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- not more than 10 figures (black and white)

CONSERVATION AND MGMT OF ARCH. SITES, Vol. 14 Nos 1–4, 2012, 159–68

The Future Preservation of a Permanently Frozen Kitchen Midden in Western Greenland

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Archaeological materials may be extraordinarily well preserved in Arctic areas, where permanently frozen conditions in the ground slow down the decay of materials such as wood, bone, flesh, hair, and DNA. However, the mean annual air temperature in the Arctic is expected to increase by between 2.5 to 7.5° C by the end of the twenty-first century. This may have a significant warming effect on the soil and could lead to permafrost thaw and degradation of currently frozen archaeological remains. Here we present a four-year monitoring and research project taking place at Qajaa in the Disko Bay area in West Greenland. Qajaa is a large kitchen midden, containing frozen remains from 4000 years of inhabitation, from when the first Palaeo-Eskimos entered Greenland, until the site was abandoned in the eighteenth century. The purpose of the project is to investigate current preservation conditions through field and laboratory measurements and to evaluate possible threats to the future preservation.

Preliminary results show that the archaeological material at Qajaa is still very well preserved, but some microbial decay is observed in the exposed wooden artefacts that thaw every summer. Maximum temperatures are above 0° C in the upper 40–50 cm of the midden and between 0 and –2° C

DOI 10.1179/1350503312Z.00000000013

down to 3 m depth. Thereby the permafrost may be vulnerable to quite small increases in air temperatures. Laboratory measurements show that the decay of the archaeological wood in the midden is temperature-dependent, with rates increasing 11–12% every time the soil temperature increases 1° C. Moreover, the soil organic material produces heat when decomposed, which could have an additional warming effect on the midden. At the moment the water or ice content within the midden is high, limiting the subsurface oxygen availability. Threats to the future preservation are related to further thawing followed by drainage, increased oxygen availability, microbial decay of the organic material, and heat production.

KEYWORDS Palaeo-Eskimo, midden, preservation, permafrost, Greenland

Introduction

Most Palaeo-Eskimo sites in Greenland lack well-preserved organic artefacts because organic materials such as wood, fat and skin quickly decompose in the presence of oxygen and above zero temperatures. However, at a few archaeological kitchen middens a combination of high disposal rates and favourable hydrological conditions have caused the permafrost to move up into the deposited material fast enough to preserve the organic material. At these sites important organic archaeological materials are found that may hold the information needed to provide insight to the earliest documented human expansion into Greenland by the Palaeo-Eskimo Saqqaq culture. This was recently shown by Rasmussen et al. (2010) who used a 4000-year-old hair from a permanently frozen kitchen midden at Qeqertasussuk in Western Greenland to extract the complete human genome of a Saqqaq man.

Temperatures are currently rising in Greenland and Global Climate Models predict an increase in the Arctic mean annual air temperature of between 2.5 to 7.5° C by the end of the twenty-first century (Chapman and Walsh, 2007). Even a small increase in the air temperature may have a great influence on the thermal state of permafrost (Romanovsky et al., 2007; Hollesen et al., 2011a) and hence the future preservation of the archaeological kitchen middens may be threatened. One of the sites that are at risk is the Qajaa kitchen midden at the Ilulissat Ice Fjord in western Greenland. With 250 cm of organic archaeological layers embedded in the permafrost, this is considered the best-preserved site for Saqqaq and Dorset culture in all of Greenland. The site was last subject to investigations in 1982 and since then the mean annual air temperature has increased by more than 2° C (Carstensen and Jørgensen, 2011). The question is whether the state of preservation has changed during the last twenty-eight years and whether future climatic changes may cause the Qajaa kitchen midden to thaw and decay.

In this paper we present a four-year monitoring and research project at the Qajaa kitchen midden that aims to investigate the current preservation conditions through field and laboratory measurements and to evaluate possible threats to the future preservation.

