ARCTIC
VOL. 78, NO. 1 (MARCH 2025) P. 84–102
https://doi.org/10.14430/arctic82341

Quantifying Degradation of Archaeological Bone In Situ and in Museum Storage: A Comparison Between Environment and Degradation over Forty-Three Years for Bones from the Aasivissuit Site, Western Greenland

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(*Received 10 July 2024; accepted in revised form 19 December 2024*)

ABSTRACT. Degradation of archaeological bone is a complex process that is influenced by both intrinsic and extrinsic parameters. Here we study the decay of bones recovered from a large midden at the Inuit summer hunting camp, Aasivissuit, in West Greenland, dating from 1200 CE to 1950 CE. The site was partly excavated in 1978 and revisited for further excavation in 2021 to study changes in the materials' state of preservation, both in situ and in museum storage. The state of preservation was described visually for several hundred bones from both investigations. The reactivity of 34 caribou bones was measured at −5˚C, 1˚C, 5˚C, 10˚C, and 15˚C, and compared to their density, composition, and histological decay pattern. Environmental monitoring on site included soil type, pH, porosity, water content, and temperature, while monitoring in storage included relative humidity and temperature.

The observed degradation patterns and changes that occurred in the period 1978–2021 in situ and in museum storage are explained. Furthermore, current climate change predictions are used to evaluate what may happen to the site in the future. Findings include: 1) the bones preserved in situ showed little change since 1978, while the excavated bones in museum storage were more degraded; 2) the decay pattern for the bones is well correlated with environmental conditions; 3) the reactivity of wet bone measured as oxygen consumption was largely controlled by bone density and temperature; 4) loss of organic and mineral components of the bone under current conditions can be estimated using numerical models; and 5) continued in situ preservation under current and future climate conditions is considered feasible.

Keywords: bone diagenesis; Arctic; burial environment; museum storage; monitoring; oxygen consumption; bone density; temperature

RÉSUMÉ. La dégradation d'ossements archéologiques est un processus complexe influencé à la fois par des facteurs intrinsèques et par des facteurs extrinsèques. Nous présentons ici les résultats de la décomposition d'ossements au campement de chasse estival inuit Aasivissuit dans l'ouest du Groenland. Les ossements, datés d'environ 1200 CE à 1950 CE, sont enterrés dans un tertre de grande dimension. Le site a fait l'objet d'une fouille partielle en 1978. Il a été examiné de nouveau en 2021 dans le but d'étudier les changements caractérisant l'état de conservation des matières, tant celles se trouvant sur place que celles stockées en musée. L'état de conservation de plusieurs centaines d'ossements provenant des deux enquêtes, soit celles de 1978 et de 2021, a été décrit visuellement. Nous avons mesuré la réactivité de 34 os de caribou à −5 ˚C, 1 ˚C, 5 ˚C, 10 ˚C et 15 ˚C. Nous avons comparé les résultats à leurs profils de densité, de composition et de décomposition histologique. Sur le terrain, nous avons déterminé le type de sol et mesuré le pH, la porosité, la teneur en eau et la température des os (c'est-à-dire les conditions environnementales). Nous avons également mesuré l'humidité relative et la température des ossements stockés.

Nous analysons les tendances de dégradation observées, les changements intervenus entre 1978 et 2021 sur place et en musée, puis nous examinons les prévisions actuelles en matière de changement climatique afin d'évaluer ce que ces dernières peuvent entraîner comme conséquences sur le site à l'avenir. Nous avons constaté 1) que les ossements préservés sur place avaient peu changé depuis 1978, contrairement à ceux conservés en musée qui se sont davantage détériorés; 2) que le profil de décomposition des os correspond bien aux conditions environnementales; 3) que la réactivité des ossements, mesurée par la consommation d'oxygène, était largement contrôlée par la densité osseuse et la température; 4) qu'il est possible d'évaluer la perte de composants organiques et de composants minéraux des ossements dans les conditions actuelles à l'aide de modèles

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numériques; et 5) qu'il est envisageable de conserver les restes osseux sur place dans les conditions climatiques actuelles et futures.

Mots-clés : diagenèse osseuse; Arctique; milieu d'enfouissement; stockage en musée; surveillance; consommation d'oxygène; densité osseuse; température

Traduit pour la revue *Arctic* par Nicole Giguère.

INTRODUCTION

Animal bones are a key component for the interpretation of many archaeological sites, especially since the introduction of a range of biomolecular analytical tools. However, to fully interpret results from bone material analyses, it is necessary to understand not only what is preserved but also what information may have been lost through pre- and post-depositional processes. Degradation of archaeological bone is complex and depends on both intrinsic and extrinsic parameters (Kendall et al., 2018). Bone consists of three main components (inorganic hydroxyapatite, organic collagen, and water) that mutually protect each other, and loss of any of these components will affect the bones' appearance and the types of analyses that can be carried out on them. The exact composition and vulnerability to decay (reactivity) depends on the bone element and the species, ontogenetic age, and the nutritional status of the animal (Turner-Walker, 2023). In addition, the bone may be subjected to different environments and threats before, during, and after burial, and excavation that may affect the bone components in different ways (Fig. 1).

It is notoriously difficult to understand and quantify all these processes and conditions, and bone assemblages often show a large variation in state of preservation that is difficult to explain. Since Efremov (1940) first addressed and defined the discipline of taphonomy as the study of how organisms decay and become fossilized, comprehensive surveys on the various taphonomic agents and trajectories have evolved (Clark and Kietzke, 1967; Meadow, 1980; Lyman, 1994). Figure 1 illustrates five different phases of the afterlife of archaeological bone. Attempts to explore aspects of the use and subaerial weathering (phases I and II) were made in the 1970s where for example, Binford and Bertram (1977) tried to model the composition and distribution of sheep and caribou bones in archaeological assemblages and focussed especially on the selection and fragmentation of bones carried out by humans, and the effects on the bones from dogs gnawing. Their study demonstrated a clear correlation between bone density and percentage of survival for different caribou bone types (Figure 3.16 in Binford and Bertram, 1977).

Behrensmeyer (1978) studied subaerial weathering (phase II) and defined different weathering stages for bone. Guadelli (2008) and Pokines et al. (2016) studied specific weathering processes relevant to the Arctic (such as the effects of freeze/thaw processes), and the importance of rapid burial of bone to minimize the impacts of weathering were underlined by Todisco and Monchot (2008).

Several studies have discussed degradation of bones that occurs while they are buried (phase III) including: the effects of leaching (Hedges and Millard, 1995; Berna et al., 2004), microbial degradation (Child, 1995; Eriksen et al., 2020) and how these processes are affected by bone porosity (Nielsen-Marsh and Hedges, 2000), species, and bone element (Nicholson, 1996; López-Costas et al., 2016). Most of these studies focus on detailed descriptions of the bone material itself and less on monitoring the dynamics of their environment, but a recent review points toward parameters such as soil pH, soil hydrology, and ambient temperature as decisive for the continued preservation of bones (Kendall et al., 2018).

Post-excavation decay (phases IV and V) has been described in conservation literature, often focusing on the drying of bone material without creating cracks (Botfeldt and Richter, 1998) and on proper handling, packaging, and storing procedures for excavated bones (Caffell et al., 2001; Bowron, 2003).

Thus, some of the key parameters affecting bone degradation are known. However, their effects have mainly been described on a qualitative rather than quantitative scale. Degradation during multiple phases has seldom been looked at in a single study (Nielsen-Marsh et al., 2007; Smith et al., 2007), and long-term studies are necessary to separate and quantify the importance of the different phases, especially phase III (burial) that may last for centuries (Crowther, 2002).

In this paper we try to fill this gap by focussing on the Arctic site Aasivissuit, where excavations were carried out in 1978 and bone material was described in detail. The site was revisited, and bone was excavated in 2021 in an adjacent area of the same midden that provided the 1978 bone samples. The collection of bone from the recent excavations allowed a comparison to the earlier samples and an evaluation of the nature and extent of change to the bone over the 43 years both in situ and in museum storage. This work is combined with monitoring key environmental parameters and conducting experiments in the laboratory to estimate and model decay on a quantitative scale. Revisiting the site and the stored material allowed us to describe and quantify changes that happened during phases III through V (burial, excavation, storage) and also to discuss future preservation in light of climate change. We briefly discuss phases I and II as they are foundational for understanding the changes. A parallel study on the same bone material focusses on the degradation of DNA and the microbiome within archaeological bone (Eriksen et al., 2025).

Phase	I	II	III	IV	V
Description	Use	Subaerial weathering	Buried	Excavation	Storage
Main threats (list not exhaustive)	Heating Boiling Fracturing	Gnaw Trampling Bleaching Wetting/drying Freeze/thaw Oxidation/mould Leaching	Leaching Oxidation Freeze/thaw Root damage Re-deposition	Oxidation/ mould Fast drying Fragmentation	Oxidation/ mould Desiccation
Duration	Days/weeks	Few years	Hundreds of years	Weeks/months	Years

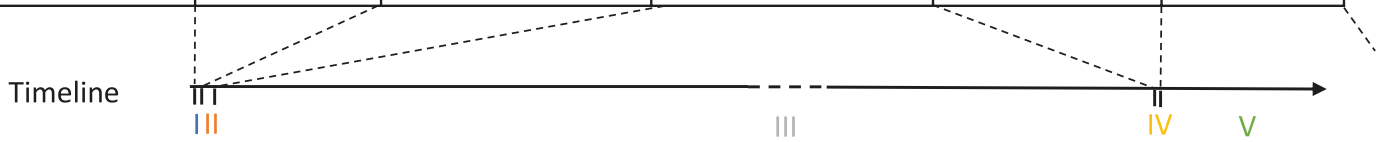

FIG. 1. Degradation of archaeological animal bones is complex as they are subjected to different environments and threats during their afterlife. The figure describes some of the main phases and their suggested duration for animal bones that are used and discarded on a midden and covered by waste and other sediments until eventually they are excavated and stored.

STUDY SITE AND METHODS

Bone samples and environmental data were collected at Aasivissuit in central West Greenland (67˚06′00″N, 51˚07′44″W), an Inuit summer camp where people gathered to hunt caribou during various periods spanning 800 years. Today, Aasivissuit is a key location within the UNESCO World Heritage Site Aasivissuit-Nipisat (Fig. 2a).

