

Two millennia of climate change, wildfires, and caribou hunting in west Greenland

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Abstract

Changing climatic conditions is a perpetual circumstance for mankind. In this study, we investigate local environmental and climatic changes near Kangerlussuaq, west Greenland. Our reconstruction is based on a lake sediment core and methods include chemical proxies and a palynological analysis. The investigated site is located 15 km from the Aasivissuit Inuit summer hunting ground, which has been in use for caribou hunting for more than 2000 years. The presented climatic reconstruction covers the time from c. 560 CE to present time. We identify three distinct periods of climate regimes: From c. 560–1100 CE conditions were stable, warm and humid, and summer temperatures were 1.5–2°C warmer than today. 1100–1600 was a period of cooler and very arid conditions with more sea ice, corresponding to the Neoglacial cooling. In this period, we detect two wildfire events and subsequent temporary caribou abandonment of the area. From 1600 to present we find increasingly warmer conditions with more precipitation and less extensive sea ice cover, gradually approaching today's climate regime in Kangerlussuaq. We review the existing literature regarding the Aasivissuit summer hunting ground, which was first used concurrently with the detected cooling. Despite climatic deterioration, the hunting ground was regularly in use throughout the Neoglacial and onwards, with peak hunting intensity in the early 1700s. The detected wildfires and reindeer abandonment are interpreted to be localized events at the coring site and did not affect the hunting ground. Our findings highlight the resilience of the Inuit hunters to climatic changes as well as the advantages and limitations of local environmental reconstructions.

Keywords

caribou hunting, Inuit cultures, multiproxy reconstruction, paleoenvironment, palynology, wildfires, West Greenland

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Introduction

Ever changing climatic and environmental conditions have set the scene for human activity throughout the history of mankind. In the Arctic, even subtle changes can have a profound impact on patterns of foraging and migration. A good example are the Inuit people of the Dorset and Thule cultures in Greenland, whose environmentally determined annual cycle is highly vulnerable to external influences and forcing. Both cultures were nomadic hunter-gatherers, living in coastal areas and hunting on the sea-ice during winters, while they migrated inland for game hunting in the summer. The Aasivissuit summer camp (Figure 1) of the Inuit Dorset and Thule cultures is a seasonally used caribou hunting ground, with its earliest record dating as far back as 200 BCE. Following a hiatus from 100 BCE to 1200 CE, the place has been in use almost continuously up to the beginning of the 20th century (Grønnow et al., 1983). The larger area of Kangerlussuaq, in which the archaeological site is embedded, has been studied thoroughly and is well-described in terms of ice sheet fluctuations, lake chemistry, environmental, and climatic changes (Anderson and Leng, 2004; Bennike et al., 2010; D'Andrea et al., 2011; Eisner et al., 1995; Forman et al., 2007; Kopec et al., 2014; Law et al., 2015; Lesnek et al., 2020; Levy et al., 2012; Olsen et al., 2013). Most of these studies have timescales encompassing the entire Holocene or focus on contemporary observations. Hence, there are currently no studies concerned with climatic and environmental changes in Kangerlussuaq that concentrate on the last two millennia – the time of archaeologically proven human activity in the area. The

previous work forms a profound understanding of the local environment, limnological dynamics and interplay with larger-scale climate fluctuations, which is fundamental for providing a high-resolution reconstruction of paleoclimate and paleoenvironment covering the time of human activity in Kangerlussuaq area. In this study, we reconstruct past climatic and environmental changes based on multiproxy data from a lake sediment core and further relate changes to the evidence of human activity in the area. Our methods include geochemical proxies, pollen, non-pollen palynomorphs, and charcoal. Our investigations are based on sediment from a lake located approximately 15 km from the Aasivissuit summer camp to avoid direct contamination from human activity. As the geographical setting and vegetation are comparable between Aasivissuit and the investigated lake, the recorded climatic and environmental changes are assumed to be representative of both areas.

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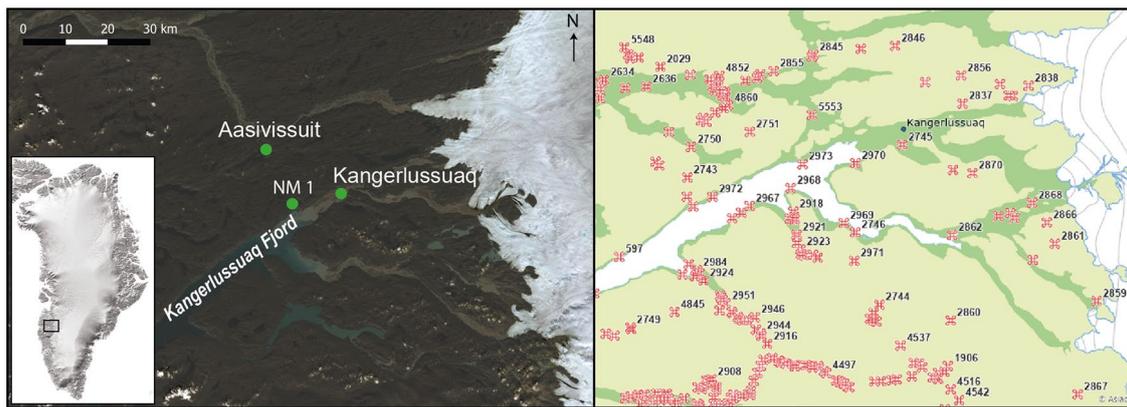


