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THE IMPACT OF CLIMATE CHANGE ON AN ARCHAEOLOGICAL SITE IN THE ARCTIC*

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Climate change may accelerate the degradation of archaeological sites in the Arctic and lead to a loss of important historical information. This study assesses the current preservation conditions and the processes controlling the physical and chemical stability of the Qajaa kitchen midden in western Greenland. Currently, the site is well protected by low ground temperatures, permafrost and a high water/ice content, keeping the deposits anoxic. Based on 5 years of monitoring data, degradation experiments and model simulation, our results suggest that the combined effects of permafrost thaw, thermal and hydrological erosion and oxygen exposure may lead to substantial loss of archaeological evidence before the end of the 21st century.

KEYWORDS: CULTURAL HERITAGE, ARCHAEOLOGY, CLIMATE CHANGE, PRESERVATION, MICROBIAL DEGRADATION, PERMAFROST, GREENLAND

INTRODUCTION

Cold and favourable hydrological conditions have preserved organic archaeological materials for millennia in Arctic areas, resulting in extraordinary finds (Grønnow 1994; Hebsgaard *et al.* 2009; Rasmussen *et al.* 2010). With many archaeological sites still being intact, their potential to provide further insight into human settlement and living conditions is considered high. The climate is changing rapidly in the Arctic (IPCC 2013), which may lead to an accelerated degradation of archaeological sites (Blankholm 2009). Changes in air temperatures cause permafrost thaw (Hollesen *et al.* 2011; Schaefer *et al.* 2011) that may expose hitherto well-preserved archaeological deposits and artefacts to accelerated chemical and physical degradation (Hollesen *et al.* 2015a; Andrews *et al.* 2016). Changes in precipitation affect the water balance and may affect the rate of degradation, as both very dry and almost saturated conditions may restrict microbial processes (Hollesen and Matthiesen 2015; Hollesen *et al.* 2016). Warmer winters and increasingly favourable growing season conditions lead to more and denser vegetation with deeper roots (Epstein *et al.* 2012; Henry *et al.* 2012) that may cause physical damage to buried artefacts and destruction of site stratigraphy. Rising sea level, reduced sea ice cover and storm surge impacts may increase coastal erosion rates and represent a threat to the many archaeological sites located close to the sea (Friesen 2015). There have been numerous discussions on the effect of climate change on natural soils in the Arctic (Vonk *et al.* 2012; Bintanja and Selten 2014; Myers-Smith *et al.* 2015; Schuur *et al.* 2015), but so far the effects

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on the preservation of archaeological sites are still largely unknown, although a few studies have focused on the effects in cold regions outside the Arctic (Bourgeois *et al.* 2007; Westley *et al.* 2011; Rogers *et al.* 2014).

In 2009, we initiated a study aiming at assessing the preservation and long-term protection of the important Palaeo Eskimo site of Qajaa in West Greenland, where 3.0 m thick, mostly frozen kitchen midden layers represent 4000 years of history. The site is part of the newly established Ilulissat Icefjord UNESCO World Heritage Site and is considered the best-preserved location of the Palaeo-Eskimo Saqqaq and Dorset cultures in the whole of Greenland (Grønnow 2011). In this area, a significant warming has already occurred over the past two decades (Danish Meteorological Institute 2016) and it is predicted that the mean annual air temperature in 2100 will be 2.2–5.2 °C higher than the 1986–2005 mean (Collins *et al.* 2013).

In this paper, we combine all of the data collected at the Qajaa midden from 2009 to 2014. Some of the results have previously been reported (Elberling *et al.* 2011; Hollesen *et al.* 2012, 2015a, 2016; Matthiesen *et al.* 2014a,b), but are presented here in a new context and in combination with new data to provide what is to date the most detailed assessment of processes controlling the preservation of an archaeological site in the Arctic. This is done by investigating: (i) the physical stability of the site; (ii) the climatic and environmental conditions at the site; (iii) the thermal and hydrological characteristics of the archaeological deposits; (iv) the degradability of the archaeological deposits and artefacts; and (v) the future preservation potential of the site.

THE STUDY SITE

The archaeological heritage site of Qajaa is situated 20 km south-east of Ilulissat, on the southern side of the Ilulissat Icefjord in the western central part of Greenland (Fig. 1). The kitchen midden at the site has been known at least since 1871, when the first Palaeo-Eskimo artefacts were collected (Meldgaard 1983). The climate in Ilulissat is Arctic, with an average annual mean temperature of −4.2 ± 2.0 °C (1984–2014) (Cappelen 2015) and mean annual precipitation of 266 mm (1961–1984) (Danish Meteorological Institute 2016). Qajaa is located in the continuous permafrost zone and the permafrost thickness in the area around Ilulissat has been estimated to be around 200 m (Kern-Hansen 1990).

