entirely satisfactory.

Figure 64 Using the steam apparatus to section high density arid Australian wood. Steam is concentrated on the wood specimen during sectioning with a microtome.

Pressure cooking

Expanding upon the use of steam to soften wood, and in the knowledge that it is used commercially to bend wood, it was suggested that a pressure cooker might be employed to trial its softening capacity (Dimitriadis 2003: *pers. comm.*). The method also experimented with the softening capacities of ethylene-diamine (ETD) and domestic detergent. The use of ETD to soften wood is described in several publications {Kukachka, 1978 #383;Ives, 2001 #639;Carlquist, 1988 #59}. Domestic detergent is used for reconstituting and

rehydration of herbarium specimens for examination of botanical structures such as flowers (Barker 2003: *pers. comm.*).

Methods

Samples measuring 1 cm^3 from the densest unvouchered wood species were placed in small, labelled petri dishes. A wire grill was positioned so that it sat approximately midway within a large pressure cooker. This created a stable stage upon which to arrange the petri dishes. The pressure cooker was filled with water to just beneath the wire grill, secured with its lid and placed on a hot plate. With the hot plate set to its limit, the pressure cooker achieved a maximum of 118 degrees and 13 lbs/in^2 (psi).

Pressure cooking occurred in bouts of approximately two hours and after each bout samples were immediately placed into vials containing either 50:50 glycerine-ethanol solution, 4% ethylene-diamine (ETD) solution, or ordinary household detergent (concentrate)[67]. Prior to subsequent bouts in the pressure cooker, samples were removed from the vials and the endgrain was tested for softening with a single-edged razor blade. On completion of the trial most samples had been pressure-cooked for a total of four to eight hours and immersed in the various solutions for up to three weeks.

Results and discussion

After comparing the softness of the tested blocks to dry equivalents, it was determined that this method was relatively effective as a softening technique for some species with a density greater than 1000 kg/m^3; two notable exceptions were *Alectryon oleifolius* ED10.1b and *Ventilago viminalis* ED22.1 which contain vessel inclusions (possibly silica). The preferred solution for immersal immediately after pressure-cooking was inconclusive but four ETD-immersed samples (*Casuarina cristata* ED20.1, *Casuarina pauper* ED20.2, *Alectryon oleifolius* ED10.1b and *Acacia loderi* ED1.17) and one glycerine-ethanol immersed sample (ED22.1 *Ventilago viminalis*) developed stress shakes. Whilst this may have been due to over-treatment, the samples were not over-softened.

[67] ETD is a noxious chemical and was handled according to the *Material Safety Data Sheet* http://msds.ehs.cornell.edu/msds/msdsdod/a96/m7547.html#Section9

It was difficult to ascertain which was a more effective softening agent: extra bouts in the pressure cooker or the solutions (and the length of time) in which the samples were subsequently immersed. Moreover, the possibility that the pressure cooker or the solutions might only soften to a point (at which time further efforts prove fruitless) was contemplated.

Thin sections produced from specimens after treatment using this method and in combination with a sledge microtome and direct steam, were an improvement on previous efforts. There were also improvements with the polish and clarity achieved on the endgrain using the microtome and/or razor blade. However, superior results may have been achievable with the use of an autoclave. An autoclave can reach 126 degrees and 20 lbs/in^2 (psi); this may produce better (and faster) results than a pressure cooker[68]. The greatly enhanced size means that it would also be useful if numerous specimens require treatment. Furthermore, an autoclave may allow longer, uninterrupted treatment times since they can process many more litres of water than a pressure cooker. The exhaust should be set to "slow" to ensure steam is kept in the chamber to allow optimum penetration of the wood fibres.

Conclusion

Techniques for softening wood trialled in this study, particularly boiling and the vacuum method, have limited application to the dense species treated in this research. Nevertheless, there is scope to trial further adaptations of these two methods including the addition of 4% ETD to the boiled water and soaking samples in 4% ETD before vacuum[69]. More promising results were had with the two methods that involved steam and it is anticipated that, used in combination and possibly with some adjustments – including the use of an autoclave for initial softening and direct heated steam during sectioning – these techniques would prove acceptable softening agents.

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[68] The pressure cooker dial suggested that it is capable of 126 degrees and 20 lbs/in^2 (psi); however, this was not achievable with the hot plate set to its maximum setting.

[69] Considering the high density of the species treated in this study, in the first instance it would be desirable to trial boiling samples with 4% ETD; Ives prefers the boiling method to the vacuum method for specimens with a density over 900 kg/m^3. In addition, the boiling method is simpler to set-up.

One limitation of this combined approach is that the direct steam method restricts sectioning to a microtome where an effective pre-sectioning, softening treatment (such as hydrofluoric acid) would allow preparation with a razor blade. Efforts to assess the value of direct steam as a softening method were compromised by the variables used to adjust the microtome knife, such as its approach and tilt, and it is possible that inexperience with this instrument may have somewhat masked the efficacy of the technique. The other limitation of this combined approach is the time required to process the samples. Whilst time and handling might be reduced by using an autoclave rather than a pressure cooker, the effort expended in setting up two softening techniques hardly justifies the results when such an effective softening agent as hydrofluoric acid is available[70].

In conclusion, where hydrofluoric acid is inaccessible or considered objectionable for reasons of health and safety, and a sledge or sliding microtome is accessible, wood greater than 800 kg/m^3 may be successfully softened with steam (using an autoclave or pressure cooker) followed by live, direct steam during sectioning. Alternatively, where hydrofluoric acid is obtainable and the appropriate safety precautions can be followed, this chemical offers the most efficient one-step, softening method for wood whilst allowing the greatest flexibility in the adopted sectioning procedure. Such is the softening capacity of hydrofluoric acid, even the endgrain of the densest wood specimens (up to 1400 kg/m^3) could be successfully polished with a razor blade. Whilst it is expected that wood can be softened sufficiently with hydrofluoric acid to enable the production of high quality thin sections with a microtome, it may occasionally be of benefit to employ the steam apparatus to keep the wood soft.

Finally, there are several softening techniques gleaned from the literature that remain untested: these include soaking wood in various solutions including 50% glacial acetic acid and 50% hydrogen peroxide (Jansen, Kitin *et al.* 1998: 43; O'Brien and McCully 1981: 4.10); and in a 20% solution of sodium hydroxide (caustic soda) (Ives 2001: 56).

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[70] In this study, the densest wood was treated in 50% hydrofluoric acid for up to 48 hours. However, apart from brief handling at the beginning and end of this period, the method takes care of itself (see Chapter Five for further details).

Appendix Six. List of wood-producing plants by region

Preface

This Appendix lists wood-producing species for each of the botanical region from where vouchered wood specimens were collected: Lake Eyre (LE), South Australia; Gregory South (GS), Queensland; and Far North West Plains (NNF), New South Wales. These lists were produced only as a general guide to woody flora as they are not likely to be exhaustive and some inaccuracies in plant names may exist. Furthermore, the research conducted to compile these lists concentrated on families and genera that contain wood-producing species; however, the extent of wood production may be variable within the lists and within families/genera and there may be some species that produce very little to no wood.

The following notes provide details of how the tables of wood-producing species were compiled.

A list of all the documented plant species that occur in the Corner Country region was obtained from census data from the relevant herbaria. A record of all the plant species in the LE botanical division was obtained from the *Census of South Australian Plants, Algae and Fungi* contained on the *Electronic Flora of South Australia* web-site (Plant Biodiversity Centre 2003). The species list for the NNF botanical division was obtained from the *National Herbarium of New South Wales*' on-line Census (accessed 2003). Staff at the *Queensland Herbarium*, Brisbane, kindly provided a spreadsheet listing all the plant species in the QGS botanical division (incorporating south-west Queensland) as per their Census. Species names in all the censuses, and therefore the tables of wood-producing species, should be reasonably up-to-date. However, south-west Queensland is poorly documented botanically so caution should be exercised when using the QGS data.

From the regional species lists, potential wood-producing families/genera/species were isolated. To do this, families were cross-checked against lists of wood-producing families/genera/species contained in the *Australian Trees & Woody Shrubs* (Lake 2003). Families that did not occur in this publication were culled resulting in considerably reduced species lists.

To determine the woodiness of the remaining species, the plant lists were cross-checked against descriptions contained in *Plants of Western New South Wales* (Cunningham, Mulham *et al.* 1981). This assisted in removing some families and species that had remained from the original list where uncertainty as to the extent of wood production existed. It also suggested a few others that were not on the list and may be wood-producing. However, given the age of the book one must be cautious of name changes and, whilst many of the species recorded for western New South Wales occur across the area of study, the regional limitations of the publication should be recognised, particularly when applied to the Queensland and South Australian lists.

Distribution data was appended by cross-checking species names against the censuses of the State Herbarium of South Australian and the Queensland Herbarium. Acronyms are as follows: LE: Lake Eyre (South Australia) botanical division, sometimes referred to as SEB (for Eyre Basin); QGS: Gregory South (Queensland) botanical division; NNF: North Far West Plains (New South Wales) botanical division. These divisions are highlighted on the map presented in Figure 70.

Common names were taken from the IWCS publication *Australian Trees & Woody Shrubs* (Lake 2003) and, where available, from the database *Australian Plant Name Index?* hosted on the *Australian National Botanic Gardens* (ANBG) website (accessed 2003).

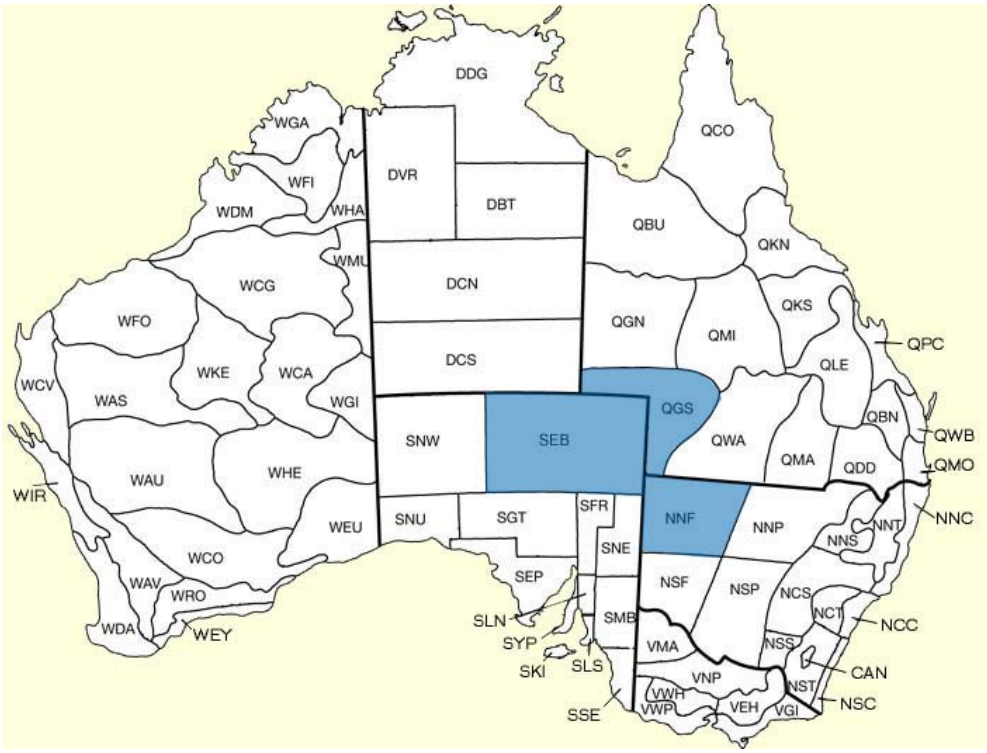

Figure 65 Map showing recognised botanical divisions of Australia (ANBG 2005). Lists of wood-producing species were compiled with the aid of up-to-date census data from QGS: Gregory South (Queensland); NNF: Far North West Plains (New South Wales); SEB: Eyre Basin (South Australia). The SEB region is also referred to as the LE (Lake Eyre) botanical division. The LE acronym has been retained in this research.

Lake Eyre (LE) Botanical Division (SA)

Family	Genus	Species	Common names	Distribution
APOCYNACEAE	*Carissa*	*lanceolata*		LE
CAPPARACEAE	*Capparis*	*mitchellii*	Bumble, Wild Orange	LE, QGS, NNF
CASUARINACEAE	*Casuarina*	*pauper*	Belah, Black Oak	LE, QGS, NNF
CUPRESSACEAE	*Callitris*	*glaucophylla*	White Cypress Pine, Marung, White Cypress, White Pine	LE, NNF
GYROSTEMONACEAE	*Codonocarpus*	*cotinifolius*	Native Poplar	LE, QGS, NNF
		pyramidalis		LE
	Gyrostemon	*ramulosus*		LE, QGS
		tepperi		LE
LEGUMINOSAE	*Acacia*	*aneura* var. *aneura*	Mulga	LE, QGS, NNF
		aneura var. *conifera*		
		ayersiana var. *ayersiana*		LE, QGS
		ayersiana var. *latifolia*		
		calcicola	Shrubby Wattle, Shrubby Mulga, Myall-Gidgee, Northern Myall, Grey Myall	LE, QGS, NNF
		cambagei	Gidgee, Gidyea, Stinking Wattle	LE, QGS, NNF
		cibaria	Grey Mulga, Turpentine Mulga	LE
		confluens	Wyrilda	LE
		coriacea	Wirewood, Dogwood, Wiry wattle	LE, QGS
		cowleana	Halls Creek Wattle	LE
		cyperophylla	Creekline Miniritchi, Red Mulga, Red-barked Gidgee, Ringed Gidgee	LE, QGS
		dictyophleba		LE, QGS
		estrophiolata	Southern Ironwood	LE
		farnesiana	Cassie, Dead Finish, Farnese Wattle, Mimosa Wattle, Mimosa Bush, Prickly Mimosa Bush, Prickly Moses, Needle Bush, North-west Curara, Sheep?s Briar, Sponge Wattle, Sweet *Acacia*, Thorny *Acacia*, Thorny Feather-wattle, Wild Briar	LE, QGS, NNF
		georginae	Poison Gidyea, Georgina Gidgee	LE, QGS
		jennerae	Coonavittra Wattle	LE, QGS, NNF
		kempeana	Witchetty Bush,	LE, QGS

Family	Genus	Species	Common names	Distribution
			Wanderrie Wattle	
		ligulata	Umbrella Bush, Dune Wattle, Sandhill Wattle, Little Cooba, Small Cooba, Marpoo	LE, QGS, NNF
		murrayana	Murray's Wattle, Colony Wattle, Powderbark Wattle, Sandplain Wattle	LE, QGS, NNF
		nilotica	Prickly *Acacia*, Babul	LE
		nyssophylla		LE
		oswaldii	Umbrella Wattle, Umbrella Bush, Miljee, Nelia, Whyacka, Middia, CurlyYarran	LE, QGS, NNF
		papyrocarpa	Western Myall	LE, QGS
		paraneura	Weeping Mulga	LE
		pickardii		LE
		ramulosa	Horse Mulga, Bowgada, Narrow Leaf Mulga	LE, QGS, NNF
		rigens	Needle Wattle, Needlebush *Acacia*, Nealie, Nealia, Nilyah	LE, NNF
		rivalis	Creek Wattle, Silver Wattle	LE, NNF
		salicina	Willow Wattle, Native Wattle, Broughton Willow, Cooba, Doolan	LE, QGS, NNF
		stenophylla	Munumula, Balkura, Gurley, Gooralee, Ironwood, Dalby Wattle, River Cooba, River Myall, Belalei, Eumong, Native Willow, Black Wattle, Dunthy	LE, QGS, NNF
		stowardii	Bastard Mulga	LE, QGS, NNF
		tenuissima	Mulga	LE, QGS
		tetragonophylla	Dead Finish, Kurara, Curara	LE, QGS, NNF
		victoriae ssp. *arida*	Elegant Wattle, Narran, Gundabluey, Prickly Wattle, Bramble Wattle	LE, QGS, NNF
		victoriae ssp. *victoriae*		
	Erythrina	*vespertilio*	Bean Tree, Bats Wing Coral Tree	LE, QGS
	Lysiphyllum	*gilvum*	Queensland Bean Tree, *Bauhinia*	LE, QGS, NNF
LILIACEAE	*Xanthorrhoea*	*quadrangulata*	Grass-Tree, Blackboy, Yacca	LE
MELIACEAE	*Owenia*	*acidula*	Colane, Emu Apple, Gooya, Gruie, Sour	LE, QGS, NNF

Family	Genus	Species	Common names	Distribution
			Apple, Sour Plum	
MYOPORACEAE	*Eremophila*	*bignoniflora*	Bignonia, Emubush, Creek Wilga, Dogwood, Eurah, Gooramurra, River Argee	LE, QGS, NNF
		deserti	Dogwood, Gooramurra	LE, QGS, NNF
		longifolia	Long-leaved *Eremophila*, Weeping Emubush, Berrigan	LE, QGS, NNF
		battii		LE
		bowmanii		LE, QGS, NNF
		dalyana		LE, QGS
		duttonii		LE, QGS, NNF
		freelingii		LE, QGS, NNF
		gilesii		LE, QGS, NNF
		latrobei ssp. *glabra*		LE, QGS, NNF
		latrobei ssp. *latrobei*		
		macdonnellii		LE, QGS
		macgillivrayi		LE, QGS
		maculata		LE, QGS, NNF
		neglecta		LE
		obovata		LE, QGS
		paisleyi		LE
		pentaptera		LE
		polyclada		LE, QGS, NNF
		rotundifolia		LE
		scoparia		LE, QGS, NNF
		serrulata		LE, NNF
		verrucosa		LE
		willsii		LE
	Myoporum	*platycarpum* ssp. *platycarpum*	False Sandlewood, Sugar Tree Wood	LE, NNF
		montanum	Western Boobialla, Water Bush, Bush Boobialla, Boomeralla, Native Daphne, Native Myrtle, Mee-Mee, Nymoo	LE, NNF
MYRTACEAE	*Corymbia*	*tumescens (*syn. *C. terminalis?)*	Inland Bloodwood, Long-fruited Bloodwood, Pale Bloodwood, Arang-mill	LE, QGS(?), NNF
	Eucalyptus	*camaldulensis* var. *obtusa*	River Red Gum, Red Gum, Murray Red Gum	LE, QGS, NNF
		coolabah ssp. *arida*	*Coolabah*, Coolibah	LE, QGS, NNF

Family	Genus	Species	Common names	Distribution
		gillii	Arkaroola Mallee, Broken Hill Mallee, Curly Mallee, Silvery Mallee, Mallee Red Gum	LE, NNF
		intertexta	Bastard Coolibah, Gum Coolibah, Gum-barked Coolibah, Smooth-barked Coolibah, Inland Redbox, Western Red Box	LE, NNF
		largiflorens	Black Box, Flooded Box, River Box	LE, NNF
		oleosa	Red Mallee, Glossy-Leaved Red Mallee, Oil Mallee, Oily Mallee, Ningham Mallee, Water Mallee, Peeneri	LE
		socialis	Christmas Mallee, Giant Mallee, Grey Mallee, Pointed Mallee, Red Mallee, Summer Red Mallee	LE, NNF
	Melaleuca	*glomerata*		LE, NNF
		linariifolia var. *trichostachya*	Flax Leaf Paperbark, Narrow Leaf Paperbark, Snow-in-Summer, Flax Leaf Teatree, Narrow Leaf Teatree	LE, QGS(?)
		uncinata	Broom Bush Honey Myrtle	LE, QGS, NNF
		dissitiflora		LE
		pauperiflora ssp. *mutica*		LE
		xerophila		LE
PITTOSPORACEAE	*Pittosporum*	*angustifolium*	Berrigan, Butterbush, Cattle Bush, Cumby-cumby, Meemeei, Native Apricot, Native Willow, Weeping *Pittosporum*, Weeping Poisonberry Tree	LE, QGS, NNF
PROTEACEAE	*Grevillea*	*striata*	Beefwood, Silvery Honeysuckle, Western Beefwood, Silky Oak	LE, QGS, NNF
		huegelii		LE, NNF
		juncifolia		LE, QGS, NNF
		nematophylla		LE, QGS, NNF
		stenobotrya		LE, QGS, NNF
	Hakea	*ednieana*	Yandena, Yantena	LE, NNF
		eyreana	Straggly corkbark	LE, QGS, NNF
		leucoptera ssp. *leucoptera*	Needlewood/ Needlebush, Water Tree, Kuloa, Kolua, Kukuva, Silver Needlewood	LE, QGS, NNF

Family	Genus	Species	Common names	Distribution
		suberea	Corkbark, Corktree, Long-leaf Corkwood	LE
RUBIACEAE	*Canthium*	*latifolium*	Native Currant	LE, QGS, NNF
SANTALACEAE	*Exocarpos*	*aphyllus*	Wining, Leafless Ballart	LE, QGS, NNF
		sparteus		LE
	Santalum	*acuminatum*	Quandong, Sweet Quandong	LE, QGS, NNF
		lanceolatum	Bush Plum, Native Plum, Cherry Bush, Northern Sandalbox, Northern Sandalwood, Sandalwood	LE, QGS, NNF
SAPINDACEAE	*Alectryon*	*oleifolius* ssp. *canescens*	Western Rosewood, Bonaree	LE, QGS, NNF
	Atalaya	*glauca*	Whitewood	LE, QGS, NNF
	Dodonaea	*viscosa* ssp. *angustissima*	Sticky Hop-bush, Akeake	LE, QGS, NNF
		viscosa ssp. *spatulata*		
		microzyga var. *microzyga*		LE, NNF

Gregory South (QGS) Botanical Division (Qld)

Family	Genus	Species	Common names	Distribution
BIGNONIACEAE	*Pandorea*	*pandorana*		QGS
CAPPARACEAE	*Apophyllum*	*anomalum*	Warrior Bush, Currant Bush	QGS
	Capparis	*loranthifolia* var. *bancroftii*	Narrowleaf Bumble	QGS
		mitchellii	Bumble, Wild Orange	QGS, LE, NNF
		lasiantha		QGS
CASUARINACEAE	*Casuarina*	*pauper*	Belah, Black Oak	QGS, LE, NNF
GYROSTEMONACEAE	*Codonocarpus*	*cotinifolius*	Native Poplar	QGS, LE, NNF
	Gyrostemon	*ramulosus*		QGS, LE
LEGUMINOSAE	*Acacia*	*adsurgens*	Wattle	QGS
		ancistrocarpa	Salt Wattle, Jila Jila	QGS
		aneura	Mulga	QGS, LE, NNF
		aneura var. *aneura*		
		aneura var. *intermedia*		
		aneura var. *major*		
		aneura var. *tenuis*		
		ayersiana		QGS, LE
		brachystachya	Umbrella Mulga, Turpentine Mulga, Grey Mulga, False Bowgeda	QGS, NNF
		calcicola	Shrubby Wattle, Shrubby Mulga, Myall-Gidgee, Northern Myall, Grey Myall	QGS, LE, NNF
		cambagei	Gidgee, Gidyea, Stinking Wattle	QGS, LE, NNF
		catenuata	Bendee	QGS
		coriacea ssp. *sericophylla*	Wirewood, Dogwood, Wiry wattle	QGS, LE
		cyperophylla var. *cyperophylla*	Creekline Miniritchi, Red Mulga, Red-barked Gidgee, Ringed Gidgee	QGS, LE
		dictyophleba		QGS, LE
		elachantha		QGS
		ensifolia		QGS
		farnesiana	Cassie, Dead Finish, Farnese Wattle, Mimosa Wattle, Mimosa Bush, Prickly Mimosa Bush, Prickly Moses, Needle Bush,	QGS, LE, NNF

Family	Genus	Species	Common names	Distribution
			North-west Curara, Sheep?s Briar, Sponge Wattle, Sweet *Acacia*, Thorny *Acacia*, Thorny Feather-wattle, Wild Briar	
		georginae	Poison Gidyea, Georgina Gidgee	QGS, LE
		jennerae	Coonavittra Wattle	QGS, LE, NNF
		kempeana	Witchetty Bush, Wanderrie Wattle	QGS, LE
		ligulata	Umbrella Bush, Dune Wattle, Sandhill Wattle, Little Cooba, Small Cooba, Marpoo	QGS, LE, NNF
		melleodora	Waxy Wattle	QGS
		microsperma	Bowyakka Wattle	QGS
		murrayana	Murray's Wattle, Colony Wattle, Powderbark Wattle, Sandplain Wattle	QGS, LE, NNF
		oswaldii	Umbrella Wattle, Umbrella Bush, Miljee, Nelia, Whyacka, Middia, CurlyYarran	QGS, LE, NNF
		papyrocarpa	Western Myall	QGS, LE
		petraea	Lancewood	QGS, NNF
		peuce	Waddy, Waddi, Waddy-wood, Birdsville Wattle	QGS
		ramulosa	Horse Mulga, Bowgada, Narrow Leaf Mulga	QGS, LE, NNF
		salicina	Willow Wattle, Native Wattle, Broughton Willow, Cooba, Doolan	QGS, LE, NNF
		stenophylla	Munumula, Balkura, Gurley, Gooralee, Ironwood, Dalby Wattle, River Cooba, River Myall, Belalei, Eumong,	QGS, LE, NNF

Family	Genus	Species	Common names	Distribution
			Native Willow, Black Wattle, Dunthy	
		stowardii	Bastard Mulga	QGS, LE, NNF
		tenuissima	Mulga	QGS, LE
		tephrina	Boree	QGS
		tetragonophylla	Dead Finish, Kurara, Curara	QGS, LE, NNF
		victoriae ssp. *victoriae*	Elegant Wattle, Narran,	QGS, LE, NNF
		victoriae ssp. *arida*	Gundabluey, Prickly Wattle, Bramble Wattle	
	Erythrina	*vespertilio*	Bean Tree, Bats Wing Coral Tree	QGS, LE
	Lysiphyllum	*gilvum* (syn. *Bauhinia gilvum)*	Queensland Bean Tree, *Bauhinia*	QGS, LE, NNF
MELIACEAE	*Owenia*	*acidula*	Colane, Emu Apple, Gooya, Gruie, Sour Apple, Sour Plum	QGS, LE, NNF
MYOPORACEAE	*Eremophila*	*bignoniiflora*	Bignonia, Emubush, Creek Wilga, Dogwood, Eurah, Gooramurra, River Argee	QGS, LE, NNF
		deserti	Dogwood, Gooramurra	QGS, LE, NNF
		mitchellii	Budda, False Sandalwood	QGS, NNF
		longifolia	Long-leaved *Eremophila*, Weeping Emubush, Berrigan	QGS, LE, NNF
		oppositifolia	Twin-leaf Embush, Weeooka	QGS, NNF
		oppositifolia ssp. *rubra*		
		bowmanii ssp. *latifolia*		QGS, LE, NNF
		bowmanii ssp. *latifolia* x *E. latrobei* ssp. *glabra*		
		bowmanii ssp. *nutans*		
		cordatisepala		QGS
		dalyana		QGS, LE
		duttonii		QGS, LE, NNF
		freelingii		QGS, LE, NNF
		gilesi		QGS, LE, NNF
		glabra		QGS, NNF
		goodwinii		QGS, NNF

Family	Genus	Species	Common names	Distribution
		latrobei		QGS, LE, NNF
		latrobei ssp. *latrobei*		
		latrobei ssp. *glabra*		
		linsmithii		QGS
		macdonnellii		QGS, LE
		macgillivrayi		QGS, LE
		maculata		QGS, LE, NNF
		obovata		QGS, LE
		obovata var. *obovata*		
		polyclada		QGS, LE, NNF
		scoparia		QGS, LE, NNF
		sturtii		QGS, NNF
	Myoporum	*acuminatum*	Mangrove Boobialla, Pointed Boobialla, Waterbush	QGS
MYRTACEAE	*Corymbia*	*aparerrinja*		QGS
		blakei ssp. *rasilis*		QGS
		terminalis	Inland Bloodwood, Long-fruited Bloodwood, Pale Bloodwood, Arang-mill	QGS, LE, NNF
	Eucalyptus	*camaldulensis*	River Red Gum, Red Gum, Murray Red Gum	QGS, LE, NNF
		coolabah	*Coolabah*, Coolibah	QGS, LE, NNF
		ochrophloia	Black Butt, Lapunyah, Napunyah, Yapunyah, Yellow Jacket	QGS, NNF
		thozetiana	Lapunyah, Mountain Yapunyah, Napunyah, Thozet's Box Ironbark	QGS
	Melaleuca	*trichostachya* (formerly *Melaleuca linariifolia* var. *trichostachya*)	Flax Leaf Paperbark, Narrow Leaf Paperbark, Snow-in-Summer, Flax Leaf Teatree, Narrow Leaf Teatree	QGS, LE
		uncinata	Broom Bush Honey Myrtle	QGS, LE, NNF
	Pittosporum	*angustifolium*	Berrigan, Butterbush, Cattle Bush, Cumby-	QGS, LE, NNF

Family	Genus	Species	Common names	Distribution
			cumby, Meemeei, Native Apricot, Native Willow, Weeping *Pittosporum*, Weeping Poisonberry Tree	
PITTOSPORACEAE	*Grevillea*	*striata*	Beefwood, Silvery Honeysuckle, Western Beefwood, Silky Oak	QGS, LE, NNF
PROTEACEAE		*juncifolia* ssp. *juncifolia*		QGS, LE, NNF
		kennedyana		QGS, NNF
		nematophylla ssp. *nematophylla*		QGS, LE, NNF
		stenobotyra		QGS, LE, NNF
	Hakea	*chordophylla*	Corkwood	QGS
		divaricata	Corkwood, Needlewood	QGS
		eyreana	Straggly corkbark	QGS, LE, NNF
		ivoryi	Corkbark tree, Corkwood, Ivory's *Hakea*, Gold-dust *Hakea*, Pincushion *Hakea*	QGS, NNF
		leucoptera ssp. *leucoptera*	Needlewood/ Needlebush,	QGS, LE, NNF
		leucoptera ssp. *sericipes*	Water Tree, Kuloa, Kolua, Kukuva, Silver Needlewood	
		lorea	Corkwood	QGS
		collina		QGS
	Ventilago	*viminalis*	Supplejack, Barndaragu, Thandorah	QGS
RHAMNACEAE	*Canthium*	*latifolium*	Native Currant	QGS, LE, NNF
RUBIACEAE	*(Eremo)Citrus*	*glauca*	Desert Lemon, Native Cumquat, Wild Lime, Desert Lime	QGS, NNF
RUTACEAE	*Flindersia*	*maculosa*	Leopard Wood, Spotted Dog, Spotted Tree	QGS, NNF
SANTALACEAE	*Exocarpos*	sp.	Wining, Leafless Ballart	QGS, LE, NNF
	Santalum	*acuminatum*	Quandong, Sweet Quandong	QGS, LE, NNF
		lanceolatum	Bush Plum, Native Plum, Cherry Bush, Northern Sandalbox, Northern	QGS, LE, NNF

Family	Genus	Species	Common names	Distribution
SAPINDACEAE	*Alectryon*	*oleifolius* ssp. *canescens*	Sandalwood, Sandalwood Western Rosewood, Bonaree	QGS, LE, NNF
	Atalaya	*hemiglauca*	Whitewood	QGS, LE, NNF
	Dodonaea	*viscosa* ssp. *angustifolia*	Sticky Hop-bush, Akeake	QGS, LE, NNF
		viscosa ssp. *angustissima*		
		viscosa ssp. *spatulata*		
		coriacea		QGS
		petiolaris		QGS, NNF

North Far West Plains (NNF) Botanical Division (NSW)

Family	Genus	Species	Common names	Distribution
APOCYNACEAE	*Alstonia*	*constricta* (type form)	Bitterbark, Quinine	NNF
CAPPARACEAE	*Capparis*	*mitchellii*	Bumble, Wild Orange	NNF, LE, QGS
CASUARINACEAE	*Allocasurina*	*leuhmannii*	Bull Oak, Buloke	NNF
	Casuarina	*cristata*	Belah	NNF
	Casuarina	*pauper*	Belah, Black Oak	NNF, LE, QGS
CUPRESSACEAE	*Callitris*	*glaucophylla*	White Cypress Pine, Marung, White Cypress, White Pine	NNF, LE
		gracilis ssp. *murrayensis* (formerly *C. preissii* ssp. *murrayensis*)	Slender Cypress Pine, Southern Cypress Pine	NNF
GYROSTEMONACEAE	*Codonocarpus*	*cotinifolius*	Native Poplar	NNF, LE, QGS
LEGUMINOSAE	*Acacia*	*acuminata* ssp. *burkittii*	Sandhill Wattle, Raspberry Jam	NNF
		aneura	Mulga	NNF, LE, QGS
		beckleri	Barrier Range Wattle	NNF
		brachystachya	Umbrella Mulga, Turpentine Mulga, Grey Mulga, False Bowgeda	NF, QGS
		calamifolia	Wallowa, Reed-leaf Wattle	NNF
		calcicola	Shrubby Wattle, Shrubby Mulga, Myall-Gidgee, Northern Myall, Grey Myall	NNF, LE, QGS
		cambagei	Gidgee, Gidyea, Stinking Wattle	NNF, LE, QGS
		cana	Cabbage-tree Wattle, Boree, Broad-leaf Nealie	NNF
		carneorum	Dead Finish, Purple-wood Wattle, Needle Wattle	NNF
		colletioides	Pin Bush, Spinebush, Wait-a-while	NNF
		doratoxylon	Currawang, Spearwood, Brown Lancewood, Hickory	NNF

Family	Genus	Species	Common names	Distribution
		excelsa ssp. *angusta*	Bunkerman, Doodlallia, Ironwood	NNF
		excelsa ssp. *excelsa*	Bunkerman, Doodlallia, Ironwood, Rosewood, Inland Wattle, Tooloo, Wallowa	
		farnesiana	Cassie, Dead Finish, Farnese Wattle, Mimosa Wattle, Mimosa Bush, Prickly Mimosa Bush, Prickly Moses, Needle Bush, North-west Curara, Sheep's Briar, Sponge Wattle, Sweet Acacia, Thorny Acacia, Thorny Feather-wattle, Wild Briar	NNF, LE, QGS
		hakeoides	Hakea Wattle, Western Black Wattle, Whipstick Wattle	NNF
		iteaphylla	Flinders Range Wattle, Willow-leaved Wattle, Winter Wattle, Gawla Range Wattle, Port Lincoln Wattle	NNF
		jennerae	Coonavittra Wattle	NNF, LE, QGS
		ligulata	Umbrella Bush, Dune Wattle, Sandhill Wattle, Little Cooba, Small Cooba, Marpoo	NNF, LE, QGS
		loderi	Nealie, Nelia, Broken Hill Gidgee, Myall	NNF
		melvillei	Yarran	NNF
		melvillei-homalophylla	Yarran?	NNF
		murrayana	Murray's Wattle, Colony Wattle, Powderbark Wattle, Sandplain Wattle	NNF, LE, QGS
		notabilis	Flinders Wattle, Notable Wattle, Stiff Golden	NNF

Family	Genus	Species	Common names	Distribution
			Wattle	
		oswaldii	Umbrella Wattle, Umbrella Bush, Miljee, Nelia, Whyacka, Middia, CurlyYarran	NNF, LE, QGS
		pendula	Boree, Weeping Myall, True Myall, Silver-leaf Boree, Balaer, Nilyah	NNF
		petraea	Lancewood	NF, QGS
		pycnantha	Golden Wattle, Australian Wattle, Broad-leaved Wattle	NNF
		ramulosa	Horse Mulga, Bowgada, Narrow Leaf Mulga	NNF, LE, QGS
		ramulosa var. *ramulosa*		NNF
		rigens	Needle Wattle, Needlebush Acacia, Nealie, Nealia, Nilyah	NNF, LE
		rivalis	Creek Wattle, Silver Wattle	NNF, LE
		salicina	Willow Wattle, Native Wattle, Broughton Willow, Cooba, Doolan	NNF, LE, QGS
		stenophylla	Munumula, Balkura, Gurley, Gooralee, Ironwood, Dalby Wattle, River Cooba, River Myall, Belalei, Eumong, Native Willow, Black Wattle, Dunthy	NNF, LE, QGS
		stowardii	Bastard Mulga	NNF, LE, QGS
		tetragonophylla	Dead Finish, Kurara, Curara	NNF, LE, QGS
		victoriae	Elegant Wattle, Narran, Gundabluey, Prickly Wattle, Bramble Wattle	NNF, LE, QGS
		victoriae ssp. *arida*		
		victoriae ssp. *victoriae*		
	Lysiphyllum	*gilvum* (syn. *Bauhinia gilvum*)	Queensland Bean Tree, Bauhinia	NNF, LE, QGS
MELIACEAE	*Owenia*	*acidula*	Colane, Emu Apple, Gooya, Gruie, Sour Apple,	NNF, LE, QGS

Family	Genus	Species	Common names	Distribution
			Sour Plum	
MYOPORACEAE	*Eremophila*	*bignoniiflora*	Bignonia, Emubush, Creek Wilga, Dogwood, Eurah, Gooramurra, River Argee	NNF, LE, QGS
		deserti	Dogwood, Gooramurra	NNF, LE, QGS
		mitchellii	Budda, False Sandalwood, Rosewood Belvory, Sandalbox	NNF, QGS
		oppositifolia ssp. *oppositifolia*	Twin-leaf Embush, Weeooka	NNF, QGS
		oppositifolia ssp. *rubra*		
		longifolia	Long-leaved Eremophila, Weeping Emubush, Berrigan	NNF, LE, QGS
		alternifolia		NNF
		bowmanii ssp. *bowmanii*		NNF, LE, QGS
		bowmanii ssp. *latifolia*		
		divaricata ssp. *divaricata*		NNF
		duttonii		NNF, LE, QGS
		freelingii		NNF, LE, QGS
		gilesii		NNF, LE, QGS
		glabra		NNF, QGS
		goodwinii		NNF, QGS
		latrobei ssp. *glabra*		NNF, LE, QGS
		latrobei ssp. *latrobei*		
		maculata		NNF, LE, QGS
		polyclada		NNF, LE, QGS
		scoparia		NNF, LE, QGS
		serrulata		NNF, LE
		sturtii		NNF, QGS
	Myoporum	*montanum*	Western Boobialla, Water Bush, Bush Boobialla, Boomeralla, Native Daphne, Native Myrtle, Mee-Mee, Nymoo	NNF, LE
		platycarpum ssp. *platycarpum*	False Sandlewood, Sugar Tree Wood	NNF, LE
MYRTACEAE	*Corymbia*	*tumescens*	Inland Bloodwood, Long-fruited	NNF, LE, QGS

Family	Genus	Species	Common names	Distribution
			Bloodwood, Pale Bloodwood, Arang-mill	
	Eucalyptus	*camaldulensis*	River Red Gum, Red Gum, Murray Red Gum	NNF, LE, QGS
		coolabah ssp. *arida*	Coolabah, Coolibah	NNF, LE, QGS
		coolabah ssp. *coolabah*		
		dumosa	Congoo Mallee, Dumosa Mallee, White Mallee	NNF
		gillii	Arkaroola Mallee, Broken Hill Mallee, Curly Mallee, Silvery Mallee, Mallee Red Gum	NNF, LE
		intertexta	Bastard Coolibah, Gum Coolibah, Gum-barked Coolibah, Smooth-barked Coolibah, Inland Redbox, Western Red Box	NNF, LE
		largiflorens	Black Box, Flooded Box, River Box	NNF, LE
		leptophylla	Narrow-leaved Red Mallee, Slender Mallee	NNF
		ochrophloia	Black Butt, Lapunyah, Napunyah, Yapunyah, Yellow Jacket	NNF, QGS
		populnea ssp. *bimbil*	(Brown's, Grey or Reid River) Bimbil Box, (Brown's, Grey or Reid River) Poplar Box	NNF
		porosa	Black Mallee Box, South Australian Mallee Box, Quorn Mallee	NNF
		socialis	Christmas Mallee, Giant Mallee, Grey Mallee, Pointed Mallee, Red Mallee, Summer Red Mallee	NNF, LE
		vicina		NNF
		viredis	Green Mallee, Whipstick Mallee	NNF

Family	Genus	Species	Common names	Distribution
	Melaleuca	*glomerata*		NNF, LE
		uncinata	Broom Bush Honey Myrtle	NNF, LE, QGS
		densispicata		NNF
PITTOSPORACEAE	*Pittosporum*	*angustifolium*	Berrigan, Butterbush, Cattle Bush, Cumby-cumby, Meemeei, Native Apricot, Native Willow, Weeping *Pittosporum*, Weeping Poisonberry Tree	NNF, LE, QGS
PROTEACEAE	*Grevillea*	*striata*	Beefwood, Silvery Honeysuckle, Western Beefwood, Silky Oak	NNF, LE, QGS
		huegelii		NNF, LE
		juncifolia		NNF, LE, QGS
		kennedyana		NNF, QGS
		nematophylla		NNF, LE, QGS
		stenobotrya		NNF, LE, QGS
	Hakea	*eyreana*	Straggly corkbark	NNF, LE, QGS
		ivoryi	Corkbark tree, Corkwood, Ivory's Hakea, Gold-dust Hakea, Pincushion Hakea	NNF, QGS
		leucoptera ssp. *leucoptera*	Needlewood/ Needlebush, Water Tree, Kuloa, Kolua, Kukuva, Silver Needlewood	NNF, LE, QGS
		tephrosperma	Hooked Needlewood, Striped Hakea	NNF
		ednieana	Yandena, Yantena	NNF, LE
RUBIACEAE	*Canthium*	*latifolium*	Native Currant	NNF, LE, QGS
		oleifolium	Myrtle Tree, Wild Lemon	NNF
RUTACEAE	*(Eremo)Citrus*	*glauca*	Desert Lemon, Native Cumquat, Wild Lime, Desert Lime	NNF, QGS
	Flindersia	*maculosa*	Leopard Wood, Spotted Dog, Spotted Tree	NNF, QGS
	Geijera	*parviflora*	Wilga, Sheepbush, Dogwood	NNF
SANTALACEAE	*Exocarpos*	*aphyllus*	Wining, Leafless Ballart	NNF, LE, QGS
		strictus	Dward Cherry, Pale Ballart	NNF
	Santalum	*acuminatum*	Quandong, Sweet	NNF, LE, QGS

Family	Genus	Species	Common names	Distribution
			Quandong	
		lanceolatum	Bush Plum, Native Plum, Cherry Bush, Northern Sandalbox, Northern Sandalwood, Sandalwood	NNF, LE, QGS
SAPINDACEAE	*Alectryon*	*oleifolius* ssp. *canescens*	Western Rosewood, Bonaree	NNF, LE, QGS
	Atalaya	*hemiglauca*	Whitewood	NNF, LE, QGS
	Dodonaea	*viscosa* ssp. *angustissima*	Sticky Hop-bush, Akeake	NNF, LE, QGS
		viscosa ssp. *cuneata*		
		viscosa ssp. *mucronata*		
		viscosa ssp. *spatulata*		
		lobulata		NNF
		microzyga var. *microzyga*		NNF, LE
		petiolaris		NNF, QGS

Appendix Seven. Compendia of results of initial, basic statistical analyses of numerical characters

