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A review of microbial deterioration found in archaeological wood from different environments

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Abstract

Wooden cultural properties are degraded by microorganisms when moisture, oxygen and other environmental factors are favorable for microbial growth. Archaeological woods recovered from most environments, even those that are extreme suffer from some form of biodeterioration. This review provides a summary of wood degradation caused by fungi and bacteria and also describes specific degradation found in archaeological wood from a variety of different terrestrial and aquatic environments. These include woods from several ancient Egyptian tombs (4000 BC to 200 AD); an 8th century BC tomb found in Tumulus MM at Gordion, Turkey; Anasazi great houses (1000 AD) from the southwestern United States, waterlogged woods (100–200 BC) from the Goldcliff intertidal site, Wales, United Kingdom; and the late Bronze Age Uluburun shipwreck found off the coast of Turkey. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Wood decay; Waterlogged wood; Ancient wood; White-rot; Brown-rot; Soft-rot

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1. Introduction

Wood deterioration is an essential process in the environment that recycles complex organic matter and is an integral component of life. These processes, however, also destroy historic wood that has been used as shelter, utility and art resulting in a loss of valuable cultural properties from archaeological sites. Woods with natural resistance to microbial degradation were often used in ancient times for applications where wood was in contact with the ground, for shipbuilding and for other uses (Meiggs, 1982). These extractive-rich woods helped to preserve the wood and resist microbial attack but even the most resistant woods are not immune from decomposition. Wood that persists for long periods of time is usually protected by an environment that limits microbial activity. These special conditions may allow wood to survive centuries or even thousands of years but even in the most extreme environments some physical and chemical modification of wood from biodeterioration takes place. What type of deterioration occurs and how these processes impact the wood are important questions that need consideration if wooden cultural properties are to be studied and properly preserved. Since there are relatively few wooden objects surviving from past civilizations, they are extremely valuable resources that deserve careful attention. It is essential to improve our understanding of the microbes and processes that affect archaeological woods and to increase our knowledge of structural and chemical changes that occur in wood from degradation. This review provides information about biodeterioration mechanisms affecting wood and describes a wide variety of examples with deterioration found in archaeological wood from different environments.

2. Structural and chemical features of wood

Wood consists of an orderly arrangement of cells with walls composed of varying amounts of cellulose, hemicellulose and lignin. The great diversity of woody plants is reflected in the varied morphology and chemical composition of their wood. Typically, two general groups, hardwoods (angiosperms) and softwoods (gymnosperms), can be easily separated. Hardwoods have pores or vessel elements that occur among fiber and parenchyma cells (Fig. 1). Cellulose content ranges from 40 to 50% with 15–25% lignin and 15–25% hemicellulose. The remaining components consist of various extracellular compounds.

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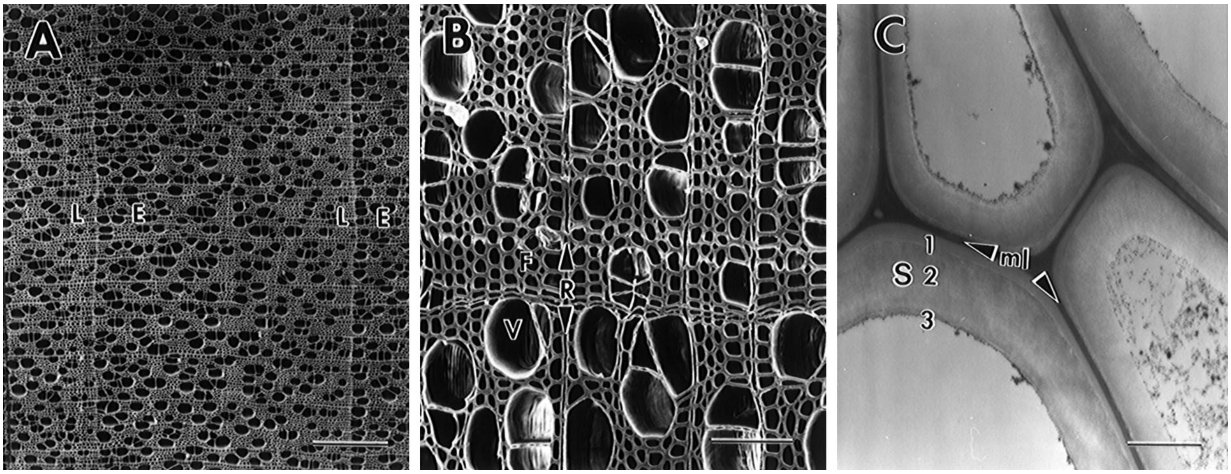

Fig. 1. Cell structure of an angiosperm. (A and B) Sections of a diffuse porous hardwood showing earlywood (E) and latewood (L). The wood consists of vessels (V) fibers (F) and ray parenchyma cells (R). (C) Cell walls with secondary wall layers (S_1, S_2 and S_3) and middle lamellae (ml). Transverse sections. A and B SEM, C TEM. Bar = 500 μm in A, 100 μm in B, and 2 μm in C.

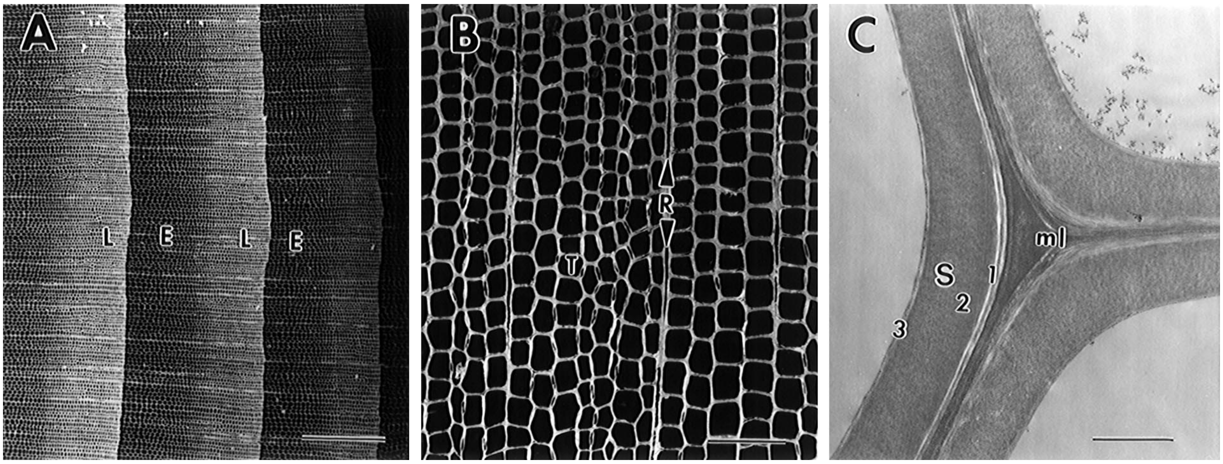

Fig. 2. Cell structure of a gymnosperm. (A and B) Thin-walled earlywood or springwood (E) and thick-walled latewood (L) tracheids. (B) Zone of earlywood showing tracheids (T) and ray parenchyma cells (R). (C) A group of tracheid cell walls showing secondary wall layers (S_1, S_2 and S_3) and middle lamella (ml). Transverse sections. A and B SEM, C TEM. Bar = 500 μm in A, 100 μm in B, and 2 μm in C.

Softwoods are composed of overlapping tracheids, connected by bordered pit apertures, and parenchyma cells and, in some cases, resin canals (Fig. 2). Greater concentrations of lignin, about 5–10% more than hardwoods, are found in softwoods, and about the same amount of cellulose 40–50% (Table 1). Less hemicellulose may be found in softwoods than hardwoods. The chemical composition of softwoods is also different from hardwoods with different types of lignin (primarily guaiacyl propane units), hemicelluloses (mannose is the most common constituent) and wood extractives (different terpenes, fatty acids, etc.). Differences in composition are also common between temperate and tropical hardwoods (Table 1). Woods such as teak, mahogany and ebony have greater concentrations of lignin and wood extractives than many temperate hardwoods such as maple, birch and aspen (Browning, 1963; Fengel and Wegener, 1984; Scheffer and Morrell, 1998).

