

13. Fossilization, permineralization, coalification, carbonization and wet wood conservation

13.1 Fossilization

When remains or traces of organisms are preserved in sediments they are called fossils. The process of fossilization (syn. petrification or permineralization) begins when organisms, e.g. stems, are buried and remain in anaerobic conditions. Most petrified stems are therefore in a horizontal position. Many fossil stems were probably driftwood that was buried by fluvial sediments. Stems in upright position were more likely embedded in volcanic ashes. When supersaturated groundwater penetrates the wood, the minerals precipitate within cellular spaces and crystallize. Most frequent are calcium carbonate (CaCO_3) or silicate minerals (SiO_2). Fossilization occurs mainly in association with marine or volcanic hydrothermal water. Characteristic for fossils is the conservation of microscopic structures that can be observed on polished disks or on micro-sections. Observations on fossilized wood leads to four principal findings:

- Taxonomic classifications are still possible on well-preserved fossils.
- Assemblages of fossils (petrified wood and pollen) in stratigraphically uniform layers allow a limited reconstruction of past vegetation types.

- Conclusions about the seasonality of past climates are possible on the basis of the presence or absence of growth rings. Banded agates can resemble growth rings in petrified wood, but they represent periodic mineral deposits, e.g. in stalactites.
- Diagenetic processes (alteration during fossilization) can be reconstructed on the basis of the preservation of tissue and cell-wall structure, and the crystalline composition of minerals. Hyphae, barrier zones and coprolites indicate a decay under aerobic conditions, while cell-wall degradation, cell deformation and root inclusions indicate decay under anaerobic conditions before petrification. Different colors on polished discs are related to different minerals, e.g. red is related to iron, blue and transparent to silicate, green to copper and pink to manganese. Mineral composition can be quantified on a microscopic section under polarized light.

See also Taylor *et al.* 2009 and Selmeier 2015.



13.1 Stem disc of a Triassic *Araucarioxylon* stem from a petrified forest in Arizona, USA.

Geological context of petrified wood



13.2 Eroded petrified stems from fluvial sediments of the Upper Triassic, approx. 200 million years ago, Petrified Forest, Arizona, USA. Photo: V. Markgraf.



13.3 Broken and dislocated petrified stems from fluvial sediments. Upper Triassic, approx. 200 million years ago, Petrified Forest, Arizona, USA. Photo: V. Markgraf.



13.4 Reconstruction of the *Araucaria* forest at the Chinle Formation (Trias). Display at the Visitor Center of the Petrified Forest.



13.5 Modern *Araucaria araucana* forest in Patagonia, Chile.

Macroscopic aspect of polished disks



13.6 *Quercoxylon* sp. with distinct annual rings. Miocene, approx. 20 million years ago, Great Basin, Idaho, USA.



13.7 Conifer with indistinct annual rings. Miocene, approx. 20 million years ago, Great Basin, Idaho, USA.



13.8 *Palmoxylon* sp., of unknown age and locality, with distinct vascular bundles.



13.9 Petrified liana of unknown age and locality.

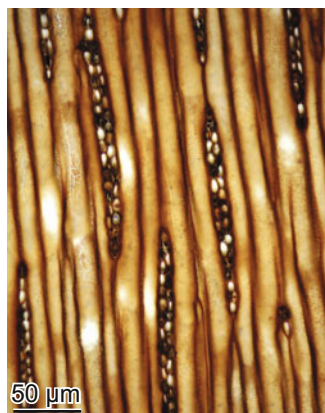
Taxonomic classification of petrified wood



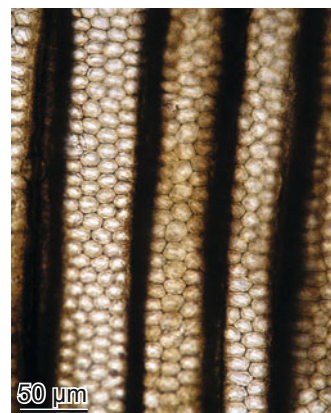
13.10 *Rhynia gwynne-vaughanii*, a herb with a central stele. Lower Devonian, approx. 400 million years ago, Scotland.



13.11 Cross section of *Paradoxylon leuthardii*, one of the Cordaitales without annual rings. Upper Triassic, approx. 220 million years ago, Vosges Mountains, France. Slide: R. Buxtorf.



13.12 Tangential section of *Paradoxylon leuthardii* with biseriate rays. Upper Triassic, approx. 220 million years ago, Vosges Mountains, France. Slide: R. Buxtorf.

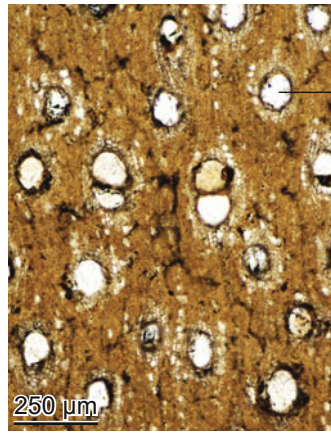


13.13 Radial section of *Paradoxylon leuthardii* with multiseriate bordered pits on tracheids. Upper Triassic, approx. 220 million years ago, Vosges Mountains, France. Slide: R. Buxtorf.

