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# Degradation of archaeological wood under freezing and thawing conditions - effects of permafrost and climate change

Matthiesen, H.; Jensen, J.B.; Gregory, D.; Hollesen, Jørgen; Elberling, Bo

# DEGRADATION OF ARCHAEOLOGICAL WOOD UNDER FREEZING AND THAWING CONDITIONS—EFFECTS OF PERMAFROST AND CLIMATE CHANGE*

H. MATTHIESEN,[1]† J. B. JENSEN,[1] D. GREGORY,[1] J. HOLLESEN[1,2] and
B. ELBERLING[2]

[1]*Conservation Department, National Museum of Denmark, Copenhagen, Denmark*
[2]*CENPERM (Centre for Permafrost), Department of Geography and Geology, University of Copenhagen, Copenhagen, Denmark*

*The degradation of archaeological wood at freezing and thawing temperatures is studied at the site of Qajaa in West Greenland through a combination of environmental monitoring, measurement of oxygen consumption and microscopy of wood samples. Permanently frozen wood is still very well preserved after 2–4000 years, while wood samples that thaw every summer show attack by soft rot and an average density loss of 0.1 g cm$^{-3}$ (corresponding to 25% of the dry mass) over the past 27 years. Future increases in temperature may increase the decay rate significantly ($Q_{10} = 4.2$ at 0–10°C) but the effects on site depend on local hydrology.*

*KEYWORDS:* WOOD, DECAY RATE, PERMAFROST, THAWING, ENVIRONMENTAL MONITORING, MICROSCOPY, OXYGEN CONSUMPTION, QAJAA, GREENLAND

## INTRODUCTION

Permafrost can ensure excellent preservation of organic archaeological materials. Extraordinary examples recovered in recent years include the discovery of the Ôtzi man (Barfield 1994), as well as the first mapping of the complete genome for a prehistoric man, using hair from a permanently frozen midden (Rasmussen *et al.* 2010). When organic materials are preserved, it is possible to obtain a much more complete picture of the people who once inhabited a site, compared to sites where only inorganic materials are preserved. However, the temperature is rising and permafrost is currently retreating (IPCC 2007), which is a particular threat to Arctic sites, where the preservation of organic material relies on the general low or freezing temperatures. Thus, it is important to know the consequences for permanently frozen archaeological sites. Will these sites be affected by thawing and how will increasing temperatures influence the decay rate of the archaeological remains?

Wood is probably the organic material that has been most abundantly used by ancient cultures. It is relatively vulnerable to decay, and can to some extent be used as an indicator for the general preservation of organic materials at a site (Kenward *et al.* 2008; Gregory *et al.* 2009). Under humid, oxic and temperate conditions, wooden artefacts suffer decay due to insects and micro-organisms, and may disappear within a few years or decades. However, under certain conditions the decay can be very slow and the wood may be preserved for long periods: under very dry conditions (e.g., in deserts), where the decay is minimized through the lack of water; under waterlogged conditions (e.g., in a bog), where the decay is reduced by the lack of oxygen; and

under frozen conditions (e.g., in snow patches), where both the low temperature and the lack of oxygen and fluid water may reduce the decay. Several studies have been made on the state of preservation and possible decay of archaeological wood from waterlogged conditions (Björdal and Nilsson 2001; Gregory and Jensen 2006; Pollard 2012), but knowledge about archaeological wood from more or less permanently frozen conditions is more sparse. Juhl *et al*. (2012) recently studied the physical effect of freezing on archaeological wood and found that repeated freezing–thawing may result in physical damage for highly degraded archaeological wood (the wood becomes spongy and cracks may occur), whereas no damage was observed for non-degraded wood. Blanchette *et al*. (2002) investigated historical wood from expedition huts in Antarctica and described decay by defibration due to a high salt content in the wood. From the same site, they have studied microbial decay (Blanchette *et al*. 2004; Held *et al*. 2005), showing that the wood was mainly attacked by soft rot, but no decay due to white rot, brown rot or bacteria was observed. Soft rot was also found in modern wood samples buried for 2–4 years in Antarctic soil (Arenz *et al*. 2011). Soft rot is one of the less damaging fungi, as it only attacks the secondary wall of the wood cells, whereas brown rot and white rot may also attack the compound middle lamella and lead to complete disintegration of the wood (Goodell *et al*. 2003).

Wood decaying insects and fungi require oxygen for their respiration, and the oxygen consumption rate of a wood sample may be taken as an indicator for the decay rate. Both under field conditions and in short-term laboratory incubation experiments, oxygen consumption rates have been used to provide a direct measure of wood decay (Stusek *et al*. 2000; Hicks and Harmon 2002; Matthiesen and Mortensen 2012). However, the oxygen-consumption rate of wood has not previously been assessed at temperatures relevant for Arctic sites.

This study is the first to assess *in situ* preservation of permanently frozen archaeological wood in Greenland, and to evaluate the decay rate at different temperatures based on three approaches: (1) study of the environmental conditions, by field measurements and monitoring equipment installed at the site; (2) study of the archaeological material, its state of preservation today and how it depends on environmental conditions; and (3) model experiments, where the decay of archaeological material is studied at different temperatures in the laboratory, and where the decay of modern reference materials is studied in the field. A similar approach has been used earlier to evaluate the preservation conditions at other archaeological sites (Matthiesen 2004; Matthiesen *et al*. 2007). Work is ongoing to model the change in ground temperature at the study site under future climate conditions (Elberling *et al*. 2011; Hollesen *et al*. 2012), and the results presented in this paper will be used to evaluate the consequences for the wooden archaeological artefacts.

STUDY SITE

Qajaa, at Ilulissat Icefjord in West Greenland, is a unique site where permafrost has preserved organic remains from the prehistory of Greenland. Three different cultures settled here (Saqqaq, 4000–3000 BP; Dorset, 2400–2000 BP; and Thule, 600–200 BP) and their waste accumulated in a kitchen midden that was up to 3 m thick. The site was first described by Nordenskiöld (1871, 1021–5), who visited it in 1870. Excavations were carried out in 1981–2 by Meldgaard (1982), documenting the amazing archaeological potential of the site. Since then, no excavations have taken place. It is considered the best preserved site for the Saqqaq and Dorset cultures in the whole of Greenland.

The kitchen midden covers an area of approximately 2900 m$^2$ and has a maximum thickness of more than 3 m. The active layer (i.e., the top layer that thaws during summer) was measured to be $32 \pm 7$ cm thick in the central part of the midden in August 2009 (Elberling *et al*. 2011),

$39 \pm 7$ cm thick in August 2010 and $34 \pm 7$ cm thick in July 2011. The entire kitchen midden is divided into several distinct units (Fig. 1), which at earlier times were probably parts of a single, larger midden. The border of the midden towards the sea is characterized by vertical erosion fronts (Fig. 2). During the excavations in 1981–2, Meldgaard's team excavated a few square metres in total over 1.5 months, describing eight different profiles at the erosion front. Excavations could only take place in the thawed midden layers, so the archaeologists worked their way inwards from the existing erosion front, cleaning the profiles until they reached frozen material, and then only excavated a few centimetres further into the midden every day, as the exposed profile thawed during the day. Since 1982, only modest physical erosion has taken place, and all the excavation profiles cleaned in 1982 are still visible and intact today.

