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The Practical Identification of Wood Pulp Fibers
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This reference source is designed to help fiber analysis identify wood fibers in pulp and paper products. Adjacent pages describe 33 softwood and 43 hardwood species.

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FORMATION AND STRUCTURE OF WOOD

Wood Sources and Taxonomy

Wood used for pulp is obtained from two general classes of seed plants known botanically as **gymnosperms** (naked seeds) and **angiosperms** (seeds borne in a vessel or fruit). In the wood products trade and in the pulp and paper industry, these same plants are referred to as **softwoods** and **hardwoods**. Unfortunately, these latter names are a little misleading since the actual hardness or density of these woods is not always compatible with these classifications. Nevertheless, the names are apparently adequate for commercial purposes. Other colloquial designations for these tree types include **conifers** versus **broadleaf trees** or **evergreen** versus **deciduous** trees. From an anatomical view, softwoods and hardwoods can be called **nonporous** and **porous** woods, respectively. The reason for this designation will be clarified in a later section.

Pulpwood trees described in this text are largely those indigenous to the United States and Canada. Other woods discussed include some types commonly used in Scandinavia and Europe, as well as some species grown on plantations in other temperate or tropical locations.

In referring to a particular wood type, it is normally convenient to use the tree's common or commercial name. However, since many woods can have several common names, varying with geography or type of industry, it is often wise to also indicate the wood's (tree's) scientific name. The latter is based on numerous characteristics of the tree and is sufficient to specify the exact botanical classification.

The scientific name of a tree consists of two parts—genus and species—both in Latin, a universal language during the period in which a system of scientific plant classification (taxonomy) was being devised. In addition, the complete scientific name includes the name or name abbreviation of the person who authored the species. Shown below are some examples of tree names.

Common Name	**Scientific Name**
Red alder	*Alnus rubra* Bong.
Incense-cedar	*Calocedrus decurrens* (Torr.) Florin
Northern red oak	*Quercus rubra* L.
Balsam fir	*Abies balsamea* (L.) Mill.
Douglas-fir	*Pseudotsuga menziesii* (Mirb.) Franco
Hard pine	*Pinus* spp.*
Loblolly pine	*Pinus taeda* L.

(*designation if exact species is unknown)

Further information on the details of tree names and author nomenclature can be found in the literature (**1,2**).

Wood Formation

Wood tissue, known technically as **xylem**, is formed through the activity of a circumferential sheath of cells at the wood/bark interface called the **vascular cambium** (Figs. 2.1, 2.2). Wood cells are produced to the inside and bark cells to the outside. Bark can be further divided into inner living bark and outer dead bark (rhytidome). Pulps sometimes contain a few bark cells, but these offer no real information in regard to species identification.

Fig. 2.1 shows the surface (labeled X) of a woody stem that results from a cut directed perpendicular to the stem axis. This surface also resembles that resulting from a similar cut through a branch or any wood-containing root. The most obvious feature here is the occurrence

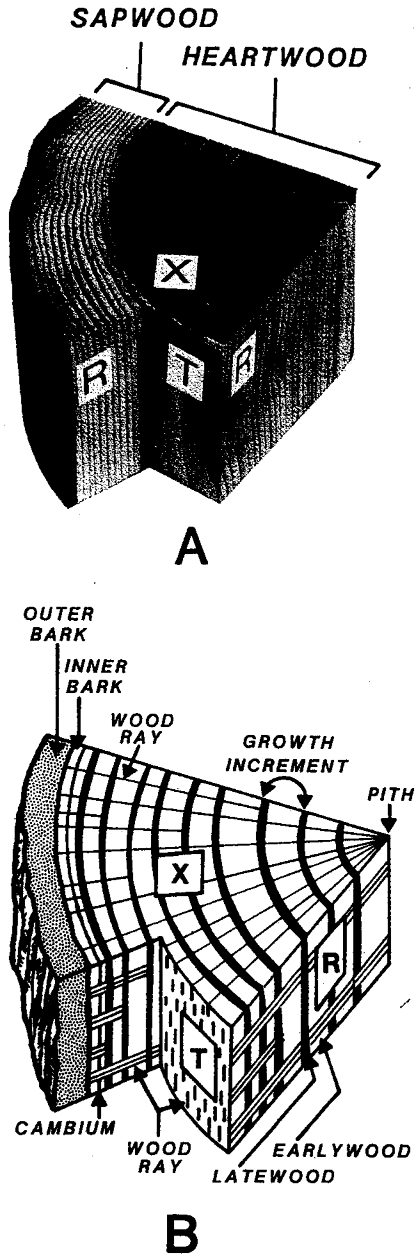

Fig. 2.1 *The three major structural planes (surfaces) of wood.*

- **A.** *Portion of a cross-sectional disk that was cut perpendicular to the tree's main axis; X-cross section, R-radial surface, T-tangential surface.*
- **B.** *Diagrammatic representation of the disk in A, showing the tissue arrangement for a stem cut in the spring of its tenth growing season. See text for explanation of terminology.*

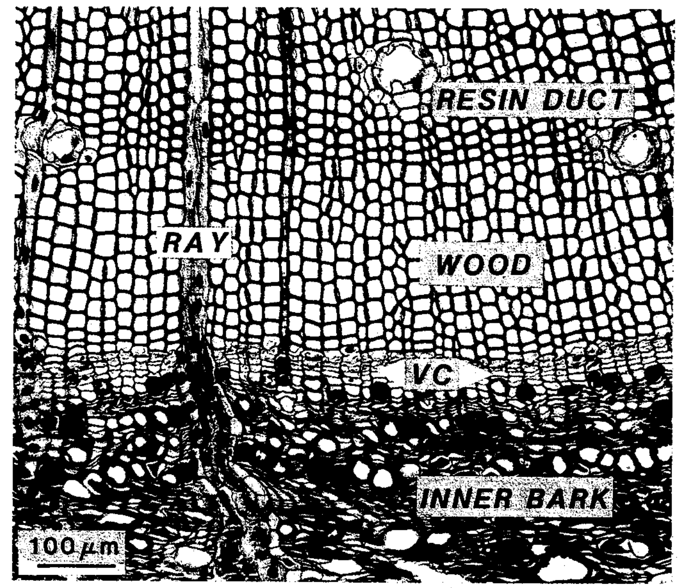

Fig. 2.2 *Transverse (cross) section of a young pine (softwood) stem as seen with the light microscope. The vascular cambium (VC) produces phloem cells (inner bark) to the outside and wood cells to the inside. Light micrograph (LM).*

of **growth rings**. These are termed annual rings in temperate climates although they may not always occur strictly on a yearly basis, resulting in **false rings**. They may also fail to encircle the entire stem, forming **discontinuous rings** (**3**). In subtropical or tropical climates, those with little or no seasonal differences, growth increments may be detected in some cases, but in others they are not decipherable (**4**,**5**).

Stems, branches, and roots also grow by elongation. This is accomplished through the activity of terminal growing points called **apical meristems**. These are housed in the bud system of the crown and beneath protective caps in the roots. Terminal growth is closely coordinated with the addition of growth rings by the vascular cambium (which can be termed a **lateral meristem**). However, since stems elongate only at their tips, this situation results in a tree form in which the number of growth rings in a given cross section becomes fewer and fewer along the vertical axis of the stem. Thus, a tree stem is analogous to a stack of inverted hollow cones, each cone representing the wood added to the stem during one growing season (Fig. 2.3).

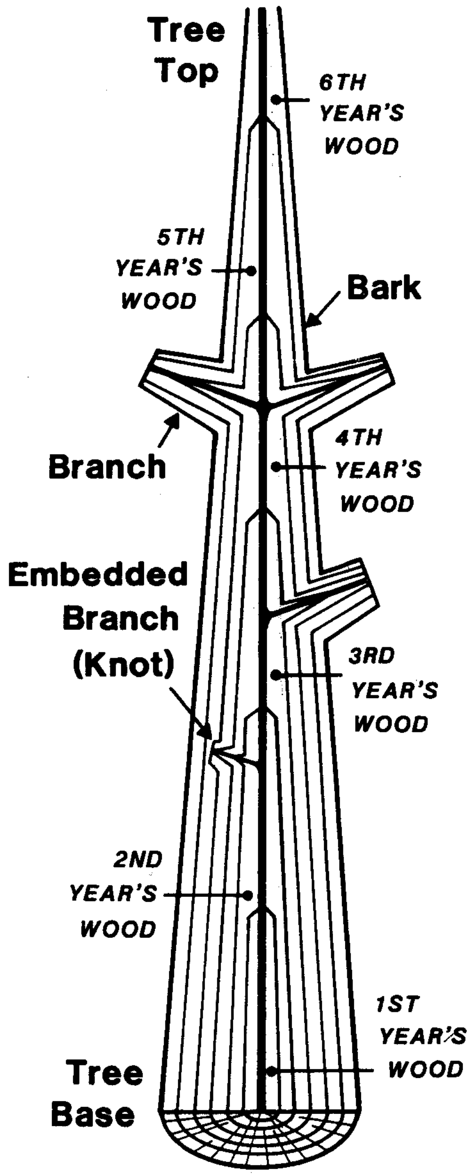

Fig. 2.3 *Diagram of growth increments in a tree illustrating their deposition as a series of inverted hollow cones. This diagram represents a longitudal section of a six-year-old stem.*

The wood near the top of the main tree stem(s), most branch wood, and the wood in the center of all older tree parts is called **juvenile** or **core** wood. It is formed while that part of the tree is young and the developing wood cells are in close association with the tree crown. As the tree becomes older and taller and increases in diameter, the lower and older portion of the tree becomes displaced further and further from the crown. Wood formed in these lower stem portions away from the crown is termed **mature** or **outer** wood. The fiber and tissue anatomies of juvenile and mature wood do not differ greatly, but the fiber analyst should be aware of some of the structural variations. These are mentioned in the later sections on wood anatomy.

In many trees, particularly older ones, the central portion of the stem, including some or all of the juvenile wood, is frequently darker in color than the outer portion (see Fig. 2.1). The outer, light-colored region of such trees is referred to as **sapwood**; the inner, darker region is called **heartwood** and is the consequence of certain biochemical processes that convert stored carbohydrates and fats into polyphenols, a type of wood extractive. This conversion process may (e.g., oak) or may not (e.g., fir, hemlock, spruce, cottonwood, aspen) result in a wood color change, or in some species it may be delayed for many years (3). However, when heartwood is formed, it signifies in all species the death of all remaining living wood cells in this zone.

The ensuing buildup of extractives in heartwood can impair the processing of wood in solid form as well as its conversion into pulp. In hardwoods, heartwood formation is accompanied by an additional physical effect, the formation of intracellular structures that plug the wood's conducting cells (see later section on Hardwood Anatomy). In the case of both softwoods and hardwoods, however, heartwood formation does not result in the generation of additional diagnostic information for separation of wood species in pulp.