Vessel diameter and vessel number per mm²

Filename	Data for vessel diameter (µm)							Data for vessel number per square millimetre						
	Mean	SD	Min	Max	Max vessel diameter - min vessel diameter	Average Max	No. of observations	No. of sampled areas	No. of specimens	Pixels	Magnification	Vessels/sq. mm	Mean/SD of vessels/sq. mm	Mean +/- SD of vessels/sq. mm
JAB100x_compendium	58.51	21.67742	22.27	104.97	82.7	88.74	186	3	1 of 4	30114	60	22.23551	22.23550333	19.64933
JAB100x3	53.69	16.84732	22.3	92.4	70.1	78.7	60			10038	60	21.51823	2.586169018	24.82167
JAB100x9	56.07	20.75682	22.27	95.52	73.25	84.61	70			10038	60	25.1046		
JAB100x8	66.74	25.17365	22.27	104.97	82.7	96.06	56			10038	60	20.08368		
JAB101x_compendium	23.36	8.503336	11.15	46.2	35.05	37.76	173	2	1	20076	121	126.1652	126.16525	94.1932
JAB101x4	24.41	7.422314	11.15	39.83	28.68	35.21	71			10038	121	103.5576	31.97204524	158.1373
JAB101x2	22.63	9.14547	11.15	46.2	35.05	37.91	102			10038	121	148.7729		
JAB105x_compendium	73.82	22.69913	30.27	125.85	95.58	109.12	56	3	1	30114	121	27.72264	27.22640667	21.7044
JAB105x4	71.59	16.13309	30.27	106.73	76.46	80.61	17			10038	121	24.79548	5.522007592	32.74841
JAB105x1	84.03	28.0094	36.64	125.85	89.21	102.43	16			10038	121	23.33692		
JB105x14	68.36	21.28608	39.83	119.48	79.65	87.3	23			10038	121	33.54682		
JAB106x_compendium	25.07	10.96966	14.34	65.32	50.98	42.85	325	3	1	30114	121	158.0104	158.0104	124.2949
JAB106x7	25.34	8.800477	14.34	47.79	33.45	35.84	94			10038	121	137.1044	33.71553503	191.7259
JAB106x5	24.97	11.5051	14.34	54.16	39.82	45.4	96			10038	121	140.0215		
JAB106x3	24.96	11.97048	14.34	65.32	50.98	44.76	135			10038	121	196.9053		
JAB107_compendium	53.5	25.84842	20.71	116.29	95.58	85.87	246	4	2 of 4	40152	121	89.70129	89.7012875	47.67221
JAB107x3	49.58	23.30492	20.71	105.14	84.43	84.43	83			10038	121	121.0603	42.02907375	131.7304
JAB107x8	49.9	28.16435	20.71	116.29	95.58	97.97	89			10038	121	129.8116		
JAB107x6	64.5	22.81537	20.71	113.11	92.4	89.53	43			10038	121	62.71797		
JAB107x5	59.05	25.1041	20.71	109.92	89.21	87.3	31			10038	121	45.21528		

Appendix Seven. Compendia of results of initial, basic statistical analyses (vessel diameter and vessel number per mm^2)

Filename	Data for vessel diameter (µm)							Data for vessel number per square millimetre						
	Mean	SD	Min	Max	Max vessel diameter - min vessel diameter	Average Max	No. of observations	No. of sampled areas	No. of specimens	Pixels	Magnification	Vessels/sq. mm	Mean/SD of vessels/sq. mm	Mean +/- SD of vessels/sq. mm
JB109x_compendium	63.43	17.46025	28.68	98.77	70.09	87.94	82	5	1	50190	121	23.92034	23.920342	19.35433
JB109x18	56.68	11.33094	38.23	81.25	43.02	65.16	19			10038	121	27.71259	4.566007366	28.48635
JB109x15	68.31	17.33141	38.23	95.58	57.35	79.49	17			10038	121	24.79548		
JB109x12	63.9	22.02588	28.68	95.58	66.9	80.61	18			10038	121	26.25403		
JB109x8	67.78	17.36889	31.86	98.77	66.91	71.37	11			10038	121	16.04413		
JB109x3	62.79	17.36046	28.68	87.62	58.94	74.24	17			10038	121	24.79548		
JAB111x4_compendium	56.1	24.80455	20.71	127.44	106.73	91.12	106	3	1	30114	121	51.5357	51.5357	37.52039
JAB111x8	54.94	24.29264	20.71	109.92	89.21	85.07	37			10038	121	53.96663	14.01531222	65.55101
JAB111x5	51.05	23.48843	20.71	109.92	89.21	86.34	44			10038	121	64.17653		
JAB111x4	66.72	25.53167	20.71	127.44	106.73	88.41	25			10038	121	36.46394		
JAB112x_compendium	18.905	8.557438	10.355	73.281	62.92569	35.9234	621	5	1			*na*	*na*	
JAB112x_compendium 121x	19.54	8.582941	11.15	71.69	60.54	21.03	431	3 of 5	1	30114	121			
JAB112x1	23.49	12.75772	11.15	71.69	60.54	45.08	143			10038	121			
JAB112x2	17.56	4.446347	11.15	31.86	20.71	25.17	149			10038	121			
JAB112x4	17.59	4.07223	11.15	31.86	20.71	21.03	139			10038	121			
JAB112x_compendium 241x	17.47	8.344829	10.35	73.28	62.93	32.34	190	2 of 5	1	20076	241			
JAB112x3	17.33	5.933809	10.35	32.66	22.31	28.04	91			10038	241			
JAB112x5	17.6	10.09597	10.35	73.28	62.93	37.44	99			10038	241			
JAB113x_compendium	31.59	8.271942	20.71	55.76	35.05	43.81	310	4	1	40152	121	*na*	*na*	
JAB113x1	32.77	8.592202	20.71	52.57	31.86	45.88	77			10038	121			
JAB113x3	30.23	7.666793	20.71	52.571	31.86	42.69	75			10038	121			
JAB113x5	31.634	8.328891	20.71	55.757	35.05	39.51	77			10038	121			
JAB113x7	31.704	8.413102	20.71	47.792	27.08	44.76	81			10038	121			

Appendix Seven. Compendia of results of initial, basic statistical analyses (vessel diameter and vessel number per mm^2)

Filename	Data for vessel diameter (µm)							Data for vessel number per square millimetre						
	Mean	SD	Min	Max	Max vessel diameter - min vessel diameter	Average Max	No. of observations	No. of sampled areas	No. of specimens	Pixels	Magnification	Vessels/sq. mm	Mean/SD of vessels/sq. mm	Mean +/- SD of vessels/sq. mm
JAB114x_compendium	21.205	8.536436	11.151	55.757	44.61	32.34	614	6	1	60228	121	149.259	149.2590489	139.9578
JAB114x4	28.273	10.5287	11.151	55.757	44.61	39.99	99			10038	121	144.3972	9.301282548	158.5603
JAB114x5	27.35	8.001303	11.151	44.606	33.45	38.87	95			10038	121	138.563		
JAB114x7	19.484	7.967538	11.151	50.978	39.83	29.79	104			10038	121	151.69		
JAB114x8	16.963	4.465205	11.151	31.861	20.71	23.1	108			10038	121	157.5242		
JAB114x9	19.117	6.421812	11.151	41.419	30.27	30.27	97			10038	121	141.4801		
JAB114x10	17.208	4.448228	11.151	31.861	20.71	22.78	111			10038	121	161.8999		
JAB115x_compendium	50.612	22.02436	11.151	100.36	89.21	84.75	122	3	1	30114	121	59.31467	59.31467092	46.16067
JAB115x3	52.252	22.3399	11.151	98.769	87.62	82.36	50			10038	121	72.92787	13.15399993	72.46867
JB115x13	49.743	25.22582	12.744	100.36	87.62	84.59	40			10038	121	58.3423		
JB115x15	49.136	17.21541	11.151	79.653	68.50	68.66	32			10038	121	46.67384		
JB117x_compendium	58.81	16.48576	31.86	93.99	62.13	85.23	62	4	1	40152	121	22.60764	22.6076425	20.08135
JB117x8	56.6	20.10438	31.86	92.4	60.54	69.62	17			10038	121	24.79548	2.526295215	25.13394
JB117x6	62.01	13.58715	41.42	87.62	46.2	66.43	13			10038	121	18.96125		
JB117x4	52.37	11.32265	36.64	74.87	38.23	58.15	16			10038	121	23.33692		
JB117x3	65.02	17.2778	35.05	93.99	58.94	75.67	16			10038	121	23.33692		
JAB119x_compendium	44.992	10.86082	25.489	76.467	50.98	60.85	103	2	1	20076	121	75.11571	75.1157103	63.7708
JAB119x1	45.5	10.15162	27.082	76.467	49.38	61.49	57			10038	121	83.13778	11.34491475	86.46063
JAB119x2	44.363	11.76403	25.489	68.501	43.01	61.33	46			10038	121	67.09364		
JAB121x_compendium	35.43	14.88817	15.931	117.89	101.96	50.02	424	3	1	30114	121	206.1428	206.1427907	148.4913
JAB121x1	29.794	12.46363	15.931	63.722	47.79	49.23	131			10038	121	191.071	57.65147176	263.7943
JAB121x5	41.891	16.11891	25.489	117.89	92.40	56.87	108			10038	121	157.5242		
JAB121x6	35.65	14.19709	22.303	105.14	82.84	54.16	185			10038	121	269.8331		

Appendix Seven. Compendia of results of initial, basic statistical analyses (vessel diameter and vessel number per mm^2)

Filename	Data for vessel diameter (µm)							Data for vessel number per square millimetre						
	Mean	SD	Min	Max	Max vessel diameter - min vessel diameter	Average Max	No. of observations	No. of sampled areas	No. of specimens	Pixels	Magnification	Vessels/sq. mm	Mean/SD of vessels/sq. mm	Mean +/- SD of vessels/sq. mm
JAB122x2_compendium	69.03	21.86917	27.08	111.51	84.43	100.04	54	5	1	50190	121	15.75242	15.752422	12.59034
JAB122x7	86.39	20.50605	54.16	111.51	57.35	95.74	13			10038	121	18.96125	3.162077425	18.9145
JAB122x5	66.38	16.44833	46.2	93.99	47.79	70.25	12			10038	121	17.50269		
JAB122x4	60.4	22.79855	27.08	106.73	79.65	66.11	12			10038	121	17.50269		
JAB122x3	72.09	18.59269	47.79	105.14	57.35	72.09	8			10038	121	11.66846		
JAB122x2	56.29	18.56098	35.05	92.4	57.35	56.29	9			10038	121	13.12702		
JAB123x_compendium	27.92	13.57352	12.74	55.76	43.02	43.97	344	5	1					
JAB123x_compendium 120x	28.74	13.94137	12.74	55.76	43.02	47.63	275	3 of 5		30114	121	133.7011	133.7011333	116.7961
JAB123x5	29.03	13.55657	12.74	55.76	43.02	47.95	104			10038	121	151.69	16.90500001	150.6061
JAB123x3	25.4	14.31533	12.74	55.76	43.02	45.88	90			10038	121	131.2702		
JB123x12	32.08	13.29689	12.74	54.16	41.42	46.52	81			10038	121	118.1432		
JB123x_compendium 240x	24.65	11.51436	12.74	49.38	36.64	42.69	69	2 of 5		20076	241	199.6209	199.62085	195.5295
JB123x13	23.94	10.79206	12.74	45.4	32.66	38.07	34			10038	241	196.7278	4.091390547	203.7122
JAB123x6	25.33	12.294	12.74	49.38	36.64	42.93	35			10038	241	202.5139		
JAB124x_compendium	67.25	26.14042	20.71	156.12	135.41	104.82	84	3	1	30114	121	*na*	*na*	
JAB124x1	58.284	19.3172	20.71	97.176	76.47	78.38	29			10038	121			
JAB124x4	81.132	28.68787	31.861	156.12	124.26	110.72	28			10038	121			
JAB124x8	62.483	24.57779	30.268	121.07	90.80	89.37	27			10038	121			
JAB125x1_compendium	62.33	19.33686	25.49	98.77	73.28	98.77	86	3	1	30114	121	41.81198	41.81198333	32.5489
JAB125x1	59.84	20.27149	30.27	95.58	65.31	79.97	25			10038	121	36.46394	9.263082774	51.07507
JAB125x9	59.26	16.1219	25.49	84.43	58.94	74.24	25			10038	121	36.46394		
JB125x10	66.2	20.53019	28.68	98.77	70.09	92.08	36			10038	121	52.50807		
JAB126x1_compendium	60.243	16.76584	15.799	97.953	82.15427	82.3439	147	5	1	50190	121-122x	42.88159	43.36574982	37.75473
JAB126x1	65.96	12.23058	41.42	93.99	52.57	78.22	27			10038	121	39.38105	5.611019822	48.97677

Appendix Seven. Compendia of results of initial, basic statistical analyses (vessel diameter and vessel number per mm^2)

Filename	Data for vessel diameter (µm)							Data for vessel number per square millimetre						
	Mean	SD	Min	Max	Max vessel diameter - min vessel diameter	Average Max	No. of observations	No. of sampled areas	No. of specimens	Pixels	Magnification	Vessels/sq. mm	Mean/SD of vessels/sq. mm	Mean +/- SD of vessels/sq. mm
JAB126x1_extra obs	56.218	19.10995	15.799	85.314	69.51515	76.9406	36			10038	122	53.37956		
JAB126x3_extra obs	64.986	16.22216	36.337	97.953	61.6157	84.2081	30			10038	122	44.48296		
JAB126x4_extra obs	55.732	15.9667	30.018	93.213	63.19559	72.359	29			10038	122	43.0002		
JAB126x5_extra obs	59.404	16.89325	20.539	90.054	69.51515	74.7288	25			10038	122	37.06914		
JAB127x_compendium	53.644	13.67071	27.082	84.432	57.35	72.17	49	3	1	30114	121	23.82311	23.82310553	17.92842
JAB127x5	52.836	13.16883	30.268	70.094	39.83	56.87	12			10038	121	17.50269	5.894689882	29.7178
JAB127x6	56.076	13.97996	33.454	76.467	43.01	68.34	20			10038	121	29.17115		
JAB127x7	51.353	13.99635	27.082	84.432	57.35	59.9	17			10038	121	24.79548		
JAB128x1_compendium	49.259	16.42861	10.009	88.077	78.06806	57.3075	279	6	1	60228	96	42.69217	42.69216975	35.53915
JAB128x1	40.69	12.73379	16.09	68.37	52.28	59.92	51			10038	96	46.82367	7.153022974	49.84519
JAB128x1_extra obs	52.131	15.75047	22.019	88.077	66.05759	75.8661	47			10038	96	43.15123		
JAB128x2_extra obs	54.194	15.65584	26.023	84.073	58.05061	73.6642	41			10038	96	37.64256		
JAB128x3_extra obs	42.783	18.64845	10.009	82.072	72.06283	64.8565	59			10038	96	54.16856		
JAB128x4_extra obs	52.227	13.33283	26.023	78.068	52.04538	70.6616	44			10038	96	40.39689		
JAB128x5_extra obs	58.754	13.50429	36.031	86.075	50.04363	75.4658	37			10038	96	33.97011		
JAB129x2_compendium	23.25	11.65647	14.34	59.75	45.41	42.77	114	3	1	10038	241	219.8723	219.8722667	179.3695
JAB129x9	20.64	9.225274	14.34	53.37	39.03	32.02	35			10038	241	202.5139	40.50281429	260.3751
JAB129x7	25.03	12.21221	15.13	52.57	37.44	41.5	33			10038	241	190.9417		
JAB129x2	23.97	12.75531	14.34	59.74	45.4	46.2	46			10038	241	266.1612		
JAB130x4_compendium	62.51	26.83226	22.3	127.44	105.14	103.07	54	3	1	30114	121	26.25403	26.25403333	20.99513
JAB130x4	75.1	27.17683	28.68	127.44	98.76	97.81	21			10038	121	30.62971	5.258907321	31.51294
JB130x21	60.42	28.48692	22.3	106.73	84.43	73.76	14			10038	121	20.4198		
JB130x10	50.14	19.0603	28.68	105.14	76.46	63.4	19			10038	121	27.71259		

Appendix Seven. Compendia of results of initial, basic statistical analyses (vessel diameter and vessel number per mm^2)

Filename	Data for vessel diameter (µm)							Data for vessel number per square millimetre						
	Mean	SD	Min	Max	Max vessel diameter - min vessel diameter	Average Max	No. of observations	No. of sampled areas	No. of specimens	Pixels	Magnification	Vessels/sq. mm	Mean/SD of vessels/sq. mm	Mean +/- SD of vessels/sq. mm
JAB132x1_compendium	43.84	28.77929	20.71	111.51	90.8	100.68	75	4	1	40152	121	27.34795	27.3479525	22.67829
JAB132x13	32.26	22.51661	20.71	111.51	90.8	41.74	20			10038	121	29.17115	4.669665498	32.01762
JAB132x5	47.11	29.31938	20.71	105.14	84.43	57.19	14			10038	121	20.4198		
JAB132x1	47.41	27.93033	20.71	111.51	90.8	70.25	21			10038	121	30.62971		
JB132x11	49.38	33.37622	20.71	109.92	89.21	73.76	20			10038	121	29.17115		
JB133x1_compendium	63.877	19.3	11.151	106.73	95.58333	81.7238	196	8	3 of 4	80304	121	35.73466	35.7346583	30.86586
JB133x1_extra obs	54.743	20.63985	14.338	76.467	62.12917	32.0883	22			10038	121	32.08826	4.86879883	40.60346
JB133x2_extra obs	67.262	20.21402	25.489	97.176	71.6875	80.9272	18			10038	121	26.25403		
JB133x3_extra obs	59.12	22.90446	11.151	90.804	79.65278	81.0865	27			10038	121	39.38105		
JB133x4_extra obs	65.939	21.01241	19.117	92.397	73.28056	83.7947	23			10038	121	33.54682		
JB133x7_extra obs	66.495	14.84978	38.233	95.583	57.35	80.9272	27			10038	121	39.38105		
JB133x8_extra obs	74.874	20.29714	28.675	106.73	78.05972	93.0344	25			10038	121	36.46394		
JB133x9_extra obs	62.864	13.63887	39.826	103.55	63.72222	75.3515	26			10038	121	37.92249		
JB133x10_extra obs	60.365	15.85568	28.675	89.211	60.53611	40.8396	28			10038	121	40.83961		
JB135x_compendium	89.809	30.5902	25.278	170.63	145.3499	125.127	239	7	1	70266	61	12.65646	12.65646259	9.797661
JB135x1_extra obs	88.372	28.90791	37.917	151.67	113.7521	119.756	31			10038	61	11.49143	2.858801824	15.51526
JB135x2_extra obs	85.103	22.66328	41.077	142.19	101.1129	109.328	30			10038	61	11.12074		
JB135x3_extra obs	93.943	22.79527	50.556	145.35	94.79339	115.016	26			10038	61	9.637976		
JB135x4_extra obs	90.772	32.94433	37.917	148.51	110.5923	130.499	33			10038	61	12.23282		
JB135x5_extra obs	91.493	34.29724	25.278	154.83	129.551	140.926	45			10038	61	16.68111		
JB135x6_extra obs	92.055	36.42541	31.598	170.63	139.0303	140.926	45			10038	61	16.68111		
JB135x7_extra obs	85.314	28.50064	25.278	129.55	104.2727	116.596	29			10038	61	10.75005		
JAB136x_compendium	38.82	14.55313	20.71	117.89	97.18	70.89	237	3	1	30114	121	115.226	115.2260333	110.8504
JAB136x6	40.03	17.00414	20.71	117.89	97.18	65.16	79			10038	121	115.226	4.37565	119.6017
JAB136x4	37.71	13.74292	20.71	78.06	57.35	58.62	82			10038	121	119.6017		

Appendix Seven. Compendia of results of initial, basic statistical analyses (vessel diameter and vessel number per mm^2)

Filename	Data for vessel diameter (µm)							Data for vessel number per square millimetre						
	Mean	SD	Min	Max	Max vessel diameter - min vessel diameter	Average Max	No. of observations	No. of sampled areas	No. of specimens	Pixels	Magnification	Vessels/sq. mm	Mean/SD of vessels/sq. mm	Mean +/- SD of vessels/sq. mm
JAB136x1	38.78	12.60442	20.71	63.72	43.01	57.83	76			10038	121	110.8504		
JB137x_compendium	67.126	17.71686	20.017	104.09	84.0733	83.2726	236	7	4 of 4	70266	96	30.95346	30.90974298	23.16997
JB137x1_extra obs	58.698	15.51892	30.026	86.075	56.04887	77.4675	34			10038	96	31.21578	7.73977343	38.64952
JB137x2_extra obs	62.454	17.83689	24.021	94.082	70.06108	81.6712	35			10038	96	32.13389		
JB137x3_extra obs	70.5	17.41928	36.031	100.09	64.05585	91.0794	41			10038	96	37.64256		
JB137x4_extra obs	63.555	16.02632	26.023	88.077	62.0541	82.0716	44			10038	96	40.39689		
JB137x5_extra obs	69.394	16.35184	20.017	104.09	84.0733	86.2752	33			10038	96	30.29767		
JB137x6_extra obs	81.023	15.87094	42.037	102.09	60.05236	93.2813	21			10038	96	19.28033		
JB137x7_extra obs	70.776	18.67671	30.026	100.09	70.06108	89.478	28			10038	96	25.70711		
JAB138x_compendium	76.672	37.15554	25.489	156.12	130.63	132.86	62	3	1	30114	60	7.411835	7.411835027	6.258978
JAB138x1	65.8	36.42377	25.489	143.38	117.89	100.04	23			10038	60	8.248655	1.152857234	8.564692
JAB138x3	62.41	20.89451	31.861	101.96	70.09	75.83	17			10038	60	6.096832		
JAB138x4	99.059	38.32059	35.047	156.12	121.07	133.18	22			10038	60	7.890018		
JAB139x_compendium	30.131	9.529526	20.71	70.094	49.38	44.45	197	4	1	40152	121	*na*	*na*	
JAB139x2	30.233	8.741961	20.71	54.164	33.45	43.49	45			10038	121			
JAB139x4	30.666	9.792051	20.71	65.315	44.61	44.45	40			10038	121			
JAB139x5	30.807	10.34474	20.71	70.094	49.38	49.07	68			10038	121			
JB139x14	28.494	8.847879	20.71	58.943	38.23	41.9	44			10038	121			
JAB140x2_compendium	18.04	4.829665	10.35	29.47	19.12	23.74	233	4	1	40152	241	337.0411	337.041075	275.5565
JAB140x7	19.1	3.921956	12.74	26.29	13.55	24.21	46			10038	241	266.1612	61.48452994	398.5256
JAB140x2	16.43	4.761647	10.35	27.88	17.53	23.82	65			10038	241	376.0973		
JB140x13	17.94	5.368719	10.35	29.47	19.12	25.33	69			10038	241	399.2418		
JB140x10	19.21	4.420164	12.74	29.47	16.73	25.73	53			10038	241	306.664		

Appendix Seven. Compendia of results of initial, basic statistical analyses (vessel diameter and vessel number per mm^2)

Filename	Data for vessel diameter (µm)							Data for vessel number per square millimetre						
	Mean	SD	Min	Max	Max vessel diameter - min vessel diameter	Average Max	No. of observations	No. of sampled areas	No. of specimens	Pixels	Magnification	Vessels/sq. mm	Mean/SD of vessels/sq. mm	Mean +/- SD of vessels/sq. mm
JAB142x_compendium	38.664	12.22516	17.524	79.653	62.13	58.31	529	5	1			*na*	*na*	
JAB142x_compendium 60x	39.663	12.07918	19.117	79.653	60.54	54.48	448	3 of 5	1	30114	60			
JAB142x2	40.393	13.05428	19.117	79.653	60.54	58.31	149			10038	60			
JAB142x9	40.095	11.24368	19.117	70.094	50.98	59.26	154			10038	60			
JAB142x10	38.453	11.88376	19.117	70.094	50.98	58.62	145			10038	60			
JB142x_compendium 121x	33.139	11.60424	17.524	66.908	49.38	51.77	81	2 of 5	1	20076	121			
JB142x11	37.437	13.32275	20.71	66.908	46.20	52.09	26			10038	121			
JB142x12	31.108	10.20907	17.524	55.757	38.23	45.56	55			10038	121			
JAB143x_compendium	76.5	30.33219	31.86	129.04	97.18	119.32	48	4	1	40152	121	17.50269	17.50269	14.35185
JAB143x9	92.75	34.15589	35.05	129.04	93.99	92.75	9			10038	121	13.12702	3.150842003	20.65353
JAB143x8	92.66	28.10479	55.76	124.26	68.5	99.57	12			10038	121	17.50269		
JAB143x5	60.05	21.34719	36.64	95.58	58.94	66.27	13			10038	121	18.96125		
JAB143x2	67.48	27.14751	31.86	109.92	78.06	80.61	14			10038	121	20.4198		
JB144x1_compendium 121x	55.47	14.03817	19.117	87.618	68.50139	73.7585	122	5	1	50190	121	35.5888	35.58880255	34.28423
JB144x1	57.732	16.05143	19.117	78.06	58.94306	71.2096	25			10038	121	36.46394	1.304573471	36.89338
JB144x4	51.742	6.838397	38.233	65.315	46.19861	58.1465	25			10038	121	36.46394		
JB144x5	50.341	12.84362	28.675	79.653	41.41944	62.7664	25			10038	121	36.46394		
JB144x21	58.943	12.7531	28.675	87.618	58.94306	69.4572	24			10038	121	35.00538		
JB144x9	59.012	18.00081	23.896	81.246	52.57083	73.1213	23			10038	121	33.54682		
JAB147x_compendium	22.755	9.726658	12.744	66.908	54.16	36.08	472	7	1					
JAB147x_compendium 121x	23.506	9.890164	12.744	66.908	54.16	38.07	331	3 of 7	1	30114	121			
JAB147x2	23.823	10.03888	12.744	66.908	54.16	39.03	109			10038	121			
JAB147x3	21.338	7.879989	12.744	55.757	43.01	35.21	142			10038	121			
JAB147x6	26.923	11.81469	12.744	66.908	54.16	42.53	80			10038	121			
JAB147x_compendium 241x	20.992	9.124694	12.744	58.147	45.40	33.45	141	4 of 7	1	40152	241			

Appendix Seven. Compendia of results of initial, basic statistical analyses (vessel diameter and vessel number per mm^2)

Filename	Data for vessel diameter (µm)							Data for vessel number per square millimetre						
	Mean	SD	Min	Max	Max vessel diameter - min vessel diameter	Average Max	No. of observations	No. of sampled areas	No. of specimens	Pixels	Magnification	Vessels/sq. mm	Mean/SD of vessels/sq. mm	Mean +/- SD of vessels/sq. mm
JAB147x1	19.368	7.650633	12.744	46.199	33.45	30.27	57			10038	241			
JAB147x4	20.039	6.621706	13.541	36.64	23.10	29.23	38			10038	241			
JAB147x7	39.826	17.00918	22.303	58.147	35.84	39.83	8			10038	241			
JAB147x10	20.416	6.76997	13.541	37.437	23.90	29.63	38			10038	241			
JAB150x_compendium	42.08	26.97868	15.93	90.8	74.87	80.77	84	4	1	40152	121	30.62971	30.6297075	15.23979
JAB150x4	33.28	23.3903	15.93	79.65	63.72	61.81	28			10038	121	40.83961	15.38991302	46.01962
JAB150x3	41.13	23.72335	15.93	73.28	57.35	43.65	11			10038	121	16.04413		
JAB150x2	39.88	28.13456	15.93	90.8	74.87	78.22	32			10038	121	46.67384		
JB150x11	67.28	20.18381	28.68	90.8	62.12	76.15	13			10038	121	18.96125		
JAB151x_compendium	30.991	11.54804	15.134	60.536	45.40	52.09	76	2	1	20076	241	219.8723	219.8722853	154.4099
JAB151x3	33.667	12.70479	15.931	59.74	43.81	48.83	30			10038	241	173.5834	65.46239324	285.3347
JAB151x9	29.246	10.50513	15.134	60.536	45.40	44.92	46			10038	241	266.1612		
JAB152x_compendium	25.136	6.434082	15.134	46.199	31.06	34.09	131	3	1	30114	241	252.6603	252.6602577	197.0614
JAB152x5	24.048	6.571253	15.134	39.826	24.69	33.45	42			10038	241	243.0167	55.59889381	308.2592
JAB152x8	24.884	5.647023	15.134	38.233	23.10	32.82	54			10038	241	312.4501		
JAB152x13	26.832	7.209687	15.134	46.199	31.06	34.81	35			10038	241	202.5139		
JAB153x2_compendium	18.65	4.114944	13.54	31.06	17.52	24.45	212	3	1	30114	241	408.8853	408.8853	316.9729
JAB153x5	18.42	3.430546	13.54	27.88	14.34	23.26	61			10038	241	352.9529	91.91239135	500.7977
JAB153x4	17.23	3.241882	13.54	28.68	15.14	22.7	62			10038	241	358.739		
JAB153x2	19.79	4.745708	13.54	31.06	17.52	26.52	89			10038	241	514.964		
JAB155x_compendium	37.52	12.97026	20.71	63.722	43.01	59.1	105	2	1	20076	121	76.57427	76.57426778	46.66495
JB155x10	37.948	14.56612	20.71	63.722	43.01	59.58	67			10038	121	97.72335	29.90932069	106.4836
JB155x15	36.766	9.66808	20.71	55.757	35.05	48.11	38			10038	121	55.42518		

Appendix Seven. Compendia of results of initial, basic statistical analyses (vessel diameter and vessel number per mm^2)

Filename	Data for vessel diameter (µm)							Data for vessel number per square millimetre						
	Mean	SD	Min	Max	Max vessel diameter - min vessel diameter	Average Max	No. of observations	No. of sampled areas	No. of specimens	Pixels	Magnification	Vessels/sq. mm	Mean/SD of vessels/sq. mm	Mean +/- SD of vessels/sq. mm
JAB156x2_compendium	87.92	32.50324	31.86	140.19	108.33	129.36	63	3	1	30114	121	30.62971	30.62970333	28.10341
JAB156x8	100.51	27.49561	55.76	140.19	84.43	125.53	22			10038	121	32.08826	2.526294252	33.156
JAB156x6	67.08	26.06806	31.86	105.14	73.28	87.78	19			10038	121	27.71259		
JAB156x2	93.34	34.50742	33.45	138.6	105.15	123.46	22			10038	121	32.08826		
JAB157x_compendium	75.35	19.63558	31.86	117.89	86.03	100.68	63	3	1	30114	121	30.62971	30.62970667	29.17115
JAB157x6	69.72	21.85975	31.86	103.55	71.69	88.73	21			10038	121	30.62971	1.458555	32.08826
JAB157x2	77.66	16.42491	50.98	117.89	66.91	90.49	20			10038	121	29.17115		
JAB157x1	78.64	19.77263	33.45	108.33	74.88	93.51	22			10038	121	32.08826		
JB158x_compendium 121x	37.28	12.38018	15.93	86.03	70.09444	54.9604	977	8	1	80304	121	178.1263	178.1263324	153.5409
JB158x1_extra obs	37.079	11.24555	15.931	68.501	52.57083	54.9604	109			10038	121	158.9828	24.58545633	202.7118
JB158x2_extra obs	38.355	12.33651	15.931	74.874	58.94306	56.0756	118			10038	121	172.1098		
JB158x3_extra obs	37.051	12.49518	15.931	78.06	62.12917	52.2522	132			10038	121	192.5296		
JB158x4_extra obs	39.356	12.97958	15.931	86.025	70.09444	53.0488	139			10038	121	202.7395		
JB158x5_extra obs	38.434	14.04512	15.931	84.432	68.50139	65.7932	127			10038	121	185.2368		
JB158x6_extra obs	36.717	10.81005	19.117	62.129	43.0125	51.615	104			10038	121	151.69		
JB158x7_extra obs	32.414	9.773507	15.931	57.35	41.41944	47.1544	147			10038	121	214.4079		
JB158x8_extra obs	46.74	15.57786	21.664	84.07	62.40571	63.5629	101			10038	121	147.3143		
JAB159x_compendium	71	21.09332	20.71	124.26	103.55	104.03	141	4	1	40152	121	51.41415	51.41415	39.78374
JAB159x2	68.39	20.60372	31.86	114.7	82.84	93.35	44			10038	121	64.17653	11.63041332	63.04456
JB159x16	70.67	20.0607	31.86	106.73	74.87	89.69	25			10038	121	36.46394		
JB159x13	73.24	20.59343	20.71	106.73	86.02	96.86	38			10038	121	55.42518		
JB159x11	72.11	23.45343	31.86	124.26	92.4	99.41	34			10038	121	49.59095		
JAB160x_compendium	59.07	30.24608	20.71	119.48	98.77	107.691	129	4	1	40152	120	46.2642	46.26419605	24.2457

Appendix Seven. Compendia of results of initial, basic statistical analyses (vessel diameter and vessel number per mm^2)

Filename	Data for vessel diameter (µm)							Data for vessel number per square millimetre						
	Mean	SD	Min	Max	Max vessel diameter - min vessel diameter	Average Max	No. of observations	No. of sampled areas	No. of specimens	Pixels	Magnification	Vessels/sq. mm	Mean/SD of vessels/sq. mm	Mean +/- SD of vessels/sq. mm
JAB160x9	67.25	26.63941	33.45	111.51	78.06	93.83	23			10038	120	32.99462	22.01849252	68.28269
JAB160x4	46.84	32.54812	20.71	113.11	92.40	94.31	55			10038	120	78.90018		
JAB160x3	65.26	23.78932	28.68	117.89	89.21	91.44	28			10038	120	40.16736		
JAB160x1	72.59	27.30181	28.68	119.48	90.8	98.29	23			10038	120	32.99462		
JAB161x_compendium	69.98	22.72042	23.9	124.26	100.36	103.07	165	4	1	40152	120	59.17513	59.17513449	50.53801
JAB161x3	77.29	16.96306	31.86	105.14	73.28	94.79	33			10038	120	47.34011	8.637127014	67.81226
JB161x12	63.72	22.9471	28.68	124.26	95.58	94.63	44			10038	120	63.12014		
JB161x11	74.06	24.50439	27.08	121.07	93.99	106.42	41			10038	120	58.8165		
JB161x17	`67.15	22.95851	23.9	122.67	98.77	98.61	47			10038	120	67.42379		
JAB162x_compendium	21.722	15.30632	12.744	86.025	73.28	42.06	192	3	1	30114	120	91.81112	91.81111775	65.4763
JAB162x2	18.682	10.78804	12.744	71.688	58.94	35.68	77			10038	120	110.4603	26.33481375	118.1459
JAB162x4	30.75	20.98373	12.744	86.025	73.28	63.4	43			10038	120	61.68559		
JAB162x7	19.581	13.46039	12.744	76.467	63.72	45.4	72			10038	120	103.2875		
JAB163x_compendium	52.95	16.26832	12.74	108.33	95.59	73.28	138	3	1	30114	120	65.98924	65.98924088	59.41531
JAB163x5	51.93	16.64081	12.74	84.43	71.69	72.64	47			10038	120	67.42379	6.573928074	72.56317
JAB163x3	55.48	18.79503	20.71	108.33	87.62	77.9	41			10038	120	58.8165		
JB163x14	51.84	13.56423	23.9	78.06	54.16	68.5	50			10038	120	71.72744		
JAB164x_compendium	51.16	18.77026	19.12	113.11	93.99	78.54	152	4	1	40152	120	54.51285	54.51285117	42.06172
JAB164x3	52.12	19.67684	20.71	113.11	92.4	78.06	46			10038	120	65.98924	12.4511336	66.96398
JAB164x2	54.27	21.40113	19.12	103.55	84.43	84.59	45			10038	120	64.55469		
JB164x15	51.03	16.25897	19.12	90.8	71.68	69.78	31			10038	120	44.47101		
JB164x17	45.14	14.53652	23.9	82.84	58.94	61.49	30			10038	120	43.03646		
JB165x_compendium	38.48	17.96983	12.74	98.77	86.03	66.11	156	4	1	40152	120	55.9474	55.94739988	49.74944

Appendix Seven. Compendia of results of initial, basic statistical analyses (vessel diameter and vessel number per mm^2)

Filename	Data for vessel diameter (µm)							Data for vessel number per square millimetre						
	Mean	SD	Min	Max	Max vessel diameter - min vessel diameter	Average Max	No. of observations	No. of sampled areas	No. of specimens	Pixels	Magnification	Vessels/sq. mm	Mean/SD of vessels/sq. mm	Mean +/- SD of vessels/sq. mm
JAB165x1	34.45	15.64298	12.74	76.47	63.73	57.67	45			10038	120	64.55469	6.197958827	62.14536
JB165x19	38.56	14.54183	19.12	74.87	55.75	57.67	39			10038	120	55.9474		
JB165x18	39.78	21.42361	14.34	95.58	81.24	66.27	35			10038	120	50.20921		
JB165x17	42.07	19.98373	14.34	98.77	84.43	68.18	37			10038	120	53.0783		
JAB166x_compendium	59.634	19.35134	17.524	109.92	92.39722	76.63	265	10	1	100380	120-121	38.01554	39.95427376	28.25083
JAB166x3	60.59	17.7624	28.68	92.4	63.72	78.86	29			10038	120	41.60191	11.70343885	51.65771
JAB166x2	52.97	16.0366	17.52	84.43	66.91	71.85	36			10038	120	51.64375		
JB166x1_extra obs	51.029	12.5941	31.861	71.688	39.82639	65.3153	31			10038	121	45.21528		
JB166x2_extra obs	69.298	15.25739	47.792	93.99	46.19861	73.2806	12			10038	121	17.50269		
JB166x3_extra obs	66.554	17.92832	30.268	97.176	66.90833	77.7411	18			10038	121	40.83961		
JB166x4_extra obs	68.979	21.57276	28.675	108.33	79.65278	85.3878	20			10038	121	29.17115		
JB166x5_extra obs	59.097	29.10937	17.524	109.92	92.39722	93.5124	31			10038	121	45.21528		
JB166x6_extra obs	58.859	13.00154	38.233	93.99	55.75694	68.1828	19			10038	121	27.71259		
JB166x7_extra obs	58.817	18.07801	22.303	93.99	71.6875	82.5203	38			10038	121	55.42518		
JB166x8_extra obs	63.311	18.91187	22.303	98.769	76.46667	83.3168	31			10038	121	45.21528		
JAb167x_compendium	27.33	9.29944	11.15	55.757	44.61	43.73	113	3	1	30114	240	216.1387	216.138673	187.8328
JAB167x2	25.04	7.433475	11.15	37.44	26.29	33.29	32			10038	240	183.6222	28.30584308	244.4445
JAB167x3	26.849	9.291154	15.134	44.606	29.47	39.19	41			10038	240	235.266		
JAB167x4	29.651	10.28706	15.134	55.757	40.62	43.89	40			10038	240	229.5278		
JAB168x_compendium	20.05	5.390976	13.54	39.83	26.29	27.08	155	5	1	50190	240	177.884	177.8840406	157.5965
JB168x14	20.21	5.208467	13.54	30.27	16.73	26.52	32			10038	240	183.6222	20.28758248	198.1716
JB168x13	23.05	6.510547	13.54	39.83	26.29	30.43	33			10038	240	189.3604		
JB168x12	18.9	3.698844	13.54	28.68	15.14	22.78	29			10038	240	166.4077		
JAB168x9	19.3	5.27062	13.54	30.27	16.73	25.17	26			10038	240	149.1931		
JAB168x6	18.59	4.775037	13.54	30.27	16.73	25.01	35			10038	240	200.8368		

Appendix Seven. Compendia of results of initial, basic statistical analyses (vessel diameter and vessel number per mm^2)

Filename	Data for vessel diameter (µm)							Data for vessel number per square millimetre						
	Mean	SD	Min	Max	Max vessel diameter - min vessel diameter	Average Max	No. of observations	No. of sampled areas	No. of specimens	Pixels	Magnification	Vessels/sq. mm	Mean/SD of vessels/sq. mm	Mean +/- SD of vessels/sq. mm
JAB169x_compendium	58.06	17.79363	17.52	93.99	76.47	80.45	115	4	1	40152	120	41.24328	41.24327555	41.24328
JAB169x2	60.59	17.75669	23.9	90.8	66.9	78.54	30			10038	120	43.03646	9.614330789	50.85761
JB169x14	51.03	17.57951	17.52	92.4	74.88	67.7	32			10038	120	45.90556		
JB169x11	60.96	15.48028	27.08	82.84	55.76	72.8	19			10038	120	27.25643		
JB169x10	60.82	18.1444	27.08	93.99	66.91	82.2	34			10038	120	48.77466		
JAB170x_compendium	49.797	15.23938	17.524	82.839	65.32	71.29	58	4	1	40152	240	83.20383	83.20382546	79.89088
JAB170x2	53.083	14.20621	26.285	82.042	55.76	59.74	14			10038	240	80.33473	3.312948347	86.51677
JAB170x4	51.774	16.44566	29.472	82.839	53.37	60.85	15			10038	240	86.07292		
JAB170x6	44.659	18.42981	17.524	74.874	57.35	54.72	15			10038	240	86.07292		
JAB170x7	49.897	10.62061	30.268	66.908	36.64	54.4	14			10038	240	80.33473		
JAB172x_compendium	33.5	19.43662	15.93	81.25	65.32	63.24	66	3	1	30114	120	31.56007	31.56007173	21.21539
JAB172x2	33.23	15.5191	19.12	62.13	43.01	38.55	14			10038	120	20.08368	10.3446779	41.90475
JAB172x7	27.25	15.93256	15.93	63.72	47.79	44.76	28			10038	120	40.16736		
JAB172x9	40.95	22.97768	19.12	81.25	62.13	65.95	24			10038	120	34.42917		
JAB174x_compendium	31.048	8.751979	13.541	53.367	39.82639	43.1718	145	9	1	90342	240-241	92.44869	93.03968254	71.85592
JAB174x7	28.24	6.836822	20.71	39.83	19.12	28.99	11			10038	240	63.12014	21.18376654	114.2234
JB174x16	23.55	8.483628	13.54	38.23	24.69	32.1	23			10038	240	131.9785		
JB174x1_extra obs	30.452	6.472279	21.506	43.809	22.30278	32.4187	13			10038	241	75.21947		
JB174x2_extra obs	30.374	9.448016	16.727	50.978	34.25069	35.2862	15			10038	241	86.79169		
JB174x3_extra obs	33.764	9.237213	13.541	47.792	34.25069	40.7026	18			10038	241	104.15		
JB174x4_extra obs	31.419	5.120147	23.896	42.216	18.32014	34.8879	18			10038	241	104.15		
JB174x5_extra obs	33.245	7.699046	20.71	46.199	25.48889	39.1892	19			10038	241	109.9361		
JB174x6_extra obs	33.17	7.534581	19.117	46.995	27.87847	36.7996	14			10038	241	81.00558		
JB174x7_extra obs	37.778	9.648358	19.117	53.367	34.25069	42.216	14			10038	241	81.00558		

Appendix Seven. Compendia of results of initial, basic statistical analyses (vessel diameter and vessel number per mm^2)

Filename	Data for vessel diameter (µm)							Data for vessel number per square millimetre						
	Mean	SD	Min	Max	Max vessel diameter - min vessel diameter	Average Max	No. of observations	No. of sampled areas	No. of specimens	Pixels	Magnification	Vessels/sq. mm	Mean/SD of vessels/sq. mm	Mean +/- SD of vessels/sq. mm
JAB175x_compendium	31.87	6.682746	20.71	52.57	31.86	43.65	232	4	1	40152	120	83.20383	83.20382546	77.3473
JAB175x9	33.32	5.349561	25.49	46.2	20.71	40.94	61			10038	120	87.50747	5.856520604	89.06035
JAB175x2	34.45	6.520856	25.49	47.79	22.3	44.13	59			10038	120	84.63837		
JB175x15	26.79	4.929725	20.71	39.83	19.12	33.29	60			10038	120	86.07292		
JB175x14	33.09	7.072594	22.3	52.57	30.27	43.81	52			10038	120	74.59653		
JAB177x_compendium	45.84	16.43677	15.93	90.8	74.87	76.15	180	3	1	30114	120	86.07292	86.07292289	58.70348
JAB177x7	58.73	14.87136	27.08	90.8	63.72	77.42	38			10038	120	54.51285	27.36944511	113.4424
JAB177x4	41.95	14.97047	15.93	84.43	68.5	62.77	72			10038	120	103.2875		
JAB177x2	42.83	15.33422	19.12	84.43	65.31	61.49	70			10038	120	100.4184		
JAB178x_compendium	55.19	17.58705	12.74	93.99	81.25	75.35	148	4	1	40152	120	53.0783	53.07830245	38.97393
JAB178x7	52.1	16.70144	12.74	81.25	68.51	73.28	41			10038	120	58.8165	14.10436935	67.18267
JAB178x6	59.47	19.34118	19.12	93.99	74.87	80.29	30			10038	120	43.03646		
JAB178x4	60.08	15.89427	28.68	86.03	57.35	77.26	28			10038	120	40.16736		
JAB178x2	52.34	17.46014	23.9	86.03	62.13	78.06	49			10038	120	70.29289		
JAB180x_compendium	44.67	10.99207	30.27	92.4	62.13	63.4	122	3	1	30114	120	58.33831	58.33831441	43.82643
JAB180x6	42.41	9.805603	30.27	63.72	33.45	54.48	29			10038	120	41.60191	14.5118861	72.8502
JAB180x3	47.31	12.1874	30.27	92.4	62.13	63.09	46			10038	120	65.98924		
JAB180x2	43.49	10.11862	30.27	71.69	41.42	59.1	47			10038	120	67.42379		
JAB181x_compendium	28.221	12.00194	15.134	64.519	49.38	45.4	165	5	1	50190	240	189.3604	189.3604304	164.3482
JAB181x2	30.168	14.66738	15.134	62.926	47.79	49.07	32			10038	240	183.6222	25.01221151	214.3726
JAB181x6	24.832	11.26444	15.134	60.536	45.40	41.1	40			10038	240	229.5278		
JAB181x9	29.841	11.75356	16.727	64.519	47.79	42.22	28			10038	240	160.6695		
JAB181x11	30.558	11.81579	15.134	57.35	42.22	44.61	33			10038	240	189.3604		