Abnormalities in trees also may result in wood with unusual characteristics. Leaning stems of trees have a different anatomy and chemical composition than normal wood from the same species. In softwoods, the wood formed on the lower side of leaning trunks or stems is called compression wood and has thicker cell walls with high concentrations of lignin. The chemical composition of the lignin, orientation of cellulose microfibrils and hemicellulose composition also varies considerably from normal wood (Blanchette et al., 1994; Timell, 1986). Compression wood imparts a greater amount of resistance to decay than normal wood (Timell, 1986). For hardwoods, the upper side of leaning trunks and branches is the area that has altered wood. This region, called tension wood, has fiber cells with an additional pure cellulose layer formed on the lumen side of the cell wall called a gelatinous layer (Panshin and de Zeeuw, 1980). This wood appears to be

Table 1
Chemical composition of various woods

	%				
Wood species	Type of wood	Lignin	Glucose[a]	Xylose[b]	Mannose[b]
Gymnosperms					
Pine[c]	Normal	29	44	7	8
(*Pinus strobus*)	Compression	39	32	7	4
Cedar[d]	Normal	33	36	11	7
(*Cedrus libani*)					
Boxwood[d]	Normal	30	43	7	12
(*Taxus baccata*)					
Angiosperms					
Maple[c]	Normal	24	46	17	4
(*Acer rubrum*)	Tension	15	56	10	1
Teak[e]	Normal	31	37	12	1
(*Tectona grandis*)					

[a] Represents cellulose component in wood.
[b] Represents hemicellulose component in wood.
[c] Data from Blanchette et al. (1994).
[d] Data from Timell (1986).
[e] Data from Browning (1963).

as susceptible to decay as normal wood (Blanchette et al., 1994).

3. Degradation of wood by fungi

Microbes that degrade wood produce extracellular enzymes that break down the woody cell wall. Growth characteristics of the microorganism in wood and the type of degradative system produced results in different decay patterns being produced (Blanchette, 1998). Depending on the type of decay, different physical, chemical and morphological changes occur in wood. These decay processes have been well characterized and provide useful insights to elucidate deterioration in archaeological woods (Table 2).

A review of decay patterns produced by different fungi suggests that three categories can be used to separate the types of decay produced in wood. Names for these categories are based on visual characteristics of the advanced decay. Two major groups of decay produced by fungi taxonomically classified in the subdivision Basidiomycota, are white- and brown-rot fungi. White rot fungi can degrade all cell wall components, including lignin. They often cause a bleaching of normal wood coloration. Their ability to metabolize large amounts of lignin in wood is unique among microorganisms. The thousands of species that cause white-rots are a heterogeneous group that may degrade greater or lesser amounts of a specific cell wall component. Some species preferentially remove lignin from wood leaving pockets of white, degraded cells that consist entirely of cellulose, while others degrade lignin and cellulose simultaneously (Table 3) (Blanchette, 1991). Degradation is usually localized to cells colonized by fungal hyphae and substantial amounts of undecayed wood remains. A progressive erosion of the cell wall occurs when components are degraded simultaneously (Fig. 3) or a diffuse attack of lignin may occur by species that preferentially remove lignin (photos not shown; see Blanchette, 1991). Strength losses are not significant until late stages of decay (Cowling, 1961; Zabel and Morrell, 1992). White-rot fungi are common parasites of heartwood in living trees and are aggressive decomposers of woody debris in forest ecosystems (Blanchette, 1991; Rayner and Boddy, 1988).

Brown-rot fungi depolymerase cellulose rapidly during incipient stages of wood colonization. Considerable losses in wood strength occur very early in the decay process, often before decay characteristics are visually evident (Wilcox, 1968). Cell wall carbohydrates are degraded extensively during decay leaving a modified, lignin-rich substrate (Fig. 4, Table 3). The residual wood is brown and often cracks into cubical pieces when dry. Brown-rot fungi commonly cause decay of timber in buildings and these fungi have had serious impact on ancient and historic buildings (Jennings and Bravery, 1991). One of the most destructive brown-rot fungi is *Serpula lacrymans* (previously called *Merulius lacrymans*). This fungus has become well adapted to attacking timber in service and can spread rapidly on wood and traverse non-nutritional surfaces. Aerial mycelia differentiates into thick strands

Table 2
Microbes that cause wood deterioration

Microorganism	Wood components utilized	Decay characteristics
Fungi		
White-rot	All cell wall components, some species preferentially attack lignin	Progressive erosion of all cell wall layers. Middle lamella is degraded
Brown-rot	Carbohydrates, some lignin modification	Diffuse depolymerization of cellulose
Soft-rot	Carbohydrates, some lignin modification	Type 1 — cavities form in secondary wall Type 2 — progressive erosion of secondary walls but middle lamella is not degraded
Bacteria		
Erosion	Carbohydrates, extent of lignin modification not known	Erosion troughs leaving large quantities of residual wall material
Tunnelling	Carbohydrates and some lignin	Minute tunnels in secondary walls and middle lamella
Cavitation	Carbohydrates, extent of lignin modification not known	Cavities form in secondary wall leaving residual wall material
Scavengers, etc.	Primary organisms: Pit membranes but no cell wall decay. Secondary organisms: Utilizes modified cell wall components	Primary organisms penetrate pits and degrade wood extractives. Secondary bacteria scavenge altered wood components

Table 3
Chemical analyses of decayed woods

			%			
Type of decay	Wood	Age	Lignin	Glucose[a]	Xylose[b]	Mannose[b]
White-rot	*Pinus*	Modern	30	47	6	13
Brown-rot	*Pinus*	Modern	60	20	1	2
Soft-rot	*Pinus*	900 yr old	44	16	3	4
	Pinus	2600 yr old	61	13	2	2
Bacteria[c]	*Fraxinus*	12000 yr old	80	6	1	0
	Torreya	6000 yr old	47	25	4	5

[a] Represents cellulose content.
[b] Represents hemicellulose content.
[c] Data from Blanchette et al. (1991c).

that allow the fungus to invade new substrates. The mycelial strands also act to transport moisture and nutrients considerable distances (Jennings, 1991). Commonly, this type of decay has been referred to as dry rot. This term, apparently first used to describe any deterioration of dead wood or wood in service (Britton, 1875), is misleading because moisture must be present for the decay to occur.

Fungi that cause soft-rot are taxonomically classified in the subdivisions, *Ascomycota* and *Deuteromycota*. Soft rot was first characterized as a soft, decayed surface of wood in contact with excessive moisture (Savory, 1954). However, soft rots can occur in dry environments and may be macroscopically similar to brown rot (Blanchette and Simpson, 1992; Blanchette et al., 1990). Two distinct types of soft rot are currently recognized. Type 1 is characterized by longitudinal cavities formed within the secondary wall of wood cells and Type 2 used to describe an erosion of the entire secondary wall (Fig. 5). The middle lamella is not degraded (in contrast to cell wall erosion by white-rot fungi), but may be modified in advanced stages of decay (Blanchette et al., 1990; Nilsson

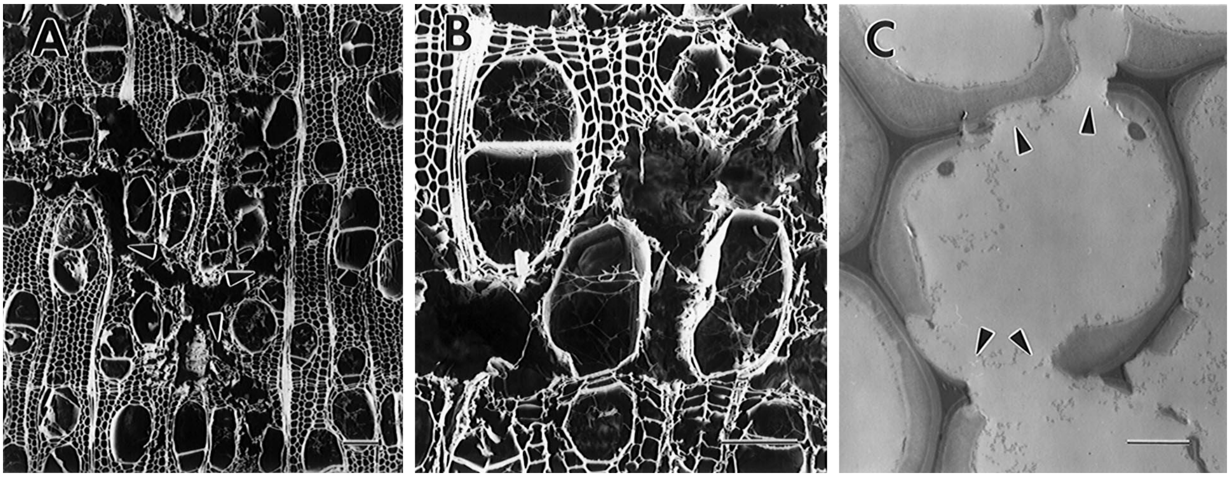

Fig. 3. Nonselective attack of wood by a white-rot fungus. (A and B) All cell wall components are degraded resulting in voids within the degraded wood. (C) A progressive attack of all cell wall components causing a localized erosion of the secondary wall layers and middle lamellae (arrowheads). Transverse sections. A and B SEM, C TEM. Bar = 100 μm in A and B, 5 μm in C.