The kitchen midden consists primarily of peat but also rocks from fireplaces, animal bones and anthropogenic materials such as tools made of wood, bone, stone, baleen and iron. It covers an area of approximately 2900 m^2, has a maximum thickness of approximately 300 cm and consists of at least four distinct layers representing three individual periods of settlement in the area (Figs 1 and 2). The deepest layer represents the Palaeo-Eskimo Saqqaq culture, which lived year-round at the site from around 2000 BC to 1000 BC, followed by peat without evidence of human activity (1000–400 BC). This layer may represent a colder and wetter period of time, and is overlain by a layer representing the Palaeo-Eskimo Dorset culture from about 400 BC to 200 BC. The uppermost archaeological layer represents the Thule people, who inhabited the site from 1200 BC to AD 1750. The topsoil layer is organic-rich and in most places contains two or three distinct but thin (1–3 cm) sand/gravel horizons. The outer margin of the midden, which faces the sea, is characterized by vertical erosion fronts. The area surrounding the midden is covered by soils less than 50 cm thick, with poor soil development (entisol/crysol) and with a few centimetres of a thick organic-rich topsoil layer. In wet locations, peat layers up to 50 cm thick are found.

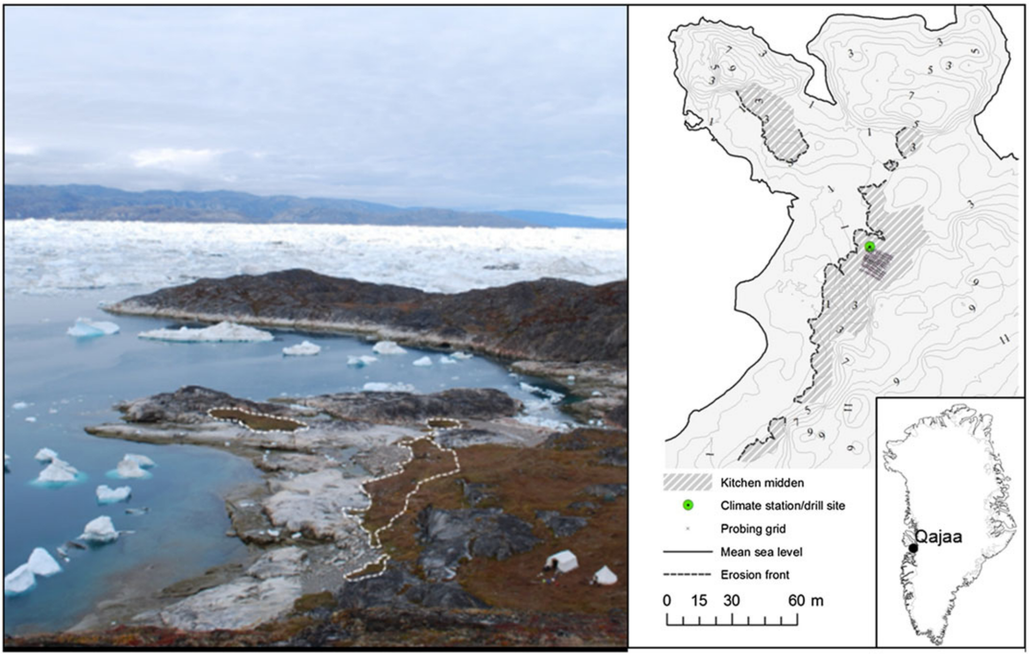

Figure 1 *The Qajaa site seen from above, with the white lines indicating the areas with kitchen midden deposits (left), and a site map showing the location of the Qajaa kitchen midden in West Greenland (right). [Colour figure can be viewed at wileyonlinelibrary.com]*

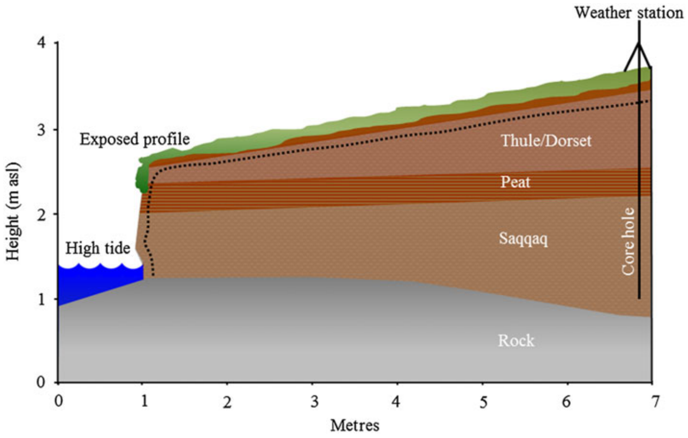

Figure 2 *A cross-section of the midden from the weather station to the exposed profile. The dotted line marks the depth of the active layer. [Colour figure can be viewed at wileyonlinelibrary.com]*

MATERIALS AND METHODS

Investigating the physical stability of the site

The midden was mapped using high-precision GPS (Trimble R8 DGPS) and the collected data was used to create a digital elevation model (DEM) of the midden using ArcGIS (Esri). An automatic water-level logger (Cera-Diver) was installed at the site in order to measure the variations in sea level throughout the year. These measurements were compensated for changes in air pressure (BaroDiver). The midden was extensively photographed during all field campaigns from 2009 to 2014, to document and quantify current erosion. In order to document erosion over a longer timescale, the photos were compared to photographs from an archaeological excavation in 1982 (Meldgaard 1983).

