

Burial conditions and wood degradation at archaeological sites in the Netherlands

D.J. Huisman^{a,*}, M.R. Manders^a, E.I. Kretschmar^b, R.K.W.M. Klaassen^c, N. Lamersdorf^b

^a*RACM, National Service for Archaeology, Cultural Landscape and Built Heritage, P.O. Box 1600, 3800 BP Amersfoort, The Netherlands*

^b*Institute for Soils Science and Forest Nutrition, Georg-August-University, Buesgenweg 2, D-37077 Göttingen, Germany*

^c*SHR Timber Research, P.O. Box 497, 6700 AL Wageningen, The Netherlands*

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Abstract

A series of waterlogged archaeological sites in the Netherlands were investigated to examine wood degradation by erosion bacteria. Chemical analyses of soil and water at the sites showed a large variation in burial conditions, reflecting differences in sediment composition, salinity, trophic levels, and past burial conditions. The most constant factor was the generally low redox state. Despite these large differences, degradation by erosion bacteria was found in all wood samples, indicating active degradation in a large number of different environments including reducing ones. The degree of degradation varied markedly, but showed no correlation with the chemical burial environment, although water movement may have had a role to play. As a result of degradation by erosion bacteria, wet wood is damaged easily and is also susceptible to damage and deformation during drying out. Sites where oxygen was available showed evidence of degradation by soft-rot fungi. Moreover, one marine site showed loss of wood strength that may be related to the oxidation of iron sulphides and the associated production of sulphuric acid. In situ protection of wood requires the maintenance or restoration of an oxygen-free burial environment, and decay by erosion bacteria may be slowed by reducing water flow at the site.

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1. Introduction

Wood is one of the most important materials found in archaeological sites. It was used by the first hominids for building shelters and as a raw material for making weapons and other tools. Throughout the course of human history, additional uses for wood have emerged, including as construction material for houses, fences, revetments, wells, quays, bridges and roads; as raw material for furniture, canoes, and ships; and as a material for artistic and religious expression (e.g., wooden statues). In addition, the archaeologist can use the remains of wood that has not been (visibly) used by humans as a source of information on ecology and landscape development. In the Netherlands, wood is one of the most common materials in archaeological sites, as a result of its use in large quantities

throughout the past and because of the favourable soil conditions for wood preservation, especially in the western part of the country.

The 1992 Valetta treaty obliges the countries that have signed it to protect their buried archaeological remains, if possible in situ (Council of Europe, 1992). If building plans are made on a site, and in situ protection is not possible, a rescue excavation has to be funded by the company that is going to disturb the site. However, the agreement also implies that where no such activities are planned, archaeological sites need to be protected from degradation. On sites that are under threat from degradation processes, measures may need to be taken to enhance the burial environment and stop or prevent decay. To enable conservators and archaeologists to do so, knowledge is needed on favourable and unfavourable soil conditions for the preservation of archaeological remains. Since wood is one of the most important types of archaeological remains, understanding the degradation mechanisms of wood decay

*Corresponding author. Tel.: +31 33 4227 606; fax.: +33 422 77 99.

E-mail address: h.huisman@racm.nl (D.J. Huisman).

Table 1
Archaeological sites investigated; site number is the number in the BACPOLES project

BACPOLES site number	Name	Sediment/soil type	Wood objects	Wood type
8	Dokkum well	Anthropogenic soil	Well	Oak
9	Dokkum casket	Anthropogenic soil	Casket	Oak
10	Borssele	Peat (marine influence)	Piles	Oak
11	Vleuten	Clay/sand (fluvial)	Pole/planking	Oak
12	Burg Zand Noord (BZN) 15	Clay/sand; under water	Ship	Oak/Spruce
13	De Rob	Clay/sand; under water	Ship; protected	Spruce
26	Elst	Sand (fluvial)	Piles	Oak
27	Almere uncovered	Clay/sand (marine; reclaimed)	Ship	Oak
28	Almere covered	Clay/sand (marine; reclaimed)	Ship; protected	Oak

and soil conditions promoting decay is of prime importance for the protection of archaeological remains in situ.

Degradation of buried archaeological wood is almost exclusively a microbiological process. Depending on the environment, different types of microorganisms are actively degrading wood. The most destructive are white-rot and brown-rot fungi (Grosser, 1985). However, they are only active in wood that is partly dried out (20–80%), and that has an ample supply of oxygen. Under these circumstances, they destroy wood completely within a few years or even months (Grosser, 1985). Because of this speed of decay and because buried wood is usually quite wet in temperate climates—even in soil layers above the groundwater table—their activity is not relevant for most buried archaeological wood except in arid regions. Wood that is water-saturated, but where there is still ample oxygen supplied, is usually mainly degraded by soft-rot fungi (Grosser, 1985). All these fungi will destroy the wood completely. Several bacteria are known to degrade wood, they include cavity, tunneling, and erosion bacteria. They degrade more slowly than the fungi and in waterlogged wood in low-oxygen environments—conditions in which wood-degrading fungi and other wood-degrading bacteria cannot be active—erosion bacteria are found (Blanchette, 2000; Björdal et al., 1999).

Although wood degradation by erosion bacteria was reported in the 1980s (Holt and Jones, 1983; Daniel and Nilsson, 1986), no such bacteria have been successfully isolated into pure culture. As a result, little is known about the specific environment in which these wood degraders thrive. For archaeological wood, information on the behaviour of erosion bacteria and on the damage they may do to archaeological wood in situ is of prime importance for the management and protection of archaeological sites: Only when the relation between soil conditions and damage to wooden artefacts is known is it possible to assess the threat posed, and—if possible—to manage the sites in order to achieve an optimal burial environment for long-term conservation.

In order to obtain such information, a series of archaeological sites containing wooden remains were selected for fieldwork within the framework of the BACPOLES project (Klaassen et al., 2005). The fieldwork

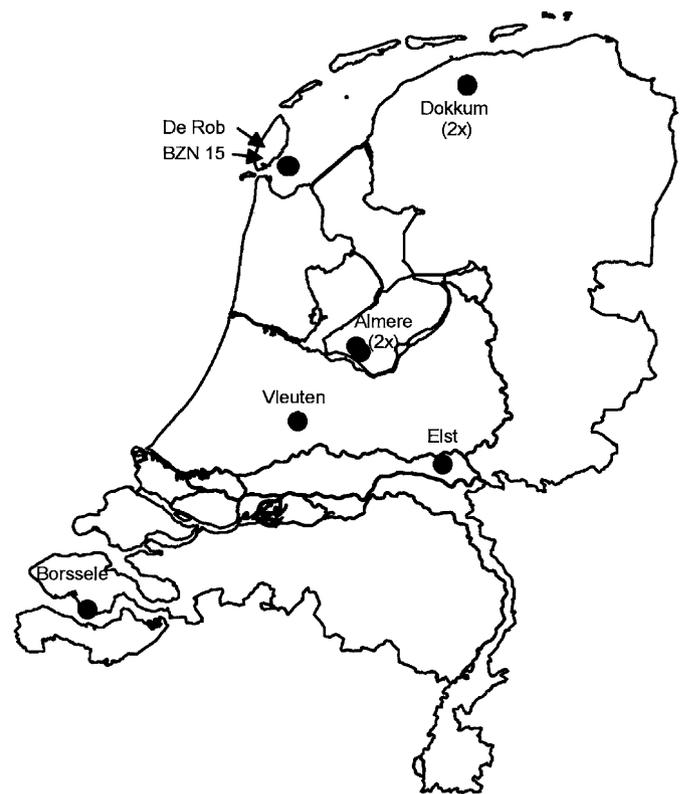


Fig. 1. Location of sites investigated.

done at these sites was aimed at characterizing the chemical burial environment and the type and degree of decay in the wood in the Netherlands. A series of nine sites considered representative of a number of different environments was chosen. They also include sites where measures had already been taken in the past to protect the archaeological remains in situ (see Table 1 and Fig. 1).