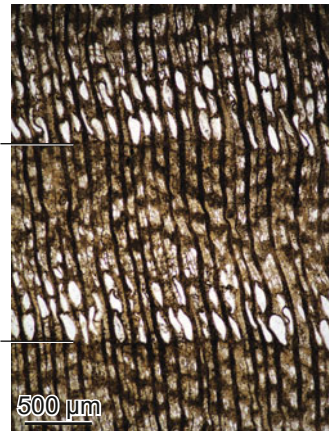
Taxonomic classification of petrified wood



13.14 *Sequoia* sp. with distinct and indistinct rings. Early Oligocene, approx. 34 million years ago, Florissant, Colorado, USA.



13.15 Mimosoideae, Fabaceae, without annual rings, with para-tracheal parenchyma. Oligocene, approx. 28 million years ago, Vosges Mountains, France. Slide: R. Buxtorf.



13.16 *Celtixylon* cf., Ulmaceae, with distinct annual rings. Oligocene, approx. 28 million years ago, Vosges Mountains, France. Slide: R. Buxtorf.



13.17 *Palmoxydon*, Arecaceae, with distinct lignified parts of vascular bundles. Oligocene, approx. 28 million years ago, Vosges Mountains, France. Slide: R. Buxtorf.

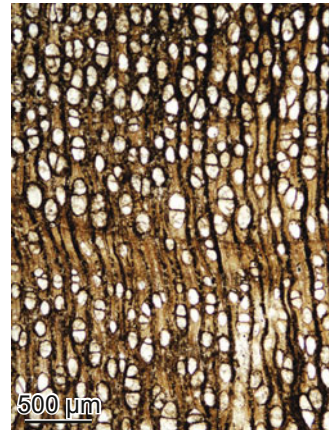
Growth rings in petrified wood



13.18 Cross section of *Paradoxydon leuthardii*, without growth rings, indicating tropical rain forest as habitat? Upper Triassic, approx. 220 million years ago, Vosges Mountains, France. Slide: R. Buxtorf.



13.19 Cross section of *Paradoxydon leuthardii*, with growth rings, indicating seasonal climate. Upper Triassic, approx. 220 million years ago, Vosges Mountains, France. Slide: R. Buxtorf.



13.20 Lauraceae cf. with growth rings, seasonal climate. Oligocene, approx. 28 million years ago, Vosges Mountains, France. Slide: R. Buxtorf.

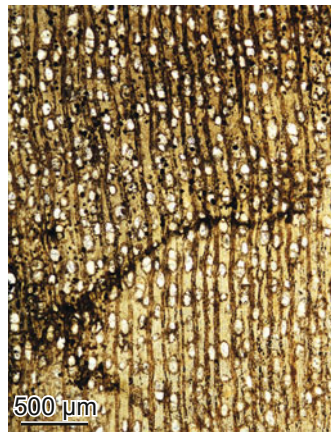


13.21 Growth rings in a petrified, ring-porous oak stem in Miocene deposits, approx. 15 million years ago, Oregon, USA.

Indicators of aerobic decay before petrification



13.22 Barrier zones in a petrified stem of a eucalypt tree. Australia, age unknown.



13.23 Barrier zones in a stem of a Lauraceae cf. tree. Oligocene, approx. 28 million years ago, Vosges Mountains, France. Slide: R. Buxtorf.

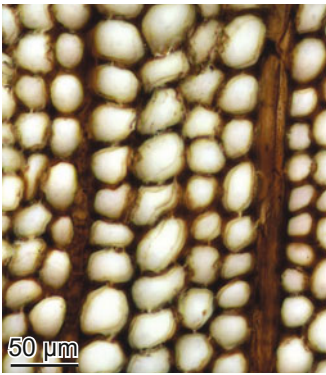


13.24 Hyphae in a vessel of a Meliaceae tree. Reprinted from Selmeier 2015.

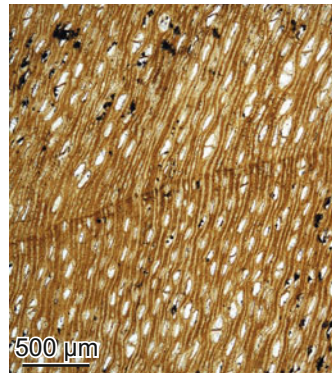


13.25 Coprolites of a beetle in a Lauraceae tree. Reprinted from Selmeier 2015.

Indicators of anaerobic decay before petrification



13.26 Decayed cell walls in *Paradoxylon leuthardii*. Preserved are the thick primary walls and thin tertiary walls. Slide: R. Buxtorf.