Investigating the environmental conditions at the site

A meteorological station was placed at the top of the kitchen midden in 2010 (Fig. 1), measuring air temperature and relative humidity (Campbell Scientific, 215 Temperature probe), wind speed and wind direction (Campbell Scientific, 05103–5 wind monitor), snow depth (Campbell Scientific, SR50 Sonic Ranging Sensor) and, from July 2011, rainfall (Campbell 52202 Tipping Bucket Rain gauge). Soil temperature probes (Campbell Scientific, 107 temperature probes) were installed at depth of 0, 7, 16, 32, 50, 120, 170, 220, 270 and 320 cm in the borehole from the core sampling (Fig. 3). Furthermore, volumetric soil water Theta Probes were installed in the upper part of the soil, which thaws every summer (the active layer), at depths of 7, 20 and 32 cm (ML2x, Delta-T Devices Ltd, Cambridge, UK), and thermal conductivity and heat capacity sensors at 7 cm depth (East 30 Sensors). All sensors were connected to a Campbell Scientific Cr1000 data logger programmed to log every 3 hours from August 2010 to September 2014. Each summer, the spatial distribution of active layer thicknesses were determined by mechanical probing in a 10 × 10 m grid with 110 measuring points (Fig. 1). Finally, in 2012 two additional soil temperature probes connected to a Tinytag (Gemini Data Loggers) were installed in the vertical erosion front (20 and 50 cm from the surface) in order to investigate the active layer thickness at the outer border of the midden (Fig. 2).

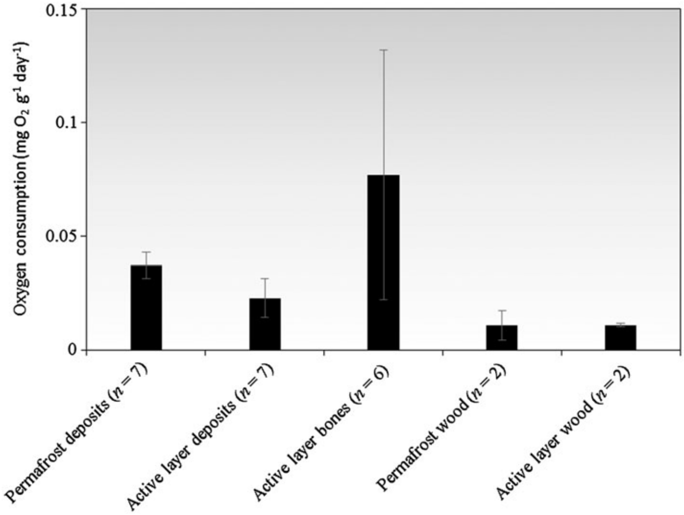

Figure 3 *The observed oxygen consumption rates at 0.5 °C in 24 different samples grouped after type and whether the samples were collected from the permafrost or the active layer. The n-values represent the number of different samples investigated. Error bars show ±1 s.d.*

Oxygen concentrations in the active layer were measured during site visits, by means of the oxygen optode technique, using oxygen sensor foil (PreSens GmbH, Germany). Calibrated sensors were constructed by gluing sensor foil to the end of a closed glass cylinder. The glass cylinder was pressed into the material to the relevant depth. During measurement, the optical fibre was moved down into the glass cylinders while connected to a fibre-optic meter (PreSens GmbH, Germany) interfaced with a data logger.

The vulnerability of the archaeological deposits to temperature increase and oxygen exposure

Measurements of oxygen consumption in soil samples from an intact core of the permanently frozen deposits and from an exposed archaeological profile have previously been reported (Hollesen *et al.* 2015a, 2016). Furthermore, the degradation of archaeological wood has previously been assesed in Matthiesen *et al.* (2014b). In order to provide a detailed assessment of the vulnerability of the main organic components in the midden to oxygen exposure and changes in temperature, we used the already existing data in combination with new measurements of oxygen consumption in six samples of archaeological bone. These measurements were made at four temperatures (0.5, 5, 10 and 15 °C). All of the measurements were made on moist samples according to Matthiesen (2007). For each depth interval, three replicate subsamples (1–2 g) were transferred to 12.2 ml glass vials, the samples were flushed with atmospheric air and the vials were closed with airtight lids. The oxygen consumption was subsequently measured by monitoring the decrease of headspace O_2 concentrations over time by using oxygen optodes (PreSens).

Future preservation potential

In Hollesen *et al.* (2015a), a new model set-up was developed in the one-dimensional numerical heat and water flow model, the CoupModel (Jansson and Karlberg 2004), and used to investigate the importance of microbial heat production on permafrost thaw and decomposition of soil organic carbon (SOC) in organic Arctic soils including the Qajaa midden. However, very little attention was paid to archaeology. In the current study, we use the existing model set-up (Hollesen *et al.* 2015a) to perform a detailed evaluation for the future preservation potential of the site.