Study site

The Qajaa kitchen midden is situated 18 km south-east of Ilulissat at the Ilulissat Icefjord in the western central part of Greenland (Figure 1). The annual mean temperature in Ilulissat is −4.5 ± 1.7° C (1974 to 2004) and the annual amount of precipitation is 266 mm (1961 to 1984) (Carstensen and Jørgensen, 2011).

The kitchen midden has been known at least since 1871 when the first Palaeo-Eskimo artefacts were collected (Meldgaard, 1983). The midden primarily consists of peat but also contains rocks from fireplaces, bones from animals, and anthropogenic materials such as tools. The midden is up to 300 cm thick and consists of at least four layers representing three individual periods of settlement in the area (Figure 2). The first 120 cm thick layer from the bottom represents the Saqqaq people who lived year-round at the site from around 2000–1000 BC, followed by 20–30 cm peat without evidence of human activity (1000–400 BC). This layer may represent a colder and wetter period of time, which is overlaid by a 2–30 cm thick layer representing the hunters of the Dorset people living in the area from about 400–200 BC. The uppermost archaeological layer (in some places up to 1 m thick) has been dated to represent the last immigration of Eskimos to Greenland (the Thule People) who inhabited the site from 1200–1750 AD. The kitchen midden is in most places covered by a sand layer of about 20 cm.

Methods

Field measurements

Fieldwork was conducted in August 2009 and 2010. A meteorological station was placed at the top of the kitchen midden (Figure 1), logging air temperature and relative humidity (Campbell Scientific, 215 Temperature probe), wind speed and wind direction (Campbell Scientific, 05103-5 wind monitor), and snow depth (Campbell Scientific, SR50 Sonic Ranging Sensor). A hole was drilled at the top of the kitchen midden down to a depth of 340 cm. Temperature sensors (Campbell Scientific T-107 sensors) were installed at 0, 7, 16, 32, 50, 120, 170, 220, 270, 320 cm depth. Moreover, soil water content, thermal conductivity, and heat capacity sensors were installed at 7, 16, 20, and 32 cm depth using Theta Probe, Soil Moisture Sensors (ML2x, Delta-T Devices Ltd, Cambridge, UK), and Specific Heat Sensors (East 30 Sensors). All of the sensors were connected to a Campbell Scientific Cr1000 datalogger programmed to log every three hours.

Oxygen concentrations were measured during the field campaigns at different depths in the soil using the oxygen optode technique (Glud et al., 2000) with calibrated oxygen sensor foils (SF-PSt3-NAU-YOP) and a fibre optic meter (Fibox3LCD) from Pre-Sens.

Depth specific soil samples were taken from the drilling core. Moreover, wooden artefacts were collected in order to investigate the current state of preservation. During the archaeological investigations in 1982 several soil profiles were made that could still be found in 2009. Artefacts were collected from the profiles to represent different environmental conditions such as frozen/thawed and wet/dry.