This study focuses on three of the profiles described by Meldgaard (1982): A, D and K (Fig. 2). Profile A faces north, is permanently in the shade and consists of a thick layer of remains from the Saqqaq culture, covered by natural turf, and a thin layer of remains from the Dorset culture. Profile D faces west, and contains remains from the Dorset culture, covered by natural turf, and remains from the Thule culture. Profile K faces west and contains remains from the Saqqaq culture, covered by a thin layer of turf—this profile is relatively thin (only 60 cm) and dried out, which means that it thaws faster and to greater depths compared to wetter parts of the midden.
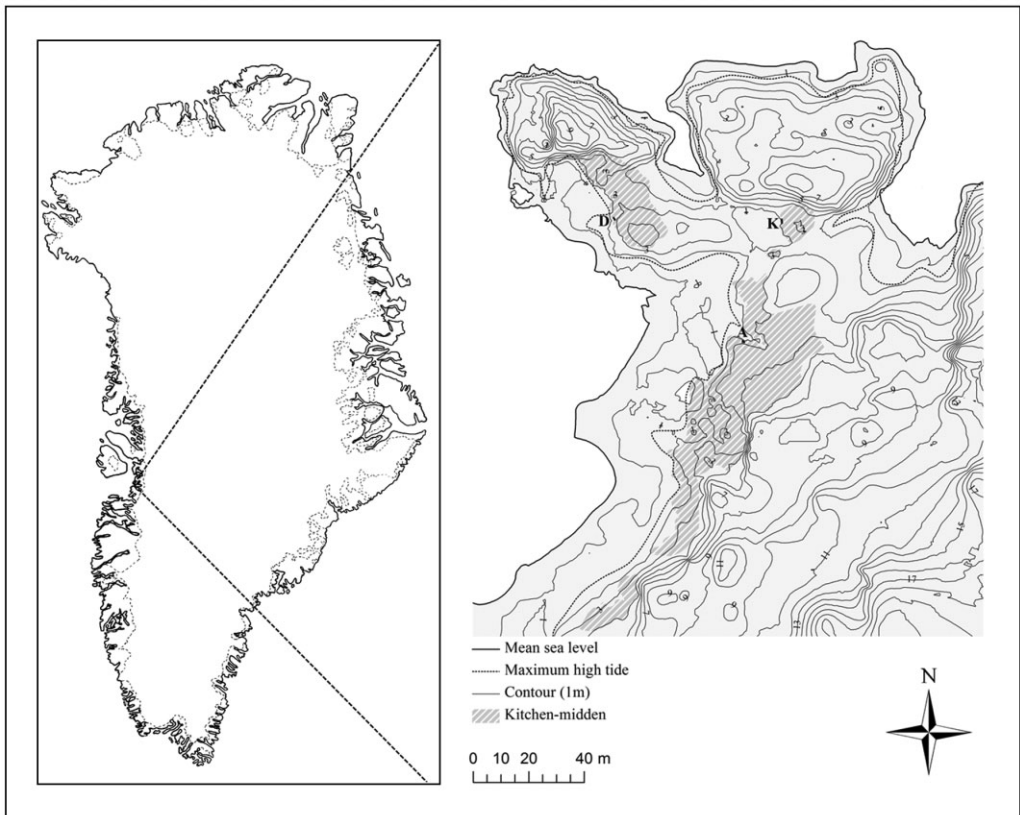


Figure 1  *A map of Qajaa, with the kitchen midden outlined (shaded area): the present study focuses on profiles A, D and K (marked).*
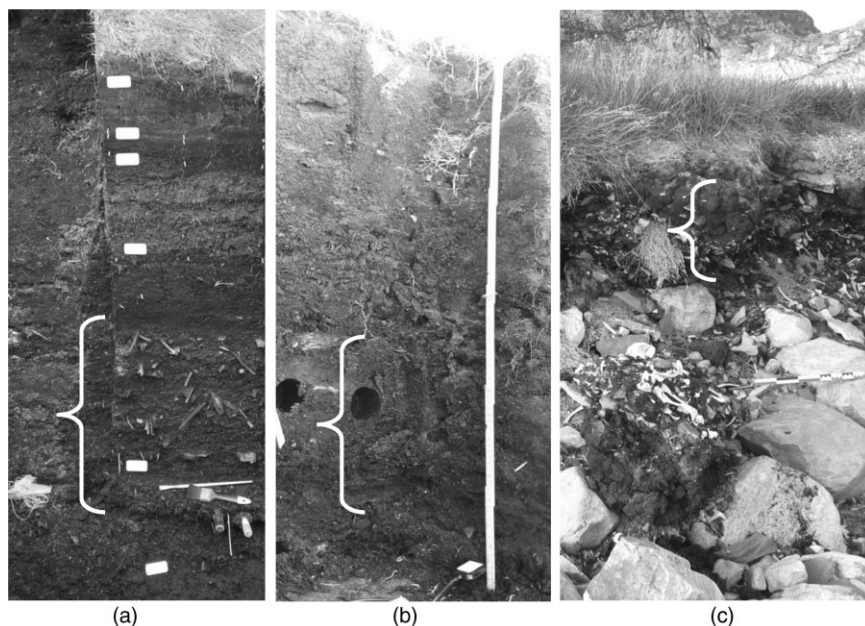
Figure 2    *Photographs of profiles (a) A (height 120 cm), (b) D (height 90 cm) and (c) K (height 60 cm): brackets indicate the midden layers where wood samples were taken.*

Trees are not present in this area of Greenland, and so all the archaeological wood found in the midden has probably been transported to Greenland as driftwood (Funder *et al*. 2011). This may give a complex decay history, as some wood decay may already have taken place during the transport as driftwood, during the time the wood was lying on the beach or during use of the wooden artefacts by the Saqqaq and Dorset peoples.