The model was originally calibrated and validated using 2 years of measurements of soil temperatures and water contents, from 1 September 2010 to 31 August 2012 (Hollesen *et al.* 2015a). Here, we further test the quality of the model by using additional measurements of soil temperatures and soil water contents from 1 September 2012 to 31 August 2014.

The tested model is used to investigate how a predicted 2–5 °C increase in air temperatures may affect the thermal stability of the Qajaa midden and the decomposition of the organic deposits. The air temperature increase is applied stepwise through four different scenarios that account for seasonal variability (Table 1). All four scenarios are simulated with and without microbial heat production (Hollesen *et al.* 2015a).

RESULTS AND DISCUSSION

The physical stability of the site

Most of the midden is characterized by a vertical erosion front facing the sea. The lowest part of this erosion front is located 1.3 m above mean sea level. During the observation period, the

Table 1 *Climate change scenarios used in the CoupModel to predict future soil temperatures. The increases in air temperature by 2100 are relative to the 2001–11 mean and include seasonal variations (MAAT, mean annual air temperature; MSAT, mean summer air temperature; MWAT, mean winter air temperature). The winter period is considered to last from 1 December to 28–29 February and the summer period from 1 June to 31 August*

Scenario	*MAAT increase (°C)*	*MSAT increase (°C)*	*MWAT increase (°C)*
1	+2	+1	+3
2	+3	+2	+4
3	+4	+3	+5
4	+5	+4	+6

tidal amplitude was >1.5 m and approximately 60 times per year the sea level exceeded the critical 1.3 m at which the sea water may reach the lower part of the erosion front (maximum sea level = 1.7 m). However, the large amounts of glacier ice found in the fjord during the summer period had a significant damping effect on wave activity and during the winter period a rim of ice prevented waves from reaching the midden (Fig. S1). The erosion front was photographed once every year from 2009 to 2014 in order to get an impression of the current rate of wave erosion. During this 5 year period, most parts of the front were stable, without any noticeable erosion. Furthermore, a comparison with photos from 1982 (Meldgaard 1983) revealed that no noticeable wave erosion or removal of material had occurred over the past 30 years. It has recently been estimated that the area around Qajaa is experiencing a land rise of approximately 6.5 mm per year (65 cm over the next century) in response to the ice mass loss occurring in Greenland (Elberling *et al.* 2011). The combined uplift at Qajaa is thus in the same range as the sea-level rise of 28–98 cm over the next century projected by the Intergovernmental Panel on Climate Change (IPCC 2013). Nevertheless, the midden consists of five separate units (Fig. 1) that are remnants of one single unit. Two or three distinct but thin (1–3 cm) horizons of coarse sand and gravel were found at the very top of the midden, up to 5–6 m above normal high tide. In this part of Greenland, high waves arising from rolling or calving of icebergs are common, and previous studies have shown that this kind of 'iceberg-generated tsunami' may leave a clear stratigraphic signature (Amundson *et al.* 2008; Long *et al.* 2015). Due to the grain-size distribution, we assume that the sand/gravel horizons found at Qajaa originate from ice that was washed over the midden by large waves. This leads to the preliminary conclusion that wave erosion at the site primarily occurs during rare catastrophic events, rather than during continuous and gradual processes.

We found a number of larger cracks in the outer 1–3 m of the midden and a quite comprehensive system of small gullies within the permafrost. On one occasion, between site visits in August 2011 and August 2012, a larger erosion event caused 1–2 m^3 of material to slide 0.5 m down the midden front along one of the larger cracks (Fig. S2). It is well known that thermo-erosion by snowmelt runoff can initiate internal tunnelling and gullying of ice-rich permafrost, which in the worst case can lead to modifications of the local terrain (Fortier *et al.* 2007; Andrews *et al.* 2016). We did not find any evidence of changes in the size and form of these gullies from 2009 to 2014, aside from the observed small-scale landslide. Nevertheless, it is clear that hydro-thermal erosion is taking place—currently at a relatively slow rate—but with a well-developed system of cracks and gullies this type of erosion could become a greater threat in future years.

The environmental conditions at the site

The meteorological measurements from Qajaa show that the site is dominated by cold conditions for most of the year and has a short summer season (Figs S3 (a) and S4 (a)). The mean annual air temperature from 2010 to 2014 was −4.5 °C with the first year (1 September 2010 to 31 August 2011) being the warmest (−3.9 °C) and the second year (1 September 2011 to 31 August 2012) the coldest (−5.5 °C) (Fig. S3 (a)). Diurnal mean air temperatures ranged from −30.8 °C in February 2012 to 11.5 °C in July 2012. Overall, air temperatures were below zero from the beginning of October until the end of May, but with regularly occurring thaw events during the winter. The summer was relatively short, with air temperatures seldom exceeding 10 °C. The longest consecutive period without frost was 104 days during the summer of 2011 (2 June to 13 September).