13.27 Radially compressed dicotyledonous wood. Slide: R. Buxtorf.

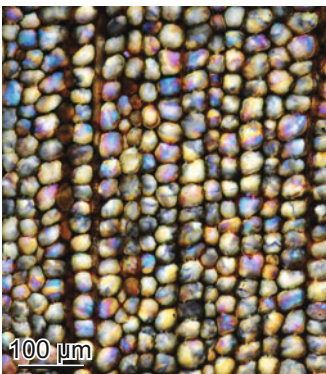


13.28 Heavily tangentially compressed wood of *Paradoxylon leuthardii*. Slide: R. Buxtorf.

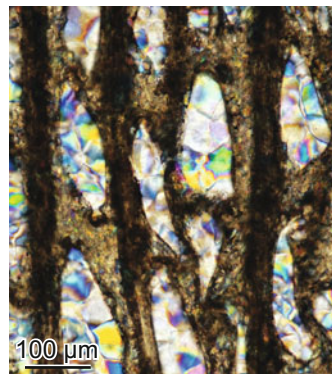


13.29 The root of a herb squeezed the soft, anaerobically decayed xylem tissue. Reprinted from Selmeier 2015.

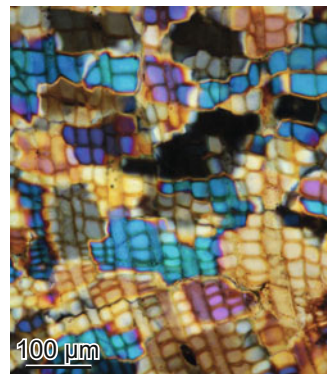
Permineralization under polarized light



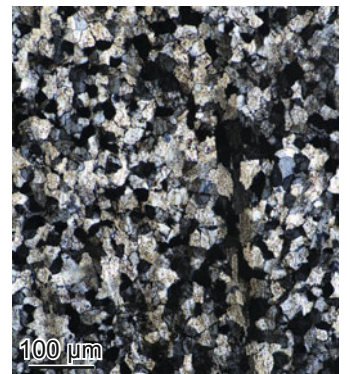
13.30 Single crystals in individual tracheids in *Paradoxylon leuthardii*. Slide: R. Buxtorf.



13.31 Many crystals in large early-wood vessels in Ulmaceae wood. Slide: R. Buxtorf.



13.32 Irregular crystallization of silicates without any wood anatomical context in Ulmaceae wood. Slide: R. Buxtorf.



13.33 Crystallization of different minerals relating to groups of tracheids in *Paradoxylon leuthardii*. Slide: R. Buxtorf.

13.2 Permineralization of archaeological artifacts

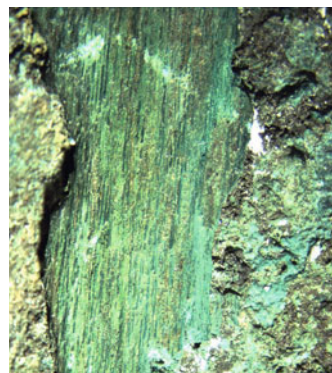
Permineralization also takes place on metallic archaeological artifacts. The scabbards and handles of iron swords, bronze daggers and axes often contain small mineralized remains of wood. Transverse and longitudinal breaks of particles clearly show the

anatomical structure. Species identification is therefore possible. If highly concentrated liquids of iron, copper or sulfur soak the wood, minerals precipitate on cell walls and preserve their structure.

Permineralization of archaeological artifacts



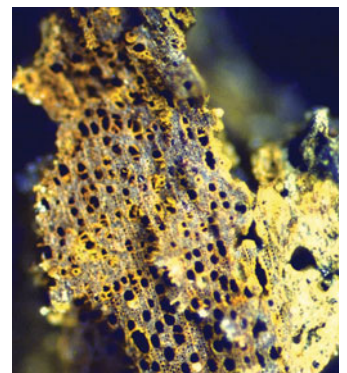
13.34 Wooden scabbard permineralized by dissolved iron. Photo: W. Tegel.



13.35 Wooden scabbard permineralized by dissolved copper. Photo: W. Tegel.



13.36 Microscopic structure of archaeological *Quercus* sp. wood, permineralized by iron. Photo: W. Tegel.



13.37 Microscopic structure of archaeological *Alnus* sp. wood, permineralized by sulfur. Photo: W. Tegel.

13.3 Coalification

Coalification is a very slow process in which wood is transformed into coal at geological time scales. The anaerobic decay of organic substances is the first stage of coalification (see Chapter 12.2). The ratio of carbon increases during anaerobic decay processes, and the wood loses its stability. The process starts with soft wood, which under high pressure and high temperatures turns into brown coal, bituminous coal and finally anthracite. An increase in carbon content defines these grades—wood contains 50%, brown coal 70% and anthracite 90% carbon. When softened logs come under mechanical pressure by sediments or ice, the thin-walled earlywood cells collapse, and the stems get deformed. Early stages of coalification are known from stems in medieval glacier deposits and late glacial clays (subfossil wood).

Remnants of wood (xylite, lignite) with well-preserved structures are frequently found in brown coal layers (Eocene to Oligocene). Genera or even species can be identified as long as the early-wood zones are not too much distorted (Dolezych 2005).

Tertiary wood is often so well preserved that even stages of cell wall decay can be recognized. However, in most cases the early-wood zones are compressed, and the corresponding ray features are difficult to observe (Dolezych 2005).