MATERIALS AND METHODS

*Sampling*

Samples of archaeological wood were taken from profiles A, D and K during a field visit in August 2009, as summarized in Table 1. At profile D, samples were only taken from the outer few centimetres of the profiles (batch 3). It is assumed that these samples have been in the active layer (i.e., thawed every summer) since 1982, when Meldgaard cleaned the profiles. At profile K, the midden was completely thawed from the top to the bottom during the visits in 2009–11; samples were taken from the outer few centimetres of the profile (batch 4) and these samples were probably in the active layer even before 1982, as the midden is too thin to be permanently frozen. At profile A, samples were taken both from the active layer in the outer few centimetres of the profile (batch 2), and from 'inner' layers that have been kept permanently frozen since deposition. The latter were sampled by first removing the outer 15–20 cm of material from the profile until frozen layers were reached, and after a few days with repeated thawing and cleaning, wood samples could be taken from the frozen layers—two batches of frozen samples were taken over 2 days (batches 1a and 1b). All samples were stored in watertight plastic bags and kept cold in a

Table 1   *Samples of archaeological and modern wood*

| Sample batch | Description | From | In the midden since | In active layer since |
|---|---|---|---|---|
| 1a | Saqqaq, frozen | Profile A, north-facing | 3000–4000 years BP | Still frozen |
| 1b | Saqqaq, frozen | Profile A, north-facing | 3000–4000 years BP | Still frozen |
| 2 | Saqqaq, thawed | Profile A, north-facing | 3000–4000 years BP | *c.* 1982 |
| 3 | Dorset, thawed | Profile D, west-facing | 2000–2400 years BP | *c.* 1982 |
| 4 | Saqqaq, thawed, dry | Profile K, west-facing | 3000–4000 years BP | At least 1982—probably longer |
| Modern | Modern, thawed | Profile A, north-facing | 2009 | 2009 |

cooling bag during transport to the laboratory, where they were frozen at –20°C until analysis. Modern pine samples were placed in the active layer in profile A in August 2009. Five of these samples were retrieved at the next field visit in August 2010 and two samples were retrieved in July 2011.

*Field measurements*

The environmental conditions in the midden layers were measured *in situ* in August 2009, taking measurements for each 5 cm from the top to the bottom of profile A. The thaw depth was measured by pressing a thin steel rod horizontally into the profile until frozen layers were reached. The water content and conductivity were measured in the outer 5 cm of the profile using a WET probe from Delta-T Devices Ltd (Cambridge, UK). The pH was measured 10 cm into the profile using an SS-37 ISFET electrode from the Hach Company (Loveland, CO, USA). The temperature was measured 5 and 10 cm into the profile using the WET probe and the ISFET electrode, respectively. The oxygen concentration was measured 10 cm into the profile, using Pst3 oxygen sensors from PreSens (Precision Sensing GmbH, Regensburg, Germany). In profile D, only the water content, conductivity and temperature were measured with the WET probe, while profile K was too dry for *in situ* measurements with the probe, so here the water content was measured in the laboratory on sampled material.

The installation of automatic monitoring equipment is described in Elberling *et al*. (2011), and the first data are presented in Hollesen *et al*. (2012).

*Wood analysis*

The density of both archaeological and modern wood samples was measured as oven-dry mass/water-swollen volume, according to Jensen and Gregory (2006). The wood samples were examined visually in terms of colour and macroscopic signs of collapse both before and after drying. Optical microscopy and scanning electron microscopy were used to identify physical damage at a microscopic level on separate undried samples. Light microscopy was also used to identify wood decaying micro-organisms according to the method of Gregory and Jensen (2006), where thin transverse, radial and tangential sections were cut from each specimen by hand, using a razor blade. Sections were stained with either 1% w/v safranin in ethanol to highlight the micromorphology of the wood, or 0.1% w/v aniline blue in 50% lactic acid to stain fungal hyphae

and bacteria. Polarized light was used to demonstrate the remains of crystalline cellulose. Fungal or bacterial decay was determined using the specific decay features summarized in Blanchette *et al*. (1990).

*Oxygen consumption at different temperatures*

The oxygen consumption was measured by placing 2–3 g of archaeological wood in a 13 ml glass vial closed with an airtight lid. Subsamples were taken from larger wood pieces, but the wood was not ground or homogenized, as grinding may cause an artificially high oxygen consumption compared to whole pieces of wood (Matthiesen and Mortensen 2012). The decreasing oxygen concentration inside the vial was measured optically using Pst3 oxygen sensors from PreSens (Precision Sensing GmbH, Regensburg, Germany) and used to calculate an oxygen consumption rate according to Matthiesen (2007). The vials were kept in a water bath at a fixed temperature for a week or more, oxygen concentrations being measured every second day. Measurements took place at –5, 0, 5, 10, 15 and 20°C, with the vials being opened and aerated between each series. For measurements at 0 and –5°C, glycol was added to the water bath to avoid freezing, and it was ensured, through careful handling and the use of blank experiments, that the glycol did not pollute the wood samples or affect the measurements.

RESULTS

*Environment*

The results from the *in situ* measurements of environmental parameters are presented in Figure 3.

During the field visit in August 2009, profile A was thawed 35 cm at the top and only 4 cm at the bottom (measured horizontally into the profile). This is probably close to the maximum thaw during the year, as the air temperature in the area normally starts dropping in September (Hansen *et al*. 2006; Hollesen *et al*. 2012) and thus it represents the whole active layer in the profile. All midden layers in the profile were wet, with a water content around 50 vol%. There was 100% oxygen saturation in most layers, apart from the most dense/wet layers at 2.1 and 1.6 m above local zero, where the oxygen saturation was around 80%, and the frozen layers beneath 1.2 m, where almost anoxic conditions were found. A marked increase in conductivity in the lowest layers indicated that salt water could influence the deepest deposits at spring tide. The pH was slightly acidic (pH 5–6) and the ground temperature was between 0 and 5°C.

In profile D (facing west), the water content and conductivity were similar to the values for profile A, but the ground temperature was higher (5–9°C). In profile K, the midden layers were very dry, with a water content of less than 1 vol% (measured in the laboratory), and the midden is possibly too thin in this area to retain water and stay moist during dry periods. Thaw depth, pH and oxygen concentrations were not measured in profiles D and K.

*Wood analysis*

A few examples of optical microscopic analyses of archaeological wood samples are presented in Figure 4, showing both sound wood as well as examples of different types of decay patterns. Figure 4 (a) (permafrozen wood sample from profile A—batch 1a) shows a piece of well-preserved wood with a thick cell wall. In Figure 4 (b) (thawed wood sample from the active layer in profile A—batch 2), the cell wall is thinner, and decay by soft rot is indicated by small holes
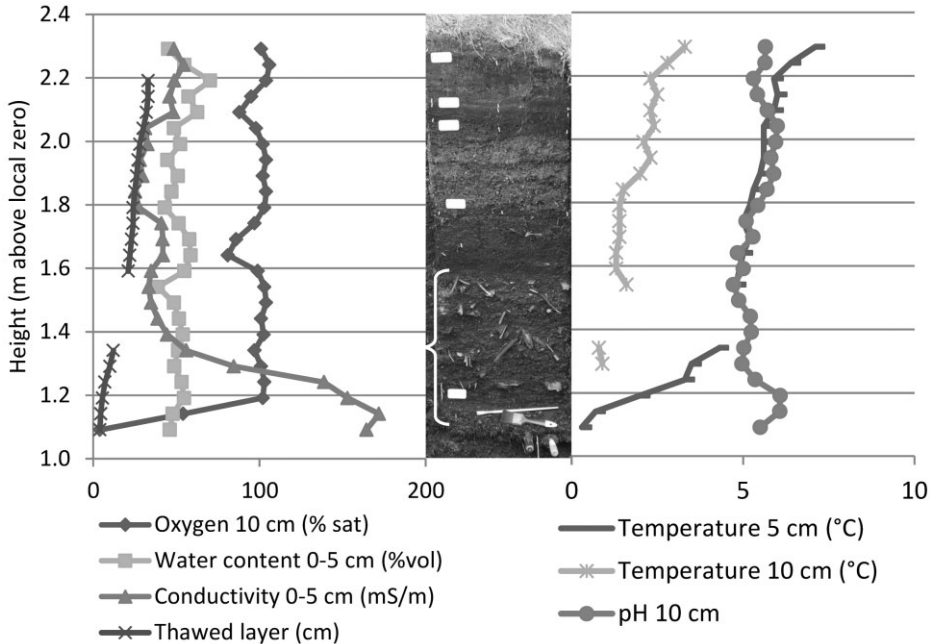
Figure 3 *Results from measurements of environmental parameters in profile A during the field visit on 2–9 August 2009: wood samples were taken from the layer between 1.1 and 1.6 m above local zero.*