In all years, the maximum active layer thickness was observed at the end of August and varied between 40 and 60 cm. Probing measurements during site visits showed that the spatial variation in active layer thickness across the midden was modest (the standard deviation for the 110 points within the 10 × 10 m grid was 7 cm). Measurements of soil temperatures were also made in the vertical erosion front and here the results showed that the outer 50 cm thawed every summer and that the soil temperatures measured in the profile were correlated significantly with those measured at the weather station (Fig. S5). The active layer thickness found in the kitchen midden at Qajaa is significantly lower than the 100–300 cm normally observed in sedimentary soils located at the same latitude in western Greenland (Christiansen *et al.* 2010; Hollesen *et al.* 2015b). The air temperatures at Qajaa are markedly lower than at Ilulissat, located 20 km to the west (Fig. S6). This is due to a more inland location (continental climate), a shorter distance to the Greenland ice sheet (25 km) and a location on the bank of an ice-filled fjord (Fig. 1). For this reason, the midden is currently being protected by a beneficial local climate that acts as a natural cooler, preventing most of the deposits from thawing. In addition to the favourable climatic conditions, the thermal properties of the organic deposits may also play an important role. The thermal diffusivity of a soil has a great influence on the variations in soil temperature, with a high diffusivity allowing rapid and deep penetration of surface temperature changes and vice versa (Jumikis 1977). The thermal diffusivity of the deposits (Fig. S7) is very low compared to other types of mineral soils (de Vries 1963) and thereby the thermal effect of higher air temperatures during the relative short summer is reduced significantly. The thermal properties found in the archaeological deposits at Qajaa are comparable to what is found in palsas (peat mounds) (Kujala *et al.* 2008; Pengerud *et al.* 2013). These landforms are often found at the outer margin of the discontinuous permafrost zone, which further suggests that the high organic content in the kitchen midden helps to protect the underlying permafrost.

The kitchen midden is located in a relatively dry area (precipitation ~250 mm per year) and is covered by a 10–25 cm thick snow cover for 7–8 months per year (Fig. S3 (b)). Nevertheless, the midden is currently very wet (Fig. S4 (b)), due to a combination of low evapotranspiration rates, the high water-holding capacity of the peat/organic material and the impermeable permafrost table greatly inhibiting drainage. The midden gets water-saturated when the snow melts at the end of May and beginning of June. During the summer, the midden remains water-saturated and anoxic from 20 cm and below and only the upper 15–20 cm is exposed to oxygen. It is well known that oxygen is a key controlling factor for the degradation of buried archaeological materials, and that some decay processes such as fungal attack on wood or bone will only take place if oxygen is available (Goodell *et al.* 2003). For most parts of the midden, the upper 20 cm consist of a natural organic-rich topsoil layer and hence the archaeological deposits are currently anoxic. However, in the vertical erosion fronts, and in other areas with active erosion (e.g., gullies and cracks), the archaeological deposits and artefacts may drain more freely and consequently be more exposed to atmospheric oxygen.

The vulnerability of the archaeological deposits to oxygen exposure

Figure 3 shows the oxygen consumption rates at 0.5 °C in 24 different samples that have been grouped by type (deposits/soil matrix, bone and wood) and whether they have been buried in the permafrost or in the active layer (exposed archaeological profile). First, the results show that all of the samples are highly degradable and vulnerable to oxygen exposure (Fig. 3 and Table S1). In accordance with other studies (Elberling 2003; Hamdi *et al.* 2013; Hollesen and Matthiesen 2015), the decay rates increase exponentially with temperature (Fig. S8 and Table S1). 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. In the temperature interval from 0.5 °C to 15 °C, Q_{10} values ranging from 2.5 to 3.8 were found for the deposits, 1.9 to 8.3 for the bone samples and 3.1 to 3.5 for the wood samples.

The oxygen consumption rates are, on average, 40% lower in soil samples taken from the outer layers of the exposed profile compared to samples taken directly from the permafrost (Fig. S9). The exposed archaeological profile was originally made in 1982 (Meldgaard 1983). It can therefore be assumed that the samples from the profile have been thawed every summer since 1982. This indicates that 30 years of exposure may have led to a significant loss of labile SOC and thus in the quality of the organic deposits. This is in accordance with optical microscopic analyses that show clear signs of decay by soft rot and a significant loss of mass in archaeological wood samples taken from the same exposed profile, whereas wood samples from the permafrost zone are almost perfectly preserved (Matthiesen *et al.* 2014b). The results thereby clearly indicate that microbial degradation can be expected whenever the archaeological layers are exposed to oxygen.

The future preservation of the site

Air temperatures have markedly increased in Ilulissat since 1990, especially in the period from 1991 to 2003, when the increase in the mean annual air temperature was 0.4 °C (Fig. S10). In 2100, the mean annual air temperature in this part of Greenland is expected to be 2.2–5.2 °C higher than the 1986–2005 mean, with the greatest warming occurring in the winter period (Rinke and Dethloff 2008; Collins *et al.* 2013). We have used an existing model set-up of the CoupModel (Hollesen *et al.* 2015a) to investigate the effect of such a warming on the stability of the permafrost within the kitchen midden. First, the accuracy of the model was tested using new measurements of soil temperatures and soil water contents from 1 September 2012 to 31 August 2014. High R^2 values and low mean differences confirmed that the model is capable of describing the seasonal variations in both soil temperatures and water contents simultaneously (Figs S11 and S12 and Tables S2 and S3).