2. Materials and methods

2.1. Site distribution

The sites used in this study were selected to represent the variation in burial conditions that can exist in waterlogged conditions. The locations

are plotted on a map in Fig. 1. Two sites in Dokkum (“Dokkum well” and “Dockum casket”) are on a medieval man-made mound (“terp”) in the northern marine-clay landscape. This mound consists of layers of sod, refuse, and dung that were used to raise the town above flood level (Dijkstra, 2003). A site in Borssele consists of farmhouses from Roman times situated in an area of peat with marine influence (Sier, 2002). One in Vleuten is a Roman river revetment made of wood and basalt that was formed to stop bank erosion on one of the now-abandoned branches of the River Rhine. One site consists of the wooden foundation of a wall belonging to a Roman temple complex in the village of Elst in the Rhine floodplain. Two sites are marine underwater sites in the Wadden sea (Burgzand Noord or BZN area) consisting of the remains of two 17th century seafaring ships that sank close to the isle of Texel. One ship (also known as BZN 3) is tentatively identified as “De Rob”, a ship of the Verenigde Oost-Indische Compagnie (VOC) that took part in the 1639 A.D. battle of Duins and sank in 1640 A.D. Here, measures have been taken to protect the site against erosion and further decay: Sandbags and polypropylene nets are used to promote sand deposition on the site (Manders, 2004). No such measures have been taken at the other site (BZN 15). Two sites have smaller shipwrecks from the 16th century. These ships sank in the Zuiderzee, a sea arm that was turned into a freshwater lake in 1932. In 1967, the area was reclaimed and the seafloor-turned-land became part of the Flevopolders, the largest polder in the Netherlands. Both ships were discovered at shallow depth when agriculture started in the new land after reclamation. At one site (Almere uncovered; also known as GZ80), a layer of sand was put over the wreck in order to provide some protection. The sand was carefully selected to have a high capillary action, and therefore a high capacity for soil water retention. At the other site (Almere covered; also known as KZ47), a layer of plastic foil overlain by sand was used to cover the wreck and promote high groundwater levels and soil moisture contents. A hole was left in the foil to facilitate access to rainwater.

2.2. Fieldwork and sampling

Fieldwork was aimed at sampling and characterization of the burial environment. At archaeological excavations, locations were sought where wood was known to be buried. In all cases, this implied that topsoil was already removed, and that the top of the wood was exposed. In the sediment surrounding this wood, measurements and sampling were carried out in the undisturbed sediments. Groundwater was sampled using mobile lysimeter probes, with a ceramic suction lysimeter head (Bredemeier et al., 1990). Three water samples were taken, if possible at +50, 0, and -50 cm relative to the top of the wood. They were stored at 4°C using a portable refrigerator. Field pH was measured directly in sub-samples of these water samples using a glass electrode. The redox potential was measured using a probe with four platinum electrodes at fixed depths and a standard pH/conductivity meter (WTW GmbH, Weilheim, Germany). As a reference an Ag/AgCl electrode was applied. The redox probe was installed to reach sediment depths of approximately 20 cm above and 25, 35, and 50 cm below the wood samples.

During further excavation, three soil samples were taken at consecutive depths. Additionally, if possible, samples were taken from the groundwater around the wood that was released during excavation. These bottles were also stored at a temperature of 4°C and kept in the dark. After measurements and sampling were completed, the wood was dug up (if necessary, it was cut first using a chain saw), labelled, and wrapped in plastic to prevent drying out. When necessary, some pieces that were too large were also kept cool and dark. Because the fieldwork was done on sites where archaeological excavations were ongoing, sampling and measurement plans often had to be adapted in order not to hamper the routine archaeological work.

The marine underwater sites were sampled following the same philosophy and strategy. However, the working environment limited the fieldwork activity and made it necessary to use different equipment. Moreover, the fieldwork was executed during monitoring of the sites and not, as was the case in many of the terrestrial sites, during excavation. This means that work had to be executed with as little intrusion as possible.

Water samples were taken just above the seabed and the environmental conditions of water and soil were measured with a WaterWatch 2681 datalogger (manufactured by EauxSys Ltd, UK). This device measured salinity, dissolved oxygen, turbidity, depth, and temperature of the water while employing two probes to determine pH and redox in the sediment. Experience with the datalogger, which was still in an experimental phase, was gained in the EU-funded project MoSS (Monitoring, Safeguarding and visualising North European Shipwreck Sites; cf. Gregory, 2004; Manders and Lüth, 2004).

The pH and redox probes were placed in the sediment around the wood to be sampled. The datalogger measured every 5 min during the 24 h prior to sampling of the wood. During wood sampling, one large sediment sample was taken from the seabed surface and four from just under the wood. Sediment samples from the BZN 15-site were taken approximately 30 cm under the seabed surface and those from BZN15 at 30 to 85 cm depth. All samples—water, sediment and wood—were packed under water and transported in a refrigerator at 4°C.

2.3. Water analyses

All water samples were analysed for pH, conductivity, dissolved organic carbon (DOC), total dissolved nitrogen (TDN), dissolved organic nitrogen (DON), NH_4^+ , NO_3^- , Na^+ , K^+ , Ca^{2+} , Mg^{2+} , Fe^{2+} , Mn^{2+} , Al^{3+} , SO_4^{2-} , PO_4^{3-} , and Cl^- . Dissolved organic carbon was measured by dry combustion at 680 °C using a TOC-5050 Shimadzu organic C analyzer (Shimadzu Europa, Duisburg, Germany).

The NH_4^+ and NO_3^- values were determined using continuous flow injection colorimetry (Cenco/Skalar Instruments, Breda, The Netherlands). NH_4^+ was determined using the Berthelot reaction method (Skalar Method 155-000); NO_3^- was determined using the copper-cadmium reduction method (Skalar Method 461-00). Total dissolved organic nitrogen (TDN) was analysed after alkaline persulphate and UV digestion to convert both NH_4^+ and DON to NO_3^- . Dissolved organic nitrogen was computed as: $\text{DON} = \text{TDN} - (\text{NH}_4^+ - \text{N} + \text{NO}_3^- - \text{N})$.