The current climate at Aasivissuit is well described; long-term monitoring occurs at Kangerlussuaq Airport, only 20 km from the site. The climate normal for the period 1991–2020 is a yearly mean temperature of −4.6˚C, which covers relatively warm summers (mean temperature in July of 11.2˚C), cold winters (mean temperature in February of −19.8˚C), and relatively modest precipitation (yearly mean of 168 mm), with most precipitation (82 mm) falling from July to September (Cappelen and Drost Jensen, 2021). Climate variations during the last 800 years have recently been studied by Strunk et al. (2024) and show that the period from 1100 CE to 1600 CE was slightly colder and more arid than today.

Excavation

Archaeological excavations carried out in 1978 focussed on a large midden area and are described in detail in Grønnow et al. (1983). A 15-metre-long section excavated through the midden revealed five main midden layers, which corresponded to five different occupation phases at the site. The deepest layer (5) originates from the Dorset period (800–100 BCE) but contains only a few bones and is not included in this study. Layer 4 covers a period of 340 years from *ca*. 1210 CE to 1550 CE, when there was low-intensity use of the site. Layer 3 covers a few decades within the period from 1680 CE to 1750 CE and is extremely rich. This layer contains the remains of hundreds of caribou from communal drive-hunting of entire herds. The period ended abruptly, as can be seen by layers of aeolian sand and silt covering the midden. Layer 2 represents a period of 30 years from 1820 CE to 1850 CE, when the local population returned to the site again to hunt using more individual hunting methods than in the previous century. Finally, layer 1 represents small-scale hunting episodes over 70 years in the period from 1880 CE to 1950 CE.

The 1978 excavation resulted in the collection of 19,747 bone fragments in total. They were all recorded according to midden layer and to a 0.50 m × 0.50 m grid system that covered the whole area. Bones from the excavation in 1978 were dried in the field and shipped to Denmark over a period of a few months. M. Meldgaard identified the bone fragments and assessed and recorded the weathering stage for each bone (Grønnow et al., 1983). Following analysis, the faunal material has been stored at the Natural History Museum of Denmark.

In 2021, the Aasivissuit site was revisited. A two-metre-long section of the backfilled trench from 1978 was reopened and the 0.5 m × 0.5 m measuring grid was re-established to allow a direct comparison between old and new material (Fig. 3). Figure 2b shows the 2 m section after excavating 25 cm into undisturbed midden deposits. After documentation, the section was enlarged by two 0.25 m × 0.25 m squares, and a small test pit of 0.5 m × 0.5 m was also opened about 2 m from the main profile. The profile, squares, and test pit were used to sample bone material, make environmental measurements, and install automatic monitoring systems. Bone samples were airdried in the

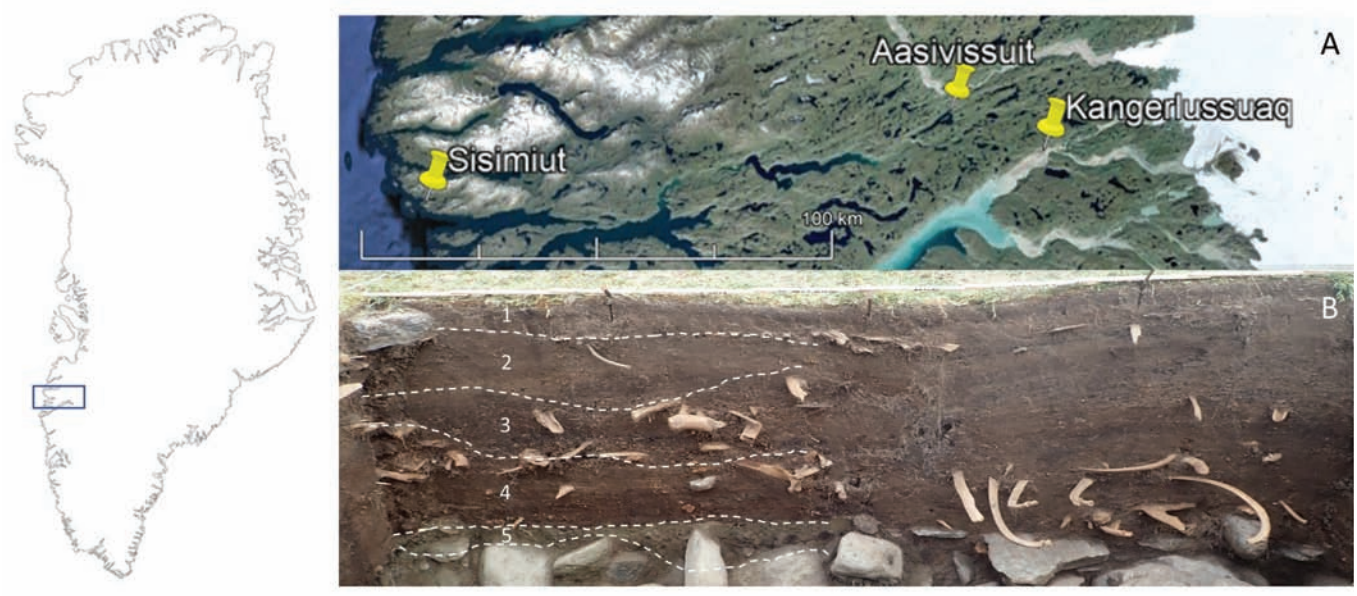

FIG. 2. A) Aasivissuit is an inland caribou hunting site about 40 km from the inland ice and 20 km from Kangerlussuaq Airport; B) photo taken during the September 2021 to August 2023 excavations showing a 2 m section of the old excavation trench after removing the outer 25 cm. White dashed lines illustrate layer boundaries.

FIG. 3. Photos of the excavation trench from 1978 and the part of the excavation trench from 1978 that was reopened in 2021.

field and shipped to Denmark. Upon arrival they were dry cleaned, assessed, and stored.

Bone Preservation

The 2021 excavation covered less than 1 m^2 and resulted in 643 caribou bone fragments, which were labelled according to the layer and grid systems. Bones from the 1978 excavation were retrieved from storage where they had been kept in bags and then boxes according to layer and grid cell; a total of 291 bones from four 0.5 m × 0.5 m grid cells located next to the 2021 excavations were retrieved. We visually assessed the bones and described their macroscopic state of preservation using the five categories described in Table 1 and Supplementary Fig. S1. We based the preservation state definitions on earlier descriptions of Arctic bone material (Todisco and Monchot, 2008; Matthiesen et al., 2021) but made some minor adjustments to better illustrate variations in this material.

Based on the categorical data, an approximate average of preservation state was calculated for different subsets of the bones according to the following Equation 1:

$$Average\ pres.state = \frac{\Sigma_{i=1}^{5} |State_i| \cdot Number\ of\ bones\ in\ State_i}{Total\ number\ of\ bones}$$

TABLE 1. Description of the macroscopic states of preservation of mammalian remains. Modified after Todisco and Monchot (2008) and Matthiesen et al. (2021). Examples of each category are shown in supplementary material (Fig. S1).

State of preservation	Description
5 = excellent	Bone surface shows no signs of cracking or flaking due to weathering. Bone has high density.
4 = good	Bone shows modest cracking, normally parallel to the fibre structure (e.g., longitudinal in long bones).
3 = medium	Partial loosening of surface (less than 50%), cracks parallel to fibre structure. Often low weight below 50% of original weight.
2 = poor	Bone surface is coarsely fibrous and rough in texture, but still identifiable; more than 50% of the surface is loose, weathering penetrates inner cavities; cracks are open.
1 = very poor	Surface is missing or is not identifiable. Bone may be falling apart in situ and turn into bone dust or flakes.

This is not a true mean value (as the preservation state is a categorical variable and not on a linear scale), but it still gives an impression of the typical preservation in, for instance, the different layers and excavation years (Matthiesen et al., 2021).

Three main age categories were used to describe the bones: adult (mineralized bone surface and fused epiphyses), subadult (adult-size bones with mineralized bone surface and unfused or fusing epiphyses), and finally juvenile (small bones with a rough, not-yet mineralized bone surface and unfused epiphyses). Furthermore, we noted whether the bones had any specific signs of degradation that had occurred during phases I and II, such as gnaw marks, bleaching, burning, fragmentation, or human-made taphonomic traces, such as butchery marks or marrow fracturing marks.

Environmental Conditions—in Situ and in Storage

Environmental parameters were measured in situ for each 5–10 cm, from top to bottom of both the trench and the test pit during excavation. Water content and conductivity were measured using a WET probe from Delta-T Devices Ltd. pH was measured using a solid state LanceFET and SI600 pH meter from Sentron. Soil ring samples of 100 cm^3 volume were taken for each 10 cm depth and used for the analysis of water content, organic content, and soil porosity. We measured the grain size of dried soil using sieves with mesh from 2 mm to 0.0625 mm. Sensors for continuous monitoring of water content (four ML3) and water matrix potential (two EQ3) were installed at 10–40 cm depth and connected to a DL6 logger (Delta-T instruments), which took measurements every six hours. Four temperature sensors (Tinytag) were installed at 10–40 cm depth, also taking measurements every six hours. The latest data were retrieved in August 2023. In 2023, optical oxygen sensors (from PreSens) were installed at four depths in the test pit to measure oxygen concentrations.

The soil ring samples were analyzed in the laboratory, which involved measuring the water content (drying at 105°C for 12 hours) and loss on ignition (after ignition at 450°C for 12 hours) according to ASTM International (2013). Loss on ignition was interpreted as a measurement of the organic content, and the soil porosity was calculated from total volume of the sample (100 cm^3), subtracting the volumes of inorganic and organic material that were estimated from their weight and using particle densities of 2.65 g/cm^3 for inorganic and 1.50 g/cm^3 for organic material (Rühlmann et al., 2006). Other soil samples were used to measure content of water-soluble ions: 5 g of wet soil were suspended in 50 mL milliQ water for one hour before filtration (0.45 µm). The content of the dissolved ions was determined by ion chromatography (Ca^{2+}, Mg^{2+}, K^+, Na^+, Cl^-, SO_4^{2-}, HPO_4^{2-}, NO_3^-) and titration (alkalinity/HCO_3^-) and recalculated to the content relative to soil dry matter.