Appendix Seven. Compendia of results of initial, basic statistical analyses (vessel diameter and vessel number per mm^2)

Filename	Data for vessel diameter (µm)							Data for vessel number per square millimetre						
	Mean	SD	Min	Max	Max vessel diameter - min vessel diameter	Average Max	No. of observations	No. of sampled areas	No. of specimens	Pixels	Magnification	Vessels/sq. mm	Mean/SD of vessels/sq. mm	Mean +/- SD of vessels/sq. mm
JAB181x16	26.684	9.669035	15.931	54.164	38.23	38.23	32			10038	240	183.6222		
JAB183x_compendium	42.205	12.18662	15.931	68.501	52.57	55.92	150	3	1	30114	120	71.72744	71.72743574	55.43409
JAB183x1	39.353	11.81361	15.931	68.501	52.57	53.21	37			10038	120	53.0783	16.29334134	88.02078
JAB183x8	42.408	12.84476	15.931	65.315	49.38	59.42	58			10038	120	83.20383		
JAB183x9	43.91	11.57638	17.524	66.908	49.38	60.7	55			10038	120	78.90018		
JAB184x_compendium	46.71	9.964988	23.9	82.84	58.94	58.94	122	4	1	40152	121	44.486	44.4860025	32.97048
JAB184x9	41.74	6.25056	27.08	54.16	27.08	48.75	40			10038	121	58.3423	11.51552395	56.00153
JAB184x5	44.65	8.268327	23.9	60.54	36.64	53.05	34			10038	121	49.59095		
JAB184x2	52.7	11.25399	31.86	82.84	50.98	62.45	24			10038	121	35.00538		
JAB184x1	51.91	10.79356	31.86	79.65	47.79	61.33	24			10038	121	35.00538		
JAB186x_compendium	47.733	14.42726	21.506	75.67	54.16	66.43	41	2	1	20076	241	118.6153	118.6153118	98.15831
JAB186x9	50.491	17.91149	21.506	75.67	54.16	63.64	18			10038	241	104.15	20.45699789	139.0723
JB186x15	45.575	10.92924	21.506	69.298	47.79	54.64	23			10038	241	133.0806		
JAB187x_compendium	46.79	12.54165	20.71	70.09	49.38	59.9	118	4	1	40152	121	43.02745	43.027445	39.16846
JAB187x6	61.65	12.30501	22.3	66.91	44.61	61.65	29			10038	121	42.29817	3.858981993	46.88643
JAB187x5	42.96	12.19618	20.71	66.91	46.2	57.35	32			10038	121	46.67384		
JAB187x4	48.97	10.4542	28.68	63.72	35.04	60.7	31			10038	121	45.21528		
JAB187x3	46.63	14.87991	20.71	70.09	49.38	60.22	26			10038	121	37.92249		
JAB189x_compendium	48.661	11.34895	22.303	76.314	54.01	63.66	198	3	1	30114	121	96.26479	96.26479378	89.58084
JAB189x2	49.85	11.27067	22.303	71.688	49.38	64.04	65			10038	121	94.80624	6.683950065	102.9487
JAB189x3	45.054	10.8086	25.489	73.281	47.79	60.7	71			10038	121	103.5576		
JAB189x13	51.543	11.11441	28.618	76.314	47.70	67.41	62			10038	121	90.43056		

Appendix Seven. Compendia of results of initial, basic statistical analyses (vessel diameter and vessel number per mm^2)

Filename	Data for vessel diameter (µm)							Data for vessel number per square millimetre						
	Mean	SD	Min	Max	Max vessel diameter - min vessel diameter	Average Max	No. of observations	No. of sampled areas	No. of specimens	Pixels	Magnification	Vessels/sq. mm	Mean/SD of vessels/sq. mm	Mean +/- SD of vessels/sq. mm
JAB190x_compendium	28.423	10.86981	14.338	70.094	55.76	49.7	209	2	1	20076	121	152.4193	153.1485356	144.8977
JAB190x4	30.902	12.28377	15.931	70.094	54.16	50.02	108			10038	121	158.9828	8.250847088	161.3994
JAB190x7	25.773	8.400694	14.338	46.199	31.86	38.55	101			10038	121	147.3143		
JAB191x_compendium	59.94	18.42934	25.49	90.8	65.31	81.88	45	3	1	30114	121	21.87836	21.87836333	14.1604
JAB191x6	57.52	19.84685	25.49	82.84	57.35	74.4	19			10038	121	27.71259	7.717958946	29.59632
JAB191x4	55.66	18.13278	30.27	82.84	52.57	68.5	17			10038	121	24.79548		
JB191x11	71.16	11.43232	50.98	90.8	39.82	71.16	9			10038	121	13.12702		

NOTE: JAB112, 113, 124, 139, 142, 147 are not measured for vessel number but are measured for vessel diameter

NOTE 2: Filenames with *_extra obs* suffix simply refer to a subsequent batch of observations that were made to increase the number of observations

Ray height

Filename	Mean	SD	Min	Max	Max ray height - min ray height	No. of observations	No. of samples
JB100t3	105.4123	25.39997	80.42786	143.3368	62.91	8	
JB100t5	116.5275	51.4833	72.4647	212.6162	140.15	6	
JB100t6	91.32743	19.82536	46.18629	117.8547	71.67	16	
JB100t8	92.17351	21.26202	62.90892	112.2805	49.37	4	
JB100t12	100.0968	28.12157	62.90892	144.1331	81.22	10	
JB100t_compendium	99.39464	28.71016	46.18629	212.6162	166.43	44	5
JB101t1	206.2397	72.78511	142.5103	321.8492	179.34	5	
JB101t13	248.73	34.53819	200.15	315.44	115.29	9	
JB101t15	347.469	#DIV/0!	347.469	347.469	0.00	1	
JB101t16	288.2231	41.89315	258.6002	317.8461	59.25	2	
JB101t5 (extra obs)	223.50	53.83	148.11	313.7483	165.63	9	
JB101t7 (extra obs)	227.75	50.14	170.41	315.3409	144.93	8	
JB101t8 (extra obs)	281.26	91.07	191.12	417.2693	226.15	5	
JB101t9 (extra obs)	221.38	38.28	175.19	285.0809	109.89	8	
JB101t10 (extra obs)	240.75	35.85	183.15	289.8588	106.71	6	
JB101t_compendium	238.6589	55.56577	142.5103	417.2693	274.76	53	9
JB105t1	134.2216	43.17871	70.45455	224.1736	153.72	17	
JB105t19	97.47546	41.08863	48.03719	200.155	152.12	24	
JB105t25	108.9785	33.71394	62.44835	198.5537	136.11	17	
JB105t_compendium	111.6174	41.97978	48.03719	224.1736	176.14	58	3
JB106t1	152.0177	29.16114	92.8719	204.9587	112.09	16	
JB106t13	173.7961	58.67917	113.688	326.6529	212.96	13	
JB106t15	162.2971	35.56498	116.8905	235.3822	118.49	14	
JB106t_compendium	161.9486	41.95298	92.8719	326.6529	233.78	43	3
JB107t2	184.4797	80.03543	116.2621	334.4525	218.19	12	
JB107t3	128.804	45.77998	67.68681	222.172	154.49	8	
JB107t12	158.3672	35.11486	113.0768	218.1904	105.11	16	
JB107t15	126.397	34.32584	82.8168	253.2283	170.41	22	
JB107t18	118.2971	20.431	84.40944	145.7257	61.32	9	
JB107t19	148.2823	38.45431	108.2989	248.4504	140.15	19	
JB107t20	122.0592	44.23884	62.1126	258.0062	195.89	25	
JB107t21	124.3579	18.69844	96.35417	145.7257	49.37	6	
JB107t_compendium	138.7903	46.99099	62.1126	334.4525	272.34	117	8
JB109t2	181.1618	71.37379	89.18733	321.7114	232.52	12	
JB109t3	168.925	43.98194	121.0399	286.6736	165.63	15	
JB109t8	176.047	59.22651	87.5947	332.8598	245.27	13	
JB109t11	168.8189	32.96143	76.44628	210.2273	133.78	13	
JB109t15	168.0226	47.03696	105.1136	256.4136	151.30	18	
JB109t21	158.5392	38.69381	106.7063	215.0052	108.30	11	
JB109t23	153.1736	46.15277	84.40944	245.2652	160.86	17	
JB109t24	147.5279	38.89271	74.85365	207.042	132.19	19	
JB109t25	167.5073	42.23189	89.18733	256.4136	167.23	17	

Appendix Seven. Compendia of results of initial, basic statistical analyses (ray height)

Filename	Mean	SD	Min	Max	Max ray height - min ray height	No. of observations	No. of samples
JB109t2_compendium	164.5483	46.89627	74.85365	332.8598	258.01	135	9
JB111t3	123.43	39.13575	95.56	218.19	122.63	10	
JB111t4	123.6127	41.55382	70.07576	194.301	124.23	13	
JB111t6	139.0898	34.58552	101.1321	168.8189	67.69	3	
JB111t3 (extra obs)	174.6585	33.75977	138.5589	205.4494	66.89	3	
JB111t4 (extra obs)	128.2068	46.40818	82.8168	208.6346	125.82	6	
JB111t5 (extra obs)	145.6372	75.77188	68.48313	296.2293	227.75	9	
JB111t6 (extra obs)	161.3108	69.38288	84.40944	285.0809	200.67	7	
JB111t7 (extra obs)	148.1147	59.7555	82.8168	229.3388	146.52	9	
JB111t_compendium	138.7447	53.35633	68.48313	296.2293	227.75	60	8
JB113t2	273.6785	86.76957	153.719	478.7707	325.05	12	
JB113t3	283.7753	93.97578	152.1178	467.562	315.44	9	
JB113t2 (extra obs)	289.2218	96.24947	213.4125	455.4924	242.08	5	
JB113t4 (extra obs)	257.7787	56.90864	170.4115	351.9714	181.56	7	
JB113t5 (extra obs)	283.6157	79.24028	156.0778	439.5661	283.49	25	
JB113t6 (extra obs)	260.9984	60.50918	165.6336	455.4924	289.86	33	
JB113t7 (extra obs)	254.2901	52.3891	160.8557	326.4893	165.63	12	
JB113t8(extra obs)	262.4302	74.52159	132.1884	361.5272	229.34	9	
JB113t_compendium	269.6908	71.53242	132.1884	478.7707	346.58	112	8
JB114t1	140.79	38.16951	75.26	188.95	113.69	14	
JB114t2	127.5654	31.20908	84.8657	190.5475	105.68	18	
JB114t14	120.093	29.70312	76.8595	200.155	123.30	20	
JB114t_compendium	128.25	33.0785	75.26	200.15	124.90	52	3
JB115t1	1091.271	346.7507	700.7576	1777.376	1076.62	10	
JB115t15	927.9729	277.6749	637.0523	1337.81	700.76	6	
JB115t18	1149.242	360.6133	789.9449	1707.3	917.36	5	
JB115t19	1385.943	654.1205	433.1956	2662.879	2229.68	9	
JB115t_compendium	1156.675	463.8948	433.1956	2662.879	2229.68	30	4
JAB117t1	132.12	29.20655	82.82	183.15	100.34	24	
JAB117t22	141.7441	59.57897	63.70523	301.0072	237.30	19	
JAB117t23	135.7528	37.96648	70.07576	238.8946	168.82	21	
JAB117t25	142.3957	60.49334	78.03891	285.0809	207.04	22	
JAB117t_compendium	132.122	47.37988	63.70523	301.0072	237.30	86	4
JB119t2	179.88	63.45584	95.56	329.67	234.12	19	
JB119t10	10.00	80.40359	111.48	334.45	222.97	10	
JB119t15	298.5045	106.1138	172.0041	477.7893	305.79	7	
JB119t_compendium	213.4125	87.90234	95.55785	477.7893	382.23	36	3
JAB121t2	117.7099	30.22568	73.26102	172.0041	98.74	22	
JAB121t3	123.5174	31.33489	63.70523	195.8936	132.19	27	
JB121t1 (extra obs)	137.0724	29.82254	100.3357	187.9304	87.59	15	
JB121t2 (extra obs)	130.7019	24.44028	90.78	179.97	89.19	15	
JB121t3 (extra obs)	126.1926	22.63924	87.5947	164.041	76.45	17	

Filename	Mean	SD	Min	Max	Max ray height - min ray height	No. of observations	No. of samples
JB121t4 (extra obs)	123.4289	20.90402	92.37259	160.8557	68.48	10	
JB121t5 (extra obs)	119.6243	11.24595	105.1136	136.9663	31.85	9	
JB121t6 (extra obs)	136.0107	38.96393	81.22417	211.8199	130.60	15	
JAB121t_compendium	126.4426	28.62308	63.70523	211.8199	148.11	130	8
JAB122t1	121.495	32.4371	68.48313	191.1157	122.63	21	
JAB122t5	118.3856	35.62774	46.18629	191.1157	144.93	21	
JAB122t8	126.7873	33.00713	82.8168	229.3388	146.52	23	
JAB122t_compendium	122.3631	33.35337	46.18629	229.3388	183.15	65	3
JB123t1	161.2677	56.68511	75.25826	283.4194	208.16	21	
JB123t12	116.8905	15.04228	96.875	129.7004	32.83	5	
JB123t16	108.56	16.25672	86.47	128.90	42.43	5	
JB123t17	105.4149	25.59313	71.25517	131.3017	60.05	6	
JB123t_compendium	139.0915	51.03307	71.25517	283.4194	212.16	37	4
JB125t1	230.4641	87.17449	121.6942	405.1136	283.42	14	
JB125t9	215.0465	45.86526	161.7252	307.438	145.71	10	
JB125t10	204.6918	40.29698	167.3295	247.3915	80.06	3	
JB125t13	236.5832	78.91343	158.5227	387.5	228.98	8	
JB125t_compendium	225.2487	70.35224	121.6942	405.1136	283.42	35	4
JB127t2	117.5577	37.3244	74.45764	168.9308	94.47	6	
JB127t3	133.7457	47.70503	57.64463	240.186	182.54	19	
JB127t4	102.0346	26.55087	73.65702	144.1116	70.45	9	
JB127t15	146.2466	63.28375	76.05888	241.7872	165.73	6	
JB127t_compendium	126.0576	46.07385	57.64463	241.7872	184.14	40	4
JB128t2	69.08205	14.62247	51.23967	87.26756	36.03	7	
JB128t7	64.34072	13.63064	51.23967	92.07128	40.83	11	
JB128t11	69.57386	33.10832	36.02789	151.3171	115.29	10	
JB128t14	72.32266	17.5407	54.44215	102.4793	48.04	9	
JB128t_compendium	68.59365	20.95172	36.02789	151.3171	115.29	37	4
JB129t1	154.3013	52.74996	81.66322	265.8058	184.14	11	
JB129t2	133.8636	17.86118	116.0899	156.9215	40.83	5	
JB129t10	130.6345	27.85553	89.66942	201.7562	112.09	12	
JB129t14	140.4724	29.44793	115.2893	217.7686	102.48	11	
JB129t_compendium	140.4985	36.19832	81.66322	265.8058	184.14	39	4
JB130t1	132.673	38.28371	93.63546	290.461	196.83	28	
JB130t2	130.8327	42.72739	74.23502	292.2017	217.97	24	
JB130t4	141.3017	31.88816	94.76812	225.864	131.10	13	
JB130t9	129.5164	30.73996	72.65556	210.0693	137.41	19	
JB130t10	113.2141	34.54577	44.22512	170.5826	126.36	28	
JB130t11	122.8635	31.94951	60.01981	176.9005	116.88	33	
JB130t17	123.9567	22.35157	72.65556	172.1621	99.51	25	
JB130t23	119.5861	37.51538	69.78499	226.8012	157.02	25	
JB130t24	120.3867	32.68863	58.68283	164.9463	106.26	21	

Filename	Mean	SD	Min	Max	Max ray height - min ray height	No. of observations	No. of samples
JB130t31	131.7619	38.34613	90.40328	293.4141	203.01	26	
JB130t_compendium	125.7006	34.81925	44.22512	293.4141	249.19	242	10
JB132t1	462.5211	224.1711	205.3309	761.3039	555.97	12	
JB132t7	406.6414	171.784	157.9469	764.4628	606.52	11	
JB132t9	548.7935	217.9946	243.2382	1077.198	833.96	11	
JB132t23	490.6882	212.2729	157.9469	732.8734	574.93	12	
JB132t_compendium	477.1369	207.3465	157.9469	1077.198	919.25	46	4
JB133t3	110.0852	26.07613	64.85021	160.124	95.27	16	
JB133t10	89.22463	28.34641	49.63843	136.1054	86.47	18	
JB133t16	134.161	59.23659	67.25207	221.7717	154.52	7	
JB133t21	106.16	45.93015	55.24	216.97	161.73	15	
JB133t22	110.60	27.07552	84.87	175.34	90.47	14	
JB133t23	96.67485	35.18418	56.04339	174.5351	118.49	16	
JB133t_compendium	104.5833	36.7736	49.63843	221.7717	172.13	86	6
JB135t3	154.472	64.16177	85.29131	273.2481	187.96	10	
JB135t4	147.3213	54.28453	85.29	255.87	170.58	11	
JB135t5	181.0314	86.80024	78.97343	375.9135	296.94	13	
JB135t6	142.8812	44.80244	74.23502	225.864	151.63	13	
JB135t7	154.5762	54.07466	84.05919	241.0754	157.02	13	
JB135t16	185.0359	82.24555	68.19896	347.3389	279.14	15	
JB135t20	194.401	68.3516	98.33339	280.726	182.39	7	
JB135t_compendium	164.9019	67.27226	68.19896	375.9135	307.71	82	7
JAB136t1	87.92421	24.38628	54.14945	152.8926	98.74	29	
JAB136t2	98.34496	19.84408	76.44628	149.7073	73.26	20	
JAB136t5	98.06931	25.29897	49.37156	146.522	97.15	26	
JAB136t_compendium	94.22004	23.82631	49.37156	152.8926	103.52	75	4
JB137t1	105.7727	21.20361	58.92734	146.522	87.59	29	
JB137t2	128.804	42.10641	86.79838	219.7831	132.98	8	
JB137t7	93.05515	32.4425	65.29787	164.041	98.74	7	
JB137t9	113.796	36.01093	54.14945	230.9315	176.78	31	
JB137t_compendium	110.3587	32.04977	54.14945	230.9315	176.78	75	4
JB138t18	158.3772	30.40914	112.0868	232.1798	120.09	22	
JB138t20	159.3767	23.94203	100.8781	193.75	92.87	30	
JB138t1 (extra obs)	170.8574	26.51671	109.8915	211.8199	101.93	25	
JB138t2 (extra obs)	173.1776	29.3467	116.2621	222.9683	106.71	19	
JB138t3 (extra obs)	178.5516	31.35639	113.0768	226.1536	113.08	18	
JB138t4 (extra obs)	159.3243	27.69339	100.3357	197.4862	97.15	26	
JB138t6 (extra obs)	140.3928	26.22745	81.22417	191.1157	109.89	33	
JB138t9 (extra obs)	147.8598	24.44347	84.40944	208.6346	124.23	25	
JB138t_compendium	159.1577	29.32515	81.22417	232.1798	150.96	198	8
JB140t1	182.4175	61.49568	82.8168	312.1556	229.34	13	
JB140t11	196.8226	52.21771	136.9663	294.6367	157.67	12	

Filename	Mean	SD	Min	Max	Max ray height - min ray height	No. of observations	No. of samples
JB140t16	173.7029	46.83862	95.55785	304.1925	208.63	15	
JB140t_compendium	183.4711	53.02951	82.8168	312.1556	229.34	40	3
JB143t3	60.53576	22.60852	33.62603	114.4886	80.86	18	
JB143t8	95.27376	34.90433	66.45145	141.7097	75.26	4	
JB143t13	69.59674	28.19529	40.03099	137.7066	97.68	14	
JB143t_compendium	67.91925	27.61616	33.62603	141.7097	108.08	36	3
JB144t1	227.376	58.19062	140.9091	337.8616	196.95	10	
JB144t2	261.2022	65.78981	220.9711	419.5248	198.55	8	
JB144t3	209.3929	43.33789	160.124	317.0455	156.92	13	
JB144t_compendium	228.564	56.75255	140.9091	419.5248	278.62	31	3
JB150t3	131.2016	36.46455	91.27066	219.3698	128.10	16	
JB150t19	120.3217	41.07199	62.44835	220.9711	158.52	21	
JB150t21	130.2061	45.84648	72.05579	241.7872	169.73	19	
JB150t_compendium	126.7839	41.10497	62.44835	241.7872	179.34	56	3
JB151t1	73.03148	17.37599	51.71757	99.67386	47.96	6	
JB151t2	73.9718	15.15831	50.77725	95.91259	45.14	6	
JB151t3	86.35267	15.81769	71.46428	113.7787	42.31	6	
JB151t5	79.3683	9.57502	70.28635	91.60918	21.32	4	
JB151t7	68.70688	8.402417	56.86087	78.97343	22.11	6	
JB151t8	72.97145	20.39289	58.44034	108.9833	50.54	5	
JB151t9	62.46798	18.18628	28.43044	105.8244	77.39	20	
JB151t10	64.41976	10.20192	37.90725	74.23502	36.33	14	
JB151t11	66.67614	14.98644	33.16884	97.92705	64.76	14	
JB151t12	86.26329	14.94996	47.38406	102.6655	55.28	13	
JB151t_compendium	71.28545	16.91462	28.43044	113.7787	85.35	94	10
JB152t2	124.7152	24.83844	92.37259	162.4483	70.08	13	
JB152t3	110.0685	31.50829	52.55682	186.3378	133.78	18	
JB152t4	132.7192	41.75552	79.63154	238.8946	159.26	15	
JB152t5	134.4635	34.63864	95.55785	226.1536	130.60	14	
JB152t6	145.0432	59.3552	74.85365	261.1915	186.34	7	
JB152t7	134.9091	46.08106	76.44628	256.4136	179.97	24	
JB152t10	132.19	39.94933	60.52	216.60	156.08	21	
JB152t11	122.9511	23.84031	97.15048	155.2815	58.13	5	
JB152t_compendium	129.2277	39.26078	52.55682	261.1915	208.63	117	8
JB153t1	196.1519	21.13914	169.7314	228.9773	59.25	8	
JB153t13	278.6157	103.3823	169.7314	453.1508	283.42	9	
JB153t14	218.1689	64.50664	128.0992	280.2169	152.12	4	
JB153t15	216.879	46.84215	144.1116	281.8182	137.71	9	
JB153t_compendium	230.0448	72.21002	128.0992	453.1508	325.05	30	4
JB155t2	203.3667	57.52751	125.8178	310.563	184.75	13	
JB155t3	246.0615	126.4656	106.7063	417.2693	310.56	8	
JB155t4	223.7646	127.7733	89.18733	430.0103	340.82	10	

Filename	Mean	SD	Min	Max	Max ray height - min ray height	No. of observations	No. of samples
JB155t11	236.1075	93.10144	105.1136	422.0472	316.93	12	
JB155t_compendium	225.1906	98.2072	89.18733	430.0103	340.82	43	4
JB156t6	101.9284	31.87252	62.1126	140.1515	78.04	4	
JB156t16	117.0584	25.07445	77.2426	146.522	69.28	5	
JB156t20	109.2943	40.08231	67.68681	164.041	96.35	4	
JB156t25	118.651	32.59548	71.66839	155.2815	83.61	5	
JB156t27	121.5177	40.75081	77.2426	170.4115	93.17	5	
JB156t1 (extra obs)	106.6067	27.18672	55.74208	156.0778	100.34	16	
JB156t2 (extra obs)	116.0345	31.96792	54.14945	175.1894	121.04	14	
JB156t3 (extra obs)	108.6023	39.21437	43.00103	186.3378	143.34	21	
JB156t4 (extra obs)	120.4029	27.79079	81.22417	167.2262	86.00	10	
JB156t6 (extra obs)	110.8974	40.12675	36.63051	205.4494	168.82	19	
JB156t7 (extra obs)	100.9045	38.52114	38.22314	186.3378	148.11	14	
JB156t8 (extra obs)	101.6221	28.9807	62.1126	162.4483	100.34	26	
JB156t_compendium	109.1453	33.44995	36.63051	205.4494	168.82	143	12
JB157t1	96.15063	31.67521	41.63223	148.9153	107.28	42	
JB157t2	93.04346	33.34209	40.83161	144.9122	104.08	14	
JB157t5	112.7273	54.32926	52.04029	251.3946	199.35	10	
JB157t8	115.1892	48.64795	52.04029	189.7469	137.71	8	
JB157t10	116.8905	35.6613	62.44835	236.9835	174.54	30	
JB157t_compendium	104.7734	37.72074	40.83161	251.3946	210.56	104	5
JB158t1	89.91728	31.19839	55.74208	194.301	138.56	24	
JB158t14	105.3791	64.1483	62.90892	179.171	116.26	3	
JB158t16	93.78826	29.71461	41.4084	160.8557	119.45	18	
JB158t17	88.50477	21.91642	50.96419	119.4473	68.48	7	
JB158t20	99.95655	22.40976	62.1126	140.1515	78.04	21	
JB158t21	79.43246	17.15778	57.33471	97.9468	40.61	4	
JB158t_compendium	93.49	28.56451	41.41	194.30	152.89	77	6
JB159t3	91.78535	36.77171	36.82851	166.5289	129.70	14	
JB159t4	74.96713	15.75116	51.23967	93.67252	42.43	11	
JB159t8	95.80751	31.38581	59.24587	153.719	94.47	12	
JB159t11	84.10956	21.94388	46.43595	148.1147	101.68	18	
JB159t20	105.2815	28.79096	49.63843	140.1085	90.47	12	
JB159t21	91.6499	29.18619	40.03099	149.7159	109.68	19	
JB159t_compendium	90.44211	28.68264	36.82851	166.5289	129.70	86	6
JB160t1	134.1495	34.85822	72.65556	206.9104	134.25	15	
JB160t3	108.0114	32.08265	58.44034	146.8906	88.45	13	
JB160t11	136.7118	49.3512	52.12246	205.3309	153.21	9	
JB160t15	119.7237	34.36166	71.08	178.48	107.40	10	
JB160t20	113.0714	32.56665	48.96353	157.9469	108.98	17	
JB160t24	114.9063	29.13314	75.81449	154.7879	78.97	8	
JB160t25	114.8704	41.75949	61.59928	162.6853	101.09	11	
JB160t26	141.6586	39.08972	75.81449	214.8077	138.99	16	
JB160t27	114.6508	29.87482	64.75821	162.6853	97.93	17	

Filename	Mean	SD	Min	Max	Max ray height - min ray height	No. of observations	No. of samples
JB160t_compendium	122.1093	36.49871	48.96353	214.8077	165.84	116	9
JB161t1	87.03881	21.56325	48.03719	134.5041	86.47	28	
JB161t11	85.27	26.21278	40.03	136.11	96.07	20	
JB161t12	84.54545	27.25036	38.42975	140.9091	102.48	10	
JB161t14	96.0299	26.03251	40.03099	156.9215	116.89	36	
JB161t15	93.23582	26.66043	48.03719	125.6973	77.66	11	
JB161t16	96.60813	25.01558	56.04339	124.0961	68.05	6	
JB161t19	91.72816	26.65338	58.44525	126.4979	68.05	7	
JB161t_compendium	90.61252	25.00683	38.42975	156.9215	118.49	118	7
JB162t1	340.6845	127.6689	165.6336	621.126	455.49	23	
JB162t4	247.2559	67.11628	103.521	315.3409	211.82	8	
JB162t5	331.9043	93.3124	224.561	431.603	207.04	5	
JB162t8	362.3235	115.7738	267.562	525.5682	258.01	4	
JB162t17	274.9279	212.007	76.44628	638.645	562.20	8	
JB162t18	359.4037	108.7181	215.0052	538.3092	323.30	6	
JB162t19	346.3972	#DIV/0!	346.3972	346.3972	0.00	1	
JB162t_compendium	320.4518	130.8934	76.44628	638.645	562.20	55	7
JB163t6	80.96935	17.53252	59.24587	116.8905	57.64	15	
JB163t11	98.31612	32.1553	43.23347	141.7097	98.48	10	
JB163t14	83.93867	25.20401	40.83161	126.4979	85.67	19	
JB163t15	76.77944	28.09312	48.83781	156.9215	108.08	20	
JB163t_compendium	83.25195	26.19614	40.83161	156.9215	116.09	64	4
JAB164t1	105.8417	36.39215	65.29787	224.561	159.26	35	
JAB164t2	107.6088	35.35765	57.33471	172.0041	114.67	30	
JAB164t3	129.6769	40.33646	73.26102	235.7094	162.45	26	
JAB164t4	124.164	27.89053	78.03891	216.5978	138.56	26	
JAB164t5	97.78753	23.67698	68.48313	176.782	108.30	40	
JAB164t_compendium	107.1288	31.51469	65.29787	224.561	159.26	157	5
JB165t1	130.2342	45.05618	75.25826	241.7872	166.53	18	
JB165t2	115.5561	52.0485	76.05888	174.5351	98.48	3	
JB165t5	129.1667	12.22967	118.4917	142.5103	24.02	3	
JB165t6	104.9702	25.03761	65.65083	140.9091	75.26	18	
JB165t7	118.2916	34.3824	88.06818	160.9246	72.86	4	
JB165t15	145.4841	39.37205	96.07438	236.9835	140.91	14	
JB165t16	150.7834	33.60061	112.8874	176.937	64.05	3	
JB165t17	110.0852	16.5698	91.27066	128.8998	37.63	4	
JB165t_compendium	124.9325	37.86697	65.65083	241.7872	176.14	67	8
JB166t1	352.6655	110.788	169.0243	499.1001	330.08	12	
JB166t3	289.9458	55.15304	241.5772	350.0079	108.43	3	
JB166t1 (extra obs)	239.3724	99.43157	78.03891	417.2693	339.23	10	
JB166t2 (extra obs)	240.1977	119.2216	93.96522	477.7893	383.82	11	
JB166t3 (extra obs)	337.0405	120.2137	186.3378	516.0124	329.67	8	
JB166t4 (extra obs)	279.1086	111.1807	168.8189	498.4935	329.67	8	

Filename	Mean	SD	Min	Max	Max ray height - min ray height	No. of observations	No. of samples
JB166t5 (extra obs)	245.1324	128.4639	82.8168	495.3082	412.49	12	
JB166t6 (extra obs)	177.285	100.479	71.66839	498.4935	426.83	19	
JB166t8 (extra obs)	251.0565	131.9757	130.5957	469.8261	339.23	11	
JB166t_compendium	256.793	122.4571	71.66839	516.0124	444.34	94	9
JB167t1	200.6353	61.26262	121.6942	344.2665	222.57	10	
JB167t2	216.3961	65.27776	121.6942	365.0826	243.39	35	
JB167t3	207.5789	66.20238	105.6818	361.8802	256.20	33	
JB167t4	211.5092	63.7947	115.2893	323.4504	208.16	11	
JB167t_compendium	210.7519	64.14482	105.6818	365.0826	259.40	89	4
JB168t2	162.2125	47.55301	83.26446	315.4442	232.18	23	
JB168t12	167.9909	60.34303	72.05579	323.4504	251.39	23	
JB168t13	117.6911	27.25637	88.06818	141.7097	53.64	3	
JB168t18	160.8445	49.25903	94.47314	301.0331	206.56	20	
JB168t19	173.9347	20.2793	149.7159	199.3543	49.64	4	
JB168t_compendium	162.471	50.82313	72.05579	323.4504	251.39	73	5
JB169t1	161.8358	44.91736	63.70523	211.8199	148.11	13	
JB169t2	182.2235	47.64582	79.63154	253.2283	173.60	12	
JB169t3	153.9543	25.93838	111.4842	202.2641	90.78	9	
JB169t4	152.5386	38.47759	98.74311	222.9683	124.23	9	
JB169t5	149.9064	63.94616	47.77893	232.5241	184.75	8	
JB169t6	129.0031	38.00448	60.51997	172.0041	111.48	8	
JB169t7	152.3617	22.90222	125.8178	195.8936	70.08	12	
JB169t_compendium	156.4592	42.43053	47.77893	253.2283	205.45	71	7
JB170t1	78.52	12.01966	57.33	100.34	43.00	20	
JB170t3	71.36977	32.18347	39.81577	129.7994	89.98	8	
JB170t4	82.48151	24.75606	47.77893	133.781	86.00	19	
JB170t5	74.2166	24.50142	47.77893	109.8915	62.11	5	
JB170t_compendium	78.45	21.79573	39.82	133.78	93.97	52	4
JB172t1	462.9038	121.8741	291.4256	656.5083	365.08	11	
JB172t4	507.7385	191.0266	208.1612	896.6942	688.53	11	
JB172t6	606.1836	266.536	214.5661	883.8843	669.32	7	
JB172t1 (extra obs)	486.2833	184.3237	226.1536	863.2059	637.05	15	
JB172t2 (extra obs)	398.1577	83.33585	339.2304	457.0851	117.85	2	
JB172t3 (extra obs)	282.692	84.20887	208.6346	383.824	175.19	4	
JB172t4 (extra obs)	418.685	176.0063	191.1157	614.7555	423.64	9	
JB172t5 (extra obs)	416.7384	157.1516	200.6715	713.4986	512.83	12	
JB172t6 (extra obs)	508.0492	#DIV/0!	508.0492	508.0492	0.00	1	
JB172t7 (extra obs)	473.2389	131.9849	283.4883	643.4229	359.93	7	
JB172t8 (extra obs)	447.5293	204.9611	302.60	592.46	289.86	2	
JB172t_compendium	464.5246	175.6454	191.1157	896.6942	705.58	81	11
JB174t1	165.6336	18.01856	152.8926	178.3747	25.48	2	
JB174t2	146.3628	62.55997	68.48313	304.1925	235.71	10	
JB174t3	174.6585	56.09739	138.5589	286.6736	148.11	6	

Filename	Mean	SD	Min	Max	Max ray height - min ray height	No. of observations	No. of samples
JB174t4	218.509	46.43823	167.2262	272.3399	105.11	5	
JB174t5	183.9489	22.98581	146.522	203.8567	57.33	6	
JB174t6	189.2045	68.91143	130.5957	307.3778	176.78	5	
JB174t7	160.3248	20.78571	138.5589	179.9673	41.41	3	
JB174t8	154.6843	60.15025	74.85365	256.4136	181.56	8	
JB174t9	176.327	75.83395	101.9284	334.4525	232.52	7	
JB174t_compendium	171.8816	56.88434	68.48313	334.4525	265.97	52	9
JB175t1	191.8576	56.72918	124.8967	299.4318	174.54	11	
JB175t3	238.0024	65.85077	136.1054	353.874	217.77	11	
JB175t5	192.2555	42.56522	123.2955	288.2231	164.93	15	
JB175t11	183.6499	38.23681	83.26446	225.7748	142.51	13	
JB175t_compendium	199.9948	53.34625	83.26446	353.874	270.61	50	4
JB177t1	75.83073	12.275	55.36847	95.08933	39.72	12	
JB177t2	81.87996	11.66349	66.8905	105.1136	38.22	17	
JB177t5	89.18733	18.44095	74.85365	132.1884	57.33	8	
JB177t10	85.30529	37.85745	43.79735	143.3368	99.54	8	
JB177t16	76.44628	18.10827	44.59366	100.3357	55.74	10	
JB177t17	84.7714	15.12446	49.37156	103.521	54.15	22	
JB177t20	89.27115	27.99325	63.70523	168.8189	105.11	19	
JB177t21	93.48743	41.56355	65.29787	166.4299	101.13	5	
JB177t22	83.54073	21.58519	50.96419	130.5957	79.63	22	
JB177t23	91.12124	22.05788	47.77893	115.4657	67.69	7	
JB177t24	99.14127	14.077	89.18733	109.0952	19.91	2	
JB177t_compendium	84.58272	21.64247	43.79735	168.8189	125.02	132	11
JB178t1	204.257	65.69503	101.5054	318.7905	217.29	14	
JB178t2	184.8597	82.05697	80.88714	299.7582	218.87	9	
JB178t3	199.4728	58.46866	103.0915	310.8604	207.77	13	
JB178t4	170.6296	62.13506	68.19896	285.484	217.29	12	
JB178t5	143.0592	64.6645	76.12908	329.8927	253.76	15	
JB178t6	185.853	69.0305	93.57532	291.8281	198.25	11	
JB178t7	164.3696	75.70254	63.4409	312.4464	249.01	11	
JB178t8	145.6875	34.18149	98.33339	190.3227	91.99	7	
JB178t_compendium	175.8933	67.01098	63.4409	329.8927	266.45	92	8
JB180t1	118.8813	47.6371	63.17874	203.7515	140.57	15	
JB180t2	127.6211	54.27689	31.58937	249.556	217.97	15	
JB180t3	121.8049	54.73686	75.81449	306.4169	230.60	17	
JB180t4	119.8422	30.60885	74.23502	178.48	104.24	8	
JB180t5	132.5437	49.54351	77.39396	262.1918	184.80	12	
JB180t6	114.9687	31.33643	64.75821	173.7415	108.98	19	
JB180t7	123.0771	37.66771	39.48672	169.0031	129.52	13	
JB180t8	138.9932	60.43059	63.17874	276.407	213.23	13	
JB180t9	134.0969	44.35823	63.17874	273.2481	210.07	20	
JB180t10	141.7877	38.15953	93.18865	236.9203	143.73	13	
JB180t_compendium	127.1309	45.55166	31.58937	306.4169	274.83	145	10

Filename	Mean	SD	Min	Max	Max ray height - min ray height	No. of observations	No. of samples
JB181t1	151.8509	16.21251	128.0992	187.345	59.25	12	
JB181t4	118.1715	38.51972	83.26446	179.3388	96.07	5	
JB181t5	143.311	6.793485	138.5072	148.1147	9.61	2	
JB181t1 (extra obs)	141.165	20.92686	111.4842	173.5968	62.11	11	
JB181t2 (extra obs)	115.772	31.58194	54.14945	181.5599	127.41	13	
JB181t3 (extra obs)	144.8069	42.84572	87.5947	222.9683	135.37	13	
JB181t4 (extra obs)	167.4917	36.48122	89.18733	235.7094	146.52	12	
JB181t5 (extra obs)	157.9155	24.73151	109.8915	191.1157	81.22	13	
JB181t6 (extra obs)	158.4668	30.01451	125.8178	221.3757	95.56	10	
JB181t_compendium	146.0165	33.7855	54.14945	235.7094	181.56	91	9
JB184t1	222.9993	94.0466	94.47314	393.905	299.43	15	
JB184t3	195.0844	76.14911	78.46074	312.2417	233.78	12	
JB184t4	192.4156	82.00028	81.66322	390.7025	309.04	12	
JB184t7	174.6583	95.09634	96.07438	424.3285	328.25	13	
JB184t_compendium	197.4144	87.11186	78.46074	424.3285	345.87	52	4
JB186t1	109.4934	34.48283	58.92734	192.7083	133.78	28	
JB186t2	118.1201	34.29001	57.33471	202.2641	144.93	18	
JB186t22	120.4206	31.58987	68.48313	173.5968	105.11	18	
JB186t_compendium	114.9929	33.47855	57.33471	202.2641	144.93	64	3
JB187t1	154.4053	79.06553	44.83471	385.8988	341.06	21	
JB187t2	134.771	65.50943	59.24587	206.5599	147.31	6	
JB187t3	157.8453	61.97136	76.8595	361.8802	285.02	26	
JB187t4	143.1108	49.09906	79.26136	198.5537	119.29	4	
JB187t5	139.1195	54.34754	59.24587	296.2293	236.98	34	
JB187t_compendium	147.8859	62.75226	44.83471	385.8988	341.06	91	5
JB189t1	121.923	17.48278	92.8719	153.719	60.85	14	
Jb189t21	144.1116	26.63791	116.8905	187.345	70.45	9	
JB189t22	127.5654	6.009095	121.6942	133.7035	12.01	3	
JB189t25	164.7498	43.70126	107.2831	248.1921	140.91	9	
JB189t26	166.2621	55.85053	103.28	209.7624	106.48	3	
JB189t_compendium	141.2673	34.46548	92.8719	248.1921	155.32	38	5
JB190t1	224.1736	58.34796	105.6818	310.6405	204.96	12	
JB190t2	191.35	15.5864	179.34	208.96	29.62	3	
JB190t8	140.1085	54.17659	78.46074	180.1395	101.68	3	
JB190t14	258.6002	14.71922	248.1921	269.0083	20.82	2	
JB190t20	196.583	78.07078	81.66322	365.0826	283.42	13	
JB190t21	201.3559	33.42528	158.5227	240.186	81.66	4	
JB190t22	219.713	68.58834	136.1054	344.2665	208.16	14	
JB190t_compendium	208.6007	64.55445	78.46074	365.0826	286.62	51	7
JB191t2	109.1837	21.76596	74.85365	135.3736	60.52	9	
JB191t3	149.4087	34.62141	79.63154	207.042	127.41	16	
JB191t4	134.5773	38.7831	100.3357	186.3378	86.00	4	
JB191t12	124.69	37.25175	73.26	205.45	132.19	17	

Appendix Seven. Compendia of results of initial, basic statistical analyses (ray height)

Filename	Mean	SD	Min	Max	Max ray height - min ray height	No. of observations	No. of samples
JB191t13	135.6921	27.26194	97.15048	192.7083	95.56	20	
JB191t21	136.3431	34.00162	95.55785	234.1167	138.56	23	
JB191t25	118.2528	25.72563	97.15048	152.8926	55.74	4	
JB191t27	109.0952	29.36666	60.51997	138.5589	78.04	5	
JB191t_compendium	131.6277	33.37015	60.51997	234.1167	173.60	98	8

NOTE: Some specimen's were not recorded for ray height. This includes all of the Proteaceae (JAB112, JAB124, JAB139, JAB142, JAB147) and JAB183 (*Senna artemisioides*) and JAB126 (*Acacia peuce*).
NOTE 2: Filenames with _extra obs suffix simply refer to a subsequent batch of observations that were made to increase the number of observations

Ray number per millimetre

Filename	Horizontal distance (µm)	No. of observations	Rays per mm	Standard deviation	Mean - SD	Mean + SD	Number of sampled areas
JB100t1	931.9375	17	18.24156663				
JB100t2	850.6916667	13	15.28168255				
JB100t3	423.7527778	8	18.87893229				
JB100t5	425.3458333	7	16.45719659				
JB100t6	404.6361111	7	17.29949406				
JB100t8	402.2465278	7	17.40226333				
JB100t12	393.4847222	7	17.78976312				
Total	3832.095139	66	17.22295444	1.183556145	16.0393983	18.40651059	7
JB101t1	807.24	5	6.1939448				
JB101t13	914.5516667	6	6.56059162				
JB101t14	309.9225	2	6.45322621				
JB101t16	183.3908333	2	10.90567049				
JB101t5 (extra obs)	538.45	4	7.428692292				
JB101t7 (extra obs)	524.1152778	4	7.631908799				
JB101t8 (extra obs)	872.99	6	6.872895971				
JB101t9 (extra obs)	681.83	3	4.399938075				
JB101t10 (extra obs)	648.37	5	7.711603178				
Total	5480.868889	37	6.750754442	1.736118274	5.014636168	8.486872717	9
JB105t1	826.46	10	12.09979914				
JB105t19	850.485	11	12.9337966				
JB105t25	876.1116667	9	10.27266311				
Total	2553.056667	30	11.7506205	1.361103062	10.38951744	13.11172356	3
JB106t1	925.7633333	7	7.561327769				
JB106t13	999.44	7	7.003922196				
JB106t15	863.2983333	4	4.633392473				
Total	2788.501667	18	6.45507952	1.554719548	4.900359972	8.009799068	3
JB107t2	857.06	14	16.33483826				
JB107t3	273.21	5	18.30100579				
JB107t12	661.12	9	13.61330238				
JB107t15	831.58	9	10.82283618				
JB107t18	258.87	6	23.17751995				
JB107t19	594.21	9	15.14616753				
JB107t20	876.18	11	12.55448997				
JB107t21	323.39	4	12.36895564				
Total	4675.62	67	14.32965636	3.985220629	10.34443573	18.31487699	8
JB109t2	485.88	5	10.29056555				
JB109t3	791.75	9	11.36724444				
JB109t11	723.25	8	11.06122465				
JB109t15	906.45	8	8.825652003				
JB109t21	678.64	6	8.841190122				
JB109t23	911.23	6	6.584522714				
JB109t24	621.29	7	11.26684998				
JB109t25	783.78	8	10.20690242				
Total	5902.27	57	9.65729998	1.639361228	8.017938752	11.29666121	8
JB111t3	576.6861111	3	5.202136729				
JB111t4	829.9819444	5	6.024227435				
JB111t1 (extra obs)	822.02	4	4.866081385				
JB111t3 (extra obs)	210.28	2	9.510977253				
JB111t4 (extra obs)	978.14	7	7.156468226				
JB111t5 (extra obs)	555.98	2	3.597275064				
JB111t6 (extra obs)	638.82	4	6.261591009				
JB111t7 (extra obs)	745.55	3	4.023874992				
Total	5357.445833	30	5.599683307	1.893734228	3.705949079	7.493417535	8
JB112t1	3703.053333	14	3.780663885				
JB112t2	1672.14	7	4.186252347				
JB112t7	1889.966667	6	3.174659165				
JB112t8	3799.153333	13	3.421815036				
JB112t1 (extra obs)	1405.075	5	3.558528904				
JB112t2 (extra obs)	3319.927778	9	2.710902346				