Determination of Cl^- was done by a continuous-flow system equipped with an Ag/AgCl ion-selective electrode. The pH and the conductivity were measured with a digital pH/conductivity meter (WTW GmbH Weilheim, West Germany). The elements phosphorus, sulphur, sodium, potassium, calcium, magnesium, manganese, iron, and aluminium were analysed by an inductive coupled plasma-atomic emission instrument (ICP-AES, Spectro Analytical Instruments, Kleve, Germany). SO_4^{2-} and PO_4^{3-} contents were derived from ICP sulphur and phosphorus measurements, respectively.

Of all water samples, the charge balance was used as a check on errors. Due to the high salinity of the samples, two Na^+ and two Cl^- analyses failed (from Borssele and from the marine sites, respectively). For presentation purposes, they have been estimated by using the resulting charge imbalance.

2.4. Soil analyses

All soil samples were analysed for pH, N_t (total nitrogen), C_t (total carbon), S_t (total sulphur), P_t (total phosphorus), and exchangeable cations (Ca^{2+} , Na^+ , K^+ , Mg^{2+} , Al^{3+} , Fe^{2+} , Mn^{2+}). Sediment samples were oven-dried at 40 °C and sieved (2 mm), and pH was measured with a digital pH-meter (WTW GmbH Weilheim, Germany) in water and 1 mol L^{-1} KCl (1:2.5). Sub-samples were ball-milled for N_t , C_t , S_t and P_t analysis. N_t and C_t were determined using an automated carbon and nitrogen analyzer (CHN-O-Rapide, VarioEL, Elementar, Hanau, Germany). S_t and P_t were analysed after HNO_3 pressure digestion (65% HNO_3 ; see Heinrichs, 1989) with the ICP-AES-technique, as described for water samples. Exchangeable cations were determined from the dried and sieved samples after percolation with 1 M NH_4Cl (Meiwes et al., 1984) and by using a flame-absorption spectrometer (Varian Spectra 300A, Darmstadt, Germany).

2.5. Wood analyses: Degradation patterns

The wood samples were transported to the SHR laboratory in Wageningen (The Netherlands) as quickly as possible while being kept cool. They usually arrived at the laboratory within a day after sampling. At SHR, samples and sub-samples were kept refrigerated at 4 °C at all times. Sub-samples were sawn for various types of analysis as soon as possible. For studying the degradation pattern, two sub-samples were taken from each wood sample, consisting of a quarter sawn wooden strip (approximately 10 mm broad and 10 mm wide) at right angles to each other. Along this sample, radial and cross sections were made with a microtome to about 25 µm thick. The analyses were carried out over the full thickness of the sample and if possible on two different places. The sections of softwoods were stained with micro-aniline blue and those of hardwoods were stained with safranin–astra blue and investigated under the microscope. The species was determined on the basis of the wood structure. The type and degree of degradation was classified according to a five-class system according to Klaassen (2007a, b).

2.6. Dating

All wood samples were dated using dendrochronology: The transverse plane of the samples was made flat with a Stanley knife or razor blade to make the tree-ring boundaries clearly visible. If necessary, the contrast was enhanced by applying chalk powder to this surface. The tree-ring widths of the consecutive tree rings were measured with a precision of 1/100 mm using a stereo-microscope connected to a measuring table (Lintab by Rinntec, Heidelberg, Germany) and a computer. The measurements were recorded and analysed with the TSAP program (Rinn, 1996). Two to four radii are measured on each sample to account for intra-tree variation in tree-ring pattern and to detect possible missing rings. The resulting tree-ring series were visually and statistically checked (TSAP programs (Rinn, 1996); and COFECHA (Holmes, 1983)). Subsequently the single radii are averaged into mean tree-ring series for every sample. If possible, tree-ring series of different samples from the same sample site were combined into site chronologies. Subsequently, all (mean) tree-ring series were cross-dated, i.e., compared with regional master chronologies from different regions in Europe using the database of the RING foundation (which holds about 100 regional master chronologies for oak, mainly from the Netherlands, Germany, Belgium, France, Great Britain, and the Baltic countries, including Poland and Scandinavia). If a successful matching could be made of the mainly climate-induced tree-ring series to these chronologies, every tree ring on a piece of wood was assigned to a calendar year. The felling date of the tree was subsequently determined. If no

sapwood was present and an unknown number of heartwood rings was missing—a very common occurrence in archaeological wood—a *terminus post quem* date was given, indicating that the tree was felled in or after the year given.

3. Results

3.1. Fieldwork

From the nine sites, a total of 39 wood samples were taken, ranging from thick piles used in constructions to planks used in ships or barrels. The age of the wood samples was Roman (around 100 A.D.) and late- to post-medieval (1480–1640 A.D.). Not all the wood was in a vertical position; especially the wood from the buried and sunken ships, which was usually lying horizontally. Wood species sampled were mainly oak, but spruce was also sampled at the marine sites. Fig. 2 gives an overview of the depths of the redox measurements, soil samples, and water samples relative to the top of the wood that was sampled.

At most sites, soil colour was black (Borssele and the marine sites) or grey to blue-grey (Dokkum, Vleuten, Elst, Almere covered). The black and especially the grey to blue-grey colour is indicative of reducing conditions, as this colour is caused by the presence of Fe(II) minerals; Fe(III) minerals, by contrast, would give the soil a more yellow- or orange-brown colour. In Elst, the wood sampled for BACPOLES had been standing in a sand layer since Roman times. This sand had a yellowish to slightly orange colour, indicating that the grains were coated with Fe(III) minerals; this is typical for Rhine sands, which are known for their relatively brown colour (De Mulder et al., 2003). The piles, however, were surrounded by sand with a blue-grey colour up to some 10 cm from the wood surface. The blue-grey colour seemed to form some kind of halo around the piles themselves, suggesting that the environment was more reducing close to the wood.

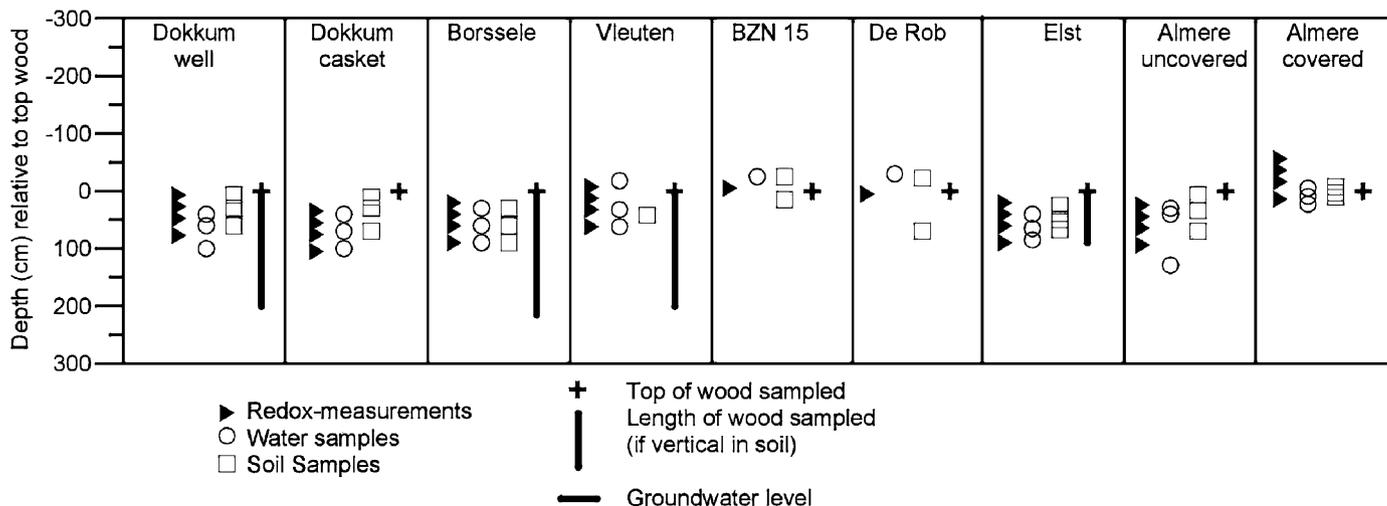


Fig. 2. Overview of samples and measurements per site. Depths relative to the top of the wood sampled.