We retrieved above-ground weather conditions (air temperature and precipitation) for the monitoring period from a weather station at Kangerlussuaq Airport, where weather data has been available since 1973 (www.dmi.dk/vejrarkiv). We used these data to interpret the soil monitoring data from 2021 to 2023 and to assess whether the current weather conditions are representative of the whole period since the 1978 excavation.

For more than a year, Tinytag dataloggers have been taking measurements of the temperature and relative humidity of the bones excavated in 1978. The measurements were taken in the storage room and within the cardboard boxes holding the bone material.

Detailed Bone Analysis and Reactivity

We selected 34 bones for more detailed analysis: 33 of them were caribou ribs and the 34th was a fragment of a tibia diaphysis from 2021. The ribs were selected to represent both excavation field seasons (16 from 2021; 17 from 1978), different find layers (three from layer 1, 12 from layer 2, 12 from layer 3, and six from layer 4), and different states of preservation (one in poor condition, two medium, 13 good, and 17 excellent). Fifteen of the ribs were from adult caribou, 12 ribs were from subadults, and one was from a juvenile. In addition, five fragmentary ribs lacking their proximal articulations were identified as subadult/adult, judging from their size. None of the ribs exhibited gnawing marks or evidence of burning, but it was not possible to assess whether they had been subjected to heating such as boiling. The bone characteristics are compiled in Table S1. The same ribs have been used in DNA studies (Eriksen et al., 2025).

The bones had all been air-dried for storage. We measured the microbial activity of whole dry ribs using respirometry techniques—that is, by measuring the oxygen consumption of bones under controlled conditions. The ribs were at 50% RH and 20°C for a few days in a climate chamber until their weight stabilized before they were

placed in individual bags made of oxygen barrier film, and sealed. Their oxygen consumption was measured for at least 10 days, as described in Matthiesen and Stemann-Petersen (2013). Thereafter, subsamples were taken for measurements of bulk density, water content, organic content, histology, and microbial activity under varied conditions.

Wedges of subsamples (about 0.2 g) were taken near the proximal end of the bone and included both compact and cancellous bone material. The samples were embedded in epoxy resin (Poly-Pox from Poly-Service), polymerized at room temperature for 24 hours, and polished to a thickness of about 40 µm using polishing instruments from Streurs (LaboPol-30) and Leico. The thin sections were examined by light microscopy in transmitted normal and polarized light using an Olympus microscope (BX51), and micrographs were taken using an Olympus camera (SC30). All samples were also studied using a scanning electron microscope (SEM). Two different types of electron microscopes were used: a Zeiss Supra 35 VP with EDAX Octane Elite Plus EDS, for which the samples had to be coated with palladium using a Leica EM ACE600 coater, and a Jeol JSM-IT800 coupled with Oxford Ultim Max 65 mm^2 EDS for which no coating was required because of the use of a low-vacuum sample chamber. In both instances, working distance was set to 10 mm, voltage was 15 kV, and magnifications of between 400× and 1400× were used to study the samples. We observed different diagenetic alterations and determined the extent of microcracking using the cracking index developed by Jans (2005), which is the percentage of cracked osteons in one field of view in the microscope. In order to quantify the overall level of preservation, both the Oxford Histological Index ([OHI], Millard, 2001) and the General Histological Index ([GHI], Hollund et al., 2012) were applied. While the OHI focusses solely on bioerosion, the GHI records the total unaltered microstructure, assessing the effects of both bioerosion and other degradation processes such as generalized destruction and staining. Finally, birefringence was also semi-quantified following Jans et al. (2002) and applying a three-step score: 1 (unaffected), 0.5 (reduced), and 0 (absent).

Further, for use in measuring the remaining parameters, 1–3 subsamples of 0.5–1 g of both compact and cancellous tissue were taken from each rib, and the same quantity of compact tissue was extracted from the tibia. The samples were first water saturated by submerging them in water under vacuum. The wet volume was determined as buoyancy in water, and their wet weight was determined after excess water had been allowed to drain off. The microbial activity of wet bone was measured by placing each subsample in a 4.9 ml glass vial closed with an airtight lid. Decreasing oxygen concentration inside each vial was measured with optical oxygen sensors (SensorDishReader from PreSens) and used to calculate an oxygen consumption rate according to Matthiesen (2007). The vials were kept in a climate chamber at fixed temperatures (−5˚C, 1˚C, 5˚C, 10˚C, and 15˚C) for a week or more, and oxygen concentrations were measured every 15 minutes. After this, the subsamples were dried to 75% RH, weighed, and placed in oxygen sensing vials to measure their oxygen consumption of the dried subsamples at 15˚C. Finally, the bone samples were dried (12 h at 105˚C) to determine their dry weight and burned (12 h at 600˚C) to determine their ignited weight.

Statistical Analysis

All statistical analyses were carried out with the software R (version 4.2.3). Oxygen consumption measurements result in continuous data where the influence from various parameters on oxygen consumption was analyzed using ANOVA (analysis of variance) for categorical parameters (such as layer and excavation year) and linear models for continuous parameters (such as temperature and density). Logarithmic transformation of the oxygen consumption data was used to approach normal distribution. A t-test was used to compare mean values of other continuous data, such as density and organic content. Our determination of the state of preservation of bones resulted in categorical data (number of bones in states 1 through 5) that were analyzed using contingency tables and χ^2-tests. A significance level of 0.05 was used in all tests.

RESULTS

Observations Made During the Excavation in 2021

Modest changes were seen during our revisit of the Aasivissuit site compared to 1978 (Fig. 3): shrubs next to the midden had grown higher and expanded slightly in area, however, they were not (yet) found on the midden itself. Caribou and muskoxen frequently cross the midden area, and their trails were visible in both 1978 and 2021; however, their wear is still superficial on the midden. The backfilled excavation trench from 1978 was visible as a slight depression but was overgrown by grass and difficult to see (Fig. 3).

When we opened the excavation trench, all the layers were still visible and had the same thickness as in 1978 (Fig. 2b). A large frost crack was already present in 1978, and it was not possible to determine whether it had expanded or whether new cracks were present. We visually investigated the old excavation trench for its possible influence on the surrounding deposits and found an influence zone of less than 5 cm thickness where the deposits were more lightly coloured. No enhanced macroscopic degradation of bone in these outer layers was observed.

Macroscopic State of Bone Preservation

Figure 4 shows the relative abundance of bones in different preservation states based on 291 caribou bones

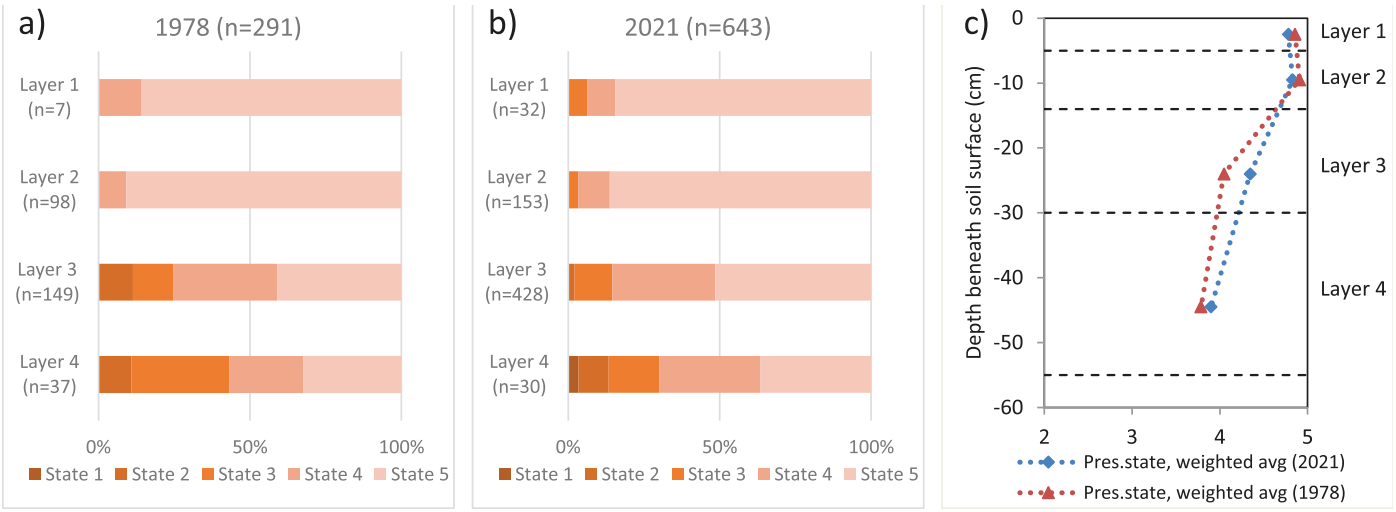

FIG. 4. The macroscopic states of preservation of caribou bones from different layers in 1978 a) and 2021 b), where state 1 is very poorly preserved and state 5 is excellently preserved. Graph c) shows an average preservation state for each year and layer: horizontal lines indicate the thickness of layer 1–4 at the left side of the reopened profile (the layer thicknesses vary across the profile).

from 1978 and 643 from 2021. Average preservation state was calculated for each layer and excavation year according to equation 1 (Table 2).

Overall, material in the deeper deposits seems more degraded and more heterogeneous than in the upper deposits in both the 1978 and 2021 samples. The weighted average preservation state is slightly lower in the 1978 material, especially in layer 3. Still, the material from Aasivissuit is generally very well preserved macroscopically compared to middens at five other sites in the Nuuk region, where the average preservation state of bone varied between 1 and 3.8—that is, more degraded than at Aasivissuit (Matthiesen et al., 2021).