General Architecture

In describing the minute anatomy of pulp elements, it is necessary to refer to various cell faces and dimensions. This would be a very difficult and confusing task were it not for the facts that all wood cells are incorporated into the tree in a preferred orientation and that this frame of reference can be extended from a macro-level down to the microscopic level of individual cells. More specifically, wood tissue as a whole can be described by three structural planes (see Fig. 2.1). One is the **cross sectional** or **transverse plane**, which is directed perpendicular to the stem axis. It also transects the wood fiber axis, which is parallel to the major axis of the stem, branch, or root in which the fiber is located. The other two planes are directed parallel to the stem (or fiber) axis and are oriented perpendicular and parallel, respectively, to the growth rings or stem surface; these are known as the **radial** and **tangential** planes. Wood cells produced by the cambium are positioned such that their faces and dimensions can also be referenced as radial, tangential, and cross sectional. This information can be used by the pulp microscopist in describing the location of details on a particular pulp element as well as in referencing the dimensions of that element.

Softwood Anatomy

Over 90% of the wood volume in softwoods is composed of a single cell type—the **longitudinal tracheid**. This cell is a **fiber** and functions primarily in mechanical support and in conduction of water and nutrients from the roots. At maturity, fibers are dead, hollow with a central cavity or **lumen**, and aligned in radial rows (Fig. 2.2).

The other major cell type in softwoods is the **parenchyma** cell. These are short, brick-like elements, often thin-walled, which are arranged in vertical or horizontal series (Fig. 2.2). Parenchyma are often living, even in mature wood tissue, and function largely as a storage site for gums, starch, resin, tannins, latex, and other extraneous materials. They are also a repository for most of the wood inorganics, including both crystalline and amorphous deposits. They serve a similar function in hardwoods.

Longitudinal or axial parenchyma are sparse in most softwoods and abundant in only a few species (**3**,**4**). However, horizontal parenchyma are prevalent in all species, forming thin ribbons of tissue along the stem radius. These ribbons are called **rays** (Figs. 2.1, 2.2, 2.4).

In some species the ray tissue also contains cells known as **ray tracheids**. These cells are dead at maturity and have some wall markings similar to those in longitudinal tracheids, but ray tracheids are not fibrous cells. They are similar in size to parenchyma and are also arranged in a horizontal series (Fig. 2.5). Since they occur in some species and not in others, they are of some diagnostic value in wood identification (Table 2.1). However, due to their small size they are an infrequent component of finished pulps and have little diagnostic value in fiber analysis. The possible exception to this is the case of hard pines (see Table 2.1). The ray tracheids here are distinctly marked by irregular wall outgrowths called **dentations** (Figure 2.5), and the presence of a dentate ray tracheid in pulp confirms the incorporation of at least some hard pine.

In temperate zones, the wood produced during the first part of the growing season or spring is called **earlywood**. The fibers here are thin-

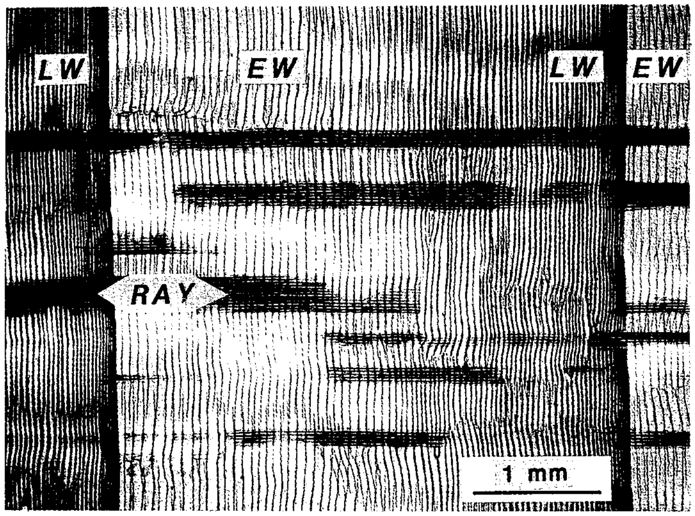

Fig. 2.4 *A radial section of eastern hemlock wood. Note that the rays extend as narrow ribbons across three growth increments; EW - earlywood, LW - latewood. LM.*

walled and have a wide radial diameter (Fig. 2.6). Fibers produced during the latter part of the growing season or summer are thicker-walled and show a steadily decreasing radial diameter. These are **latewood** fibers. The transition from earlywood to latewood of the same year varies with species and is generally either gradual or abrupt (Fig. 2.6). However, some species border on these two classifications naturally or tend toward one or the other as a result of changing patterns in tree growth. The ultimate proportion of earlywood and latewood in a given ring or in the tree as a whole also varies with factors related to tree growth (**3**).

The wood of all pines, spruces, larches, and Douglas-firs contain normal longitudinal and horizontal **resin ducts** (Figs. 2.2, 2.6, 2.7). These are tube-like cavities lined with specialized secreting parenchyma called **epithelial cells**. Resin duct anatomy is useful for wood identification, but it is of no value to the fiber microscopist since these structures and cells are destroyed or lost during pulping.

The details of wood anatomy valued most for identifying softwoods in pulp are those structures that provide communication between contiguous

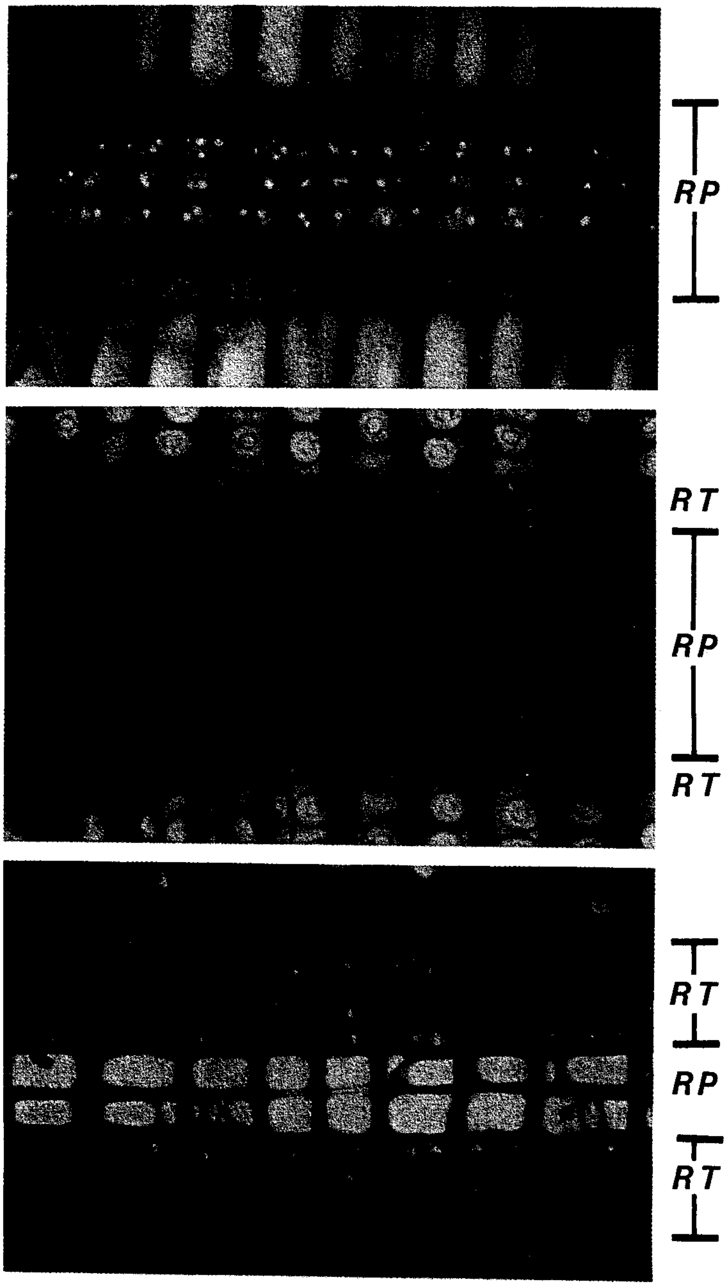

Fig. 2.5 *Ray structure in softwoods as seen in radial section. LM.*

A. *Homocellular ray of procumbent parenchyma (RP) in white fir.*

B. *Heterocellular ray with nondentate ray tracheids (RT) in black spruce.*

C. *Heterocellular ray with dentate ray tracheids (RT) in red pine.*

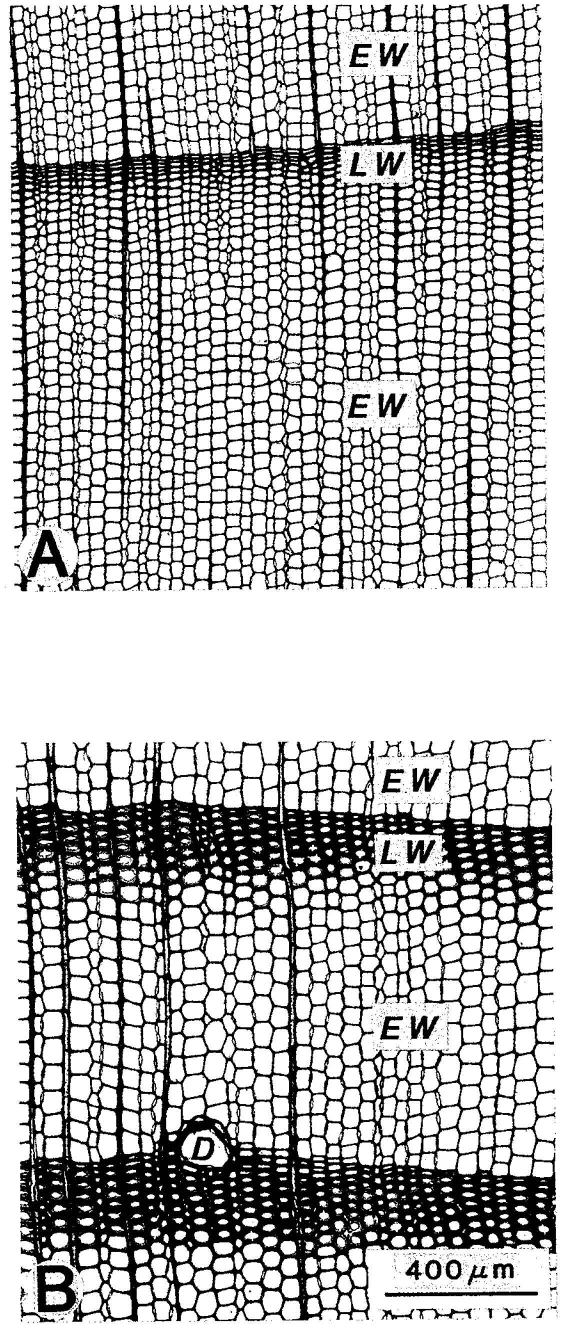

Fig. 2.6 *Earlywood-to-latewood (EW/LW) transition in softwood growth increments as viewed in cross section. LM.*