Figure 1. (a) Locations of lake NMI and the Aasivissuit hunting ground at the head of Kangerlussuaq Fjord in west Greenland. Landsat-9 image courtesy of the U.S. Geological Survey. (b) Map showing the abundance of archaeological findings around Kangerlussuaq. Cultures shown here include Greenlandic Dorset, Paleo Eskimo, Late Paleo Eskimo, Saqqaq, Thule, Colonial, and recent. Numbers refer to identification codes which can be found at <https://da.nka.gl/>. Map courtesy of Asiaq.

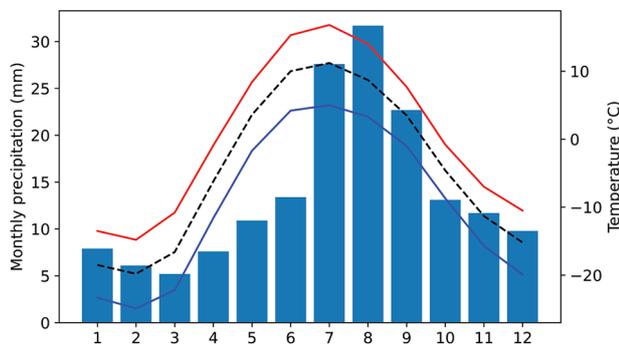


Figure 2. Precipitation (left) and temperatures (right) showing the monthly climatological normal for Kangerlussuaq 1991–2020 (DMI, 2023). Stippled line shows the monthly average temperature while blue and red lines are the averages of the monthly minimum and maximum temperatures, respectively. Bars show the average sum of monthly precipitation.

Geographical setting

Kangerlussuaq Fjord is located in southwest Greenland and stretches 180 km from its mouth in the Davis Strait to its head 25 km west of the margin of the Greenland Ice Sheet (Figure 1). The stretch of the fjord represents a strong climate gradient from wet, windy, and cool maritime climate conditions at the coast, to a dry and stable, subarctic continental climate at the fjord head. Temperatures in Kangerlussuaq at the fjord head range between -10 and -20°C in winter months and 5 – 18°C during the summer (30-year average, 1991–2020, (DMI, 2023)). Mean annual precipitation is 158.5 mm a^{-1} (1949–2003) and annual evapotranspiration has been calculated to 300 mm a^{-1} , primarily occurring during the summer months (Hasholt and Søgaard, 1978) (Figure 2). Sea ice currently covers the fjord from mid-November through May (Lund-Hansen et al., 2018). The Greenland Ice Sheet retreated from Kangerlussuaq at 5.3 ka BCE (Van Tatenhove et al., 1996). Since the ice margin retreat, the area has been subject to glacial isostatic uplift of 100 m, approaching the present sea level at c. 4000 BP (Lecavalier et al., 2014). The landscape consists of numerous lakes dispersed between rounded and ice scoured hills with scattered Late Quaternary deposits of glacial, marine, fluvial, and aeolian origin. Bedrock consists of Archean gneisses (Henriksen, 2005). The vegetation is very homogenous, dominated by different *Poaceae* (grasses) and minor patches of *Salix glauca* (greyleaf willow) and *Betula nana* (dwarf birch), reflecting arctic tundra vegetation patterns of the wider region.

The edges of the littoral zone are presently colonized by different species of *Potamogeton* (pondweed) and the shoreline features a narrow belt of *Menyanthes trifoliata* (bog bean). As the growth position of these plants are depth-dependent their distribution can reveal seasonal lake level lowering.

Human activity through millennia

The large ice-free tracts in central west Greenland are the most prominent areas of traditional caribou hunting in Greenland. In older times many families left their coastal winter settlements and ventured inland to hunt caribou for several months during the warm season. Caribou is the principal resource of the interior, and in periods with numerous caribou, Inuit gathered in large communal hunting camps, where hunting drive systems, shooting blinds other stone-built infrastructure was set up to enhance the hunt. Kayaks were carried to the lakes as a means of transport but also to be used to hunt swimming caribou where topographical bottlenecks forced the migrating caribou into lakes (Grønnow et al., 1983).