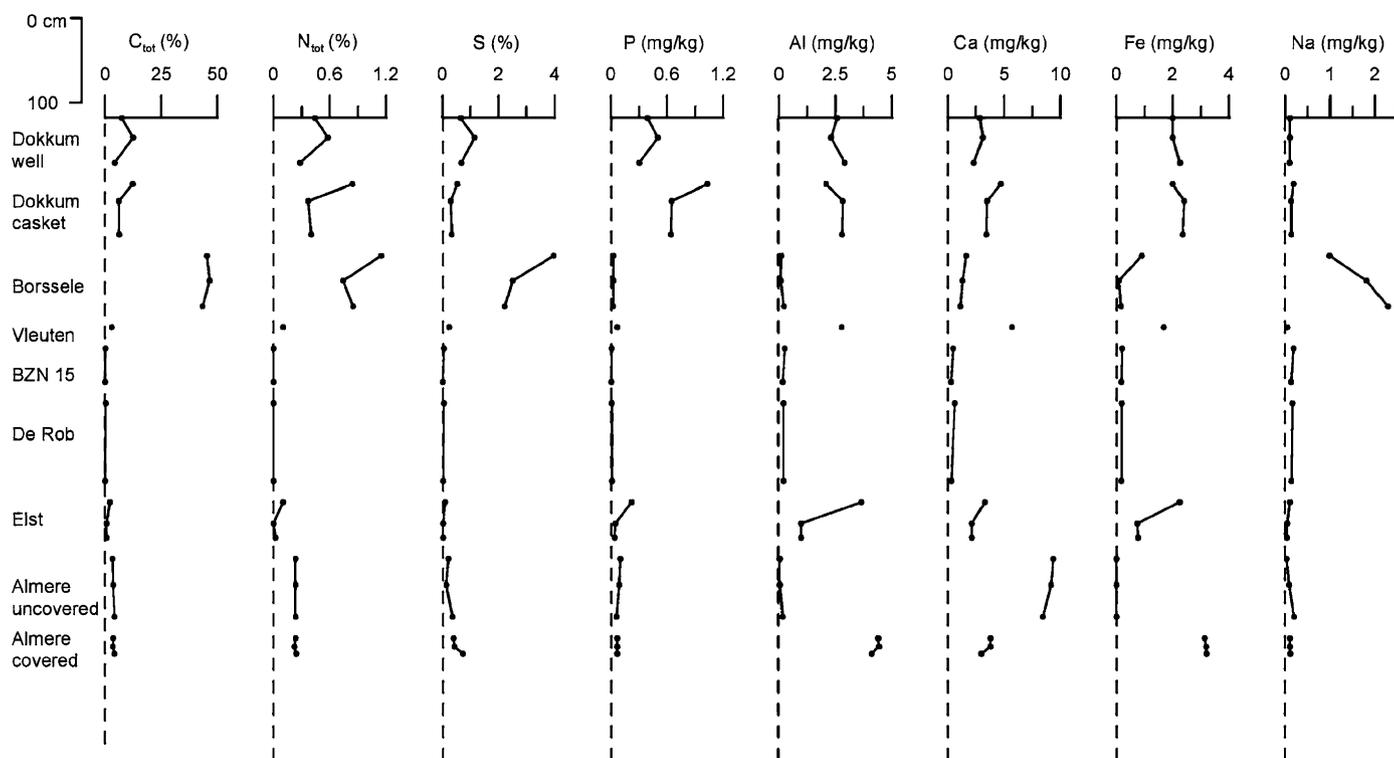


Fig. 3. Depth profiles of the composition of the soil material at the sites investigated.

3.2. Characterization of the burial environment

The burial environment varies strongly from site to site. The results of the measurements are presented in a series of plots that demonstrate the variability between sites with regard to soil composition, salinity, trophic levels, and redox: Fig. 3 gives the variation in solid-phase composition. The Dokkum sites (terp) and Borssele (peat) showed high concentrations of carbon and nitrogen due to their high organic matter. The other sites were mostly minerogenic, although the Almere sites seemed to have somewhat higher organic contents. The sulphur contents were very high in Borssele and Dokkum and still significant in Almere. This is normal for anoxic marine influenced sediments that contain organic matter and iron. In such environments, ample pyrite (FeS_2) can form in the soil mass. The very low contents of sulphur at the marine sites is explained by the very sandy, organic-poor sediment in which pyrite usually does not form. The high sulphur concentrations in Dokkum might be explained by the incorporation of marine sediments or sods in the terp soil. However, it may also be a reflection of the presence of ample excrement and other types of refuse in these soils. Vleuten and Elst have low sulphur levels because they lie in a continental environment. Phosphorus is high in the terp sites (Dokkum), but quite low in the peaty material (Borssele) and in the minerogenic sediments (the other sites). This reflects the relatively high trophic levels in the terp material—which contains large contents of refuse and excrement—compared with the peat. High aluminium and

iron contents, as found in Dokkum, Vleuten, Elst, and Almere uncovered, indicate a high proportion of clay in the soil material. All sites showed high concentrations of calcium, which is most probably related to the presence of calcite. The sandy nature of the marine sites apparently precluded the presence of shell material that could elevate the calcium contents. Sodium was generally low, but high concentrations were found in Borssele. Here, sodium from seawater seems to have adsorbed onto the organic matter in the peat.