A. *Gradual transition in balsam fir with relatively thin-walled latewood fibers.*

B. *Abrupt transition in Douglas-fir with thick-walled latewood fibers; D-resin duct.*

Table 2.1 Summary of diagnostic information[a] used for the identification of softwoods in pulp

Cell Types and Features[b]	Longitudinal Tracheids (Fibers): Spirals	Longitudinal Tracheids (Fibers): Cross-Field Pitting					Ray Tracheids	
Common Name of Species or Genus	Present	Fenestriform	Pinoid	Piceoid	Taxodioid	Cupressoid	Present	Dentate
Baldcypress					+	S		
Cedar, Incense-						+	R	
N. White-					+		R	
W. Red-					+		R	
S. White-						+	R	
Alaska-						+	+	
Port-Orford-						+	R	
Douglas-fir	+			+			+	
Firs					+		S	
Hemlocks				+		+	+	
Larches	S LW			+			+	
Pine, White		+					+	
Sugar		+					+	
Red, Scots		+					+	+
Yellow	S LW		+				+	+
Caribbean			+				+	+
Monterey			+				+	+
Parana						+		
Podocarp		±		±	±	±		
Redwood					+			
Spruces				+			+	

a
+—The feature is typical of the species/genus
S—The feature is present only sporadically
R — The feature is rarely present
LW—In latewood fibers only
± -Varies with species

b See also references 3-11

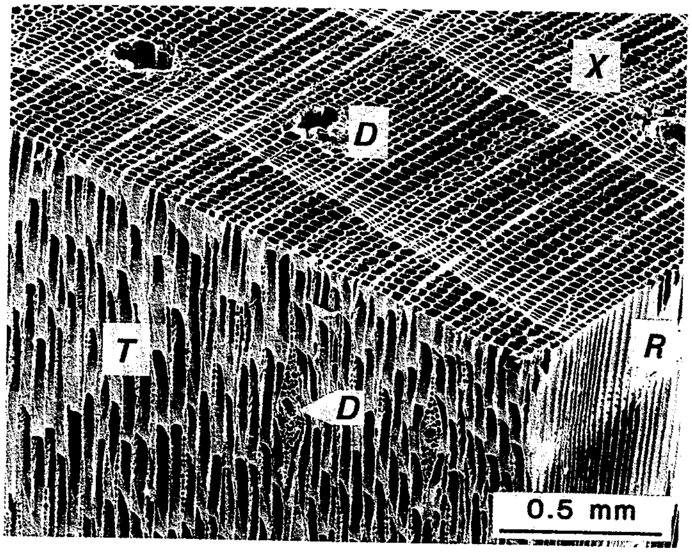

Fig. 2.7 *Scanning electron micrograph (SEM) of sugar pine wood showing the three major structural planes. Resin ducts (D) are visible on both the cross sectional (X) and tangential (T) surfaces; R-radial surface.*

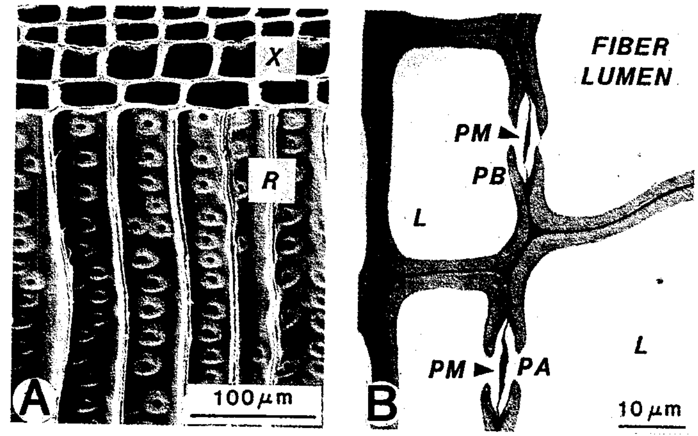

Fig. 2.8 *Interfiber bordered pitting in softwoods.*

A. *Radial/transverse (R/X) view of Engelmann spruce wood showing donut-shaped pit borders in earlywood fibers. SEM.*

B. *Transverse section of interfiber bordered pits in western hemlock earlywood; L-fiber lumen, PM-pit membrane, PB-pit border; PA-pit aperture. LM.*

fibers and between fibers and ray cells. These structures are called **pits**. A pit is actually a recess in the cell wall together with an external closing membrane. Figs. 2.5 and 2.8 show that softwood pits occur primarily on the radial faces of the longitudinal tracheids. Between adjacent fibers, they are arranged (usually) in complementary pairs with a centrally located membrane. The latter structure in softwoods is usually quite permeable. Intertracheid pits are known as **bordered pits** because a portion of the fiber wall overarches the actual hole or **aperture** in the wall. Similar but smaller bordered pits occur between the fibers and ray tracheids (Figs. 2.5 and 2.9); only here the membranes are not as open (3).

In pulp, the softwood fiber appears as shown in Fig. 2.9. Pit membranes have been destroyed, and the borders are now seen (in the light microscope) as two concentric circles or, collectively, as a series of donuts along the fiber face. Depending on the wood species and radial width of the fiber, these pits may occur in one to four vertical rows (see Chapter 4).

Intertracheid pits are the most conspicuous structures on softwood fibers, but they are not as valuable to the fiber analyst as those marking the regions where fibers contact ray cells, especially ray parenchyma. These areas are called **cross fields**. There are usually several of these per ray crossing and several **cross-field areas** along an unbroken fiber (Fig. 2.9). The morphology of these pits is best illustrated in the wide earlywood fibers; in latewood fibers, it is reduced and distorted.

Five types of ray parenchyma cross-field pits are distinguishable in softwoods (3,6). These are illustrated in Fig. 2.10, and their distribution in softwood genera is given in Table 2.1. The shape, size, and number of these pits will differ some between juvenile and mature wood and between earlywood and latewood. Therefore, the fiber analyst should become familiar with this type of variability.

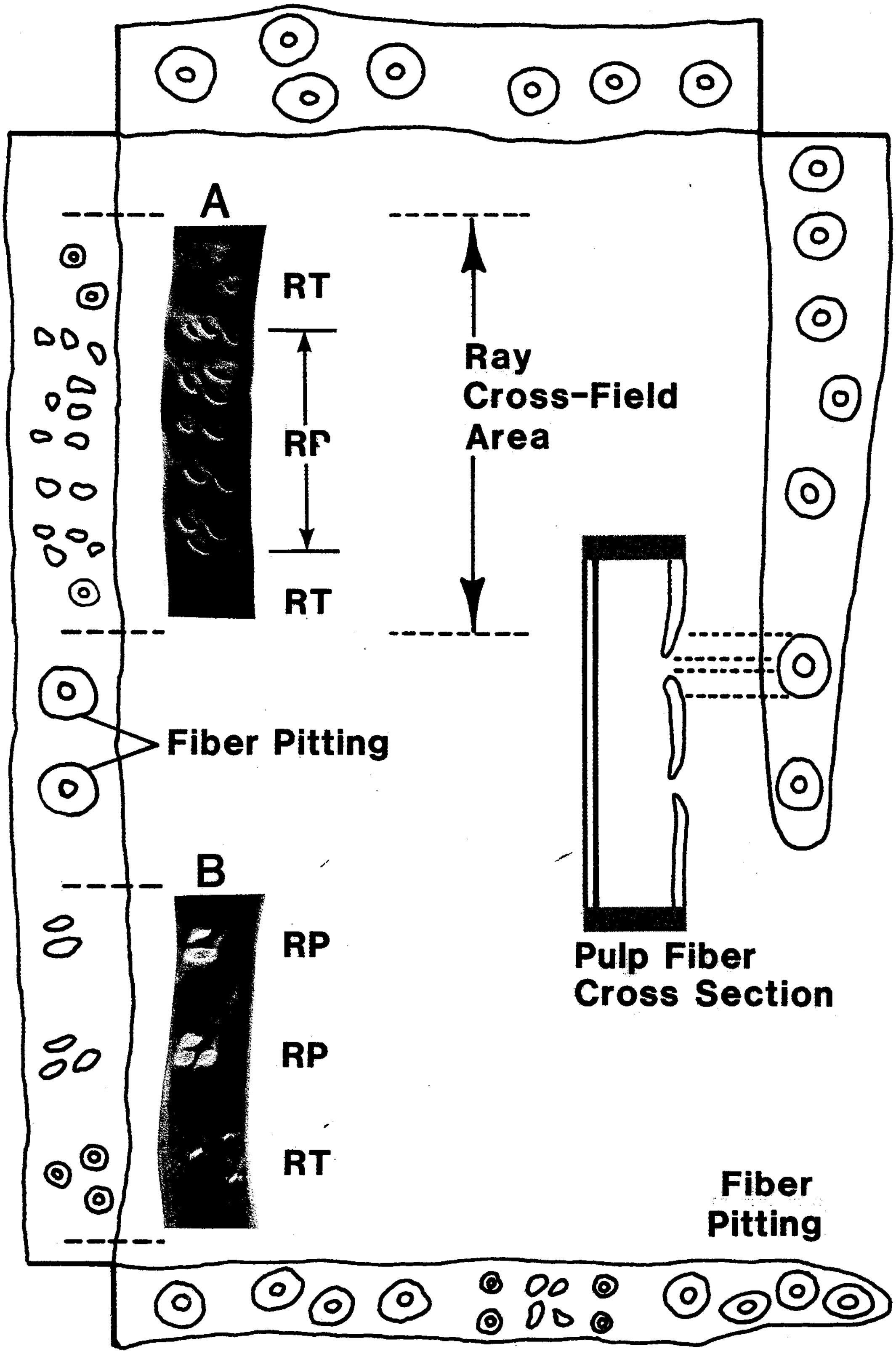

Fig. 2.9 Diagram of a hypothetical, unbroken softwood pulp fiber.
A. Cross-field area in an earlywood fiber of ponderosa pine; RT-small bordered pits to ray tracheids, RP-pinoid pits to ray parenchyma. SEM of wood radial section.
B. Cross-field area in an earlywood fiber of jack pine. LM of pulp fiber.