After the initial validation, we used the model to simulate four different climate change scenarios (Table 1). The simulations show that the maximum active layer thickness could increase from the current 40–60 cm to 75–200 cm, depending on the degree of warming (Fig. 4). It has previously been estimated that the top 35 cm of the permafrost might have been thawed during the so-called medieval warming (1000 AD), when temperatures were >1.0 °C higher than today (Elberling *et al.* 2011). Accordingly, layers below approximately 80 cm depth are expected

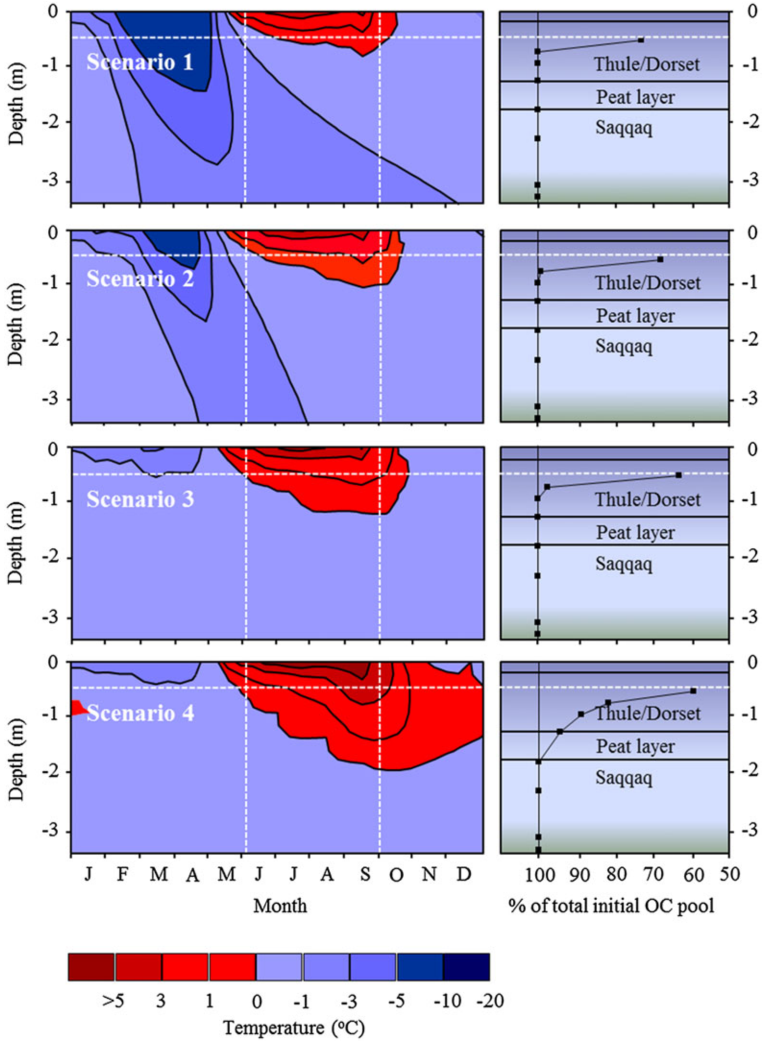

Figure 4 *Simulated soil temperatures (left) and loss of organic carbon (right) in year 2100 for climate change scenarios 1–4. The dashed white lines show the length of the thawing period and the maximum thawing depth for 2013. The climate change scenarios are presented in Table 1. [Colour figure can be viewed at wileyonlinelibrary.com]*

to have been kept frozen since their initial incorporation in the permafrost zone up to 4000 years ago. The CoupModel simulations suggest that these layers may begin to thaw within the next 40–50 years and if air temperatures increase by more than 3 °C at the end of the century (scenarios 3 and 4), the Thule/Dorset layers may be completely thawed during summer. Furthermore, the upper part of the deeper-lying Saqqaq layers (> 200 cm depth) may begin to thaw at the end of the century, but only if air temperatures exceed 4 °C (scenario 4).

A carbon decomposition module was used in the CoupModel (Hollesen *et al.* 2015a) to estimate the degradation of SOC with time. For the Thule/Dorset layers, the higher soil temperatures may have a significant impact on the preservation of the organic archaeological deposits and could, in the worst case, lead to a 40% loss of the initial SOC pool (Fig. 4). It has previously been shown that the microbial decomposition of the organic material may produce enough heat to trigger a feedback loop between soil temperatures and decomposition (Hollesen *et al.* 2015a). The simulations show that air temperatures have to increase by more than 4 °C in order for this feedback loop to kick in (Fig. 5). However, in the case of a 5.0 °C warming, the internal heat production could additionally increase soil temperatures up to 11 °C, causing the entire kitchen midden to thaw and leading to a significant loss of SOC and archaeological information (Fig. 5).