In addition to the bones' overall state of preservation, we noted that many of the marrow-containing caribou bones were marrow fractured. Of the long bones (humerus, radius, femur, tibia, and metapodials), 80% (212 out of 265) of the 2021 material exhibited old breakages, typically with sharp edges and spiral fractures. In layers 1 and 2, the bones were fragmented to a higher degree than bones in layers 3 and 4. In the two lowest layers, some bones were found in articulation, indicating that joints or parts of limbs had been discarded. The bones were nearly devoid of gnawing marks: one bone of the 291 (0.3%) caribou bones from 1978 was gnawed, and five out of 646 (0.8%) caribou bones from 2021 were gnawed. None of the bones were burned and very few showed bleaching or other explicit signs of subaerial weathering.

Environmental Conditions

The midden at Aasivissuit consists mainly of bones embedded in a matrix of windblown silt in which 70% of the material is < 0.0625 mm in diameter. Results from soil ring samples are presented in Figure 5, showing porosities between 65% vol and 76% vol, organic content between 9% vol and 11% vol, and inorganic content between 13%

TABLE 2. Average preservation state of bones in layers 1–4 from 1978 and 2021.

Layer	1978	2021
1	4.86	4.78
2	4.91	4.83
3	4.05	4.35
4	3.78	3.90

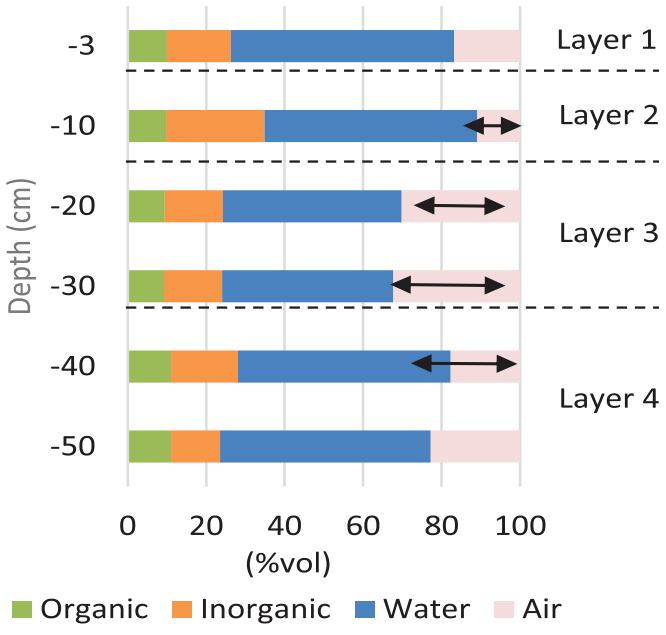

FIG. 5. Results from soil ring samples taken from the test pit at Aasivissuit on 3 September 2021. The organic and inorganic content is (relatively) stable over time, while the water and air content varies. Arrows indicate the range of water content/air content measured during the two-year monitoring period (from Figure 7). Dashed horizontal lines show layer boundaries.

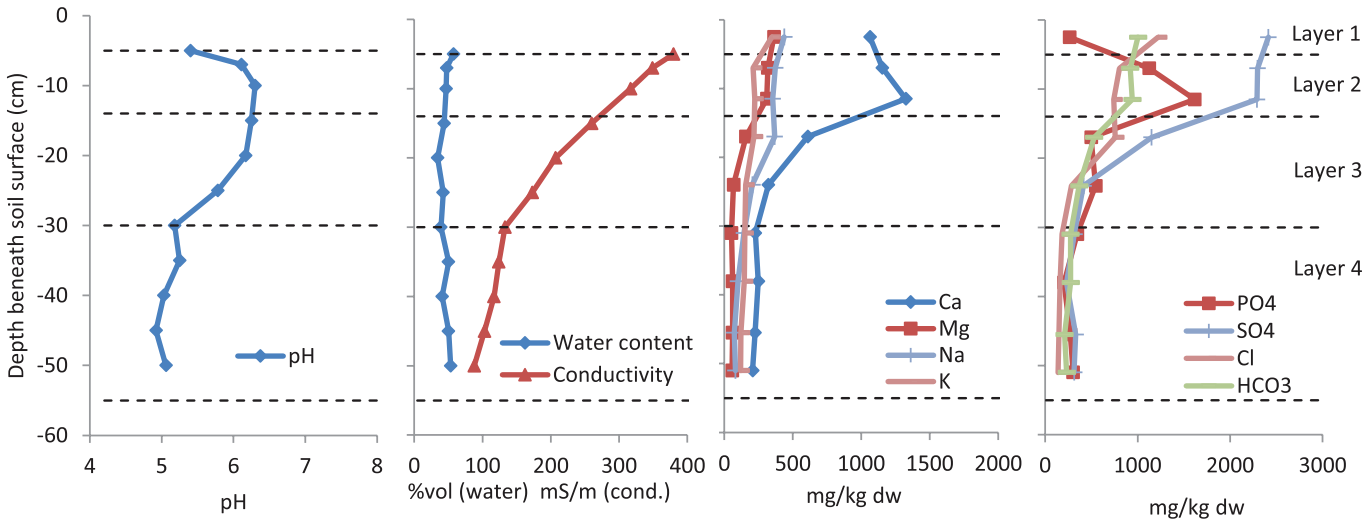

FIG. 6. Field measurements and results from soil samples taken from the test pit at Aasivissuit on 3 September 2021. Dashed horizontal lines show approximate layer boundaries at the measuring and sampling spot (layer numbers shown to the right). Nitrate was below detection limits in all samples.

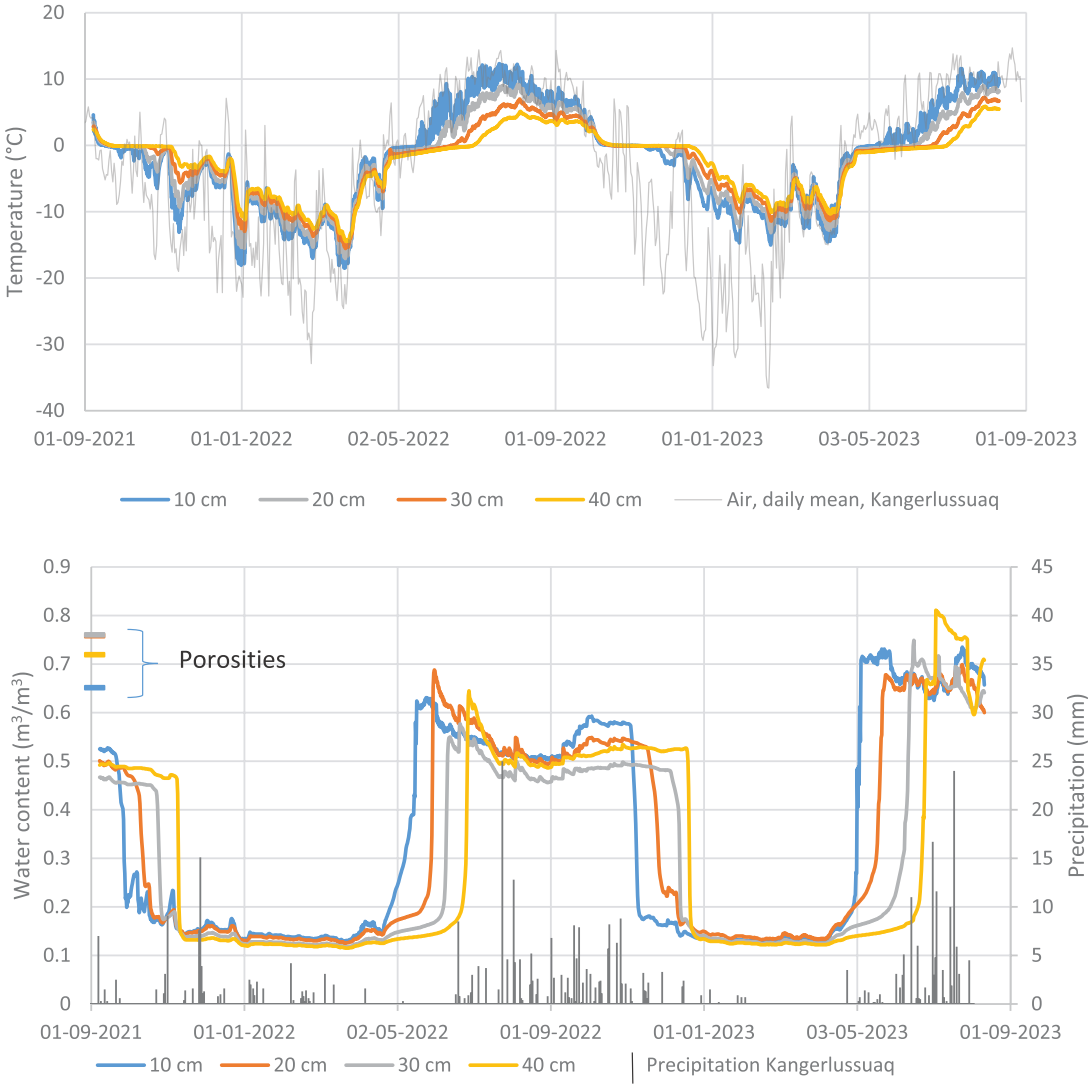

FIG. 7. Variation in temperature (top) and water content (bottom) during the first two years of monitoring. The water content sensors measure only fluid water; when water freezes in winter, the water content appears to drop.

vol and 25% vol. On the day of sampling, the different soil layers had water content between 44% vol and 57% vol, leaving an air-filled pore space of 11% vol and 32% vol.

Results from field measurements in the open soil profile and from laboratory analysis of ions are shown in Figure 6. pH changed with depth: low pH values (about 5) occurred in layers 1 and 4, and more neutral values (about 6.2) in layers 2 and 3. Conductivity was highest in the uppermost layers, probably due to loss of water through evaporation from the topsoil. We carried out these measurements in September 2021, which was relatively dry (Fig. 7), and it is likely that the profile would look different in a wetter period. Analysis of water-soluble ions in soil samples also showed increasing concentrations toward the top, with calcium being the dominating cation and sulphate the dominating anion. Phosphate concentrations were relatively high and probably came from excrement/urine or decay of flesh or bone dumped on the midden.

