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WOOD IDENTIFICATION – A REVIEW[1]

by

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SUMMARY

Wood identification is of value in a variety of contexts – commercial, forensic, archaeological and paleontological. This paper reviews the basics of wood identification, including the problems associated with different types of materials, lists commonly used microscopic and macroscopic features and recent wood anatomical atlases, discusses types of keys (synoptic, dichotomous, and multiple entry), and outlines some work on computer-assisted wood identification.

Key words: Wood identification, keys, computer-aided wood identification.

INTRODUCTION

In the last decade, computerized keys have made the identification of uncommon woods easier. Nevertheless, 'traditional' methods remain important because often they are more efficient and convenient, particularly for common commercial woods. This paper discusses some applications of wood identification, logistics, the macroscopic and microscopic features used for wood identification (particularly for hardwoods, i.e., dicotyledonous angiosperms), identification procedures, some recent computer-aided wood identification projects, and the need for additional work.

APPLICATIONS

Proper processing of wood, especially drying, depends upon correct species identification because different species and species groups require different protocols. When problems arise during wood processing (drying, machining, or finishing), one of the first questions asked is whether the wood was correctly identified.

Customs officials need to know whether logs, timbers, or wood products are correctly labeled so that tariffs can be properly assessed and trade regulations enforced. The International Timber Trade Organization (ITTO) has proposed limiting international trade to timber that is cut from sustainably managed concessions. Verifying the source and identity of timber in order to enforce bans on trade in woods of endangered species will require wood identification skills (Baas 1994).

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One means of conserving tropical forests is ensuring that any tree cut is properly used, and its full value realized, thereby reducing waste, and resulting in fewer trees being cut to meet demand. In tropical forests with a high species diversity, identification is an integral part of timber grading, and often difficult because the anatomy of many species is not well known. Oteng-Amoako (1992b) discussed the problems of timber identification in Papua New Guinea (PNG) and the financial consequences of the lack of personnel able to do identification.

When restoring historically significant wooden structures, restorers prefer to use the same type of wood as used originally, and that requires identification of whatever original wooden fragments remain. The value of a wooden object often is affected by the type of wood used. Art historians use evidence from wooden frames and panels to establish the authenticity and provenance of an art work.

Wood identification has forensic value, e.g., determining whether wooden fragments at the scene of a crime match those taken from the clothing or a vehicle belonging to a suspect. In the U.S., the analysis of the wooden ladder used in the infamous Lindbergh kidnapping of the 1930s provided crucial evidence for the conviction of the alleged kidnapper (Miller 1993).

Different tree species and different wood anatomies characterize different climates (Wheeler & Baas 1991). Therefore, identification of ancient woods helps to reconstruct ancient ecosystems and to document climate change. Knowing the affinities of fossil woods can help determine the age of a geologic formation (Stone et al. 1987). Paleontologists are interested in knowing what trees were present when dinosaurs lived, and in what type of vegetation early primates and hominids evolved. Geologically ancient woods provide information helpful for explaining present-day distributions of plants, the history of particular families and genera, and the past distribution and diversity of woody plants. Woody remains provide archaeologists with information useful for reconstructing trade routes. At Pompeii and Herculaneum, identification of woody remains helped to reconstruct the land use patterns and gardening practices of Italy in A.D. 79 (Jashemski 1990).

LOGISTICS

Levels of difficulty

Questions of the type "Is this wood teak?" or "Is this wood *Acer* (maple) or *Betula* (birch)?" are easier to answer than "What is this wood from northern Europe?" and this question is easier to answer than "What is this wood? I don't know what continent it came from."

The size of the pool of possible matches for an unknown affects the ease and also the approach for determining a wood's identification. There are significantly fewer tree species in the north temperate region than in the tropics. Identifying wood from a sawmill that only uses trees from nearby is easier to do in the north temperate regions than in the tropics. Identifying a commercially important wood whose geographic source is known is easier than identifying woods whose geographic source is unknown.

Geologically ancient dicotyledonous woods may have nearest living relatives that now occur on different continents, so that they need to be compared with thousands of species of extant woods. Fossil woods (approximately 44 million years old) from the Clarno Nut Beds in the western United States have nearest living relatives that today occur in eastern North America, Asia, South America, and Africa (Scott & Wheeler 1982). Cretaceous and early Tertiary dicotyledonous fossil woods can be difficult to 'identify' because they may represent extinct genera or species that have not been described before.

Types of material

The type of material affects the ease of identification. The material needing identification is variable, ranging from logs, large pieces of lumber and solid pieces of wood, to various types of composite wood products such as plywood, fibreboard, particleboard, and splinters, sawdust, and pulp. Some woods are unaltered and retain the original characteristics, microscopic and macroscopic. Woods treated with preservatives or stained or finished would not have the original colour; decayed and petrified woods would not have the original colour or density. Decayed wood, charcoal, or poorly preserved petrified wood is difficult to section and prepare and may not show all anatomical features originally present in the wood. Cell sizes are altered in charcoalified woods, so quantitative features only can be used with extreme caution. Very small fragments may show relatively few features; veneers may not provide enough of all the surfaces necessary to reveal diagnostic characteristics. Unaltered pieces of wood that are large enough to provide an end-view for examination with a 10× handlens, and to section to provide cross, radial, and tangential sections for microscopic study are most likely to reveal a diagnostic combination of features.

THE BASIS OF MACROSCOPIC AND MICROSCOPIC WOOD IDENTIFICATION

Macroscopic features

Macroscopic features include physical features such as colour and lustre, and anatomical features visible with a handlens or unaided eye, including porosity, vessel arrangement and grouping, axial parenchyma arrangement and abundance, ray size relative to vessel diameter, ray height, presence or absence of storied structure. Other features are presence of included phloem, abundance of tyloses, and deposits in vessels and their colour. Categories of vessel diameter and density (number per unit area) are also used; vessels more than 100 µm in diameter are easily seen with a handlens, vessels more than 200 µm are easily seen with the unaided eye. Determining vessel diameter and density (number per mm^2 or per 10 mm^2) is helped by using transparent overlays with scale lines marked in some set increment (e.g., 50 µm increments on a 1 mm long line, and 1 mm^2 or 10 mm^2 circles within which the number of vessels can be counted).

Some woods have distinctive combinations of macroscopic anatomical features so that they are readily identified with a handlens. For example, temperate northern hemisphere species of the elm family (Ulmaceae) have a distinctive combination of ring porosity and latewood vessels arranged in wavy tangential bands (ulmiform bands) (Fig. 3). Most *Quercus* species (oak) are also distinct (ring-porous, rays of two distinct sizes, and latewood vessels in radial to dendritic patterns, Fig. 11, 12).