In all of the investigated scenarios (with or without heat production), the effect of higher air temperatures on the active layer thickness is limited during the first 30–40 years, as most of the available energy is used for melting the great amounts of ice in the midden (~80 vol%). It is only after this initial 'thaw period' that the active layer thickness starts to increase—at rates that are highly dependent on the degree of warming. This suggests that the combination of a high ice content and a low thermal diffusivity of the material of the organic deposits may be capable of buffering the effect of higher air temperatures and delay the thawing and degradation of the kitchen midden.

The simulations are limited with two main assumptions: (1) that decomposition takes place only in non-saturated thawing layers, excluding anoxic decay processes; and (2) that the present-day water balance and vegetation cover are representative for the future. Furthermore, oxygen depletion caused by the decomposition itself is not included in our model, which could be an important limiting factor, especially in soils where temperatures increase rapidly due to heat production. The simulations only include the microbial degradation of the organic deposits in which the different types of artefacts are embedded. However, based on the results from the oxygen consumption measurements presented above, we expect the loss of organic deposits to

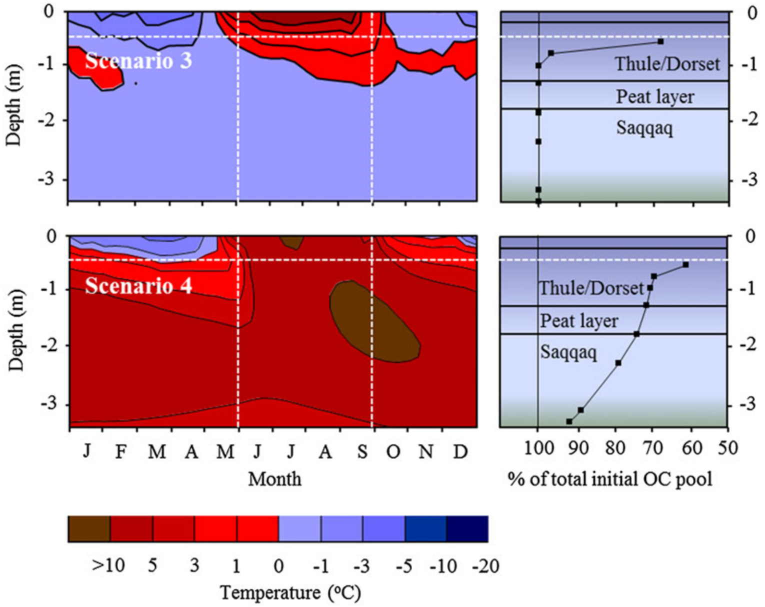

Figure 5 *Simulated soil temperatures (left) and loss of organic carbon (right) in year 2100 for climate change scenarios 3 and 4 with added heat production from the decomposition of organic matter. The dashed white lines show the length of the thawing period and the maximum thawing depth for 2013. The climate change scenarios are presented in Table 1. [Colour figure can be viewed at wileyonlinelibrary.com]*

be closely linked to a loss in quality of other buried organic artefacts. The simulations were made using a one-dimensional model. As a consequence, the results are not representative for the parts of the midden that are influenced from all sides; for example, in the vertical erosion fronts and in other areas with active erosion. As described above, the archaeological deposits may degrade at a much higher rate in these areas. Furthermore, increasing soil temperatures and changes in soil water content may lead to soil settling and erosion, which may expose new areas to oxic conditions and obscure archaeological legibility.

The results from this study indicate that there are no immediate threats to the preservation of the kitchen midden at Qajaa. However, the site should be revisited every 5–10 years in order to monitor for changes. If monitoring shows increased signs of erosion or degradation, it is important to have a response strategy. In some cases, low-tech remediation actions could be an option to at least slow down the degradation processes. Previous studies have shown that it is possible to limit the oxidation of sulphides within Arctic mine waste/tailings using thermal covers that limit the depth of seasonal thaw to the cover system (Kyhn and Elberling 2001). Furthermore, a study from the Netherlands has recently shown how a soil cover in combination with buried plastic foil may help to prevent oxygen from penetrating into underlying archaeological deposits (Speleers *et al.* 2016). However, for Qajaa and other Arctic kitchen middens, the application of such protective measures will be challenged by the high costs and the logistical challenges in accessing these often very remote locations. Studies from Arctic Station (120 km west of Qajaa) show that it is possible to increase the snow depths from 40 to 140 cm using snow fences (Blok *et al.* 2016). This could be a low-tech method to increase the soil water content within the archaeological deposits at Qajaa and thus limit the oxygen availability. However, as a thicker snow cover may also increase winter soil temperatures and increase the erosion from meltwater, this type of response strategy will require thorough testing before being applied on a large scale.