When examining the water composition (Fig. 4a and b), the most striking differences between the sites are related to differences between saline and freshwater conditions. The marine underwater sites show extremely high Na, K, Cl^- and SO_4^{2-} , whereas Borssele and Almere, which have freshwater after a marine origin or episode, still show elevated concentrations. The other sites showed low concentrations of these components, which is typical for freshwater sites. Ca and Mg levels were high in all sites, but Borssele and Almere showed even further elevated Mg contents. The water composition reflects the hydrochemical history of the sites:

A number of sites showed the effects of interchanging saline and freshwater conditions. This is best demonstrated by using a so-called Piper plot (see Fig. 5): A Piper-plot consists of a triangular diagram for the cations (lower left) and the anions (lower right). The central diamond combines both triangles, with four different water types at the corners. Fresh water—usually dominated by Ca^{2+} and HCO_3^- —will plot in the lower left of both the triangles

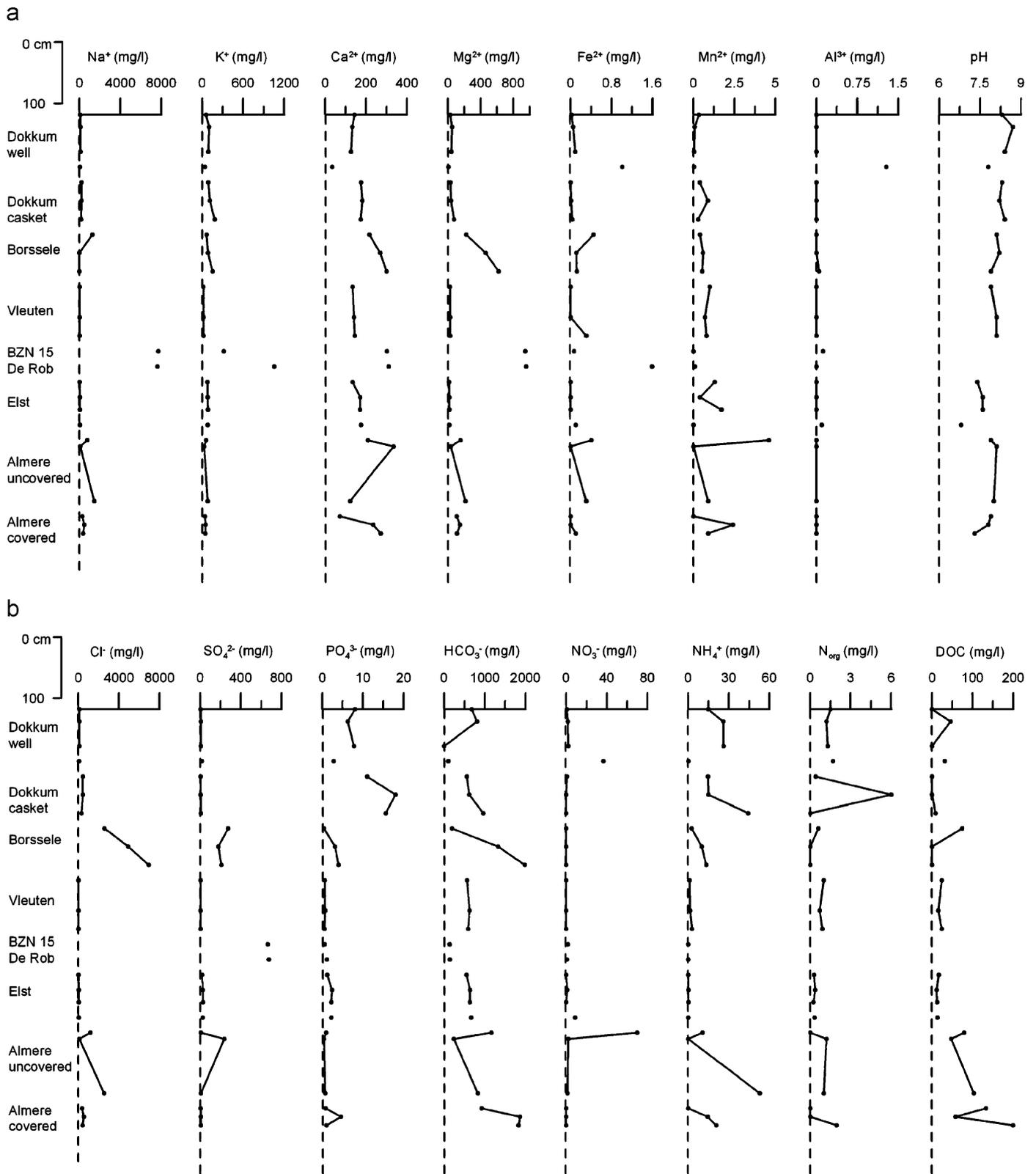


Fig. 4. Depth profiles of the pore water composition at the sites investigated.

and in the left of the diamond. Saline water—dominated by Na⁺ and Cl⁻—plots in the lower right of both triangles and in the right of the diamond. If sediment containing saline water is freshened (or the other way around), the

anions are exchanged more readily than the cations since they adhere more strongly to the soil matrix. As a result, in the middle diamond the water composition will not change in a straight line from the fresh to the saline corner, but it

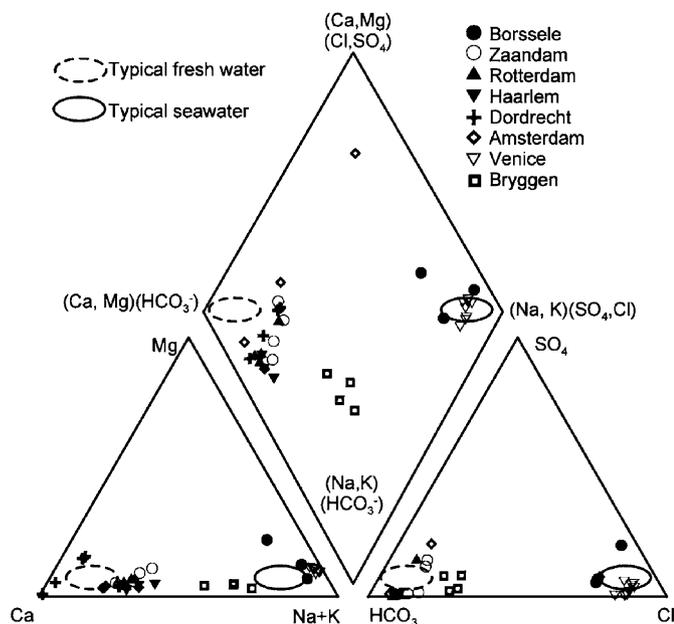


Fig. 5. Piper plot, characterizing the water composition. Normal fields for saline and fresh water are indicated.

will tend toward the lower corner if freshening occurs, and toward the upper corner in the case of salinization (Appelo and Postma, 1999). The Piper-plot in Fig. 5 shows clearly the differences between saline and freshwater samples: The samples from Elst and Vleuten are clearly fresh, and the samples from Borssele, the marine sites, and some samples from Almere uncovered are clearly saline. Sites Dokkum, Almere covered, and part of Almere uncovered form a group of intermediate samples between fresh and saline. This group tends to drift toward the $(\text{Na}, \text{K})(\text{HCO}_3^-)$ -corner of the central diamond shape, which is typical for freshening of saline environments (Appelo and Postma, 1999). It is remarkable that the terp material falls within this range, as it is usually regarded as fresh. Although it is possible that part of the sodium came from dung, a marine influence seems very possible, especially given the high concentrations of sulphur in the soil material (see above). Possibly, the sods used to build the terp body came from salt marshes or tidal flats, thus introducing saline conditions when the terp was built. Two outliers in the upper half of the diamond (from Dokkum and Almere uncovered) could reflect relatively elevated concentrations of sulphate (SO_4^{2-}) due to pyrite oxidation or possibly a large contribution from refuse or dung at Dokkum.