Appendix Seven. Compendia of results of initial, basic statistical analyses (ray number per mm)

Filename	Horizontal distance (μm)	No. of observations	Rays per mm	Standard deviation	Mean - SD	Mean + SD	Number of sampled areas
JB112t3 (extra obs)	3065.038889	8	2.610081076				
JB112t5 (extra obs)	1570.752778	5	3.183187113				
JB112t6 (extra obs)	3154.25	8	2.536260601				
JB112t7 (extra obs)	1526.147222	5	3.276223897				
JB112t8 (extra obs)	3574.816667	10	2.797346251				
JB112t9 (extra obs)	1382.772222	5	3.615924532				
Total	30063.09389	95	3.160020733	0.508136029	2.651884704	3.668156763	12
JB113t1	1886.763333	13	6.890106337				
JB113t2	797.63	7	8.775998897				
JB113t3	1012.253333	7	6.915264953				
JB113t2 (extra obs)	820.4236111	6	7.31329513				
JB113t4 (extra obs)	753.5152778	8	10.61690484				
JB113t5 (extra obs)	1781.036111	13	7.299122078				
JB113t6 (extra obs)	1959.458333	15	7.655176813				
JB113t7 (extra obs)	775.8180556	7	9.022734067				
JB113t8 (extra obs)	911.2277778	6	6.584522714				
Total	10698.12583	82	7.664893952	1.317890436	6.347003516	8.982784388	9
JB114t1	914.5516667	8	8.747455493				
JB114t2_2	973.81	7	7.188235938				
JB114t14	856.8916667	7	8.169060655				
Total	2745.256667	22	8.01382263	0.78821775	7.225604879	8.80204038	3
JB115t1	3574.816667	12	3.356815501				
JB115t2	1749.175	7	4.001886604				
JB115t15	3797.844444	13	3.42299433				
JB115t16	1991.319444	6	3.013077594				
JB115t18	3848.822222	13	3.377656657				
JB115t19	3785.1	11	2.906131938				
JB115t20	1714.127778	6	3.500322483				
Total	20461.20556	68	3.323362341	0.35633669	2.967025652	3.679699031	7
JAB117t1	927.1583333	8	8.628515446				
JAB117t22	951.05	8	8.411718575				
JAB117t23	930.3444444	8	8.598965736				
JAB117t25	992.4736111	9	9.068251185				
Total	3801.030556	33	8.681856017	0.278023828	8.403832189	8.959879845	4
JB119t2	893.7041667	10	11.189385				
JB119t10	898.4833333	9	10.0168803				
JB119t15	939.9027778	8	8.511518626				
Total	2732.090278	27	9.882543128	1.342376585	8.540166543	11.22491971	3
JAB121t2	992.47	7	7.053084255				
JAB121t3	986.1013889	8	8.112756041				
JB121t1 (extra obs)	653.1527778	6	9.186212176				
JB121t2 (extra obs)	860.25	7	8.137169427				
JB121t3 (extra obs)	689.7930556	6	8.698260952				
JB121t4 (extra obs)	707.3166667	5	7.06896958				
JB121t6 (extra obs)	845.9125	7	8.275087553				
Total	5735.00	46	8.02092415	0.787927152	7.232996997	8.808851302	7
JAB122t1	981.32	7	7.13323294				
JAB122t5	986.1013889	6	6.084567031				
JAB122t8	987.6944444	10	10.12458869				
Total	2955.12	23	7.783106992	2.096412984	5.686694008	9.879519976	3
JB123t1	730.36	6	8.215126787				
JB123t6	800.8333333	9	11.23829344				
JB123t12	234.6441667	3	12.78531677				
JB123t15	938.5766667	7	7.458101451				
JB123t16	394.01	3	7.614019949				
JB123t17	360.375	6	16.64932362				
JB123t23	898.535	7	7.790458914				
JB123t24	360.375	4	11.09954908				
Total	4717.709167	45	9.538527792	3.249624557	6.288903235	12.78815235	8
JB124t7	3186.111111	5	1.569311247				

Appendix Seven. Compendia of results of initial, basic statistical analyses (ray number per mm)

Filename	Horizontal distance (μm)	No. of observations	Rays per mm	Standard deviation	Mean - SD	Mean + SD	Number of sampled areas
JB124t10	3045.922222	5	1.641538961				
JB124t1 (extra obs)	2370.466667	4	1.687431448				
JB124t2 (extra obs)	901.67	2	2.218107769				
JB124t3 (extra obs)	3479.23	7	2.011937496				
JB124t4 (extra obs)	1647.22	3	1.821250963				
JB124t5 (extra obs)	1526.15	3	1.965734338				
JB124t6 (extra obs)	2268.51	4	1.763271064				
JB124t7 (extra obs)	2994.94	6	2.00337606				
JB124t8 (extra obs)	1306.31	2	1.531035363				
JB124t9 (extra obs)	3383.65	5	1.477694206				
JB124t10 (extra obs)	1271.26	2	1.573244358				
Total	27381.43889	48	1.753012331	0.23346991	1.519542421	1.98648224	12
JB125t1	938.5766667	9	9.58898758				
JB125t9	623.0483333	6	9.630071503				
JB125t13	903.34	7	7.749020302				
Total	2464.965	22	8.925076015	1.074361911	7.850714104	9.999437926	3
JB127t1	901.7383333	12	13.30762989				
JB127t2	418.035	7	16.74500939				
JB127t3	720.75	9	12.48699272				
JB127t4	405.2216667	6	14.80671073				
JB127t15	381.9975	5	13.0890909				
Total	2827.7425	39	14.08708673	1.713640938	12.37344579	15.80072766	5
JB128t2	414.0308333	2	4.830558111				
JB128t7	465.2841667	6	12.89534532				
JB128t11	419.6366667	3	7.149041631				
JB128t14	327.5408333	3	9.159163361				
Total	1626.4925	14	8.607478977	3.417755513	5.189723464	12.02523449	4
JB129t1	872.9083333	6	6.873573972				
JB129t10	916.1533333	8	8.732162738				
JB129t14	788.02	7	8.883023274				
Total	2577.081667	21	8.148752238	1.119151285	7.029600953	9.267903524	3
JB130t1	1043.644763	9	8.623623978				
JB130t2	947.9338843	10	10.54925894				
JB130t4	745.707989	11	14.75108241				
JB130t9	823.1225895	10	12.14885866				
JB130t10	770.9862259	8	10.37632027				
JB130t11	808.9035813	11	13.5986541				
JB130t17	612.9972452	5	8.156643507				
JB130t23	901.1009682	11	12.20728907				
JB130t24	805.9142462	7	8.685787642				
JB130t31	923.3112033	11	11.91364294				
Total	8383.622695	93	11.09305647	2.211412471	8.881644001	13.30446894	10
JB132t1 (extra obs)	1434.539945	6	4.182525569				
JB132t7 (extra obs)	1488.256198	7	4.703491246				
JB132t9 (extra obs)	1595.688705	10	6.266886497				
JB132t12 (extra obs)	1383.98	8	5.780415856				
JB132t23 (extra obs)	1541.972452	7	4.539640116				
Total	7444.440771	38	5.10448013	0.885638938	4.218841192	5.990119069	5
JB13t2	922.56	17	18.42698578				
JB13t3	482.9025	9	18.63730256				
JB13t10	475.695	11	23.12406059				
JB13t20	938.5766667	18	19.17797516				
JB13t21	426.8441667	10	23.42775369				
JB13t22	402.0183333	8	19.89958999				
JB13t23	419.6366667	7	16.68109714				
Total	4068.233333	80	19.66455546	2.499521474	17.16503398	22.16407693	7
JB135t3	764.6666667	8	10.46207498				
JB135t4	782.0454545	7	8.95088637				
JB135t5	671.453168	8	11.91445715				
JB135t6	764.6666667	10	13.07759372				
JB135t7	717.0733057	6	8.367345364				

Appendix Seven. Compendia of results of initial, basic statistical analyses (ray number per mm)

Filename	Horizontal distance (μm)	No. of observations	Rays per mm	Standard deviation	Mean - SD	Mean + SD	Number of sampled areas
JB135t16	950.2807746	11	11.5755262				
JB135t20	763.0802213	8	10.48382565				
Total	5413.266257	58	10.71441848	1.658199515	9.056218961	12.37261799	7
JAB136t1	1011.590278	7	6.919797623				
JAB136t2	994.0666667	5	5.02984374				
JAB136t5	979.7291667	8	8.165521934				
Total	2985.386111	20	6.699300947	1.578830394	5.120470552	8.278131341	3
JB137t1	978.1361111	16	16.35764166				
JB137t2	485.0854167	11	22.67641867				
JB137t7	427.7354167	12	28.0547262				
JB137t9	916.0069444	18	19.65050605				
Total	2806.963889	57	20.30663815	4.969112437	15.33752572	25.27575059	4
JB138t18_2	975.415	15	15.37806985				
JB138t20	935.3733333	19	20.312745				
JB138t1 (extra obs)	936.7166667	13	13.87826273				
JB138t2 (extra obs)	952.6472222	16	16.79530431				
JB138t3 (extra obs)	756.70	13	17.17982839				
JB138t4 (extra obs)	911.23	17	18.65614769				
JB138t6 (extra obs)	900.0763889	16	17.77626899				
JB138t9 (extra obs)	801.31	10	12.4796123				
Total	7169.464722	119	16.5981708	2.553260176	14.04491062	19.15143098	8
JB139t1	2876.593333	7	2.433433993				
JB139t4	3638.986667	10	2.748017763				
JB139t1	2924.85	6	2.051387251				
JB139t2	1360.469444	3	2.20512119				
JB139t3	1475.169444	3	2.033664683				
JB139t4	1494.286111	4	2.676863534				
JB139t5	1644.033333	4	2.433040693				
JB139t6	2357.722222	5	2.120690874				
JB139t7	2427.816667	6	2.471356294				
JB139t8	1443.308333	4	2.77141059				
JB139t9	672.2694444	2	2.974997624				
Total	22315.505	54	2.419842168	0.319496872	2.100345296	2.73933904	11
JB140t1	815.6444444	7	8.582170881				
JB140t2	1914.852778	18	9.40020048				
JB140t11	750.3291667	8	10.66198724				
JB140t16	959.0194444	7	7.299122078				
Total	4439.845833	40	9.009321833	1.412931973	7.59638986	10.42225381	4
JB142t12	1931.61	4	2.070811396				
JB142t1	3198.855556	8	2.500894417				
JB142t5	3441	8	2.324905551				
JB142t9	3370.905556	7	2.076593332				
Total	11942.37111	27	2.260857559	0.208612704	2.052244855	2.469470264	4
JB143t1_2	909.7466667	7	7.694449737				
JB143t2	896.9333333	9	10.03419058				
JB143t7	839.2733333	11	13.10657632				
JB143t8_2	449.2675	4	8.903381616				
JB143t13	361.1758333	3	8.30620358				
Total	3456.396667	34	9.836833928	2.137434542	7.699399386	11.97426847	5
JB144t1	778.41	9	11.56203029				
JB144t2	800.8333333	8	9.989594173				
JB144t3_2	919.3566667	7	7.614019949				
Total	2498.6	24	9.605379012	1.987573643	7.617805369	11.59295266	3
JB147t2	1655.72	6	3.623791238				
JB147t5	1681.00	5	2.974415114				
JB147t6	1557.77	4	2.567770938				
JB147t7	3286.17	9	2.738749916				
JB147t11	1820.03	5	2.747202848				
JB147t16	1424.63	5	3.509688293				
Total	11425.33	34	2.975843915	0.439130688	2.536713227	3.414974602	6

Appendix Seven. Compendia of results of initial, basic statistical analyses (ray number per mm)

Filename	Horizontal distance (μm)	No. of observations	Rays per mm	Standard deviation	Mean - SD	Mean + SD	Number of sampled areas
JB150t1	781.6133333	8	10.23523993				
JB150t3	786.4183333	8	10.17270282				
JB150t19_2	965.805	8	8.283245583				
JB150t21	807.24	7	5.65068				
Total	3341.076667	31	9.27844617	2.156028819	7.122417351	11.43447499	4
JB151t1	490.97766	1	2.036752548				
JB151t3	142.0261047	2	14.08191828				
JB151t4	526.1033058	3	5.702302128				
JB151t5	137.4504132	2	14.55070198				
JB151t6	330.1969697	3	9.085486165				
JB151t9	462.9077135	3	6.480773408				
JB151t10	725.1694215	6	8.273928578				
JB151t11	492.9256198	4	8.114814566				
JB151t12	842.0812672	3	3.562601517				
Total	4149.838475	27	6.506277331	4.242712195	2.263565136	10.74898953	9
JB152t2	731.2125	11	15.0435065				
JB152t3	882.5527778	14	15.86307397				
JB152t4	904.8555556	11	12.15663642				
JB152t5	925.5652778	11	11.88462906				
JB152t6_2	449.2416667	8	17.8077872				
JB152t7	909.6347222	14	15.39079331				
JB152t10	935.1236111	11	11.76315074				
JB152t11	489.8645833	6	12.2482829				
Total	6228.050694	86	13.8084939	2.29705326	11.51144064	16.10554716	8
JB153t1	860.095	11	12.7892849				
JB153t13	863.2983333	9	10.42513307				
JB153t14	895.3316667	8	8.93523629				
JB153t15_2	988.2283333	10	10.11911889				
Total	3606.953333	38	10.535207	1.614716339	8.92049066	12.14992334	4
JB155t1	1921.225	13	6.766516155				
JB155t2	831.575	7	8.417761477				
JB155t3	755.1083333	6	7.94587973				
JB155t4_2	694.5722222	7	10.07814562				
JB155t5	1851.130556	13	7.022735355				
JB155t11	1021.148611	8	7.834315116				
Total	7074.759722	54	7.632768054	1.183166184	6.44960187	8.815934238	6
JB156t2	712.0958333	3	4.212916099				
JB156t15	721.6541667	2	2.77141059				
JB156t17	649.9666667	6	9.231242628				
JB156t19_2	630.85	5	7.925814377				
JB156t24	801.3069444	6	7.48776738				
JB156t26	678.6416667	9	13.26178518				
JB156t1 (extra obs)	960.6125	7	7.287017398				
JB156t2 (extra obs)	761.4805556	6	7.879387013				
JB156t3 (extra obs)	965.3916667	9	9.32264107				
JB156t4 (extra obs)	766.2597222	9	11.74536484				
JB156t6 (extra obs)	637.2222222	6	9.41586748				
JB156t7 (extra obs)	833.1680556	10	12.00238047				
JB156t8 (extra obs)	952.6472222	8	8.397652156				
Total	10071.29722	86	8.539118457	2.914418781	5.624699677	11.45353724	13
JB157t1	855.29	10	11.69194075				
JB157t5	448.4666667	8	17.83856102				
JB157t8	459.6783333	8	17.40347417				
JB157t10_2	783.215	9	11.49109759				
JB157t11	422.0391667	5	11.84724167				
JB157t22	498.1183333	6	12.04533059				
Total	3466.8075	46	13.26869173	3.03062032	10.23807141	16.29931205	6
JB158t1	458.8	3	6.538796861				
JB158t2	548.0111111	5	9.123902597				
JB158t12	893.70	4	4.475754001				
JB158t13	457.2069444	3	6.561580126				

Appendix Seven. Compendia of results of initial, basic statistical analyses (ray number per mm)

Filename	Horizontal distance (μm)	No. of observations	Rays per mm	Standard deviation	Mean - SD	Mean + SD	Number of sampled areas
JB158t15	779.0041667	7	8.98583127				
JB158t16	614.9194444	4	6.504917085				
JB158t17	252.4993056	4	15.84162773				
JB158t20	274.0055556	3	10.94868312				
JB158t21	320.2041667	3	9.369022369				
Total	4598.354861	36	7.828886871	3.329309406	4.499577465	11.15819628	9
JB159t1_2	669.4966667	8	11.94927533				
JB159t2	880.9166667	16	18.1628985				
JB159t3	396.4125	7	17.65837354				
JB159t4	400.4166667	7	17.4817898				
JB159t8	380.3958333	5	13.14420286				
JB159t10	877.7133333	11	12.53256568				
JB159t11	422.0391667	6	14.21669				
JB159t19	863.2983333	12	13.90017742				
JB159t20_2	482.9025	9	18.63730256				
JB159t21	466.085	8	17.16425116				
Total	5839.676667	89	15.24056983	2.570269747	12.67030008	17.81083957	10
JB160t1	810.4834711	9	11.10448309				
JB160t3	875.2589532	10	11.42519018				
JB160t11	895.7975207	11	12.27956067				
JB160t15	913.1763085	10	10.95078782				
JB160t20	627.2162534	6	9.566078632				
JB160t24	832.6019284	9	10.80948734				
JB160t25	769.4063361	8	10.39762688				
JB160t26	829.4421488	6	7.233777556				
JB160t27	733.0688705	7	9.548898175				
Total	7286.451791	76	10.43031673	1.457176525	8.973140203	11.88749325	9
JB161t1	866.5016667	12	13.84879044				
JB161t11_2	733.5633333	10	13.63208812				
JB161t14	675.9033333	13	19.23351959				
JB161t15	486.9066667	5	10.26890848				
JB161t16	369.1841667	5	13.54337605				
JB161t19	396.4125	7	17.65837354				
Total	3528.471667	52	14.73725877	3.229305842	11.50795292	17.96656461	6
JB162t1	1717.313889	10	5.823047298				
JB162t4	892.1111111	8	8.967492838				
JB162t5	777.4111111	7	9.004244858				
JB162t7	845.9125	5	5.910776824				
JB162t8	839.5402778	4	4.764512324				
JB162t17	923.9722222	6	6.493701711				
JB162t18	826.7958333	6	7.256930621				
Total	6823.056944	46	6.741846122	1.617232711	5.124613411	8.359078833	7
JB163t1	784.8166667	12	15.29019516				
JB163t5	794.4266667	10	12.58769427				
JB163t6	496.5166667	8	16.11224867				
JB163t11	315.5283333	6	19.01572495				
JB163t14	368.3833333	6	16.2873818				
JB163t15	439.6575	10	22.74497762				
Total	3199.329167	52	16.25340729	3.485842023	12.76756527	19.73924931	6
JAB164t1	901.6694444	11	12.19959273				
JAB164t2	806.0861111	9	11.16506025				
JAB164t3	804.4930556	8	9.944150474				
JAB164t4	957.4263889	11	11.48913392				
JAB164t5	935.1236111	10	10.6937734				
Total	4404.798611	49	11.12423162	0.846427293	10.27780433	11.97065892	5
JB165t1	605.43	6	9.910311679				
JB165t5_2	245.055	2	8.161433148				
JB165t6	744.775	4	5.370749555				
JB165t7	320.3333333	3	9.365244537				
JB165t15	826.46	6	7.259879486				
JB165t16	301.1133333	2	6.642017402				
Total	3043.166667	23	7.557916644	1.706844481	5.851072163	9.264761125	6

Appendix Seven. Compendia of results of initial, basic statistical analyses (ray number per mm)

Filename	Horizontal distance (μm)	No. of observations	Rays per mm	Standard deviation	Mean - SD	Mean + SD	Number of sampled areas
JB166t1	966.56653	14	14.48425904				
JB166t3_2	417.89	7	16.75087973				
JB166t7	980.22	13	13.26232886				
JB166t1 (extra obs)	938.3097222	18	19.1834312				
JB166t2 (extra obs)	906.4486111	15	16.54809751				
JB166t3 (extra obs)	990.8805556	17	17.15645736				
JB166t4 (extra obs)	794.9347222	11	13.8376142				
JB166t5 (extra obs)	901.6694444	16	17.74486215				
JB166t6 (extra obs)	963.7986111	19	19.71366194				
JB166t7 (extra obs)	936.7166667	15	16.01338007				
JB166t8 (extra obs)	938.3097222	12	12.78895413				
Total	9735.743085	157	16.12614452	2.318420231	13.80772429	18.44456475	11
JB167t1	679.1066667	4	5.890090904				
JB167t2	1880.356667	15	7.977209997				
JB167t3	1749.02	10	5.717487507				
JB167t4_2	957.7966667	9	9.396566425				
Total	5266.28	38	7.215719635	1.76393898	5.451780655	8.979658615	4
JB168t2_2	932.17	12	12.87318837				
JB168t3	381.9975	6	15.70690908				
JB168t12	917.755	12	13.07538504				
JB168t13	406.8233333	6	14.74841659				
JB168t18	741.5716667	11	14.83336068				
JB168t19	422.84	6	14.18976445				
Total	3803.1575	53	13.93578888	1.094475596	12.84131328	15.03026448	6
JB169t1	901.6694444	7	7.763377192				
JB169t2	567.13	6	10.57962638				
JB169t3	959.0194444	6	6.256390352				
JB169t4	780.5972222	6	7.686422433				
JB169t5	535.2666667	4	7.472910699				
JB169t6	884.1458333	8	9.048281062				
JB169t7	912.8208333	7	7.668536633				
Total	5540.647222	44	7.941310507	1.372543034	6.568767473	9.313853541	7
JB170t1	890.5180556	10	11.22941858				
JB170t2	909.6347222	7	7.695396656				
JB170t3	482.6958333	6	12.43018809				
JB170t4	767.8527778	8	10.41866388				
JB170t5	274.0055556	2	7.299122078				
JB170t12	551.1972222	7	12.69962859				
JB170t13	274.8020833	4	14.5559304				
Total	4150.70625	44	10.60060562	2.662137501	7.938468119	13.26274312	7
JB172t1	1899.576667	10	5.264330825				
JB172t4	1678.546667	6	3.574520816				
JB172t5	698.3266667	4	5.72797831				
JB172t6	1765.036667	6	3.399362808				
JB172t7	820.0533333	4	4.87773153				
JB172t8	876.1116667	3	3.424221037				
JB172t1 (extra obs)	1918.038889	9	4.692292764				
JB172t3 (extra obs)	759.8875	3	3.947952822				
JB172t4 (extra obs)	1841.572222	10	5.430142722				
JB172t5 (extra obs)	1481.541667	8	5.399780634				
JB172t6 (extra obs)	836.3541667	4	4.782662847				
JB172t7 (extra obs)	1774.663889	8	4.507895861				
JB172t8 (extra obs)	804.4930556	4	4.972075237				
Total	17154.20306	79	4.605285349	0.796139168	3.809146181	5.401424516	13
JB174t1	936.975	6	6.403586008				
JB174t2	373.1883333	4	10.71844868				
JB174t18	273.0841667	2	7.323749394				
JB174t19	246.66	3	12.16265524				
JB174t1 (extra obs)	906.45	6	6.619239002				
JB174t2 (extra obs)	888.93	6	6.749725792				
JB174t3 (extra obs)	995.66	7	7.030514385				
JB174t4 (extra obs)	786.97	6	7.624184195				

Appendix Seven. Compendia of results of initial, basic statistical analyses (ray number per mm)

Filename	Horizontal distance (μm)	No. of observations	Rays per mm	Standard deviation	Mean - SD	Mean + SD	Number of sampled areas
JB174t5 (extra obs)	916.01	8	8.733558243				
JB174t6 (extra obs)	598.99	4	6.677920199				
JB174t7 (extra obs)	624.48	3	4.804014021				
JB174t8 (extra obs)	444.46	5	11.24954299				
JB174t9 (extra obs)	865.03	7	8.09221269				
Total	8856.872222	67	7.564747274	2.14747807	5.417269204	9.712225344	13
JB175t1	898.535	9	10.01630432				
JB175t3	791.2233333	9	11.37479094				
JB175t4	308.3208333	5	16.21687366				
JB175t5_2	898.535	7	7.790458914				
JB175t6	417.2341667	4	9.586942584				
JB175t11	853.6883333	8	9.371101475				
Total	4167.536667	42	10.07789574	2.926598517	7.151297218	13.00449425	6
JB177t1	469.5534975	7	14.90777949				
JB177t2	947.8680556	9	9.494992417				
JB177t10	440.4798611	6	13.62150811				
JB177t16	412.6013889	5	12.11823357				
JB177t17	917.6	10	10.89799477				
JB177t20	912.8208333	11	12.05055757				
JB177t21	477.1201389	6	12.57544906				
JB177t22	721.6541667	7	9.699937066				
Total	5299.697942	61	11.51008995	1.857869061	9.652220886	13.36795901	8
JB178t1	876.1116667	7	7.989849087				
JB178t2	325.9391667	5	15.34028589				
JB178t9	669.4966667	7	10.45561591				
JB178t10	351.5658333	4	11.3776699				
JB178t1 (extra obs)	761.4937759	8	10.50566696				
JB178t2 (extra obs)	894.7551867	9	10.0586173				
JB178t3 (extra obs)	786.8769018	9	11.43762128				
JB178t4 (extra obs)	840.8160443	9	10.70388709				
JB178t5 (extra obs)	897.9280775	9	10.02307448				
JB178t6 (extra obs)	943.9349931	9	9.534554886				
JB178t7 (extra obs)	937.5892116	9	9.59908656				
JB178t8 (extra obs)	920.1383126	9	9.781138202				
JB178t9 (extra obs)	693.2766252	9	12.98183102				
Total	9899.922462	103	10.40412189	1.812742467	8.591379423	12.21686436	13
JB180t1	906.4486111	8	8.825652003				
JAB180t3_2	799.71	8	10.00357767				
JB180t4	799.7138889	8	10.00357767				
JB180t5	804.4930556	8	9.944150474				
JB180t6	677.0486111	6	8.861992923				
JB180t1 (extra obs)	966.892562	10	10.34241072				
JB180t2 (extra obs)	740.97	7	9.447097555				
JB180t3 (extra obs)	630.38	6	9.518128364				
JB180t4 (extra obs)	911.60	8	8.775813327				
JB180t5 (extra obs)	774.15	6	7.750475953				
JB180t6 (extra obs)	884.74	8	9.042221945				
JB180t7 (extra obs)	827.86	7	8.455512888				
JB180t8 (extra obs)	1007.97	10	9.920933169				
JB180t9 (extra obs)	633.54	6	9.470656402				
JB180t10 (extra obs)	880.00	7	7.954557905				
Total	12245.50208	113	9.227878064	0.782150429	8.445727635	10.01002849	15
JB181t1	938.5766667	6	6.392658387				
JB181t4	333.1466667	2	6.003361883				
JB181t5	480.5	4	8.324661811				
JB181t1 (extra obs)	712.10	6	8.425832197				
JB181t2 (extra obs)	892.11	7	7.846556234				
JB181t3 (extra obs)	998.85	8	8.009244002				
JB181t4 (extra obs)	790.1555556	7	8.859015103				
JB181t5 (extra obs)	895.30	7	7.818632546				
JB181t6 (extra obs)	501.81	5	9.963880932				
Total	6542.541389	52	7.947981818	1.198645842	6.749335975	9.14662766	9
JB183t1	944.9833333	11	11.64041694				

Appendix Seven. Compendia of results of initial, basic statistical analyses (ray number per mm)

Filename	Horizontal distance (µm)	No. of observations	Rays per mm	Standard deviation	Mean - SD	Mean + SD	Number of sampled areas
JB183t2	1944.423333	20	10.28582596				
JB183t3	832.8666667	10	12.00672377				
JB183t4	546.1683333	7	12.81656144				
JB183t5	884.12	11	12.44174999				
JB183t6	1902.78	20	10.51093663				
JB183t12	876.1116667	13	14.83829116				
JB183t13	842.4766667	9	10.68278845				
JB183t1 (extra obs)	974.0033371	7	7.186833693				
JB183t2 (extra obs)	1067.04	11	10.30892286				
JB183t3 (extra obs)	1120.20	13	11.60508327				
JB183t4 (extra obs)	1167.66	12	10.27692177				
JB183t5 (extra obs)	1125.89	12	10.65819037				
JB183t6 (extra obs)	1097.42	12	10.934787				
JB183t7 (extra obs)	1091.72	13	11.90782457				
Total	16417.86262	181	11.02457757	1.660358929	9.36421864	12.6849365	15
JB184t1	935.3733333	12	12.82910211				
JB184t2	365.18	7	19.16862917				
JB184t3	778.41	14	17.98538046				
JB184t4	949.7883333	17	17.8987248				
JB184t7	957.80	14	14.61688111				
JB184t8	385.2008333	5	12.98024191				
JB184t9	434.8525	9	20.69667301				
JB184t10	363.5783333	7	19.25307247				
JB184t22	387.6033333	7	18.05970021				
Total	5557.783333	92	16.5533621	2.862558306	13.6908038	19.41592041	9
JB186t1	793.3416667	5	6.302454806				
JB186t2	828.3888889	7	8.450137482				
JB186t20	458.8	5	10.89799477				
JB186t22	702.5375	4	5.693646247				
Total	2783.068056	21	7.545629349	2.358984051	5.186645297	9.9046134	4
JB187t1	808.8416667	10	12.36335912				
JB187t2	337.9516667	4	11.83601205				
JB187t3	864.9	10	11.56203029				
JB187t4	296.3083333	4	13.49945158				
JB187t5	914.5516667	9	9.840887429				
Total	3222.553333	37	11.48157879	1.332243172	10.14933562	12.81382196	5
JB189t1	669.4966667	3	4.480978247				
Jb189t21	530.1516667	3	5.658758028				
JB189t25	855.29	4	4.676776298				
JB189t26	371.5866667	3	8.07348667				
Total	2426.525	13	5.357455621	1.649860164	3.707595457	7.007315785	4
JB190t1	800.8333333	9	11.23829344				
JB190t2	380.3958333	4	10.51536229				
JB190t8	467.6866667	4	8.552734737				
JB190t14	358.7733333	4	11.14910064				
JB190t20	831.265	8	9.623886486				
JB190t21	348.3625	5	14.35286519				
JB190t22	786.4183333	9	11.44429068				
Total	3973.735	43	10.82105374	1.808941018	9.012112727	12.62999476	7
JB191t2	836.3541667	4	4.782662847				
JB191t3	552.7902778	5	9.045021595				
JB191t4	358.4375	4	11.15954664				
JB191t5	355.2513889	4	11.25963226				
JB191t12	928.7513889	6	6.460286436				
JB191t13	705.7236111	7	9.918897271				
JB191t21	874.5875	7	8.003773207				
JB191t25	381.54	4	10.48391647				
JB191t27	390.2986111	6	15.37284487				
Total	5383.73125	47	8.730004864	3.068284399	5.661720466	11.79828926	9

NOTE: One specimen has not been recorded for rays per mm: JAB126 (*Acacia peuce*)
NOTE 2:Filenames with *_extra obs* suffix simply refer to a subsequent batch of observations that were made to increase the number of observations; filename with suffix JB13 was mislabelled; this refers to specimen JAB133 (*Eucalyptus coolabah*)

Ray width

Filename	Mean ray width	Number of observations	Min	Max	Number of sampled areas
JB100t1	1.1	30	1	2	
JB100t2	1.125	24	1	2	
JB100t3	1.111111111	9	1	2	
JB100t4	1.214285714	14	1	2	
JB100t5	1.090909091	11	1	2	
JB100t6	1.166666667	18	1	2	
JB100t7	1.12195122	41	1	2	
JB100t8	1	10	1	1	
JB100t12	1.111111111	9	1	2	
JB100t13	1	12	1	1	
JB100t_compendium	1.112359551	178	1	2	10
JB101t5 (extra obs)	1.888888889	9	1	2	
JB101t6 (extra obs)	2.111111111	9	2	3	
JB101t7 (extra obs)	2.083333333	12	2	3	
JB101t8 (extra obs)	2.25	8	2	3	
JB101t9 (extra obs)	1.909090909	11	1	3	
JB101t10 (extra obs)	2.222222222	9	2	3	
JB101t1	1.9	10	1	2	
JB101t2	1.25	4	1	2	
JB101t13	2	11	1	3	
JB101t14	2	2	2	2	
JB101t15	1.909090909	11	1	2	
JB101t16	2	3	2	2	
JB101t_compendium	1.960311448	99	1	3	12
JB105t1	1.818181818	22	1	3	
JB105t2	1.9	10	1	3	
JB105t4	1.777777778	9	1	3	
JB105t8	1.818181818	11	1	3	
JB105t19	1.666666667	36	1	3	
JB105t20	1.454545455	11	1	3	
JB105t25	1.666666667	15	1	2	
JB105t_compendium	1.719298246	114	1	3	7
JB106t1	1.588235294	17	1	3	
JB106t10	1	3	1	1	
JB106t13	1.352941176	17	1	3	
JB106t15	1.692307692	13	1	2	
JB106t_compendium	1.5	50	1	3	4
JB107t2	1.277777778	18	1	2	
JB107t3	1.2	10	1	2	
JB107t12	1.384615385	26	1	2	
JB107t15	1.206896552	29	1	2	
JB107t18	1.375	8	1	2	
JB107t19	1.318181818	22	1	2	
JB107t20	1.269230769	26	1	2	

Appendix Seven. Compendia of results of initial, basic statistical analyses (ray width)

Filename	Mean ray width	Number of observations	Min	Max	Number of sampled areas
JB107t21	1.363636364	11	1	2	
JB107t_compendium	1.299417333	150	1	2	8
JB109t2	1.428571429	14	1	2	
JB109t3	1.416666667	12	1	2	
JB109t8	1.5	18	1	2	
JB109t11	1.333333333	18	1	2	
JB109t15	1.5	18	1	2	
JB109t21	1.461538462	13	1	2	
JB109t23	1.555555556	18	1	2	
JB109t24	1.444444444	18	1	2	
JB109t25	1.411764706	17	1	2	
JB109t_compendium	1.450208288	146	1	2	9
JB111t1 (extra obs)	2.857142857	7	2	3	
JB111t2 (extra obs)	3	4	3	3	
JB111t3 (extra obs)	3	3	3	3	
JB111t4 (extra obs)	2.166666667	12	2	3	
JB111t5 (extra obs)	2	7	1	3	
JB111t6 (extra obs)	2.5	6	2	3	
JB111t7 (extra obs)	2.444444444	9	2	3	
JB111t3	2.5	9	1	3	
JB111t4	2.181818182	11	1	3	
JB111t6	2.4	5	1	3	
JB111t9	3	4	3	3	
JB111t19	3	2	3	3	
JB111t_compendium	2.587506013	79	1	3	12
JB112t2	7.5	8	3	12	
JB112t7	10.5	4	8	13	
JB112t1 (extra obs)	9	3	7	11	
JB112t4 (extra obs)	9.75	4	8	12	
JB112t5 (extra obs)	9.5	4	7	11	
JB112t7 (extra obs)	10.25	4	7	13	
JB112t9 (extra obs)	9	5	6	12	
JB112t_compendium	9.357142857	32	3	13	7
JB113t2	3.642857143	14	2	5	
JB113t3	4	13	2	5	
JB113t4	4.142857143	7	3	5	
JB113t5	4	5	3	5	
JB113t2 (extra obs)	4.166666667	6	3	5	
JB113t4 (extra obs)	4	6	3	5	
JB113t7 (extra obs)	3.888888889	9	3	5	
JB113t8 (extra obs)	4	10	3	5	
JB113t_compendium	3.98015873	70	2	5	8
JB114t1	1.764705882	17	1	2	
JB114t2	1.9	20	1	3	
JB114t3	1.875	8	1	2	

Filename	Mean ray width	Number of observations	Min	Max	Number of sampled areas
JB114t14	1.666666667	21	1	2	
JB114t15	1.75	8	1	2	
JB114t_compendium	1.783783784	74	1	3	5
JB115t1	10.16666667	6	8	12	
JB115t3	9.333333333	3	7	12	
JB115t7	9.125	8	5	11	
JB115t16	10.28571429	7	6	15	
JB115t20	10.66666667	6	6	13	
JB115t_compendium	9.933333333	30	5	15	5
JAB117t13	2.111111111	9	2	3	
JAB117t14	2	6	2	2	
JAB117t19	2.111111111	9	1	3	
JAB117t26	1.888888889	9	1	3	
JAB117t_compendium	2.03030303	33	1	3	4
JB119t2	1.666666667	27	1	3	
JB119t3	1.777777778	9	1	3	
JB119t10	2.130434783	23	1	3	
JB119t14	2.166666667	6	1	3	
JB119t15	2.25	16	1	3	
JB119t16	2	6	1	3	
JB119t_compendium	1.965517241	87	1	3	6
JAB121t2	1	28	1	1	
JAB121t1 (extra obs)	1	15	1	1	
JAB121t2 (extra obs)	1	18	1	1	
JAB121t3 (extra obs)	1	17	1	1	
JAB121t4 (extra obs)	1	11	1	1	
JAB121t5 (extra obs)	1.166666667	12	1	2	
JAB121t6 (extra obs)	1.117647059	17	1	2	
JAB121t_compendium	1.040616246	118	1	2	7
JAB122t1	1.323529412	34	1	2	
JAB122t5	1.5	28	1	3	
JAB122t8	1.40625	32	1	3	
JAB122t9	1.636363636	11	1	2	
JAB122t_compendium	1.428571429	105	1	3	4
JB123t12	2	7	2	2	
JB123t16	2	8	1	3	
JB123t17	2.142857143	7	2	3	
JB123t24	2	9	2	2	
JB123t_compendium	2.032258065	31	1	3	4
JB124t8	18	2	16	20	
JB124t9	16	2	13	19	
JB124t2 (extra obs)	21	2	19	23	
JB124t4 (extra obs)	19.5	2	16	23	

Filename	Mean ray width	Number of observations	Min	Max	Number of sampled areas
JB124t5 (extra obs)	18	2	13	23	
JB124t8 (extra obs)	15.5	2	14	17	
JB124t10 (extra obs)	13.66666667	3	12	16	
JB124t_compendium	17.38095238	15	12	23	7
JB125t1	2.7	20	2	4	
JB125t2	2.666666667	6	2	3	
JB125t9	2.6	20	1	3	
JB125t10	2.571428571	7	2	3	
JB125t13	2.578947368	19	1	3	
JB125t14	3	4	3	3	
JB125t_compendium	2.644736842	76	1	4	6
JB127t1	2.3	30	1	3	
JB127t2	2	10	1	3	
JB127t3	2.416666667	24	1	3	
JB127t4	1.909090909	11	1	3	
JB127t8	1.857142857	7	1	3	
JB127t15	2.25	8	1	3	
JB127t_compendium	2.122150072	90	1	3	6
JB128t2	1	10	1	1	
JB128t7	1	11	1	1	
JB128t11	1	15	1	1	
JB128t14	1	14	1	1	
JB128t_compendium	1	50	1	1	4
JB129t1	2.066666667	15	1	3	
JB129t2	2	5	2	2	
JB129t10	2.066666667	15	1	3	
JB129t11	2	9	2	2	
JB129t14	2.090909091	11	1	3	
JB129t15	2	4	2	2	
JB129t_compendium	2.050847458	59	1	3	6
JB130t1	1.588235294	17	1	2	
JB130t2	1.619047619	21	1	2	
JB130t4	1.888888889	9	1	2	
JB130t9	1.692307692	13	1	2	
JB130t10	1.5	16	1	2	
JB130t11	1.384615385	13	1	2	
JB130t17	1.5	14	1	2	
JB130t23	1.6	15	1	2	
JB130t24	1.5	14	1	2	
JB130t31	1.722222222	18	1	2	
JB130t_compendium	1.59953171	150	1	2	10
JB132t2 (extra obs)	5.4	5	3	7	
JB132t5 (extra obs)	4.833333333	6	1	7	
JB132t6 (extra obs)	6.25	4	4	7	

Filename	Mean ray width	Number of observations	Min	Max	Number of sampled areas
JB132t8 (extra obs)	6.6	5	4	8	
JB132t10 (extra obs)	7.5	4	6	8	
JB132t11 (extra obs)	6.8	5	6	8	
JB132t13 (extra obs)	4.833333333	6	3	8	
JB132t14 (extra obs)	5	7	1	8	
JB132t_compendium	5.902083333	42	1	8	8
JB133t3	1.117647059	17	1	2	
JB133t10	1.125	16	1	2	
JB133t16	1.2	15	1	2	
JB133t21	1.071428571	14	1	2	
JB133t22	1.0625	16	1	2	
JB133t23	1.1875	16	1	2	
JB13t_compendium	1.127659574	94	1	2	6
JB135t3	1.909090909	11	1	3	
JB135t4	2.125	8	1	3	
JB135t5	1.555555556	9	1	3	
JB135t6	1.538461538	13	1	2	
JB135t7	1.6	10	1	3	
JB135t16	1.615384615	13	1	2	
JB135t20	2	9	1	3	
JB135t21	1.333333333	3	1	2	
JB135t_compendium	1.709603244	76	1	3	8
JAB136t1	1.181818182	33	1	2	
JAB136t2	1.153846154	26	1	2	
JAB136t3	1	8	1	1	
JAB136t5	1.2	30	1	2	
JAB136t6	1	10	1	1	
JAB136t13	1.125	8	1	2	
JAB136t_compendium	1.147826087	115	1	2	6
JB137t1	1.027777778	36	1	2	
JB137t2	1	15	1	1	
JB137t7	1.076923077	13	1	2	
JB137t9	1.046511628	43	1	2	
JB137t_compendium	1.037383178	107	1	2	4
JB138t3	1.8125	16	1	3	
JB138t19	1.571428571	14	1	2	
JB138t21	2.071428571	14	1	3	
JB138t1 (extra obs)	1.913043478	23	1	3	
JB138t2 (extra obs)	2.178571429	28	1	3	
JB138t3 (extra obs)	2.043478261	23	1	3	
JB138t4 (extra obs)	1.931034483	29	1	3	
JB138t6 (extra obs)	1.757575758	33	1	3	
JB138t9 (extra obs)	1.911764706	34	1	3	
JB138t_compendium	1.910091695	214	1	3	9

Filename	Mean ray width	Number of observations	Min	Max	Number of sampled areas
JB139t3	19.5	2	19	20	
JB139t5	20	3	17	23	
JB139t11	15.5	2	13	18	
JB139t2 (extra obs)	16	3	13	20	
JB139t3 (extra obs)	19	3	13	23	
JB139t4 (extra obs)	13.5	4	12	15	
JB139t5 (extra obs)	17.33333333	3	10	26	
JB139t8 (extra obs)	19.5	4	15	25	
JB139t9 (extra obs)	20	2	20	20	
JB139t_compendium	17.81481481	26	10	26	9
JB140t1	1.055555556	18	1	2	
JB140t3	1.166666667	6	1	2	
JB140t11	1.15	20	1	2	
JB140t12	1.25	4	1	2	
JB140t16	1.2	15	1	2	
JB140t17	1.25	4	1	2	
JB140t_compendium	1.149253731	67	1	2	6
JB142t2	14	4	12	17	
JB142t3	16.5	2	13	20	
JB142t4	14.66666667	3	8	20	
JB142t6	13.33333333	3	9	18	
JB142t7	19	1	19	19	
JB142t_compendium	15.5	13	8	20	5
JB143t1	1.166666667	36	1	2	
JB143t2	1.25	36	1	2	
JB143t3	1.1	10	1	2	
JB143t7	1.35	40	1	2	
JB143t8	1.3	10	1	2	
JB143t13	1.153846154	13	1	2	
JB143t_compendium	1.24137931	145	1	2	6
JB144t1	2.764705882	17	1	4	
JB144t2	2.25	20	1	3	
JB144t3	2.666666667	18	1	3	
JB144t_compendium	2.545454545	55	1	4	3
JB147t3	13	2	13	13	
JB147t4	12	2	11	13	
JB147t5	10.33333333	3	9	12	
JB147t6	9.75	4	5	15	
JB147t13	11	2	11	11	
JB147t_compendium	11.21666667	13	5	15	5
JB150t1	1.777777778	27	1	3	
JB150t3	1.64	25	1	3	
JB150t19	1.625	32	1	3	
JB150t21	1.739130435	23	1	3	