Classic examples of woods with distinctive colour include purpleheart (*Peltogyne* spp.), pink ivory (*Rhamnus zeyheri* Sand.), and the yellow-coloured boxwood (*Buxus* spp.). Describing colour can be difficult as individual perceptions of colour differ. Woods have varying shades of colour and combinations of different colours. Reference to colour charts used for soil classification may provide some consistency while describing colour (Vetter et al. 1990), but this has not yet been widely applied. Multiple entry keys (see below) generally use no more than seven descriptors for wood colour. Unfortunately, wood colour changes with time and exposure to light, and the heartwood colour of freshly felled trees often differs from dried wood samples (IAWA Committee 1989). Nonetheless, if the sources of variation in heartwood colour are understood, whether or not the heartwood is dark or light, in shades of red, brown, yellow, white to grey, or other colours, or has streaks is important for macroscopic identification of untreated wood.

Macroscopic features such as texture (coarse / fine; even / uneven), grain (straight, spiral, interlocked, wavy), figure (many types) and lustre have poorly defined categories and require experience before they can be effectively applied in wood identification, but they can be very helpful as complementary diagnostic features. Although not strictly a macroscopic feature, the physical property of specific gravity or density is used in many keys.

There is a variety of other supplementary features. Whether or not a freshly smoothed surface of wood fluoresces and the colour it fluoresces can be diagnostic, as can be odours and chemical tests. Avella et al. (1989) surveyed over 10,000 species of woods for fluorescence. Sandalwood (*Santalum album* L.), 'cigar-box' cedars (*Cedrela* spp.), raspberry jam wood (*Acacia acuminata* Benth.), and stink wood (*Ocotea bullata* E. Meyer) have distinctive odours (Jane 1970). However, odour is ephemeral, and woods may acquire smells from their surroundings. Some woods with similar anatomy differ in the type of residue left after burning a splinter in still air (Dadswell & Burnell 1932; IAWA Committee 1989). The chrome azurol-S test indicates the presence of aluminum in a wood (Kukachka & Miller 1980) and woods of families (e.g., Vochysiaceae) with a high aluminum content react with a distinct blue colour. There are other chemical tests useful for distinguishing between closely related woods (see examples in Panshin & DeZeeuw 1980, and Jane 1970). Chemical tests seem most useful for conifers (softwoods) because conifers have few useful macroscopic features (presence or absence of resin canals, whether the transition from earlywood to latewood is abrupt or gradual, colour, and odour).

Macroscopic features often can be used to quickly establish whether a wood is correctly labeled, or to which family it is likely to belong. As recognized long ago by Bailey (1917), commercial timbers must be handled quickly and often in large volumes, so that it is only practical to use the most obvious characters in their identification, i.e., macroscopic features. However, many genera have similar macroscopic features. and more species can be distinguished using microscopic characters than using macroscopic ones. Sudo (1994) asked a timber dealer to sort a batch of Sarawakan timber to type. The timber dealer recognized fewer types on the basis of colour, grain, texture, and, to a lesser extent, easily visible end-grain characters than were distinguished by a more detailed anatomical examination.

A given microscopic feature is often not any more useful or reliable (consistent from one sample to another of a particular taxon) than any one macroscopic character, but the larger the number of features to choose from, the more likely it is that a combination of characters diagnostic of a particular family, genus, or species will be observed. Macroscopic keys typically have fewer features than microscopic keys. The CSIRO macro key has 50 features (Ilic 1990), while the CSIRO microscopic key has 91 anatomical features (Ilic 1987). The anatomical features visible and useful macroscopically are equally valuable for microscopic wood identification.

Microscopic features

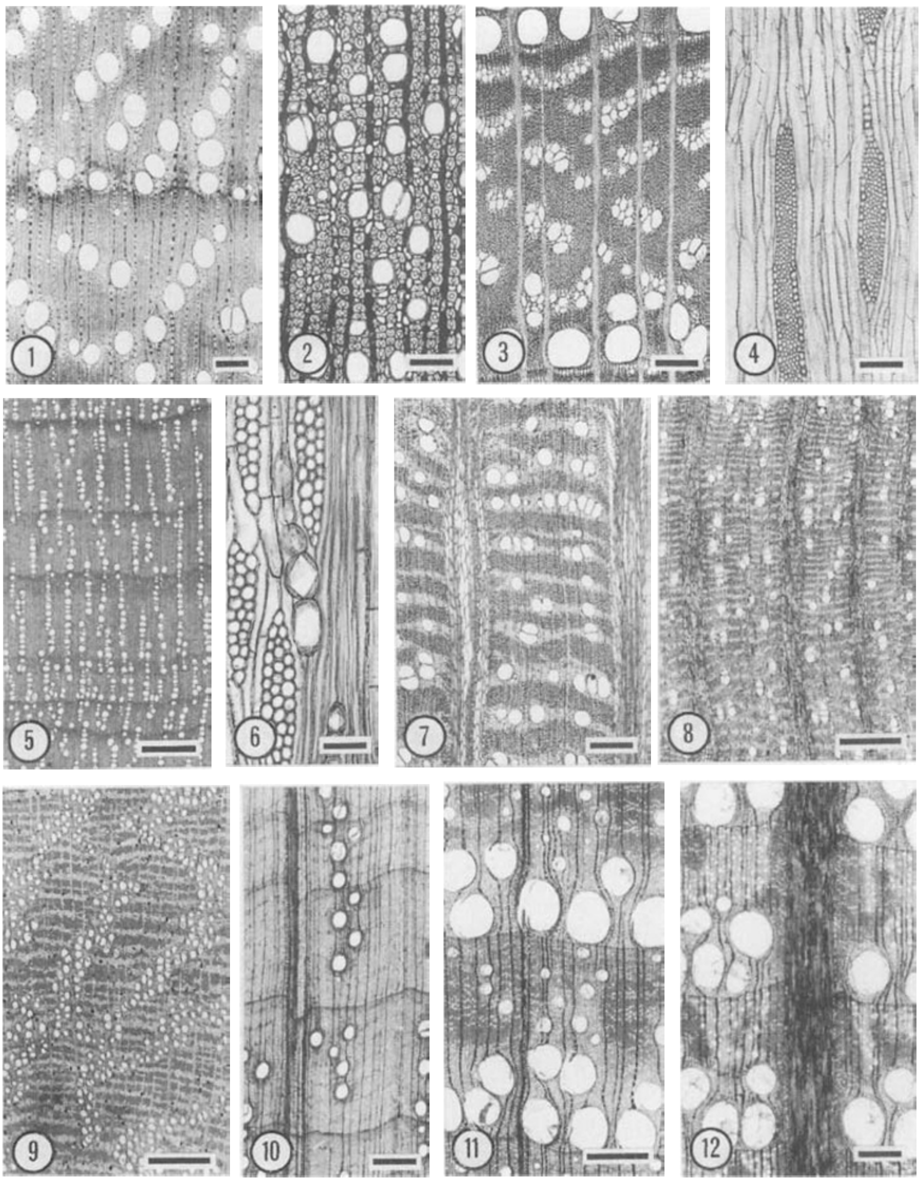
The IAWA List of Microscopic Features for Hardwood Identification (IAWA Committee 1989) was intended to be a concise list of features useful for hardwood identification, and to help reduce ambiguity in the description of anatomical features. The anatomical features in this list are: growth rings (distinct, indistinct, absent); porosity (ring-porous or diffuse-porous); vessel arrangement; vessel groupings; outline of solitary vessels; perforation plate type; intervessel pit arrangement and size; presence or absence of vestured pits; type of vessel-ray pitting; presence or absence of helical thickenings; tangential diameter of vessel lumina; vessels per square millimetre; mean vessel element length; presence or absence of tyloses or other deposits in vessels; presence or absence of vascular or vasicentric tracheids; type of fibre wall pitting; presence or absence of septate fibres; fibre wall thickness; fibre length; axial parenchyma distribution; number of cells per axial parenchyma strand; ray width; presence or absence of aggregate rays; whether rays are of two distinct sizes; cellular composition of rays (procumbent, upright, and square cells); presence or absence of sheath cells, tile cells, perforated ray cells, or disjunctive ray cells; rays per millimetre; presence or absence of storied structure, and, if storied, which elements are storied; presence or absence of oil / mucilage cells, intercellular canals (radial or axial), laticifers or tanniniferous tubes, or cambial variants (e.g., included phloem); presence or absence of prismatic crystals, druses, silica bodies, or other crystal types, and their cellular location (in ray parenchyma and/or axial parenchyma).