The iron contents are very variable. Probably this reflects variations in redox conditions that cause local dissolution and precipitation of iron minerals, especially Fe(hydr)-oxides. The pH is neutral to basic, which conforms with the more or less uniform HCO_3^- concentrations. Dokkum and Borssele—the sites with high organic matter contents in the soil mass—show high phosphate (PO_4^{3-}) levels. This is remarkable, since in the soil material the phosphate is lower in Borssele (10) when compared with the other two

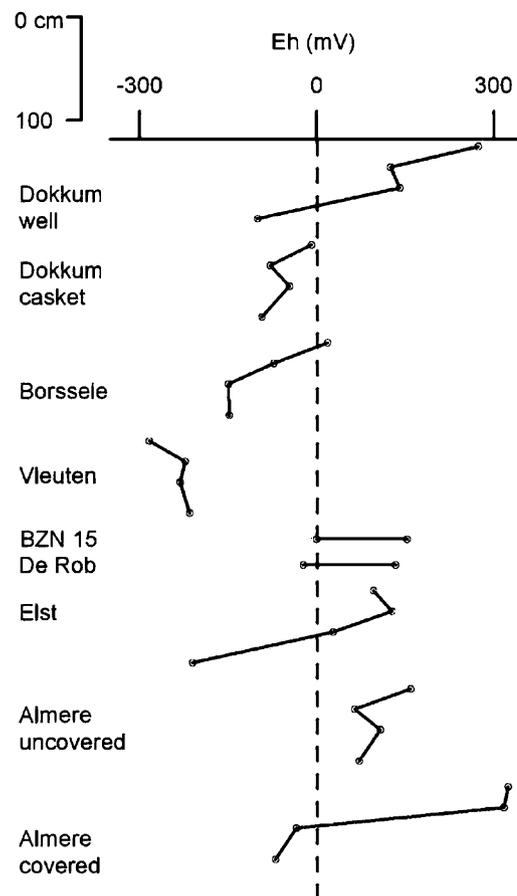


Fig. 6. Depth profiles of redox values. High values in the tops of the profiles are probably due to intrusion of oxygen during excavation. At the marine sites (BZN 15 and De Rob), redox values decreased steadily after installation of the datalogger. The values here give the trend of 2 days of monitoring. All sites reach reducing conditions except Almere uncovered, which is oxic throughout its depth.

sites. The high content of NH_4^+ —which correlates with N_{org} —demonstrates high trophic levels at Dokkum, Borssele, and Almere. The excessively high N_{org} in one sample from Dokkum could be the result of this sample being derived from a layer of dung within the terp material. In combination with the very low levels—or better, absence—of NO_3^- , the high levels of NH_4^+ are a clear indication of reducing conditions at all the sites investigated during sampling.

The depth profile of redox potential (Fig. 6) confirms that reducing conditions are reached at all sites except Almere uncovered. The Eh–pH diagram in Fig. 7 shows that the most reducing layers at most sites reach values that are normal for Fe-reducing conditions, and in some locations (Vleuten and Elst) for sulphate-reducing conditions. The oxic conditions in the upper levels at most sites are probably caused by the introduction of air-oxygen into these layers during the first phases of the archaeological excavation. We assume, therefore, that the burial conditions around the wood at all sites, except Almere uncovered, have been reducing up until the start of the archaeological excavation.

3.3. Characterization of wood degradation

Despite the large variation in burial conditions between the sites, degradation of the cell walls (cf. Fig. 8a) by erosion bacteria was found in all wood samples without exception (Klaassen et al., 2005). The same was true for

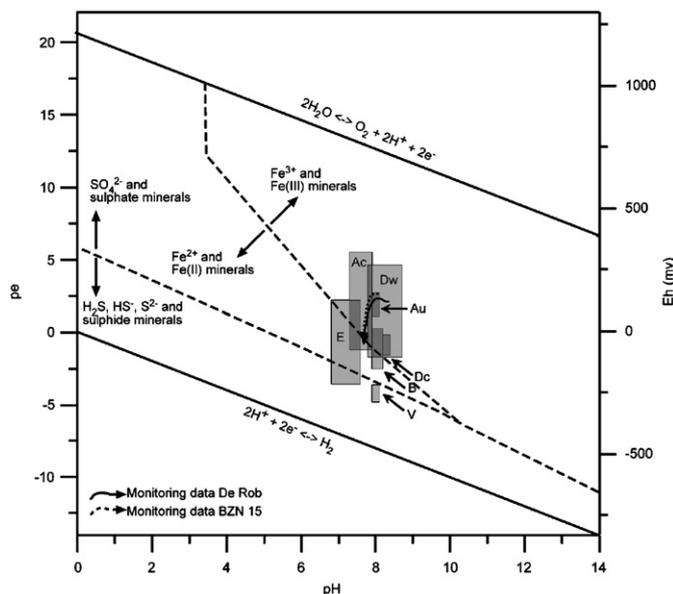


Fig. 7. Eh–pH diagram, showing the range of Eh and pH at each site (Dw = Dokkum well, Dc = Dokkum casket, B = Borssele, V = Vleuten, E = Elst, Ac = Almere covered, Au = Almere uncovered). The fields for iron-reducing and sulphate-reducing conditions are indicated by broken lines (“Fe³⁺ and Fe(III) minerals” and “H₂S, HS⁻ and S²⁻ and sulphide minerals”, respectively), based on Appelo and Postma (1999), Kölling et al. (2000), and Fors (2005). Since the depths of measurement for Eh and pH were different at most sites, it is not possible to plot sample points in this diagram. Therefore, the range of variation in Eh and pH between the sample points is shown. The data from the marine sites (De Rob and BZN 15) show the changing conditions from the installation of the equipment up to the recovery 2 days later. All sites except Almere uncovered reach the field of iron- and sulphur-reducing conditions. The Dokkum well and Almere covered sites reach into the oxic zone with Eh over 200 mV (see also Fig. 6).

active wood-degrading bacteria (Klaassen et al., 2005). The intensity of the degradation, however, varied (see also Table 2).

All samples (oak and pine) were degraded by erosion bacteria; non-degraded tissue in the wood was rare. Sapwood, if present, was always severely degraded. It seems that the dimension of the timber is negatively correlated with the degree of degradation, so that thicker oak piles (Dokkum well, Borssele, Vleuten, Elst sites) were severely degraded on the outside, but in deeper layers the degree of degradation was less and sometimes even absent. The sawn oak timbers (Dokkum casket and Vleuten) were severely degraded. The oak shipwreck timber from the marine sites consisted of sawn heartwood only, but in all beams a gradient in the degree of degradation was still found (severe to moderate). Furthermore, the pine from BZN 15 was severely degraded. In both shipwrecks from Almere, soft-rot decay had been active. The degree of degradation by soft-rot was moderate in Almere uncovered, and slight in Almere covered.

During the study of degradation patterns, wood from several sites appeared to contain substantial amounts of pyrite (FeS₂; see Fig. 8b). This was noted especially for the Dokkum sites, BZN 15, De Rob, and the Almere sites. The chemical wood analyses that are available for some of these sites confirm that high concentrations of iron (1.1–2.3%) and sulphur (0.8–2.4%) occur in the wood from Almere, BZN15, and in one of the samples from Dokkum (Klaassen et al., 2005).