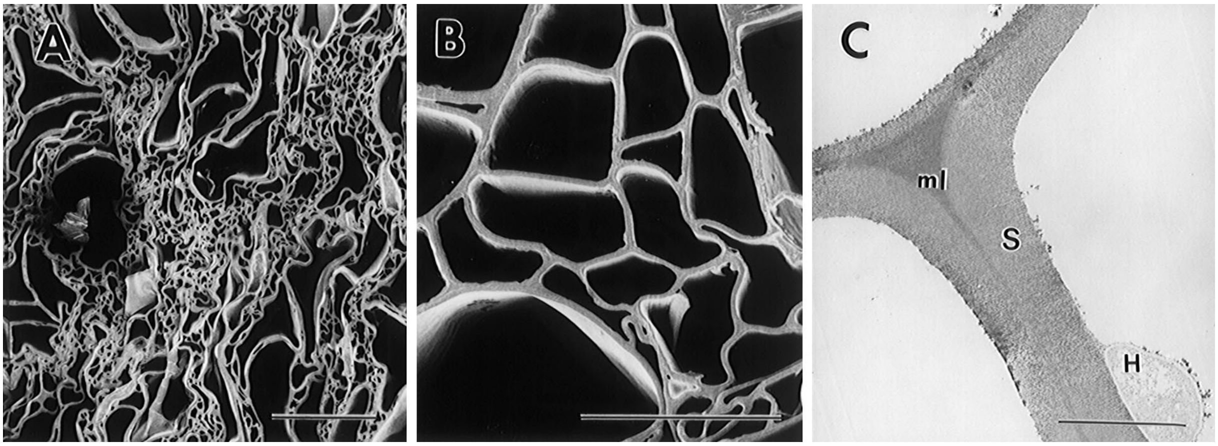

Fig. 4. Decay of wood by brown-rot fungi. (A) Degradation of cellulose in woody cell walls leaves a residual network of lignin. Cell walls collapse and appear distorted. (B) Degraded cells showing walls that are porous and fragile: (C) Ultrastructure of a cell consisting primarily of residual lignin that has little binding strength and is loosely held together. H = hypha, S = secondary wall, ml = middle lamellae.

et al., 1989). Large strength losses in wood can be associated with soft-rot attack. Cavities formed in the wood as well as extensive cellulose degradation can result in extremely poor strength characteristics when soft-rotted wood is visually evident (Hoffmeyer, 1976). As decay progresses, extensive carbohydrate loss occurs and lignin concentrations increase in the residual wood (Table 3).

4. Bacterial degradation

In most terrestrial environments, fungal decomposition of wood appears to predominate. However, wood in aquatic environments or buried in saturated soils usually is attacked by bacteria (Bjordal et al., 1999; Blanchette, 1995). Investigations on the decay characteristics associated with bacterial attack of wood have only recently begun. Although a comprehensive understanding of how bacteria degrade wood is not presently available, recent studies have shown that distinct patterns of attack occur, and several categories of bacterial decay have been described (Daniel and Nilsson, 1998; Daniel et al., 1987; Singh and Butcher, 1991). Three groups, erosion, cavitation and tunnelling bacteria have distinctly different patterns (Table 2) (Fig. 6). In addition to these forms of bacterial attack on cell walls, bacterial scavengers commonly can be found in altered wood utilizing previously degraded cell wall components. Some primary bacterial colonists of wood have been found to preferentially attack only pit membranes (Blanchette et al., 1990; Eriksson et al., 1990).

Erosion bacteria degrade secondary wall layers and deplete cellulose and hemicellulose from the wood.

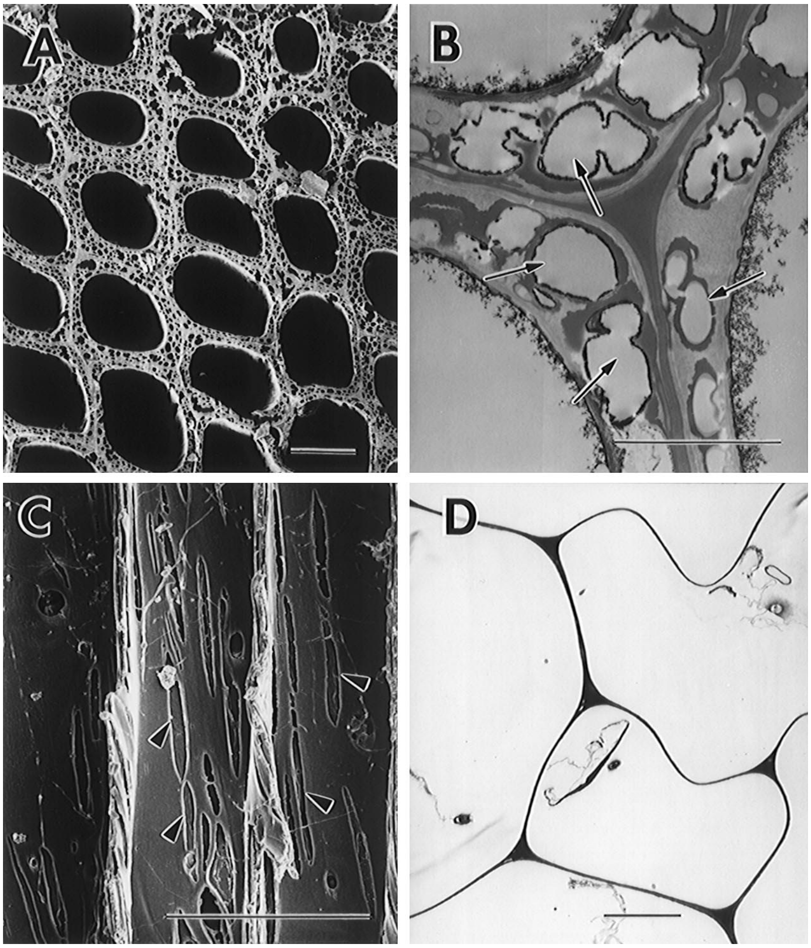

Fig. 5. Soft-rot attack of wood. (A–C). Type I attack forms chains of cavities within the secondary wall (arrows). In advanced stages of decay, cell walls contain numerous cavities that often coalesce together (arrows). In some cells, the chains of cavities are visible from the cell lumina (arrowheads) where holes in the wall have been exposed. (D) Type II form of attack showing an erosion of the secondary wall but no degradation of the middle lamella. In advanced decay, the secondary walls are completely degraded and only the middle lamellae remains. A, B and D transverse sections, C radial section. A and C SEM, B and D TEM. Bar = 50 µm in A and C, 5 µm in B and D.

Undegraded wall materials, consisting of lignin from the secondary wall layers and compound middle lamellae, remain resulting in a porous, high lignified residue (Table 3). Bacteria can also cause cavities or tunnels within cell walls. Tunneling bacteria characteristically produce minute tunnels that occur within the secondary cell wall (Fig. 6). Tunnels can also be found penetrating and degrading the middle lamellae, and even the highly lignin-rich primary structure of bordered pits in coniferous wood (Singh, 1989, 1997). Lignin may be degraded to a limited extent (Daniel et al., 1987) but large amounts of lignin present in wood with advanced bacterial degradation suggests that lignin loss is not extensive (Table 3). Cavitation bacteria may form small diamond shaped or irregular cavities within the secondary wall that are oriented perpendicular to the long direction of the fiber (Fig. 6) (Singh and Butcher, 1991). These cavities may start in the cell wall near a pit chamber or directly within the secondary wall in other areas (Blanchette et al., 1990; Singh and Butcher, 1991).

5. Decomposition in cultural properties

5.1. Terrestrial environments

Environmental factors greatly influence microbial growth and decomposition. In most terrestrial environments wood is degraded rapidly, but when buried in a dry tomb chamber or kept under conditions that impede microbial activity, decay processes are inhibited. The most important requirement for wood-inhabiting microbes is moisture. Optimum moisture levels for white- and brown-rot fungi are approximately 40–80% based on an oven dry weight of wood. Soft-rot fungi tolerate a much wider range of conditions and often are found in excessively wet or dry woods. Bacteria are most prevalent in saturated woods.