The Aasivissuit camp is a such a large communal hunting camp. The surplus caribou meat was dried and transported back to the coast for winter storage or it could be stored in caches for later retrieval by dog sledge. The caribou furthermore supplied raw materials such as antler and bone for the manufacture of tools and household utensils as well as skins for clothing. These products entered the traditional Inuit bartering system as goods exchanged for desired products from other regions such as soap stone from the south and in exchange for European goods when whalers and traders began frequenting the coasts in the 17th century.

The interior region is accordingly dotted with smaller and some larger human settlements, way finder cairns, graves, rock shelters, fox traps, caches, and other traces of human presence throughout millennia (Pasda, 2004).

The Aasivissuit site north of Kangerlussuaq stands out as a well investigated and spectacular settlement, showing reoccurring seasonal use throughout millennia. Relatively few other nearby settlements have been investigated although several are known. The earliest absolute dating of human use of the interior area in focus of this study is 1280–1340 BCE from a Saqqaq hearth, but centuries older settlements can be anticipated since Greenland's oldest anthropogenic dating of 1970–2150 BCE, have been made on charcoal from a Saqqaq settlement on the coast a few kilometers to the south of westernmost Aasivissuit-Nipisat (Kramer, 1996).

The caribou hunting site of Aasivissuit is spectacular for its many dwelling remains, large hunting systems and well-preserved

stratified midden dating back more than 2000 years. The well-preserved refuse layers form an up to 1 m thick stratified midden with dense bone beds alternating between layers with silt and sparser faunal remains. The deepest midden deposits with lithic artefacts of Dorset origin have been radiocarbon dated to 205 ± 75 BCE (Grønnow et al., 1983).

The overlying layers of Thule origin have been dated to 1220 ± 70 CE (Grønnow et al., 1983) and an additional dating of this stratum from 2022 has dated the early Thule presence at Aasivissuit to 1125 ± 30 CE (Jensen et al., 2022) which is relatively early when considering that Norse farmers still lived in Nuuk Fjord 300 km beeline further south. From this point in time and onwards the Aasivissuit site was in regular seasonal use as a focal point for hunting caribou. Variations in the deposition of caribou bone and antler demonstrate heavy variations in intensity of site use. The excavated section shows that periods with the accumulation of dense bone beds alternated with periods of vegetation regrowth and deposition of silt with only a few deposited bones, indicating less human activity at the site. The early 18th century and mid 19th century CE are characterized as periods of especially intensive site use, seen from dense accumulation of bones. These layers most likely result from large scale communal hunts during periods of maximum caribou population, whereas strata with more scattered faunal materials stem from visits by smaller hunting parties. The archaeological dating of the dense bone heaps overlaps with periods of peak caribou populations deduced from hunting statistics and historical records (Grønnow et al., 1983; Meldgaard, 1986), showing that the early 18th century and mid-19th century were periods of peak caribou populations inviting for mass hunts.

The continuous seasonal use of Aasivissuit and the surrounding interior all the way to the ice sheet is documented in historical accounts (Müller, 1906) and in contemporary oral tradition. However, beyond detailed recordings of the stratigraphy at Aasivissuit and the oscillations recorded in hunting statistics and trade lists, there is little evidence for chronological and geographical variations in the use of the interior.

Previous work

Holocene-scale climate changes in Kangerlussuaq have been investigated in previous studies using lake sediments (Aebly and Fritz, 2009; Anderson and Leng, 2004; Bennike et al., 2010; D'Andrea et al., 2011; Law et al., 2015; Olsen et al., 2012, 2013). However, the existing data covering the last 2000 years is sparse. The Kanger Stack (D'Andrea et al., 2011) is a local paleo-temperature curve from Kangerlussuaq, based on alkenones in lake sediment, which encompasses the Holocene and includes the common era. The Kanger Stack reflects lake temperature and shows an abrupt cooling event at c. 0 CE, where average summer lake water temperatures decreased 2–3°C simultaneously with a large Neoglacial advance in the area (Forman et al., 2007). The temperature rose slowly from 650 CE and peaked at 1100 CE, demonstrating that the Medieval Warm Period (MWP) was affecting the area (D'Andrea et al., 2011). A sudden temperature decline occurred after 1100 CE and temperatures remained cool until the end of the record in the 19th century (D'Andrea et al., 2011). Aebly and Fritz (2009) provide a reconstruction of summer temperature and precipitation in Kangerlussuaq, which is modeled based on measurements of paleo-shoreline terraces and constrained with the GRIP borehole temperature curve (Dahl-Jensen et al., 1998). Aebly and Fritz (2009) find that the period from c. 500 BCE to 1250 CE was characterized by monthly summer temperatures 1°C warmer than today and a mean annual rainfall of +40 mm a⁻¹ relative to today, while the summer was estimated to be 5 days longer. The period from c. 1250 CE to the present is described as the windiest and driest time in the

Kangerlussuaq record, with mean annual precipitation 20 mm a⁻¹ lower than today and temperatures similar to present (Aebly and Fritz, 2009; Willemse, 2002). The temperature fluctuations recorded by the Kanger Stack is in general concordance with the GRIP and Dye3 temperature records (Dahl-Jensen et al., 1998). However, the local record is able to capture larger amplitude in fluctuations, which is most likely due to the geographical location of Kangerlussuaq, where changes in ocean temperatures and wind patterns have a strong effect on the local temperature gradient. These local variations are not captured by ice core temperature reconstructions, which primarily reflect super-regional changes in the northern hemisphere (Dahl-Jensen et al., 1998).