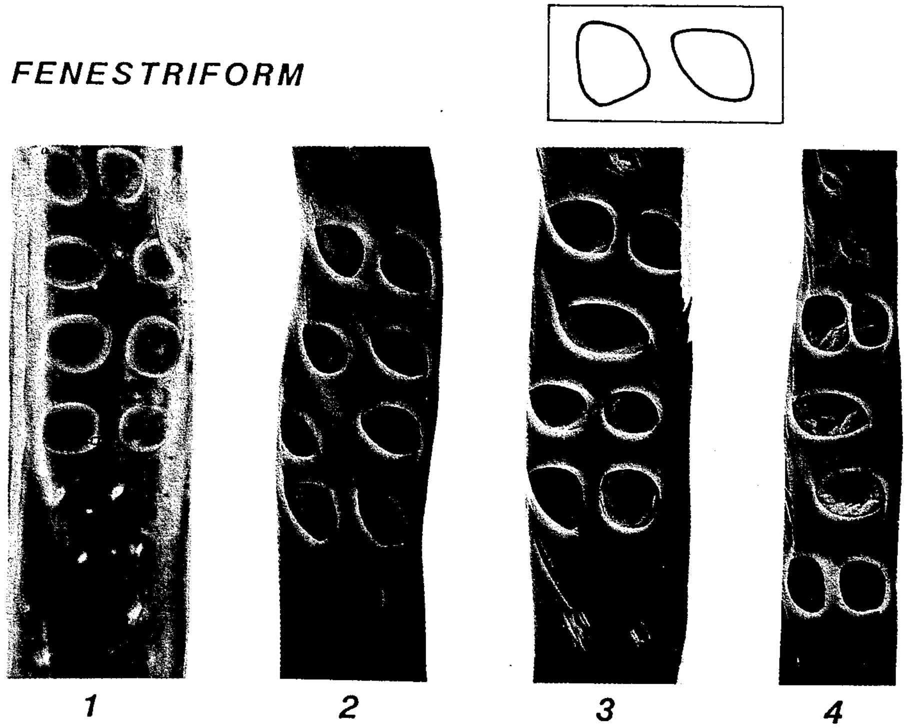

Fig. 2.10 *The five major types of ray parenchyma cross-field pits in North American pulpwoods. (All LMs are at 400X and SEMs are at 500X).*
A. **Fenestriform** *(windowlike) pits in western white pine; LM-1, SEM-2,3,4.*

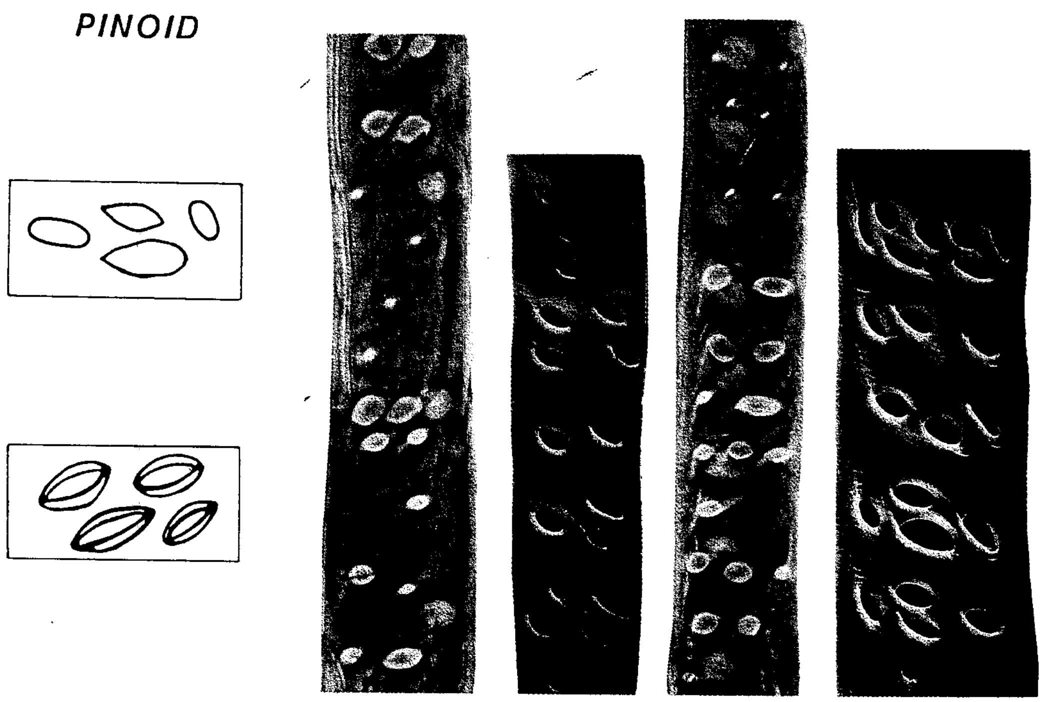

Fig. 2.10.B. ***Pinoid*** *pits in loblolly pine (LM-1, SEM-2) and in ponderosa pine (LM-3, SEM-4).*

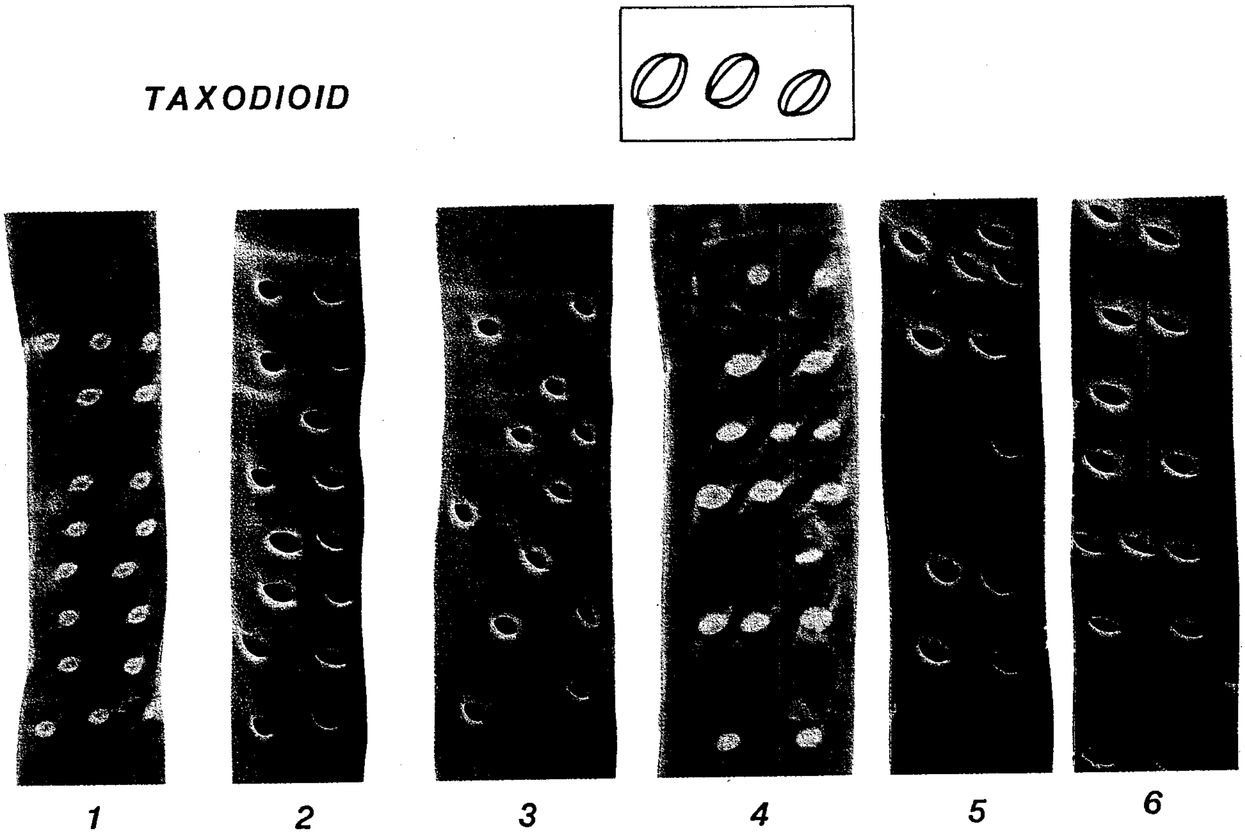

Fig. 2.10.C. **Taxodioid** *pits in amabilis fir (LM-1, SEM-2,3) and in redwood (LM-4, SEM-5,6).*

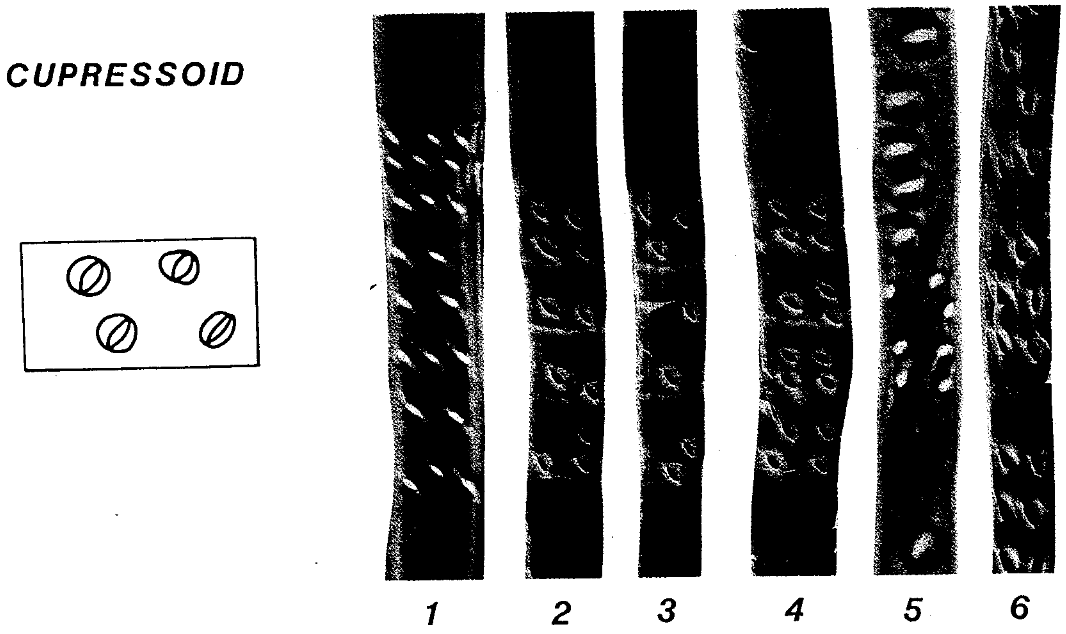

Fig. 2.10.D **Cupressoid** *pits in southern white-cedar (LM-1, SEM-2,3,4), and in Alaska-cedar (LM-5, SEM-6).*