To prevent decay, moisture must be reduced to below the fiber-saturation point (i.e. the amount of moisture sufficient to saturate the cell wall and allow some free water to be present in cell lumina) of 28–30%. A wood moisture content of 20% (based on oven dry weight) is

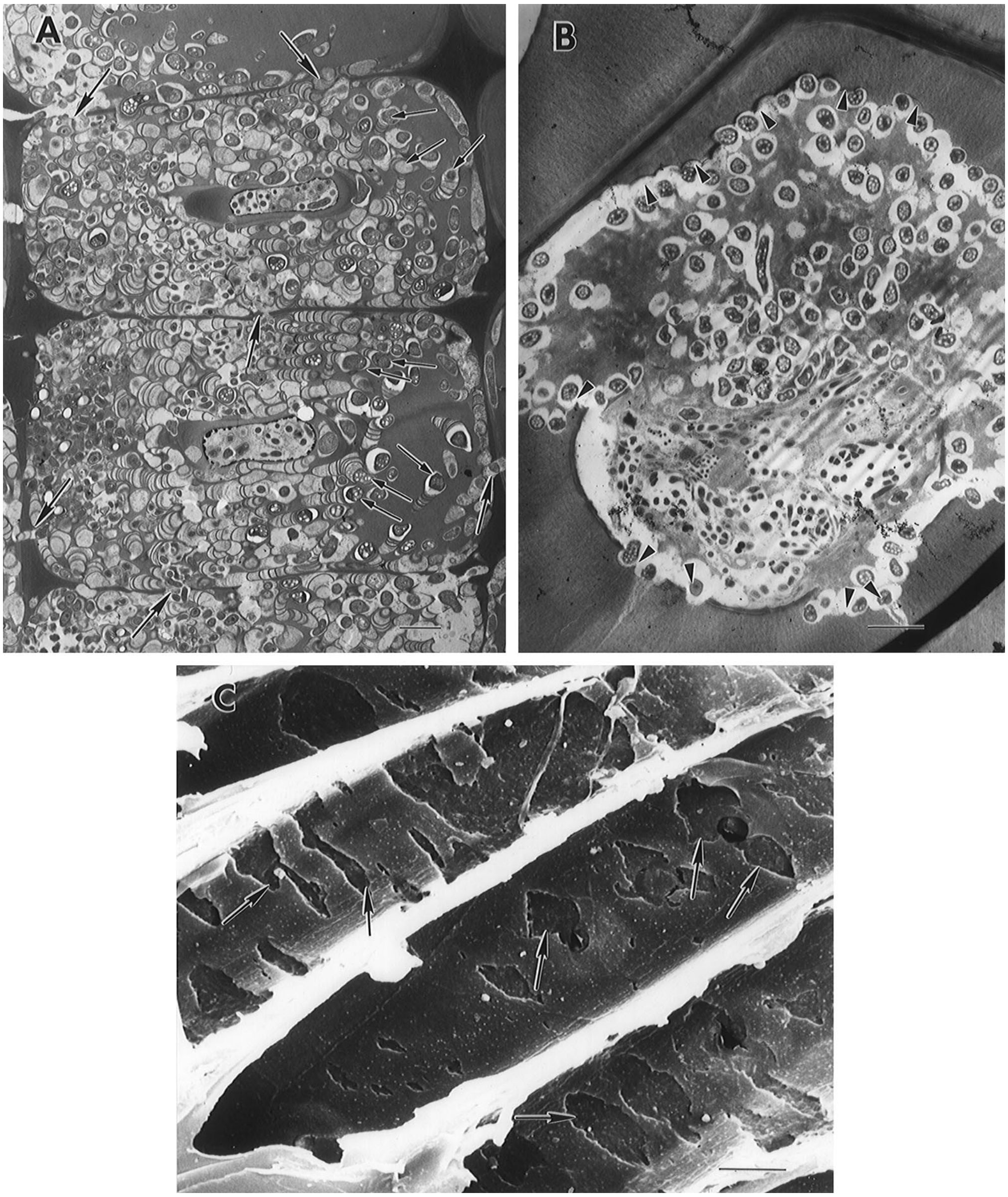

Fig. 6. Bacterial degradation of wood: (A) Tunnelling bacteria degrading the secondary wall (small arrows) and middle lamellae (large arrows). Tunnels produced by the penetrating bacteria are often filled with concentric bands of residual granular material. (B) Erosion bacteria causing a progressive attack on the secondary wall (arrowheads). Bacteria and degraded cell wall materials fill the eroded zones. (C) Cavitation bacteria cause diamond shaped and irregular cavities in the secondary wall (arrows). A and B TEM, C SEM. Bar = 1 μm in A and B, 10 μm in C. Micrographs courtesy of A.P. Singh (Adapted from Singh and Butcher, 1991).

considered best to insure that microbial growth does not occur in wood (Cartwright and Findley, 1958). Wooden cultural properties that survive long periods of time are rarely free of some form of deterioration. Non-biological processes may occur (Blanchette et al., 1991a, b), and depending on available moisture, different types of microbial degradation are present.

5.1.1. Wood from ancient Egyptian tombs

Ancient Egyptian tombs along the Nile Valley have produced large collections of wooden cultural properties that have often been preserved in extraordinarily good condition for thousands of years. Several investigations on fragments of wood dating 2000–4000 BP have shown many woods to be free of microbial degradation but they often contain fissures, cracks and evidence of mechanical damage (Borgin et al., 1975; Fengel, 1991). A study by Nilsson and Daniel (1990) showed evidence of soft-rot attack on a hardwood sample from a coffin. Although decay has been commonly encountered in excavated woods (Zayed, 1956), little information is available on the specific degradative processes that have taken place.

In a study of decay in wooden artifacts from museum collections of ancient Egyptian art, it was clearly

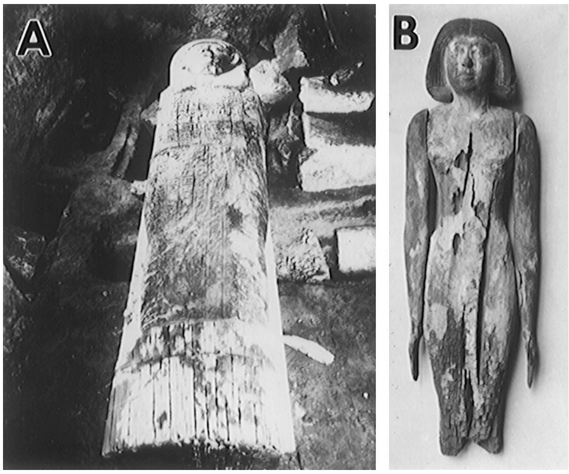

Fig. 7. Decay in objects from ancient Egyptian tombs. (A) Outer coffin of Gem-hap, 664-524 BC (Adapted from Museum of Fine Arts, Boston 29.1860) with severe surface degradation. (B) Statue of the wife of Mitry V Dynasty, 2340 BC (Adapted from Metropolitan Museum of Art, New York 26.2.5) showing extensive decay at base of statue and at midsections.

demonstrated that a variety of different types of deterioration are present in these woods and often many objects are extensively decayed (Blanchette et al., 1994). Brown-rot and soft-rot are the two types of fungal degradation observed repeatedly in objects from collections in the Museum of Fine Arts, Boston and The Metropolitan Museum of Fine Arts, New York.

Deterioration in various statues, coffins, furniture and other cultural properties is often very severe (Figs. 7A and B). The surface of the decayed wood usually is brown and often has numerous cracks. Decayed areas are exceedingly fragile and easily fragment and detach resulting in large voids.

Micromorphological investigations of cells from affected areas showed characteristics of brown- or soft-rot from the different samples examined. In transverse section, soft-rotted wood had numerous cavities located within the secondary wall (Fig. 8). These cavities were often found to coalesce forming large degraded zones inside the wood cells. The perforated wood cells were extremely weak and had lost a great deal of strength and integrity. The unusual anatomy of some hardwoods used to make the objects resulted in atypical characteristics of soft-rot attack. Apparently an extra cell wall layer was present in fibers that resisted decay by the soft-rot fungi. These cells, with anatomical features similar to tension wood, were free of cavities but the inner secondary walls were attacked (Fig. 8).