Time series for temperature and soil moisture are presented in Figure 7. The air temperature gets very low during winter (below −30˚C). Still, there are quite a few days during winter when the mean temperature is above 0˚C (Fig. 7), and even more days when the temperature is positive during the day and negative at night. When we looked at the hourly measurements of air temperature (not shown), we found at least 46 freeze/thaw events during autumn 2021. Deeper in the soil, conditions fluctuate less, and there is only one freeze event and one thaw event per year. Instead, there is a long zero curtain during which soil water slowly freezes and thaws keeping the temperature at 0˚C over a month or more.

The measurements of water content showed relatively modest variation. The sensors measure only water, not ice, and thus the low values during winter are due not to drying, but to freezing (Fig. 7). In spring, when ice and snow melt, the water content peaks, but it is relatively stable over the summer. Measurements from other archaeological sites show a distinct correlation between water content and oxygen saturation and also that anoxia occurs when the air content decreases below about 10–15% vol (Matthiesen et al., 2015). Comparison between soil porosity and water content (Fig. 7) showed low air content in summers that were relatively wet (especially 2023). Preliminary oxygen measurements on site in August 2023 showed decreased oxygen content (5–60% oxygen saturation) in the different soil layers, however, oxygen content can vary greatly over time and from day to day, so automated logging would be necessary to reveal the oxygen dynamics (Matthiesen et al., 2015). Measurements of the soil matrix potential showed no extreme drying of the soil—the lowest values were measured in the dry September 2021 where the potential briefly reached −13 kPa (not shown), corresponding to a relative humidity in the soil of 99.99%.

A long-time series of data on weather conditions at nearby Kangerlussuaq Airport is available from the Danish Meteorological Institute (Supplementary Fig. S2). This series shows that the excavation year (2021) was relatively dry, while 2022 and 2023 were relatively wet but not extreme.

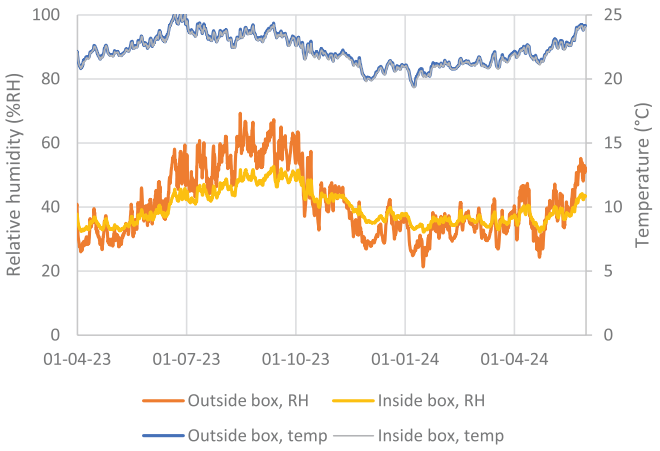

FIG. 8. Temperature and relative humidity in the storage room and inside the cardboard box containing the bone collection at the Natural History Museum of Denmark. The temperatures inside and outside the box are identical and their graphs overlap.

Bones stored at the Natural History Museum of Denmark have been in a dry storage facility since 1978. Measurements taken from the beginning of April 2023 to the end of June 2024 are presented in Figure 8, which show that the relative humidity in the storage room varied between 20% RH during winter and 70% RH during summer. Within the boxes containing bones, however, the variation was less, with values between 32% and 53% RH. The temperature varied between 20˚C and 25˚C.

Detailed Analysis of Caribou Ribs

Table S1 shows the results from measurement of the bones' bulk density, unbound water content, and organic content. Figure 9 shows the results for each of the four find layers. There is a rather large variation in the results, with no distinct difference between find layers or excavation year.

The bulk density (Fig. 9a) is measured as the dry weight of the sample divided by its wet volume (measured as buoyancy), that is, the pores are included in the volume measurement (Lyman, 2014). Ribs contain both cancellous and compact bone tissue, and a low density may reflect a sample with a relatively high amount of cancellous tissue. Also, degraded bones in which the compact part contains enlarged pores or where the bone is demineralized will have a lower density. There are several possible explanations for the large variation in density observed here.

The unbound water content (Fig. 9b) is measured as weight loss for the water-saturated bone when dried at 105˚C for 12 hours. At this temperature, free water in the pore spaces will evaporate, while water bound on surfaces and within the collagen typically requires a higher temperature to be released (Turner-Walker, 2023), thus the term "unbound water content" is used.

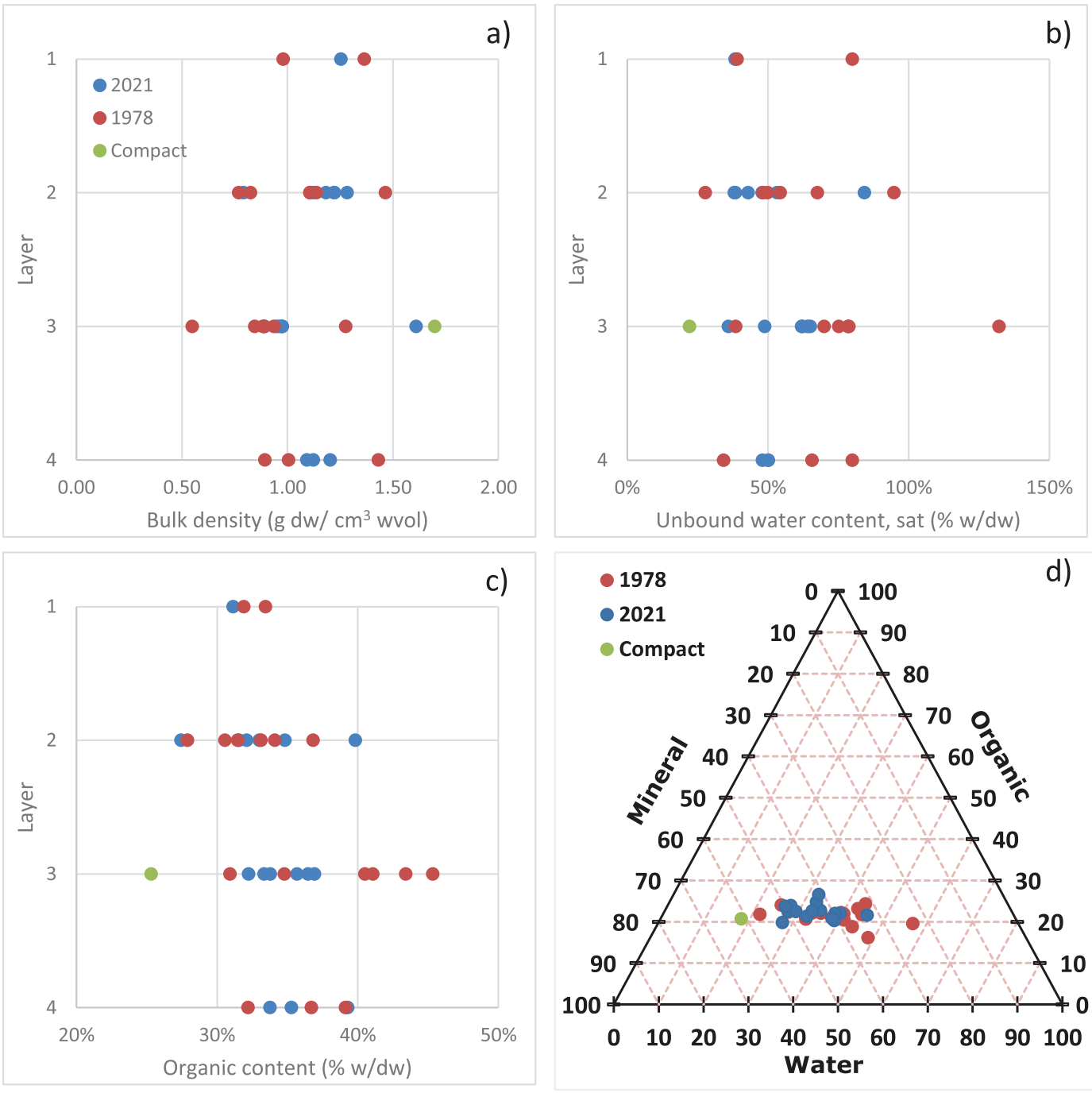

FIG. 9. Bulk density a); unbound water content b); and organic content c); presented according to find layer, and ternary diagram of the relative proportions of water, organic material, and mineral d) in 33 archaeological rib samples and 1 compact tibia. Each point is an average of 2 or 3 subsamples, and the standard deviation between samples from the same bone is typically a few percent.

The bones' organic content (Fig. 9c) is measured here as the loss on ignition when the dried bone is ignited at 600˚C. At this temperature, all organic material is oxidized, while the mineral phase decomposes at higher temperatures (Mkukuma et al., 2004).

Figure 9c shows a large variation in the organic content of bones relative to their dry weight (between 22% and 43%). However, as per Figure 9d, if water is included and the data are presented relative to wet weight, the variation seems to be smaller with a variation in organic content between 16% and 26% relative to wet weight (Fig. 9d). The proportions are very similar to what is described in Turner-Walker (2023).

