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Microbial degradation of waterlogged archaeological wood

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ABSTRACT

Waterlogged archaeological wood is degraded very slowly compared to wood decay above ground. The special environmental conditions below ground, results in a prolonged decay process that under extremely low oxygen concentration only allow bacterial degradation of wood. The so-called erosion bacteria are described and waterlogged archaeological wood is defined. Soft rot fungi are other microbes that often are found active in more oxygenated aquatic environment. A short historic review on the understanding of waterlogged archaeological wood and the different decay processes is given and exemplified. Knowledge on decay processes is essential for development of conservation methods and in situ preservation of wooden cultural heritage.

1. Research aims

The aim is to understand the structure of waterlogged archaeological wood and the correlation with decay processes in nature by specialized wood degrading fungi and bacteria. The degradation that takes place during hundreds or even thousands of years, decreases the strength properties and changes the micromorphology of the wood cell wall. The understanding of different decay process in various environments is the key for development of efficient in situ preservation methods, which includes shipwrecks in marine environments.

Closer studies on the remaining/degraded cell wall are also required for development of new techniques and methods to stabilize and conserve waterlogged wooden objects of importance for cultural heritage.

2. Introduction

Wood is effectively decomposed by microbial agents. Above ground, in non-waterlogged environment, wood is mainly degraded by aggressive basidiomycete fungi [1]. Wood degrading fungi and bacteria are specialized to degrade lignocellulosic materials (lignin, cellulose, and hemicelluloses) as a part of the carbon cycle in nature. This process is relatively fast; from a few years to a couple of decades. Oxygen, high humidity, and temperature are the main factors that control the process [1].

There are, however, aquatic environments in nature where the degradation of wood takes place at a much slower rate. In these so-called waterlogged environments wood can "survive" an extended time of exposure in nature [2–4].

Archaeological wood is a term used to describe man-made wooden objects and constructions recovered by archaeologists at historical sites. Since the end of the 19th century archaeologists observed that archaeological wood can be found well preserved in different types of waterlogged environments. From peats, lakes, rivers, sea, and other waterlogged environments, unique historical objects of wood have been excavated, documented, and conserved. One example is the Oseberg Viking ship, which was found embedded in waterlogged clay at a land site excavation in Norway year 1902. Another is the warship Vasa, which was raised in 1961 after 333 years in the brackish and cold waters of the Baltic Sea.

Wooden objects from waterlogged environments often look extremely well preserved judged by the naked eye. The physical integrity remains, just as colour, ornamentation, and tool marks [4,5]. This is the situation at the excavation site when the wooden object has just been rescued and is still wet. For archaeologists and conservators there was a sort of contradiction between the well-preserved appearance and the fact that the same piece of wood was indeed very soft and spongy when pressed. Already in year 1857, Herbst from the National museum of Denmark noticed and reported that wooden archaeological finds from peats had to be handled with care and kept wet until it reach the museum [6]. If the wood was allowed to dry out during excavation or transport, it would crack, shrink and disintegrate (Fig. 1a, b). This behaviour has been experienced by archaeologists through time and conservation treatments have therefore continuously been developed in order to stabilise the wood so that damage to the integrity of

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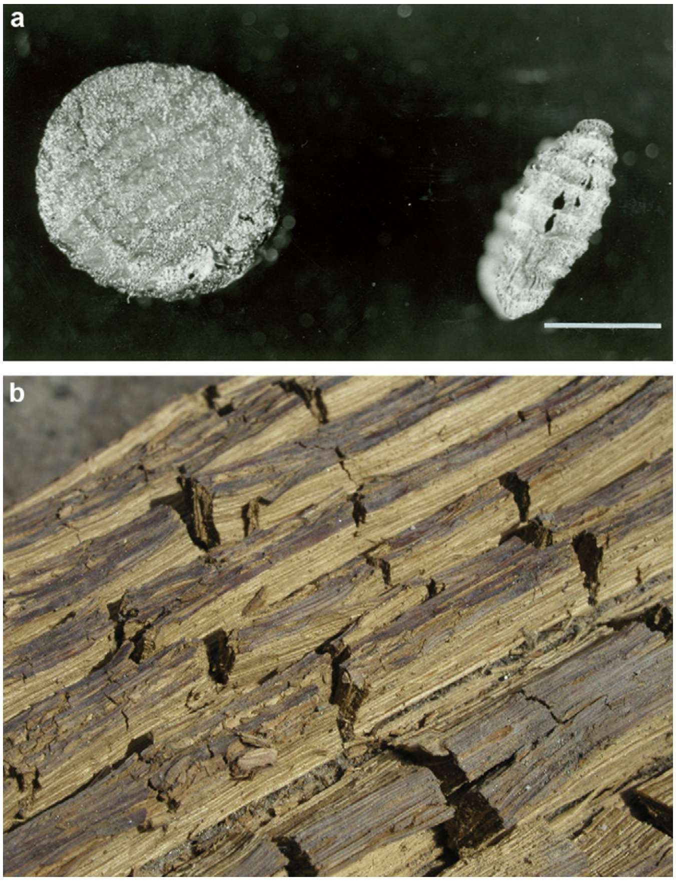

Fig. 1. Waterlogged archaeological wood that are allowed to dry out without conservation treatment, will shrink, twist, collapse and disintegrate: a: shows two discs of same dimensions taken from a heavily degraded lance of ash wood (iron age), observed in wet (left) respective dry (right) condition (bar: 1,3 cm); b: shows a close up of an old foundation pole of pine, where a strong shrinkage of the degraded sapwood results in deep cracks and a total destruction of the surface.

the surface and dimensional changes are minimized upon drying [7,8].