4. Discussion

4.1. Erosion bacteria and their environment

The sites investigated show a large variation in burial environment. Organic matter content, clay content, salinity, and trophic levels all vary considerably (Table 3). The only factor that is more or less constant is the redox. All sites (except Almere uncovered) have low redox, as indicated directly by the redox measurements and indirectly by the

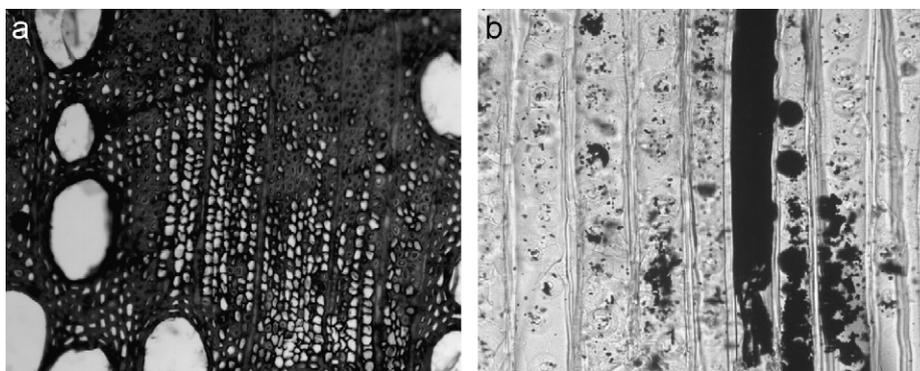


Fig. 8. Light microscope photographs of wood samples. (a) Wood that has suffered from decay by erosion bacteria. In the centre of the photograph, the cells in one region clearly have lost their secondary cell walls. The surrounding regions show cells that are hardly affected. (b) Opaque pyrite minerals in wood. In addition to the groups of spherical clusters of minerals (“framboids”, the most common form of sedimentary pyrite), one cell has been filled completely with “massive” pyrite, and a large number of small euhedral minerals are present scattered throughout the wood.

Table 2
Classification of degradation patterns in the heartwood of the different sites (sapwood is severely degraded on all sites)

Site	Wood type	Wood degradation	Remarks
Dokkum well	Oak	Severe (outside) to moderate or absent (inside)	Pyrite
Dokkum casket	Oak	Severely degraded	Pyrite
Borssele	Oak	Severe (outside) to moderate or absent (inside)	
Vleuten	Oak	Severe (outside) to moderate or absent (inside)	
BZN 15	Oak	Severe (outside) to moderate (inside)	Pyrite
BZN 15	Pine	Severely degraded	Pyrite
De Rob	Oak	Severe (outside) to moderate (inside)	
Elst	Oak	Severe (outside) to moderate or absent (inside)	
Almere uncovered	Oak	Substantial soft rot degradation	Pyrite
Almere covered	Oak	Limited soft rot degradation	Pyrite

Table 3
Summary of sample site conditions

Site + number	Sediment/soil type	Wood objects	Wood type	Age	Mineral matter	Organics	Trophic levels	Water type	Redox	Decay
Dokkum well	Anthropogenic soil	Well	Oak	1480 AD	Clay	Organic-rich	Very high	Freshening	Reducing	Moderate
Dokkum casket	Anthropogenic soil incl. dung	Casket	Oak	1412 AD	Clay	Organic-rich	Very high	Freshening	Reducing	Strong
Borssele	Peat	Piles	Oak	100 AD	None	Organic-rich	High ?	Saline	Reducing	Strong
Vleuten	Clay/sand	Pole/planking	Oak	100 AD	Clay	Mineral	Low	Fresh	Reducing	Strong
BZN 15	Clay/sand; under water	Ship	Oak/spruce	1628 AD	Sand	Mineral	Low	Saline	Reducing	Weak
De Rob	Clay/sand; under water	Ship; protected	Spruce	1640 AD	Sand	Mineral	Low	Saline	Reducing	Weak
Elst	Sand/clay	Piles	Oak	106 AD	Sand	Mineral	Low	Fresh	Reducing	Weak
Almere uncovered	Clay/sand	Ship	Oak	1549 AD	Clay	Low organic	High	Freshening	(Sub-) Oxidic	Moderate
Almere covered	Clay/sand	Ship; protected	Oak	1519 AD	Sand	Low organic	High	Freshening	Reducing	Weak

predominance of NH_4^+ over NO_3^- in the water samples. From this perspective, it is striking that all wood samples from this very heterogeneous group of sites show the effects of degradation by erosion bacteria. Apparently, the burial environment at all these sites is favourable for this form of wood degradation. Since the sites chosen represent the most common types of burial environment for waterlogged wood, it stands to reason that erosion bacteria are active in virtually all waterlogged environments. Moreover, the low redox values encountered at these sites are typical for Fe- and sometimes for sulphate-reducing environments that are essentially without oxygen ($[\text{O}_2] < 10^{-6} \text{ M}$; Appelo and Postma, 1999). Until now, it was not known whether erosion bacteria have a requirement for oxygen which would be needed for lignin modification (Blanchette, 2000). However, our results indicate that erosion bacteria may be active in essentially oxygen-free environments (i.e. $[\text{O}_2] < 10^{-6} \text{ M}$), and therefore have to be considered anaerobes. It would seem that erosion bacteria have developed a method for lignin modification that works under anoxic conditions.

The observations at Elst, of blue-grey haloes around poles in yellowish sand, suggest that the wood itself causes

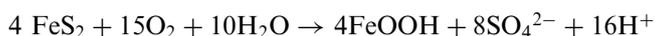
its environment to become reducing. In itself that is not surprising, since reducing conditions normally arise in soil due to the breakdown of organic matter. However, since the wood decay at this site is carried out solely by erosion bacteria, and since, apart from the wood, no other major organic matter sources are present, it can be deduced that it is the decay by erosion bacteria that has caused more reducing conditions in the immediate vicinity of the wood. Either the erosion bacteria themselves or other scavenging bacteria feeding on their remains apparently influence the redox conditions in the wood as a direct consequence of the decay process.

The environment inside the wood at this site may very well be methanogenic. Sulphate is present in only very low amounts since it is a freshwater site; Fe(III) is not present inside the wood but $\text{Fe(II)}_{\text{aq}}$ may be transported into the wood by groundwater. This rules out all electron acceptors apart from organic matter, and therefore points to methanogenic conditions. This suggests that (1) erosion bacteria are either methanogenic themselves or that they stimulate activity of other bacteria that are methanogenic, and (2) erosion bacteria can survive and degrade wood in methanogenic environments.