Soft-rot fungi have most frequently been reported from woods subjected to excessive moisture. The results from investigations of many different Egyptian objects from various locations and dynasties show soft-rot is also common to relatively dry environments. The pH of the wood is also an important factor that could have an effect on the type of fungi that may become established. The limestone environments of many tomb sites in the Nile Valley could influence which decay fungi became established in these alkaline conditions. Moisture percolating through limestone could have a sufficiently high pH to inhibit white- and brown-rot fungi. However, these conditions appear suitable for decay by some soft-rot fungi (Blanchette and Simpson, 1992; Blanchette et al., 1994). The alkaline conditions also appear responsible for initiating nonbiological deterioration mechanisms that may affect the physical and chemical properties of the wood (Blanchette et al., 1994).

Some objects examined also revealed brown-rot. Wood from these decayed regions had a diffuse degradation that caused extensive loss of wood integrity. Decayed wood had cells with swollen, porous walls that appeared severely distorted (Fig. 9). The wood was often so degraded that the walls disintegrated into a granular mass of residual cell wall material. The zone of middle lamellae between cells was disrupted and cells easily fragmented into minute particles (Fig. 9). These examples demonstrate how severely compromised the residual wood may be after decay. The depletion of cellulose and hemicellulose from the cell walls leaves only a lignified framework of cells that are not held together. These cells easily crush into dust-like particles.

Brown rot in objects appeared to be most prevalent to areas that were affected by moisture such as the bottom of statues in contact with the tomb floor. Flooding and moisture accumulations in the wood could have provided the necessary water for brown-rot to occur. These sites were not affected by high alkaline concentrations that would have inhibited brown-rot fungi. Most of this decay could have been initiated soon after burial if moisture was present. However, evidence of termite damage and other insect activity in some tombs suggests the possibility that insects may have vectored decay fungi. The decay fungus could have been introduced at any time over the past centuries with degradation occurring whenever conditions were favorable for growth.

5.1.2. Wood from the tomb structure and furniture of Tumulus MM, Gordion Turkey

The largest tumulus (ancient burial mound) in Turkey, located at the Phrygian site of Gordion contains what is believed to be one of the oldest wooden structures (Young, 1981). The wooden tomb consists of an outer log structure of huge junipers that surround an inner tomb chamber made from finished pine timbers. Within the tomb an enormous log coffin, magnificent inlaid furniture and numerous other exceptional works of art were found (Simpson, 1985; Simpson and Payton, 1986; Young, 1981). The date of the burial suggests that the tomb belonged to the legendary King Midas who ruled the Kingdom of Phrygia in the late 8th Century. In general, the wooden tomb structure, coffin and furniture has survived remarkably well but

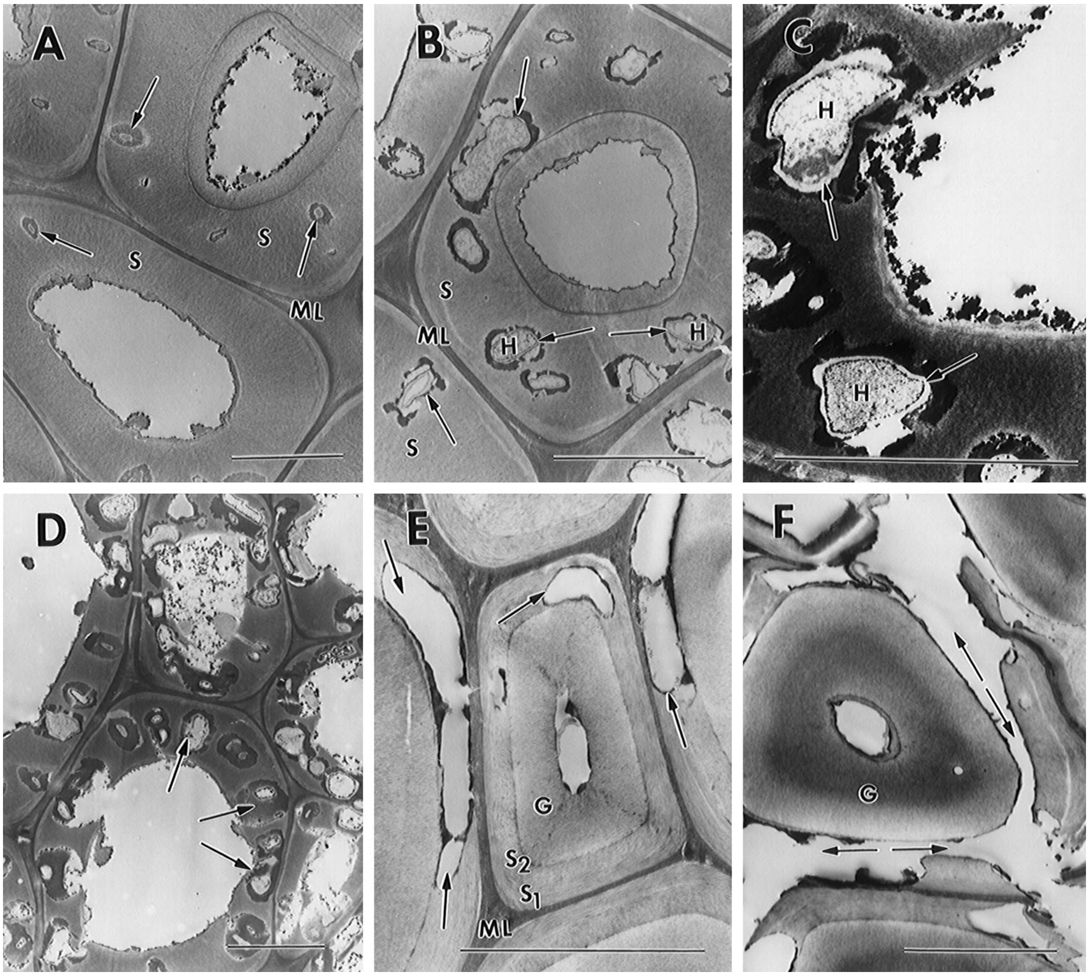

Fig. 8. Soft-rot Type I attack within wood cells from various ancient Egyptian objects. (A) Early stage of decay with small cavities (arrows) in the secondary wall. (B–D) Large soft-rot cavities in the secondary walls (arrows) with remnants of fungal hyphae (H) present inside some of the cavities. (E and F) An unusual form of soft-rot with cavities in the interior portions of the wood cells. The thick layer (G) resembles the gelatinous layer found in tension wood. Soft-rot attack (arrows) occurs in the secondary wall but not the gelatinous layer. S_1 and S_2 = secondary wall layers, ML = middle lamellae A, C and D from wood stand, 1991–1784 BC, MFA 21.899; B from coffin, 1570–1293 BC, MFA 01.7431; E and F from statue, 2363–2275 BC, MMA 27.9.5. TEM. Bar = 5 μm. Adapted from Blanchette et al. (1994).

deterioration was severe in many of the woods (Fig. 10). Soft-rot was the prevalent form of biological degradation found in all woods of the tomb. Typical Type I form of soft-rot attack was evident throughout the different coniferous woods (Fig. 11). The decay of the cedar coffin measuring over 3 m long and 1 m wide, and massive juniper logs suggests the soft-rot fungus was active for an appreciable length of time. Cedar and juniper wood are among the most resistant wood species to microbial decay and a great deal of time would appear to be needed to cause this advanced decay.

The unusual tomb environment appears to have governed the type and extent of decay. Layers of limestone rubble, wet clay and earth covered the tomb to more than 50 m. Moisture from the clay and possibly other external sources could have provided a limited but sufficient amount of moisture for soft-rot fungi to cause decay. Elevated pH of water passing through the limestone rubble, and the natural decay resistance of some woods within the tomb may have had a selective influence on promoting soft-rot and inhibiting other forms of decay. The low levels of moisture in the woods also could have played a role in providing an environment where only soft-rot fungi could survive.