Fossil tree stump



13.38 Stumps from a brown coal bed. Photo: Elbwestfale 2003, via Wikimedia Commons, CC BY-SA 3.0.

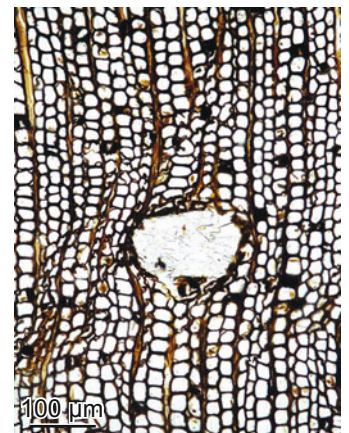
Taxonomically and climatologically relevant features in cross sections of conifers



13.39 Conifer *Taxodium taxodii* cf. without growth zones. Oligocene, approx. 34–23 million years ago. Material: M. Dolezych.

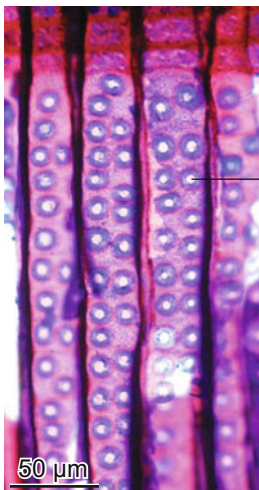


13.40 Conifer *Sciadopityoxylon wettsteinii* without resin ducts and distinct earlywood and latewood zones. Miocene, approx. 25–5 million years ago. Material: M. Dolezych.

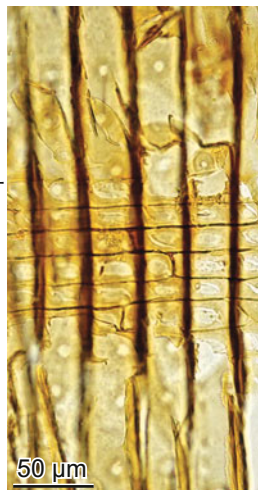


13.41 Conifer *Doliostroboxylon priscum* with resin ducts. Eocene, approx. 56–38 million years ago. Material: M. Dolezych.

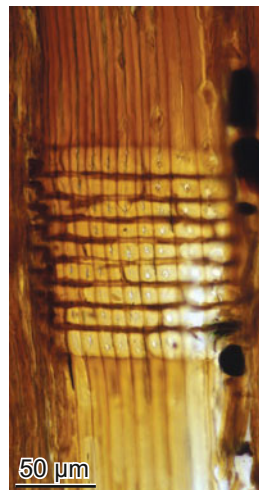
Taxonomically relevant features in radial and tangential sections of conifers



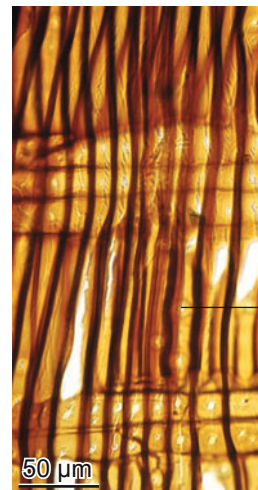
13.42 Conifer *Larix decidua* with biseriate tracheid pits. Interglacial period, Italian Alps, >50,000 years ago.



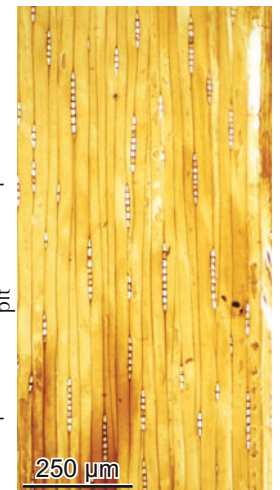
13.43 Fenestrate vessel-ray pits in the earlywood of *Sciadopityoxylon wettsteinii*. Miocene, approx. 25–5 million years ago. Material: M. Dolezych.



13.44 Small round pits in the latewood of *Taxodium gypsacum*. Miocene, approx. 25–5 million years ago. Material: M. Dolezych.

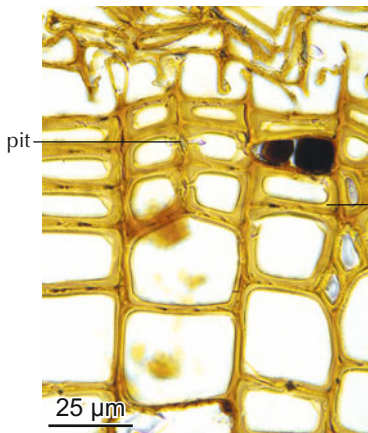


13.45 Large round pits in the early- and latewood of *Doliostroboxylon priscum*. Eocene, approx. 56–38 million years ago. Material: M. Dolezych.

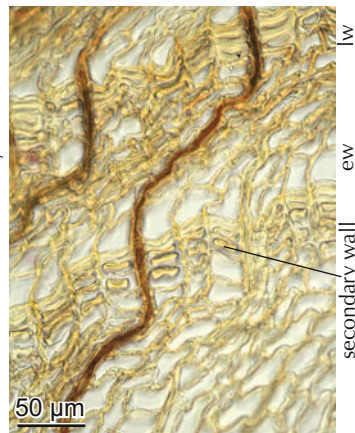


13.46 Uniseriate rays with three to ten cells in *Taxodium gypsacum*. Miocene, approx. 25–5 million years ago. Material: M. Dolezych.