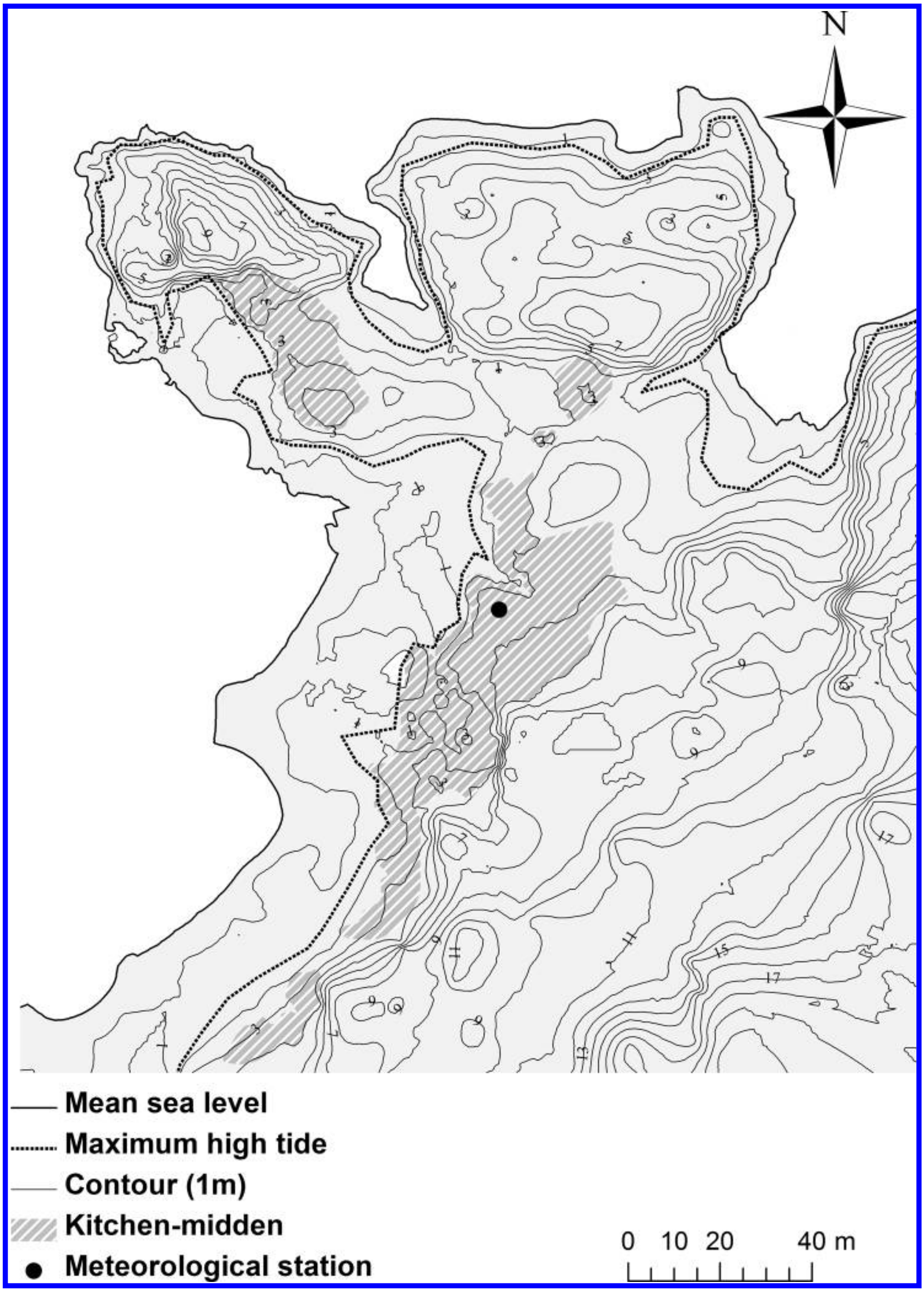

FIGURE 1 Map of Qajaa, with the kitchen midden outlined (shaded area).

FIGURE 2 The Qajaa kitchen midden contains thick layers of refuse that represents three individual periods of settlement during the last 4000 years. The archaeological layer representing the Thule People is very limited on this picture.
Photograph by Jesper Stub Johnsen

Laboratory experiments

The oxygen consumption rates were measured in wood samples from the Saqqaq layers at 0, 5, 10, 15, and 20° C to investigate the temperature dependency of the decay. Two permafrozen samples (sample 1 and 2) and one unfrozen sample (sample 3) were used. Measurements were made in three replicates of each sample according to Matthiesen (2007). In short: 3–5 g samples of wood were transferred to 12.1 ml glass vials, the samples were flushed with atmospheric air and the vials closed with an airtight lid. The oxygen consumption was subsequently measured by monitoring the decrease of headspace O_2 concentrations over time by using oxygen optodes from PreSens (www.presens.de).