in the secondary cell wall, caused by penetrating hyphae. In Figure 4 (c) (thawed wood sample from the active layer in profile D—batch 3), the cell wall is thin and appears distorted, which makes it difficult to verify if there has been microbial decay. Figure 4 (d) (thawed and dry wood sample from profile K—batch 4) shows an example of collapsed cell walls, which are often seen for archaeological wood that is dried under uncontrolled conditions. The secondary cell wall has been removed (possibly by micro-organisms, but it is difficult to confirm this), which has reduced the physical strength of the wood cells. If the wood dries out, capillary forces may cause the weakened wood cells to collapse. Evidence of decay by bacteria and soft rot was found in several wood samples, whereas no evidence of brown rot or white rot has been found.

All results from the analysis of wood samples are summarized in Table 2, including microscopy studies, density measurements, and visual observations of colour and collapse. All samples investigated were of coniferous wood.

*Oxygen consumption*

Table 3 shows oxygen consumption rates measured at different temperatures for 14 samples of archaeological wood, distributed as three samples from each batch (1a, 1b, 2 and 3), and two samples from batch 4. The average consumption and standard deviation for each batch is shown graphically in Figure 5. For the experiments at 5–20°C, the oxygen concentration in the vials was followed for a week, but at 0 and –5°C the rates were so low that measurements continued for 3 and 6 weeks, respectively, before there was a significant decrease in oxygen concentration inside the vials. At –5°C, the rates for half the samples were below the detection limit of the method, which gives an increased uncertainty on the average rates.
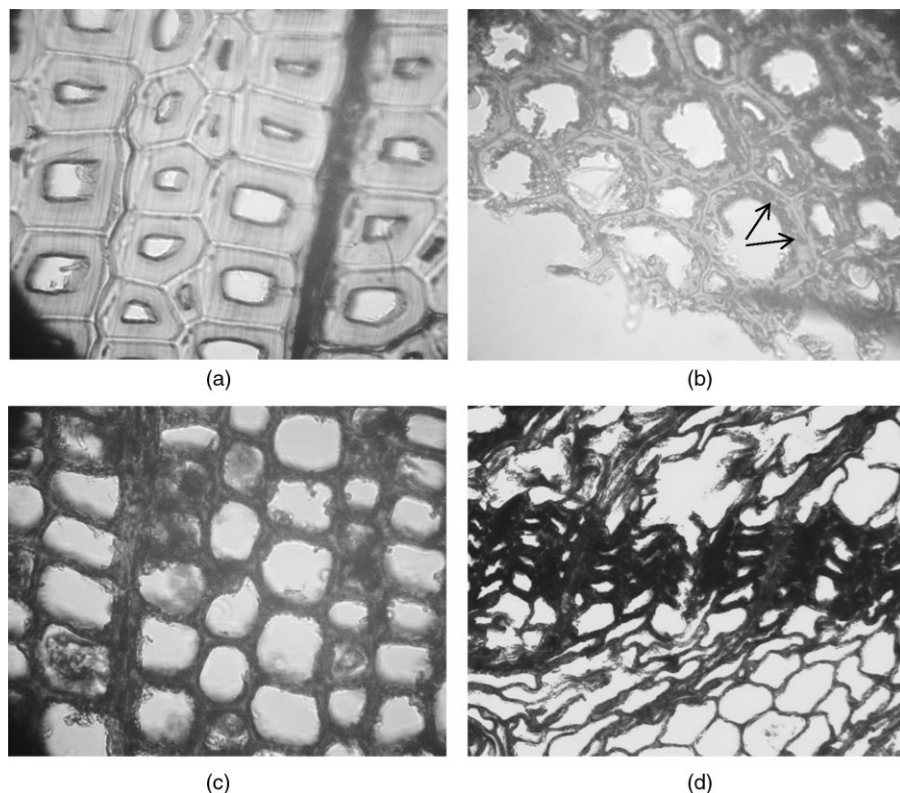
Figure 4 *Microscopy of wood—examples of different decay patterns: (a) a well-preserved wood sample; (b) decay by soft rot; (c) a distorted cell wall; (d) the cell walls have collapsed. The arrows in (b) show some of the holes in the secondary cell wall that indicate soft rot attack. The origin of the wood samples is given in the text.*

Minimum rates are found for the dry samples from batch 4, where the microbial activity may be reduced due to the lack of water. Furthermore, the microscopy studies indicate that the cellulose-rich secondary cell wall has been degraded already, leaving only the compound middle lamella, which is not degraded by soft rot (Blanchette 2000). The wet samples (batch 1–3) all show higher oxygen consumption rates, but there is no clear correlation with the batch number, origin or state of preservation of the samples. For instance, at 10°C ($R_{10}$ value), the three samples from batch 1a (profile A, frozen) show oxygen consumptions of 0.05–0.07 mg oxygen per g sample per day, but batch 1b comes from the same conditions and here the three samples only consume 0.01–0.03 mg oxygen per g sample per day. For both batch 2 and 3 (thawed samples), there is a large variation between the three samples, which consume 0.02–0.07 mg oxygen per g sample per day. As the data do not show a systematic difference between the well-preserved samples in batch 1 and the partly degraded samples in batches 2 and 3, data from all wet samples are pooled (12 samples) and the average oxygen consumption measured at different temperatures are given in Table 3, along with the standard deviation (lower row).