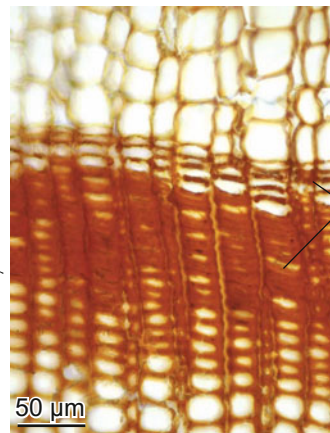
Cell wall decay in latewood



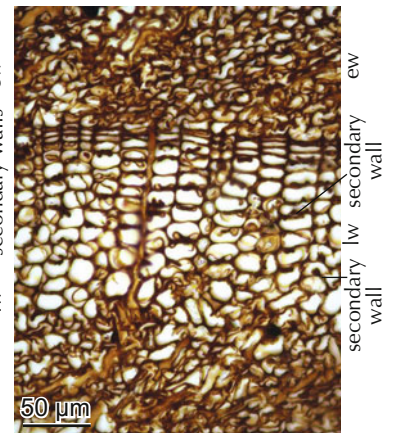
13.47 Perfectly preserved cell walls in latewood tracheids of *Glyptostroboxylon rudolfii*. Middle Miocene, approx. 15 million years ago. Material: M. Dolezych.



13.48 Anaerobically decayed cell walls in latewood tracheids of *Larix decidua* from the moraine of an alpine glacier. Middle Ages, approx. 1400 AD. Material: M. Dolezych.

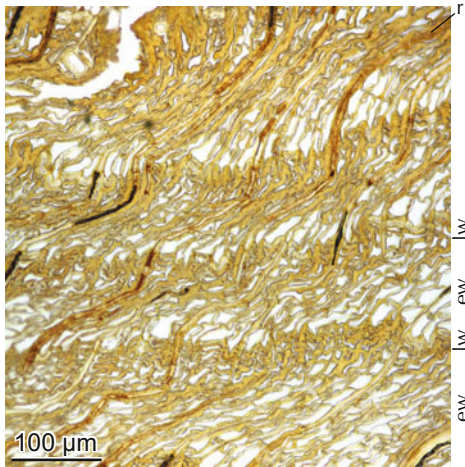


13.49 Various stages of anaerobic decay in the latewood zone of *Sciadopityoxylon wettsteinii*. Miocene, approx. 15 million years ago. Material: M. Dolezych.



13.50 Primary and tertiary cell walls are preserved, secondary walls are completely decayed in latewood tracheids of *Taxodium taxodii* cf. *Oligocene*, approx. 34–23 million years ago. Material: M. Dolezych.

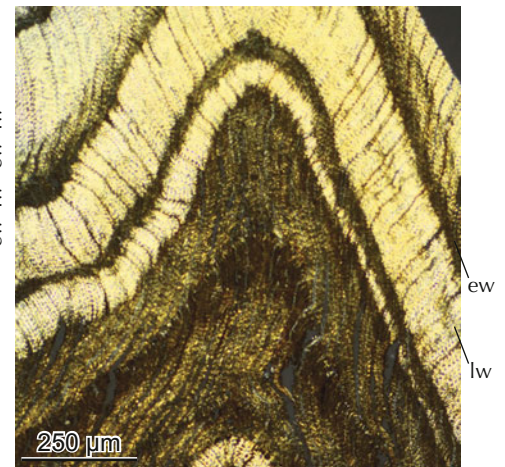
Mechanical deformation of cells



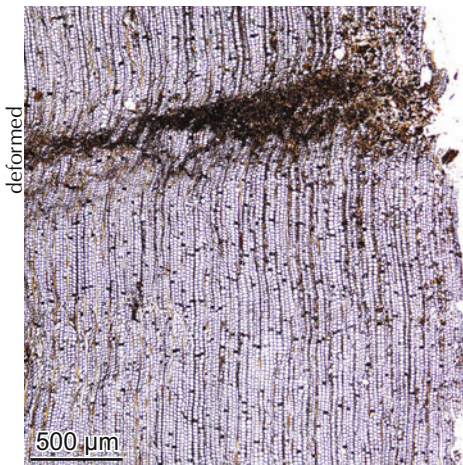
13.51 Wood of *Larix decidua*, heavily radially compressed by a glacier. Moraine of an alpine glacier, Middle Ages, approx. 1400 AD.



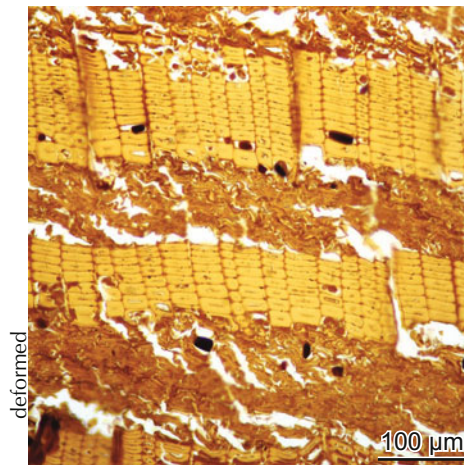
13.52 Radial compression is indicated by bent rays in wood of *Larix decidua*. Interglacial period, Italian Alps, >50,000 years ago. Slide stained with Astrablue/Safranin.