Lakes as climate archives

Lakes are excellent local archives of changes in local climate and environment, as the deposited sediment records changes in the catchment that are ultimately governed by climate, such as types and abundance of surrounding vegetation, local hydrology, characteristics of erosional input, in-lake chemistry, primary productivity, and atmospheric changes (Anderson and Leng, 2004; Lasher et al., 2017, 2020; Olsen et al., 2012a; Thomas et al., 2020). The abundance of specific elements and elemental ratios are commonly used as proxies for environmental alterations in the catchment, which can be climate-driven. Typically applied environmental proxies in arctic lakes are elemental counts and ratios of Ti, Si, S, Ca, and Cl (Björk et al., 2018; Larsen et al., 2017; Olsen et al., 2012). Ti and Si are mainly derived from clastic erosional products, and changes in Ti and Si content therefore reflects changes in catchment erosion and/or aeolian transport (Davies et al., 2015). S is a primary constituent of organic matter and is delivered to the lake through catchment erosion of terrestrial vegetation, autochthonous aquatic vegetation, and from soil organic matter via soil leaching (Olsen et al., 2013). Variations in S/Ti ratio thus indicates excess or restricted S which is not due to erosion, but because of changes in either vegetation or groundwater movement. The ratio of Ca/Ti reflects an increase or decrease in carbonates derived from sources other than catchment erosion, which in this environment is autochthonous primary production (Olsen et al., 2013) – which is in turn controlled by climate and nutrient supply. Abundance of Cl in ice cores has previously been used to reflect sea ice cover, as Cl is mobilized as an aerosol via sea spray, but the mobilization is hindered when fjords or coastal waters are frozen for an extended time of the year (Abram et al., 2013; Mayewski et al., 1994).

Methods

Site description and sample collection

We extracted a sediment core (NM1-BH2) from lake NM1 (66.98347N, 50.975903W; 230 m a.s.l.), which is a small, roughly circular lake with a diameter of c. 60 m. The lake has a maximum depth of 4.2 m. The lake receives water from surface runoff and is drained by a small creek. During sampling in August 2019, we observed subaerial exposed aquatic plants indicating a recent water level fall due to excess evaporation (Figure 3). The extracted sediment core is 33.5 cm long and consists of dark brown, organic-rich gyttja. We measured the lake bathymetry prior to coring with a Chirp © Sonar and proceeded to collect sediment cores in the deepest part of the lake. Cores were extracted from a floating coring platform using a gravity corer (Renberg, 1991). Immediately after extraction, cores were subsampled into slices of 0.5 cm (uppermost 10 cm) and 0.25 cm (10 cm to bottom) that were stored in air-tight sample bags. Samples were stored frozen prior to analysis with the exception of samples submitted for ¹⁴C dating.

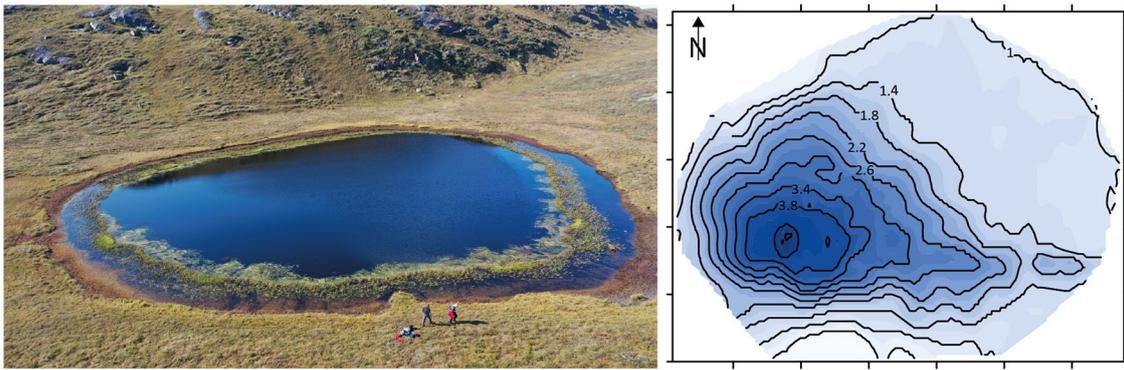


Figure 3. Aerial view of the lake with visibly lowered lake level and shallow-water plants growing along the edge (looking west, persons for scale). The photograph was taken in August 2019. Bathymetry map of the lake with depth in m. The sediment core was extracted from the deepest spot in the lake.