Despite the variations in reactivity, all wet samples show a similar response to temperature, with a significant increase in oxygen consumption with increasing temperature. Microbial activity often increases exponentially within a certain temperature region, if there are no other limitations to their activity, such as a lack of water or nutrients. Correspondingly, a logarithmic

Table 2   Short descriptions and results for different batches of wood samples. For the archaeological wood, the density was measured for two samples from each batch and both results are shown. Microscopy studies were made on two or three samples from each batch. For the modern samples, all seven samples were analysed; the results are pooled, as there were no systematic difference between the five samples that were exposed for 1 year and the two samples that were exposed for 2 years

| Sample batch | Description | Density (g cm⁻³) | Colour | Fungal decay | Bacterial decay | Collapse | Distorted cell wall |
|---|---|---|---|---|---|---|---|
| 1a | Saqqaq, frozen | 0.50/0.34 | Light | None | Superficial (traces) | None | No |
| 1b | Saqqaq, frozen | 0.38/0.29 | Light | None | Superficial (traces) | None | No |
| 2 | Saqqaq, thawed | 0.29/0.28 | Slightly discoloured | Soft rot (abundant) | Superficial | Superficial ('hollow-cheek' after drying) | No |
| 3 | Dorset, thawed | 0.20/0.25 | Dark | Possibly soft rot | Possibly erosion bacteria | Superficial ('hollow-cheek' after drying) | Yes |
| 4 | Saqqaq, thawed, dry | 0.35/0.29 | Dark | Impossible to see due to collapse | Impossible to see due to collapse | Severe (also before drying) | Yes |
| Modern | Modern, thawed | 0.35–0.43 | Light to slightly discoloured | Soft rot (outer 0.5 mm) | Not identified | No | No |

Table 3 Oxygen consumption rates (in mg oxygen per g sample per day) for 14 wood samples from batches 1–4 measured at –5 to 20°C. The samples were analysed 'as found'; that is, the samples from batches 1–3 were wet, whereas the samples from batch 4 were dry. The lower row shows the average oxygen consumption ± 1 standard deviation for the 12 wood samples from batches 1–3 (profiles A and D), excluding the dry samples from batch 4 (profile K)

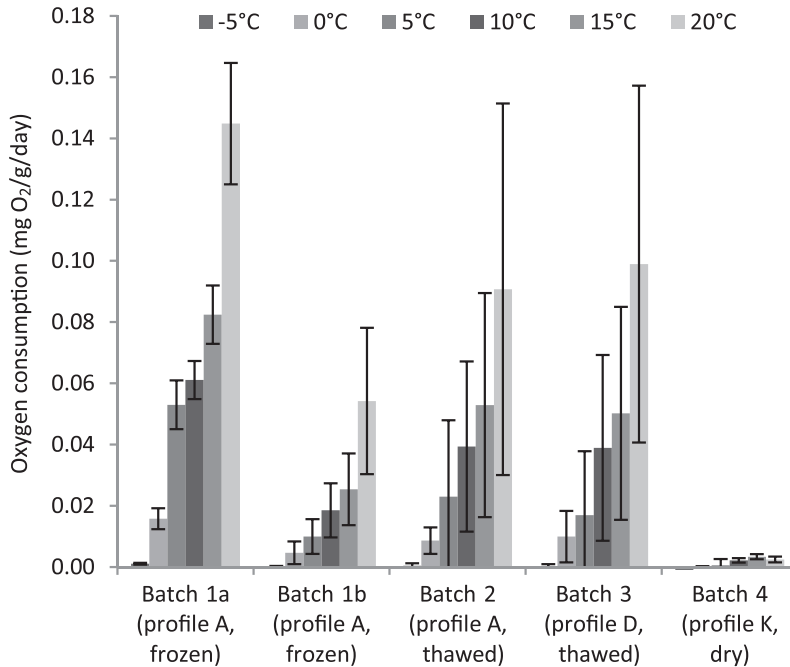| | Temperature | | | | | |
|---|---|---|---|---|---|---|
| | –5°C | 0°C | 5°C | 10°C | 15°C | 20°C |
| Batch 1a, I | 0.001 | 0.013 | 0.045 | 0.054 | 0.072 | 0.122 |
| Batch 1a, II | 0.001 | 0.020 | 0.060 | 0.065 | 0.084 | 0.153 |
| Batch 1a, III | 0.001 | 0.015 | 0.054 | 0.064 | 0.091 | 0.159 |
| Batch 1b, I | 0.000 | 0.009 | 0.016 | 0.029 | 0.039 | 0.082 |
| Batch 1b, II | 0.000 | 0.003 | 0.008 | 0.014 | 0.020 | 0.044 |
| Batch 1b, III | nm | 0.002 | 0.006 | 0.013 | 0.017 | 0.037 |
| Batch 2, I | 0.000 | 0.005 | 0.004 | 0.018 | 0.025 | 0.046 |
| Batch 2, II | 0.001 | 0.008 | 0.013 | 0.030 | 0.039 | 0.066 |
| Batch 2, III | 0.001 | 0.013 | 0.051 | 0.071 | 0.094 | 0.160 |
| Batch 3, I | 0.000 | 0.005 | 0.007 | 0.020 | 0.028 | 0.055 |
| Batch 3, II | 0.000 | 0.005 | 0.003 | 0.023 | 0.032 | 0.077 |
| Batch 3, III | 0.001 | 0.020 | 0.041 | 0.074 | 0.090 | 0.165 |
| Batch 4, I | nm | 0.000 | 0.002 | 0.003 | 0.004 | 0.002 |
| Batch 4, II | nm | 0.000 | nm | 0.002 | 0.003 | 0.003 |
| Average (batches 1–3) | $0.0004 \pm 0.0007$ | $0.010 \pm 0.006$ | $0.026 \pm 0.022$ | $0.039 \pm 0.024$ | $0.053 \pm 0.031$ | $0.097 \pm 0.051$ |

nm, Oxygen consumption 'not measurable'.

Figure 5 *Oxygen consumption rates measured at different temperatures for wood from each batch: the bars show the average and the error lines show the standard deviation of three subsamples from each batch (only two subsamples for batch 4).*

plot of the activity will often give a straight line in a certain temperature region, and the slope of this line is used to find the $Q_{10}$ value of the process; that is, the increase in activity for a 10°C increase in temperature (Fig. 6).

Different $Q_{10}$ values can be calculated for different temperature intervals: between 10 and 20°C, the oxygen consumption increases by a factor of 2.2–3.3 in the 12 wood samples from batches 1–3; between 0 and 10°C it increases by a factor of 3.2–5.3; and between –5 and 0°C it increases by a factor of 8–23 (the measurements under frozen conditions are close to the detection limit of the method and have an increased uncertainty). The dry samples (batch 4) show other $Q_{10}$ values, as the microbial activity is limited by the lack of free water and/or degradable substrate. Average values and standard deviations for the wet samples are given in Table 4. The results are in line with Kirschbaum (1995), who has reviewed several laboratory studies of the decay of soil organic matter, which give typical $Q_{10}$ values of 8 at 0°C, 4.5 at 10°C and 2.5 at 20°C. The abrupt change in reactivity for temperatures below 0°C is in line with Elberling *et al.* (2008) and Elberling and Brandt (2003), who measured $CO_2$ production of Arctic plant–soil systems and found $Q_{10}$ values of 2 for temperatures above 0°C and 22 for temperatures below 0°C.