Ten bones were selected representing different layers and reactivities for histological analysis. Figure 10 shows optical microscopy of four of these as examples, while the remainder are presented in Supplementary Fig. S3. Generally, the bones are well preserved on a microscopic level, with an OHI value of five for all bones and GHI values of three to five (Supplementary Table S1). There were few

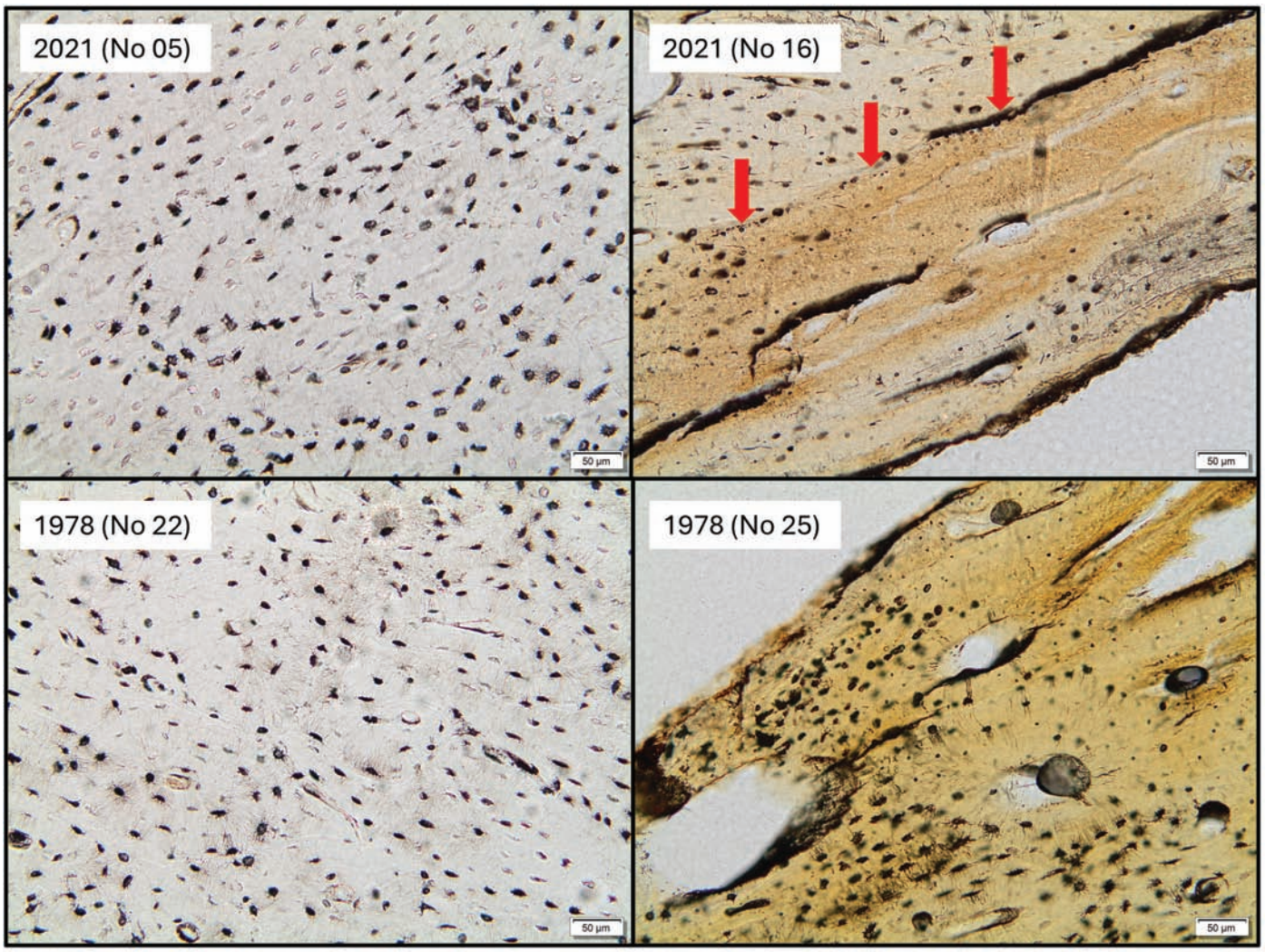

FIG. 10. Optical microscopy of thin sections from four bones representing variations in preservation from both excavation campaigns. Samples 16 and 25 display yellow and orange staining and etching along surfaces. The red arrows show an etched and cracked zone along the periosteal surface of sample 16. Details on the four bones are presented in Table S1, and overview images showing a larger portion of the sections of all samples can be found in Figure S3.

or no microcracks and a high birefringence for all samples, also indicating good preservation. The surfaces and the areas around some of the osteocyte lacunae and canaliculi show signs of etching and yellow staining, possibly from Fe/Mn compounds. Some of the bones show a decreased Ca and P content in the outer surface layer (about 0.5 mm), and all bones display evidence of dissolution (to a depth of approximately 0.2–0.5 mm from the surface) in the form of generalized destruction, as seen in the light microscope. They also show lower density and enlarged pores (as seen in the SEM).

Reactivity of Bones

We studied the reactivity in 34 bones. The oxygen consumption has been measured for water-saturated subsamples of bone at −5˚C, 1˚C, 5˚C, 10˚C, and 15˚C and for subsamples stabilized at 75% RH at 15˚C. Furthermore, we measured the oxygen consumption for whole bones at 50% RH 20˚C, resembling the conditions in storage.

For the whole bones at 50% RH and the subsamples at 75% RH, the oxygen consumption rates were all below 0.001 mg O_2/g/day (or 0.4 mg O_2/g/year), which is very low and close to the detection limit for the method. Oxygen consumption rates at different temperatures for wet samples are presented in Figure 11 and in Supplementary Table S1. For each sample, the oxygen consumption rate increased with temperature, especially at temperatures below 5˚C, above which the slope of the temperature response curve decreases. For each temperature, the reactivity of different samples varied by up to two orders of magnitude.

DISCUSSION

Based on the data from bones excavated at Aasivissuit, we tried to elucidate the answers to five main questions: 1) what caused the large variation in reactivity of bones; 2) what might explain the overall decay pattern at the site; 3) what has happened to the bone material between 1978

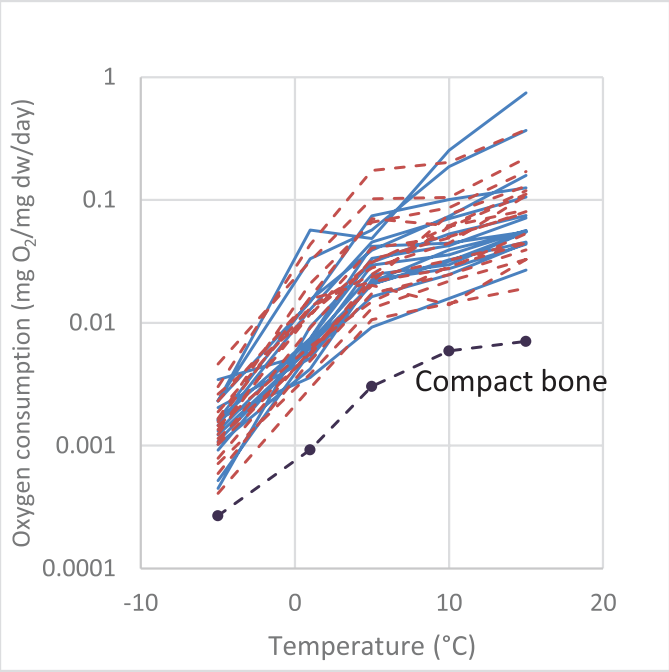

FIG. 11. Oxygen consumption rate for 33 archaeological ribs measured at −5°C, 1°C, 5°C, 10°C, and 15°C, with a compact bone (tibia) for comparison. Ribs from 2021 are shown with blue lines, and ribs from 1978 with dashed red lines (left).

and 2021; 4) can the bone degradation be modelled on a quantitative scale based on environmental analyses; and 5) can the same model be used to predict what will happen with the bone material if or when the environment changes?

Causes of the Large Variation in Reactivity of Bones

A previous study using different bone elements from different species and sites showed highly variable reactivities. For example, saturated bones at 5˚C had oxygen consumptions between 0.004 µg O_2/g dw/day and 0.27 µg O_2/g dw/day; the variation was explained by the large number of variables (Matthiesen et al., 2021). Surprisingly, the current study showed almost the same range, with oxygen consumption at 5˚C varying between 0.009 µg O_2/g dw/day and 0.17 µg O_2/g dw/day (0.003 µg for the tibia, Fig. 11), despite the fact that the same bone element (rib) from one species (caribou) and a single site was studied. So what caused the variation we found, where some rib samples are 20 times more reactive than others?

First, we looked at possible effects by excavation year. A one-way ANOVA analysis showed no statistically significant difference in the log-transformed oxygen consumption at any temperature in bones from both 1978 and 2021, respectively (e.g., $F(1,32) = 0.43$, $p = 0.52$ for results at 5˚C). As soon as the bones that had been in dry museum storage for 43 years were rewetted, they became just as reactive as the more recently excavated bones (Fig. 11). Similar one-way ANOVA analyses showed no statistically significant effects from find layer ($F(3,30) = 1.92$, $p = 0.15$) or macroscopic state of preservation ($F(3,30) = 1.66$, $p = 0.20$) on the oxygen consumption at 5 ˚C, or at any of the other temperatures. However, Figure 11 shows that the compact bone (tibia) is less reactive than the ribs, which hints at the importance of bone structure and density. Figure 12 shows the correlation between oxygen consumption (at 5˚C) and different variables related to bone structure. The different variables are strongly interrelated: a high mineral content gives a high density and a low water content (due to less room for the water molecules). The organic content is relatively constant when given relative to the wet weight of the samples (Fig. 9d) but more variable when given relative to the dry weight (Fig. 9c).

The most reactive samples had low density, low mineral content, high water content, and high organic content. A correlation between density and degradation was already observed by Binford and Bertram (1977). They describe how caribou bone of low density has a much lower percentage survivorship than high-density bones because dogs eat the cancellous tissue of low-density bones. Our data points toward a further selective mechanism: low-density bone parts are more reactive and prone to decay upon burial. Low-density bones have a more porous structure with a larger surface area where oxygen consumption for microbial degradation of organic material can take place. There are also more transport channels for oxygen and decay products.

Figure 12 indicates a linear correlation between the density and log reactivity, while Figure 11 indicates a partial linear or curved correlation between temperature and log reactivity. To investigate this further, we set up and tested a number of multiple linear regression models in R, with the reactivity of the different subsamples correlated to combinations of different variables. We were trying to find a good compromise between complexity and explanatory power of the models. A simple model including only density and temperature is presented in Equation 2:

$$log\,(O_2\ consumption) \sim temp + temp^2 + density$$

where oxygen consumption is given in mg O_2/g dry weight/day, temperature (t) in ˚C and density (ρ) in g dry weight / cm^3 wet volume. A best fit of this model explains 85% of the variation (Supplementary Fig. S4) and gives the coefficients presented in Equation 3:

$$\log_{10}(O_2\ consumption) = -1.258 + 0.126t - 0.00397t^2 - 0.820\,\rho$$

This model may be used to estimate oxygen consumption rates for wet caribou ribs with a given density for temperatures between −5˚C and +15˚C under conditions with full oxygen access but should not be used outside these conditions without validation.