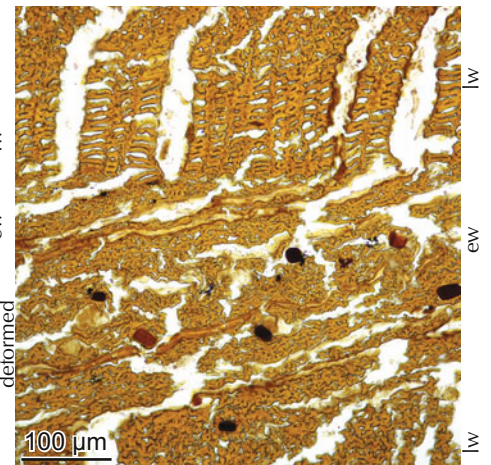
13.53 Compression in a branch of *Abies alba* cf., polarized light. Interglacial period, Switzerland, approx. 45,000 years ago.



13.54 Compression of two weak zones in ringless wood of the conifer *Doliostroboxylon priscum*. Eocene, approx. 56–37 million years ago. Material: M. Dolezych.



13.55 Intensively compressed earlywood zones between thick-walled latewood zones in *Taxodium gypsacum*. Miocene, approx. 15 million years ago. Material: M. Dolezych.



13.56 Intensively compressed earlywood and latewood zones in *Sequoiadendroxylon* sp. Czech Republic, middle Miocene, approx. 15 million years ago.

13.4 Carbonization

Carbonization is the process of transforming wood into charcoal by pyrolysis. Charcoal used to be one of the most important energy resources in pre-industrial times because it was easy to transport. Most human civilizations produced charcoal in kilns, with the wood losing 50–70% of its weight. Charcoal burning and grazing were the main reasons for the depletion of ancient forests all over the world. With the switch to fossil fuels like coal and coal oil, charcoal lost some of its importance. It also used to be important for the production of gun powder (black powder). Today, charcoal is still widely used, e.g. for local metallurgic processes, chemical filtering, barbecues and charcoal crayons.

The carbonization process does not destroy the species-specific anatomical structures of the material. Also, charcoal is very stable against biodegradation in both dry and wet environments. Charcoal is therefore of relevance to historical studies,

as ancient prehistoric fires—changing human behavior and vegetation patterns from the tropics to the arctic—can be documented with the identification of particles as small as a cubic millimeter.

During the carbonization process, cell walls shrink by approx. 50% and also lose their fibrillose structure. However, the structure of pits and perforations, and of artifacts caused during decay before the carbonization process, remain. Longitudinal cracks and tangential cell collapses are a sign of vapor pressure during the heating phase.

Binocular stereomicroscopes and episcopic microscopes facilitate the observations. Thin sections, embedded in two component epoxy resin, are the basis for photographic presentations (see Chapter 2).

Charcoal production

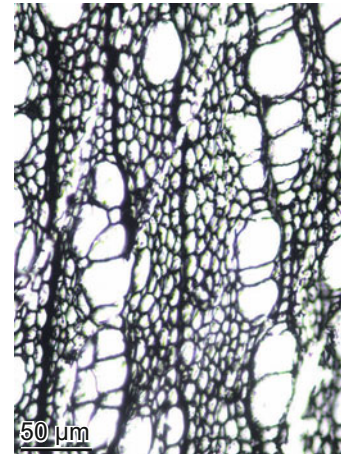


13.57 Establishment of a charcoal kiln in the Black Forest. Photo: T. Lude-mann.

Carbonization artifacts



13.58 Radial cracks in this conifer are caused by vapor pressure during the heating phase.

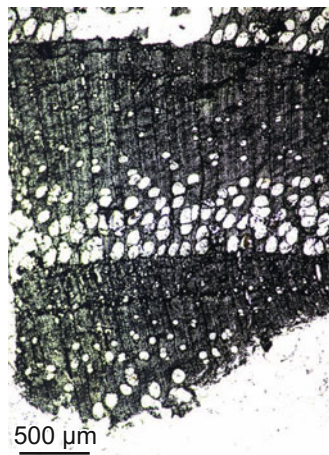


13.59 Thin carbonized cell walls in *Alnus* sp.

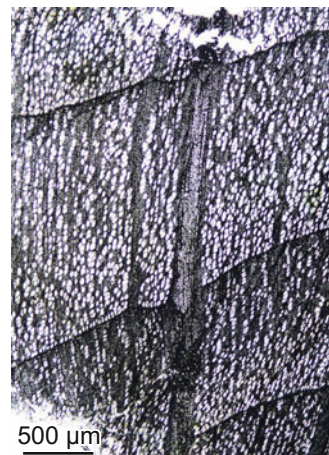
Species identification from anatomical structures preserved in charcoal



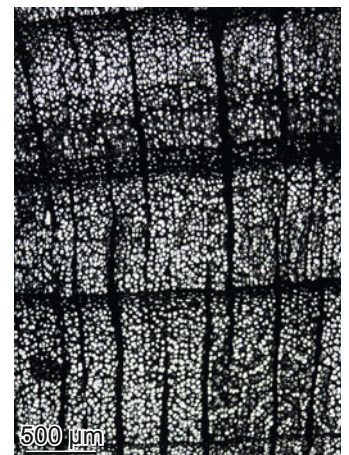
13.60 Conifer with an insect gallery, filled with coprolites.