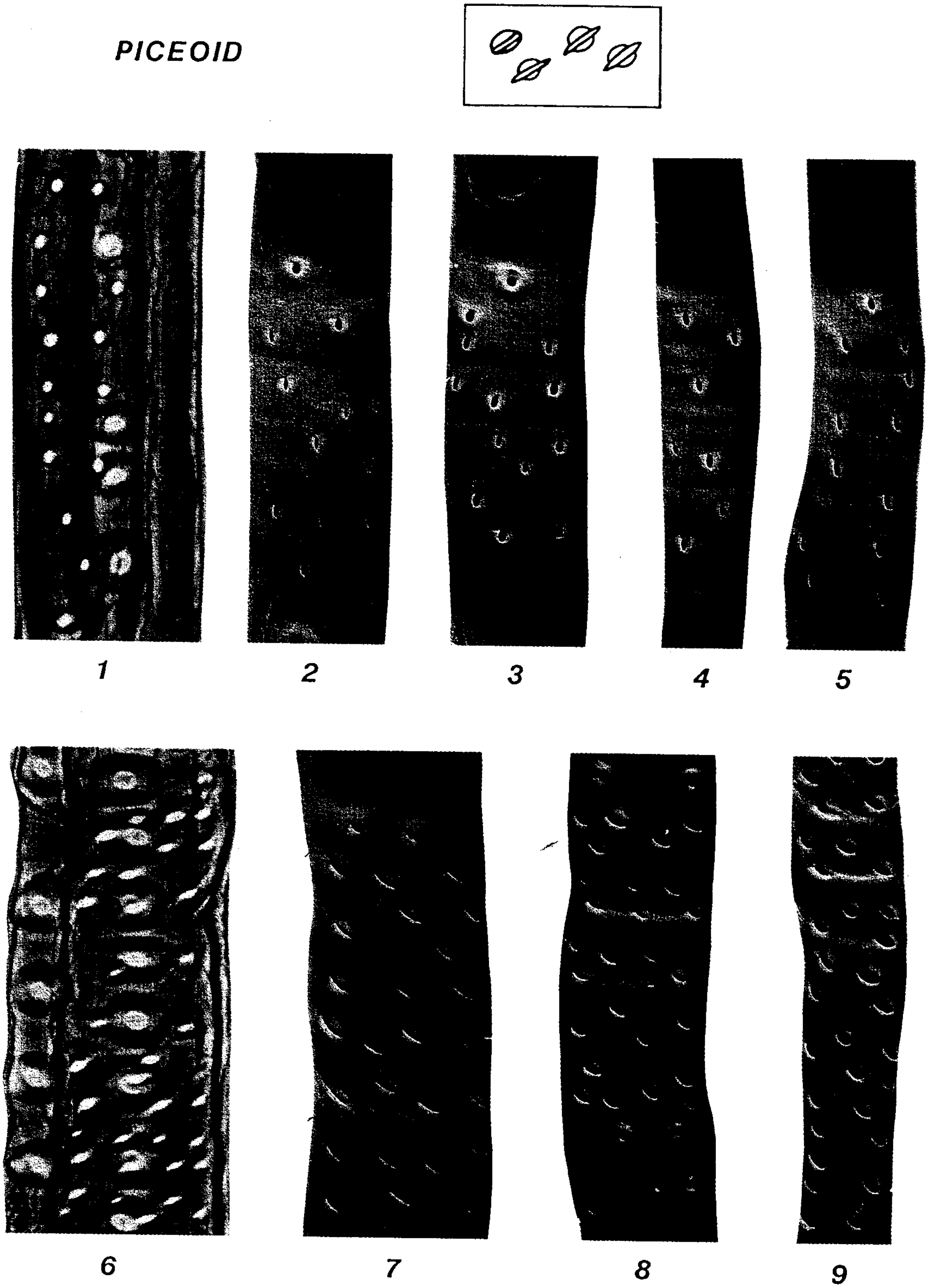

Fig. 2.10.E. ***Piceoid*** *pits in western hemlock (LM-1, SEM-2,3,4,5) and in eastern larch (LM-6, SEM-7,8,9).*

(All LMs are at 400X and SEMs are at 500X.)

A few softwood genera contain structures known as **spiral thickenings**, which are ridges of wall material that spiral along the inner wall surface (at the lumen) (Fig. 2.11). They are a regular feature in only one commercial pulpwood, Douglas-fir, although they occur sporadically in the latewood of eastern larch, juvenile wood of spruce, and the latewood of some hard pines (**3,6,9**). Spirals should not be confused with helical checks or fissures that occur in compression wood fibers. The latter fibers can be found in any softwood. The properties of this special type of fiber are discussed later under "Reaction Wood."

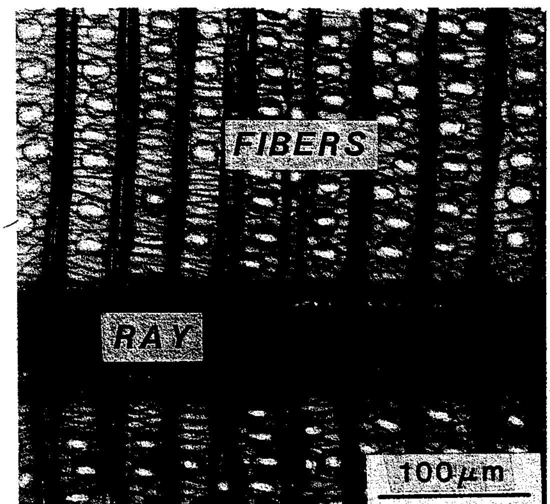

Fig. 2.11 *Radial section of Douglas-fir wood showing spiral thickenings in the longitudinal tracheids. Note that the spirals are oriented at a large angle (flat helix) with respect to the fiber axis. LM.*

Hardwood Anatomy

Wood from angiosperm trees differs from that in gymnosperms in several respects, the most distinctive of which is the presence of **vessels**. These are tube-like structures that run vertically in the tree and appear as **pores** in cross section (Fig. 2.12). Thus, the name **porous woods**.

Individual vessels are composed of a vertical series of short, usually thin-walled cells—**vessel elements**—which are joined end-to-end along the grain (Fig. 2.13). These cells are open or perforate at their ends, providing a free path for the upward movement of water and nutrients from the roots. The necessity of this conduction system becomes evident upon examination of the pits that occur between adjacent vessel elements, between vessels and fibers, and between adjacent fibers. The pit membrane here is unlike the open membrane in softwood bordered pits; it is a thin but nonporous partition of cell wall material, permitting intercellular transport through the pits only by diffusion (**3,6**).

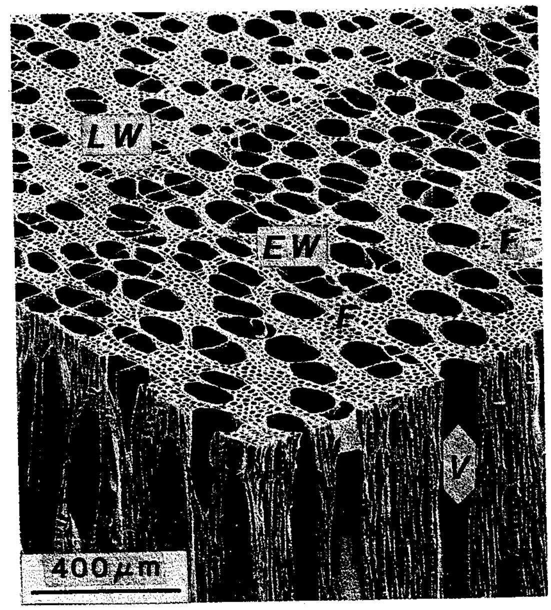

Fig. 2.12 *Three-plane view of a hardwood (eastern cottonwood). Note the orientation and distribution of the pores or vessels; EW-earlywood, LW-latewood, F-fibers, V-vessels. SEM.*

Within an annual growth increment, pore size and distribution pattern will vary with wood species. Among temperate hardwoods, there are three generally recognized patterns (**3,6**). Those woods in which the earlywood pores are large and show an abrupt transition to notably smaller latewood pores are called **ring-porous** (Fig. 2.14). The other extreme is the case in which there is no obvious difference between earlywood and latewood pores, and all pores are usually small; these woods are **diffuse-porous**. Still other woods show a gradual transition from relatively large earlywood pores to small pores in the last-formed latewood. These are called either **semi-ring-porous** or **semi-diffuse-porous** woods. In subtropical and tropical zones, most woods tend to be diffuse-porous with little or no ring structure at all (**4**).

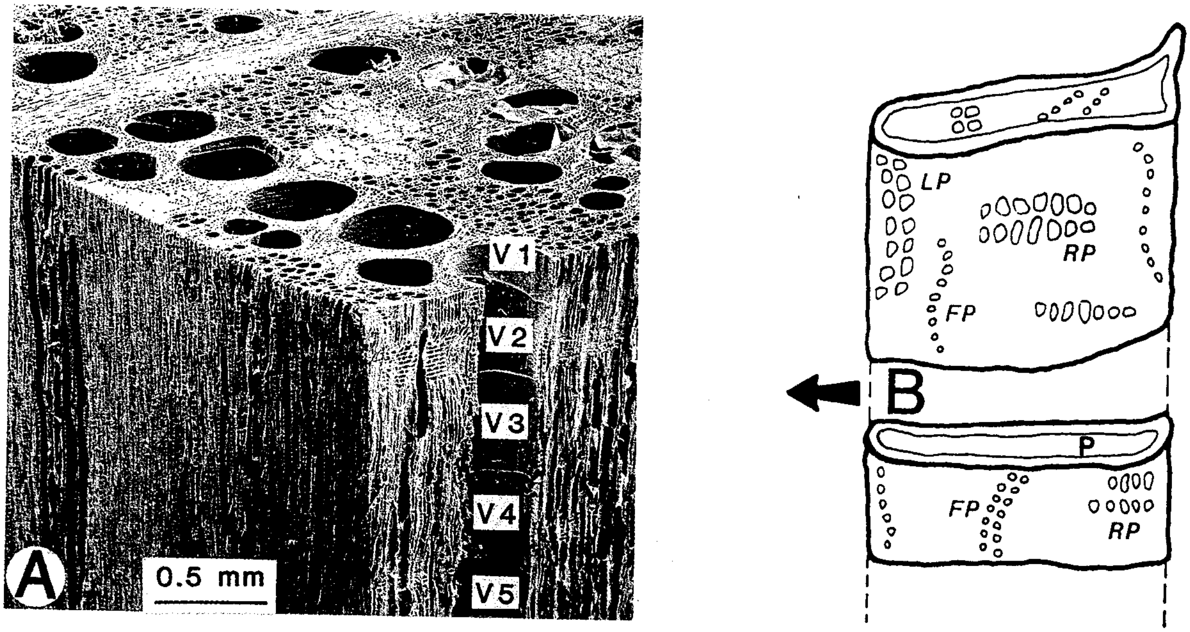

Fig. 2.13 The articulation of vessel elements in hardwoods to form a vessel.
A. Oblique view of white oak wood showing a vertical series of five earlywood vessel elements (segments) in radial section (V1–V5). SEM.
B. Diagram of two vertically contiguous vessel elements connected by a simple perforation plate, P: LP-longitudinal parenchyma pitting, RP-ray parenchyma pitting, FP-pitting to contiguous fibers.