In furniture made from walnut or boxwood, advanced stages of soft-rot was also present. These hardwood objects had some Type I decay characteristics of soft-rot fungi but Type II attack was most common (Fig. 11). Cell walls were attacked and secondary wall layers were eroded. Often only a mass of residual middle lamellae remained making this wood extremely fragile. Many exquisite objects were located in areas of the tomb that apparently received little moisture and were not as severely degraded. Several elaborate tables and inlaid screens have

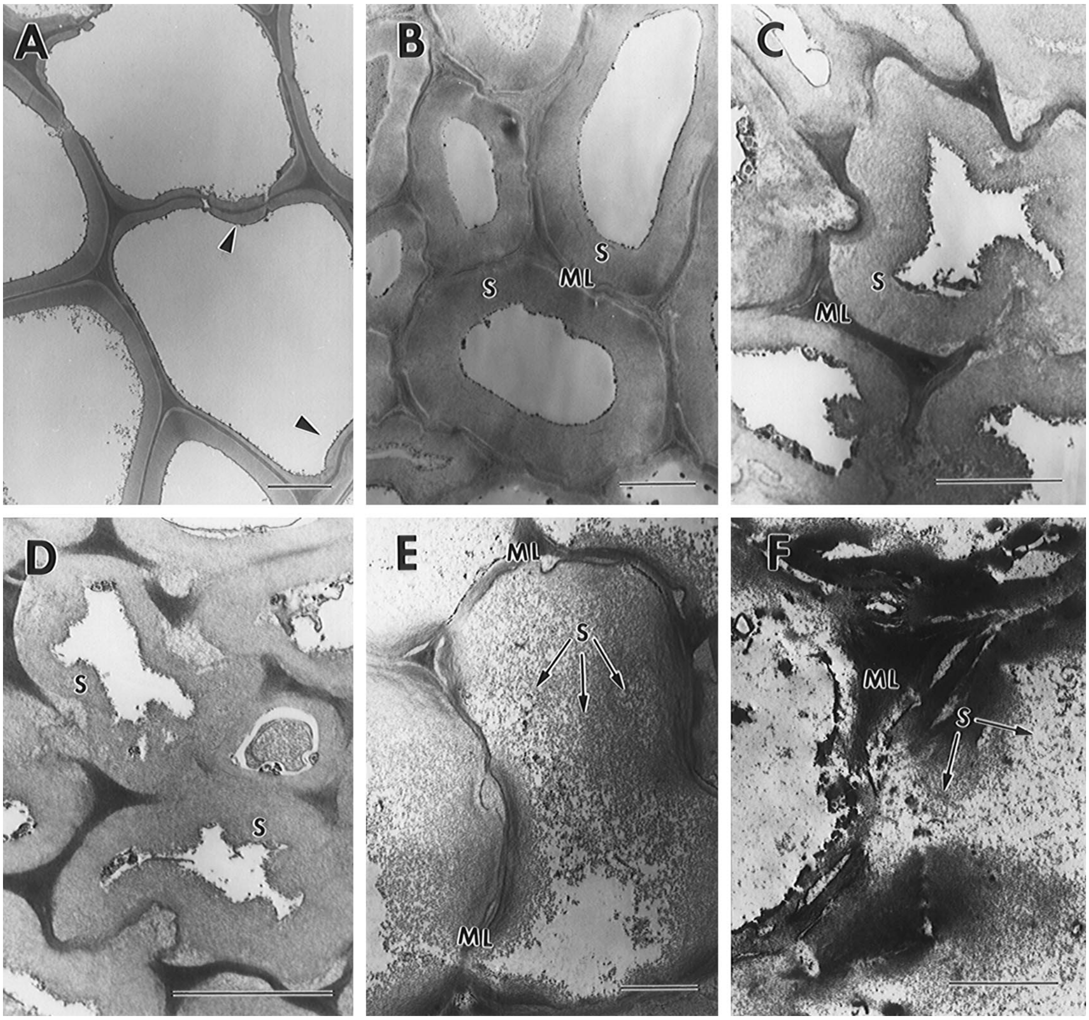

Fig. 9. Brown-rot in wood from ancient Egyptian objects. (A and B) Early stages of decay showing cells with little integrity (arrowheads) and cell walls exhibiting a swollen appearance. (C–F) Disruption of cell walls with advanced decay. The secondary wall (S) consists of granular material that disrupts and disintegrates into minute particles. ML = middle lamellae. A toilet box, AD 100–200, MFA 02.813; B couch frame, 3100–3890 BC, MMA 12.187.52; C and D statues, 2340 BC, MMA 26.2.5 and 26.2.4; E coffin, 1962–1786, MMA 32.1.133; F coffin, 664–525 BC, MFA 29.1860. TEM. Bar = 5 μm.

been restored demonstrating the extraordinary features of this ancient furniture (Simpson and Payton, 1986).

5.1.3. Wood from ancient great houses in Chaco Canyon, New Mexico

The Chaco Canyon region of New Mexico in the southwestern United States contains numerous ancient Anasazi sites of historical and cultural importance. Architectural structures, dating to AD 850–1120, are part of the Chaco Culture National Historical Park and have been designated a World Heritage Site. Great houses at Chaco Canyon, such as Pueblo Bonito and Chetro Ketl are massive structures that contained large amounts of wood. It has been estimated that within Chetro Ketl alone, over 20,000 trees were used for beams, roofing materials, lintels, etc. (Lekson, 1983). The wood remaining in the archaeological ruins of Chaco Canyon have been exposed to the environment for varying lengths of time since the Anasazi culture ended in the 12th to 13th century. The region is arid and annual precipitation averages about 21 cm (Lekson et al., 1988).

Samples of wood examined from structural timbers of Pueblo Bontio, Chetro Ketl and other dwellings showed considerable surface weathering of the wood and zones of fungal decay. Some pine, and Douglas-fir wood used in construction of the great houses often had localized areas of decay and in some *Populus* woods extensive decay was evident. Decay patterns observed repeatedly in these different samples were caused by soft-rot fungi (Fig. 12). This is another example where arid conditions and alkaline soil environments (soil pH is approximately pH 8) have restricted many decay causing organisms but a slow,

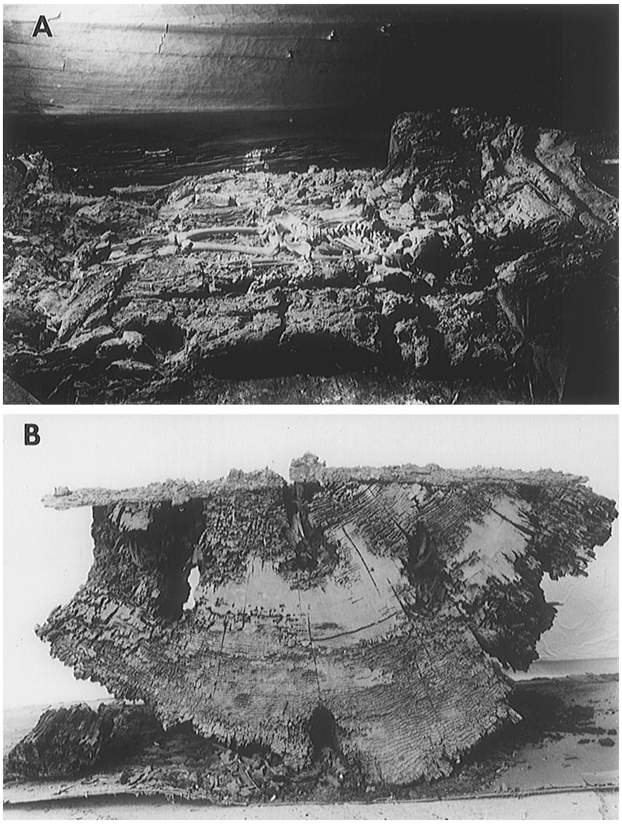

Fig. 10. Deteriorated remains of an ancient coffin, 700 BC from Tumulus MM at Gordion, Turkey: (A) Massive coffin showing skeleton of the king as found when the tomb was opened. (B) Ledge of the coffin as viewed from the interior showing extensive decay. Adapted from Blanchette and Simpson (1992).

persistent soft-rot attack was found in all exposed woods. Most advanced stages of decay were found in locations where the wood was exposed to the environment. Woods well protected from moisture, such as the roofs of the inner rooms in great houses, are relatively free of decay and remain in good condition. In situations such as these Chaco Canyon sites, ancient woods exposed to moisture, even intermittent small amounts, will slowly deteriorate by the progressive actions of soft-rot fungi. This degradation may take many years to cause appreciable losses but will undoubtedly have significant impact on the long-term survival of the wood. To prevent decay in wood from excavated sites, protection from moisture, even small amounts, is essential. This may require installation of protective shelters or possibly reburial so that conditions exclude moisture from contacting the wood.