This IAWA list (163 anatomical, 58 miscellaneous features) is not all inclusive, but was intended to serve as a framework for descriptions of woods for databases for wood identification, and to a lesser extent also for systematic descriptions. Some recent works have included as part of the wood descriptions a list of IAWA feature numbers that apply (e.g., Nardi Berti & Edlmann Abbate 1988; Oteng-Amoako 1992a). A recent PROSEA volume (Sosef et al. 1998) on the trees of Southeast Asia provides concise descriptions of woods of approximately 300 genera by using a large subset of IAWA feature numbers. Different features are useful within and between different groups; no one list of features can be expected to include all diagnostic features for all woods (Brazier 1976; IAWA Committee 1989).

Figures 1–42 illustrate selected anatomical features. These figures show most of the anatomical features that have been used in multiple entry keys.

Illustrations and definitions of some features are available on the World Wide Web at a site providing supplementary information for a course in wood structure and properties:

[url of http://www2.ncsu.edu/unity/lockers/class/wps202002/hw/hwanat.html]



What sorts of features are valuable?

There has been considerable discussion in the taxonomic literature on how to determine useful features for biological identification and classification. The features useful for identification and those useful for determining evolutionary relationships and developing phylogenetic schemes are not always the same. Phylogenetic relationships are established on the basis of shared derived characters, yet wood features that are considered primitive in the Baileyan sense are uncommon in the dicotyledons as a whole. Woods with 'primitive' features such as exclusively solitary vessels (Fig. 2), scalariform perforation plates, opposite to scalariform pits (Fig. 13, 14), and fibres with distinctly bordered pits (Fig. 41) can be relatively easy to recognize because they occur in relatively few families.

Woods belonging to different botanical families may superficially appear similar because there has been considerable convergent and parallel evolution in wood structure, e.g., *Robinia pseudoacacia* (Leguminosae, Legume family) and *Morus rubra* (Moraceae, Mulberry family), both of which are ring-porous with latewood vessels in small clusters. Nevertheless, *Robinia* and *Morus* can be separated by microscopic features; *Robinia* has vestured pits and vessel-ray parenchyma pits that are similar in appearance to intervessel pits, while *Morus* has non-vestured pits and vessel-ray parenchyma pits that are coarse and with reduced borders. Ring-porosity is a distinctive, easily observed feature (Fig. 3, 11, 12), and often one of the first features used in dichotomous keys, particularly for north temperate woods. This feature is highly correlated with climate (common in temperate woods, rare in tropical woods), and so its usefulness for determining phylogenetic relationships is compromised.

Stable and reliable characters that are consistent from one sample to the next are best (Brazier 1976). Therefore, understanding the range of variation within a species is of utmost importance. Choosing useful characters is dependent upon systematic wood anatomical studies that use large numbers of reliably identified samples, accompanied by herbarium vouchers. If the characterization of species, species groups, and genera is based on only a few samples, there is the risk that some features will be chosen that are not always useful for separating the taxa. For example, Philips (1948)

Fig. 1–12. – 1: Solitary vessels in a diagonal arrangement, *Eucalyptus globulus* (Myrtaceae). – 2: Solitary vessels with an angular outline, *Curtisia* sp. (Cornaceae). – 3: Ring-porous wood with latewood vessels in wavy tangential bands, *Celtis laevigata* (Ulmaceae). – 4: Rays heterocellular with square to upright marginal rows and sheath cells, *Celtis laevigata* (Ulmaceae). – 5: Vessels in long radial multiples and in a radial pattern, *Amyris sylvatica* (Rutaceae). – 6: Idioblasts, enlarged cells with crystals, *Citrus aurantium* (Rutaceae). – 7: Vessels and parenchyma in tangential 'festoons', *Cardwellia* sp. (Proteaceae). – 8: Large rays and regular tangential bands of parenchyma (scalariform parenchyma bands), *Sapranthus* sp. (Annonaceae). – 9: Vessels in a diagonal to dendritic pattern, *Bumelia angustifolia* (Sapotaceae). – 10: Solitary vessels in a radial pattern, diffuse-porous, *Lithocarpus* sp. (Fagaceae). – 11: Solitary vessels in a radial to diagonal pattern, wood ring-porous, latewood vessels rounded to oval in outline, *Quercus falcata* (i.e., a red oak, Fagaceae). – 12: Solitary vessels in dendritic pattern, wood ring-porous, latewood vessel angular in outline, *Quercus alba* (i.e., a white oak, Fagaceae). — Scale bar = 500 μm in Fig. 5, 7–12; 250 μm in Fig. 1, 3; 100 μm in Fig. 2, 4, 6.