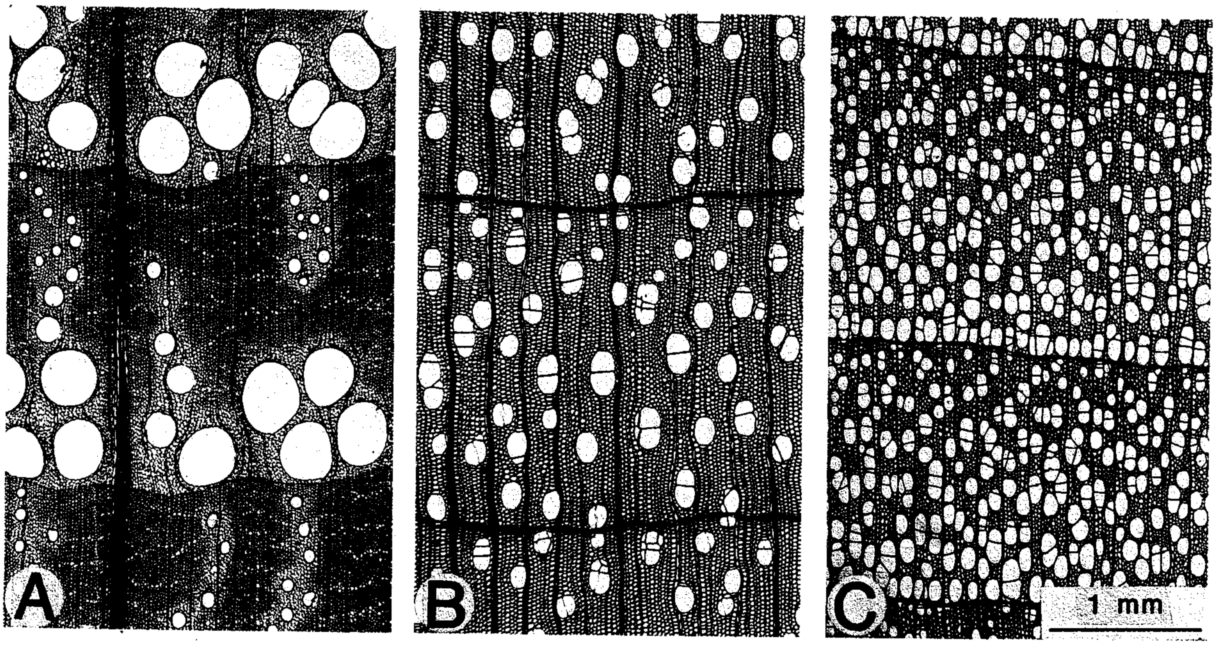

Fig. 2.14 The three types of pore patterns or growth increments in hardwoods as seen in transverse section. LM.
A. Ring-porous (red oak).
B. Diffuse-porous (birch).
C. Semi-ring-porous (cottonwood).

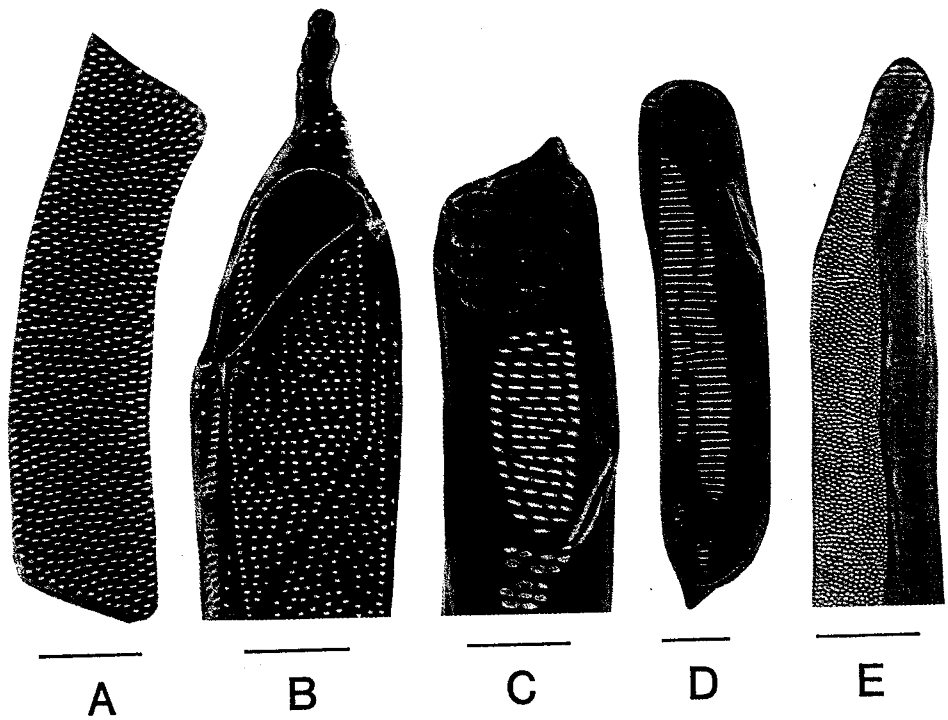

Fig. 2.15 *The major types of intervessel pitting in hardwoods. The line under each micrograph represents 80 μm. LM.*
A. ***Alternate***, *crowded pits in black willow.*
B. ***Alternate to opposite***, *widely spaced pits in sycamore.*
C. ***Opposite to linear*** *pits in yellow-poplar.*
D. ***Linear to scalariform*** *pits in cucumber magnolia.*
E. ***Confluent*** *pit-apertures in alternate, very small pits in paper birch.*

Along the tree axis, vessels may remain solitary or they may join and depart from other vessels. Furthermore, they may be arranged in radial groups or files, clusters, or even tangential bands. This information is of interest to the pulp microscopist because the particular type of pore arrangement dictates how much intervessel pitting will be available for use as diagnostic information. For example, woods with most or all solitary pores rarely show intervessel pits while woods with vessel groups can have abundant and distinctive intervessel pitting. Those pit arrangements common to North American hardwoods are illustrated in Fig. 2.15. In a few species the vessel element pit-chambers are lined with a wart-like deposition, giving rise to what is called **vestured pitting** (Fig. 2.16) (**3**,**6**). As seen in pulp, vestures tend to mask other pit details (see Chapter 4).

In addition to intervessel pitting, pits between vessels and fibers, ray parenchyma, and axial parenchyma can also be of diagnostic value, depending on the species (Fig. 2.17). Furthermore, the vessel elements in some woods also contain spiral thickenings in their tips or over their entire inner wall surface (see Table 2.2 and Fig. 2.17). The size, spacing, and pattern of such spirals are valuable diagnostic information (see Chapter 4).

Another detail of vessel element structure important to the fiber analyst is the architecture of the **perforation** area or plate. Woods described in this book have **simple** and/or **scalariform** plates. These are illustrated in Fig. 2.17. Other types of perforation plates can be identified in various hardwoods and are also of diagnostic value (**3**,**6**,**10**,**11**), but the species involved are not common pulpwoods.

In hardwood xylem the regions between the vessels are composed of fibers and parenchyma (see Fig. 2.18). However, vessel-less tissue here differs considerably from the analogous tissue in softwoods. The notable distinctions are:

1. There are several different types of hardwood **fibers**; they are all short, in contrast to softwoods, and they are not aligned in radial files.
2. There is much more axial parenchyma, arranged in various patterns.

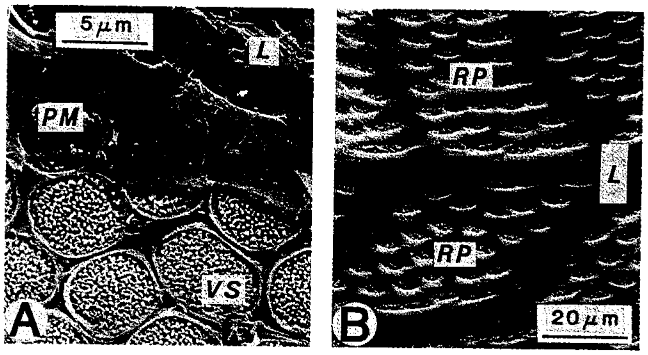

Fig. 2.16 *Vestured pitting in hardwood vessel elements. SEM.*

A. *Intervessel pits of anthocephalus. The lumen lining (L) has been torn away to reveal vestures (VS) and pit membranes (PM).*

B. *Ray cross-field area in anthocephalus as seen from the vessel side; RP-ray parenchyma pitting.*

3. The rays are more variable in width, and most hardwoods have rays more than one cell wide (multiseriate); some are extremely wide (e.g., oaks, beech).
4. There are no ray tracheids, but the ray parenchyma can have different arrangements (see Fig. 2.17).

Of these listed differences, only the fact that some hardwood species have different fiber types is of any real diagnostic value to the fiber analyst. Pulping eliminates all details based on cell arrangement.

The fibrous cells in hardwoods are generally classed in two categories as **true fibers** and **tracheids** (3,6). The true fibers occur in all species as **fiber tracheids** and/or **libriform fibers**, the latter having fewer and simpler pits, thicker walls, and more pointed ends (Fig. 2.19). However, these two types of fibers intergrade, sometimes even in the same growth ring. The other fibrous cells are **vascular tracheids** and **vasicentric tracheids**. These occur in only a few species but can be of diagnostic value (see Table 2.2).

Vascular tracheids closely resemble, and are positioned close to, short latewood vessels and are arranged in a vertical series (Fig. 2.19G). They are imperforate but may contain spiral thickenings (e.g., elms, hackberry). Vasicentric tracheids are short, irregularly shaped cells and contain numerous bordered pits (Fig. 2.19B, 2.19E, 2.19F). These also occur only in a few wood types (e.g., oaks, eucalyptus). They are usually associated with earlywood vessels and occur in clusters (Fig. 2.18).

As hardwoods develop heartwood, or in sapwood as a response to injury or general loss of wood moisture, the vessel system in the affected portion of the stem may become plugged with structures called **tyloses** (3). These are intrusive, bubble-like growths which originate from adjacent parenchyma cells (Figs. 2.18, 2.20). The living contents of the parenchyma cell invade the vessel through an adjoining pit, expand, and together with tyloses from other parenchyma can entirely fill the vessel, cutting off water and nutrients from the roots. In pulp, tyloses are often still in the vessel elements, or they can be dislodged and separated from the vessels, appearing as isolated, balloon-like elements with no markings except possibly a few small pits (Fig. 2.21).

Reaction Wood

In all trees there is some wood tissue that is anatomically and/or chemically dissimilar to the typical or so-called normal wood produced in straight, vertically erect stems. Such tissue is often referred to as abnormal wood, but it is perhaps more appropriately termed **reaction wood** because it develops as a result of the tree responding to certain stimuli. More specifically, reaction wood is often concentrated in stems and branches as a means by which to achieve and maintain a preferred orientation. In other cases, it assists the tree in gaining a more suitable exposure to light. Other factors involved in the formation of reaction wood are discussed in the literature (3).

Reaction wood in conifers is called **compression wood** because it is common on the lower and seemingly compressed side of branches and leaning stems. However, this side of the stem or branch actually exhibits much wider growth rings, which can cause the stem or branch to develop an eccentric cross section (Fig. 2.22).