Heat production from the decomposition of the soil organic bulk material was measured calorimetrically under aerobic conditions at 15° C for ten permafrost samples (< 2 mm). Samples from the following depth intervals were included: 40–46 cm, 56–62 cm, 76–86 cm, 100–16 cm, 136–48 cm, 168–90 cm, 192–94 cm, 226–38 cm, 267–80 cm, and 323–38 cm. Measurements were made using a thermal-activity monitor (type 2277, Thermometric, Sweden, or C3-analysentechnik, Germany) equipped with ampoule cylinders (4 ml twin, type 2277-201, and 20 ml twin, type 2230) and measured according to Elberling et al. (2000). Glass ampoules containing 10 g of soil were freely drained and exposed to air for 2 days before inserted in the measurement cylinders. After thermal equilibration (within 12 h), the heat output was recorded.

In order to identify macroscopic damages the collected wooden artefacts were first visually inspected and then the density (oven-dry mass/swollen volume) was measured in order to determine the degree of degradation. Optical and scanning electron microscopic imaging (SEM) was used to identify microscopic damages of the wood tissue.

Results and discussion

The mean air temperature during the observation period (26 August 2010–19 July 2011) is −4.9° C with a temperature variation from 10.6° C to −23.0° C (Figure 3a). The mean soil temperatures vary from −3.1° C at the surface to −2.1° C in the deepest layers (−320 cm depth). The temperature variation at the surface is somewhat lower than in the air (6° C to −15° C) which is mainly due to surface evaporation lowering temperatures during the summer and a surface snow cover increasing

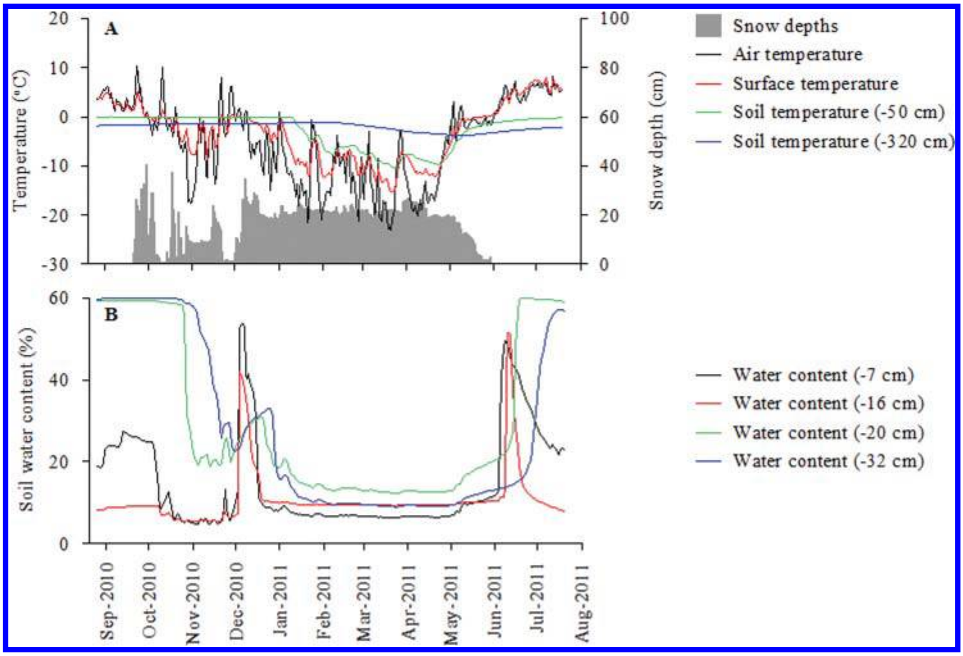

FIGURE 3 (A) The lines show measured air and soil temperatures in the Qajaa kitchen midden and the bars show measured snow depths. (B) Measured soil water contents in upper layers of the kitchen midden. NB. The low water contents seen during the winter period are due to freezing.