## DISCUSSION

Three main issues need to be addressed: what is the current state of preservation of the midden and the archaeological wood; what has happened since the excavations in 1982; and what is the current decay rate? And, finally, from the two first issues, can we predict future decay rates
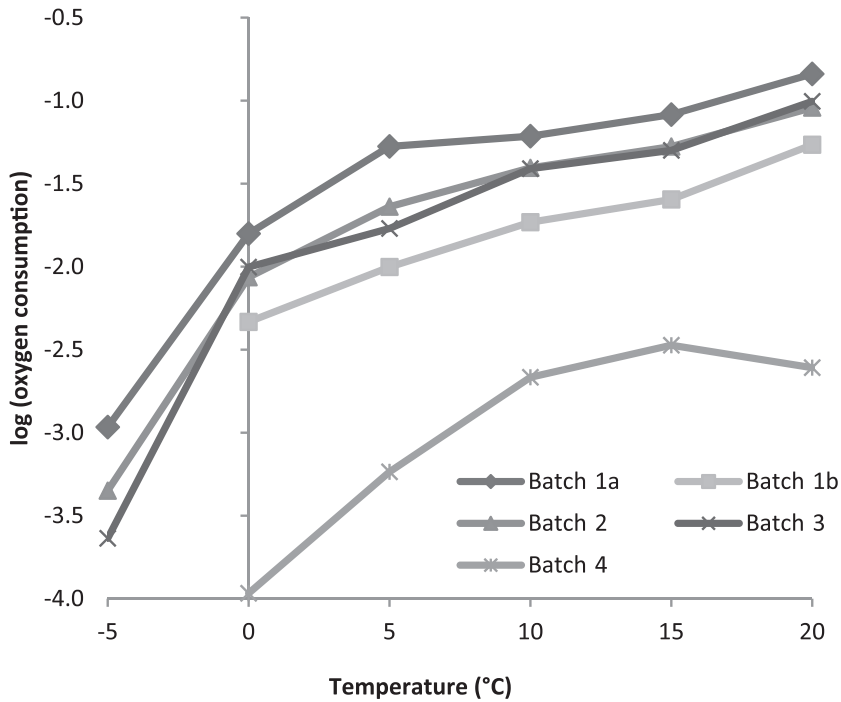
Figure 6   *A logarithmic plot of the average oxygen consumption rates for each batch of wood.*

Table 4   *Average $Q_{10}$ values for the 12 wood samples from profiles A and D (batches 1–3) for different temperature regions. The dry samples from profile K have not been included. Values are given as average $\pm$ 1 standard deviation*

| Temperature region | $Q_{10}$ value for oxygen consumption |
|---|---|
| –5 to 0°C | $16 \pm 5$ |
| 0 to 10°C | $4.2 \pm 0.8$ |
| 10 to 20°C | $2.6 \pm 0.4$ |
| 0 to 20°C | $3.2 \pm 0.6$ |

regarding future climate change? These key questions are crucial for both the permanently frozen parts of the midden and the exposed profiles where part is thawing every summer.

*The current state of preservation*

It is documented that the main part of the kitchen midden is still frozen. During the visits in 2009–11, the thaw depth was measured at 30–40 cm, which means that in the thickest part of the midden, where it is up to 3 m thick, almost 90% of the material remains permanently frozen, including the entire Saqqaq section (Elberling *et al.* 2011). The examined wood samples from the

permafrozen layers (batches 1a and 1b) were in an excellent state of preservation, with a light colour (Table 2), almost intact wood cells (Fig. 4 (a)) and a high density (0.38 g cm$^{-3}$ on average). For comparison, the density of fresh coniferous wood varies between 0.3 and 0.5 g cm$^{-3}$. No attack by fungi, and only a limited superficial decay by bacteria, was observed for the frozen samples.

The wood samples in batches 2 and 3 (from profiles A and D) have been exposed to annual thawing since 1982, and here the state of preservation is not as good: the colour of the wood has changed (Table 2), the wood cells are not intact (Figs 4 (b) and 4 (c)) and the density of the samples is reduced (0.20–0.29 g cm$^{-3}$) compared to the frozen wood and to fresh wood. There is evidence of superficial decay by bacteria, severe attack by soft rot (batch 2) and distorted cell walls (batch 3). The occurrence of soft rot (but no white rot or brown rot) is in accordance with other studies of wood decay in Arctic/Antarctic areas (Blanchette *et al*. 2004; Arenz *et al*. 2011); the absence of white rot and brown rot is particularly significant, as their presence can lead to complete disintegration of wood. The distorted cell walls (Fig. 4 (c)) could possibly be due to physical damage caused by repeated freeze–thaw cycles, or high concentrations of salts (Blanchette *et al*. 2002). The samples from batches 2 and 3 still looked relatively well preserved to the naked eye, but they showed a slight collapse of the surface ('hollow-cheek') if they were allowed to dry out in an uncontrolled manner—this means that wooden artefacts from these midden layers would have to go through a controlled conservation if they were to be excavated at some point. As for profile K (batch 4), the wood samples have already collapsed and cracked, and are of decreased archaeological value. The density of the samples is relatively high (0.32 g cm$^{-3}$), which may to some extent be explained by the collapse of the structure of the wood and changes in volume. Profile K represents a small 'island' where the midden is very thin, and all the material is thawed and very dry during the summer.

*The current decay rate*

The current decay rate is difficult to measure directly, but there are several indirect estimates. For the layers that are still permanently frozen, the decay rate is estimated to be *very* slow. Measurements of the oxygen consumption (Table 3) show that the average activity is 25 times lower at –5°C (0.0004 mg oxygen per g sample per day) compared to the activity at 0°C (0.010 mg oxygen per g sample per day), where the low activity at –5°C may be due to micro-organisms lacking fluid water and also ice blocking the diffusion of oxygen to the wood surface. Furthermore, measurements of oxygen *in situ* in the frozen layers in profile A (Fig. 3, at 1.0–1.2 m asl) indicated that only limited oxygen is available in these frozen layers.

As for the thawed layers in profiles A and D, the environmental conditions described in Figure 3 (wet and with plenty of oxygen) are much more conducive for fungi, and fungal decay is ongoing, as demonstrated by the modern wood samples placed for 1–2 years in the active layer in profile A (Table 2). The densities of the modern samples (0.35–0.43 g cm$^{-3}$) are still similar to the density of non-decayed wood (0.3–0.5 g cm$^{-3}$), indicating that 2 years in the active layer is not enough to give a measurable decrease in wood density, but after a longer period it may be possible to quantify a decay rate from these modern samples.

Until then, the decay rate of the archaeological wood may be roughly estimated from the laboratory measurements of oxygen consumption combined with the environmental measurements: At the time of sampling (August 2009), the ground temperature varied between 0 and 5°C in the outer layers of profile A (Fig. 3). A few metres from profile A, the ground temperature is measured continuously at different depths (Hollesen *et al*. 2012) and during the first

year of monitoring the deposits at 7 and 16 cm depth were thawed for 4 months (June to September), with temperatures between 0 and 5°C. At these temperatures, the average oxygen consumption rate for wet samples was measured as 0.010–0.026 mg oxygen per g wet wood per day, with a large variation between samples (Table 3). If it is assumed that the outer layers in profile A are thawed for 4 months every year and that decay only takes place in this period, a daily rate of 0.010–0.026 mg oxygen per g wet wood per day would correspond to a yearly oxygen consumption of 1–3 mg oxygen per g wet wood. If it is further assumed that the oxygen is used by micro-organisms to oxidize wood material (with an assumed empirical formula of $CH_2O$) completely to $CO_2$, 1–3 mg of oxygen may oxidize 1–3 mg of wood material; that is, the yearly loss of wood material is 1–3 mg wood per g wet wood. This corresponds to a yearly decrease in the dry density of the wood of ~0.001–0.003 g cm$^{-3}$, corresponding to 0.3–0.8% of the dry mass.