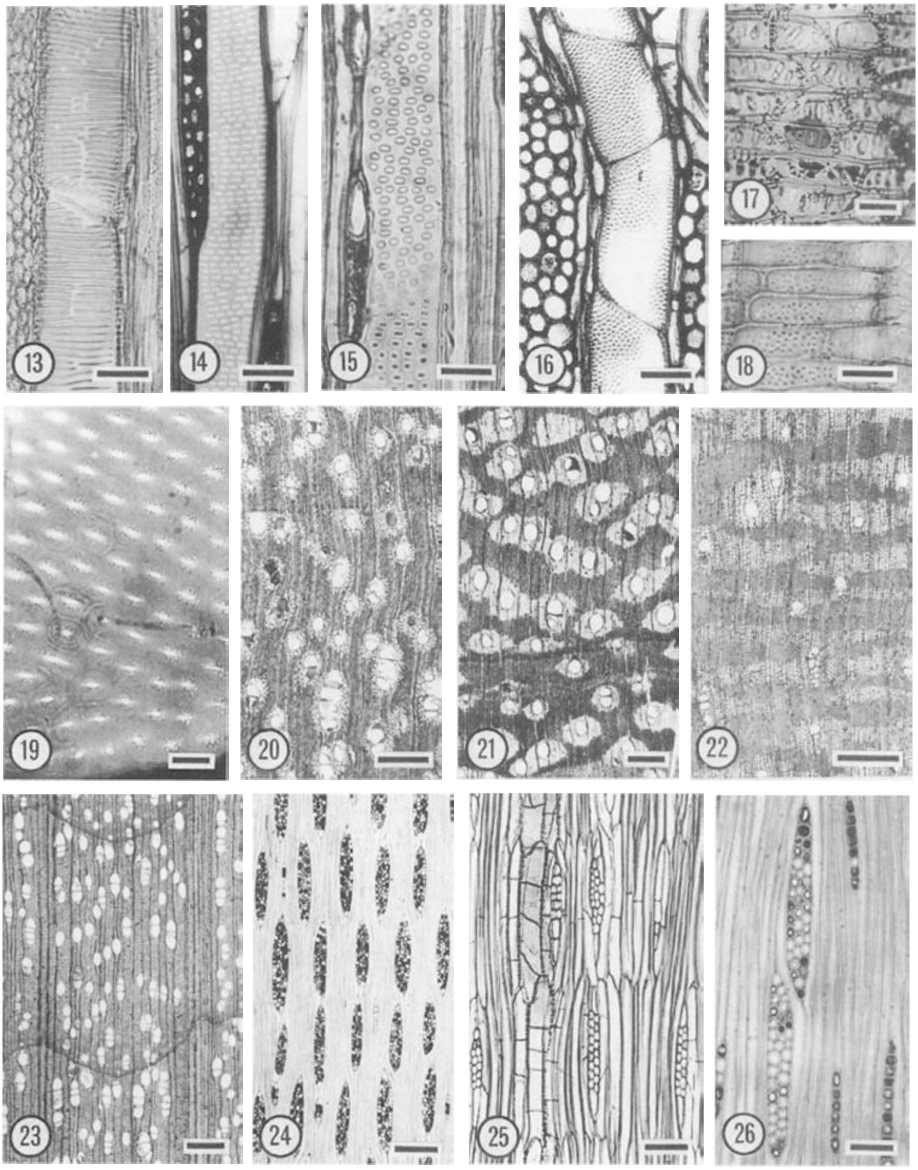


Fig. 13–26. – 13: Scalariform intervessel pits, and simple perforation plate viewed from the side, *Ampelopsis* sp. (Vitaceae). – 14: Opposite intervessel pits, *Liriodendron tulipifera* (Magnoliaceae). – 15: Alternate and widely spaced intervessel pits, *Halesia caroliniana* (Styracaceae). – 16: Alternate intervessel pits, *Cordia* sp. (Boraginaceae). – 17: Vessel-ray parenchyma pits, *Quercus falcata* (Fagaceae). – 18: Vessel-ray parenchyma pits with reduced borders, *Hypelate trifoliata* (Sapindaceae). – 19: Vestured intervessel pits, *Terminalia* sp. (Combretaceae). – 20: Vasicentric parenchyma, *Hypelate trifoliata* (Sapindaceae). – 21: Aliform-confluent parenchyma, *Pentacletra macrophylla* (Leguminosae). – 22: Confluent-banded parenchyma, *Andira inermis* (Leguminosae). – 23: Aggregate rays at left and right, *Carpinus*

suggested that ray shape was useful for distinguishing *Larix* from *Picea*. However, later detailed studies of large numbers of samples representing many species showed that ray shape was not a reliable feature for distinguishing these two genera. Recent studies, including one that examined over 87 samples representing 39 species, show that ray tracheid pitting is consistently useful for distinguishing these two genera (Anagnost et al. 1994; Bartholin 1979).

Some features are 'useful' for identification because they occur in relatively few taxa. Many of the features chosen by Clarke (1938) for a multiple entry card key for dicotyledonous woods (see below) and used by Chalk while gathering data for the first edition of 'Anatomy of the Dicotyledons' (Metcalfe & Chalk 1950) are not common. Forty-six of the 63 anatomical features they used occur in less than 25% of the world's hardwoods (percentages based on the OPCN database with 5260 entries, Wheeler et al. 1986). Of those 46 features, 20 occur in 10% or less of the world's hardwoods. These uncommon features and their per cent occurrence are:

- Presence of vascular or vasicentric tracheids (10%);
- Storied rays (Fig. 24, 25); axial parenchyma absent–rare (9% each);
- Axial parenchyma bands more than 4 cells wide (8%);
- Semi-ring-porous woods (7%);
- Scalariform perforation plates with more than 20 bars, canals or latex tubes (Fig. 29, 30), rays more than 10 cells wide (Fig. 12) (6% each);
- Tangential vessel arrangement (Fig. 3), rays with the uniseriate portion equal in width to the multiseriate portion, (Fig. 30) ring-porosity (Fig. 3, 11, 12) (5% each);
- Axial canals (Fig. 33–35) (4%);
- Crystals in idioblasts (Fig. 6), oil or mucilage cells (Fig. 36), fusiform parenchyma cells common (3% each);
- Sclerotic tyloses, fibres with spiral thickenings, included phloem (Fig. 27, 28), raphides (Fig. 38) or druses (Fig. 37) (2% each);
- Aggregate rays (Fig. 10, 23), tile cells (Fig. 31, 32) (1% each).

Woods with a few of these unusual features in combination with more common features may be quickly identified, particularly if their geographic source is known. Ring-porosity, tangential bands of latewood vessels, and rays with sheath cells in a North American wood indicate *Celtis* (Fig. 3, 4); solitary vessels arranged in a radial to dendritic pattern (Fig. 10–12), rays of two distinct sizes (Fig. 10–12), and vessel-ray parenchyma pits with reduced borders (Fig. 17) occur in combination only in the Fagaceae. It is rare that a single feature identifies a single group; tile cells appear to be confined to the Malvales (Fig. 31, 32).

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caroliniana (Betulaceae). – 24: Storied rays, *Entandrophragma cylindricum* (Meliaceae). – 25: All elements storied, *Hibiscus* sp. (Malvaceae). – 26: Homocellular rays, *Acer rubrum* (Aceraceae). — Scale bar = 500 μm in Fig. 21, 22; 250 μm in Fig. 20, 23, 24; 100 μm in Fig. 25; 50 μm in Fig. 13, 14, 26; 25 μm in Fig. 15–18; 5 μm in Fig. 19.