temperatures during the winter. The temperature variation decreases further with depth and is only −1.2 to −3.8° C in the deepest part of the midden. Only the upper 50 cm of the kitchen midden thaw every summer and the midden is permanently frozen below (Figure 3a). As seen in Figure 3a and b, the freezing of the soil is significantly delayed by a mild period in December where snow melt and water infiltration causes the upper layers of the soil to thaw. Thereby the soil is first completely frozen in the beginning of January. Such a thaw event may result in the formation of a thick ice layer that may change insulating effect of snow and act as an impermeable layer that can prevent cold winds from penetrating the midden. The soil remains frozen until the beginning of June where above zero air and surface temperature initiates snow melt and soil thaw. During the snow melt period in the beginning of June the whole soil profile gets water saturated but this only lasts for a couple of weeks in the upper 15–20 cm (Figure 3b). Thereafter, the upper 15–20 cm of kitchen midden remains relatively dry during the summer whereas the midden remains water saturated from 20 cm and below. These results are in good agreement with measurements of oxygen that show 90 to 100 per cent oxygen saturation in the dry upper part of the midden and almost no oxygen in the water saturated parts or in the deeper, frozen parts. The decrease in water content seen during the autumn is due to freezing and thus has no influence on the oxygen content in the kitchen midden. As the vast majority of the archaeological layers are located in the permanently frozen and water saturated part of the kitchen midden the current preservation conditions are considered to be good. This is confirmed by the investigations of the collected wooden artefacts which show that the permanently frozen artefacts are in excellent conditions (Matthiesen et al., in press).

Laboratory investigations confirm that soil temperatures and water content play a very important role in relation to the preservation of the organic archaeological materials found at Qajaa. Investigations of decay patterns show that wood which have been submitted to freeze/thaw the last twenty-seven years are significantly more decayed than the permafrozen wooden artefacts (Matthiesen et al., in press).

Investigations of oxygen consumption rates show that the oxygen consumption in the wood samples increases exponentially with temperature (Figure 4). The temperature dependency is often expressed using the Q_{10} value — which is the proportional change in rates given a 10° C change in temperature:

$$Q_{10} = \left(\frac{R_2}{R_1}\right)^{\left(\frac{10}{T_2 - T_1}\right)} \qquad \text{(eq. 1)}$$

where R_1 and R_2 are the reaction rates at temperatures T_1 and T_2.

In the temperature interval from 0 to 20° C Q_{10} values from 2.7 to 3.4 were found for the exponential fits. The percentage change in decomposition rates (D_x) due to a change in temperature can then be calculated as:

$$D_x = \left(Q_{10}^{\left(\frac{T_2 - T_1}{10}\right)} - 1\right) * 100\% \qquad \text{(eq. 2)}$$

Thereby, a temperature increase of 1° C could increase decomposition rates of the wooden material by 11–12%, a 5° C increase by 65–85% and a 10° C increase by 170–240%. The temperature dependency was measured in samples with *in situ* water

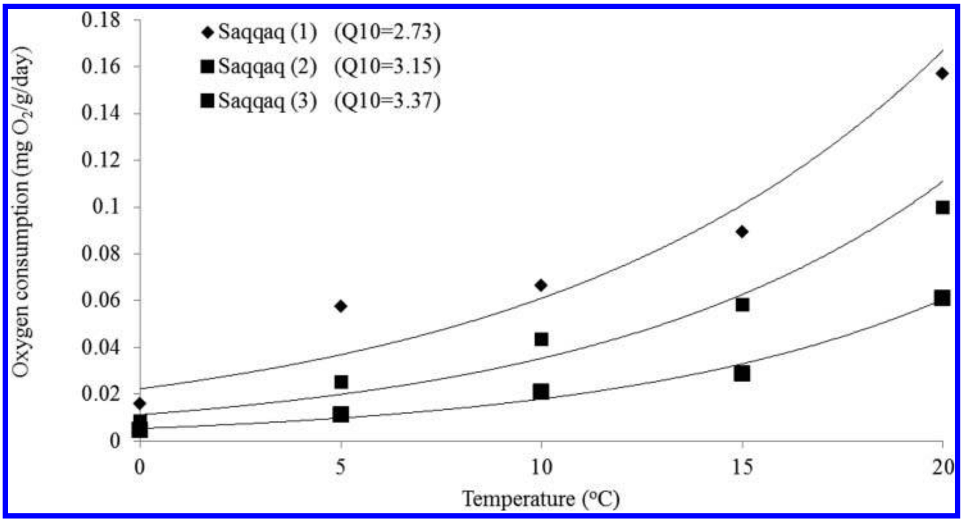

FIGURE 4 Temperature dependent oxygen consumption rates measured in wooden samples taken from the Saqqaq layers. Samples 1 and 2 were taken from permafrozen layers and sample 3 from soil layers that thaw during the summer.

contents. As discussed above, the future preservation of the archaeological materials will depend on a combination of soil temperatures and soil water contents. Consequently, to fully understand the sensitivity of the materials to future changes the oxygen consumption should be measured not only at different temperatures but also at different water contents.