13.61 Charcoal cross section of *Fraxinus excelsior*.



13.62 Charcoal cross section of *Alnus* sp.



13.63 Charcoal cross section of *Fagus sylvatica*.

13.5 Wet wood conservation

Woods in anoxic sediments can keep their form over millennia. However, decomposition takes place on a cellular level. Alterations become obvious when logs or archaeological artifacts dry out. Radial shrinking and weight loss are macroscopic signs of intensive decomposition, cell collapses are visible on a microscopic level. Despite many deformation artifacts, parts such as roots from plants along lake shores can be identified.

Natural preservation occurs in the heartwood of logs of pines soaked in resin, and of oaks with high levels of phenols. The central parts of stems resist decomposition at the air, but the sapwood decays. The situation is much worse in wood of lake dwellings. Most wooden artifacts are of small dimensions,

and made mostly of wood of deciduous trees. Five-thousand-year-old Neolithic stems of deciduous trees with a diameter of 10 cm lose approximately 50% of their original weight, and shrink radially when dehydrated up to 80%. Therefore a large part of human cultural heritage would be lost without artificial preservation. Archaeologists preserve the form of large artifacts mainly with polyethylene glycol (PEG), e.g. the Swedish warship Vasa. Smaller wooden instruments are preserved by freeze drying or dimethyl ether treatment. The form and superficial traces of human treatment of ancient wet wood can therefore be kept in museums. The cell wall structures of wet wood do survive preservation techniques.

Macroscopic changes on wet wood after dehydration



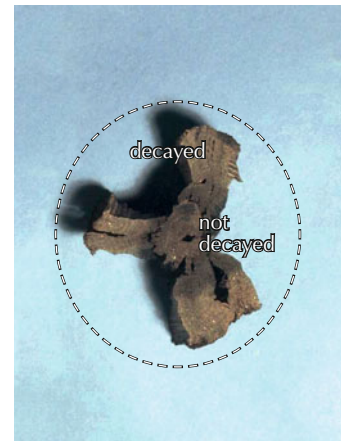
13.64 Late glacial stems of *Pinus sylvestris* that have been exposed to air. The stump surfaces decay and scientific information about the life of those trees is lost.



13.65 Disc of an air-exposed *Pinus sylvestris* stem. The large central part is preserved due to natural impregnation with resin. The peripheral zone without resin decays.

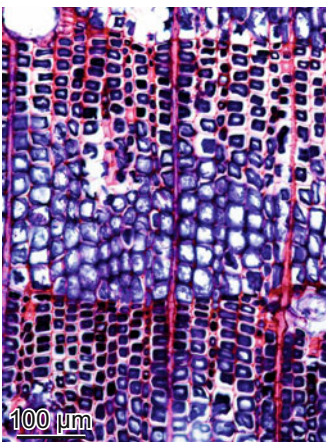


13.66 Disc of a water-saturated archaeological *Quercus* sp. Its form is perfectly preserved.

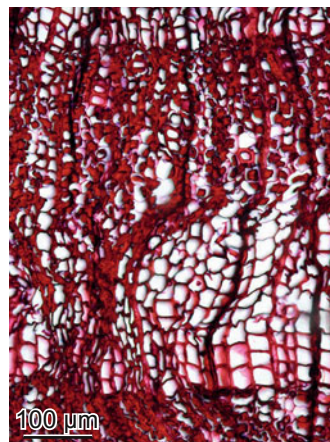


13.67 Disc of the same *Quercus* stem, but dehydrated. Intensively decayed parts shrink dramatically, as indicated by the original outline.

Microscopic changes on wet wood after dehydration



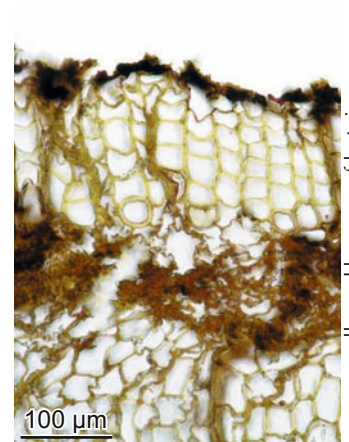
13.68 Not dehydrated, heavily degraded wood of late glacial *Pinus sylvestris*. The cell form and primary cell walls (red) remain. Secondary walls lost their original structure and are delignified (blue).