The large variation in density (and reactivity) of the ribs may have several causes. First, the ribs consist of both compact and cancellous material, and the exact ratio between the two is not the same in all analyzed samples. Second, the mineralization of bones depends on various

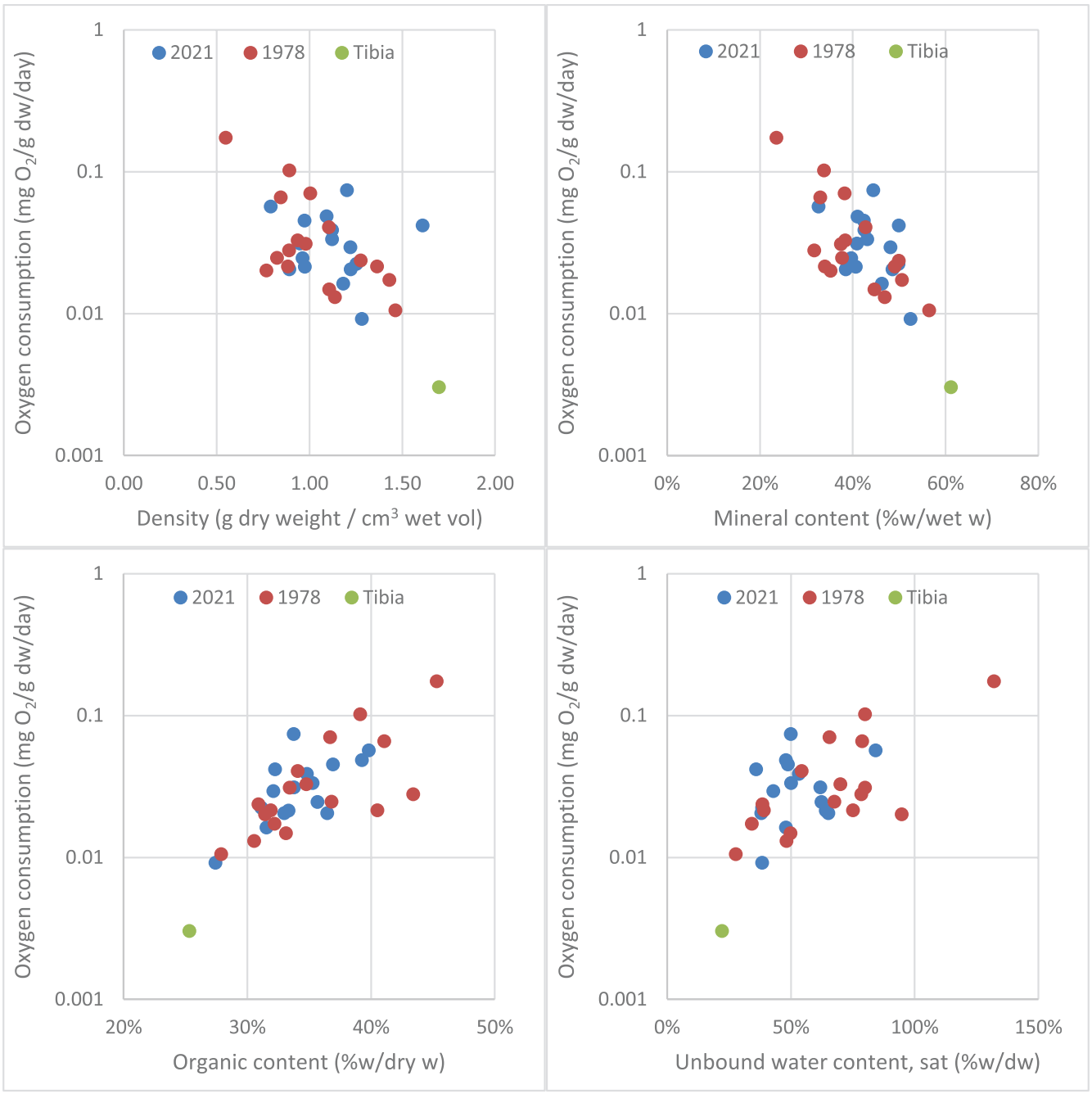

FIG. 12. Correlations between oxygen consumption at 5°C and physical parameters characterizing the water-saturated bone, including density (upper left), mineral content relative to wet weight (upper right), organic content relative to dry weight (lower left) and water content relative to dry weight (lower right).

factors including the ontogenetic age and the nutritional and health condition of the animal (Boskey and Coleman, 2010; Landete-Castillejos et al., 2012). And third, results from histology show a superficial demineralization of some of the bones, which decreases their mineral content and density (Fig. 10). Thus, the exact density and reactivity are determined by several components. For instance, some of the more degraded bones in terms of histology (e.g., no.16 and no. 25 from Figure 10) also have some of the lowest densities (1.09 g/cm^3 and 0.55 g/cm^3, respectively) and highest oxygen consumption rates (reaching 0.05 mg O_2/g dw/day and 0.17 mg O_2/g dw/day at 5°C, respectively).

General Decay Pattern at Aasivissuit (phases I to III)

The bone material at Aasivissuit is generally very well preserved, with most bones assessed to be of preservation state 5 based on a visual inspection (Fig. 4). Still, bones from the deeper layers are more degraded, with more bones assessed at states 4, 3, or even 2. This pattern is unusual, as bones in the upper deposits covered by thin layers of soil are often more degraded than bones in the deeper layers (e.g., Todisco and Monchot, 2008; Matthiesen et al., 2021).

To explain the observed decay pattern, it is necessary to understand both the site formation and the current

environment. The deeper deposits have been frozen for longer periods and have experienced lower maximum temperatures and probably longer periods with anoxic conditions than the upper deposits (Fig. 7). Consequently, we would expect that the degradation due to oxidation is slower in the deeper deposits. However, there is a large variation in age of the various layers. Bones in layer 1 are only 70 – 140 years old, whereas bones in layer 4 are between 470 and 810 years old, that is, the bones found deeper in the ground have been exposed to phase III degradation for a longer period (Fig. 1). Furthermore, layer 4 has accumulated over a long period—more than 300 years—and thus the bones there may have been exposed to weathering for a relatively long time before being covered (phase II in Figure 1). Finally, the deeper deposits (layer 4) have a lower pH than the upper ones (Fig. 6), which may increase the demineralization and degradation of the bones. It is assumed that some of the high amounts of water-soluble calcium and phosphate found in the upper deposits in 2021 may derive from the released ions of demineralization of bone that have subsequently been transported upward with rising soil water during the dry summer (Fig. 7).

The bones do not degrade uniformly, and their state of preservation varies (especially in layer 4), even if bones from the same layer have been exposed to similar environmental conditions. Some of this variation may be due to differences in density causing large variations in reactivity (as described above); where the reactivity of one type of bone element could vary by more than an order of magnitude (Figs. 11 and 12). However, some of the variation may also have been influenced by degradation that occurred during phases I and II, for example through human use (cooking, fragmentation) and subaerial weathering.

Degradation between 1978 and 2021 (phases III to V)

Figure 4 shows a comparison between the macroscopic state of preservation of material excavated in 1978 and 2021, which indicates that the material from 1978 (from the deeper deposits) is in a slightly poorer state of preservation. A chi-square analysis shows that the association between excavation year and state of preservation is statistically significant ($\chi^2(4\ df) = 19.8$, $p = 0.0005$). The difference is mainly due to a higher proportion of poorly preserved bones from the rich layer 3 in the 1978 material ($\chi^2(4\ df) = 26.1$, $p = 0.00003$ for layer 3 alone). The average preservation state in the upper two layers is slightly poorer in 2021 than in 1978 (Fig. 4c), however, the difference is not statistically significant ($\chi^2(2\ df) = 0.57$, $p = 0.75$ for layer 1, and $\chi^2(2\ df) = 3.4$, $p = 0.18$ for layer 2).

The difference between the 1978 and 2021 material indicates that the macroscopic degradation after excavation and during storage (phases IV and V) has been faster than degradation in situ. Correspondingly, DNA studies of bone material shows that the endogenous DNA is more degraded in bones excavated in 1978 compared to recently excavated bones from 2021 (Eriksen et al., 2025). It is well known that fast drying and fluctuating humidity can cause strain in bones and result in cracks and loss of surface that may affect the visual appearance (Pokines et al., 2018). Bones were dried in the field to avoid mould, and it is possible that some of the damage has occurred immediately after excavation (phase IV). The current storage environment shows fluctuating humidity between 32% and 53% RH within the storage boxes (Fig. 8). This is quite dry for the storage of bone (Botfeldt and Richter, 1998), and it's possible that the low humidity may cause further cracking over time (phase V).

Degradation in situ since 1978 is difficult to evaluate as the reference material in storage seems to have changed. However, detailed descriptions of the preservation were made back in 1978 when the bones were shipped to the Natural History Museum and all bones were characterized in terms of weathering stage (Grønnow et al., 1983). The authors use the term "desquamation" (that we interpret as exfoliation) to describe the weathering where cat1 had no desquamation of the bone surface, cat2 had local desquamation, cat3 showed widespread desquamation, and cat4 had total desquamation. The weathering stage of different types of bone had also been summarized for each layer (Grønnow et al., 1983); we redrew the results in Figure S5.

Overall, the picture observed in 1978 is very similar to what we have registered in 2021 (Fig. 4), confirming that there has been no substantial degradation going on in situ during the last 43 years. More detailed comparison of the data is difficult because of differences in how the preservation categories are defined.

The detailed investigation of 33 bone samples (17 from 1978 and 16 from 2021) allows a small-scale comparison to be made between the two excavation campaigns (Fig. 10). We determined, for instance, that the mean density was 1.03 g/cm^3 for the 1978 samples, and 1.12 g/cm^3 for the 2021 samples, but the difference is not significant ($t(31) = 1.14$, $p = 0.26$, two-sample t-test). When looking at the content of the three main components relative to wet weight (Fig. 9d), we found the water content was slightly higher in the rewetted samples from 1978 (38%) than in the samples from 2021 (34%), however the difference is not significant ($t(31)=1.73$, $p=0.09$), and there is also no significant difference in the mineral ($t(31) = 1.48$, $p = 0.15$) or organic ($t(31) = 1.47$, $p = 0.15$) content. Finally, it was not possible to document systematic or significant differences for the histological investigations of ten bone samples (five from each excavation year). This does not necessarily mean that no degradation has taken place in situ during the last 43 years, only that it was too small to be documented. Before predicting future preservation, it is, however, necessary to have a deeper understanding of what controls the current decay rates.