Radiocarbon dating

We searched the core for terrestrial plant macrofossils that were picked out, species determined, and rinsed with deionized (DI) water before being dried at 40°C. Samples were then pretreated with an acid-base-acid pretreatment, following the procedure of Brock et al. (2010), and subsequently graphitized and measured. Sample pretreatment and dating of all samples was carried out at Aarhus AMS Centre (AARAMS), Aarhus University (Olsen et al., 2017). Results are calibrated using OxCal v4.4.4 with the IntCal20 calibration curve (Reimer et al., 2020) and the calculation of a depositional sequence (Ramsey, 2008; Ramsey and Lee, 2013).

^{210}Pb dating

The samples were analyzed for the activity of ^{210}Pb , ^{226}Ra , and ^{137}Cs via gamma spectrometry at the Gamma Dating Center, Institute of Geography, University of Copenhagen. The measurements were carried out on a Canberra ultralow-background Ge well-detector. ^{210}Pb was measured via its gamma-peak at 46.5 keV, ^{226}Ra via the granddaughter ^{214}Pb (peaks at 295 and 352 keV) and ^{137}Cs via its peak at 661 keV.

Pollen analysis

Pollen sample preparation was conducted according to standard techniques including the addition of *Lycopodium* spore tablets (Erdman, 1960; Stockmarr, 1971) to enable the calculation of microfossil concentrations and influx values/pollen and particle accumulation rates. Pollen identification and nomenclature follows (Beug, 1961) while also regularly occurring non-pollen palynomorphs (NPPs) were recorded following (Van Geel, 1978; Van Geel et al., 1984). Charcoal identification was made based on morphological characteristics such as sharp breaking edges (including a halo effect at phase contrast setting around these), angular, opaque usually planar and often asymmetric shape and a deep black color (Krüger, 2020; Krüger et al., 2017; Patterson et al., 1987; Tipping, 1996). Charcoal particles have individually been subject to control with a neodymium magnet during the counting process following Krüger et al. (2023) to exclude the possibility of falsely recording detrital biotite. For the recording of palynomorphs and visualization of the results we used the CountPol software by I. Feeser (Kiel University).

Sedimentological analyses

We analyzed the sedimentological variation and elemental composition with x-ray fluorescence (XRF) scan and loss-on-ignition (LOI) measurement. The XRF scan was performed on discrete

samples of 4 g (wet sediment mass) that were freeze-dried and gently pulverized prior to analysis. Measurements were carried out with a Bruker S2 PUMA XRF analyzer at Globe Institute, Copenhagen University at ranges of 20, 40, and 50 kV, with currents of 1000, 1250, and 2000 μA , and for measurement times of 200, 100, and 10 s, respectively. The LOI was determined at 550 and 950°C using a thermo-gravimetric analyzer (ELTRA TGA Thermostep) at the Palynological laboratory, Institute for Pre- and Protohistoric Archaeology at Kiel University. Samples of 1 g of sediment were proceeded following Heiri et al. (2001). In addition, further sediment samples were examined for larger pieces of charcoal (>350 μm). Here, samples of 2–3 g sediment were taken in intervals of 0.5 cm across the sequence. The sediment was filtered through a 350 μm sieve using H_2O . The extracted material was treated with 39% H_2O_2 (hydrogen peroxide) for 24 h to bleach organic materials, following Rhodes (1998).

Results and interpretation

Age model

We established an age-depth model (Figure 4) of core NM1-BH2 based on five radiocarbon dates (Table 1) together with a series of ^{210}Pb measurements of the top 5 cm (Table 2). All ^{14}C -dated material were subfossil terrestrial plant remains (species are declared in Table 1). The sediment core showed surface contents of unsupported ^{210}Pb of around 280 Bq kg^{-1} with a clear tendency for exponential decrease with depth (Supplemental Figure S1). The calculated flux of unsupported ^{210}Pb is only 35 $\text{Bq m}^{-2}\text{year}^{-1}$ which is only about half the expected flux (based on data shown in Appleby, 2001). This may be caused by low rainfall in the region. The content of the isotopes ^{137}Cs and ^{241}Am showed a distinct peak at a depth of 3.25 cm. CRS-modelling has been applied on the profile using a modified method (Andersen, 2017; Appleby, 2001) where the activity below 7 cm is calculated on the basis of the regression shown in Supplemental Figure S2. This initial chronology places the peak in ^{137}Cs and ^{241}Am in 1954 which is reasonably close to the expected year of 1963. An adjusted chronology has therefore been calculated in which the depth 3.25 cm was set to 1963, following the procedure described in Appleby (2001). The exponential decline in unsupported ^{210}Pb and the distinct peak in ^{137}Cs and ^{241}Am gives confidence in the chronology and it is therefore considered to be reliable.