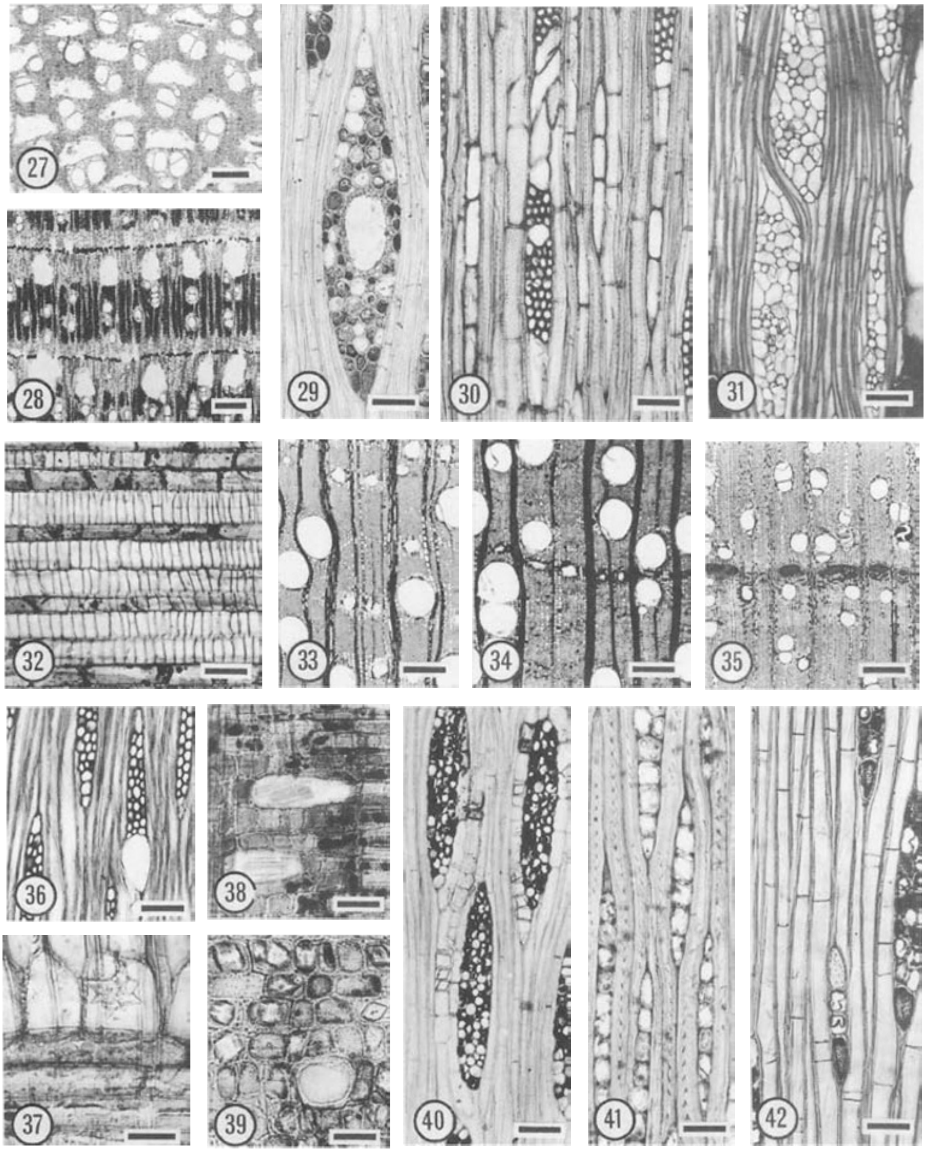

Fig. 27–42. – 27: Areas of diffuse included phloem torn out during sectioning, *Pisonia aculeata* (Nyctaginaceae). – 28: Areas with concentric included phloem torn out during sectioning, *Avicennia officinalis* (Avicenniaceae). – 29: Ray with radial canal, *Loxopterygium sagotti* (Anacardiaceae). – 30: Heterocellular rays with latex tubes, and rays with uniseriate portions as wide as multiseriate portions, *Rauwolfia macrocarpa* (Apocynaceae). – 31: Rays with tile cells, *Ochrosia* sp. (Bombacacae). – 32: Tile cells in radial view, *Guazuma latifolia* (Sterculiaceae). – 33: Scattered axial canals, *Dipterocarpus* sp. (Dipterocarpaceae). – 34: Canals in tangential lines, *Dryobalanops* sp. (Dipterocarpaceae). – 35: Traumatic axial canals, *Khaya* sp. (Meliaceae). – 36: Oil cell in ray, *Michelia champaca* (Magnoliaceae). – 37: Druse in

Levels of identification

One of the harder things about doing wood identification is knowing to what level (family, genus, species group, or species) a wood can be identified and when to be satisfied with an identification. Isolated pieces of wood usually cannot be identified to species, and often not to a single genus. There are no all purpose rules. The level to which an identification can be done varies within and between families. In the Annonaceae it usually is not possible to identify individual genera; in the Betulaceae (Birch family) it is possible to identify individual genera, but not species; in the Ulmaceae (Elm family) native to the United States, it is not possible to distinguish any one ring-porous species of *Celtis* from another, but it is possible to distinguish *Ulmus americana* from *Ulmus rubra* and from the hard elm group. Most *Eucalyptus* species can only be identified to a group, e.g., gum, ash, bloodwood, etc. (cf. Dadswell 1972). Because of this lack of rules, it is important to use the literature and reference material to determine what level of identification is possible within particular taxa.

Some families and genera are relatively homogeneous in their wood anatomical characteristics (e.g., Betulaceae, Hamamelidaceae, Magnoliaceae, families that are relatively small), while others are heterogeneous (e.g., Icacinaceae, Euphorbiaceae, Olacaceae) with as much difference between genera as exists between some families. Higher levels of classification also show variation, some orders are stable for vestured pitting, while in other orders this feature varies between and within families (Van Vliet & Baas 1984).

The differential value of different wood anatomical features for identification at different levels of the taxonomic hierarchy can perhaps best be demonstrated by an example from a large woody plant order whose delimitation is now widely accepted: the Myrtales (Van Vliet & Baas 1984). The combination of included phloem and vestured pits (Fig. 19) is largely restricted to this order. Within the order, the individual families are only poorly defined on wood anatomical features, but the combination of solitary vessels (Fig. 1) and fibres with distinctly bordered pits defines most members of the Myrtaceae, and is typical of a few aberrant genera in the Melastomataceae and Combretaceae. Included phloem is diagnostic of a group of closely related genera in the Combretaceae, but variable within the type genus of that group, *Combretum* (Van Vliet 1979). In most Myrtalean families it is possible to key out individual genera using microscopic features, and within some genera it is possible to key out individual species (e.g., within *Terminalia* using characters such as crystal shape, size and distribution). None of the features cited here have universal

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square ray cell, *Hibiscus tiliaceus* (Malvaceae). – 38: Raphides in enlarged procumbent ray cells, *Vitis* sp. (Vitaceae). – 39: Prismatic crystals abundant, and in square ray cells, perforated ray cells, *Drypetes keyensis* (Euphorbiaceae). – 40: Prismatic crystals in axial parenchyma, *Entandrophragma cylindricum* (Meliaceae). – 41. Imperforate elements with distinctly bordered pits in tangential walls, *Canella winterana* (Canellaceae). – 42: Septate fibres, *Aucoumea* sp. (Burseraceae). — Scale bar = 500 µm in Fig. 27, 28; 250 µm in Fig. 33–35; 100 µm in Fig. 30, 31, 36, 40; 50 µm in Fig. 29, 32, 38, 39, 41, 42; 25 µm in Fig. 37.

diagnostic value at the same taxonomic level in other orders. Diagnostic value can thus only be determined '*a posteriori*', i.e., after studying a large sample of specimens of a taxon (order, family, tribe, genus, section or species).