Filename	Mean ray width	Number of observations	Min	Max	Number of sampled areas
JB150t_compendium	1.691588785	107	1	3	4
JB151t1	1	5	1	1	
JB151t2	1	6	1	1	
JB151t3	1	4	1	1	
JB151t5	1	3	1	1	
JB151t7	1	6	1	1	
JB151t8	1	6	1	1	
JB151t9	1	10	1	1	
JB151t10	1	8	1	1	
JB151t11	1	12	1	1	
JB151t12	1	9	1	1	
JB151t_compendium	1	69	1	1	10
JB152t2	1.071428571	14	1	2	
JB152t3	1.1	20	1	2	
JB152t4	1	28	1	1	
JB152t5	1.24	25	1	2	
JB152t6	1	8	1	1	
JB152t7	1.083333333	24	1	2	
JB152t10	1.12	25	1	2	
JB152t11	1.142857143	7	1	2	
JB152t_compendium	1.132653061	151	1	2	8
JB153t1	1.722222222	18	1	2	
JB153t13	1.764705882	17	1	2	
JB153t14	1.933333333	15	1	2	
JB153t15	1.733333333	15	1	2	
JB153t_compendium	1.784615385	65	1	2	4
JB155t2	4.0625	16	2	6	
JB155t3	4.058823529	17	2	6	
JB155t4	4.071428571	14	2	7	
JB155t11	4.375	16	2	6	
JB155t_compendium	4.142857143	63	2	7	4
JB156t6	2	4	1	3	
JB156t16	2.5	4	2	3	
JB156t20	1.6	5	1	2	
JB156t25	2.166666667	6	2	3	
JB156t27	2	9	1	3	
JB156t1 (extra obs)	1.857142857	21	1	3	
JB156t2 (extra obs)	1.823529412	17	1	3	
JB156t3 (extra obs)	2.133333333	15	1	3	
JB156t4 (extra obs)	1.875	8	1	3	
JB156t6 (extra obs)	2.214285714	14	1	3	
JB156t7 (extra obs)	1.875	16	1	3	
JB156t8(extra obs)	2	17	1	3	
JB156t_compendium	2.028571429	136	1	3	12

Filename	Mean ray width	Number of observations	Min	Max	Number of sampled areas
JB157t1	1.5	36	1	2	
JB157t2	1.384615385	13	1	2	
JB157t5	1.5	10	1	2	
JB157t8	1.428571429	7	1	2	
JB157t10	1.774193548	31	1	2	
JB157t_compendium 120x	1.777777778	9	1	2	
JB157t_compendium 240x	1.4	10	1	2	
JB157t_compendium	1.568965517	116	1	2	7
JB158t1	1.136363636	22	1	2	
JB158t2	1	11	1	1	
JB158t12	1.0625	16	1	2	
JB158t13	1	16	1	1	
JB158t14	1	6	1	1	
JB158t15	1.2	15	1	2	
JB158t16	1.214285714	14	1	2	
JB158t17	1	6	1	1	
JB158t20	1.136363636	22	1	2	
JB158t21	1	5	1	1	
JB158t_compendium	1.097744361	133	1	2	10
JB159t3	1	12	1	1	
JB159t4	1.153846154	13	1	2	
JB159t8	1	15	1	1	
JB159t11	1.222222222	18	1	2	
JB159t20	1.076923077	13	1	2	
JB159t21	1.176470588	17	1	2	
JB159t_compendium	1.113636364	88	1	2	6
JB160t1	1.388888889	18	1	3	
JB160t3	1.454545455	11	1	3	
JB160t4	1.615384615	13	1	3	
JB160t11	1.666666667	9	1	3	
JB160t15	1.5	10	1	3	
JB160t20	1.555555556	18	1	2	
JB160t25	1.75	12	1	3	
JB160t26	1.692307692	13	1	3	
JB160t27	1.8125	16	1	3	
JB160t_compendium	1.603983208	120	1	3	9
JB161t1	1.081081081	37	1	2	
JB161t11	1.142857143	35	1	2	
JB161t12	1.090909091	11	1	2	
JB161t13	1.363636364	11	1	2	
JB161t14	1.088888889	45	1	2	
JB161t15	1.1	10	1	2	
JB161t16	1	10	1	1	
JB161t19	1	12	1	1	
JB161t_compendium	1.105263158	171	1	2	8

Filename	Mean ray width	Number of observations	Min	Max	Number of sampled areas
JB162t4	3.333333333	9	2	5	
JB162t5	3.166666667	6	2	4	
JB162t7	3.444444444	9	3	4	
JB162t8	3.875	8	2	6	
JB162t10	4.5	2	4	5	
JB162t17	3.333333333	9	1	5	
JB162t18	3.875	8	3	5	
JB162t19	4.5	2	4	5	
JB162t_compendium	3.753472222	53	1	6	8
JB163t2	1.230769231	13	1	2	
JB163t6	1.333333333	18	1	2	
JB163t11	1.416666667	12	1	2	
JB163t14	1.3	20	1	2	
JB163t15	1.238095238	21	1	2	
JB163t_compendium	1.297619048	84	1	2	5
JAB164t1	1.155555556	45	1	2	
JAB164t2	1.256410256	39	1	2	
JAB164t3	1.096774194	31	1	2	
JAB164t4	1.064516129	31	1	2	
JAB164t5	1.255813953	43	1	2	
JAB164t7	1.1875	16	1	2	
JAB164t_compendium	1.175609756	205	1	2	6
JB165t1	1.777777778	18	1	2	
JB165t2	1.833333333	6	1	2	
JB165t5	2	3	2	2	
JB165t6	1.92	25	1	3	
JB165t7	2	4	1	3	
JB165t15	1.80952381	21	1	3	
JB165t16	2	3	1	3	
JB165t17	2.2	5	2	3	
JB165t_compendium	1.882352941	85	1	3	8
JB166t1	3.666666667	15	2	5	
JB166t3	2.875	8	1	5	
JB166t7	2.769230769	13	1	4	
JB166t14	2.714285714	7	1	4	
JB166t1 (extra obs)	3.285714286	14	1	5	
JB166t2 (extra obs)	3	14	1	5	
JB16631 (extra obs)	3.666666667	12	2	5	
JB166t4 (extra obs)	3.181818182	11	1	5	
JB166t5 (extra obs)	3	17	1	4	
JB166t6 (extra obs)	2.761904762	21	1	5	
JB166t7 (extra obs)	3.133333333	15	1	5	
JB166t8 (extra obs)	3.142857143	14	1	5	
JB166t_compendium	3.099789794	161	1	5	12
JB167t1	2.8	10	2	3	

Appendix Seven. Compendia of results of initial, basic statistical analyses (ray width)

Filename	Mean ray width	Number of observations	Min	Max	Number of sampled areas
JB167t2	2.315789474	38	2	3	
JB167t3	2.078947368	38	1	3	
JB167t4	2.3	10	1	3	
JB167t_compendium	2.270833333	96	1	3	4
JB168t2	1.558823529	34	1	2	
JB168t3	1.5	8	1	2	
JB168t12	1.555555556	27	1	2	
JB168t13	1.5	6	1	2	
JB168t18	1.75	28	1	3	
JB168t19	1.625	8	1	2	
JB168t_compendium	1.603603604	111	1	3	6
JAB169t1	1.96	25	1	2	
JAB169t2	1.904761905	21	1	2	
JAB169t3	2	7	2	2	
JAB169t4	2.3	20	1	3	
JB169t1 (extra obs)	2	10	1	3	
JB169t2 (extra obs)	2	10	1	3	
JB169t3 (extra obs)	2.285714286	7	2	3	
JB169t4 (extra obs)	2.166666667	12	1	3	
JB169t5 (extra obs)	2	7	2	2	
JB169t6 (extra obs)	2.166666667	6	2	3	
JB169t7 (extra obs)	2.4	5	2	3	
JAB169t_compendium	2.107619048	130	1	3	11
JB170t2	1.185185185	27	1	2	
JB170t3	1.222222222	9	1	2	
JB170t4	1.230769231	26	1	2	
JB170t5	1.428571429	7	1	2	
JB170t12	1.130434783	23	1	2	
JB170t13	1	7	1	1	
JB170t_compendium	1.191919192	99	1	2	6
JB172t5	6.8	5	5	8	
JB172t7	6.5	4	4	9	
JB172t8	4.8	5	2	7	
JB172t2 (extra obs)	6.166666667	6	5	8	
JB172t3 (extra obs)	5	6	2	7	
JB172t6 (extra obs)	6.4	5	2	8	
JB172t8 (extra obs)	6.333333333	3	4	9	
JB172t_compendium	6	34	2	9	7
JB174t2	3	2	3	3	
JB174t18	2	5	1	3	
JB174t19	2.333333333	6	1	3	
JB174t1 (extra obs)	3	3	3	3	
JB174t2 (extra obs)	2.8	10	1	4	
JB174t3 (extra obs)	2.75	4	2	3	
JB174t4 (extra obs)	3	7	3	3	

Filename	Mean ray width	Number of observations	Min	Max	Number of sampled areas
JB174t5 (extra obs)	2.333333333	9	1	4	
JB174t6 (extra obs)	3.142857143	7	2	4	
JB174t7 (extra obs)	2.625	8	1	3	
JB174t8 (extra obs)	2.5	6	1	3	
JB174t9 (extra obs)	3	7	2	4	
JB174t_compendium	2.707043651	74	1	4	12
JB175t1	1.733333333	15	1	2	
JB175t3	1.705882353	17	1	3	
JB175t4	1.5	6	1	2	
JB175t5	1.666666667	15	1	2	
JB175t6	1.5	4	1	2	
JB175t11	1.578947368	19	1	2	
JB175t_compendium	1.644736842	76	1	3	6
JB177t1	1.5	8	1	2	
JB177t2	1.4	20	1	2	
JB177t5	1.111111111	9	1	2	
JB177t10	1	7	1	1	
JB177t16	1	7	1	1	
JB177t17	1.1875	16	1	2	
JB177t20	1.411764706	17	1	3	
JB177t21	1	7	1	1	
JB177t22	1.285714286	14	1	2	
JB177t23	1	6	1	1	
JB177t24	1.666666667	3	1	2	
JB177t_compendium	1.254385965	114	1	3	11
JB178t1	2.066666667	15	1	3	
JB178t2	1.666666667	6	1	3	
JB178t9	1.882352941	17	1	3	
JB178t10	1.9	10	1	2	
JB178t1 (extra obs)	2	15	1	3	
JB178t2 (extra obs)	2.090909091	11	1	3	
JB178t3 (extra obs)	2.181818182	11	1	3	
JB178t4 (extra obs)	2	16	1	3	
JB178t5 (extra obs)	2.133333333	15	1	3	
JB178t6 (extra obs)	2.555555556	9	1	3	
JB178t7 (extra obs)	2.083333333	12	1	3	
JB178t8 (extra obs)	2.333333333	15	2	3	
JB178t9 (extra obs)	2.214285714	14	1	3	
JB178t_compendium	2.085250371	166	1	3	13
JB180t1	1.454545455	11	1	2	
JB180t2	1.5	4	1	2	
JB180t4	1.571428571	21	1	2	
JB180t5	1.545454545	11	1	2	
JB180t6	1.294117647	17	1	2	
JB180t7	1.5	8	1	2	
JB180t11	1.4	5	1	2	

Filename	Mean ray width	Number of observations	Min	Max	Number of sampled areas
JB180t12	2	3	1	3	
JB180t1 (extra obs)	1.363636364	11	1	2	
JB180t2 (extra obs)	1.214285714	14	1	2	
JB180t3 (extra obs)	1.266666667	15	1	2	
JB180t4 (extra obs)	1.111111111	9	1	2	
JB180t5 (extra obs)	1.461538462	13	1	3	
JB180t6 (extra obs)	1.2	15	1	2	
JB180t7 (extra obs)	1.25	16	1	2	
JB180t8 (extra obs)	1.615384615	13	1	2	
JB180t9 (extra obs)	1.642857143	14	1	2	
JB180t10 (extra obs)	1.583333333	12	1	2	
JB180t_compendium	1.443019979	212	1	3	18
JB181t1	2.214285714	14	2	3	
JB181t4	2.333333333	6	2	3	
JB181t5	2.4	5	1	3	
JB181t1 (extra obs)	2.083333333	12	1	3	
JB181t2 (extra obs)	2.0625	16	1	3	
JB181t3 (extra obs)	2.384615385	13	1	3	
JB181t4 (extra obs)	2.461538462	13	1	3	
JB181t5 (extra obs)	2.615384615	13	2	3	
JB181t6 (extra obs)	2.5625	16	1	3	
JB181t_compendium	2.346387871	108	1	3	9
JB183t1	2.5625	16	1	5	
JB183t3	2.666666667	9	2	3	
JB183t4	2.636363636	11	1	4	
JB183t5	2.545454545	11	2	4	
JB183t12	2.153846154	13	1	3	
JB183t13	2.5	10	1	4	
JB183t1 (extra obs)	2.444444444	9	1	3	
JB183t2 (extra obs)	3.285714286	7	2	5	
JB183t3 (extra obs)	2.6	10	1	4	
JB183t4 (extra obs)	2.923076923	13	1	4	
JB183t5 (extra obs)	2.909090909	11	1	4	
JB183t6 (extra obs)	3.090909091	11	2	4	
JB183t_compendium	2.693172221	131	1	5	12
JB184t1	2.55	20	1	4	
JB184t2	2.5	8	1	4	
JB184t3	2	24	1	3	
JB184t4	1.791666667	24	1	3	
JB184t7	2.071428571	14	1	3	
JB184t8	2.333333333	6	1	3	
JB184t9	1.9	10	1	3	
JB184t10	1.833333333	6	1	3	
JB184t22	1.888888889	9	1	3	
JB184t_compendium	2.082644628	121	1	4	9
JB186t1	1	18	1	1	

Filename	Mean ray width	Number of observations	Min	Max	Number of sampled areas
JB186t2	1.125	16	1	2	
JB186t20	1	8	1	1	
JB186t21	1	18	1	1	
JB186t22	1.111111111	9	1	2	
JB186t_compendium	1.043478261	69	1	2	5
JB187t1	2.181818182	33	1	4	
JB187t2	2	13	1	3	
JB187t3	2.413793103	29	1	4	
JB187t4	2.5	10	2	3	
JB187t5	2.071428571	28	1	4	
JB187t_compendium	2.221238938	113	1	4	5
JB189t1	1.692307692	13	1	2	
JB189t2	1.75	4	1	2	
Jb189t21	1.5	10	1	2	
JB189t22	2.333333333	3	2	3	
JB189t25	1.727272727	11	1	2	
JB189t26	1.666666667	3	1	2	
JB189t_compendium	1.704545455	44	1	3	6
JB190t1	3.117647059	17	2	5	
JB190t2	2.75	4	2	3	
JB190t8	3.25	4	3	4	
JB190t14	3.4	5	3	5	
JB190t20	2.666666667	18	2	4	
JB190t21	2.8	5	2	3	
JB190t22	2.772727273	22	2	3	
JB190t_compendium	2.893333333	75	2	5	8
JB191t2	1.875	24	1	2	
JB191t3	1.909090909	22	1	3	
JB191t4	2	6	2	2	
JB191t5	1.714285714	7	1	2	
JB191t12	1.739130435	23	1	2	
JB191t13	1.964285714	28	1	3	
JB191t21	1.967741935	31	1	3	
JB191t25	1.6	10	1	2	
JB191t27	1.666666667	6	1	2	
JB191t_compendium	1.866242038	157	1	3	9

NOTE: One specimen has not been recorded for ray width: JAB126 (*Acacia peuce*)

NOTE 2: Filenames with _extra obs suffix simply refer to a subsequent batch of observations that were made to increase the number of observations

Appendix Eight. Results of test of identification tool using 10 unknown specimens

Specimen A

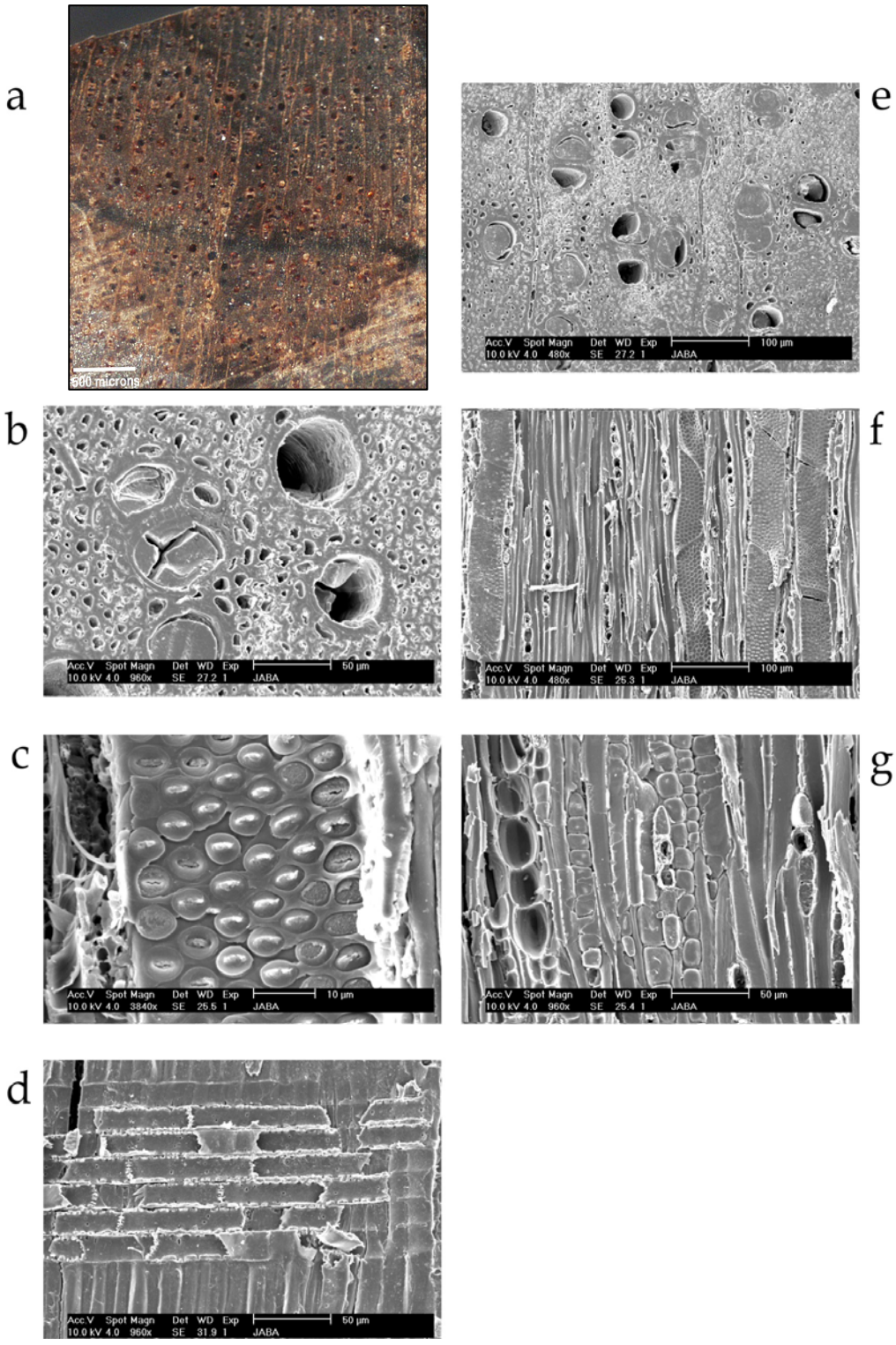

Figure 66 Test Specimen A. A. Endgrain image (scale = 500 µm); B. Vessels in radial multiples, some with inclusions (XS) (scale = 50 µm); C. Vestured vessel-vessel pits (TLS) (scale = 10 µm); D. Homocellular ray cells (RLS) (scale = 50 µm); E. Transverse surface (XS) (scale = 100 µm); F. Tangential surface (TLS) (scale = 100 µm); G. Chambered axial parenchyma (TLS) (scale = 50 µm).

Table. Results of test using Specimen A

Applied key/sub-key	Selected character states	Taxa remaining
PHYSICAL PROPERTIES		
Sub-key to a Selection of Arid Australian Hardwoods	Kino (gum deposits), not visible to the naked eye Rays, fleck not visible on longitudinal surface with naked eye Rays, not distinctly visible on cross-section with naked eye Heartwood, colour clearly distinct from sapwood colour Heartwood, colour not purple Heartwood, fluorescent Heartwood, odour not distinctly evident from freshly cut wood	**11 taxa remaining** *Acacia* *Anthobolus* *Bauhinia* *Casuarina* Myoporaceae (*Eremophila* & *Myoporum*) Myrtaceae A (*Eucalyptus* & *Melaleuca*) Myrtaceae B (*Corymbia*) *Psydrax* *Schinus* *Senna* *Ventilago*
CHEMICAL OBSERVATIONS		
Sub-key to a Selection of Arid Australian Hardwoods	Heartwood, fluorescent Heartwood, froth test negative Heartwood, ethanol extract not fluorescent Heartwood, ethanol extract discoloured Heartwood, water extract discoloured	**11 taxa remaining** *Acacia* *Anthobolus* *Bauhinia* *Capparis* *Casuarina* Myoporaceae (*Eremophila* & *Myoporum*) Myrtaceae A (*Eucalyptus* & *Melaleuca*) Myrtaceae B (*Corymbia*) *Psydrax* *Schinus* *Tamarix*
ANATOMICAL: ENDGRAIN (LIGHT MICROSCOPY)		
Sub-key to a Selection of Arid Australian Hardwoods	Vessels, in radial multiples Rays, not distinctly wider than vessels Rays, not of two distinct widths Vessels, not in tangential bands	**15 taxa remaining** *Acacia* *Atalaya* *Bauhinia* *Capparis* *Dodonaea* *Flindersia* Myoporaceae (*Eremophila* & *Myoporum*) Myrtaceae B (*Corymbia*) *Owenia* *Psydrax* *Schinus* *Senna* *Tamarix* *Ventilago* *Anthobolus*
ANATOMICAL: SCANNING ELECTRON MICROSCOPY		
Sub-key to a Selection of Arid Australian Hardwoods	Vessels, diameter: #:15-74 µm Vessels, difference in diameters: #:43-58 µm Vessels, >100 per square mm Vessels, in radial multiples Vessels, not in radial multiples of 4 or more Vessels, not in tangential bands Vessels, not solitary Vessels, vessel to vessel pits vestured Vessels, helical thickenings absent Parenchyma, scanty to vasicentric (paratracheal)	**1 taxon remaining** *Acacia*

	Parenchyma, in a wing-like to confluent sheath (paratracheal) Parenchyma, not banded Parenchyma, chambered (and often with crystals) S Rays, height: #:58-177 µm S Rays, difference in heights: #:68-118 µm Rays, exclusively one cell wide (uniseriate) Rays, with uniseriate rays present Rays, 4 - 12 per mm Rays, >12 per mm Rays, cells homocellular (procumbent only) Fibres/tracheids, with numerous, distinctly bordered pits not present Rays, not distinctly wider than vessels Rays, not of two distinct widths	
Sub-key to *Acacia*	Vessels, diameter: #:15-74 µm Vessels, difference in diameters: #:43-58 µm Vessels, >100 per square mm Vessels, in radial multiples Vessels, not in radial multiples of 4 or more Vessels, not solitary Parenchyma, scanty to vasicentric (paratracheal) Parenchyma, in a wing-like to confluent sheath (paratracheal) Parenchyma, not banded Rays, height: #:58-177 µm Rays, difference in heights: #:68-118 µm Rays, exclusively one cell wide (uniseriate) Rays, 4 - 12 per mm Rays, >12 per mm	**2 taxa remaining** *Acacia stowardii* *Acacia murrayana*
ALL CHARACTER SETS		
Sub-key to a Selection of Arid Australian Hardwoods	All of the above	**1 taxon remaining** *Acacia*
Sub-key to *Acacia*	All of the above	**No remaining taxa**

Specimen B

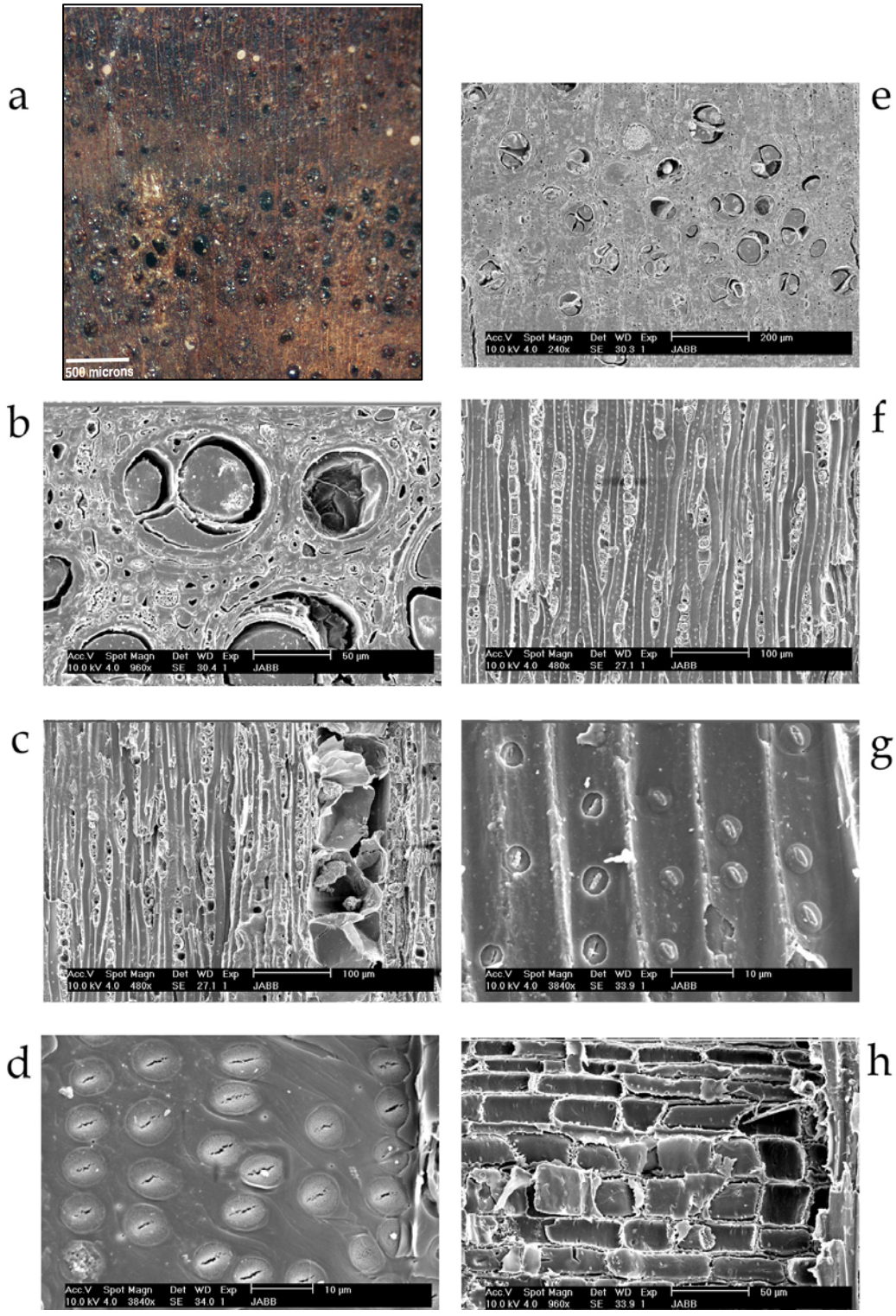

Figure 67 Test Specimen B. A. Endgrain image (scale = 500 µm); B. Vessels solitary, some with inclusions (XS) (scale = 50 µm); C. Rays, vessels with tyloses (TLS) (scale = 100 µm); D. Vestured vessel-vessel pits (TLS) (scale = 10 µm); E. Transverse surface (XS) (scale = 200 µm); F. Tangential surface (TLS) (scale = 100 µm); G. Fibres/tracheids with large bordered pits (RLS) (scale = 10 µm); H. Heterocellular ray cells (RLS) (scale = 50 µm).

Table. Results of test using Specimen B

Applied key/sub-key	Selected character states	Taxa remaining
PHYSICAL PROPERTIES		
Sub-key to a Selection of Arid Australian Hardwoods	Heartwood, colour clearly distinct from sapwood colour	**10 taxa remaining**
	Heartwood, colour not purple	*Anthobolus*
	Heartwood, not fluorescent	*Bauhinia*
	Heartwood, odour not distinctly evident from freshly cut wood	*Casuarina*
		Dodonaea
	Rays, not distinctly visible on cross-section with naked eye	Myoporaceae (*Eremophila* & *Myoporum*)
	Rays, fleck not visible on longitudinal surface with naked eye	Myrtaceae A (*Eucalyptus* & *Melaleuca*)
	Kino (gum deposits), not visible to the naked eye	Myrtaceae B (*Corymbia*)
		Owenia
		Psydrax
		Schinus
CHEMICAL OBSERVATIONS		
Sub-key to a Selection of Arid Australian Hardwoods	Heartwood, not fluorescent	**12 taxa remaining**
	Heartwood, froth test negative	*Anthobolus*
	Heartwood, ethanol extract not fluorescent	*Bauhinia*
	Heartwood, water extract discoloured	*Capparis*
		Casuarina
		Myoporaceae (*Eremophila* & *Myoporum*)
		Myrtaceae A (*Eucalyptus* & *Melaleuca*)
		Myrtaceae B (*Corymbia*)
		Owenia
		Proteaceae (*Grevillea* & *Hakea*)
		Psydrax
		Schinus
		Tamarix
ANATOMICAL: ENDGRAIN (LIGHT MICROSCOPY)		
Sub-key to a Selection of Arid Australian Hardwoods	Vessels, solitary	**8 taxa remaining**
	Rays, not distinctly wider than vessels	*Anthobolus*
	Rays, not of two distinct widths	*Bauhinia*
		Casuarina
		Myrtaceae A (*Eucalyptus* & *Melaleuca*)
		Santalum
		Acacia
		Capparis
		Myrtaceae B (*Corymbia*)
ANATOMICAL: SCANNING ELECTRON MICROSCOPY		
Sub-key to a Selection of Arid Australian Hardwoods	Vessels, diameter: #:20-114 µm	**1 taxon remaining**
	Vessels, difference in diameters: #:60-93 µm	Myrtaceae A (*Eucalyptus* & *Melaleuca*)
	Vessels, < 50 per square mm	
	Vessels, solitary	
	Vessels, vessel to vessel pits vestured	
	Parenchyma, diffuse to diffuse-in-aggregate (apotracheal)	
	Parenchyma, scanty to vasicentric (paratracheal)	
	Rays, number of cells wide: #:1-2 cells wide	
	Rays, with uniseriate rays present	
	Rays, not exclusively one cell wide	
	Rays, height: #:73-225 µm	
	Rays, difference in heights: #:129-152 µm	
	Rays, number per mm: Rays, >12 per mm	
	Rays, cells heterocellular (procumbent and upright)	
	Fibres/tracheids, with numerous, distinctly bordered pits present	
	Rays, not distinctly wider than vessels	
	Rays, not of two distinct widths	

	Parenchyma, not in a wing-like to confluent sheath Parenchyma, not banded Vessels, not in radial multiples Vessels, not in clusters Vessels, not in tangential bands	
Sub-key to Myrtaceae A (*Eucalyptus* & *Melaleuca*)	Vessels, diameter: #:20-114 µm Vessels, difference in diameters: #:60-93 µm Vessels, < 50 per square mm Parenchyma, diffuse to diffuse-in-aggregate (apotracheal) Parenchyma, scanty to vasicentric (paratracheal) Rays, number of cells wide: #:1-2 cells wide Rays, not exclusively one cell wide Rays, height: #:73-225 µm Rays, difference in heights: #:129-152 µm Rays, >12 per mm Parenchyma, not in a wing-like to confluent sheath	**3 taxa remaining** *Eucalyptus camaldulensis* var. *obtusa* *Eucalyptus coolabah* *Eucalyptus populnea*
ALL CHARACTER SETS		
Sub-key to a Selection of Arid Australian Hardwoods	All of the above	**1 taxon remaining** Myrtaceae A (*Eucalyptus* & *Melaleuca*)
Sub-key to Myrtaceae A (*Eucalyptus* & *Melaleuca*)	All of the above	**2 taxa remaining** *Eucalyptus coolabah* *Eucalyptus populnea*

Specimen C

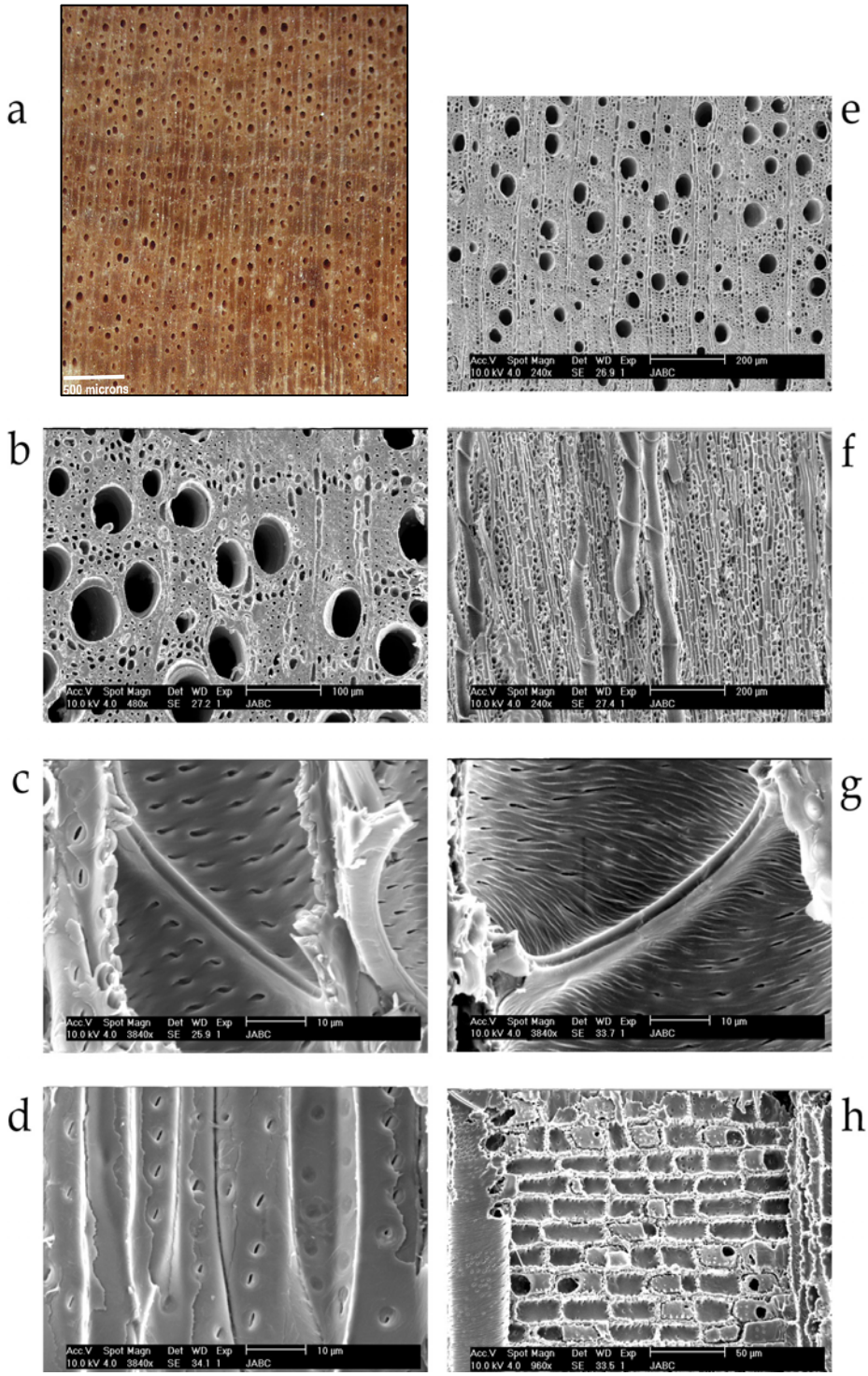

Figure 68 Test Specimen C. A. Endgrain image (scale = 500 µm); B. Vessels solitary, parenchyma banded (XS) (scale = 100 µm); C. Simple perforation rim (TLS) (scale = 10 µm); D. Fibres/tracheids with large, bordered pits (RLS) (scale = 10 µm); E. Transverse surface (XS) (scale = 200 µm); F. Tangential surface (TLS) (scale = 200 µm); G. Simple perforation rim, helical thickenings (RLS) (scale = 10 µm); H. Ray cells (RLS) (scale = 50 µm).

Table. Results of test using Specimen C.

Applied key/sub-key	Selected character states	Taxa remaining
PHYSICAL PROPERTIES		
Sub-key to a Selection of Arid Australian Hardwoods	Heartwood, colour clearly distinct from sapwood colour Heartwood, colour not purple Heartwood, odour not distinctly evident from freshly cut wood Rays, not distinctly visible on cross-section with naked eye Rays, fleck not visible on longitudinal surface with naked eye Kino (gum deposits), not visible to the naked eye	**13 taxa remaining** *Acacia* *Anthobolus* *Bauhinia* *Casuarina* *Dodonaea* Myoporaceae (*Eremophila* & *Myoporum*) Myrtaceae A (*Eucalyptus* & *Melaleuca*) Myrtaceae B (*Corymbia*) *Owenia* *Psydrax* *Schinus* *Senna* *Ventilago*
CHEMICAL OBSERVATIONS Shavings were not removed from specimen C for chemical observation because it was unclear if heartwood was present.		
ANATOMICAL: ENDGRAIN (LIGHT MICROSCOPY)		
Sub-key to a Selection of Arid Australian Hardwoods	Vessels, solitary Parenchyma, banded Rays, not distinctly wider than vessels Rays, not of two distinct widths	**5 taxa remaining** *Bauhinia* *Casuarina* *Acacia* *Capparis* Myrtaceae B (*Corymbia*)
ANATOMICAL: SCANNING ELECTRON MICROSCOPY		
Sub-key to a Selection of Arid Australian Hardwoods	Vessels, diameter: #:20-58 µm Vessels, difference in diameters: #:20-37 µm Vessels, 50-100 per square mm Vessels, solitary Vessels, not in radial multiples Vessels, not in clusters Vessels, not in tangential bands Vessels, vessel to vessel pits not vestured Vessels, helical thickenings present Parenchyma, not diffuse to diffuse-in-aggregate Parenchyma, not scanty to vasicentric Parenchyma, not in a wing-like to confluent sheath Parenchyma, banded Rays, height: #:105-408 µm Rays, difference in heights: #:157-303 µm Rays, number of cells wide: #:1-4 cells wide Rays, not exclusively one cell wide Rays, with uniseriate rays present Rays, >12 per mm Fibres/tracheids, with numerous, distinctly bordered pits present Rays, not distinctly wider than vessels Rays, not of two distinct widths	**1 taxon remaining** *Casuarina* (No sub-key attached; treated specimen is *C. pauper*)

Specimen D

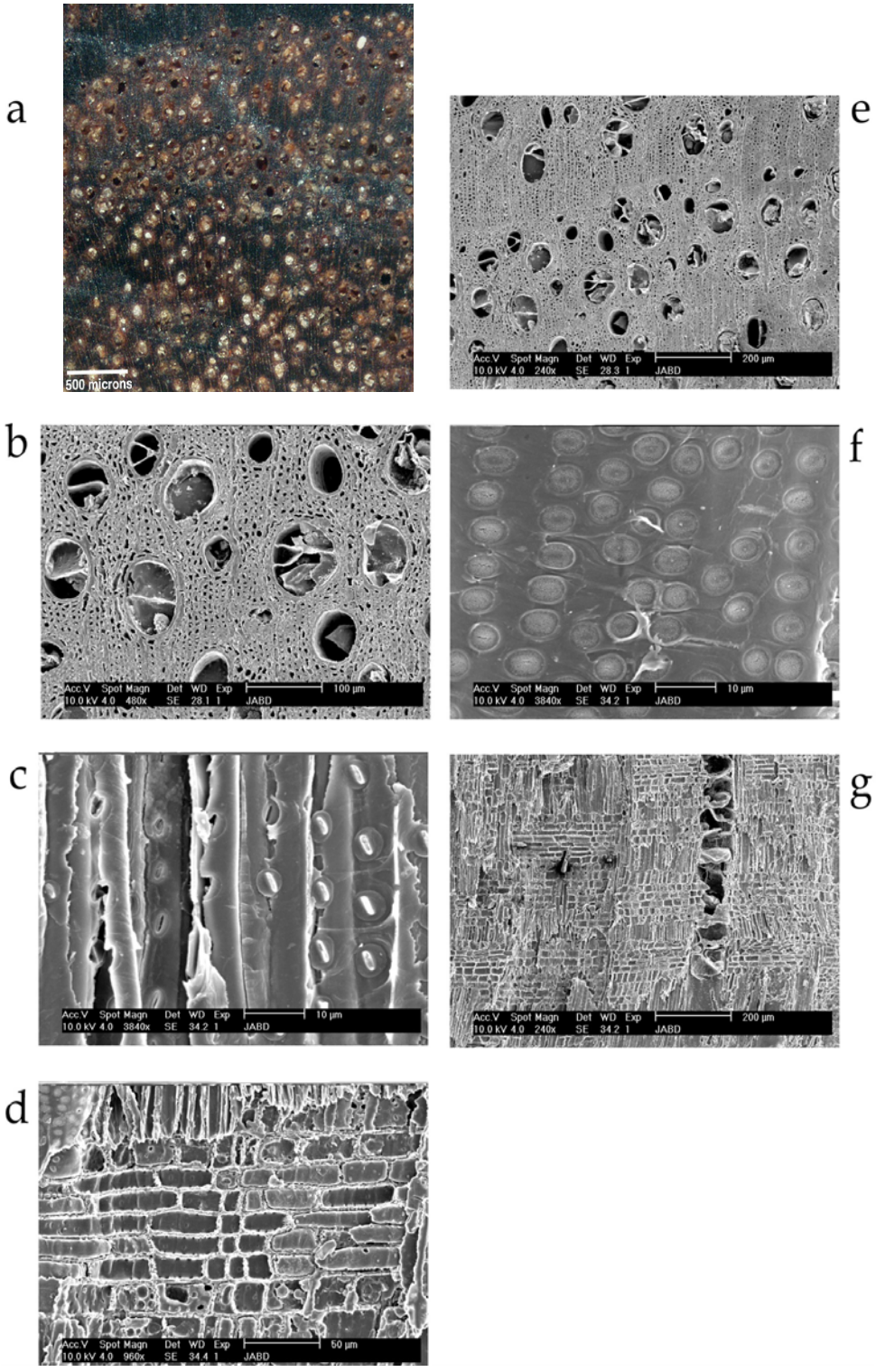

Figure 69 Test Specimen D. A. Endgrain image (scale = 500 µm); B. Vessels solitary, some with tyloses (XS) (scale = 100 µm); C. Fibres/tracheids with large, bordered pits (RLS) (scale = 10 µm); D. Heterocellular ray cells (RLS) (scale = 50 µm); E. Transverse surface (XS) (scale = 200 µm); F. Vestured vessel-vessel pits (RLS) (scale = 10 µm); G. Radial surface (RLS) (scale = 200 µm).

Table. Results of test using Specimen D.