Pollen analysis

Pollen data from the NM1 core was arranged in seven pollen assemblage zones (PAZ) after constrained cluster analysis in R

(version 4.2.2, package: rioja, vegan). The resulting pollen diagram is plotted on age and is found in Figure 5.

PAZ 1

(567–893 CE). *Betula nana*-type (dwarf birch) pollen dominate the overall spectrum of this zone with >50% of the total terrestrial pollen, but also *Betula pubescens*-type (downy birch) pollen, *Salix* (willow), *Empetrum* (crowberry), *Artemisia* (mugwort) and Poaceae (grasses) are important pollen contributors. The spectrum of this zone comprises a closed curve of *Juniperus*

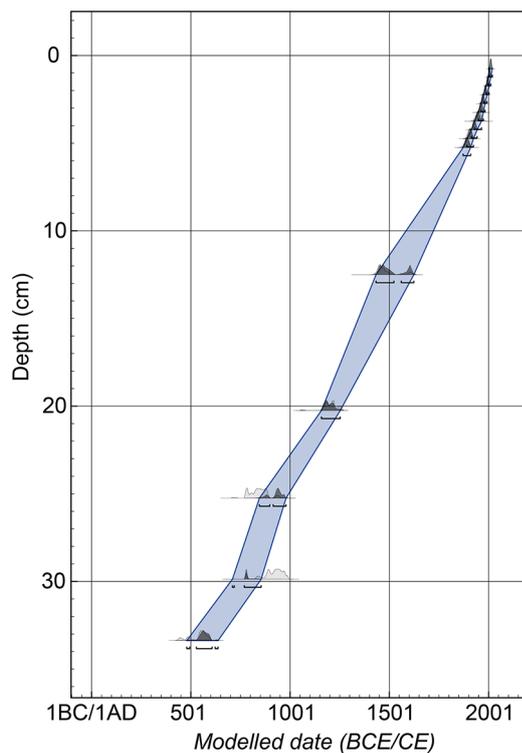


Figure 4. Age-depth model based on five ^{14}C dates and the ^{210}Pb series (uppermost 5.25 cm).

Table 1. Overview of ^{14}C dating results from core NMI-BH2.

Sample name	Depth (cm)	Dated material (^{14}C)	Age (^{14}C yr BP)	Calibrated age (95% range CE)	Lab. number
NMI-BH2-29+30	12.25	<i>Betula nana</i>	421 ± 34	1434–1624	AAR-34117
NMI-BH2-62	20.25	Poaceae, <i>Betula nana</i> , <i>Juniperus</i> , <i>Carex</i> , <i>Salix polaris</i>	846 ± 26	1159–1253	AAR-32138
NMI-BH2-81	25.25	<i>Betula nana</i> , <i>Empetrum</i> , <i>Juniperus</i>	1185 ± 26	846–980	AAR-32139
NMI-BH2-100	29.86	<i>Betula nana</i>	1139 ± 29	710–855	AAR-34118
NMI-BH2-114	33.38	<i>Betula nana</i> , <i>Stellaria</i>	1531 ± 27	480–638	AAR-32,140

Table 2. Overview of ^{210}Pb dating results from core NMI-BH2.

Sample name	Depth (cm)	Dated material (^{210}Pb)	Age (CE)	Error (years)
NMI-BH2-3	0.75	Bulk sediment	2011	4
NMI-BH2-4	1.25	Bulk sediment	2005	4
NMI-BH2-5	1.75	Bulk sediment	1996	4
NMI-BH2-6	2.25	Bulk sediment	1984	5
NMI-BH2-7	2.75	Bulk sediment	1972	6
NMI-BH2-8	3.25	Bulk sediment	1963	8
NMI-BH2-9	3.75	Bulk sediment	1950	6
NMI-BH2-10	4.25	Bulk sediment	1929	8
NMI-BH2-11	4.75	Bulk sediment	1906	10
NMI-BH2-12	5.25	Bulk sediment	1891	11

(juniper) and further also a low variety of herbs, including Campanulaceae (cf *C. rotundifolia*/ harebell). This composition indicates a sporadic distribution of the vegetation including open areas for very low-growing heliophilous species, and furthermore reflects a nutrient poor tundra community. The wetland vegetation around the lake featured Cyperaceae (sedges) and *Sphagnum* mosses in higher quantities while *Menyanthes trifoliata* (bog bean) and *Sparganium* (bur-reed) flourished in the shallow waters of the lake shore, suggesting that summer temperatures were slightly ($1.5\text{--}2^\circ$) warmer than today's, with a mean July temperature of 12°C (Bos, 1998). Continuous values of spores of coprophilous fungi (SCF; especially HdV-113/*Sporormiella*) reflect the presence of large herbivores, most probably caribou (Davies et al., 2022; Raper and Bush, 2009; Räsänen et al., 2007). It is noteworthy that pollen values of the individual types are characterized by consistency throughout the zone. This alludes to very stable environmental conditions.