The fibers in compression wood tend to be rounded in cross section, thicker walled than normal, and possibly exhibiting helical fissures or checks (Fig. 2.23). Since compression wood can be found in all softwoods, it is of no diagnostic value for species identification. However, since the fiber analyst sees both sides of a pulp fiber at the same time in the light microscope, the helical fissures in compression wood fibers appear as a

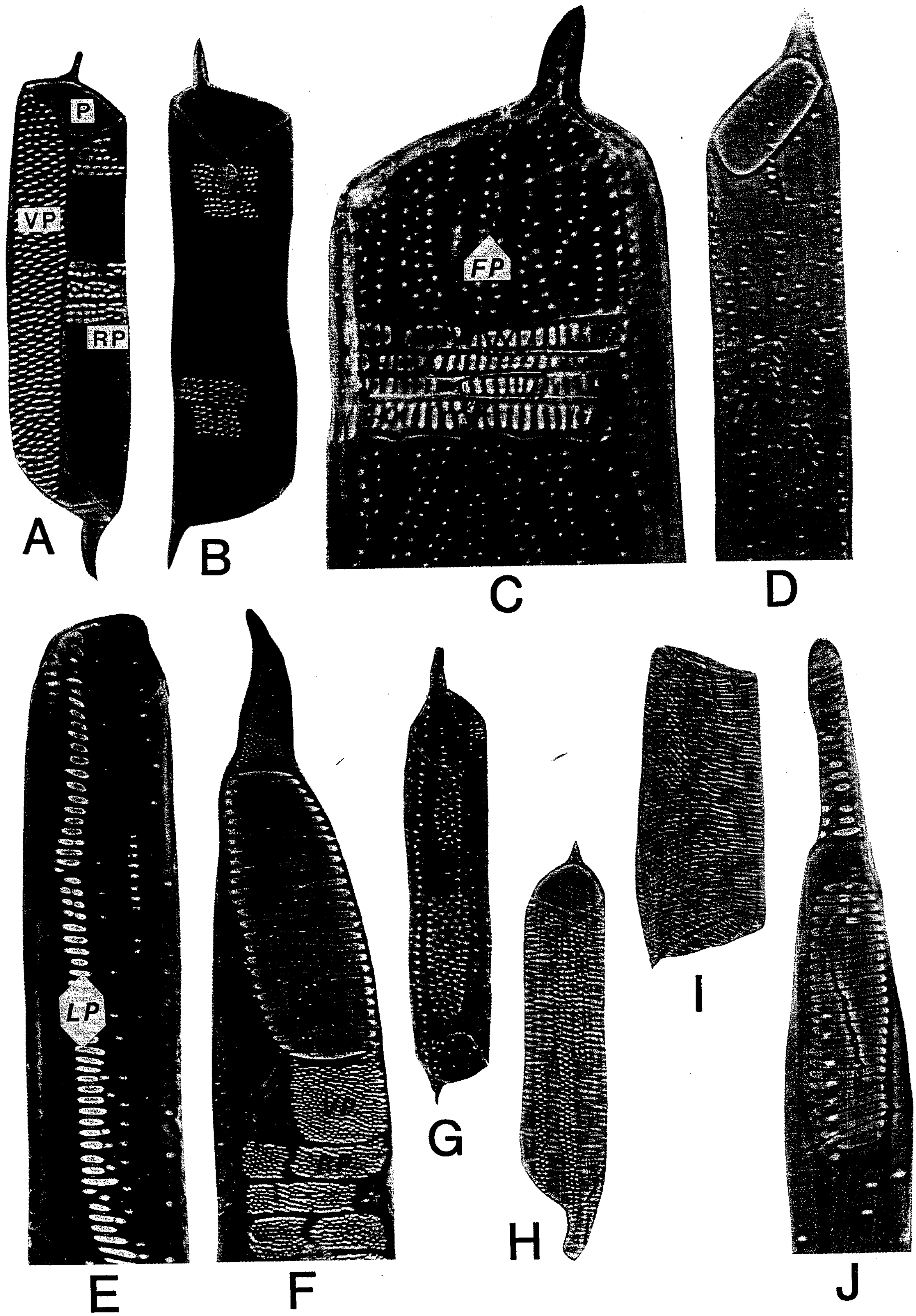
P
VP
RP
A
B
FP
C
D
LP
E
F
G
H
I
J

Fig. 2.17 *Variability in the morphology and architecture of hardwood vessel elements as seen in pulp. LM.*

A. ***Aspen*** *vessel element with simple perforation plates (P), crowded and alternate intervessel pits (VP), and pitting to homocellular rays with vessel contact only at the ray margins (RP). 160X.*

B. ***Black willow*** *vessel element with simple perforation plates and pitting to heterocellular rays with vessel contact only at the ray margins via upright parenchyma cells. 160X.*

C. *Portion of a vessel element from* ***tanoak*** *with four rows of procumbent ray-cell pits and several areas of contact with vasicentric tracheids (FP). No vessel pitting is seen here due to the solitary nature of the wood pores. 250X.*

D. *Portion of a vessel element from* ***American beech*** *(solitary pores) with simple perforation plates; the pits scattered here in the cell wall are those leading to contiguous fibers. 250X.*

E. *Portion of a* ***sycamore*** *vessel element with a vertical series of longitudinal parenchyma pits (LP). A few pits leading to adjacent fibers are also evident. 250X.*

F. *Portion of a vessel element from* ***paper birch*** *containing scalariform perforation plates of 25+ thin bars; the latter are branched in four locations. The vessel pitting (VP) is very small and similar to ray parenchyma pitting (RP); note the confluent pit-apertures. 250X.*

G. *A vessel element from* ***black cherry*** *with simple perforation plates, alternate vessel pitting, and spiral thickenings; the latter occur throughout the cell but are faint and irregular in some areas. 160X.*

H. ***Red (soft) maple*** *vessel element with simple perforation plates and spiral thickenings throughout; the latter are swirled in some areas. The pitting seen here is that leading to axial parenchyma. 160X.*

I. ***Sugar (hard) maple*** *vessel element with simple perforation plates and spiral thickenings throughout. 160X.*

J. *Portion of a vessel element from* ***redgum (sweetgum)*** *exhibiting a scalariform perforation plate with 20+ thin bars. Spiral thickenings (ST) in this wood are restricted to the tips of the vessel elements (as in the tupelo gums). 250X.*

pattern of crisscrossing lines (Fig. 2.24) and are sometimes confused with spiral thickenings. Therefore, it should be kept in mind that spirals are not actual splits in the fiber wall; furthermore, they are also usually oriented at a much larger angle to the fiber axis than are the fissures (compare Figs. 2.11 and 2.24).

In hardwoods, reaction wood tissue is called **tension wood** and, in contrast to compression wood, is common on the upper sides of branches and leaning stems (Fig. 2.25). Fibers are the only cell type modified in tension wood, the most noticeable change being the addition in some species of a special wall layer called a **gelatinous layer** or **G-layer** (Fig. 2.26). However, in other species, even the fibers are unaltered. In either case, in pulp form, tension wood fibers closely resemble normal hardwood fibers. This situation, together with the fact that vessel elements in tension wood are structurally unaltered, means that tension wood presents neither problems nor advantages for the fiber analyst.

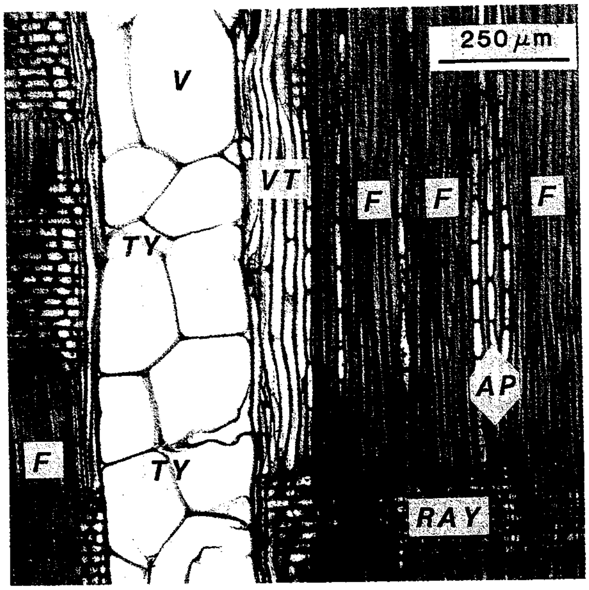

Fig. 2.18 Radial section of white oak wood showing the spatial relationship between vessels, fibers, and parenchyma cells. The earlywood vessel here is filled with bubble-like growths called "tyloses" (TY) which originated from adjacent parenchyma (see also Fig. 2.20); V-vessel, VT-vasicentric tracheids, AP-axial parenchyma, F-libriform fibers. LM.

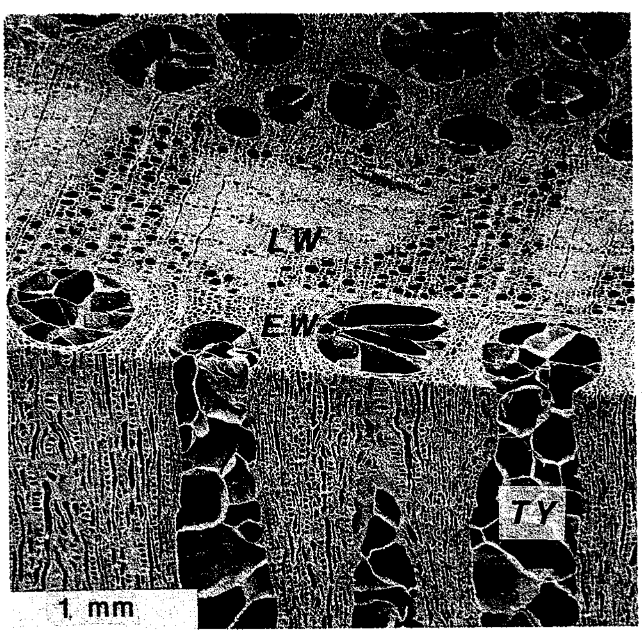

Fig. 2.20 Transverse/tangential view of white oak wood showing the nature and abundance of tyloses (TY) in the heartwood; EW-earlywood, LW-latewood. SEM.