IDENTIFICATION PROCEDURES

Comparison

Identification by comparison is one of the most frequently used methods of identification, and is the basis of most natural history field guides (Pankhurst 1978). Wood anatomical atlases are the equivalent of such field guides. In the United States, Europe, and Japan, there are relatively few domestic woods that are commonly used commercially, and often it is relatively easy to determine the identity of an unknown wood by comparing it with descriptions and illustrations in introductory wood anatomy texts and atlases (e.g., Fagerstedt et al. 1996; Grosser 1977; Hoadley 1980; Panshin & DeZeeuw 1980; Saiki 1982; Schweingruber 1978, 1990; Wagenführ 1996; Wilson & White 1986).

Atlases with good quality photographs illustrating the salient characters of woods are widely used, and useful for many years. Atlases prepared in the 1920s and 1930s are still useful in the 1990s. It is somewhat surprising that the number of atlases produced in the last decade is as high as in previous decades, even though most anatomists do not perceive current conditions as supportive of anatomical studies. A particularly valuable atlas is the CSIRO Hardwood Atlas (Ilic 1991) that has photographs (no text descriptions) of some 1800 species (cross, radial, and tangential sections are illustrated) and was intended to be a portable wood anatomical slide collection.

A selected list of some additional recent microscopic atlases follows:

- Europe (Schweingruber 1990), Mediterranean (Edlmann Abbate et al. 1994) [text and photographs], roots of trees and shrubs of Britain and northern Europe (Cutler et al. 1987).
- Israel and adjacent regions (Fahn et al. 1986) [text and photographs].
- Iran (Parsa Pajouh & Schweingruber 1985).
- Mexico (Barajas Morales & León Gómez 1989) [text and photographs].
- Chile (Rancusi et al. 1987).
- North America (Furono 1985, photographs only).
- Commercially important woods from Africa and Tropical America (Nadi Berti & Edlmann Abbate 1988, 1992; Liu Peng et al. 1996), including Peru (Acevedo Mallque & Kikata 1994/1995) [text and photographs].
- Southeast Asia and Pacific (Ogata 1985, Japanese text, line drawings; Menon 1993 – a revision by Sulaiman & Choon; Soerianegara & Lemmens 1993; Lemmens et al. 1995; Sosef et al. 1998; Martawijaya et al. 1986, 1989), Papua New Guinea (Sudo 1988, in Japanese), Brunei (Ogata & Kalat 1997).
- Korea (Lee Pil-Woo 1994; Wong Yong Lee 1997).
- Himalayas (Suzuki & Noshiro 1988; Suzuki et al. 1991), wood descriptions are included along with descriptions of the rest of the plant.

Many earlier atlases are listed by Gregory (1980).

Data in tabular form are particularly valuable for showing which combinations of features are useful for distinguishing between small groups of closely related woods or woods of similar appearance. Brazier and Franklin (1961) provided tables useful for distinguishing related species of some genera, related genera, and unrelated woods that appear similar. For example, one table shows the combination of features that can be used to distinguish *Swietenia* and *Carapa*, both members of the Meliaceae (Mahogany family), and often used interchangeably.

Dichotomous keys

Diagnostic keys have been used for centuries in biological identification (Pankhurst 1978). Dichotomous keys present a series of paired contrasting choices, with one or more features used at each dichotomy / couplet. At each couplet, one of the two statements is chosen as applying to the unknown. The key user is directed to another couplet, and this process is continued until finally reaching a name (which for wood could be a species, species group, genus, group of genera or family). The starting point and sequence in which features are used are predetermined by the author of the dichotomous key. The unknown must match every characteristic of the taxon as defined in the key and there usually is only one path to one identity.

Computer programs can help develop keys by calculating the information content of features, and how to use the features to divide species into groups (e.g., Dallwitz & Paine 1986). Dichotomous keys direct the observer to look for the features the key constructor considered useful distinguishing features; a well-constructed dichotomous key can quickly lead to an identification.

Dichotomous keys are useful for unknowns for which there is a small number of possible matches, and for material without missing features. The longer the key, the more likely there will be an error in choosing the correct descriptor at any one couplet; keys with over 200 taxa are unwieldy (Pankhurst 1978, 1991). Dichotomous keys are particularly useful as regional works, and for commercially important woods, and for woods of a particular family or genus.

Many recent systematic works contain dichotomous keys to the woods (e.g., Baas et al. 1988, lists in Gregory 1994). Some experts can recognize that a wood belongs to a particular family or genus, and so would immediately refer to these keys, if they knew they existed. Otherwise, to determine the family or genus the unknown belongs to, it will be necessary to use a key (e.g., CSIRO family key), use lists giving by-family occurrence of features (Metcalfe & Chalk 1950, 1983), or read the short generalized family descriptions in 'Anatomy of the Dicotyledons' (Metcalfe & Chalk 1950). There is a need for a family key that would indicate in which families particular combinations of features occur, and for that key to be linked to specific publications and keys for families and genera.

Multiple entry keys

The simplest multiple entry key is the so-called synoptical key, which lists for each diagnostic feature the taxa that have that feature. Good examples of this type of key are the lists at the end of Metcalfe and Chalk (1950, 1983), in Fahn et al. (1986), and those for the Combretaceae and *Terminalia* (Van Vliet 1979). Such keys have the advantage that the sequence of characters used in an identification procedure is inspired by the unknown wood sample, not by the author of the key.

Apparently, the first application of multiple entry card keys was for wood identification (Clarke 1938; Pankhurst 1991). In such card keys, there is one card per taxon. Cards have perforated edges, the perforations are numbered sequentially, and each numbered perforation represents one feature. Usually, if a wood has a particular feature the edge of the card will be notched to indicate presence of that particular feature. To identify an unknown, a needle is passed through a stack of cards at a perforation representing a feature seen in the wood. Cards of species with the feature absent stay on the needle. The cards with feature present fall out. The sorting process is repeated until a single or only a few cards remain.

When using multiple entry keys it is possible to stop short of a single name, and this is one of their advantages over dichotomous keys. For certain situations a list rather than a single name may be a better strategy for getting to an 'accurate' identification, e.g., 1) tropical woods of unknown provenance, because that wood might represent a species not included in a key, either because no or little anatomical data are available for it, or with 2) fossil woods that differ in one or more features from extant species. Subsequent comparison of the taxa with a combination of features similar to the unknown helps narrow down the likely affinities of the unknown, and the observer can decide which features he considers most reliable in determining the affinities of the wood.

In multiple entry keys only one feature is used at a time, but the sequence in which features are used and the total number of features used are up to the observer. Because of this flexibility, such keys are particularly useful for unknowns in which some features cannot be observed. Another advantage of multiple entry keys is that it is easy to add new species to a key, just by inserting a new card or new entry to a computer database. The number of features used in card keys was limited by the number of holes that could be fitted along the margin of the card (generally this was less than 100). Multiple entry keys are easily computerized, so this is no longer a limitation.