PAZ 2

(893–1198 CE). *Betula nana*-type pollen concentration strongly and suddenly decline. In the pollen percentage diagram this results in a calculated increase in mainly Poaceae and only slowly decreasing but strongly fluctuating values of *Betula nana*-type pollen. Synchronously, *Artemisia* – a very drought tolerant genus – increases. A plausible explanation is that dryness suppresses the pollen production of *Betula nana*, and at the same time causes a propagation of drought-resistant species like *Artemisia* and some Poaceae. This is further supported by the continuous increase in *Hordeum*-type pollen in this zone. This pollen type comprises many large pollen grains with characteristic surface pattern including the locally growing *Elymus mollis* (Lyme grass) (Beug, 1961; Edwards et al., 2008; Fredskild, 1988), that certainly is the only producer of *Hordeum*-type pollen in the area of investigation.

The decline of *Equisetum* (horsetail), *Sphagnum*, Cyperaceae and *Betula nana*-type pollen, as well the termination of a continuous *Juniperus* curve indicate a change in hydroclimate. A change towards dryer conditions is in line with higher levels of *Artemisia* and *Hordeum*-type pollen and a constant increase in charcoal particles, or the charcoal-particle-background-component, respectively.

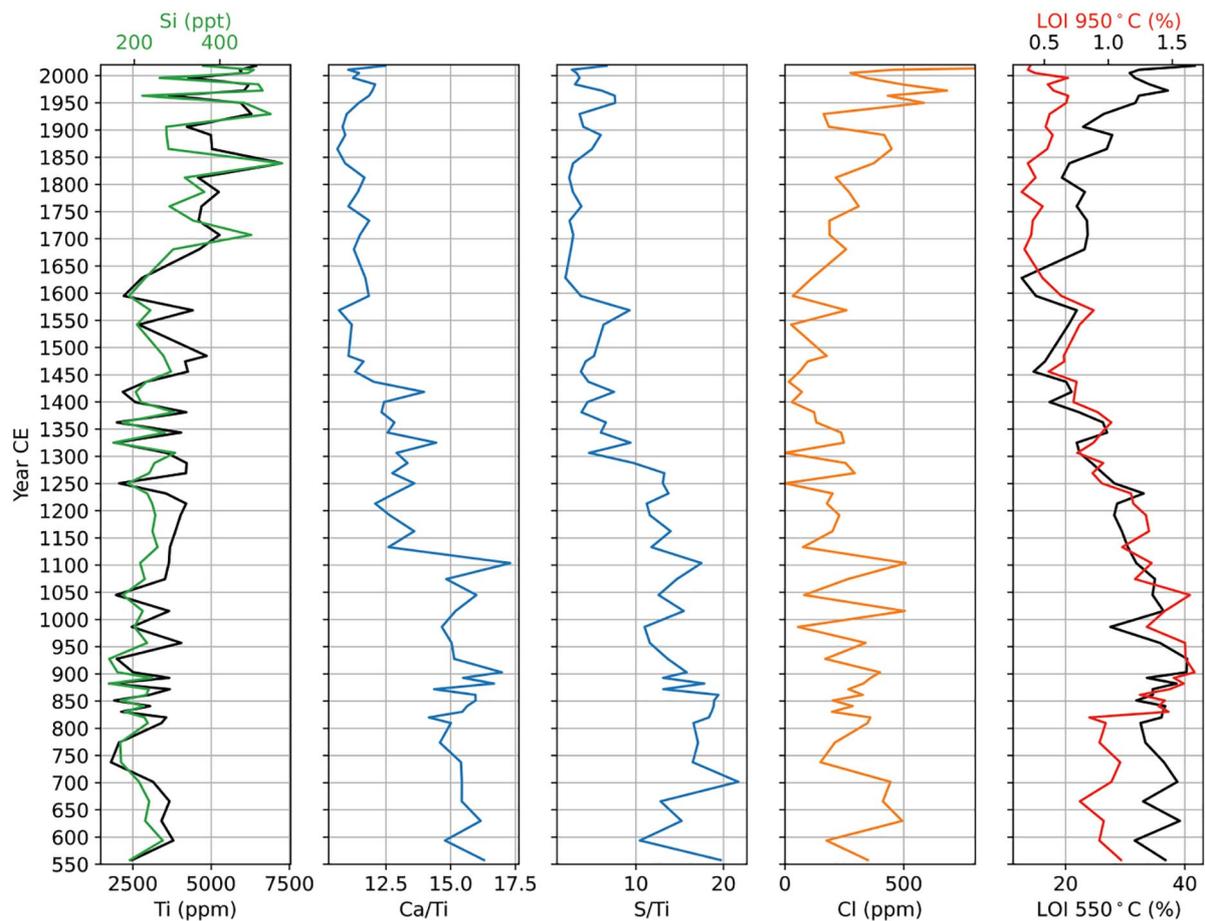


Figure 6. Results of measurements of XRF and LOI. From left to right: Ti and Si which are indicators of catchment stability and erosion. Ratio of Ca/Ti which is an indicator of excess Ca derived from autochthonous primary production. Ratio of S/Ti which indicates general biogenic production. Cl which indicates sea spray from open fjord waters. LOI at 550°C and 950°C which indicates the abundance of plant organic material and carbonates, respectively (references are to be found in main text).