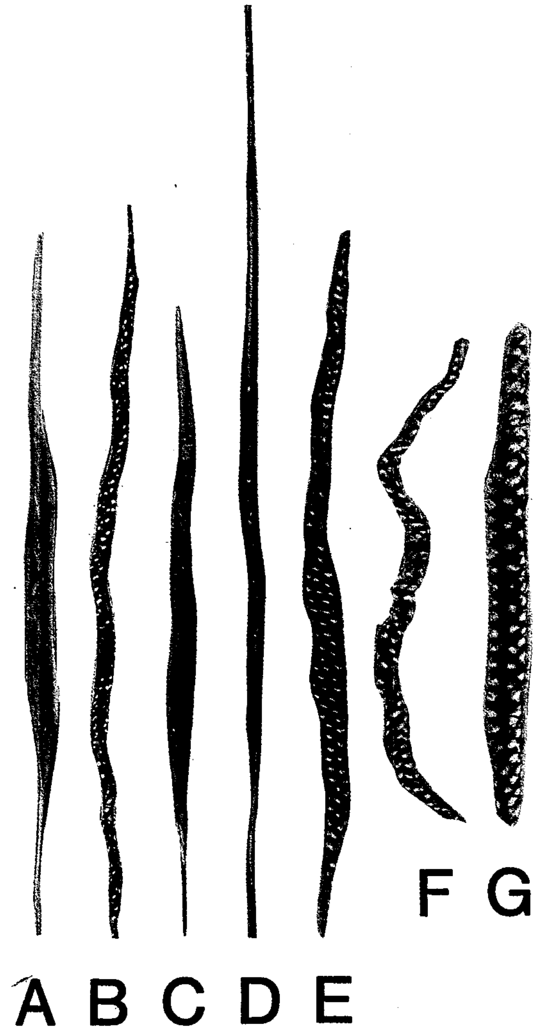

Fig. 2.19 Typical morphological variability in fibrous cells from hardwoods. LM of pulp.

A. Fiber from albizia. *100X.*

B. Vasicentric tracheid from eucalyptus. *100X.*

C. Fiber from catalpa. *160X.*

D. Fiber from tanoak. *160X.*

E. Vasicentric tracheid from tanoak. *160X.*

F. Vasicentric tracheid from white oak. *160X.*

G. Vascular trachied from red elm. *250X.*

Table 2.2 Summary of diagnostic information[a] used for the identification of hardwoods in pulp

Cell Types and Features[b]			Vessel Elements										Tracheids
			Perforation Plates			Intervessel Pitting				Ray Pitting			
Common Name of Species or Genus	Distribution	Spirals	Simple	Scalariform <10 BARS	Scalariform >10 BARS	Opposite	Alternate	Linear	Scalariform	Heterocellular	Homocellular	Vasicentric	Vascular
Albizia	DP		+				+				+		
Alder	DP				>15	S	+			A	+		
Anthocephalus	DP		+				+			+			
Ash	RP		+				+				+	+	
Aspen	SR		+				+				+		
Basswood	DP	+	+				+				+		
Beech	DP		+	S LW			+			S	+		
Birch	DP				>15		+				+		
Buckeye	DP	±	+				+			+	+		
Butternut	SR		+				+			S	+		
Catalpa	RP	±	+				+			S	+		
Cherry	SR	+	+				+			S	+		
Cottonwood	SR		+				+				+		
Elm	RP	+ LW	+				+				+		+
Eucalyptus	DP		+				+			+	+	+	
Gmelina	DP		+				+			+			
Hackberry	RP	+ LW	+				+			+			+
Hickory, True	RP		+				+			S	+		
Hickory, Pecan	SR		+				+			S	+		
Holly	DP	+			>15	+				+	S		
Kentucky Coffeetree	RP	+ LW	+				+				+		
Locust, Black and Honey-	RP	+ LW	+				+			S	+		
Magnolia, Cucumber	DP	R	+	R				+	+	+	+		
Magnolia, Southern	DP	+		+	S			+	+	+	+		
Maple	DP	+	+				+				+		
Oak, Red	RP		+				R				+	+	
Oak, White	RP		+				R				+	+	
Oak, Live	SR		+				R				+	+	
Pacific Madrone	DP	+		+			+			+	S		
Redgum (Sweetgum)	DP	Tips			>15	+		+	S	+	+		
Sassafras	RP		+	S LW			+			+	+		
Sycamore	DP		+	S LW		S	+				+		
Tanoak	DP		+				R			A	+	+	
Tupelo, Blackgum	DP	Tips			>15	+		S		+			
Tupelo, Water	DP	S Tips			>15	+		S		+			
Yellow-poplar	DP		+	+	S	+		S	S	+	+		
Walnut, Black	SR		+				+			S	+		
Willow	SR		+				+			+			

a
+—The feature is typical of the species/genus
S—The feature is present only sporadically
R—The feature is rarely present
LW—In latewood vessel elements only
A—Aggregate ray
RP—Ring-porous wood
DP—Diffuse-porous wood
SR—Semi-ring-porous wood

b
See also references 3–11

Fig. 2.21 *A single tylosis isolated from pulp of pecan hickory. LM.*

Fig. 2.22 *Surface of a cross-sectional disk cut from the trunk of a severely leaning Douglas-fir. The tree contained a large proportion of compression wood (CW) on its underside. The bark and cambium were removed from the upperside by mechanical damage induced when the tree was pushed into a leaning position.*

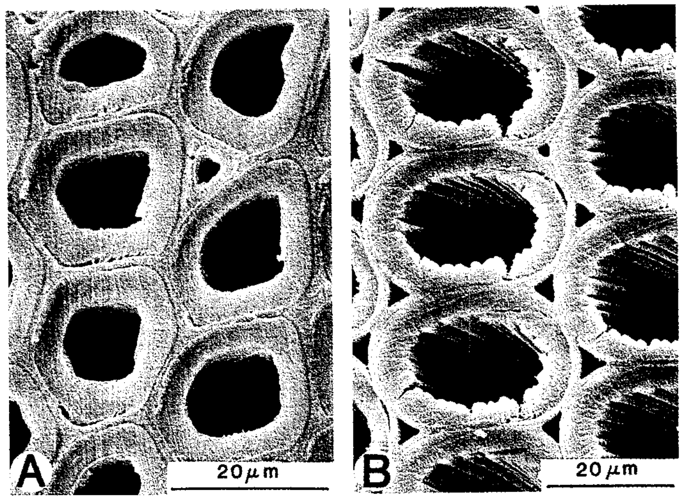

Fig. 2.23 *Cross-sectional views of normal and compression wood fibers in Sitka spruce. SEM.*

- ***A.*** *Normal wood.*
- ***B.*** *Compression wood with interfiber spaces and helically fissured fiber walls.*

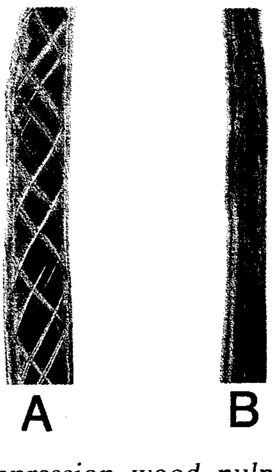

Fig. 2.24 *Compression wood pulp fibers as seen with a light microscope. Note the criss-cross pattern due to wall fissures; the latter form a steep helix along the fiber axis. LM. 250X.*

- ***A.*** *Large diameter fiber from ponderosa pine.*
- ***B.*** *Narrow fiber from eastern larch (tamarack).*

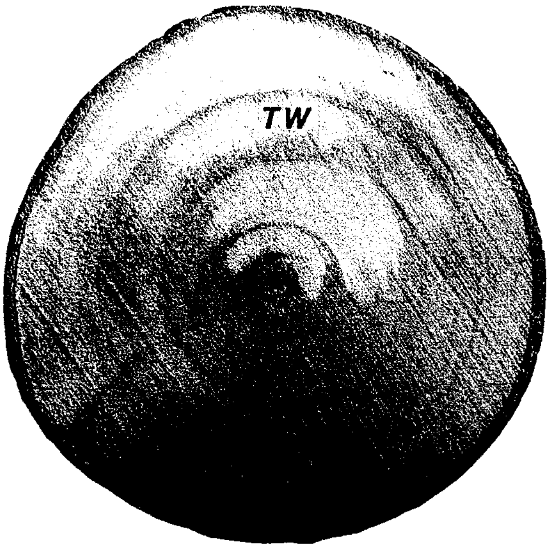

Fig. 2.25 *Surface of a cross-sectional disk cut from the trunk of a young, rapidly growing* ***Populus*** *hybrid. In this particular case, the tree was not leaning noticeably, but it still contained a large proportion of tension wood (TW). In leaning hardwoods, this tissue is normally formed on the upperside of the trunk.*

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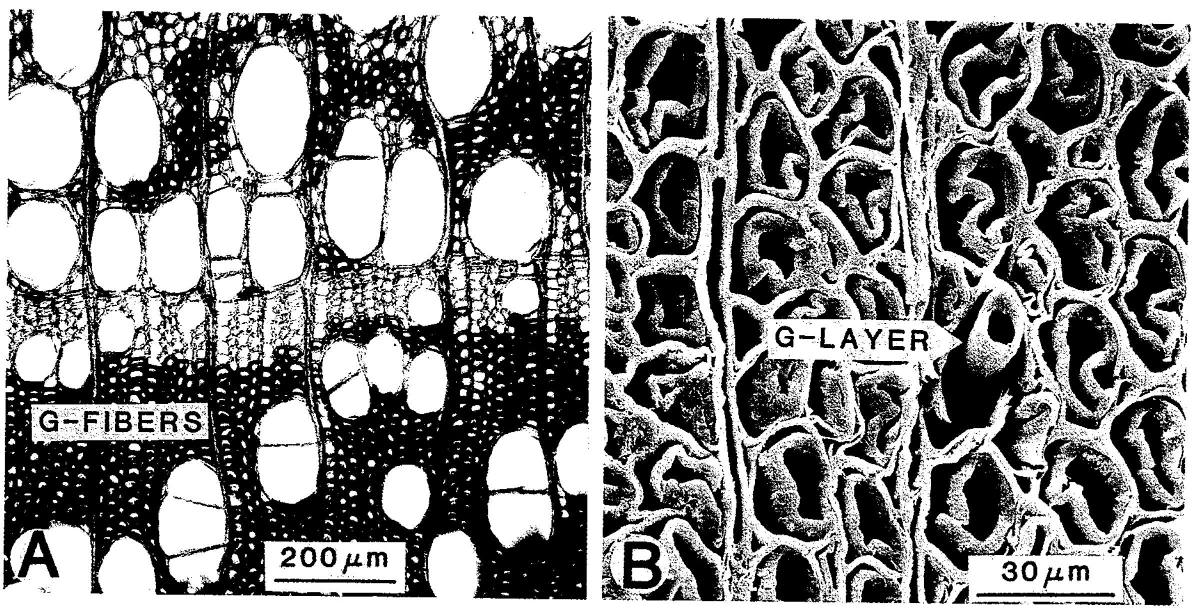

Fig. 2.26 *Cross-sectional views of the tension wood area shown in Fig. 2.25 illustrating the nature and distribution of gelatinous (G) fibers.*

A. *Wood section that was differentially stained to accentuate fiber G-layers. LM.*

B. *Transverse surface of pure tension wood. The G-layers easily displaced from the rest of the fiber wall during sectioning and wood drying. SEM.*

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