Applied key/sub-key	Selected character states	Taxa remaining
PHYSICAL PROPERTIES		
Sub-key to a Selection of Arid Australian Hardwoods	Heartwood, colour clearly distinct from sapwood colour Heartwood, colour not purple Heartwood, not fluorescent Heartwood, odour not distinctly evident from freshly cut wood Rays, not distinctly visible on cross-section with naked eye Rays, fleck not visible on longitudinal surface with naked eye Kino (gum deposits), not visible to the naked eye	**10 taxa remaining** *Anthobolus* *Bauhinia* *Casuarina* *Dodonaea* Myoporaceae (*Eremophila* & *Myoporum*) Myrtaceae A (*Eucalyptus* & *Melaleuca*) Myrtaceae B (*Corymbia*) *Owenia* *Psydrax* *Schinus*
CHEMICAL OBSERVATIONS		
Sub-key to a Selection of Arid Australian Hardwoods	PC Heartwood, fluorescent or not: Heartwood, not fluorescent C Heartwood, froth test positive or negative: Heartwood, froth test positive C Heartwood, ethanol extract fluorescent or not: Heartwood, ethanol extract not fluorescent C Heartwood, water extract colourless or discoloured: Heartwood, water extract discoloured C Heartwood, ethanol extract colourless or discoloured: Heartwood, ethanol extract discoloured	**11 taxa remaining** *Anthobolus* *Bauhinia* *Capparis* *Casuarina* Myoporaceae (*Eremophila* & *Myoporum*) Myrtaceae A (*Eucalyptus* & *Melaleuca*) Myrtaceae B (*Corymbia*) Proteaceae (*Grevillea* & *Hakea*) *Psydrax* *Schinus* *Tamarix*
ANATOMICAL: ENDGRAIN (LIGHT MICROSCOPY)		
Sub-key to a Selection of Arid Australian Hardwoods	Vessels, solitary Vessels, not in radial multiples Vessels, not in radial multiples of 4 or more Vessels, not in clusters Vessels, not in tangential bands Parenchyma, not in a wing-like to confluent sheath Parenchyma, not banded Rays, not distinctly wider than vessels Rays, not of two distinct widths	**4 taxa remaining** *Anthobolus* Myrtaceae A (*Eucalyptus* & *Melaleuca*) *Santalum* *Acacia*
ANATOMICAL: SCANNING ELECTRON MICROSCOPY		
Sub-key to a Selection of Arid Australian Hardwoods	Vessels, diameter: #:17-91 µm Vessels, difference in diameters: #:55-74 µm Vessels, 50-100 per square mm Vessels, solitary Vessels, not in radial multiples Vessels, not in clusters Vessels, not in tangential bands Vessels, vessel to vessel pits vestured Vessels, helical thickenings absent Parenchyma, diffuse to diffuse-in-aggregate (apotracheal) Parenchyma, scanty to vasicentric (paratracheal) Parenchyma, not in a wing-like to confluent sheath Parenchyma, not banded Parenchyma, not in marginal bands Rays, height: #:84-321 µm Rays, difference in heights: #:73-188 µm Rays, not exclusively one cell wide Rays, number of cells wide: #:1-3 cells wide Rays, with uniseriate rays present Rays, >12 per mm	**1 taxon remaining** Myrtaceae A (*Eucalyptus* & *Melaleuca*)

	Rays, cells heterocellular (procumbent and upright) Fibres/tracheids, with numerous, distinctly bordered pits present Heartwood, vessels commonly with tyloses Rays, not distinctly wider than vessels Rays, not of two distinct widths	
Sub-key to Myrtaceae A (*Eucalyptus* & *Melaleuca*)	Vessels, diameter: #:17-91 µm Vessels, difference in diameters: #:55-74 µm Vessels, 50-100 per square mm Parenchyma, diffuse to diffuse-in-aggregate (apotracheal) Parenchyma, scanty to vasicentric (paratracheal) Parenchyma, not in a wing-like to confluent sheath Parenchyma, not banded Parenchyma, not in marginal bands Rays, height: #:84-321 µm Rays, difference in heights: #:73-188 µm Rays, not exclusively one cell wide Rays, number of cells wide: #:1-3 cells wide Rays, >12 per mm	**5 taxa remaining** *Eucalyptus camaldulensis* var. *obtusa* *Eucalyptus coolabah* *Eucalyptus ochrophloia* *Eucalyptus populnea* *Eucalyptus thozetiana*
ALL CHARACTER SETS		
Sub-key to a Selection of Arid Australian Hardwoods	All of the above	**1 taxon remaining** Myrtaceae A (*Eucalyptus* & *Melaleuca*)
Sub-key to Myrtaceae A (*Eucalyptus* & *Melaleuca*)	All of the above	**3 taxa remaining** *Eucalyptus coolabah* *Eucalyptus populnea* *Eucalyptus thozetiana*

Specimen E

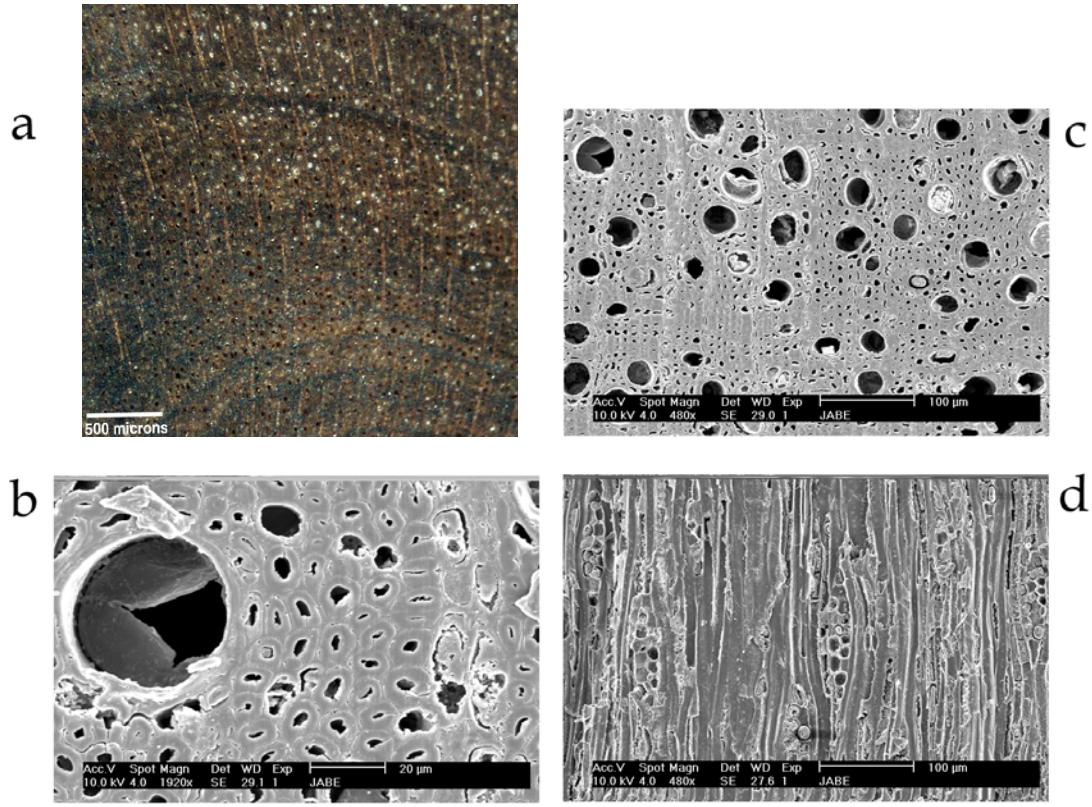

Figure 70 Test Specimen E. A. Endgrain image (scale = 500 µm); B. Vessels solitary (XS) (scale = 20 µm); C. Transverse surface (XS) (scale = 100 µm); D. Tangential surface (TLS) (scale = 100 µm).

Table. Results of test using Specimen E.

Applied key/sub-key	Selected character states	Taxa remaining
PHYSICAL PROPERTIES		
Sub-key to a Selection of Arid Australian Hardwoods	Kino (gum deposits), not visible to the naked eye Rays, fleck not visible on longitudinal surface with naked eye Rays, not distinctly visible on cross-section with naked eye Heartwood, colour clearly distinct from sapwood colour Heartwood, colour not purple Heartwood, not fluorescent Heartwood, odour not distinctly evident from freshly cut wood	**10 taxa remaining** *Anthobolus* *Bauhinia* *Casuarina* *Dodonaea* Myoporaceae (*Eremophila* & *Myoporum*) Myrtaceae A (*Eucalyptus* & *Melaleuca*) Myrtaceae B (*Corymbia*) *Owenia* *Psydrax* *Schinus*
CHEMICAL OBSERVATIONS		
Sub-key to a Selection of Arid Australian Hardwoods	Heartwood, not fluorescent Heartwood, froth test negative Heartwood, ethanol extract not fluorescent Heartwood, ethanol extract colourless Heartwood, water extract discoloured	**12 taxa remaining** *Anthobolus* *Bauhinia* *Capparis* *Casuarina* Myoporaceae (*Eremophila* & *Myoporum*) Myrtaceae A (*Eucalyptus* & *Melaleuca*) Myrtaceae B (*Corymbia*) *Owenia* Proteaceae (*Grevillea* & *Hakea*) *Psydrax* *Schinus* *Tamarix*
ANATOMICAL: ENDGRAIN (LIGHT MICROSCOPY)		
Sub-key to a Selection of Arid Australian Hardwoods	Vessels, solitary Vessels, not in radial multiples of 4 or more Vessels, not in clusters Vessels, not in tangential bands Rays, not distinctly wider than vessels Rays, not of two distinct widths	**8 taxa remaining** *Anthobolus* *Bauhinia* *Casuarina* Myrtaceae A (*Eucalyptus* & *Melaleuca*) *Santalum* *Acacia* *Capparis* Myrtaceae B (*Corymbia*)
ANATOMICAL: SCANNING ELECTRON MICROSCOPY		
Sub-key to a Selection of Arid Australian Hardwoods	Vessels, diameter: #:10-47 µm Vessels, difference in diameters: #:25-37 µm Vessels, >100 per square mm Vessels, solitary Vessels, not in radial multiples Vessels, not in clusters Vessels, not in tangential bands Vessels, vessel to vessel pits vestured Vessels, helical thickenings absent Parenchyma, diffuse to diffuse-in-aggregate (apotracheal) Parenchyma, scanty to vasicentric (paratracheal) Parenchyma, not in a wing-like to confluent sheath Parenchyma, not banded Rays, height: #:116-216 µm Rays, difference in heights: #:46-99 µm Rays, number of cells wide: #:1-3 cells wide Rays, not exclusively one cell wide	**1 taxon remaining** Myrtaceae A (*Eucalyptus* & *Melaleuca*)

	Rays, with uniseriate rays present Rays, <4 per mm Rays, 4 - 12 per mm Rays, >12 per mm Fibres/tracheids, with numerous, distinctly bordered pits present Rays, not distinctly wider than vessels Rays, not of two distinct widths	
Sub-key to Myrtaceae A (*Eucalyptus* & *Melaleuca*)	Vessels, diameter: #:10-47 µm Vessels, difference in diameters: #:25-37 µm Vessels, >100 per square mm Parenchyma, diffuse to diffuse-in-aggregate (apotracheal) Parenchyma, scanty to vasicentric (paratracheal) Parenchyma, not in a wing-like to confluent sheath Parenchyma, not banded Rays, height: #:116-216 µm Rays, difference in heights: #:46-99 µm Rays, number of cells wide: #:1-3 cells wide Rays, not exclusively one cell wide Rays, <4 per mm Rays, 4 - 12 per mm Rays, >12 per mm	**No taxa remaining**
ALL CHARACTER SETS		
Sub-key to a Selection of Arid Australian Hardwoods	All of the above	**1 taxon remaining** Myrtaceae A (*Eucalyptus* & *Melaleuca*)
Sub-key to Myrtaceae A (*Eucalyptus* & *Melaleuca*)	All of the above	**No taxa remaining**

Specimen F

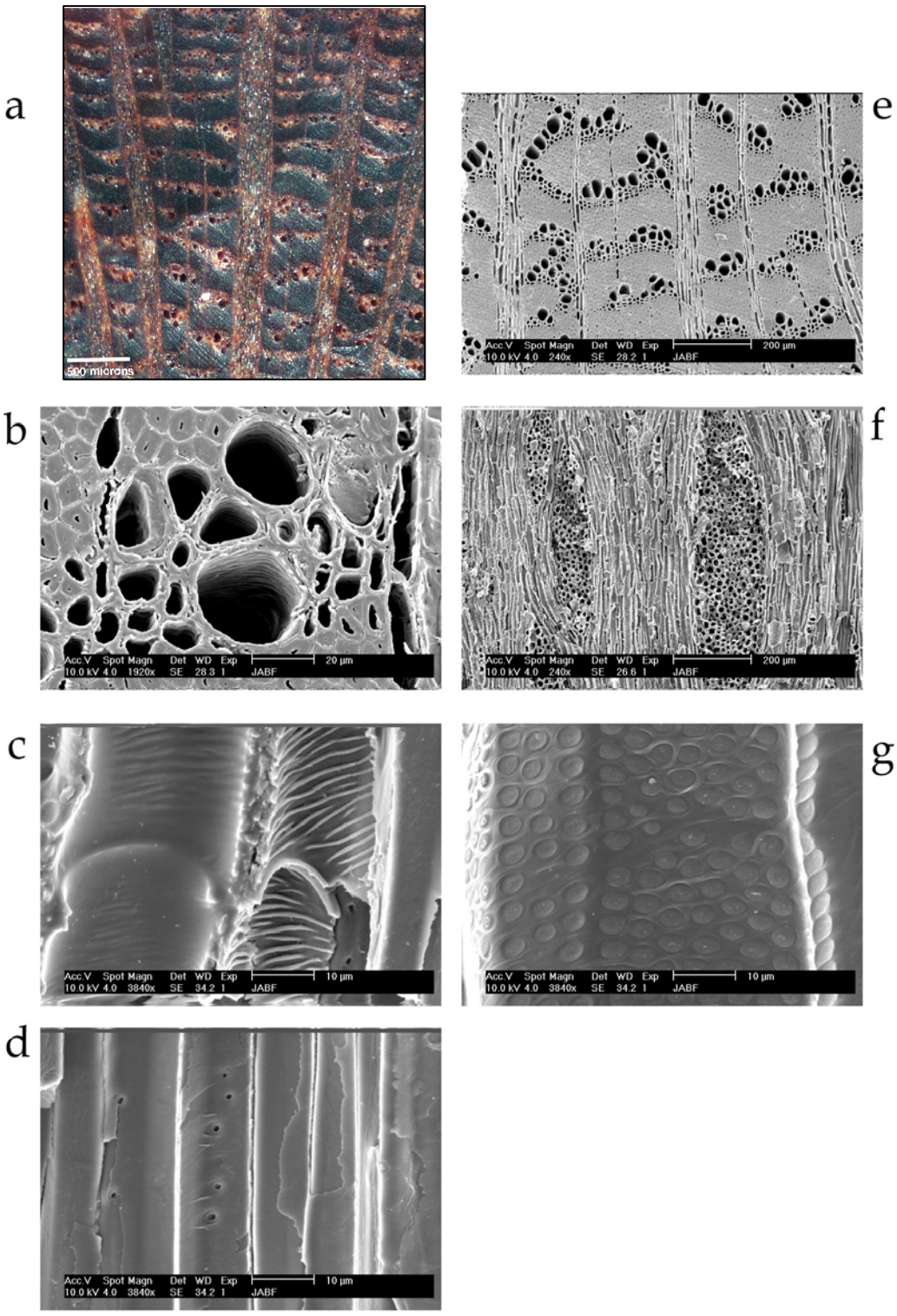

Figure 71 Test Specimen F. A. Endgrain image (scale = 500 µm); B. Vessels in clusters (XS) (scale = 20 µm); C. Simple perforation rim, helical thickenings (RLS) (scale = 10 µm); D. Fibres/tracheids with simple pits (RLS) (scale = 10 µm); E. Transverse surface, parenchyma banded, vessels in tangential bands (XS) (scale = 200 µm); F. Tangential surface with wide multiseriate rays (TLS) (scale = 200 µm); G. Vessel-vessel pits (RLS) (scale = 10 µm).

Table. Results of test using Specimen F.

Applied key/sub-key	Selected character states	Taxa remaining
PHYSICAL PROPERTIES		
Sub-key to a Selection of Arid Australian Hardwoods	Heartwood, colour clearly distinct from sapwood colour Rays, distinctly visible on cross-section with naked eye Rays, fleck visible on longitudinal surface with naked eye Kino (gum deposits), not visible to the naked eye Heartwood, colour not purple Heartwood, not fluorescent Heartwood, odour not distinctly evident from freshly cut wood	**3 taxa remaining** *Capparis* Proteaceae (*Grevillea* & *Hakea*) *Tamarix*
CHEMICAL OBSERVATIONS		
Sub-key to a Selection of Arid Australian Hardwoods	Heartwood, not fluorescent Heartwood, froth test negative Heartwood, ethanol extract not fluorescent Heartwood, ethanol extract discoloured Heartwood, water extract discoloured	**11 taxa remaining** *Anthobolus* *Bauhinia* *Capparis* *Casuarina* Myoporaceae (*Eremophila* & *Myoporum*) Myrtaceae A (*Eucalyptus* & *Melaleuca*) Myrtaceae B (*Corymbia*) Proteaceae (*Grevillea* & *Hakea*) *Psydrax* *Schinus* *Tamarix*
ANATOMICAL: ENDGRAIN (LIGHT MICROSCOPY)		
Sub-key to a Selection of Arid Australian Hardwoods	Vessels, in tangential bands Parenchyma, banded Rays, distinctly wider than vessels Rays, of two distinct widths Banded parenchyma, unbroken Banded parenchyma, with a bandwidth not commonly larger than ray width Banded parenchyma, in bands not commonly further apart than rays Parenchyma, not in marginal bands Parenchyma, not in a wing-like to confluent sheath Vessels, not solitary Vessels, not in radial multiples Vessels, not in radial multiples of 4 or more	**1 taxon remaining** Proteaceae (*Grevillea* & *Hakea*)
Sub-key to Proteaceae (*Grevillea* & *Hakea*)	Rays, distinctly wider than vessels Banded parenchyma, with a bandwidth not commonly larger than ray width	**4 taxa remaining** *Grevillea juncifolia* ssp. *juncifolia* *Grevillea striata* *Hakea eyreana* *Hakea leucoptera* ssp. *leucoptera*
ANATOMICAL: SCANNING ELECTRON MICROSCOPY		
Sub-key to a Selection of Arid Australian Hardwoods	Vessels, diameter: #:11-63 µm Vessels, difference in diameters: #:22-51 µm Vessels, >100 per square mm Vessels, not solitary Vessels, not in radial multiples Vessels, in tangential bands Vessels, simple perforation rim prominent (and often wide) Vessels, helical thickenings present Parenchyma, not diffuse to diffuse-in-aggregate Parenchyma, not scanty to vasicentric Parenchyma, not in a wing-like to confluent sheath Parenchyma, banded Parenchyma, not in marginal bands Rays, number of cells wide: #:5-17 cells wide	**1 taxon remaining** Proteaceae (*Grevillea* & *Hakea*)

	Rays, not exclusively one cell wide Rays, with uniseriate rays absent Rays, number per mm: Rays, <4 per mm Rays, number per mm: Rays, 4 - 12 per mm Rays, distinctly wider than vessels Rays, of two distinct widths	
Sub-key to Proteaceae (*Grevillea* & *Hakea*)	Vessels, diameter: #:11-63 µm Vessels, difference in diameters: #:22-51 µm Vessels, >100 per square mm Vessels, helical thickenings present Rays, number of cells wide: #:5-17 cells wide Rays, <4 per mm Rays, 4 - 12 per mm Rays, distinctly wider than vessels	**3 taxa remaining** *Grevillea juncifolia* ssp. *juncifolia* *Hakea leucoptera* ssp. *leucoptera* *Hakea eyreana*
ALL CHARACTER SETS		
Sub-key to a Selection of Arid Australian Hardwoods	All of the above	**1 taxon remaining** Proteaceae (*Grevillea* & *Hakea*)
Sub-key to Proteaceae (*Grevillea* & *Hakea*)	All of the above	**1 taxon remaining** *Hakea eyreana*

Specimen G

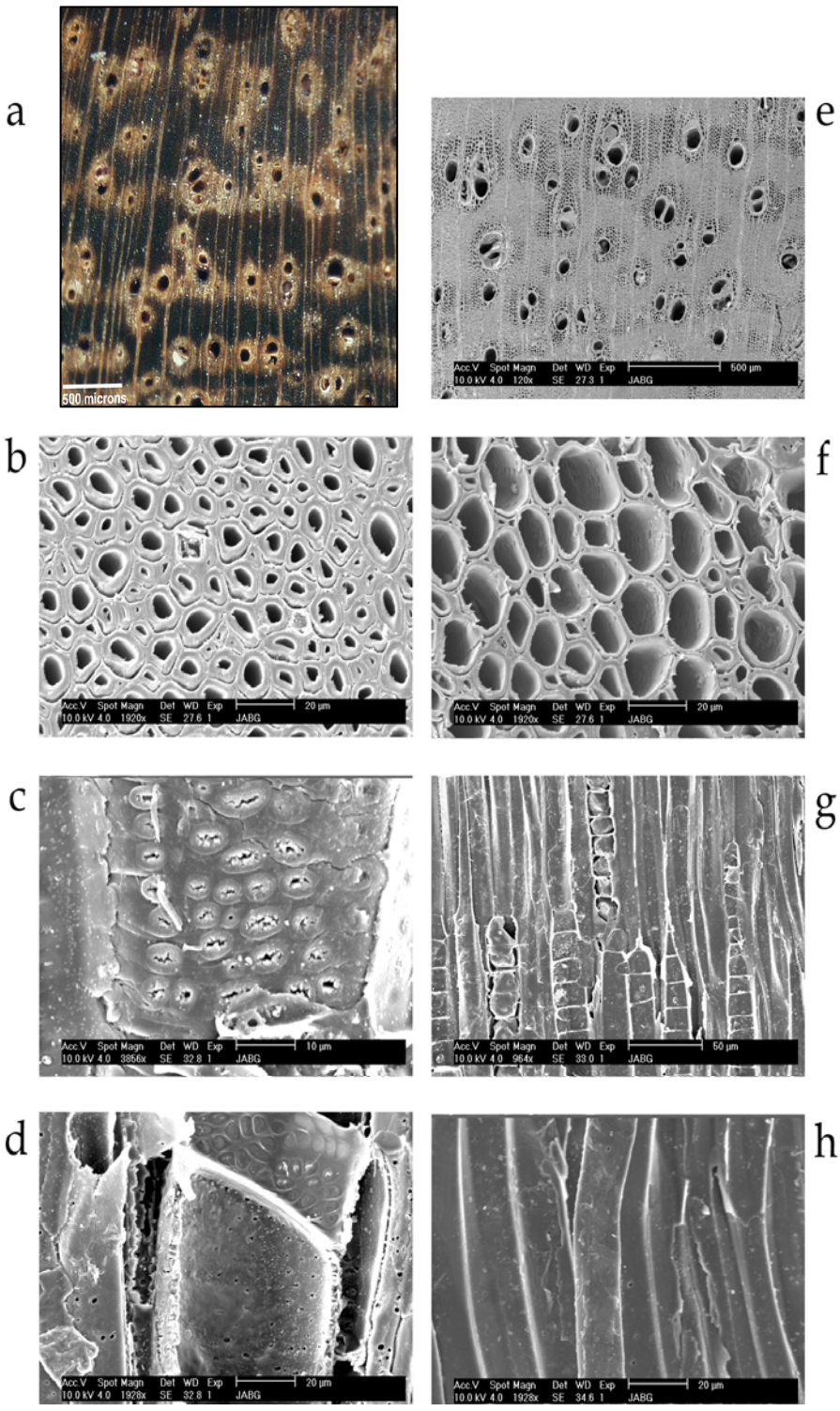

Figure 72 Test Specimen G. A. Endgrain image (scale = 500 µm); B. Fibres (XS) (scale = 20 µm); C. Vestured vessel-vessel pits (RLS) (scale = 10 µm); D. Simple perforation rim (RLS) (scale = 20 µm); E. Transverse surface, vessels in radial multiples, parenchyma banded (XS) (scale = 500 µm); F. Parenchyma (XS) (scale = 20 µm); G. Chambered axial parenchyma (scale = 50 µm); H. Fibres/tracheids with simple pits (RLS) (scale = 20 µm).

Table. Results of test using Specimen G.

Applied key/sub-key	Selected character states	Taxa remaining
PHYSICAL PROPERTIES		
Sub-key to a Selection of Arid Australian Hardwoods	Kino (gum deposits), not visible to the naked eye Rays, fleck not visible on longitudinal surface with naked eye Rays, not distinctly visible on cross-section with naked eye Heartwood, colour clearly distinct from sapwood colour Heartwood, colour not purple Heartwood, fluorescent Heartwood, odour not distinctly evident from freshly cut wood	**11 taxa remaining** *Acacia* *Anthobolus* *Bauhinia* *Casuarina* Myoporaceae (*Eremophila* & *Myoporum*) Myrtaceae A (*Eucalyptus* & *Melaleuca*) Myrtaceae B (*Corymbia*) *Psydrax* *Schinus* *Senna* *Ventilago*
CHEMICAL OBSERVATIONS		
Sub-key to a Selection of Arid Australian Hardwoods	Heartwood, fluorescent Heartwood, froth test negative Heartwood, ethanol extract not fluorescent Heartwood, ethanol extract colourless Heartwood, water extract discoloured	**12 taxa remaining** *Acacia* *Anthobolus* *Bauhinia* *Capparis* *Casuarina* Myoporaceae (*Eremophila* & *Myoporum*) Myrtaceae A (*Eucalyptus* & *Melaleuca*) Myrtaceae B (*Corymbia*) Proteaceae (*Grevillea* & *Hakea*) *Psydrax* *Schinus* *Tamarix*
ANATOMICAL: ENDGRAIN (LIGHT MICROSCOPY)		
Sub-key to a Selection of Arid Australian Hardwoods	Vessels, not solitary Vessels, in radial multiples Vessels, not in radial multiples of 4 or more Vessels, not in clusters Vessels, not in tangential bands Parenchyma, in a wing-like to confluent sheath (paratracheal) Banded parenchyma, broken Banded parenchyma, with a bandwidth commonly larger than ray width Rays, not distinctly wider than vessels Rays, not of two distinct widths Parenchyma, banded	**4 taxa remaining** *Acacia* *Atalaya* Myoporaceae (*Eremophila* & *Myoporum*) Myrtaceae B (*Corymbia*)
ANATOMICAL: SCANNING ELECTRON MICROSCOPY		
Sub-key to a Selection of Arid Australian Hardwoods	Vessels, diameter: #:25-147 µm Vessels, difference in diameters: #:50-122 µm Vessels, < 50 per square mm Vessels, not solitary Vessels, in radial multiples Vessels, not in radial multiples of 4 or more Vessels, not in clusters Vessels, not in tangential bands Vessels, vessel to vessel pits vestured Vessels, helical thickenings absent Vessels, simple perforation rim not prominent Parenchyma, not diffuse to diffuse-in-aggregate Parenchyma, not scanty to vasicentric	**1 taxon remaining** *Acacia*

	Parenchyma, in a wing-like to confluent sheath (paratracheal) Parenchyma, banded Parenchyma, chambered (and often with crystals) Rays, height: #:66-423 µm Rays, difference in heights: #:172-356 µm Rays, number of cells wide: #:1-4 cells wide Rays, not exclusively one cell wide Rays, with uniseriate rays present Rays, number per mm: Rays, 4 - 12 per mm Rays, number per mm: Rays, >12 per mm Fibres/tracheids, with numerous, distinctly bordered pits not present Rays, not distinctly wider than vessels Rays, not of two distinct widths	
Sub-key to *Acacia*	S Vessels, diameter: #:25-147 µm S Vessels, difference in diameters: #:50-122 µm Vessels, < 50 per square mm Vessels, not solitary Vessels, in radial multiples Vessels, not in radial multiples of 4 or more Parenchyma, not diffuse to diffuse-in-aggregate Parenchyma, not scanty to vasicentric Parenchyma, in a wing-like to confluent sheath (paratracheal) Parenchyma, banded S Rays, height: #:66-423 µm S Rays, difference in heights: #:172-356 µm S Rays, number of cells wide: #:1-4 cells wide S Rays, number per mm: Rays, 4 - 12 per mm S Rays, number per mm: Rays, >12 per mm	**12 taxa remaining** *Acacia cana* *Acacia farnesiana* *Acacia stenophylla* *Acacia victoriae* ssp. *victoriae* *Acacia ligulata* ?intergrade with *A. bivenosa* *Acacia ligulata* *Acacia peuce* *Acacia cambagei* *Acacia murrayana* *Acacia oswaldii* *Acacia pickardii* *Acacia salcina*
ALL CHARACTER SETS		
Sub-key to a Selection of Arid Australian Hardwoods	All of the above	**1 taxon remaining** *Acacia*
Sub-key to *Acacia*	All of the above	**1 taxon remaining** None

Specimen H

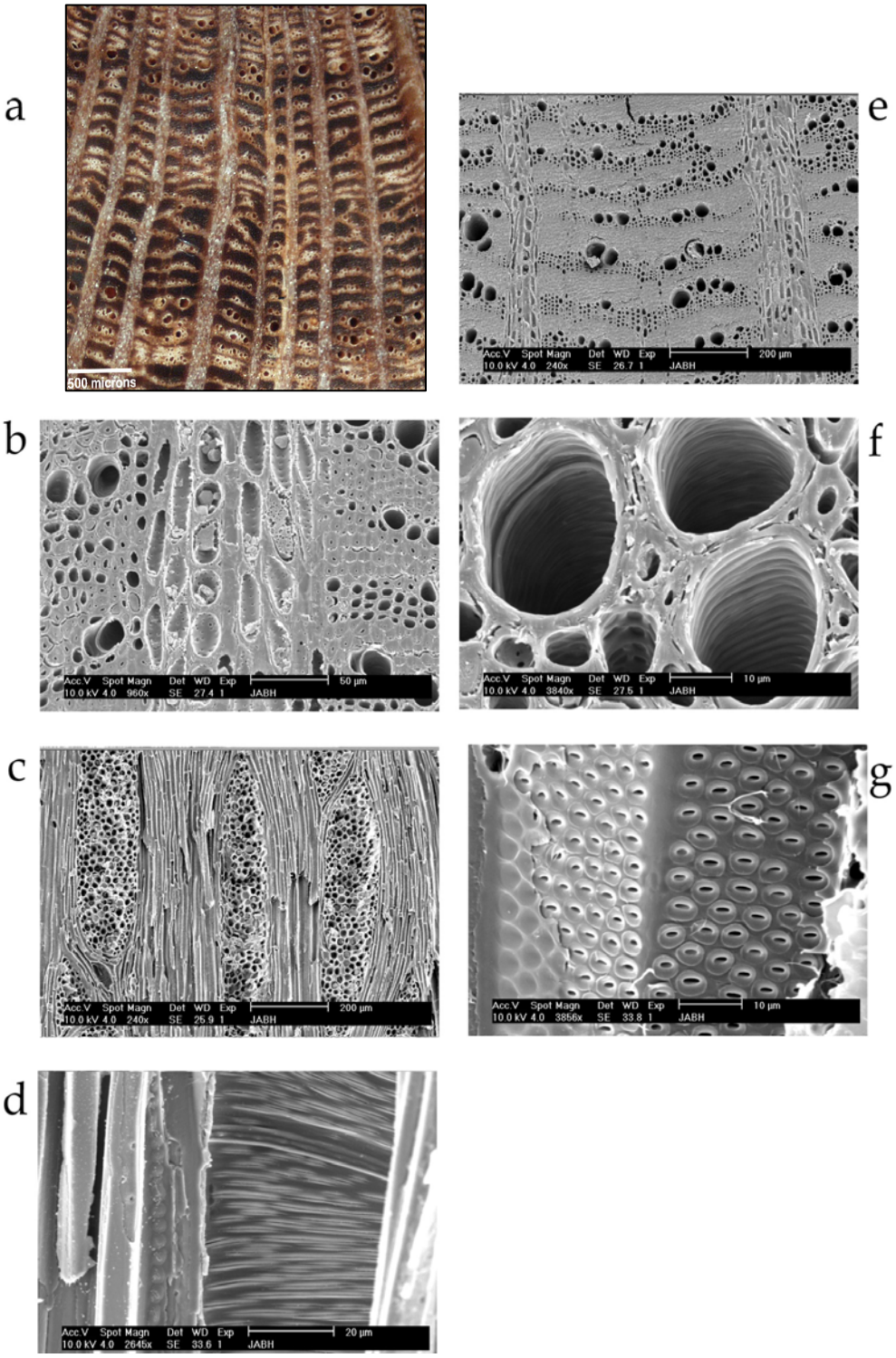

Figure 73 Test Specimen H. A. Endgrain image (scale = 500 µm); B. Vessels in tangential bands, parenchyma banded (XS) (scale = 50 µm); C. Wide multiseriate rays (TLS) (scale = 200 µm); D. Simple perforation rim, helical thickenings (RLS) (scale = 20 µm); E. Transverse surface (XS) (scale = 200 µm); F. Vessels, parenchyma cells (TLS) (scale = 10 µm); G. Vessel-vessel pits (RLS) (scale = 10 µm).

Table. Results of test using Specimen H.

Applied key/sub-key	Selected character states	Taxa remaining
PHYSICAL PROPERTIES		
Sub-key to a Selection of Arid Australian Hardwoods	Rays, distinctly visible on cross-section with naked eye Rays, fleck visible on longitudinal surface with naked eye Kino (gum deposits), not visible to the naked eye	**3 taxa remaining** *Capparis* Proteaceae (*Grevillea* & *Hakea*) *Tamarix*
CHEMICAL OBSERVATIONS		
Heartwood on specimen H was either absent or visually indiscernible from sapwood; since all chemical observations in the tool are heartwood-dependent this set was not applied to this specimen.		
ANATOMICAL: ENDGRAIN (LIGHT MICROSCOPY)		
Sub-key to a Selection of Arid Australian Hardwoods	Vessels, not solitary Vessels, not in radial multiples Vessels, not in radial multiples of 4 or more Vessels, in tangential bands Parenchyma, not in a wing-like to confluent sheath Parenchyma, not in marginal bands Parenchyma, banded Banded parenchyma, unbroken Banded parenchyma, with a bandwidth not commonly larger than ray width Rays, distinctly wider than vessels Rays, of two distinct widths Banded parenchyma, in bands not commonly further apart than rays	**1 taxon remaining** Proteaceae (*Grevillea* & *Hakea*)
Sub-key to Proteaceae (*Grevillea* & *Hakea*)	Banded parenchyma, with a bandwidth not commonly larger than ray width Rays, distinctly wider than vessels	**4 taxa remaining** *Grevillea juncifolia* ssp. *juncifolia* *Grevillea striata* *Hakea eyreana* *Hakea leucoptera* ssp. *leucoptera*
ANATOMICAL: SCANNING ELECTRON MICROSCOPY		
Sub-key to a Selection of Arid Australian Hardwoods	S Vessels, diameter: #:15-99 µm S Vessels, difference in diameters: #:46-83 µm Vessels, >100 per square mm Vessels, not solitary Vessels, not in radial multiples Vessels, in tangential bands Vessels, vessel to vessel pits not vestured Vessels, helical thickenings present Vessels, simple perforation rim prominent (and often wide) Parenchyma, not diffuse to diffuse-in-aggregate Parenchyma, not scanty to vasicentric Parenchyma, not in a wing-like to confluent sheath Parenchyma, banded S Rays, number of cells wide: #:7-12 cells wide Rays, with uniseriate rays absent Rays, not exclusively one cell wide Rays, <4 per mm Rays, 4 - 12 per mm Rays, distinctly wider than vessels Rays, of two distinct widths	**1 taxon remaining** Proteaceae (*Grevillea* & *Hakea*)
Sub-key to Proteaceae (*Grevillea* & *Hakea*)	S Vessels, diameter: #:15-99 µm S Vessels, difference in diameters: #:46-83 µm S Vessels, number per square mm: Vessels, >100 per square mm S Vessels, helical thickenings present or not: Vessels, helical thickenings present S Rays, number of cells wide: #:7-12 cells wide S Rays, number per mm: Rays, <4 per mm S Rays, number per mm: Rays, 4 - 12 per mm	**4 taxa remaining** *Grevillea juncifolia* ssp. *juncifolia* *Grevillea striata* *Hakea eyreana* *Hakea leucoptera* ssp. *leucoptera*

	SE Rays, distinctly wider than vessels or not: Rays, distinctly wider than vessels	
ALL CHARACTER SETS		
Sub-key to a Selection of Arid Australian Hardwoods	All of the above	**1 taxon remaining** Proteaceae (*Grevillea* & *Hakea*)
Sub-key to Proteaceae (*Grevillea* & *Hakea*)	All of the above	**4 taxa remaining** *Grevillea juncifolia* ssp. *juncifolia* *Grevillea striata* *Hakea eyreana* *Hakea leucoptera* ssp. *leucoptera*

Specimen I

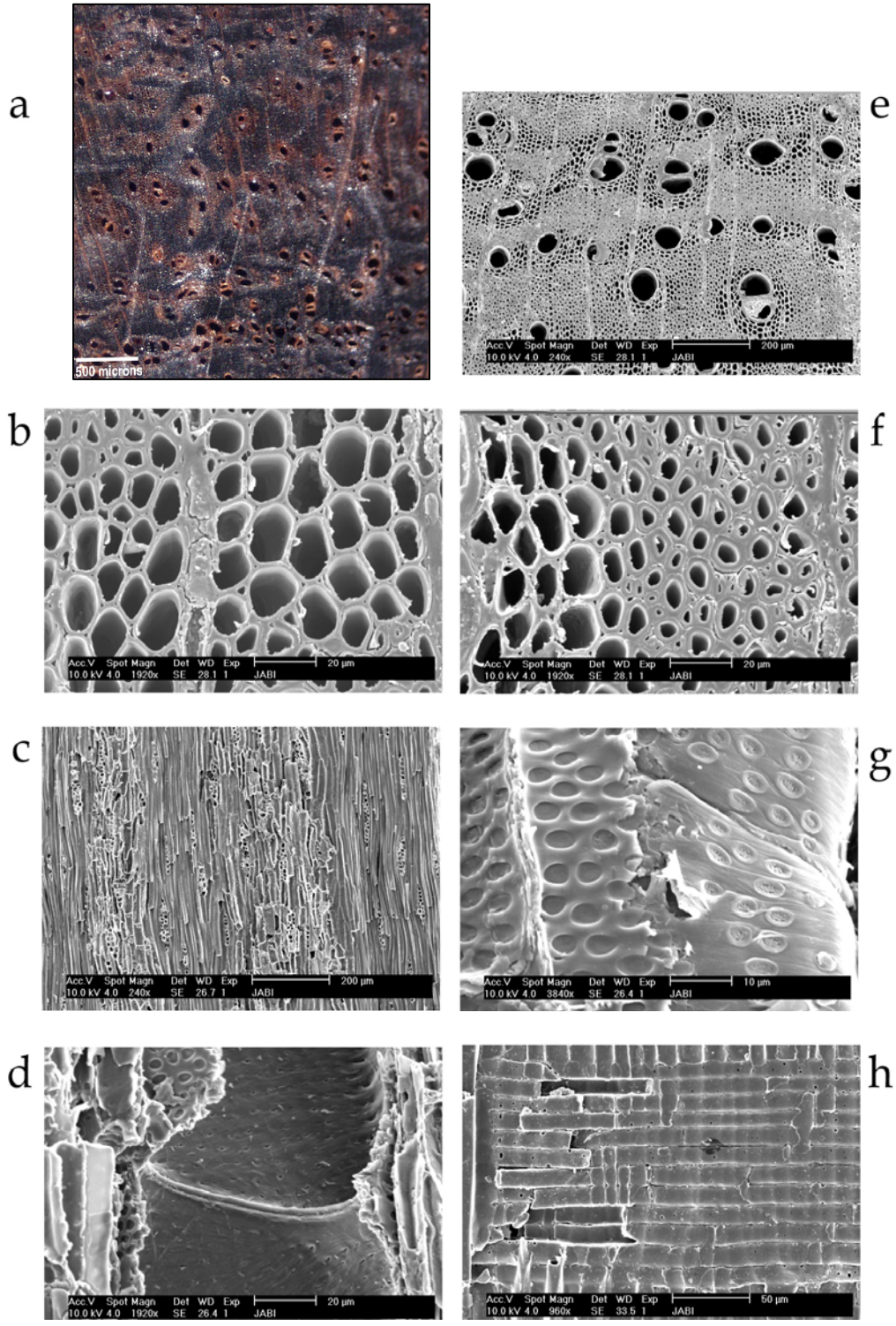

Figure 74 Test Specimen I. A. Endgrain image (scale = 500 µm); B. Parenchyma cells (XS) (scale = 20 µm); C. Tangential surface (TLS) (scale = 200 µm); D. Simple perforation rim (TLS) (scale = 20 µm); E. Transverse surface, vessels in radial multiples, parenchyma confluent to banded (XS) (scale = 200 µm); F. Parenchyma/fibre cells (XS) (scale = 20 µm); G. Vestured vessel-vessel pits (TLS) (scale = 10 µm); H. Homocellular rays (RLS) (scale = 50 µm).

Table. Results of test using Specimen I.