To conclude, waterlogged archaeological wood is a material that looks like wood but behaves very differently.

In order to understand more about this very sensitive and “self-destructive” material, chemical analyses were carried out during the 20th century. They showed that the wood suffered from significant loss of hemicelluloses and celluloses; two of the main components [9–12]. Conclusions were drawn and the main hypothesis among conservators and wood chemists until the 1990s was the general assumption that the wood material was affected by acid hydrolysis during the long-term exposure in a waterlogged environment [13,14]. Meanwhile, in the field of degradation of plant tissue, biologists studied microbial degradation of wood [1]. With help of light microscopy, fungal attack was successfully identified, but occasionally also atypical decay patterns were reported. These came usually from foundation poles situated in a waterlogged environment. In a few reports from the 1940s, 1950s and 1960s, it was suggested that these peculiar degradation patterns could be a result of bacterial attack on the wood cell wall [15–19]. It was not until the 1980s, with help of electron microscopy with a much higher resolution than light microscopy, that it was possible to verify that bacterial degradation in fact was the most dominant type of wood degradation taking place in waterlogged terrestrial and aquatic environments [4,20–23].

A brief overview of the two most common degraders in waterlogged environments, erosion bacteria and soft rot fungi is given in the following text.

3. Erosion bacteria

Today, we know that the so-called erosion bacteria are the main degraders of archaeological wood found under waterlogged near anaerobic conditions. This is based on results from both experimental laboratory work as well as investigations on degraded archaeological wood from various terrestrial and aquatic sites worldwide [3,4,21,24,25]. In contrast to other wood degrading fungi and bacteria, erosion bacteria are able to degrade wood under very low oxygen concentrations which include interior parts of solid wood constructions and wood situated in waterlogged soil, sediments, or waters low in oxygen. The bacteria are rod shaped and 2–8 μm in length and 0.5–0.9 μm in diameter (Fig. 2). Invasion starts from the wood surface through rays and pits, from where the bacteria enter the cell lumen of the tracheids. From here, the bacteria attack and erode the wood cell wall and align themselves along the microfibrils. The bacteria convert the cellulose rich secondary cell wall into an amorphous slimy material, whereas the lignin rich middle lamellae remain seemingly unaffected (Fig. 3). As a result, a coherent network of middle lamellae is still intact despite intense decay by erosion bacteria [26]. This inability to degrade the middle lamellae or one might say incomplete decay, is the reason why archaeological wood still remain its form and integrity in wet condition. Water fills out the degraded cell wall inside each fibre and the fragile middle lamellae provide enough physical strength to maintain the integrity of the wood. But if the wood is allowed to dry out, the capillary forces upon drying are so strong that the wood fibres will collapse and disintegrate.

Erosion bacteria decay develops slowly from surface and inwards until all cellulose rich areas in the wood are utilised. In a Viking pole, 1200 years old, this process was found to be still active in the interior parts [26]. This allowed us to suggest that the process may go on for thousands of years. However, the rate of decay is not just dependent on time of burial. In fact, it has been shown that environmental parameters and wood species may play a just as important role for progression of decay [4,27,28].

The true identity of the erosion bacteria has been very difficult to clarify despite many efforts during the last twenty year. Isolation and cultivation of single species with traditional methods has failed, which is the case for a majority of bacteria in nature. However, in a

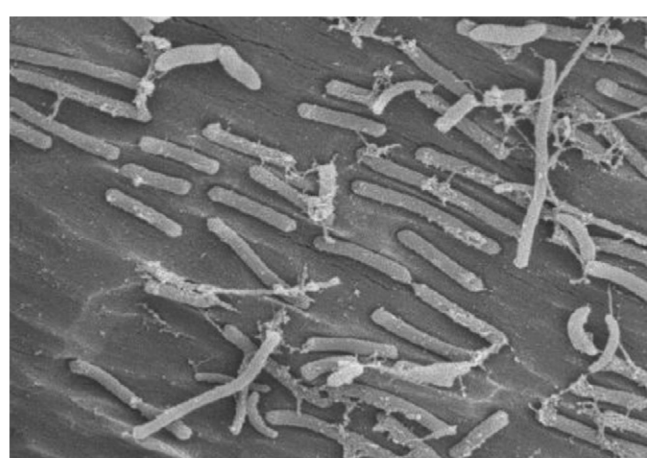

Fig. 2. SEM micrograph showing a group of erosion bacteria aligned in individual troughs degrading the wood cell wall. The length of the bacteria varies between 2–8 μm.