The excavations in 1982 provided a unique opportunity to estimate the decay rates in an independent way: if it is assumed that the thawed samples from profile A (batch 2) had been permanently frozen until the archaeological excavation in 1982, where all thawed material was removed from the profiles, the decay of the samples has mainly taken place during the 27 years from 1982 to 2009. The average density of the thawed samples in profile A is 0.28 g cm$^{-3}$, compared to 0.38 g cm$^{-3}$ for the frozen samples deeper in the profile (batches 1a and 1b). A decrease in wood density of 0.10 g cm$^{-3}$ over 27 years corresponds to a yearly loss of 0.004 g cm$^{-3}$, or 1% of the dry mass; that is, surprisingly close to the rate estimated on the basis of laboratory measurements. Both estimates rely on assumptions that are questionable and need to be validated: for instance, the correlation between oxygen consumption, density loss and $CO_2$ production needs to be further investigated, and the environmental conditions at Qajaa over the past 27 years need further evaluation. Furthermore, the samples are very variable and may have a complex degradation history. Still, the good correspondence between numbers indicates that the decay studies in the laboratory give results comparable to *in situ* decay, which is a prerequisite for their use in the discussion of future preservation conditions.

The samples from profile D (batch 3) showed lower densities than the thawed samples from profile A (0.22 g cm$^{-3}$ compared to 0.28 g cm$^{-3}$). If it is assumed that these samples were also permanently frozen until 1982, this indicates a slightly higher decay rate that can be explained by higher temperatures (5–9°C was measured in August 2009) and/or longer annual thawing in the west-facing profile D. The wood samples from profile K (batch 4) were heavily degraded, which may partly or completely be due to decay taking place before 1982 in this thin and dry part of the midden. A low oxygen consumption for samples from profile K indicated that further microbial decay is very slow, due to lack of moisture and substrate for the wood-degrading soft rot, whereas some physical decay due to freeze–thaw cycles may still be ongoing.

From the above discussion, we conclude that the current decay rate is low for most of the wood at Qajaa. A minor part of the midden has dried out and the wood has collapsed, but further decay will be slow. In the main part of the midden, most wood is permanently frozen and very well preserved. Only in the uppermost and outermost parts of the main midden is the wood exposed to annual thawing and decay by soft rot, but even here the decay rate is so low that the wood is relatively well preserved after 27 years.

*Future preservation*

The mean annual air temperature in the area is expected to increase by 2.5–7.5°C by the end of the 21st century (Chapman and Walsh 2007). Initial estimates of the future thawing of the midden

have been made (Elberling *et al*. 2011), and work is ongoing to model the future subsurface temperature and water regime (Hollesen *et al*. 2012). When the ground temperature is estimated, the $Q_{10}$ values found in this study may be used to estimate the consequences for the wooden artefacts in the kitchen midden.

Apart from the direct temperature effect, the exact consequences will be determined by the future water regime in the midden. At the moment, the permafrozen midden layers are filled with ice; there are anoxic conditions and a very low decay rate. If all water remains in the midden upon thawing, the midden layers will become waterlogged, the conditions will stay anoxic and non-conducive to fungi and the decay of wood will still be very slow. If most water runs off and the midden becomes unsaturated, the conditions are expected to become oxic and the decay rates will probably be similar to what we measured in the laboratory study (Table 3). If new wood-decay species of fungi such as brown rot or white rot are introduced (Ludley and Robinson 2008), the decay may accelerate even more.

## CONCLUSIONS

The results show that: (1) most of the midden at Qajaa is still permanently frozen and wood from the permafrost zone is almost perfectly preserved; (2) midden layers that have been exposed and thawed every summer since the excavations in 1982 contain wood with marked decay by soft rot and significant loss of mass; (3) short-term decay studies of archaeological wood based on laboratory measurements of oxygen consumption are in line with the 27 years *in situ* decay rates; and (4) increased temperatures give a markedly increased decay rate in the laboratory ($Q_{10} = 4.2$ between 0 and 10°C), but the exact consequences *in situ* will depend on the future water regime and thawing of the midden.

## ACKNOWLEDGEMENTS

## REFERENCES

Arenz, B. E., Held, B. W., Jurgens, J. A., and Blanchette, R. A., 2011, Fungal colonization of exotic substrates in Antarctica, *Fungal Diversity*, **49**(1), 13–23.

Barfield, L., 1994, The Iceman reviewed, *Antiquity*, **68**(258), 10–26.

Björdal, C., and Nilsson, T., 2001, Decomposition of waterlogged archaeological wood, in *Proceedings of the 8th ICOM Group on Wet Organic Archaeological Materials Conference, Stockholm, 11–15 June 2001* (eds. P. Hoffmann, J. A. Spriggs, T. Grant, C. Cook and A. Recht), 235–44, ICOM, Bremerhaven.

Blanchette, R. A., 2000, A review of microbial deterioration found in archaeological wood from different environments, *International Biodeterioration and Biodegradation*, **46**, 189–204.

Blanchette, R. A., Held, B. W., and Farrel, R. L., 2002, Defibration of wood in the expedition huts of Antarctica: an unusual deterioration process occuring in the polar environment, *Polar Record*, **38**(207), 313–22.

Blanchette, R. A., Nilsson, T., Daniel, G., and Abad, A., 1990, Biological degradation of wood, in *Archaeological wood properties, chemistry and preservation* (eds. R. M. Rowell and R. J. Barbour), 158–61, American Chemical Society, Washington, DC.

Blanchette, R. A., Held, B. W., Jurgens, J. A., McNew, D. L., Harrington, T. C., Duncan, S. M., and Farrel, R. L., 2004, Wood-destroying soft rot fungi in the historic expedition huts of Antarctica, *Applied and Environmental Microbiology*, **70**, 1328–35.

Chapman, W. L., and Walsh, J. E., 2007, Simulations of Arctic temperature and pressure by global coupled models, *Journal of Climate*, **20**, 609–32.

Elberling, B., and Brandt, K. K., 2003, Uncoupling of microbial $CO_2$ production and release in frozen soil and its implications for field studies of arctic C cycling, *Soil Biology and Biochemistry*, **35**, 263–72.

Elberling, B., Matthiesen, H., Jørgensen, C. J., Hansen, B. U., Grønnow, B., Meldgaard, M., Andreasen, C., and Khan, S. A., 2011, Paleo-Eskimo kitchen midden preservation in permafrost under future climate conditions at Qajaa, West Greenland, *Journal of Archaeological Science*, **38**, 1331–9.

Elberling, B., Nordstrøm, C., Grøndahl, L., Søgaard, H., Friborg, T., Christensen, T. R., Stroem, L., Marchand, F., and Nijs, I., 2008, High Arctic soil $CO_2$ and $CH_4$ production controlled by temperature, water, freezing, and snow, *Advances in Ecological Research*, **40**, 441–72.