5.2. Aquatic environments and waterlogged archaeological woods

Waterlogged archaeological wood has unique properties that require special consideration for successful conservation and preservation. If ancient wood is removed from wet environments and allowed to dry, the wood may shrink, fragment and collapse into small pieces. An example of the destruction that can occur when waterlogged wood is air-dried can be seen in Fig. 13 showing a waterlogged canoe after drying. The intact wet canoe shattered and was destroyed during the drying process (Purdy, 1991). This demonstrates how waterlogged woods, altered by deterioration, will remain intact as long as a wet environment is maintained and physical disruption is limited. However, drying, no matter how slow, can have serious consequences. Preservation of woody materials from archaeological wet sites requires special considerations and treatments to avoid irreversible destruction (Hoffmann and Blanchette, 1997; Macleod, 1987; Purdy, 1991). Morphological and chemical analyses of ancient waterlogged woods have demonstrated that bacterial attack is primarily responsible for depleting wood carbohydrates leaving a porous and unstable woody cell wall structure consisting mainly of residual lignin (Blanchette, 1995; Blanchette and Hoffmann, 1994; Blanchette et al., 1991; Donaldson and Singh, 1990; Hedges, 1990; Hedges et al., 1985; Iiyama et al., 1988; Kim, 1990).

5.2.1. Wet buried wood from the Goldcliff prehistoric site

Goldcliff is an intertidal site with buried, wet wood from structures and trackways that date to 200–100 BC (Fig. 13) (Bell, 1993). Wood from the Goldcliff site has been identified as *Acer*, *Alnus*, *Betula*, *Salix* and other hardwoods (Johnson, 1993). Micromorphological observations of wood samples from the site indicated a variety of degradation stages were present. In some cells with moderate amounts of decay, bacteria were observed and degradation patterns characteristic of tunneling and erosion bacteria were evident (Fig. 14).

The decay produced by bacteria disrupts the secondary walls and removes extensive amounts of cellulose. As minute tunnels form and the adjacent cell wall material is depleted of carbohydrates, a loose mass of nondecomposed wall material, consisting of modified lignin, remains (Fig. 14). If undisturbed, this mass of degraded tissue will stay intact and water fills the porous, sponge-like cell wall material. Since cell wall integrity has been compromised by the depolymerization and degradation of cellulose, the remaining cells have very poor strength properties in comparison to sound wood. Disruption of the wall residues within the cells occurs as physical and chemical changes, brought about by the action of tides, accumulation of salts or other factors, takes place. Often wood that is waterlogged will not have distinct patterns of bacterial attack clearly evident. Instead the disorganized, highly lignified decayed cell walls are all that may be observed (Fig. 14). Since this wood lacks binding strength, even the physical changes brought about by drying causes drastic changes in cell walls. Fragmentation and total disruption of the wood results.

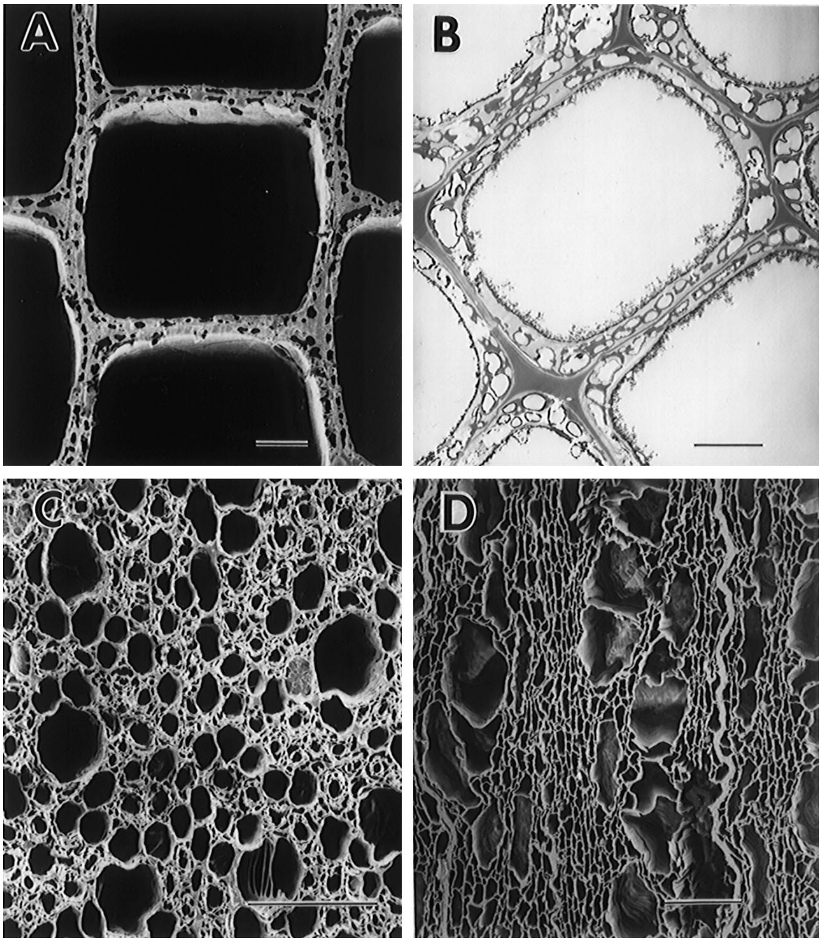

Fig. 11. Soft-rot in the coffin, furniture and wooden tomb structure of Tumulus MM, Gordion, Turkey. (A and B) Type I attack showing distinct cavities within the cell wall. An advanced stage of decay is present with numerous cavities throughout the tracheid walls. (C) A combination of Types I and II attack in boxwood from the tomb furniture. Soft-rot cavities and cell wall erosion are evident. (D) Type II attack in a sample from the top of a walnut table showing erosion of the cell walls with only middle lamellae remaining. A, C and D SEM. B TEM. Bar = 10 μm in A and B, 50 μm in C and D.

5.2.2. *Wood from the Uluburun Shipwreck*

Waterlogged woods from shipwrecks have posed serious problems for conservators interested in preserving these unique structures. The example presented here is wood from the hull of the Uluburun shipwreck, a late Bronze Age ship that sunk off the Turkish coast approximately 1400 BC (Fig. 13). Thousands of artifacts representing many different cultures were recovered as well as parts of the wooden hull and several logs carried as cargo on the ship (Pulak, 1988, 1993). Wood samples from the ships hull revealed the presence of bacterial degradation in all sections examined (Fig. 14). Minute holes were visible within the woody cell walls. These bacterial tunnels were present within the secondary wall as well as parts of the middle lamellae. In many regions, the extensively degraded wood had little integrity and cells were often collapsed (Fig. 14). Although the middle lamellae remained within these woods, this thin, lignified framework did not provide much strength to the decayed cell wall and an exceedingly weak matrix of cells was left. In addition to tunneling bacteria, patterns of decay caused by erosion bacteria were also observed (Fig. 14).

The waterlogged wood environment appears to provide conditions that promote bacterial degradation of wood. Other recent investigations of waterlogged ancient woods have also reported bacteria to be the main cause for the observed decay (Bjordal et al., 1999; Blanchette, 1995; Kim et al., 1996). The limiting factor for decay in saturated environments is the availability of oxygen. In wood from the Uluburun shipwreck, the extensive amount of bacterial degradation throughout the wood indicates that degradation had occurred for long periods after the ship had sunk. Sections of the hull that were protected by the heavy cargo and deep burial in sediments survived for several thousand years. Since decay patterns in woods that were waterlogged for only a few hundred years may have similar amounts of bacterial decay as found in the Uluburun (Bjordal et al., 1999; Blanchette and Hoffmann, 1994), environmental factors at the site and conditions of burial appear responsible for protecting the wood from disinte-