Ground warming and decomposition of organic material may also produce heat, which can impose a positive feedback on soil temperatures leading to further soil thaw and decomposition of organic materials (Khvorostyanov et al., 2008). Measurements of heat production rates show an average heat production at 15° C of 18 μW/g dry soil which is twenty times higher than what have been measured in a natural permafrost soil (Hollesen et al., 2011a) and ten times higher than what have been measured in Arctic coal mine waste (Elberling et al., 2007; Hollesen et al., 2011b). The results therefore suggest that heat production from the decaying organic layers could become very important as a positive feedback mechanism (additional warming) if the kitchen midden starts to thaw and particularly if thawing occurs in combination with drainage.

Although the current preservation conditions at Qajaa are considered good, preliminary results indicate that the future preservation of the kitchen midden may be threatened by soil thaw.

The permafrost is surprisingly warm at the moment with annual mean temperatures in the deepest layers of the kitchen midden (220–320 cm) varying from −2.2 to −2.1° C. Considering that air temperatures are expected to increase with 2.5 to 7.5° C by the end of the twenty-first century (Chapman and Walsh, 2007) the upper layers of the permafrost are in great risk of thawing. At the moment only the upper 50 cm of the soil thaws every summer, but the thickness of this 'active layer' will increase if air temperatures increase. Investigations from Zackenberg in central North-east

Greenland show that an increase in the mean annual air temperature of 1° C from 1996 to 2007 caused the active layer to increase by more than 1 cm per year (Hollesen et al., 2011a). The important Dorset and Saqqaq layers are found at 110 cm depth and below and hence the preservation of these layers will only be threatened if the thickness of the active layer exceeds this depth. Moreover, if the archaeological layers thaw, the preservation of the organic material will depend on whether the layers remain water saturated or not. A simple analytical model investigation (Elberling et al., 2011) indicates that maximum thawing depth at Qajaa will increase by 10–30 cm the next seventy years depending on the degree of climate change, thus, the important Dorset and Saqqaq layers do not seem directly threatened by thawing. However, this model was not based on meteorological data from Qajaa and it did not include temporal trends in precipitation and soil water content or the effect of heat production from the decomposition of organic layers. Considering the high soil temperatures and heat production rates presented in this study, future preservation conditions can only be fully evaluated by including site-specific data from Qajaa.

Conclusion and future investigations

Preliminary results show that archaeological materials in the Qajaa kitchen midden are very well preserved because permafrost and a high water and ice content limit decay processes. However, current mean annual soil temperatures of −2° C questions whether or not the permafrost will survive the predicted increase in air temperatures of 2.5 to 7.5° C. Investigations of wooden artefacts show that summer thaw and draining cause microbial decay. Laboratory measurements show that the decay of the wooden artefacts in the midden could increase by 12 per cent every time the soil temperature increases with 1° C and hence even small changes in soil temperature may have a great effect on the preservation. Moreover, the decaying soil organic material produces heat that may increase soil temperatures and thereby increase decay rates even more. However, decay rates and heat production will only increase if the soil drains and the availability of oxygen increases. The exact sensitivity of the decay rates to soil water content is still unknown. Future investigations will focus on performing measurements of decay rates at different water contents on samples from both the soil bulk material and from the different archaeological artefacts. Additionally, factors such as air temperature, precipitation rates, snow, vegetation, and topography will be investigated to fully evaluate the future risk of permafrost thaw and draining. This will be done by using a numerical heat and water flow model.

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