Funder, S., Goosse, H., Jepsen, H., Kaas, E., Kjær, K. H., Korsgaard, N. J., Larsen, N. K., Linderson, H., Lyså, A., Møller, P., Olsen, J., and Willerslev, E., 2011, A 10,000-year record of Arctic Ocean sea-ice variability—view from the beach, *Science*, **333**, 747–50.

Goodell, B., Nicholas, D. D., and Schultz, T. P., 2003, *Wood deterioration and preservation*, American Chemical Society, Washington, DC.

Gregory, D., and Jensen, P., 2006, The importance of analysing waterlogged wooden artefacts and environmental conditions when considering their *in situ* preservation, *Journal of Wetland Archaeology*, **6**, 65–81.

Gregory, D., Helms, A. C., and Matthiesen, H., 2009, The use and deployment of modern wood samples as a proxy indicator for biogeochemical processes on archaeological sites preserved *in situ* in a variety of environments of differing saturation level, *Conservation and Management of Archaeological Sites*, **10**, 204–22.

Hansen, B. U., Elberling, B., Humlum, O., and Nielsen, N., 2006, Meteorological trends (1991–2004) at Arctic Station, central West Greenland (69°15'N) in a 130 years perspective, *Danish Journal of Geography*, **106**, 45–55.

Held, B. W., Jurgens, J. A., Arenz, B. E., Duncan, S. M., Farrel, R. L., and Blanchette, R. A., 2005, Environmental factors influencing microbial growth inside the historic expedition huts of Ross Island, Antarctica, *International Biodeterioration and Biodegradation*, **55**, 45–53.

Hicks, W. T., and Harmon, M. E., 2002, Diffusion and seasonal dynamics of $O_2$ in wood debris from the Pacific Northwest, USA, *Plant and Soil*, **243**, 67–79.

Hollesen, J., Jensen, J. B., Matthiesen, H., Elberling, B., Lange, H., and Meldgaard, M., 2012, The future preservation of a permanently frozen kitchen midden in Western Greenland, *Conservation and Management of Archaeological Sites*, **14**, 1–2, 158–67.

IPCC (Intergovernmental Panel on Climate Change), 2007, *Climate change 2007: synthesis report. Summary for policymakers*, IPCC, Geneva.

Jensen, P., and Gregory, D., 2006, Selected physical parameters to characterize the state of preservation of waterlogged archaeological wood: a practical guide for their determination, *Journal of Archaeological Science*, **33**, 551–9.

Juhl, H. B., Botfeldt, K., and Andersen, L. B., 2012, The ability of waterlogged wood to resist freezing, in *Proceedings of the 11th ICOM–CC conference on Waterlogged Organic Archaeological Materials, Greenville, May 2010* (eds. K. Strætkvern and E. Watson), 343–54, ICOM–CC, Paris.

Kenward, H., Hall, A., and Matthiesen, H., 2008, Patterns of early-stage taphonomy in plant and insect macrofossils: testing hypothesis in relation to post-depositional mass decay of organic-rich archaeological deposits, in *Proceedings of the conference 'Preserving Archaeological Remains in situ 3', Amsterdam, December 2006* (eds. H. Kars and R. M. van Heeringen), 29–36, Geoarchaeological and Bioarchaeological Studies 10, Institute for Geo- and Bioarchaeology, VU University Amsterdam.

Kirschbaum, M. U. F., 1995, The temperature dependence of soil organic matter decomposition, and the effect of global warming on soil organic C storage, *Soil Biology and Biochemistry*, **27**, 753–60.

Ludley, K. E., and Robinson, C. H., 2008, 'Decomposer' Basidiomycota in Arctic and Antarctic ecosystems, *Soil Biology and Biochemistry*, **40**, 11–29.

Matthiesen, H., 2004, *In situ* preservation and monitoring of the cultural layers below Bryggen, in *Safeguarding historic waterfront sites: Bryggen in Bergen as a case study* (eds. A. Christensson and Z. Paszkowski), 69–73, Stiftelsen Bryggen, Sczcecin/Bergen.

Matthiesen, H., 2007, A novel method to determine oxidation rates of heritage materials *in vitro* and *in situ*, *Studies in Conservation*, **52**, 271–80.

Matthiesen, H., and Mortensen, M. N., 2012, Oxygen measurements in conserved archaeological wood, in *Proceedings of the 11th ICOM–CC conference on Waterlogged Organic Archaeological Materials, Greenville, May 2010* (eds. K. Strætkvern and E. Williams), 123–35, ICOM–CC, Paris.

Matthiesen, H., Hilbert, L. R., Gregory, D., and Sørensen, B., 2007, Long-term corrosion of iron at the waterlogged site of Nydam in Denmark: studies of environment, archaeological artefacts, and modern analogues, in *Corrosion of metallic heritage artefacts: investigation, conservation and prediction for long-term behaviour* (eds. P. Dillmann, G. Béranger, P. Piccardo and H. Matthiesen), 272–92, Woodhead Publishing Ltd, Cambridge.

Meldgaard, J., 1982, Qajâ, en køkkenmødding i dybfrost: feltrapport fra arbejdsmarken i Grønland, *Nationalmuseets Arbejdsmark*, 83–96, National Museum of Denmark, Copenhagen.

Nordenskiöld, A. E., 1871, Redogörelse for en expedition till Grönland år 1870, *Öfersigt af Kongl, Vetenskaps-Akademicus Förhandlinger*, **10**, 973–1087.

Pollard, A. M., 2012, Can the principles of soil organic matter turnover models be applied to archaeological organic material? *Quaternary International*, **275**, 104–11; http://dx.doi.org/10.1016/j.quaint.2011.05.013

Rasmussen, M., Li, Y., Lindgreen, S., Pedersen, J. S., Albrechtsen, A., Moltke, I., Metspalu, M., Metspalu, E., Kivisild, T., Gupta, R., Bertalan, M., Nielsen, K., Gilbert, M. T., Wang, Y., Raghavan, M., Campos, P. F., Kamp, H. M., Wilson, A. S., Gledhill, A., Tridico, S., Bunce, M., Lorenzen, E. D., Binladen, J., Guo, X., Zhao, J., Zhang, X., Zhang, H., Li, Z., Chen, M., Orlando, L., Kristiansen, K., Bak, M., Tommerup, N., Bendixen, C., Pierre, T. L., Grønnow, B., Meldgaard, M., Andreasen, C., Fedorova, S. A., Osipova, L. P., Higham, T. F. G., Ramsey, C. B., Hansen, T., Nielsen, F. C., Crawford, M. H., Brunak, S., Sicheritz-Pontén, T., Villems, R., Nielsen, R., Krogh, A., Wang, J., and Willerslev, E., 2010, Ancient human genome sequence of an extinct Palaeo-Eskimo, *Nature*, **463**, 757–62.

Stusek, P., Pohleven, F., and Capl, D., 2000, Detection of wood boring insects by measurement of oxygen consumption, *International Biodeterioration and Biodegradation*, **46**, 293–8.