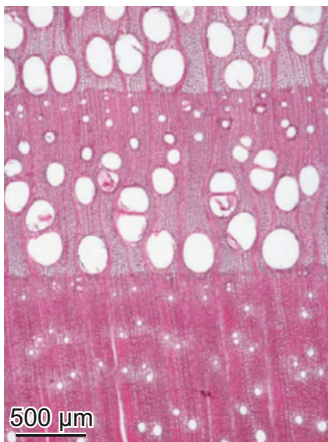
13.69 Dehydrated, heavily degraded wood of late glacial *Pinus sylvestris*. Cells lost their original form due to contraction, and degraded secondary cell walls appear as unstructured bodies.



13.70 Dehydrated, heavily degraded wood of late glacial *Pinus sylvestris*. The cell forms remain, but the secondary walls are gone.



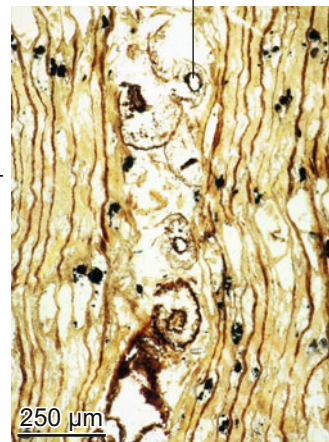
13.71 Dehydrated, heavily degraded wood of *Pinus sylvestris*. Latewood cells are collapsed, earlywood cells of the outer ring kept their form. The tree died during earlywood formation in early summer approx. 13,000 years ago.



13.72 Modern wood of *Fraxinus excelsior*, stained with Safranin. All microscopic structures can be recognized.



13.73 Dehydrated, heavily degraded wood of Neolithic *Fraxinus excelsior*. Lateral contraction deformed the original structure, but major anatomical characteristics for the species remain. collapsed vessels



13.74 Dehydrated, heavily degraded wood of Neolithic *Fraxinus excelsior*. It maintained its anatomical structure despite some lateral deformation by roots from plants of the lake shore. roots collapsed vessels parenchyma cell fiber



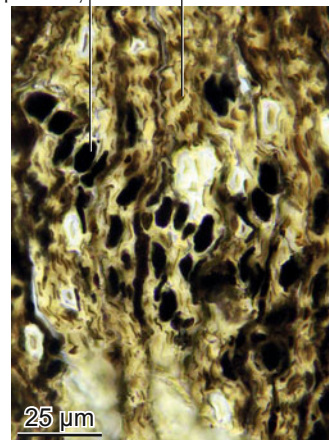
13.75 Dehydrated, heavily degraded wooden artifacts, made from *Fraxinus excelsior*, maintained their original form after conservation treatment by freeze drying.



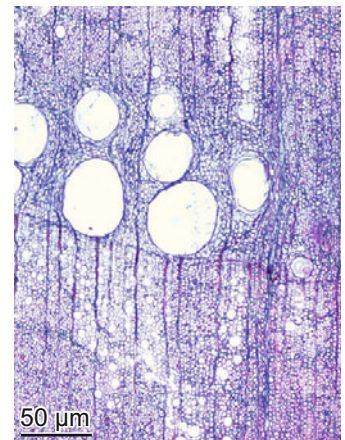
13.76 Modern wood of *Quercus petraea*, stained with Safranin. All microscopic structures can be recognized.



13.77 Dehydrated, heavily degraded wood of Neolithic *Quercus* sp. Lateral contraction deformed the original structure, but major anatomical characteristics for *Quercus* remain e.g. ring porosity, large rays, dark heartwood.



13.78 Dehydrated, heavily degraded wood of Neolithic *Quercus* sp. Alterations due to dehydration are specific to cell types. Fibers are heavily compressed, parenchyma cells with cell contents less so.

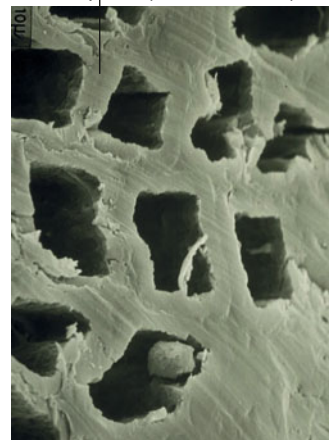


13.79 Well preserved anatomical structure of wood of Neolithic *Quercus* sp. after conservation treatment by freeze drying and polyethylene. Cell walls are decomposed.

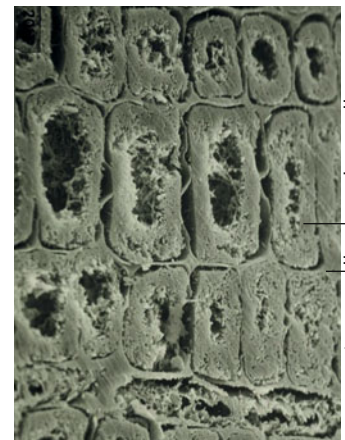
Effect of conservation



13.80 Neolithic wooden bowl conserved with diethyl ether resin.



13.81 Cell walls without structure after freeze drying. Electron-optical photograph. Reprinted from Bräker et al. 1979.



13.82 Partially preserved cell wall structure after diethyl ether treatment. Electron-optical photograph. Reprinted from Bräker et al. 1979.

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