There are multiple entry keys based on macroscopic and microscopic features. The Princes Risborough microscopic key to hardwoods (Brazier & Franklin 1961) has been one of the most valuable. This key covers 380 timbers representing 800 botanical species. Species descriptions are based on at least four samples, with more than 60% of the samples having herbarium vouchers (estimated from data in the first 10 pages of their publication). There are accompanying notes on distinguishing features, tables, and short dichotomous keys.

Multiple entry keys are still published today. Features used in the key are numbered and defined, and then for each taxon examined, a list of the numbered features present in that wood is given (e.g., Verbenaceae, *Tectona grandis* 1, 3, 7, 13, 14, 16, 18, 21, 23, ... 105, from Sudo 1992, Ilic 1990). Recording these feature numbers serves as a shorthand description of a wood, and this information can readily be entered into a database for computer-assisted wood identification.

Computer-assisted wood identification

When computer-aided wood identification was first discussed (Miller 1980), before personal computers were commonplace, it was envisioned that an anatomist would access a large computer housed in one spot, and use a program and database stored in that large central computer. However, after personal computers became widely available, there were many separate projects to develop computer-assisted wood identification programs and databases (discussion to follow). Many of the identifications an institution does are of woods from nearby, so that it is sensible to ensure that there is a comprehensive database for that region, and a quick, easy, and reliable means of identifying the woods of a particular region. Data collected at one institution can be shared with others, with the data transmitted on paper, on diskette, or electronically via the internet.

Computer databases and programs based on card key data

Two computer-aided wood identification projects that have been strongly data driven, by using existing key card data, are here discussed at some length below. One project started with data from the Oxford cards collected by Chalk during the preparation of 'Anatomy of the Dicotyledons' (Metcalfe & Chalk 1950) and recorded on the marginally perforated cards developed by Clarke (1938). The other is based on the multiple entry keys developed by Ingle and Dadswell at CSIRO.

Oxford based key — The GUESS program (LaPasha 1986; LaPasha & Wheeler 1987), with both DOS and Macintosh versions, accompanies the OPCN databases (Wheeler et al. 1986), and evolved from a program that was used on the mainframe computer (Pearson & Wheeler 1981). The OPCN database (5260 entries) includes the Chalk data (2227 entries as originally described, and 510 entries edited to reflect new information from more recent literature), data from the Princes Risborough Key (400 entries, Brazier & Franklin 1961) edited so as to be comparable to the Chalk data, data from the CTFT keys (929 entries, Normand & Paquis 1976; Détienne & Jacquet 1983), again with editing so that they would be comparable to the Chalk cards, and data from post-1950 literature on systematic wood anatomy (1194 entries). Because the OPCN database is based on multiple entry key card data, the number of features used is the same as on the cards Chalk used, 69 anatomical and 15 miscellaneous features.

The GUESS program functions as a batch job, as a list of character states is entered. Mismatches are allowed, so that there need not be a 1:1 correspondence in the characters of the unknown and entries in the database. If the presence or absence of a particular feature is considered important or unambiguous, then the presence or absence of that feature can be required as characteristic of suggested matches from the database. This program is useful for generating lists of woods that have a particular set of features, and has been helpful for indicating which family or genus might be related to an unknown. The initial 'run' may (and often does) result in a long list of woods with features similar to that described for the unknown, or in no matches whatsoever. It then is necessary to go back and edit the description of the unknown; if the list is long, then more features can be added, or if there were no matches then more mismatches can be allowed or features deleted. An alternative program (for the Macintosh) allows entering one or more features at a time. After each feature or group of features is entered, the number of entries in the database matching the unknown appears, so that the user can choose an end point when a small number of names is reached. Neither of these programs features on-screen help for suggesting useful features. For a wood whose geographic origin is unknown or is from Southeast Asia or South and Central America, a successful identification with the GUESS program is a list of roughly 10 or fewer taxa. To reach a single name, further comparative work is needed.

The GUESS program was intended to shorten the process of comparative identification, and to direct the user to relevant literature, either publications on a particular group of woods or regional atlases. The entries in the OPCN database that represent information published since the first edition of 'Anatomy of the Dicotyledons' are coded to indicate the literature source for that entry. The GUESS program and OPCN databases are helpful for the 'hard to identify' or unusual woods, e.g., woods whose geographic source is unknown, or geologically ancient woods where a one-to-one correspondence may be unlikely because of evolutionary differences between the fossil and extant plants. However, for common commercial woods in Europe and North America, it probably is quicker to use keys in textbooks or compare the unknown to illustrations and descriptions in atlases.

The OPCN database is the largest one (5260 entries) available with all taxa coded with the same set of feature numbers. It includes taxa from throughout the world. There is a manual that describes and illustrates the features, gives their relative frequency in the database, and provides suggestions on how to use the features (Wheeler et al. 1986), and a manual describing the identification program (LaPasha 1986). There is a program (VIEW) for retrieving taxon descriptions from the database.

CSIRO keys — CSIROID is a program developed to use the card keys developed at CSIRO (Ilic 1993), and includes the Family key (based on data collected by Dadswell in the 1930s through '50s and for the southwest Pacific region, Ilic 1987), the Macro key (using data collected from the 1940s through 1960s and also emphasizing the southwest Pacific region, Ilic 1990), and the *Eucalyptus* key (Dadswell & Eckersley 1941). This identification program is interactive and one or more features can be entered at a time. There is an option for suggesting 'best subsequent feature' that suggests which features might be useful for eliminating other taxa. What seems particularly helpful with this program is that its 'features help' option provides on-screen text definitions of the features, and there are plans to incorporate images. The accompanying publications for the CSIRO keys are well-illustrated. One of the major problems with using keys is 'learning the features' used in the key. The CSIRO books describing and illustrating the key features, and the on-screen help address this problem for these keys.

The CSIROID program does not allow for mismatched features and so does not have required absence or required presence. This reflects different levels of confidence in the databases, and somewhat different objectives from the GUESS program.

The OPCN database has limitations. Comparison of the Oxford card data with recent studies indicates that some of the woods that Chalk examined were misidentified. Some species descriptions are based on only one or a few samples so that only a small sampling of the variability of a species is recorded. It also appears that some of the vessel density entries in the Oxford cards are based on counting vessel groups as a unit, rather than counting each individual vessel separately (Wheeler 1986). Thus, it seemed appropriate to have an option to allow for mismatches to accommodate variability, which seemed especially important for geologically ancient woods.

'New' databases and keys — The number of features in the IAWA list (163 anatomical and 58 miscellaneous features) exceeds the number that could be accommodated on marginally perforated cards, and allows more complete descriptions of woods, which should permit distinguishing more species.

In Argentina, Monteoliva and Olivera (1994) are working on developing a system of identification for Argentinian woods. They started with the IAWA feature list as a base, but are using additional features suitable for local woods. They are using the literature as well as gathering new data. They have found discrepancies between literature descriptions and their own observations, which indicates that while existing wood anatomical data are useful, it is necessary to continue to add to and refine the existing data.