Applied key/sub-key	Selected character states	Taxa remaining
PHYSICAL PROPERTIES		
Sub-key to a Selection of Arid Australian Hardwoods	Kino (gum deposits), not visible to the naked eye Rays, fleck not visible on longitudinal surface with naked eye Rays, not distinctly visible on cross-section with naked eye Heartwood, colour clearly distinct from sapwood colour Heartwood, colour not purple Heartwood, fluorescent Heartwood, odour not distinctly evident from freshly cut wood	**11 taxa remaining** *Acacia* *Anthobolus* *Bauhinia* *Casuarina* Myoporaceae (*Eremophila* & *Myoporum*) Myrtaceae A (*Eucalyptus* & *Melaleuca*) Myrtaceae B (*Corymbia*) *Psydrax* *Schinus* *Senna* *Ventilago*
CHEMICAL OBSERVATIONS		
Sub-key to a Selection of Arid Australian Hardwoods	Heartwood, fluorescent Heartwood, froth test positive Heartwood, ethanol extract not fluorescent Heartwood, ethanol extract discoloured Heartwood, water extract discoloured	**12 taxa remaining** *Acacia* *Anthobolus* *Bauhinia* *Capparis* *Casuarina* Myoporaceae (*Eremophila* & *Myoporum*) Myrtaceae A (*Eucalyptus* & *Melaleuca*) Myrtaceae B (*Corymbia*) Proteaceae (*Grevillea* & *Hakea*) *Psydrax* *Schinus* *Tamarix*
ANATOMICAL: ENDGRAIN (LIGHT MICROSCOPY)		
Sub-key to a Selection of Arid Australian Hardwoods	Vessels, not solitary Vessels, in radial multiples Vessels, not in radial multiples of 4 or more Vessels, not in clusters Vessels, not in tangential bands Parenchyma, in a wing-like to confluent sheath (paratracheal) Banded parenchyma, broken Banded parenchyma, with a bandwidth commonly larger than ray width Rays, not distinctly wider than vessels Rays, not of two distinct widths Parenchyma, banded	**4 taxa remaining** *Acacia* *Atalaya* Myoporaceae (*Eremophila* & *Myoporum*) Myrtaceae B (*Corymbia*)
ANATOMICAL: SCANNING ELECTRON MICROSCOPY		
Sub-key to a Selection of Arid Australian Hardwoods	Vessels, diameter: #:20-91 µm Vessels, difference in diameters: #:39-71 µm Vessels, < 50 per square mm Vessels, not solitary Vessels, in radial multiples Vessels, not in radial multiples of 4 or more Vessels, not in clusters Vessels, not in tangential bands Vessels, vessel to vessel pits vestured Vessels, helical thickenings absent Parenchyma, not diffuse to diffuse-in-aggregate Parenchyma, not scanty to vasicentric Parenchyma, in a wing-like to confluent sheath (paratracheal)	**1 taxon remaining** *Acacia*

	Parenchyma, banded Rays, height: #:57-219 µm Rays, difference in heights: #:66-161 µm Rays, number of cells wide: #:1-3 cells wide Rays, not exclusively one cell wide Rays, with uniseriate rays present Rays, 4 - 12 per mm Rays, >12 per mm Fibres/tracheids, with numerous, distinctly bordered pits not present Rays, not distinctly wider than vessels Rays, not of two distinct widths Parenchyma, chambered (and often with crystals)	
Sub-key to *Acacia*	Vessels, diameter: #:20-91 µm Vessels, difference in diameters: #:39-71 µm Vessels, < 50 per square mm Vessels, not solitary Vessels, in radial multiples Vessels, not in radial multiples of 4 or more Parenchyma, not diffuse to diffuse-in-aggregate Parenchyma, not scanty to vasicentric Parenchyma, in a wing-like to confluent sheath (paratracheal) Parenchyma, banded Rays, height: #:57-219 µm Rays, difference in heights: #:66-161 µm Rays, number of cells wide: #:1-3 cells wide Rays, not exclusively one cell wide Rays, number per mm: Rays, 4 - 12 per mm Rays, number per mm: Rays, >12 per mm	**11 taxa remaining** ?*Acacia aneura* var. *intermedia* *Acacia cana* *Acacia petraea* *Acacia ligulata* ?intergrade with *A. bivenosa* *Acacia ligulata* *Acacia tetragonophylla* *Acacia peuce* *Acacia cambagei* *Acacia murrayana* *Acacia pickardii* *Acacia salcina*
ALL CHARACTER SETS		
Sub-key to a Selection of Arid Australian Hardwoods	All of the above	**1 taxon remaining** *Acacia*
Sub-key to *Acacia*	All of the above	**4 taxa remaining** *Acacia aneura* var. *intermedia* *Acacia cana* *Acacia pickardii* *Acacia salcina*

Specimen J

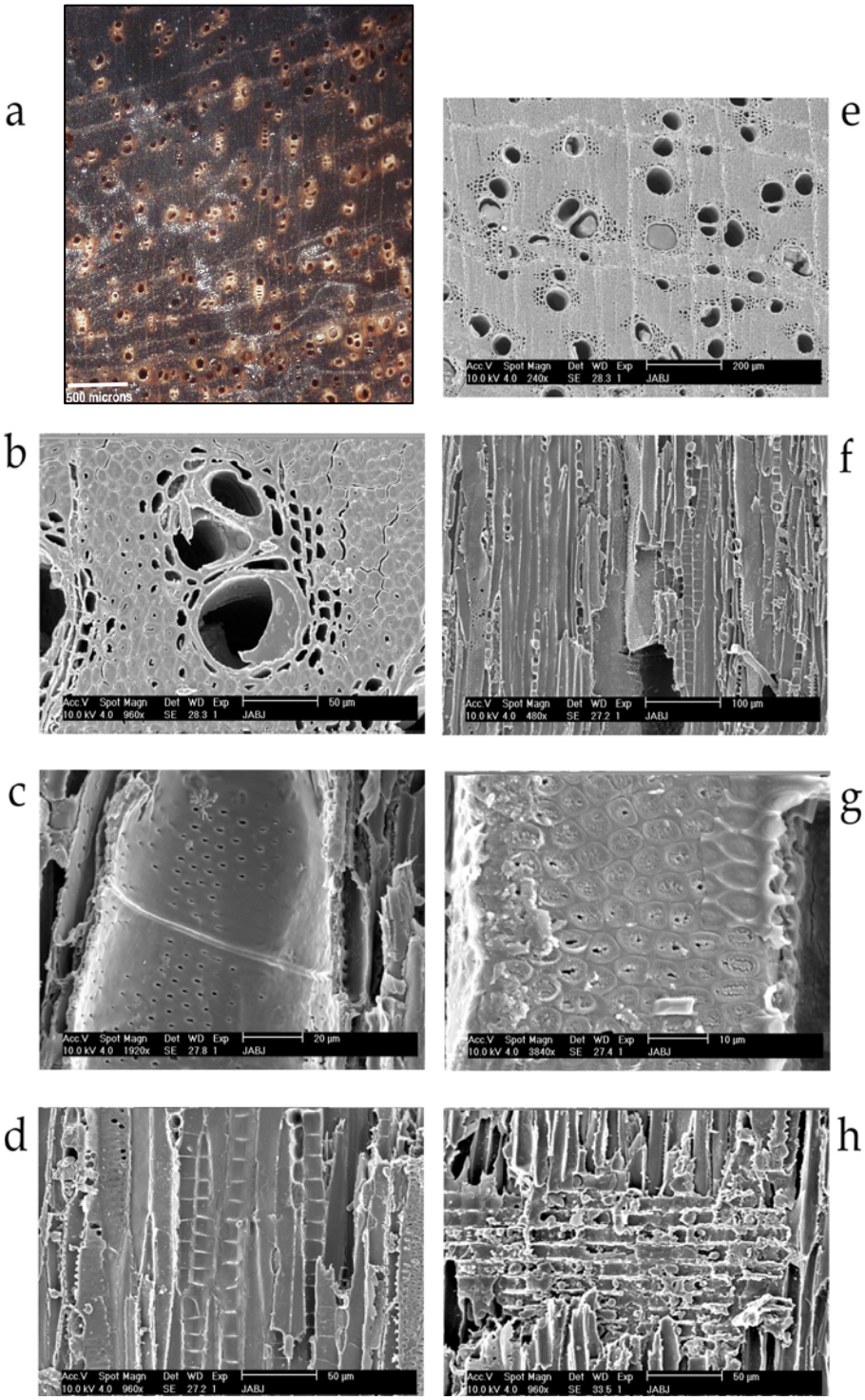

Figure 75 Test Specimen J. A. Endgrain image (scale = 500 µm); B. Vessels in radial multiples, parenchyma wing-like (XS) (scale = 50 µm); C. Simple perforation rim (TLS) (scale = 20 µm); D. Chambered axial parenchyma (TLS) (scale = 50 µm); E. Transverse surface, marginal bands of parenchyma, parenchyma wing-like to confluent (XS) (scale = 200 µm); F. Tangential surface (TLS) (scale = 100 µm); G. Vestured vessel-vessel pits (TLS) (scale = 10 µm); H. Ray cells (RLS) (scale = 50 µm).

Table. Results of test using Specimen J.

Applied key/sub-key	Selected character states	Taxa remaining
PHYSICAL PROPERTIES		
Sub-key to a Selection of Arid Australian Hardwoods	Kino (gum deposits), not visible to the naked eye Rays, fleck not visible on longitudinal surface with naked eye Rays, not distinctly visible on cross-section with naked eye Heartwood, colour clearly distinct from sapwood colour Heartwood, colour not purple Heartwood, fluorescent Heartwood, odour not distinctly evident from freshly cut wood	**11 taxa remaining** *Acacia* *Anthobolus* *Bauhinia* *Casuarina* Myoporaceae (*Eremophila* & *Myoporum*) Myrtaceae A (*Eucalyptus* & *Melaleuca*) Myrtaceae B (*Corymbia*) *Psydrax* *Schinus* *Senna* *Ventilago*
CHEMICAL OBSERVATIONS		
Sub-key to a Selection of Arid Australian Hardwoods	Heartwood, fluorescent Heartwood, froth test positive Heartwood, ethanol extract fluorescent Heartwood, ethanol extract colourless Heartwood, water extract discoloured	**12 taxa remaining** *Acacia* *Anthobolus* *Bauhinia* *Capparis* *Casuarina* Myoporaceae (*Eremophila* & *Myoporum*) Myrtaceae B (*Corymbia*) Proteaceae (*Grevillea* & *Hakea*) *Psydrax* *Schinus* *Tamarix* Myrtaceae A (*Eucalyptus* & *Melaleuca*)
ANATOMICAL: ENDGRAIN (LIGHT MICROSCOPY)		
Sub-key to a Selection of Arid Australian Hardwoods	Vessels, not solitary Vessels, in radial multiples Vessels, not in radial multiples of 4 or more Vessels, not in clusters Vessels, not in tangential bands Parenchyma, in a wing-like to confluent sheath (paratracheal) Parenchyma, in marginal bands Parenchyma, not banded Rays, not distinctly wider than vessels Rays, not of two distinct widths	**6 taxa remaining** *Acacia* *Atalaya* *Flindersia* Myoporaceae (*Eremophila* & *Myoporum*) Myrtaceae B (*Corymbia*) *Senna*
ANATOMICAL: SCANNING ELECTRON MICROSCOPY		
Sub-key to a Selection of Arid Australian Hardwoods	Vessels, diameter: #:14-93 µm Vessels, difference in diameters: #:58-79 µm Vessels, 50-100 per square mm Vessels, not solitary Vessels, in radial multiples Vessels, not in radial multiples of 4 or more Vessels, not in clusters Vessels, not in tangential bands Vessels, vessel to vessel pits vestured Vessels, helical thickenings absent Vessels, simple perforation rim not prominent Parenchyma, not diffuse to diffuse-in-aggregate Parenchyma, in a wing-like to confluent sheath (paratracheal) Parenchyma, not banded Parenchyma, in marginal bands	**1 taxon remaining** *Acacia*

	Parenchyma, chambered (and often with crystals) Rays, height: #:50-176 µm Rays, difference in heights: #:62-125 µm Rays, number of cells wide: #:1-2 cells wide Rays, not exclusively one cell wide Rays, with uniseriate rays present Rays, number per mm: Rays, 4 - 12 per mm Rays, number per mm: Rays, >12 per mm Rays, not distinctly wider than vessels Rays, not of two distinct widths	
Sub-key to *Acacia*	Vessels, diameter: #:14-93 µm Vessels, difference in diameters: #:58-79 µm Vessels, 50-100 per square mm Vessels, not solitary Vessels, in radial multiples Vessels, not in radial multiples of 4 or more Parenchyma, not diffuse to diffuse-in-aggregate Parenchyma, in a wing-like to confluent sheath (paratracheal) Parenchyma, not banded Rays, height: #:50-176 µm Rays, difference in heights: #:62-125 µm Rays, number of cells wide: #:1-2 cells wide Rays, not exclusively one cell wide Rays, 4 - 12 per mm Rays, >12 per mm	**3 taxa remaining** *Acacia tetragonophylla* *Acacia cambagei* *Acacia murrayana*
ALL CHARACTER SETS		
Sub-key to a Selection of Arid Australian Hardwoods	All of the above	**1 taxon remaining** *Acacia*
Sub-key to *Acacia*	All of the above	**No taxa remaining**

Appendix Nine. Results of test of identification tool by a novice user

Specimen A

Table. Results of test using Specimen A.

Applied key/sub-key	Selected character states	Taxa remaining
PHYSICAL PROPERTIES		
Sub-key to a Selection of Arid Australian Hardwoods	Density, very dense > 1000 kg/m^3 Rays, fleck not visible on longitudinal surface with naked eye Rays, not distinctly visible on cross-section with naked eye	**15 taxa remaining** *Acacia* *Anthobolus* *Atalaya* *Bauhinia* *Casuarina* *Dodonaea* *Flindersia* Myoporaceae Myrtaceae A Myrtaceae B *Owenia* *Psydrax* *Santalum* *Senna* *Ventilago*
CHEMICAL OBSERVATIONS		
Sub-key to a Selection of Arid Australian Hardwoods	Heartwood, fluorescent Heartwood, froth test positive Heartwood, ethanol extract not fluorescent Heartwood, ethanol extract discoloured Heartwood, water extract discoloured	**12 taxa remaining** *Acacia* *Anthobolus* *Bauhinia* *Capparis* *Casuarina* Myoporaceae Myrtaceae A Myrtaceae B Proteaceae *Psydrax* *Schinus* *Tamarix*
ANATOMICAL: ENDGRAIN (LIGHT MICROSCOPY)		
Sub-key to a Selection of Arid Australian Hardwoods	Heartwood, vessels not commonly with tyloses Vessels, solitary Rays, not of two distinct widths Rays, not distinctly wider than vessels Vessels, not in tangential bands Parenchyma, not banded Parenchyma, not in marginal bands	**6 taxa remaining** *Anthobolus* Myrtaceae A (*Eucalyptus* & *Melaleuca*) *Santalum* *Acacia* *Capparis* Myrtaceae B (*Corymbia*)
ANATOMICAL: SCANNING ELECTRON MICROSCOPY		
Sub-key to a Selection of Arid Australian Hardwoods	S Vessels, diameter: #:15-50 µm S Vessels, difference in diameters: #:35 µm S Rays, height: #:50-70 µm S Rays, difference in heights: #:20 µm S Rays, number of cells wide: #:1 cells wide Rays, with uniseriate rays present Rays, exclusively one cell wide (uniseriate) Rays, cells homocellular (procumbent only) Vessels, solitary Vessels, not solitary Vessels, in radial multiples Vessels, not in radial multiples of 4 or more Parenchyma, not banded Parenchyma, not in marginal bands	**1 taxon remaining** *Acacia*

	Parenchyma, chambered (and often with crystals) Vessels, vessel to vessel pits vestured Rays, 4 - 12 per mm Rays, not in horizontal rows Rays, not distinctly wider than vessels Rays, not of two distinct widths	
Sub-key to *Acacia*	S Vessels, diameter: #:15-50 µm S Vessels, difference in diameters: #:35 µm S Rays, height: #:50-70 µm S Rays, difference in heights: #:20 µm S Rays, number of cells wide: #:1 cells wide Rays, exclusively one cell wide (uniseriate) Vessels, solitary Vessels, not solitary Vessels, in radial multiples Vessels, not in radial multiples of 4 or more Parenchyma, not banded Rays, 4 - 12 per mm	**No remaining taxa**
ALL CHARACTER SETS		
Sub-key to a Selection of Arid Australian Hardwoods	All of the above	**1 taxon remaining** *Acacia*
Sub-key to *Acacia*	All of the above	**No remaining taxa**

Specimen B

Table. Results of test using Specimen B.

Applied key/sub-key	Selected character states	Taxa remaining
PHYSICAL PROPERTIES		
Sub-key to a Selection of Arid Australian Hardwoods	Kino (gum deposits), not visible to the naked eye Rays, fleck not visible on longitudinal surface with naked eye Rays, not distinctly visible on cross-section with naked eye Heartwood, colour clearly distinct from sapwood colour	**13 taxa remaining** *Acacia* *Anthobolus* *Bauhinia* *Casuarina* *Dodonaea* Myoporaceae Myrtaceae A Myrtaceae B *Owenia* *Psydrax* *Schinus* *Senna* *Ventilago*
CHEMICAL OBSERVATIONS		
Sub-key to a Selection of Arid Australian Hardwoods	Heartwood, froth test positive Heartwood, ethanol extract not fluorescent Heartwood, not fluorescent Heartwood, water extract discoloured Heartwood, ethanol extract discoloured	**11 taxa remaining** *Anthobolus* *Bauhinia* *Capparis* *Casuarina* Myoporaceae Myrtaceae A Myrtaceae B Proteaceae *Psydrax* *Schinus* *Tamarix*
ANATOMICAL: ENDGRAIN (LIGHT MICROSCOPY)		
Sub-key to a Selection of Arid Australian Hardwoods	Heartwood, vessels commonly with tyloses Parenchyma, not banded Rays, not distinctly wider than vessels Rays, not of two distinct widths	**9 taxa remaining** *Anthobolus* *Capparis* *Flindersia* Myoporaceae Myrtaceae A Myrtaceae B *Psydrax* *Schinus* *Tamarix*
ANATOMICAL: SCANNING ELECTRON MICROSCOPY		
*A*Sub-key to a Selection of Arid Australian Hardwoods	S Vessels, diameter: #:37-100 µm S Vessels, difference in diameters: #:63 µm Vessels, 50-100 per square mm Vessels, < 50 per square mm Vessels, solitary Vessels, not in radial multiples Vessels, not in clusters Vessels, not in tangential bands Parenchyma, not banded Parenchyma, not in marginal bands Heartwood, vessels commonly with tyloses Rays, not distinctly wider than vessels Rays, not of two distinct widths Parenchyma, not in a wing-like to confluent sheath Vessels, vessel to vessel pits vestured Fibres/tracheids, with numerous, distinctly bordered pits	**1 taxon remaining** Myrtaceae A (*Eucalyptus & Melaleuca*)

	present S Rays, height: #:150-250 µm S Rays, difference in heights: #:100 µm Rays, cells heterocellular (procumbent and upright) Rays, >12 per mm	
Sub-key to Myrtaceae A (*Eucalyptus & Melaleuca*)	S Vessels, diameter: #:37-100 µm S Vessels, difference in diameters: #:63 µm Vessels, 50-100 per square mm Vessels, < 50 per square mm Parenchyma, not banded Parenchyma, not in marginal bands Parenchyma, not in a wing-like to confluent sheath S Rays, height: #:150-250 µm S Rays, difference in heights: #:100 µm Rays, >12 per mm S Rays, not exclusively one cell wide	**4 taxa remaining** *Eucalyptus thozetiana* *Eucalyptus camaldulensis var. obtusa* *Eucalyptus coolabah* *Eucalyptus populnea*
ALL CHARACTER SETS		
Sub-key to a Selection of Arid Australian Hardwoods	All of the above	**1 taxon remaining** Myrtaceae A (*Eucalyptus & Melaleuca*)
Sub-key to Myrtaceae A (*Eucalyptus & Melaleuca*)	All of the above	**3 taxa remaining** *Eucalyptus coolabah* *Eucalyptus populnea Eucalyptus thozetiana*

Specimen C

Table. Results of test using Specimen C.

Applied key/sub-key	Selected character states	Taxa remaining
PHYSICAL PROPERTIES		
Sub-key to a Selection of Arid Australian Hardwoods	Kino (gum deposits), not visible to the naked eye Rays, fleck not visible on longitudinal surface with naked eye Rays, not distinctly visible on cross-section with naked eye	**17 taxa remaining** *Acacia* *Anthobolus* *Atalaya* *Bauhinia* *Casuarina* *Dodonaea* *Flindersia* Myoporaceae Myrtaceae A Myrtaceae B *Owenia* *Pittosporum* *Psydrax* *Santalum* *Schinus* *Senna* *Ventilago*
CHEMICAL OBSERVATIONS		
Shavings were not removed from specimen C for chemical observation because it was unclear if heartwood was present.		
ANATOMICAL: ENDGRAIN (LIGHT MICROSCOPY)		
Sub-key to a Selection of Arid Australian Hardwoods	Vessels, solitary Vessels, not in radial multiples Vessels, not in radial multiples of 4 or more Vessels, not in clusters Vessels, not in tangential bands Rays, not distinctly wider than vessels Rays, not of two distinct widths Parenchyma, not banded	**6 taxa remaining** *Anthobolus* Myrtaceae A *Santalum* *Acacia* *Capparis* Myrtaceae B
ANATOMICAL: SCANNING ELECTRON MICROSCOPY		
Sub-key to a Selection of Arid Australian Hardwoods	S Vessels, diameter: #:25-50 µm S Vessels, difference in diameters: #:25 µm Vessels, 50-100 per square mm Vessels, solitary Vessels, not in radial multiples Vessels, not in clusters Vessels, not in tangential bands Vessels, vessel to vessel pits not vestured Vessels, helical thickenings present Vessels, simple perforation rim prominent (and often wide) S Rays, height: #:250 µm S Rays, number of cells wide: #:2-3 cells wide Parenchyma, banded	**1 taxon remaining** *Casuarina*
ALL CHARACTER SETS		
Sub-key to a Selection of Arid Australian Hardwoods	All of the above	**No remaining taxa**

Specimen D

Table. Results of test using Specimen D.

Applied key/sub-key	Selected character states	Taxa remaining
PHYSICAL PROPERTIES		
Sub-key to a Selection of Arid Australian Hardwoods	Heartwood, colour clearly distinct from sapwood colour Rays, fleck not visible on longitudinal surface with naked eye Rays, not distinctly visible on cross-section with naked eye	**13 taxa remaining** *Acacia* *Anthobolus* *Bauhinia* *Casuarina* *Dodonaea* Myoporaceae Myrtaceae A Myrtaceae B *Owenia* *Psydrax* *Schinus* *Senna* *Ventilago*
CHEMICAL OBSERVATIONS		
Sub-key to a Selection of Arid Australian Hardwoods	Heartwood, froth test positive Heartwood, ethanol extract not fluorescent Heartwood, not fluorescent Heartwood, water extract discoloured Heartwood, ethanol extract discoloured	**11 taxa remaining** *Anthobolus* *Bauhinia* *Capparis* *Casuarina* Myoporaceae Myrtaceae A Myrtaceae B Proteaceae *Psydrax* *Schinus* *Tamarix*
ANATOMICAL: ENDGRAIN (LIGHT MICROSCOPY)		
Sub-key to a Selection of Arid Australian Hardwoods	Heartwood, vessels commonly with tyloses Rays, not distinctly wider than vessels Rays, not of two distinct widths Parenchyma, not banded	**9 taxa remaining** *Anthobolus* *Capparis* *Flindersia* Myoporaceae Myrtaceae A Myrtaceae B *Psydrax* *Schinus* *Tamarix*
ANATOMICAL: SCANNING ELECTRON MICROSCOPY		
Sub-key to a Selection of Arid Australian Hardwoods	S Vessels, diameter: #:25-65 µm S Vessels, difference in diameters: #:40 µm Vessels, solitary Vessels, not in radial multiples Vessels, not in clusters Heartwood, vessels commonly with tyloses S Rays, height: #:175 µm Rays, not exclusively one cell wide S Rays, number of cells wide: #:2-3 cells wide Rays, not in horizontal rows Vessels, < 50 per square mm Vessels, not in tangential bands Vessels, vessel to vessel pits vestured Parenchyma, not banded	**1 taxon remaining** Myrtaceae A (*Eucalyptus* & *Melaleuca*)

Sub-key to Myrtaceae A (*Eucalyptus* & *Melaleuca*)	S Vessels, diameter: #:25-65 µm S Vessels, difference in diameters: #:40 µm Vessels, < 50 per square mm Parenchyma, not banded	**1 taxon remaining** *Eucalyptus camaldulensis* var. *obtusa*
ALL CHARACTER SETS		
Sub-key to a Selection of Arid Australian Hardwoods	All of the above	**1 taxon remaining** Myrtaceae A (*Eucalyptus & Melaleuca*)
Sub-key to Myrtaceae A (*Eucalyptus & Melaleuca*)	All of the above	**1 taxon remaining** *Eucalyptus camaldulensis var. obtusa*

Specimen E

Table. Results of test using Specimen E.

Applied key/sub-key	Selected character states	Taxa remaining
PHYSICAL PROPERTIES		
Sub-key to a Selection of Arid Australian Hardwoods	Kino (gum deposits), not visible to the naked eye Density, very dense > 1000 kg/m3 Rays, fleck not visible on longitudinal surface with naked eye Rays, not distinctly visible on cross-section with naked eye Heartwood, colour clearly distinct from sapwood colour	**12 taxa remaining** *Acacia* *Anthobolus* *Bauhinia* *Casuarina* *Dodonaea* Myoporaceae Myrtaceae A Myrtaceae B *Owenia* *Psydrax* *Senna* *Ventilago*
CHEMICAL OBSERVATIONS		
Sub-key to a Selection of Arid Australian Hardwoods	Heartwood, froth test negative Heartwood, ethanol extract not fluorescent Heartwood, water extract discoloured Heartwood, ethanol extract colourless Heartwood, not fluorescent	**12 taxa remaining** *Anthobolus* *Bauhinia* *Capparis* *Casuarina* Myoporaceae Myrtaceae A Myrtaceae B *Owenia* Proteaceae *Psydrax* *Schinus* *Tamarix*
ANATOMICAL: ENDGRAIN (LIGHT MICROSCOPY)		
Sub-key to a Selection of Arid Australian Hardwoods	Heartwood, vessels not commonly with tyloses Parenchyma, not in marginal bands Rays, not distinctly wider than vessels Rays, not of two distinct widths	**10 taxa remaining** *Anthobolus* *Bauhinia* *Capparis* *Casuarina* Myoporaceae Myrtaceae A Myrtaceae B *Psydrax* *Schinus* *Tamarix*
ANATOMICAL: SCANNING ELECTRON MICROSCOPY		
Sub-key to a Selection of Arid Australian Hardwoods	Vessels, diameter: #:10-47 µm Vessels, difference in diameters: #:25-37 µm Vessels, >100 per square mm Vessels, solitary Vessels, not in radial multiples Vessels, not in clusters Vessels, not in tangential bands Vessels, vessel to vessel pits vestured Vessels, helical thickenings absent Parenchyma, diffuse to diffuse-in-aggregate (apotracheal) Parenchyma, scanty to vasicentric (paratracheal) Parenchyma, not in a wing-like to confluent sheath Parenchyma, not banded Rays, height: #:116-216 µm Rays, difference in heights: #:46-99 µm	**1 taxon remaining** Myrtaceae A (*Eucalyptus & Melaleuca*)

	Rays, number of cells wide: #:1-3 cells wide Rays, not exclusively one cell wide Rays, with uniseriate rays present Rays, <4 per mm Rays, 4 - 12 per mm Rays, >12 per mm Fibres/tracheids, with numerous, distinctly bordered pits present Rays, not distinctly wider than vessels Rays, not of two distinct widths	
Sub-key to Myrtaceae A (Eucalyptus & Melaleuca)	Vessels, diameter: #:10-47 µm Vessels, difference in diameters: #:25-37 µm Vessels, >100 per square mm Parenchyma, diffuse to diffuse-in-aggregate (apotracheal) Parenchyma, scanty to vasicentric (paratracheal) Parenchyma, not in a wing-like to confluent sheath Parenchyma, not banded Rays, height: #:116-216 µm Rays, difference in heights: #:46-99 µm Rays, number of cells wide: #:1-3 cells wide Rays, not exclusively one cell wide Rays, <4 per mm Rays, 4 - 12 per mm Rays, >12 per mm	**1 taxon remaining** *Melaleuca glomerata*

ALL CHARACTER SETS		
Sub-key to a Selection of Arid Australian Hardwoods	All of the above	**1 taxon remaining** Myrtaceae A (*Eucalyptus & Melaleuca)*
Sub-key to Myrtaceae A (*Eucalyptus & Melaleuca*)	All of the above	**1 taxon remaining** *Melaleuca glomerata*

Specimen F

Table. Results of test using Specimen F.

Applied key/sub-key	Selected character states	Taxa remaining
PHYSICAL PROPERTIES		
Sub-key to a Selection of Arid Australian Hardwoods	Rays, fleck visible on longitudinal surface with naked eye Rays, distinctly visible on cross-section with naked eye Heartwood, colour not clearly distinct from sapwood colour	**3 taxa remaining** *Capparis* *Tamarix* Proteaceae
CHEMICAL OBSERVATIONS		
Sub-key to a Selection of Arid Australian Hardwoods	Heartwood, froth test negative Heartwood, ethanol extract not fluorescent Heartwood, water extract colourless Heartwood, ethanol extract discoloured Heartwood, not fluorescent	**11 taxa remaining** *Anthobolus* *Bauhinia* *Capparis* *Casuarina* Myoporaceae Myrtaceae B Proteaceae *Psydrax* *Schinus* *Tamarix* Myrtaceae A
ANATOMICAL: ENDGRAIN (LIGHT MICROSCOPY)		
Sub-key to a Selection of Arid Australian Hardwoods	Heartwood, vessels not commonly with tyloses Vessels, not solitary Vessels, not in radial multiples Vessels, in clusters Vessels, not in radial multiples of 4 or more Vessels, in tangential bands Parenchyma, not in marginal bands Parenchyma, banded Banded parenchyma, unbroken Banded parenchyma, with a bandwidth not commonly larger than ray width Banded parenchyma, in bands not narrower than vessels Banded parenchyma, in bands not commonly further apart than rays Rays, distinctly wider than vessels Rays, of two distinct widths Parenchyma, not in a wing-like to confluent sheath	**1 taxon remaining** Proteaceae
Sub-key to Proteaceae (*Grevillea & Hakea*)	Rays, distinctly wider than vessels	**4 taxa remaining** *Grevillea juncifolia ssp. juncifolia* *Grevillea striata* *Hakea eyreana* *Hakea leucoptera ssp. leucoptera*
ANATOMICAL: SCANNING ELECTRON MICROSCOPY		
Sub-key to a Selection of Arid Australian Hardwoods	S Vessels, difference in diameters: #:55 µm S Vessels, diameter: #:10-65 µm Vessels, not solitary Vessels, in clusters Vessels, in tangential bands	**1 taxon remaining** Proteaceae

Sub-key to Proteaceae (*Grevillea & Hakea*)	S Vessels, difference in diameters: #:55 µm S Vessels, diameter: #:10-65 µm Vessels, helical thickenings present Rays, distinctly wider than vessels	**3 taxa remaining** *Grevillea juncifolia ssp. juncifolia* *Hakea eyreana* *Hakea leucoptera ssp. leucoptera*

ALL CHARACTER SETS		
Sub-key to a Selection of Arid Australian Hardwoods	All of the above	**1 taxon remaining** Proteaceae
Sub-key to Proteaceae (*Grevillea & Hakea*)		**3 taxa remaining** *Hakea eyreana* *Hakea leucoptera ssp. leucoptera*

Specimen G

Table. Results of test using Specimen G.

Applied key/sub-key	Selected character states	Taxa remaining
PHYSICAL PROPERTIES		
Sub-key to a Selection of Arid Australian Hardwoods	Kino (gum deposits), not visible to the naked eye Rays, fleck not visible on longitudinal surface with naked eye Rays, not distinctly visible on cross-section with naked eye Heartwood, colour clearly distinct from sapwood colour	**13 taxa remaining** *Acacia* *Anthobolus* *Bauhinia* *Casuarina* *Dodonaea* Myoporaceae Myrtaceae A Myrtaceae B *Owenia* *Psydrax* *Schinus* *Senna* *Ventilago*
CHEMICAL OBSERVATIONS		
Sub-key to a Selection of Arid Australian Hardwoods	Heartwood, froth test negative Heartwood, ethanol extract not fluorescent Heartwood, fluorescent Heartwood, ethanol extract discoloured	**12 taxa remaining** *Acacia* *Anthobolus* *Bauhinia* *Capparis* *Casuarina* Myoporaceae Myrtaceae A Myrtaceae B Proteaceae *Psydrax* *Schinus* *Tamarix*
ANATOMICAL: ENDGRAIN (LIGHT MICROSCOPY)		
Sub-key to a Selection of Arid Australian Hardwoods	Heartwood, vessels not commonly with tyloses Vessels, not solitary Vessels, in radial multiples Vessels, not in radial multiples of 4 or more Vessels, not in tangential bands Parenchyma, in a wing-like to confluent sheath (paratracheal) Parenchyma, not in marginal bands Parenchyma, not banded Rays, not distinctly wider than vessels Rays, not of two distinct widths	**8 taxa remaining** *Acacia* Myoporaceae Myrtaceae B *Owenia* *Schinus* *Senna* *Tamarix* *Dodonaea*
ANATOMICAL: SCANNING ELECTRON MICROSCOPY		
Sub-key to a Selection of Arid Australian Hardwoods	Vessels, not solitary Vessels, in radial multiples Vessels, not in radial multiples of 4 or more Vessels, not in tangential bands Vessels, vessel to vessel pits vestured Parenchyma, chambered (and often with crystals)	**1 taxon remaining** *Acacia*
Sub-key to *Acacia*	Vessels, not solitary Vessels, in radial multiples Vessels, not in radial multiples of 4 or more Parenchyma, in a wing-like to confluent sheath (paratracheal) S Vessels, diameter: #:50-100 S Vessels, difference in diameters: #:50 Vessels, < 50 per square mm	**4 taxa remaining** *Acacia cana* *Acacia ligulata* *Acacia salicina* *Acacia victoriae ssp. arida*

	S Rays, number of cells wide: #:2-4 S Rays, height: #:80-300 S Rays, difference in heights: #:220 S Rays, number per mm: Rays, <4 per mm S Rays, number per mm: Rays, 4 - 12 per mm	
ALL CHARACTER SETS		
Sub-key to a Selection of Arid Australian Hardwoods	All of the above	**1 taxon remaining** *Acacia*
Sub-key to *Acacia*	All of the above	**No taxa remaining**

Specimen H

Table. Results of test using Specimen H.

Applied key/sub-key	Selected character states	Taxa remaining
PHYSICAL PROPERTIES		
Sub-key to a Selection of Arid Australian Hardwoods	Kino (gum deposits), not visible to the naked eye Rays, fleck visible on longitudinal surface with naked eye Rays, distinctly visible on cross-section with naked eye	**3 taxa remaining** *Capparis* Proteaceae *Tamarix*
CHEMICAL OBSERVATIONS		
Heartwood on specimen H was either absent or visually indiscernible from sapwood; since all chemical observations in the tool are heartwood-dependent this set was not applied to this specimen.		
ANATOMICAL: ENDGRAIN (LIGHT MICROSCOPY)		
Sub-key to a Selection of Arid Australian Hardwoods	Heartwood, vessels not commonly with tyloses Vessels, not solitary Vessels, not in radial multiples Vessels, not in radial multiples of 4 or more Vessels, in clusters Vessels, in tangential bands Parenchyma, not in marginal bands Parenchyma, not in a wing-like to confluent sheath Parenchyma, banded Banded parenchyma, unbroken Banded parenchyma, with a bandwidth not commonly larger than ray width Banded parenchyma, in bands not narrower than vessels Rays, distinctly wider than vessels Banded parenchyma, in bands not commonly further apart than rays Rays, of two distinct widths	**1 taxon remaining** Proteaceae
Sub-key to Proteaceae (*Grevillea & Hakea*)	Banded parenchyma, with a bandwidth not commonly larger than ray width Rays, distinctly wider than vessels	**4 taxa remaining** *Grevillea juncifolia ssp. juncifolia* *Grevillea striata* *Hakea eyreana* *Hakea leucoptera ssp. leucoptera*
ANATOMICAL: SCANNING ELECTRON MICROSCOPY		
Sub-key to a Selection of Arid Australian Hardwoods	Vessels, in tangential bands Rays, of two distinct widths	**1 taxon remaining** Proteaceae
Sub-key to Proteaceae (*Grevillea & Hakea*)	S Vessels, diameter: #:20-75 µm S Vessels, difference in diameters: #:50 µm Vessels, helical thickenings absent	**1 taxon remaining** *Hakea eyreana*
ALL CHARACTER SETS		
Sub-key to a Selection of Arid Australian Hardwoods	All of the above	**1 taxon remaining** Proteaceae
Sub-key to Proteaceae (*Grevillea & Hakea*)	All of the above	**1 taxon remaining** *Hakea eyreana*

Specimen I

Table. Results of test using Specimen I.

Applied key/sub-key	Selected character states	Taxa remaining
PHYSICAL PROPERTIES		
Sub-key to a Selection of Arid Australian Hardwoods	Kino (gum deposits), not visible to the naked eye Rays, fleck not visible on longitudinal surface with naked eye Rays, not distinctly visible on cross-section with naked eye Heartwood, colour clearly distinct from sapwood colour	**13 taxa remaining** *Acacia* *Anthobolus* *Bauhinia* *Casuarina* *Dodonaea* Myoporaceae Myrtaceae A Myrtaceae B *Owenia* *Psydrax* *Schinus* *Senna* *Ventilago*
CHEMICAL OBSERVATIONS		
Sub-key to a Selection of Arid Australian Hardwoods	Heartwood, froth test positive Heartwood, ethanol extract not fluorescent Heartwood, ethanol extract discoloured Heartwood, water extract discoloured Heartwood, not fluorescent	**11 taxa remaining** *Anthobolus* *Bauhinia* *Capparis* *Casuarina* Myoporaceae Myrtaceae A Myrtaceae B Proteaceae *Psydrax* *Schinus* *Tamarix*
ANATOMICAL: ENDGRAIN (LIGHT MICROSCOPY)		
Sub-key to a Selection of Arid Australian Hardwoods	Heartwood, vessels not commonly with tyloses Vessels, not solitary Vessels, in radial multiples Vessels, not in radial multiples of 4 or more Vessels, not in tangential bands Parenchyma, in a wing-like to confluent sheath (paratracheal) Parenchyma, in marginal bands Parenchyma, not banded Rays, not distinctly wider than vessels Rays, not of two distinct widths	**6 taxa remaining** *Acacia* *Atalaya* *Flindersia* Myoporaceae Myrtaceae B *Senna*
ANATOMICAL: SCANNING ELECTRON MICROSCOPY		
Sub-key to a Selection of Arid Australian Hardwoods	Parenchyma, in a wing-like to confluent sheath (paratracheal) Parenchyma, not banded Vessels, not solitary Vessels, solitary Vessels, not in radial multiples of 4 or more Vessels, not in tangential bands Heartwood, vessels not commonly with tyloses Vessels, vessel to vessel pits vestured Vessels, helical thickenings absent S Vessels, diameter: #:20-100 µm S Vessels, difference in diameters: #:80 µm Vessels, < 50 per square mm Rays, not exclusively one cell wide	**1 taxon remaining** *Acacia*

	S Rays, height: #:125-150 µm S Rays, difference in heights: #:25 µm	
Sub-key to *Acacia*	Parenchyma, in a wing-like to confluent sheath (paratracheal) Parenchyma, not banded Vessels, not solitary Vessels, solitary Vessels, not in radial multiples of 4 or more S Vessels, diameter: #:20-100 µm S Vessels, difference in diameters: #:80 µm Vessels, < 50 per square mm Rays, not exclusively one cell wide S Rays, height: #:125-150 µm S Rays, difference in heights: #:25 µm	**2 taxa remaining** *Acacia murrayana* *Acacia peuce*
ALL CHARACTER SETS		
Sub-key to a Selection of Arid Australian Hardwoods	All of the above	**1 taxon remaining** Myrtaceae B
Sub-key to Myrtaceae B		**No remaining taxa**

Specimen J

Table. Results of test using Specimen J.

Applied key/sub-key	Selected character states	Taxa remaining
PHYSICAL PROPERTIES		
Sub-key to a Selection of Arid Australian Hardwoods	Density, very dense > 1000 kg/m3 Kino (gum deposits), not visible to the naked eye Rays, fleck not visible on longitudinal surface with naked eye Rays, not distinctly visible on cross-section with naked eye Heartwood, colour clearly distinct from sapwood colour	**10 taxa remaining** *Acacia* *Bauhinia* *Casuarina* Myoporaceae Myrtaceae A Myrtaceae B *Owenia* *Psydrax* *Schinus* *Ventilago*
CHEMICAL OBSERVATIONS		
Sub-key to a Selection of Arid Australian Hardwoods	Heartwood, froth test negative Heartwood, ethanol extract not fluorescent Heartwood, fluorescent Heartwood, ethanol extract colourless	**13 taxa remaining** *Acacia* *Anthobolus* *Bauhinia* *Capparis* *Casuarina* *Flindersia* Myoporaceae Myrtaceae A Myrtaceae B Proteaceae *Psydrax* *Schinus* *Tamarix*
ANATOMICAL: ENDGRAIN (LIGHT MICROSCOPY)		
Sub-key to a Selection of Arid Australian Hardwoods	Vessels, not solitary Vessels, in radial multiples Heartwood, vessels not commonly with tyloses Vessels, in radial multiples of 4 or more Vessels, not in radial multiples of 4 or more Vessels, not in tangential bands Parenchyma, in a wing-like to confluent sheath (paratracheal) Parenchyma, in marginal bands Parenchyma, not banded Rays, not distinctly wider than vessels Rays, not of two distinct widths	**6 taxa remaining** Myoporaceae *Acacia* Myrtaceae B *Atalaya* *Flindersia* *Senna*
ANATOMICAL: SCANNING ELECTRON MICROSCOPY		
Sub-key to a Selection of Arid Australian Hardwoods	Parenchyma, in marginal bands Vessels, not solitary Vessels, vessel to vessel pits vestured S Rays, height: #:75-110 µm S Rays, number of cells wide: #:1-2 cells wide Parenchyma, chambered (and often with crystals) Rays, cells homocellular (procumbent only) Vessels, simple perforation rim not prominent Parenchyma, in a wing-like to confluent sheath (paratracheal) S Vessels, diameter: #:25-85 µm S Vessels, difference in diameters: #:60 µm	**1 taxon remaining** *Acacia*
Sub-key to Acacia	Vessels, not solitary S Rays, height: #:75-110 µm	**13 taxa remaining** *Acacia aneura var. aneura*

	S Rays, number of cells wide: #:1-2 cells wide Parenchyma, in a wing-like to confluent sheath (paratracheal) S Vessels, diameter: #:25-85 µm S Vessels, difference in diameters: #:60 µm Vessels, not in radial multiples of 4 or more Vessels, in radial multiples	*Acacia cambagei* *Acacia cana* *Acacia ligulata* *Acacia ligulata ?intergrade with A.bivenosa* *Acacia murrayana* *Acacia petraea* *Acacia pickardii* *Acacia salicina* *Acacia stenophylla* *Acacia tetragnophylla* *Acacia victoriae ssp. arida* *Acacia peuce*
ALL CHARACTER SETS		
Sub-key to a Selection of Arid Australian Hardwoods	All of the above	**1 taxon remaining** *Acacia*
Sub-key to *Acacia*	All of the above	**No remaining taxa**

Appendix Ten. Literature survey of Aboriginal use of wood from species occurring in eastern central Australia

Plant species occurring in eastern central Australia and with a documented use in the manufacture of wooden objects in this region

Species	Artefact type	Description	Reference
Acacia aneura	Spears	Stems used for making spears.	Johnston & Cleland 1943: 154
Acacia aneura	Clubs	Timber used for making clubs when suitable mallee roots were not available.	Johnston & Cleland 1943: 160
Acacia aneura	Axe handle; long spear or digging stick; point attached to light spears; boomerang; two-handed fighting boomerang; woman's digging stick; throwing stick	Wood of mulga used for making the short handle, into the cleft end of which the axe head was inserted and then secured by binding it with hair or fur string together with mindri gum. Long spear or digging stick (piranburra) was made from its root. The flattened, sharpened point attached to light spears (kutchie) was usually of mulga. The hardwood of this species was used for making such implements as the kirra (boomerang), murrawirrie (two-handed fighting boomerang), wadna (woman's digging stick), and wirrie (throwing stick.	Johnston & Cleland 1943: 164
Acacia aneura	Fire-making apparatus	For fire-making, a hardwood stick of mulga was twirled into a split stick of Crotalaria cunninghamii, shredded bark or pith being added to the spark obtained.	Johnston & Cleland 1943: 165
Acacia aneura	Straight smoothed spears kukerra; long, slender playing stick a form of club marriwirri; a kind of boomerang	Wooden artefacts attributed to mulga.	Johnston & Cleland 1943: 166
Acacia aneura	Clubs nulla-nullas	Wooden artefacts attributed to mulga.	Johnston & Cleland 1943: 166
Acacia aneura	Digging stick	Made from mulga root.	Johnston & Cleland 1943: 162
Acacia cambagei	Clubs nulla-nullas message sticks short hunting spears boomerangs framework of huts. Firewoods and fire-sticks	Wooden artefacts attributed to gidgee.	Johnston & Cleland 1943: 166
Acacia cambagei	Boomerangs	"It was a preferred species for making hunting boomerangs as it is resistant to splitting when dry"	Kutsche & Lay 2003: 15
Acacia cyperophylla	Clubs nulla-nullas long churingas boomerangs spears	Wooden artefacts attributed to minareechie.	Johnston & Cleland 1943: 166
Acacia dictyophleba	One-piece spear barbed spear digging stick		Kamminga 1988: 34
Acacia estrophiolata	Unspecified heavy artefacts		Kamminga 1988: 35
Acacia stenophylla	Spindles	Wood of a twig used for making spindles for the manufacture of string from hair, fur or plant fibre; information obtained from aborigines at Pandi Pandi	Johnston & Cleland 1943: 154
Acacia tetragonophylla	Boomerangs and woomeras	Wood used for making boomerangs and woomeras.	Johnston & Cleland 1943: 152
Acacia tetragonophylla	Spears	Stems used for making spears.	Johnston & Cleland 1943: 154