CONCLUSIONS

The loss of archaeological sites and degradation of organic deposits is an important and overlooked aspect of climate change in the Arctic. Here, we have presented a systematic approach on how to perform a detailed assessment of the processes controlling preservation conditions at one of the most important archaeological sites in Greenland. The main part of the site is currently well protected by low temperatures, permafrost and a high water/ice content that keeps the deposits anoxic. Furthermore, the high organic content in the deposits insulates the permafrost and has a high water-holding capacity that largely prevents fluctuations in soil water content. The outer margins of the kitchen midden are dominated by vertical erosion fronts that face the sea. No evidence of active wave erosion was found during the 5 years of study. Instead, distinct sand/gravel horizons were found at the top of the midden, which could be the stratigraphic signature of iceberg-generated tsunamis, indicating that wave erosion at the site primarily occurs during rare catastrophic events. Clear evidence of hydro-thermal erosion was found at the site, with larger cracks in the outer 1–3 m of the midden and a system of small gullies within the permafrost. In the vertical erosion fronts, and in other areas with active erosion, the archaeological deposits and artefacts may drain more freely and be more widely exposed to oxygen, with a considerable influence on the microbial degradation of deposits. Our results show that the soil matrix and archaeological wood and bone are highly degradable and vulnerable to oxygen exposure. Furthermore, the reactivity is on average 40% lower in soil samples taken from layers exposed since 1982 compared to samples taken directly from the permafrost, signalling a significant loss of quality caused by 30 years of summer thaw.

A predicted 2.2–5.2 °C warming from 2016 to 2100 could increase soil temperatures by 1.8–11.0 °C and cause up to 40% of the organic carbon to be lost. For the main part of the midden, the degradation will be limited during the next 30–40 years due to a combination of a high ice content and a low thermal diffusivity of the organic deposits that effectively buffers the effect of higher air temperatures. However, in areas with active erosion, the archaeological deposits may degrade much faster. Furthermore, the soil is likely to settle as the midden thaws, which may expose layers that are currently well below the surface.

Our results emphasize the complexity of evaluating the effect of climate change on preservation conditions in an environment where multiple processes are in play. The site-specific environmental conditions and the soil thermal and hydrological characteristics of the deposits are just some of the factors that need to be considered when assessing the effect of climate change. Other processes such as vegetation, root penetration and the presence of specific lignin-degrading fungi (white rot and brown rot) are also of great importance and need further attention. The climate at Qajaa is relatively cold compared to the climate at the many archaeological sites located further south (Hollesen *et al.* 2016). Therefore, more and different types of sites should be investigated in other parts of Greenland. Given that it will obviously be impossible to carry out site observations and monitoring at every single site in Greenland, future research should also focus on developing regional impact models that can be used to pinpoint the areas that are most vulnerable to climate change. This will make it possible to prioritize and optimize future archaeological investigations and the development of mitigation actions, and ultimately help to decide which sites should be excavated immediately and which sites can be saved for future research.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

Table S1. Oxygen consumption rates (mg O_2/g/day) and Q_{10} values for the samples included in the study.
Table S2. Statistics on the agreement between observed (x) and simulated soil temperatures (y) for the Qajaa midden.
Table S3. Statistics on the agreement between observed (x) and simulated (y) soil water contents for the Qajaa midden.
Figure S1. The midden at Qajaa in August 2010 (upper photo) and in February 2011 (lower photo). The red line shows the erosion front towards the sea.
Figure S2. Several larger cracks are found in the outer 1–3 m of the midden at Qajaa. In the time period from August 2011 to August 2012 one larger erosion event caused 1–2 m3 of material to slide of the midden front along one of these cracks.
Figure S3. Meteorological measurements at Qajaa for the period 2010–2014: (A) mean diurnal air temperatures; (B) daily precipitation rates (black) and snow depths (weather station = solid blue and automatic camera = dotted blue).
Figure S4. (A) Measured soil temperatures and (B) soil water contents in the Qajaa kitchen midden.
Figure S5. Soil temperatures from Qajaa measured at the weather station and in the exposed profile.
Figure S6. A) Daily mean air temperatures from Qajaa and Ilulissat. B) correlation between daily mean air temperatures measured at Qajaa and Ilulissat.
Figure S7. Observed thermal diffusivities in the top of the midden (open squares) and in a block of kitchen midden material (solid squares) (modified from Elberling et al., 2011).
Figure S8. Oxygen consumption measured at 0.5, 5, 10 and 15 °C in samples in 24 different samples grouped after type and whether the samples were collected from the permafrost or the active layer. Data are normalized in relation to the maximum rate and error bars show ±1 s.d.
Figure S9. Measured oxygen consumption rates at 0.5 °C in the soil samples from the profile exposed since 1982 (left) and from the permafrost core (right).
Figure S10. Mean annual air temperatures from 1991–2014 measured at Ilulissat airport located 20 km north-west of Qajaa. The lines show the linear regression for two the periods 1991–2003 and 2004–2014. Data is provide by Danish Meteorological Institute (2016).
Figure S11. Simulated (black) and measured (white) soil temperatures in the Qajaa midden from 1 September 2010 to 31 August 2014.
Figure S12. Simulated (black) and measured (white) soil water contents in the Qajaa midden from 1 September 2010 to 31 August 2014. The low water contents seen during the winter is due to freezing.