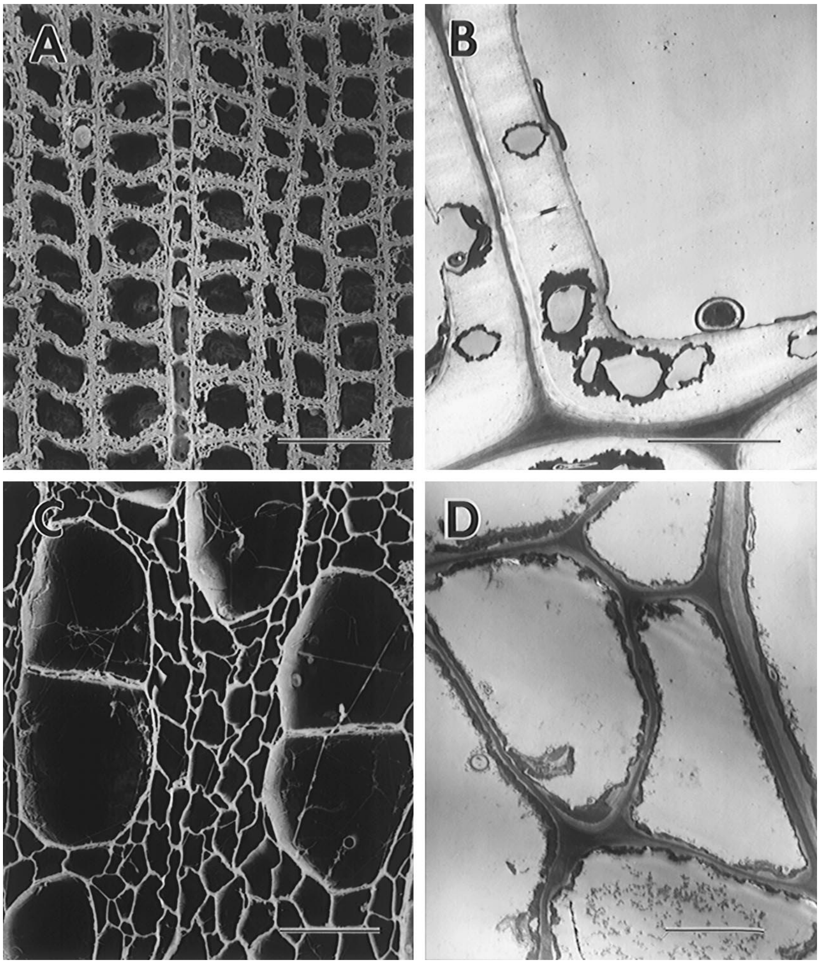

Fig. 12. Degradation in wood from construction timbers in great houses at Chaco Canyon, New Mexico. (A and B) Type I form of soft-rot attack showing cavities within tracheid cell walls in wood used as beams in the Pueblo structures. (C and D) Hardwood samples showing a Type II attack of vessels and fibers. Secondary walls were eroded leaving the middle lamellae. A and C SEM, B and D TEM. Bar = 50 μm in A and C, 5 μm in B and C.

gration. In addition, the depletion of oxygen in the buried waterlogged woods and establishment of anaerobic conditions could also have influenced the duration of bacterial attack and limited the progression of degradation.

Erosion bacteria have been reported to be among the most common types of bacterial degraders where wood has been exposed to oxygen limiting environments (Bjordal et al., 1999; Blanchette et al., 1990; Kim et al., 1996; Singh and Butcher, 1991; Singh et al., 1990). Evidence of tunneling bacteria present in the Uluburun shipwreck indicates that sufficient oxygen was available for this type of bacteria to become established. In a recent study, tunneling bacteria have been found to be most concentrated on surface layers of waterlogged woods and not associated with the inner wood where less oxygen was available (Bjordal et al., 1999). Further information is needed to understand more completely how these different forms of bacteria can degrade wood under these unusual conditions and to determine the associated chemical and physical changes that occur in decayed wood when waterlogged conditions are present for hundreds and even thousands of years. An important aspect that needs consideration is the potential reactivation of extant bacteria and continuation of bacterial attack when excavated wood is exposed to greater concentrations of oxygen. The threat of colonization and decay by new populations of bacteria in archaeological wood that is left exposed, reburied at the site or when moved to holding tanks is also of great concern and needs to be evaluated.

6. Conclusions

The examples presented here show an array of different biological forms of degradation in archaeological woods recovered from different environments. The environment dictates the type and extent of decay that will take place. Each type of decay, (white-rot, brown-rot, soft-rot or various forms of bacterial degradation) have unique degradation patterns that display distinct morphological

Fig. 13. Degradation in waterlogged archaeological woods. (A) A waterlogged canoe excavated from Florida wetlands after drying. The canoe collapsed and fragmented during drying and was totally destroyed (courtesy of B. Purdy, Adapted from Purdy (1991)). (B) Wood from the Uluburun shipwreck at the excavation site off the coast of Turkey (photo courtesy of C. Pulak). (C) Buried wet wood from the Goldcliff intertidal site, Wales (photo courtesy of J. Bell).

and chemical characteristics. Knowledge of these specific decay signatures provides important information about the organic substrate that is needed to understand the condition of the wood and to plan appropriate conservation methods. The degradation processes most prevalent in archaeological wood (i.e., soft-rot of wood from terrestrial sites and bacterial degradation of waterlogged woods) have not been adequately studied and only limited information is available. Additional investigations on these decay processes are needed to define conditions required for decay, to determine the rate of decay in various environments and identity what biological processes accelerate when wood is excavated, reburied or exposed to different conditions. Information on the unique features associated with different types of decayed wood are also important to plan appropriate conservation procedures, and to select or develop specific consolidation procedures or other treatments for each decay situation.

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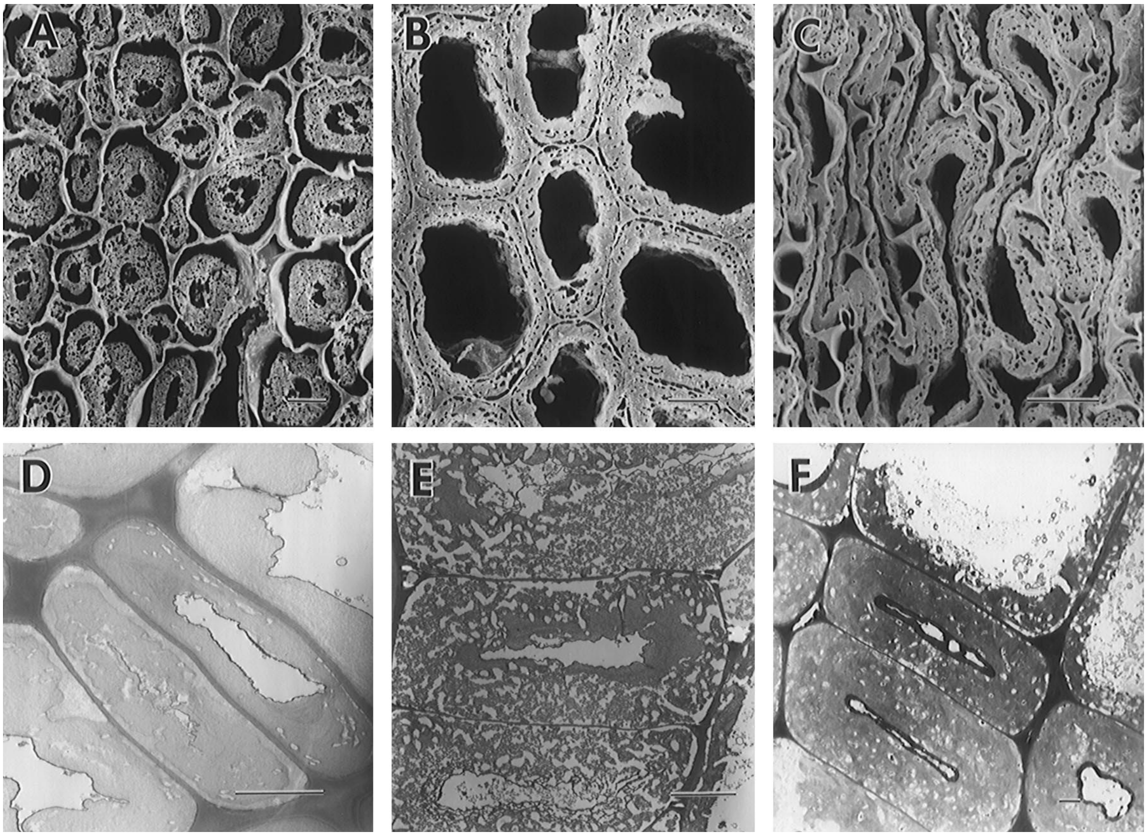

Fig. 14. Bacterial degradation in wood from the Uluburun shipwreck off the coast of Turkey (1400 BC) (A–C) and the Goldcliff intertidal site, Wales (200–100 BC) (D–F). (A and B) The secondary walls are altered extensively. The residual cell walls are porous and contain minute holes. (C) The decayed wood has lost normal wood strength properties and easily collapses and becomes distorted. (D) Tunnels formed by bacteria are evident within the secondary walls of cells. (E and F) Cells with advanced decay have extensive degradation and remnants of tunnels can be seen within secondary walls. The degraded secondary wall often consists of a residual, degraded wall matrix that is often disrupted and in various stages of disintegration. A–C SEM, D–F TEM. Bar = 100 μm in A–C, and 5 μm in D–F.

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