Acacia tetragonophylla	Boomerang & ceremonial stick	"dead finish" was used in making the koondi, a boomerang, nearly round in section; and a sharpened stick to which emu feathers were bound in order to make a head decoration for one of the corroborees.	Johnston & Cleland 1943: 164
Atalaya hemiglauca	Artefacts, spear shafts	"Aboriginal people have used the timber for artefacts, and the roots, when straightened with fire, have been used as spear shafts."	Kutsche & Lay: 22
Bauhinia carronii (now lysiphyllum gilvum kamminga 1988: 53)	Shields	Shields are made of soft wood obtained by barter from the north and north-east, i.e., mainly from western Queensland, via cooper's creek, the Yantruwunta people supplying weapons and grinding stones in exchange. The Dieri made fire by drilling the edge of a shield with a sharp-pointed stick.	Johnston & Cleland 1943: 162
Bauhinia carronii (now lysiphyllum gilvum kamminga 1988: 53)	Worra; large shields.		Johnston & Cleland 1943: 166
Crotalaria cunninghamii	Fire-making apparatus	For fire-making, a hardwood stick of mulga was twirled into a split stick of Crotalaria cunninghamii, shredded bark or pith being added to the spark obtained.	Johnston & Cleland 1943: 165
Crotalaria cunninghamii	Fire-making apparatus	Fire-making by the twirling method was adopted by the Dieri tribe, needlebush (*Hakea leucoptera*) being selected for the harder twirling stick and hack's pea, Crotalaria [*C.* cunninghamii] for the softer basal piece.	Johnston & Cleland 1943: 166
Eremophila longifolia	Ceremonial items: nose-peg & tooth evulsion stick	Piece of wood, six inches long, was pointed at one end and used to pierce the nasal septum of children, the ceremony being called moodlawillpa. Also two pieces of woods, about a foot in length, sharpened at one end to a wedge-like shape and forced between the upper incisors of children during the tooth evulsion chirrinchirrie ceremony.	Johnston & Cleland 1943: 158
Eremophila longifolia	Branches used for covering corpse.		Johnston & Cleland 1943: 160
Eremophila longifolia	"nose peg"	Ornament made of the wood of the kuyamara	Johnston & Cleland 1943: 161
Erythrina vespertilio	Shields (Wongkanguru: Murrawarroo)	[error for *Bauhinia* carronii). Shields were made of soft wood and were obtained by barter from Queensland.	
Eucalyptus sp.	Coolamons: water carriers, both shield-shaped and canoe-shaped	Wooden artefacts attributed to *Eucalyptus* species.	Johnston & Cleland 1943: 166
Eucalyptus microtheca (now e. Coolebah)	Spear	Piranburra, long pole-like spear, serving also as a digging stick to be used by men hunting dingos	Johnston & Cleland 1943: 164
Eucalyptus microtheca (now e. Coolebah)	Fire-making apparatus message sticks coolamons	Timber was used for firewood and firesticks, for making message sticks and large coolamons (koordoo).	Johnston & Cleland 1943: 169
Eucalyptus microtheca (now e. Coolebah)	Wooden dish	Pirrha fashioned from the bend of a branch of ?box-tree. *Eucalyptus microtheca*?	Johnston & Cleland 1943: 164
Eucalyptus microtheca (now e. Coolebah)	Throwing stick	Munkerara were usually made from the box-tree? *Eucalyptus microtheca*.	Johnston & Cleland 1943: 164

Eucalyptus macrocarpa (probably e. Coolebah)	Digging stick	[error for *E. microtheca*] wonno, woman's digging stick.	Johnston & Cleland 1943: 160
Eucalyptus oleosa	Clubs	Mallee, roots used as clubs.	Johnston & Cleland 1943: 160
Hakea ivoryi (now h. Eyreana)	Shields, coolamons		Johnston & Cleland 1943: 169
Hakea leucoptera	Pointing bone (Wongkanguru: wirra-garoo Dieri: moko-ellie)	Made of bone or wood such as needlewood.	Johnston & Cleland 1943: 165
Hakea leucoptera	Fire-making apparatus	Fire-making by the twirling method was adopted by the Dieri tribe, needlebush being selected for the harder twirling stick and hack's pea, Crotalaria [*C.* cunninghamii] for the softer basal piece.	Johnston & Cleland 1943: 166
Muehlenbeckia cunninghamii (now m. Florulenta)	Light spears (kutchie)	From lignum and marshmallow light spears were made but some kind of hardwood, usually mulga (see *Acacia aneura*), had to be used for the point.	Johnston & Cleland 1943: 165
Lavatera plebeja (now l. Plebeia)	Light spears (kutchie)	From lignum and marshmallow light spears were made but some kind of hardwood, usually mulga (see *Acacia aneura*), had to be used for the point.	Johnston & Cleland 1943: 165
	Dunpara; food platform made of four stakes wadna; woman's digging stick pirrha; wooden dish kulchera; playing stick inchitcha; bull-roarer message sticks – toas? Various kinds of boomerangs (kirra) and throwing sticks (wirra, koondie)	Wooden implements of Wongkanguru people.	Johnston & Cleland 1943: 166
	Musical instrument; dejeridu. Wooden cradle; poo-tee-poo-tee-ya – used for drying meat in the sun.	Artefacts made from wood.	Johnston & Cleland 1943: 169

Plant species occurring in eastern central Australia with references to their use in artefact manufacture from other regions of Australia

Species	Artefact type	Locality of use in artefact manufacture	Reference
Acacia aneura	"Wood used for making boomerangs kali, spear-throwers miru and other items requiring hardwood."	North west SA	Goddard & Kalotas 1985: 141
	"The hard wood is used to make spear-throwers miru, barbs mukul(pa) and spearheads wata for spears, boomerangs kali and digging sticks wana. It is also excellent and abundant firewood waru."	North west SA	Goddard & Kalotas 1985: 38
	hunting implements, tools and tourist items	outback South Australia	Kutsche & Lay 2003: 14
Acacia calcicola	spear from root and other unspecified artefacts	Central Australia	Kamminga 1988: 34
Acacia coriacea	boomerang, spear	Western Desert, WA	Kamminga 1988: 34
Acacia cowleana	hunting spear	Western Desert, WA	Kamminga 1988: 34
Acacia dictyophleba	one-piece spears, barbed spears	Central and Western Deserts	Kamminga 1988: 34
Acacia farnesiana	hatchet handle, clap sticks	North Qld; Central Australia	Kamminga 1988: 35
Acacia georginae	boomerang, throwing stick	Sandover River drainage, Central Australia	Kamminga 1988: 35
Acacia kempeana	spearthrower, spear point; roots are used for making spears	Cundeelee, WA; Finke River, Central Australia	Kamminga 1988: 36
	"The roots are also used for making spears, when the superior spear-bush urtjan(pa) [*Pandorea doratoxylon*] are not available."	North west SA	Goddard & Kalotas 1985: 138
Acacia oswaldii	boomerang, club	Central Australia	Kamminga 1988: 37
Acacia rigens	unspecified	unspecified	Kamminga 1988: 38
Acacia salicina	boomerang	unspecified	Kamminga 1988: 38
Acacia tetragonophylla	artefacts	outback South Australia	Kutsche & Lay 2003: 49
Acacia victoriae	spear point	Central Australia	Kamminga 1988: 38
Alectryon oleifolius (formerly *Heterodendrum oleifolium*)	boomerang, shield, club	Ooldea, SA; Aranda territory, Central Australia	Kamminga 1988: 48
Atalaya hemiglauca	ceremony ornaments	Central Australia	Kamminga 1988: 39
Callitris glaucophylla	ceremonial board; unspecified 'implements'	Central Australia	Kamminga 1988: 40
	firewood	outback South Australia	Kutsche & Lay 2003: 24
Carissa lanceolata	spear head	Warlpiri territory, Central Australia	Kamminga 1988: 40
Dodonaea viscosa ssp. *angustissima*	dead branches used for shelters	outback South Australia	Kutsche & Lay 2003: 69
Eucalyptus camaldulensis	club; carrying vessel; roots are used to make bowls	Yarra River, Victoria; Central Australia	Kamminga 1988: 43

	"The roots iwiri are used to make bowls mimpu, kanil(pa), wira, tjanum(pa)."	North west SA	Goddard & Kalotas 1985: 48
	artefacts, firewood, ornaments, toys	outback South Australia	Kutsche & Lay 2003: 30
Eucalyptus coolabah ssp. *arida*	artefacts, ornaments	outback South Australia	Kutsche & Lay 2003: 31
Grevillea striata	unspecified artefacts	Warlpiri territory, Central Australia	Kamminga 1988: 47
Gyrostemon ramulosus	unspecified traditional artefacts, carved figures of animals for tourist trade	Central Australia	Kamminga 1988: 47
Melaleuca glomerata	children's spear, unspecified artefacts	Musgrave Ranges, Central Australia	Kamminga 1988: 49
	"Stems used for children's spears."	North west SA	Goddard & Kalotas 1985: 138
Melaleuca dissitiflora(formerly *M. linophylla*)	children's spear	Musgrave Ranges, Central Australia	Kamminga 1988: 49
Pittosporum angustifolium	shield	Cundeelee, WA	Kamminga 1988: 50
Santalum acuminatum	Bowl, unspecified artefacts (formerly *P. phylliraeoides*)	NW of SA	Kamminga 1988: 51
	"The wood is used to carve snakes, lizards and similar items for sale; the leaves are used for smoothing these down."	North west SA	Goddard & Kalotas 1985: 32
	bowls, objects	outback South Australia	Kutsche & Lay 2003: 42
Santalum lanceolatum	"The wood is used for carving small animals."	North west SA	Goddard & Kalotas 1985: 68

Appendix Eleven. Non-refereed publications on the importance of botanical vouchers

Preface

In October 2003, the following article was published in the journal of the *International Wood Collectors Society* (IWCS), *World of Wood.* This journal is not a refereed publication but enjoys a healthy readership of approximately 1200 members from over thirty countries who share various interests in wood (International Wood Collectors Society 2004); the organisation was established nearly 60 years ago. The article was written to highlight the purpose of wood samples authenticated with botanical vouchers, their relevance to IWCS members wood-related pursuits, and their necessity in scientific research; to expose common misconceptions about taxonomy and name changes; to promote a "best practice" in wood collection that includes the collection of wood samples, complete with an associated herbarium voucher; and to emphasise the important role that IWCS members may play in contributing to science with the establishment of collaborative and reciprocal relationships with local herbaria.

In preparing the paper, the assistance of *World of Wood* editor Alan Brooks and associate editors Eugene Dimitriadis and Jim Flynn is acknowledged, as well as the comments of IWCS members Morris Lake and Ian McLaughlin.

Following the article is correspondence published in response to the following article: van Rijckevorsel, P. Notes on practical aspects of botanical vouchering. *World of Wood*, March 2004.

Barker, J.A. 2003 Ensuring & maintaining accuracy in wood identification: a cautionary tale about taxonomy and the need for botanical vouchers, World of Wood

Cautionary tale of taxonomy, need for vouchers

Ensuring, sustaining accuracy in wood identification

by Jenny Barker (8556)

(Editor's note: We extend to Jenny Barker a hearty welcome to our Society. It is a pleasure to have a member with keen insight for the need to keep open the lines of communication between the many scientific disciplines associated with wood collecting. In my former employment, we would call the author's paper published here a "think piece." It is intended to be provocative, but in a constructive way; in other words, a stimulant for more creative ideas that lead to orderly changes. In concert with Eugene Dimitriadis and Chuck Holder, other associate editors who helped with and reviewed this article, we trust our members will find this paper most stimulating. — *Jim Flynn, associate editor*)

If the latest *IWCS Membership Directory* is any indication, there may be a growing interest amongst members in wood identification. As a new member of the Society and one who shares this interest, I wish to write a cautionary note to members who are concerned about ensuring *accurate* identifications of wood samples in light of plant-name changes.

The fact is that most IWCS members will have misidentified wood in their back shed, acquired through personal collection or via trade with other members — understandably, this may be of little concern to many of you, especially those not collecting standard or reference samples.

I write this, then, for those of you who *are* concerned about "getting it right," particularly those of you who may be unwittingly ascribing incorrect names to your wood. However, I hope that this article will also inform the wider membership. Along with a discussion of the role of taxonomy and why plant names change, I have sought to expose some misconceptions commonly associated with name changes.

In addition, I describe the *only* method that will ensure members can accurately identify their wood now and into the future and propose the establishment of ties between the IWCS and their local herbaria.

On what authority do I write this paper? A large part of my research as a Ph.D. degree candidate (environmental biology discipline, Adelaide University, Australia) involves the development of an identification tool for arid Australian wood species used to construct north-east South Australian aboriginal artefacts held at the South Australian Museum.

Also, I am the daughter of plant taxonomists based at the State Herbarium of South Australia who are forever revising species and changing names (much to the chagrin, I'm sure, of many IWCS members). As such, I have an awareness of plant taxonomy and the implications of plant-name changes as well as a vested interest in ensuring that my developed identification tool retains its accuracy in the future.

Taxonomists and taxonomy: Why do plant names change?

The identification, classification and revision of living organisms are the roles of the taxonomist.

Taxonomists exist in most areas of biology including entomology (study of insects), ornithology (study of birds) and botany (study of plants) — organising organisms into hierarchies (family/genus/species) based on similar characteristics. Many IWCS members who manage and organise large reference wood collections practise their own version of taxonomy.

People often are surprised to learn that, in every area of biological research, there remain many thousands of species that are yet to be discovered. For example, by 1992 about 250,000 species of plants had been described but taxonomists estimated that around 300,000 to 500,000 species remain undocumented, many in underdeveloped countries.

Some species discovered in the future may be new and previously unheard of. However, many more new species are simply "created" by taxonomists; as research continues and knowledge increases, previously identified organisms are revised and reclassified, often changing names.

For example, a single species may be revised to include subspecies or sufficient differences in the characteristics may exist that it is split into two separate species. Splits can occur even at the family and genus level; this is best typified by the current taxonomic debate in Australia over the classification of the *Eucalyptus* genus (for further information, see the February 2002 *WOW*).

Division of the largest Australian genus, *Acacia*, into up to five separate genera may follow.

Staying on top of name changes: Collecting botanical vouchers

So taxonomy is about making sense and maintaining order in the complex and diverse living world around us. We do this in the only way we know how: by tidily arranging organisms into hierarchies and frequently rearranging species within these hierarchies in light of new information.

But how do adjustments within plant taxonomies and subsequent name changes affect our wood collections? When a plant species is revised into separate species, how can a wood collector know from which species their wood sample came? The simple answer (and occasionally there may be exceptions) is that they cannot.

Let me provide you with an example: A wood collector has a specimen identified as mulga or *Acacia aneura*; new research published in the 2001 *Flora of Australia* indicates that this plant now consists of several species and plant taxonomists recognise *Acacia ayersiana*, *A. minyura*, *A. paraneura* and *A. brachystachya*, besides *A. aneura*. The wood collector cannot reliably determine from which species the sample has come.

Can the wood collector avoid this problem by simply ignoring the scientific names and using the common name for the wood specimen? Yes, but he or she would need to be aware that the common name now refers to several species, where previously it may only have been used to refer to one. Again, this may (justifiably) be acceptable for many IWCS members but some of you may wish to guarantee your wood can be accurately identified and classified now and in the future.

There is a way: Ensure your samples are linked to botanical "vouchers."

Vouchers refer to botanical specimens that are professionally identified and lodged in herbaria; a wood sample associated with a "voucher" often is referred to as "authenticated." Vouchers usually comprise a branch from a plant that (ideally) contains all the botanical characteristics available on collection, including fruits, flowers and leaves.

They are the foundation of all good scientific and taxonomic research as they provide evidence of a particular species' presence at a particular time and place. In addition, vouchers are essential because they allow the original botanical specimens

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to be revisited for further treatment, or if any disputes arise over identification.

Had the wood in the earlier example been associated with a botanical voucher, the collector could probably determine which of the five *Acacia* species the wood belongs to by returning to the voucher for verification. The reality is that the collection of vouchers in association with wood samples is the only way collectors can reliably stay ahead of name changes.

It goes without saying then that plant taxonomists take the issue of vouchers seriously. Speak with taxonomists — the people who change the names — and they will tell you themselves about the need to retain vouchers to ensure reliable and accurate identifications.

Most botanical journals recommend or even require research based on vouchered collections (e.g., *Australian Systematic Botany*, *Annals of the Missouri Botanical Garden*). The same should be required of forestry wood collections and professional journals, but this is not always so.

A few months ago, however, I stumbled across an article by member Regis Miller that traces the history of the Forest Products Laboratory wood collection in Madison, Wisconsin, USA. Regis writes that in 1948 Bohumil Francis Kukachka, a trained taxonomist, became curator of the collection and that it was "his philosophy to keep only samples that were well authenticated with herbarium material."

Regis records that Kukachka "may have discarded several thousand samples, possibly as many as 6,000." Disposing of unvouchered wood samples is a drastic measure and not an action that contemporary taxonomists encourage, particularly since the advent of DNA analysis that may one day render void the current problems of identifying unvouchered material.

However, it is interesting to note the lengths this taxonomist went to ensure the accuracy of a wood collection used for scientific research.

Identifying wood: Some common mistakes, misconceptions

Many IWCS members probably will acknowledge that some of their collection may be misidentified, but they also will commonly believe that most of the collection probably is correctly identified. Unfortunately, this is a shortsighted notion that fails to understand just how frequently species names change or appreciate the implications of these changes.

Even if members have confidence in the identity of most of their wood samples, in time there is every chance that their names will change and, without vouchers to return to, there can be no certainty as to the identity of the specimens.

In this next section, I list some common practises and misconceptions that can result in the misidentification of unvouchered wood. It is illustrated with examples from Australian wood-producing species as these are the plants with which I am familiar. However, the errors and misconceptions apply on a global scale.

1. Replacing one name with another in light of name changes.

In the example provided earlier, I mentioned that occasionally replacing an old name with a new name can be acceptable; for example, in a 1987 revision of the Sapindaceae family, the genus *Heterodendrum* was reclassified as *Alectryon* and the names of the species' belonging to this genus were only subtly changed; e.g., *Heterodendrum oleifolium* now is referred to as *Alectryon oleifolius*.

Often name changes are geographically based; recently it was recognised that there was more than one species within *Eucalyptus microtheca* and, for much of its previous distribution, it now is known as *Eucalyptus coolabah*.

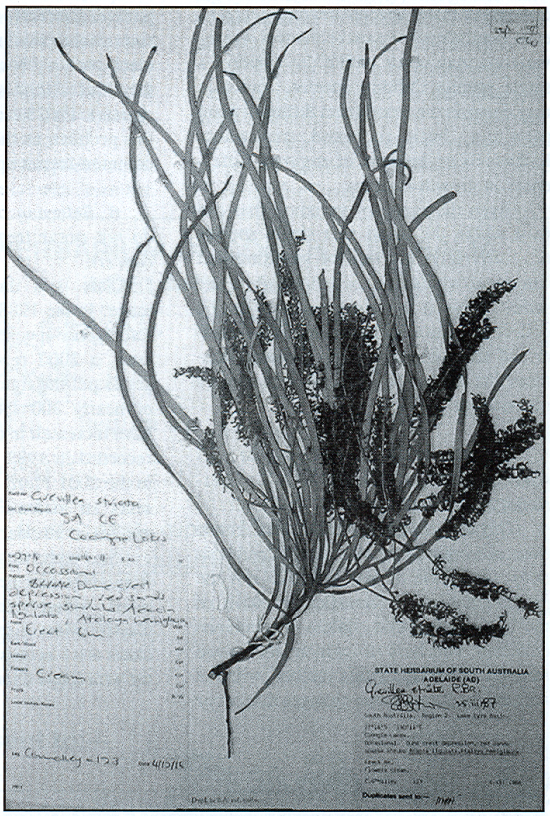
However, it is not always possible to substitute names so easily, particularly when botanists divide such complex species as mulga (*Acacia aneura*) with 10 proposed varieties, and salwood (*A. aulacocarpa*), which now is divided into eight species. In these cases, and without a voucher to return to, it will almost certainly be impossible to determine just what name to apply to a wood sample.

2. Using botanical publications to help with identification of plants in the field.

Within a few years of publication, many of the books will contain out-of-date information and some incorrectly named species as plants continue to undergo active revision. This is not to say that members should not use the many helpful publications that are available, but we do need to be cognisant of their limitations.

All international herbaria maintain censuses of plants that list all former names used for a plant, and many Australian censuses now are available on the

(Continued on Page 6)



An example of an herbarium specimen lodged in the State Herbarium of South Australia in Adelaide. The herbarium specimen includes a small branch containing flowers and leaves from beefwood (*Grevillea striata*) along with a printed label recording the collection details and a professional identification. Appended to the left of the specimen are the original notes written by the collector, C. O'Malley.

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(Continued from Page 5)

Internet through Australia's Virtual Herbarium (http://www.chah.gov.au/avh/). However, one still cannot be tempted to simply replace one name with another.

3. Comparing an unvouchered wood sample to another unvouchered wood sample and, if it looks the same, ascribing it the same name.

The botanical names given to plants are based on variations in their features — the fruit, flowers, leaves, etc. Accordingly, in botany, one *Acacia* or *Eucalyptus* species is distinguished from another by examining these features. However, the variation in botanical features that exists between two species may not be evident in their wood.

Consequently, without any other plant parts, the lack of variation in wood can make it difficult, sometimes impossible, to distinguish many species beyond genus or even family level. To make matters worse, variation may occur within the wood of a single species. Within species, variation may occur in the wood from different plant parts (e.g., burls, rootwood, trunkwood, limbwood) or because of regional differences in growth regimes.

Given the range of variation that can exist within the wood of a single species or, conversely, the lack of variation that can occur within species belonging to the same genus, it is usually only with the collection of an associated botanical voucher and an assessment of the botanical features that we can be sure of which species of wood we have.

4. Assuming if a wood sample was collected during a field trip with a professional botanist, the wood is "authentic."

This is a common argument that I have even seen put forth in scientific publications. The issue at stake here is not the professionalism or identification skills of the botanist but that, unless the botanist collected vouchers to which the wood samples are related, this method will not account for future name changes that occur because of botanical revisions.

5. Assuming that, if one ignores the scientific names and uses only the common names, this will avert any confusion over name changes.

The use of common names produces its own problems; one common name can be used to describe several different species. For example, black wattle is the common name for *Acacia mearnsii*, *A. decurrens*, *A. falciformis*, *A. mabellae*, *A. stenophylla*, *A. mangium* and *A. neriifolia*. Ironwood has been used for *A. stenophylla*, *A. excelsa* and *A. estrophiolata*; and rosewood has been referred to *A. excelsa*, *A. rhodoxylon* and *A. fasciculifera*. Sometimes a single but widespread species can be ascribed many common names.

For example, *Acacia stenophylla* is variously known as munumula, balkura, gurley, gooralee, ironwood, dalby wattle, river cooba, river myall, native willow and black wattle (these examples come from the 2001 *Flora of Australia* account of *Acacia*). IWCS members will be aware of this problem as the same issues exist with common names applied to wood.

6. Believing that plant-name changes do not occur frequently enough to be of concern.

This is a dangerous assumption to make. In the 1988 *Flora of Australia*, 513 *Eucalyptus* species were recorded. However, a 2000 revision of the *Eucalyptus* genus put the figure at 800 — an increase of nearly 300 species. The acacias also have increased in number from 700 species recorded in 1982 to 955 species recorded in the 2001 *Flora of Australia*. This represents an increase in *Acacia* of 250-odd species in 18 years.

So, with woody names changing so frequently and new species being recognised (often because of revision and reclassification of existing collections), vouchers are a necessity if one wishes to keep up with these changes.

A way forward: Establishing links between the IWCS and the herbaria

There is another way that interested members can overcome the problem of identifying unvouchered wood samples. I propose the establishment of a reciprocal relationship between the IWCS branches or regions and their local herbarium, whereby the IWCS provides reference wood specimens complete with vouchers to the herbarium in return for accurate identifications.

Herbaria are repositories especially designed for the preservation of dried plant specimens; plant taxonomists usually are attached to these institutions and they use the collections to carry out scientific research. Herbaria exist in every state and territory of Australia, and in every country of the world; the New York Botanical Gardens maintains an on-line version of *Index Herbariorum*, a searchable database of worldwide herbaria (http://www.nybg.org/bsci/ih/).

While most herbaria probably would have wood samples, they do not necessarily maintain a wood reference collection attached to their botanical collections.

As IWCS members would be aware, botanists do not generally collect wood (except opportunistically) and botanical publications, including state and national floras, do not usually mention wood properties. This largely is because the study of wood is, in itself, a specialist science and plant taxonomists have traditionally used other plant parts (leaves, fruits and flowers) as the basis for their research and classification.

Having said this, I would imagine most herbaria would be interested in amassing a reference wood collection, and this is where the IWCS could play a role.

By donating reference wood samples, complete with associated herbarium vouchers, the IWCS can keep abreast of name changes when they occur and to regularly update their wood samples to the correct names. Moreover, members could teach botanists a thing or two about the physical (and anatomical) properties of wood.

Collection of a voucher is a simple process. When members are in the field collecting wood, they usually will cut some branches of the plant containing leaves, flowers, fruits, etc. Many of us will use these characteristics to locate the plant in the first place, frequently with the aid of botanical publications. I suspect most members discard these branches when many of them would do for a voucher.

A good rule of thumb is to collect too much rather than too little, and to ensure the branch includes as many diagnostic

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features as possible. Ideally, vouchers will contain both flowers and fruits, but many plants flower and fruit at different times of the year. Where none of the reproductive features exist, identification can prove difficult or impossible but, even without these parts, it is still worth collecting a herbarium specimen.

On collection of a voucher specimen and whilst still in the field, the branch should be transferred to a press. A plant press can easily be made with a few pieces of sturdy cardboard or timber, some blotting paper, newspaper and a couple of old belts or rope for tightening and securing the plant press.

Adequate labelling and documentation for accompaniment with a voucher also are important. Labels should be as comprehensive as possible and include the name of the collector, the date and locality of collection with reference to a point on a map (e.g., 10km north of Birdsville, Queensland; the distance from a road; a GPS reading; or a map grid reference).

A collection number also is vital; vouchers and wood specimens should *always* be removed from the same tree and bear a common and unique number that ensures their continued association if or when they are separated. If possible, a description of the form or habit (tree, shrub or vine), the habitat (e.g., soil and vegetation type, geology) and a field identification could prove useful. Photographic documentation also can be helpful.

Of course, further information and advice on the collection of vouchers can be obtained from local herbaria. Many may be willing to lend members such equipment as plant presses and botanical field notebooks, as well as identify the collections, in return for good herbarium specimens.

Conclusion

Whilst I am of the firm opinion that the use of vouchers in professional research is a necessity and best practise, my views are more relaxed when it comes to the IWCS, a nonprofessional organisation.

In no way is this paper intended to diminish the hard work and enthusiasm of IWCS members in amassing their wood collections. I acknowledge that most IWCS wood collections have not been created for scientific purposes and have a sentimental value to collectors who will accept and absorb inconsistencies and inaccuracies.

Furthermore, in many cases some uncertainty or inaccuracy in wood identification will be comfortably tolerated; for example, it does not matter whether a turned bowl labelled "mulga" could be one of several species.

However, I hope I have gone some way to addressing some common misconceptions about plant-name changes. It is important that IWCS members have an awareness of botanical vouchers, what they are and the purpose they serve, so they can make up their own minds.

For members concerned about accurately identifying wood and were hitherto unaware of the perils and pitfalls of identifying unvouchered wood, I strongly encourage you to foster your own relationship with a local herbarium and collect vouchers for every new wood sample.

Members also might be interested to know that my own Ph.D. research is presently based on unvouchered wood samples. However, since my academic studies involve scientific research, I am obliged to employ best practise techniques if my work is to withstand the test of time and the criticism of my peers.

Accordingly, an impending field trip to north-east South Australia with member Eugene Dimitriadis aims to collect contemporary vouchered wood specimens that will eventually form the foundation of my identification tool.

Addendum

That *IWCS Membership Directory* is a useful and informative document!

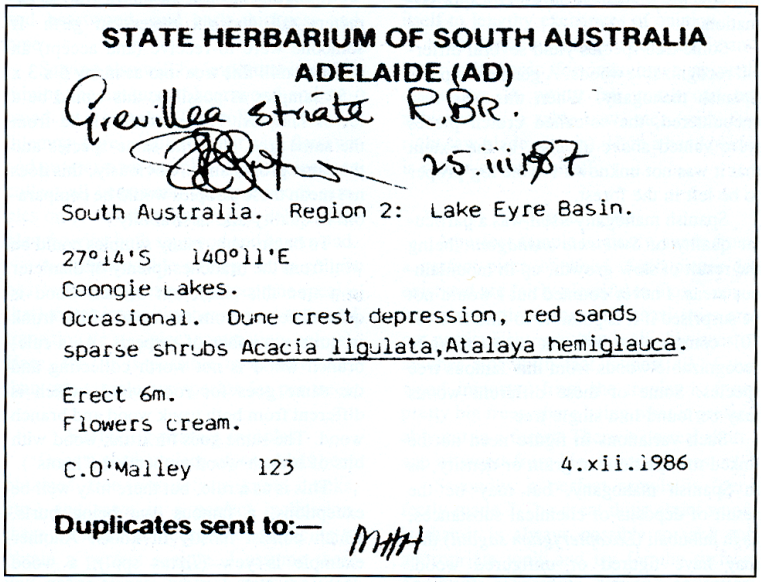
I thank Eugene Dimitriadis for pointing out that my article is in keeping with the following points in the IWCS Constitution contained on page 23 of the directory (the italics are my own):

3. To assist in *accurate* naming and classification of specimens whenever the collector or crafters cannot obtain the service from the source of the specimens.

5. To encourage the adoption of standard methods for wood-sample collecting. This shall include specimen sizes, numbering systems, *authenticity*, ratings and other details relating to standardization and improvement of individual collections.

7. *To cooperate with institutions*, universities and schools *in the augmenting of their scientific collections of herbarium specimens and woods, and to receive aid in the proper naming of specimens.*

Food for thought?



STATE HERBARIUM OF SOUTH AUSTRALIA
ADELAIDE (AD)

Grevillea striata R.Br.

25.iii.87

South Australia. Region 2: Lake Eyre Basin.

27°14'S 140°11'E
Coongie Lakes.
Occasional. Dune crest depression, red sands
sparse shrubs Acacia ligulata, Atalaya hemiglauca.

Erect 6m.
Flowers cream.

C.O'Malley 123 4.xii.1986

Duplicates sent to:— MHH

An enlarged view of the descriptive label that accompanied the beefwood (*Grevillea striata*) botanical specimen shown on Page 5. The map coordinates and the descriptions of this woody plant's habit and habitat were all taken from the original notes of the collector, C. O'Malley, which also are appended to the specimen. In his description of the habitat, this collector has recorded the woody plant's association with dune wattle (*Acacia ligulata*) and whitewood (*Atalaya hemiglauca*). The handwriting on the label is the professional determination, or identification, of the specimen by a plant taxonomist associated with the State Herbarium of South Australia.

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References were not incorporated in the text of the article or included in a bibliography as World of Wood *is not a refereed journal and articles do not usually contain cited references. The references consulted for this article are listed here.*

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Response from Jennifer Barker in Australia

I was pleased to read Paul's views on the practicalities of collecting vouchered wood samples, and hope that the article may stimulate others to debate the virtues of such a practise.

I agree that, for many wood collectors (e.g., those involved in cabinet making, wood turning, etc.), ensuring and maintaining accuracy in identification is not always of importance.

However, I imagine that for some members, particularly those who maintain reference collections, wood that carries a certain identification would be preferred — it was largely this IWCS audience that I had in mind when I wrote the article. But I also acknowledge that maintaining accuracy can be difficult with the healthy trade and exchange that occurs amongst our members. And, not all wood collectors are field collectors.

Thus, amongst the IWCS at times it is not only unnecessary (in certain circumstances) but unrealistic to expect that all wood should carry a voucher; my article simply offers a suggestion for "best practise."

In relation to herbaria, I wrote from my own experience with the local herbarium in Adelaide, Australia, and I know that they would be pleased to begin a vouchered wood collection. Our local IWCS branch recently made the herbarium their permanent meeting place and, whilst it is early, I hope that a healthy relationship may be fostered.

It is a relationship that other local IWCS branches may wish to consider. The interests of individual herbaria will depend on logistical constraints (like the ones you mentioned) and, ultimately, the value they may place on a collection.

That a fine voucher specimen may yield a worthless wood sample depends on your methods of collecting and selection criteria. In the field, I will be looking for individuals with mature-stemmed wood (required for wood anatomical purposes) and removing a voucher specimen from said individual. It is more likely that the voucher specimen may not be a fine example, if the individual is not fruiting or flowering.

However, advice sought from local botanists indicates that identification should still be possible. Of course, where an individual is found with the mature-stemmed wood and fruiting or flowering, this will make an ideal collection and, again, "best practise."

I should also mention that I intend to deposit a wood sample in the South Australian herbarium along with a voucher on my return from the field.

In Australia, where there are thousands of wood-producing species, wood remains severely under-researched and there is only a handful of wood anatomists and xylaria (mainly attached to forestry departments); in the state of South Australia, to my knowledge there are no wood anatomists or xylaria.

If IWCS members who collect in the field sacrifice a sample from the collected wood (complete with a voucher) for deposition in their local herbarium, the growth in the herbarium's wood collection (and its research potential) might stimulate interest in wood amongst forthcoming botany students. In turn, this may increase our knowledge of wood and we may eventually find descriptions of wood appearing in botanical treatments and influencing plant taxonomy.

This is where the IWCS members can make a valuable contribution to science, even if collection of vouchered wood samples occurs opportunistically; whether individual members choose to retain the association between the herbarium voucher and the wood they have collected will depend on the importance they place on maintaining correct identifications.

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Glossary of terms used in thesis

Note: Further explanations of wood structure and anatomy are contained in the glossary and the character state factsheets attached to the identification tool developed in this research

angiosperm: A taxonomic subdivision of the spermatophytes (seed-producing plants) that is further divided into dicotyledons (hardwoods) or monocotyledons.

average maximum: A statistical calculation whereby 50 values are randomly selected from a data set and the average of the largest ten values is taken.

bark: Outermost layer of a wood-producing stem which serves a protective role; inner bark cells are living (see phloem).

bordered pit: A pit with margins extending across the pit aperture.

cambium: Living tissue between the phloem and xylem; through cell division within the cambium growth rings are created and the tree's girth is increased, as new phloem and xylem cells are formed.

character: Taxonomic term referring to the features of an organism

character set: In a key, like characters may be placed in sets to simplify navigation through the list of characters and to allow omission of sets of characters that are not applicable or relevant to the user.

character state factsheet: Information pages attached to each taxon and describing its salient features with both text and images.

character states (or states): Taxonomic term referring to the range of variation that can occur within a particular character. Used to describe and distinguish organisms.

conifer: Common name for the taxonomic order Coniferae, the cone-producing division of gymnosperms that includes important commercial timbers such as Pine (*Pinus*), Fir (Abies) and Spruce (*Picea*) and the Australian Native Pine (*Callitris*). Referred to as softwoods in the forestry industry and in wood identification.

cross-section: The transverse surface.

density: A measure of mass per unit of volume; in wood identification density is usually expressed in kilograms per cubic metre (or pounds per cubic foot) or using the alternative expression of specific gravity.

dicotyledons: The taxonomic division of angiosperms that are characterised by two seed leaves; includes includes common and commercial timbers such as Maple (*Acer*), Birch (*Betula*), Hickory (*Carya*), Chestnut (*Castanea*), Walnut (*Juglans*), Ash (*Fraxinus*), Beech (*Fagus*), Oak (*Quercus*), Poplar (*Populus*) and Elm (*Ulmus*) and Australian species such as Gum (*Eucalyptus*) and Wattle (*Acacia*). Referred to as hardwoods in the forestry industry and in wood identification.

dissecting light microscope: An optical microscope that utilises reflected light to observe the surface of an opaque specimen at low magnifications (usually up to 50x). In wood identification this microscope is used to examine the polished endgrain.

earlywood: A term usually applied to temperate species to describe the initial part of a growth ring added at the beginning of the growing season; it is usually lighter in colour and less dense than latewood. Also called springwood.

endgrain analysis: A simple method of wood identification that involves polishing a small area on the cross-section of wood with a razor blade and examining the surface with a hand-lens or low-powered dissecting light microscope.

endgrain: The cross-section of wood.

extractive: Extraneous substances that have been collected by the tree. Extractives stored in the heartwood often stain it a characteristic colour and can make it resistant to decay and repellent to wood -boring insects and fungi.

family: The taxonomic division that contains genera and commonly ends in -aceae.

fibres: Small cells elongated parallel to the stem axis that largely contribute to the strength of wood; they are often densely packed with thick cell walls. Also known as ground tissue.

figure: Distinctive patterning on the longitudinal surfaces of wood as a result of anatomical structure.

fluorescence: Light that is absorbed at one wavelength and re-emitted at a different wavelength as occurs with some organisms/objects when they are exposed to ultraviolet (UV) light.

genera: The taxonomic divisions contained within families and the first name in the binomial classification that identifies a species. Genus (sing.)

grain: A broad term that may be used to describe wood figure but usually refers to the direction and orientation of wood cells.

growth ring: The layer of cells added to the stem of a wood-producing plant during a growing period. Also referred to as annual rings when referring to temperate species that experience an annual growing season; see earlywood and latewood.

gymnosperm: A taxonomic subdivision of the spermatophytes (seed-producing plants) that includes the economically important wood -producing conifers (or softwoods).

hardwood: See dicotyledon; those wood -producing plants characterised by vessels.

heartwood: The innermost part of the wood, excluding the pith, where all cells are non-living and inactive. The heartwood provides important structural support to the tree, and is often distinguished from the sapwood by the presence of extractives.

helical thickenings: Ridges that coil across the inner vessel wall of some species, visible only at high magnification. They vary in prominence, thickness, interval and orientation and may occur in combination with pits; they may also occur in tracheids and rarely in parenchyma and may be limited to the ends of vessels. Also known as spiral thickenings.

herbarium: A repository for the curation, identification and analysis of plant material (often includes a limited collection of wood specimens).

identification tool: A term used in this presentation to describe the entire hierarchy of keys and their attached taxa factsheets, character factsheets and other information.

inclusion: Various organic and inorganic materials that may be evident in wood occurring extraneously or within wood cells and including tyloses, resin, starch, silica (and other minerals) and crystals.

key: A tool or system developed to enable the identification of any group of similar organisms or objects.

kino: Exudates produced in some woods in response to an injury to the cambium; usually visible to the naked eye.

latewood: A term usually applied to temperate species to describe the part of a growth ring added towards the end of the growing season; it is usually denser and darker in colour than earlywood. Also called summerwood.

longitudinal plane: Any plane that is parallel to the stem axis of the tree including the radial and tangential surfaces.

mean: A statistical calculation whereby the sum of two or more values is divided by the number of values; also referred to as the average.

micrometre: A unit of measure: one micrometre (µm) is equal to one thousandth of a millimetre.

microtome: A mechanical instrument for cutting uniformly-sized thin sections of biological tissue for microscopic analysis using specially-designed knives.

monocotyledon: The taxonomic division of angiosperms that are characterised by a single seed leaf; includes bamboos and palms.

multiseriate ray: Rays two or more cells wide; the terms biseriate and triseriate are also used to describe rays two and three cells wide.

parenchyma: Short, thin-walled cells elongated parallel to the stem axis and involved in the storage of nutrients in both the heartwood and sapwood. Where they occur in the sapwood, they are the only living cells in wood. Also referred to as axial parenchyma, longitudinal parenchyma or soft tissue.

perforation plate: Adjoining end walls of vessel elements are separated by a perforation which allows the axial transport of sap through the tree. This end wall is known as a perforation plate. They occur in a number of different forms but the most common type is the simple perforation plate. Simple perforation plates refer to a large circular opening surrounded by a perforation rim.

phloem: Living plant tissue between the outer bark and the cambium involved in the transport of nutrients from the leaves to the stem and roots. Also referred to as inner bark.

pit: A small hole in the secondary cell wall that allows the passage of substances from contiguous cells.

pith: Soft, spongy tissue composed mainly of parenchyma cells that makes up the core of a woody stem.

pore: Same as vessel; commonly used to refer to vessels on the transverse surface.

radial multiple: Vessel multiples aligned parallel to the rays that share a tangential boundary. Also known as radial vessel multiples.

radial: The radial surface refers to the surface exposed by bisecting the pith at the centre of a woody stem. Like the tangential surface, it occurs parallel with the longitudinal grain direction. Abbreviated to R or RLS.

range: A statistical calculation defined by the minimum and maximum value in a data set.

ray fleck: The distinctive appearance of rays on the radial surface.

rays: Parenchyma cells extending horizontally in a radial direction from the centre of the tree to the outside of the tree. Ray parenchyma provide an important passage for the transport of substances from the pith to the cambium. Sometimes loosely referred to as medullary rays.

redundant character: Characters (or character states) that are not applicable to the remaining taxa

saponin: Chemical compounds that creates a foaming lather when agitated in water.

sapwood: Sapwood is situated between the cambium and the heartwood; consisting of living and non-living cells, its main purpose is the storage of food and the conduction of water and sap.

scanning electron microscope (SEM): A sophisticated microscope that uses an electron beam to produce a three-dimensional image of an object's surface at magnifications up to several hundred thousand times.

simple pit: A pit without a border.

softwood: Those wood -producing plants that lack vessels; see conifers.

species: The basic unit of taxonomic classification, a group of organisms belonging to the same genus that share similar diagnostic characteristics and are capable of inter-breeding; may be further subdivided into sub-species (ssp.) or varieties (var.).

specific gravity: An alternative expression of density; the ratio of the density of an object relative to the density of water where the specific gravity of water is equal to 1.0. Wood with a specific gravity greater than 1.0 will sink in water whilst wood with a specific gravity less than 1.0 will float in water.

standard deviation: A statistical calculation that indicates how widely values deviate from the mean (or average) value within a data set.

sub-key: One or several key(s) attached to a source or parent key which will usually reflect taxonomic hierarchies.

tangential: One of two longitudinal planes, the tangential surface occurs perpendicularly to the rays and parallel to the growth rings. Like the radial surface, it occurs parallel with the longitudinal grain direction. Abbreviated to T or TLS.

taxa: A term used to describe a group of individuals; it can be used to refer to families, genera or species. Taxon (sing.)

taxa factsheet: Information pages attached to each taxon and describing its salient features with both text and images

taxon: See taxa.

taxonomy: A scientific system of classification and naming to provide order to organisms and objects. In biology this involves classifying organisms into hierarchies of family, genus and species.

thin section: A small slice of wood usually 10 to 30 µm thick removed from the radial, tangential and transverse surface with a razor blade or microtome; sections are mounted on a microscope slide and examined using a transmitted light microscope for identification purposes.

tracheid: Non-living cells elongated parallel to the stem axis and with closed or imperforate end walls. They are the predominant cell in softwoods - but much less significant in hardwoods - and are involved in the conduction of food and water as well as providing structural support. Tracheids can intergrade with fibres. See vasicentric tracheid and vascular tracheid.

transmission light microscope: An optical microscope that illuminates thin, transparent specimens mounted on to slides by passing light through the specimen. In wood identification, the transmission light microscope is used to examine thin sections of wood.

transverse: The transverse plane (or cross-section) occurs across the grain and perpendicularly to the longitudinal axis of the tree. Abbreviated to X or XS.

tyloses: Distinctive vessel inclusions that adjacent ray or axial parenchyma cells through a pit in the vessel wall.

uniseriate ray: Rays one cell wide as viewed on the tangential surface.

vascular tracheid: Vascular tracheids are indistinguishable from small vessels on the transverse surface; however, the absence of perforation plates distinguishes them from vessels on the longitudinal surfaces.

vasicentric tracheids: Vasicentric tracheids are small, thin-walled cells with rounded ends. They usually occur in association with vessels and mixed with parenchyma. Heavily pitted and elongated they are distinguishable from parenchyma on the longitudinal surface.

vessel: Occurring parallel to the longitudinal axis of the tree, vessels are the conduits that transport water and sap from the roots of the tree to its leaves. A single vessel is made up of cells (vessel elements) separated by perforation plates.

vessel multiple: Two or more vessels that share adjacent cell walls. Vessel multiples may be classified according to their orientation with radial vessel multiples sharing a tangential boundary and aligned parallel to the rays.

voucher: A term for a botanical specimen linked to scientific data (such as a wood specimen) that is stored in an herbarium to enable future reference particularly in the event of taxonomic name changes.

wood: See xylem.

xylarium: A repository for the curation, identification and analysis of wood specimens.

xylem: The scientific term for wood the xylem is that part of a stem involved in the transport of nutrients and water from the roots to the leaves. Predominantly consisting of non-living cells, and making up the largest proportion of a mature stem, the xylem also provides important structural support for the tree. Typically, the xylem is characterised by both sapwood and heartwood.

xylology: The study of wood structure. Closely related to xylotomy: the preparation and microscopic analysis of wood sections.

xylologist: One who studies wood structure; usually involving the preparation and microscopic analysis of wood sections.