The TISS system (Kyoung et al. 1994) was developed for Korean woods. There is one dataset for wood identification that also uses the IAWA Feature List, and one dataset for properties and uses (information from Chudnoff 1984). It is possible to generate lists of woods that share certain characteristics and uses, e.g., woods with a specific gravity of more than 0.50, naturally durable and used for cross-ties. Linking anatomical databases to other databases allows anatomists to explore relationships between wood structure and properties (as above), wood structure and uses (Gasson & Cutler 1990), or wood structure and climate (Wheeler & Baas 1993; Woodcock 1994; Wiemann et al. 1998).

The programs developed to accompany the DELTA format for recording taxonomic descriptions (Dallwitz & Paine 1986) have been accepted by many taxonomists as their standard. There is a powerful identification key (INTKEY) for data in the DELTA format. The key is interactive, one or more characters can be entered at a time, and a list of possible matches obtained at any point. The program can suggest which features may be useful in distinguishing between remaining taxa. There are few wood anatomical data in DELTA format. The conversion of numeric key card data has not yet been done.

It would be a real service if there was an interface that would allow easier entry into the DELTA-associated programs, and the translation of data from the existing wood databases. The DELTA system was intended as "a general system for processing taxonomic descriptions" and its primary objective was not to help the casual or occasional user with identification.

Espinoza de Pernia and Miller (1991) adapted the IAWA Feature List to the DELTA format and developed a database for 40 commercially important Venezuelan woods.

The quality of this database is high, as descriptions are based on 5 samples per species. Reliability of data is always a concern, and the DELTA program allows one to record the number of samples on which a description is based. In contrast to the programs such as GUESS or CSIROID, the DELTA format accommodates both numeric characters and text characters. These characters are not used when identifying the wood, but are useful information in text descriptions. Espinoza de Pernia and Miller have made an important contribution as they have developed a framework for other anatomists to put newly acquired data into DELTA format. The two DELTA-based programs they have created are VWOOD.CHA for producing text descriptions, and VWOODINT.CHA for the identification option INTKEY.

More recently, Richter and Trockenbrodt (1993, 1996) have set up the IAWA feature list for use with DELTA, option INTKEY (interactive wood identification). A database with over 200 entries (trade timbers) is currently available, and new entries are made as time allows. There are English and German versions. When using this key, explanatory notes and illustrations can be accessed. A recent thesis on conifer anatomy (Heinz 1997), supervised by J. Richter, Hamburg and D. Grosser, Munich, Germany, reviews characters suitable for conifer identification and presents a list suitable for use with DELTA-INTKEY.

Brunner et al. (1994) have prepared an interactive computer key based on the macroscopic features of 115 of the most important Guyanese tree species. The key is designed for use by forest products industry personnel, and is accompanied by a synoptic key, and information on the distribution, appearance, wood structure and properties of these species. Other computer-assisted wood identification projects include ones for Japanese woods (Kuroda 1987; Izumoto & Hayashi 1990), tropical woods (Tochigi et al. 1984), and Chinese woods (Yang & Cheng 1990; Zhang et al. 1986). A program and database for South African woods is used in teaching wood anatomy and identification at the University of Stellenbosch (Malan, personal communication 1995).

OTHER ASPECTS OF WOOD IDENTIFICATION

Verifying an identification

No matter what key is used, it is imperative that the identification be verified by reference and comparison to reliably identified samples, or descriptions and illustrations in atlases or other publications. The bibliographies prepared by Gregory (1980, 1994) are invaluable for entry into the literature on woods of a given region or of particular families and genera. If one has access to a wood collection, then whole samples and slides of woods can and should be compared with the unknown. Stern (1988) compiled a list of the various institutional wood collections and the regional specialities of these collections.

Problems in identification of biological material

The problems associated with wood identification and reasons for not reaching an accurate identification are the same for wood as those for any biological material (see McNeill 1975; Pankhurst 1978, 1993; Fortuner 1993) and include: 1) An inadequate basis for comparison because a) the unknown lacks critical features, as in decayed wood or poorly preserved fossil wood, or b) an inadequate reference base, because not all species are included in a key and the full range of variability of a taxon might not be known, and 2) Difficulty in using keys because of errors in feature recognition, either incorrectly interpreting a feature in an unknown because of the observer's lack of background or training, or interpreting a feature differently from the way a key constructor intended.

There are thousands of species of woody plants, and woods of some have never been described or incorporated into any key. Descriptions of many woods are only based on one or a few samples, and so the range of variability of some species and genera is not known. Not only is there the variability expected when comparing different individuals of the same species from different localities and/or with different genotypes, but also the huge amount of wood anatomical variation that depends on position in the tree (root, trunk, branch, sapwood or heartwood) or age of the wood material (from juvenile or mature stems). Trunk wood and root wood often differ in both quantitative (cell diameters and lengths) and qualitative features (parenchyma abundance and distribution, porosity, ray type). Juvenile wood of trees (wood near the pith and formed by a young cambium) and branchwood usually have smaller cells than mature trunk wood and ray cellular composition and ray size often vary with position in the tree (cf. Jane 1970; Panshin & DeZeeuw 1980).

There are some terms that wood anatomists have applied differently (e.g., use of fibre-tracheid, reticulate parenchyma). The IAWA Features List (IAWA Committee 1989) is helping to increase consistency in the use of wood anatomical terminology. Many wood anatomical features are not discrete, so that the boundaries between some features are not sharp. Intermediates between two features may be interpreted differently by different people (what one anatomist terms semi-ring-porous, another might term diffuse-porous or ring-porous).

Error in feature recognition is as likely a source of misidentification as any other. Most of the multiple entry keys are accompanied by introductory sections that explain the features used (e.g., Brazier & Franklin 1961; Normand & Paquis 1976; Détienne & Jacquet 1983). When these keys were on punch cards, most users would take the time to read the introductory material before attempting to use the key. Since computerization of multiple entry keys, users are apt to try wood identification programs without reading the explanatory material on the accompanying databases. This is likely to result in misuse and misinterpretation of features.

An objective for the new computer keys is to provide a means of accessing illustrated feature definitions directly from the identification program (Richter & Trockenbrodt 1996), or, if desired, use illustrated prompts while describing an unknown (some of these aspects have been incorporated in the new version of CSIROID; Ilic, personal communication). Multimedia presentations on wood identification are likely to be developed in the next few years, with information on sample preparation, illustrated feature descriptions, images of woods, interactive keys, and with linkages to tabular data, dichotomous keys, and pertinent literature references. An interactive CD-ROM of the information on wood anatomy and wood properties of the 400+ genera of Southeast Asian wood documented in Volume 5 (1–3) of the PROSEA Series is currently being produced by the Expert Center of Taxonomic Identification (ETI) in Amsterdam, the Netherlands. Atlases probably will be available not only as printed copies, but also on compact disks, and on the world wide web.

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