4.2. The occurrence of pyrite

As a result of the predominance of reducing conditions inside wood with active degradation by erosion bacteria, some specific minerals may form inside the wood. One typical effect of this is an apparently increased volumetric mass of the wood. One of the minerals that may be formed inside the wood is pyrite: It is formed in reducing environments where ample reducible iron, sulphate, and organic matter are available. The organic matter is used by bacteria to reduce iron to form Fe^{2+} and sulphate to form HS^- , which subsequently react to form sulphides. The presence of pyrite minerals has been observed under the microscope in many wood samples (Table 2; Fig. 8b), but the amount of such minerals formed would be dependent on the supply of sulphate and iron. In freshwater, little sulphate is available, so pyrite will be scarce, whereas in seawater, sulphate is present in much larger amounts. Iron may be available in the sediment and in wood close to iron objects (e.g., nails), but will be in shorter supply elsewhere inside the wood.

Pyrite may cause degradation in addition to bacterial activity if burial conditions change. It is unstable in oxygenated environments, and releases sulphuric acid when it comes into contact with oxygen, according to:



The acid produced by this process is detrimental to the wood because of the localized low pH (<3), which causes hydrolysis of cellulose. Several ships that have been recovered from the seafloor—including icons such as the *Vasa*, the *Mary Rose*, and the *Batavia*—are suffering severe damage as a result of such processes (MacLeod and Kenna, 1990; Sandström et al., 2002, 2005; Fors, 2005). There are some indications that wood from the marine shipwrecks in this study may also have become subject to the same damage under oxygenated conditions. Telltale orange-brown iron oxide precipitates were observed (Nilsson, personal communication) during microbial culturing of wood samples from De Rob (Nilsson and Björdal, 2007). The presence of pyrite was also shown separately in one of these samples by Fors (2005). Finally, the presence of holes made by shipworms (teredinids) in the wood of BZN 15 shows that it had been in an aerobic environment some time before sampling, and therefore under direct threat of damage by pyrite oxidation.

4.3. Soft-rot fungi

The presence of soft-rot fungi in Almere indicates that the wood here had been exposed to a more oxygenated environment. Most likely this started when that part of the sea in which these ships sank was reclaimed in 1968. The measures taken to enhance the burial environment at the covered site in 1978 have since been successful. Here, the conditions are at present reducing. Moreover, monitoring data that were gathered for a few years after the

protective measures were put in place (Anonymous, 1988) show that the water levels were indeed high enough to keep the wood saturated and—probably—keep the oxygen levels low. We assume, therefore, that the soft-rot degradation took place between 1968 and 1978, and is not related to the present burial conditions. The observation that soft-rot degradation on the uncovered site is much more substantial when compared to the covered suggests that this form of decay has continued since 1978. Since the protective measures at the uncovered site are very limited (with only a covering layer of sand), the burial environment here is still oxygen-rich and may dry out now and then. Therefore, fungal decay may still be active. At the covered site it appears to have been halted successfully.

4.4. Factors affecting degradation

Erosion bacteria appeared to be active in all waterlogged environments. However, we did find differences in the degree of degradation between the sites. Logically, one would expect that these differences are related to the age of the wood, and therefore to the exposure time of the wood to degradation by erosion bacteria. The archaeological sites fall broadly into two age groups: the Roman sites (Borssele, Vleuten, Elst; ca. 100 A.D.), which have experienced close to 2000 years of degradation; and the late- and post-medieval sites (ca. 1412–1640 A.D.), which have been subject to degradation for 400–600 years. However, the degree of degradation does not follow this division, but is firstly dependent on the size of the timber: Thick dimensions were less degraded. However, despite their relatively small dimensions, the sawn timber from the marine sites showed relatively less degradation compared with the timber from the freshwater soil conditions. Apparently, these factors affect the speed of degradation to such an extent that the effect of age (and, therefore, the exposure time) is minimal (see also Björdal et al., 1999).

The relatively smaller degree of bacterial decay at the marine sites could indicate that marine seafloor conditions are less favourable for erosion bacteria than freshwater soil conditions. A possible reason for this could be the high concentrations of HS^- that are formed in the marine sediments of the Wadden Sea due to sulphur reduction in a sulphate-rich environment.

4.5. The effects of degradation by erosion bacteria

Due to the widespread occurrence of erosion bacteria in waterlogged environments, it may seem that wooden archaeological remains are under threat irrespective of the chemical soil conditions. However, it is important to realize that even the wood that is worst affected by decay from erosion bacteria is still valuable for archaeological study. Shape, species, traces of surface treatment, and growth-ring patterns are preserved, and can still be used for archaeological research. Wood degraded by erosion bacteria is, therefore, valuable from an archaeological

point of view and is, therefore, worthwhile to conserve or protect. Only fungal degradation causes such severe damage to archaeological wood that these features and sources of archaeological information are destroyed. Therefore, in situ protection of wood in archaeological sites implies that the soil environment must be kept waterlogged and oxygen-free.

Degradation by erosion bacteria causing mass loss and associated increased water content makes the wood extremely sensitive to warping, cracking, and even disintegration during drying out. If archaeological wood needs to be excavated, it has to be thoroughly protected during and after an excavation to prevent such damage. Excavation and recovery of large degraded wooden objects (e.g., ships, wells, fish traps) is difficult because of a massive loss of strength, and although large objects therefore need ample support before they can be lifted, it must be recognized that the supporting material may deform the wood surface locally.

4.6. *Implications for protection and monitoring of archaeological wood*

In situ protection of archaeological wood requires maintaining a burial environment that minimizes decay. The results of this study show that all archaeological wood in situ is degraded by erosion bacteria, but that there is a large variation in the degree of attack. Apparently, factors other than the chemical burial environment control the decay process. Huisman et al. (2005), Klaassen et al. (2005), and Klaassen (2007a, b) suggest that water flow through wood may be the prime factor that determines the degree of degradation by erosion bacteria. Possibly, minor changes in the hydrology of a site can have major effects on the degradation—positively or negatively.

At Almere covered, measures have been taken to protect the wood (and other materials) present against decay. The characterization of the burial environment shows that these measures have been successful in maintaining conditions that prevent fungal decay of the wood. Probably, the soft-rot decay patterns that were observed in the wood from this site were formed prior to the date that the protective measures were put into place.

For monitoring of archaeological sites containing wood, the most important parameters to measure or monitor in the soil are redox potential and moisture content. These methods can be used to distinguish between aggressive fungal activity or slow erosion bacterial degradation. Site hydrological data—especially water flux—may influence the rate of degradation by erosion bacteria, but how that occurs is not yet established.

When assessing the state of an archaeological site, it is important to determine not only the degree of degradation, but also the type of degradation that is presently active. The former gives information on the present archaeological value and the quality and strength of the wood. The latter defines the future prospects for the site by offering a

prediction of the archaeological information value of the wood in years to come. The Almere site demonstrates that it is difficult to determine the present degradation type by looking only at the decay patterns in the archaeological wood. This decay pattern is cumulative from all decay that has happened in the past. Sites like Almere, where burial conditions have been adverse in the past but have since been ameliorated, may still show fungal decay patterns even though fungi are no longer active. It is therefore advisable to introduce fresh wood (or other cellulosic substrates such as kapok fibres) into the soil at such sites and determine the type of degradation that occurs. At a site (BZN 10) in the Wadden Sea, near the marine sites discussed here, such tests have been executed successfully in the EU-funded project MOSS (cf. Manders, 2004; Manders and Lüth, 2004).

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