Modelling Decay on a Quantitative Scale

The bones at Aasivissuit are generally well preserved, and degradation in situ in the period 1978 to 2021 seems to

be limited. Still, it is relevant to try to model the degradation on a quantitative scale to investigate both why it is so slow and what parameters may increase the rate. Because bone consists of three main components (water, organic material, and minerals), dehydration, loss of organics, and demineralization must be considered. We have no absolute controls on decay models because the reference bones in storage seem to have changed, there is a big variation among the bones, and the loss of one component influences others (e.g., demineralization may give an apparent increase in organic content). Still, we can compare some worst-case scenarios.

Bones in storage are mainly vulnerable to variations in relative humidity. Formation of cracks due to wet-dry cycles is a known risk (Pokines et al., 2018). Variations within the storage boxes (Fig. 8) are not extreme, but as the absolute humidity is quite low in winter, the formation of cracks cannot be excluded. Loss of organic material due to oxidation may be estimated from the oxygen consumption measurements of dry bones. For bones and subsamples stabilized at 50% RH and 75% RH, the oxygen consumption rates were below 0.001 mg O_2/g/day or 0.4 mg O_2/g/year. The oxygen may be used to oxidize either organic material (such as collagen or lipids) or inorganic material (such as reduced iron, manganese, and sulphur compounds) in the bone. In the worst-case scenario, 0.4 mg O_2 may oxidize up to 0.2 mg of organics (using a ratio between consumed oxygen and oxidized organic material of 2.13 [Matthiesen et al., 2021]). This would give a maximum loss of 8 mg organic material/g since 1978. A mean organic content of 355 mg/g dw in the 1978 bones represents a maximum loss of about 2% of the organic content—which would not be measurable given the large variation in the bone material. And indeed, no significant loss was measured. As for the loss of mineral content, this is considered highly unlikely for bones in storage.

For bones lying in situ, dehydration is not a major threat. Most of the time, the soil is either frozen or there is free unbound water in the soil, giving a matrix potential of 0 and a relative humidity of 100%. The soil matrix potential has been monitored for two years. The lowest potential measured during a dry period was approximately −10 kPa and corresponded to a relative humidity of 99.99%. It is unlikely that this drying will cause dehydration and cracks. Repeated freeze/thaw cycles could be a larger threat: Pokines et al. (2016) observed cracks in metapodials after only 75 freeze/thaw cycles, but recent studies of caribou ribs showed no crack formation after 200 cycles, indicating that these relatively flexible bones may be less vulnerable to damage (Culmsee, 2025).

We considered the loss of organic material from bones in situ. The laboratory measurements of oxygen consumption represented a worst-case scenario, where bones are fully exposed to atmospheric air. Equation 3 describes the relationship between temperature and oxygen consumption for bones with different densities. This equation may be used along with measured soil temperatures (Fig. 7) to calculate a potential oxygen consumption for bones at each depth and for each day, which is subsequently summarized to yearly values. For instance, for the year 2022, the potential oxygen consumption for bones with a density of 1.0 g/cm^3 is 5.8 mg O_2/g dw at 10 cm depth and 2.8 mg O_2/g dw at 40 cm depth (while the consumption is significantly lower for a very dense bone such as the tibia, see Figure 11). Again, both inorganic and organic compounds may contribute to the oxygen consumption but, as a worst-case scenario, this is equivalent to a potential oxidation of 2.7 and 1.3 mg organic matter/g dw/year in bones at the two depths. Comparing this to a total organic content of 342 mg/g dw of the 2021 bones, this is equivalent to a yearly loss of between 0.4% and 0.8% of the organic content. If this was really the case, we would have seen a significant loss of organic material during the 43 years from 1978 to 2021, and not the least during the 800 years since the first bones in layer 4 were disposed of at the site. So, the worst-case scenario grossly overestimates the real loss, and one of the main reasons is probably lack of oxygen in the deposits. Monitoring shows that the silty deposits have a very high water content and probably prolonged periods with anoxic conditions—for example, during the wet summer of 2023, when the deposits were close to saturated. This effect from silty deposits has previously been used to ensure mine tailings are not oxidized (Elberling and Nicholson, 1996).

Demineralization of bones may take place when water percolates down through the midden deposits and dissolves bone mineral. Berna et al. (2004) studied the solubility of bone mineral and found that in deionized unbuffered water, at 25˚C and atmospheric CO_2 pressure, the solubility of mineral from subrecent bone (buried for less than 50 years) was similar to that of synthetic hydroxyapatite (20 mg/L) at a steady state pH value of 7. McDowell et al. (1977) studied the solubility of hydroxyapatite at other pH values and temperatures. Their data indicate that solubility at pH 5 and 5˚C may be significantly higher, with a resulting Ca^{2+} concentration of 5 mM, corresponding to a solubility of hydroxyapatite of 500 mg/L. The exact solubility will depend also on the phosphate concentration. Experiments with a surplus of water show a fast demineralization of bone at low pH values (e.g., High et al., 2015; Turner-Walker, 2023), however, at Aasivissuit, the water supply is more limited. The precipitation is only about 100−250 mm/year (Fig. 7), and much of it is lost through evapotranspiration. Johansson et al. (2015) have calculated water balance in an area near the inland ice (about 40 km from Aasivissuit) and found that in a normal year, only 10 mm of the precipitation actually infiltrates the ground; this covers a range from 100 mm during very wet years to −40 mm during dry years, that is, there is a net upward water transport during dry years. This was also reflected in our measurements of the conductivity and water-soluble salts (Fig. 6). If we estimate that, on average, 10 mm of precipitation percolates through the bone layers in a year, this corresponds to 10 L/m^2. The 0.5 m × 0.5 m^2 grid cells of the midden contain up to 5000 g of bone (Grønnow et al., 1983), or 20,000 g/m^2 containing

about 8000 g hydroxyapatite. If we estimate that all percolating water dissolves hydroxyapatite until saturation, 10 L may dissolve up to 0.2 g at pH 7 or 5 g at pH 5, that is, less than 1‰ will disappear within an average year, even at pH 5. This rough estimate fits nicely with the histological analyses that showed beginning, but far from complete, demineralization of the surface of some bones.

Thus, the bone material at Aasivissuit is relatively stable under the current environmental conditions, where the low temperatures, high water content, and limited water flow through the deposits are all important factors.

Future Changes

Climate is changing rapidly in the Arctic. From 1974 to 2012, the mean temperature at Kangerlussuaq Airport increased by about 2˚C, and a further increase of between 2˚C and 4˚C has been predicted to occur by 2100, depending on carbon emission scenario (Christensen et al., 2016). A total temperature increase of 5˚C would—all other factors being equal—result in an increased oxidation rate of bones (Figure 11 and Eq. 3). However, factors are not all equal, and the degradation today seems to be limited by the high water content and limited oxygen access to the deposits, rather than the temperature. Precipitation is very variable in the area, but, overall, it hasn't changed over the last 40 years, and the predictions for 2100 indicate an increase in precipitation in the Qeqqata area of between 10% and 30%, especially at the coast (Christensen et al., 2016). The effect of a slight increase in precipitation may well be prolonged periods with anoxic conditions, which could benefit the future preservation of the organic part of the bones. On the other hand, increased precipitation may also result in increased infiltration and thus increased demineralization. Overall, the predicted change in precipitation is relatively small, however, and there are no alarming predictions for the future preservation of the Aasivissuit material. However, it is necessary to continue monitoring at the site to see whether there are other risks, such as overgrowth, increased tourism, or wear from animals (Harmsen et al., 2023).

CONCLUSION

Some of the key parameters affecting bone degradation are well known, but their effects are mainly described on a qualitative rather than quantitative scale. Revisiting excavated material and archaeological sites over a period of several decades is crucial to understand and quantify what happens over prolonged periods. This study has focused on the Aasivissuit site, where observed degradation patterns and changes occurring in the period from 1978 to 2021 in situ and in museum storage are explained. Some of the main findings include: 1) bones preserved in situ showed little change since 1978, while the excavated bones in museum storage were more degraded; 2) the decay pattern for the bones is well correlated to the environmental conditions; 3) the reactivity of wet bone (measured as oxygen consumption) was largely controlled by bone density and temperature; 4) loss of organic and mineral components of the bone under current conditions can be estimated using numerical models; and 5) continued preservation in situ under current and future climate conditions is considered feasible for the Aasivissuit site.

Current studies in the Arctic often focus on the dramatic effects of climate change and how it may lead to loss of cultural remains (Hollesen et al., 2018). This is not an immediate threat at Aasivissuit, but other sites may be more at risk. The current study suggests that site visits, monitoring, and modelling are necessary tools for making qualified predictions for individual sites. Further research is necessary to investigate whether the reactivity of other types of bone show an equally strong correlation to density and temperature, as is described in this study of caribou ribs. If the correlation of factors (eq. 3) can be expanded to cover other species, bone elements, and sites, it will allow quantitative estimates of bone decay from oxidation under current and future temperature regimes. Further research is also necessary to investigate how the damage of bones during excavation and storage can be minimized to ensure that excavations actually help to preserve the bones for the future, and not the opposite.

ACKNOWLEDGEMENTS

The authors would like to thank the Greenland National Museum for permission to work at Aasivissuit, and Hans Harmsen and Fuuja Larsen for participating in the field work. Jacob Frydendahl and Emmett Schødt Culmsee from Royal Danish Academy—Conservation are thanked for help with the analysis of sediments and subsampling of bones; Espen Undheim for invaluable help with the SEM-work; and Bouke Lacet from Vrije Universiteit Amsterdam for preparation of thin sections. The Carlsberg Foundation (CF18 – 1106) is warmly thanked for financial support to the Activating Arctic Heritage Project, which includes these investigations.

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