higher precipitation. However, a lake level lowering – due to lowered precipitation or higher evaporation – is indicated especially by the aquatic species. Lower water levels would again create larger shallow water areas for *Menyanthes trifoliata* to spread. These plants would shade-out *Potamogeton* while no deeper waters remain at which the latter could outcompete *Menyanthes trifoliata*. The former bank areas provide space for the propagation of *Sphagnum* mosses. The lowered diversity of pollen types and the large input of *B. nana* and *Salix* pollen would be resulting from a severely shrunken pollen catchment area due to the reduction of the size of the water surface.

Elemental analyses

From the XRF measurement, we selected specific elements and element ratios that reflect environmental changes in the catchment. Counts of Ti and Si follow each other closely (Figure 6). From the core bottom at c. 560–1600 CE, values scatter at low levels with no general trend. From 1600 to 1700 CE there is a steep increase to a stable level of high values. The data indicates stable catchment conditions until 1600 CE, where increasing Ti and Si counts indicate increased influx of detrital erosion products, which could be caused by catchment destabilization or increased runoff. From 1700 to present the catchment is again stable, however with a higher input of clastic material, suggesting that the sudden increase was not a singular event, but rather an environmental shift towards increased runoff, which could be an indicator of increased precipitation. The Ca/Ti ratio (Figure 6) is stable from the core bottom at c. 560 CE to 1140 where a sudden decrease occurs, followed by a continuous decreasing trend

until 1450 CE. From 1450 to present the ratio remains stable and low. We interpret this signal to reflect a trend of decreasing primary production in the lake, beginning at 1140 CE. The S/Ti ratio (Figure 6) shows a brief drop in the core bottom, but then stable and high values from 700 to 860 CE. A decrease occurs from 860 to 1450 CE, and broken by a brief increase, the ratio remains low and stable from 1450 to the present. We interpret that the supply of excess S was initially high and stable due to abundant terrestrial vegetation delivered to the lake through erosion. Declining S/Ti values reflect a decrease in available vegetative matter as the erosion remains constant in the same interval. The rate of annual organic production and, hence, available plant material by the surrounding vegetation then stabilizes and appears to remain low. Counts of Cl (Figure 6) show a large degree of scatter between values of 0 and 500 ppm, with a general trend of decrease from c. 560 to 1600 CE, indicating a transition towards temperature conditions favoring prolonged sea ice cover, yielding less sea spray. Cl values then increase from 1600 to present from values close to 0 ppm to above 500 ppm, reaching approximately 1500 ppm in the top sample (out of scale), indicating decreased sea ice cover and more sea spray in the ice-free period.

LOI(550°C) (Figure 6) yields initially high and stable values, reflecting an abundance of organic production, until a decrease from 980 to 1630 CE. The values increase again from 1630–present. The measurement of LOI (950°C), which reflects carbonates from primary production as there is no carbonate-bearing bedrock in the catchment, shows initially low values that increase at 825 CE to remain stable and high, before a general decrease from 1050 to present (Figure 6). Organic matter abundance is highly governed by climatic control, such as temperature and precipitation.

The initial high LOI-values are interpreted to reflect an environment with sufficient summer temperatures and precipitation for a relatively lush subarctic vegetation. The decreasing trend reflects gradual cooling and/or less precipitation.

Discussion

Our multiproxy analyses can be sorted into three main groups that reflect: i) organic productivity (LOI, Ca/Ti, and S/Ti), ii) catchment stability (Ti, Si, pollen types and charcoal particles), and iii) temperature/precipitation (CI, pollen types, NPPs and charcoal). During the investigated time period from c. 600 CE to present, we identify three intervals that are distinct based on XRF and LOI (Figure 7) as well as from the stable pollen spectra. In the first interval, from c. 560 to 1100 CE, the organic productivity is at a high and stable level, while climate proxies are at a high level with a gradual decline, and synchronously erosion is low. This reflects a stable environment with high organic production and relatively high summer temperatures and open water for an extended time of the year, as seen from the increased CI flux. The very stable and warm environment is also evident from the pollen record, which suggests that summer temperatures were on average approximately 1°C higher than today in this period (compared to climatic normal 1991–2020, where the average temperature in July was 11.2°C (DMI, 2023)) and that caribou were abundant in the area, as inferred from SCF (Figure 5). Our results show that the elevated temperatures characterizing the MWP last from 590 to 1100 CE in Kangerlussuaq, which is in agreement with local lake temperatures recorded in the Kanger Stack (D’Andrea et al., 2011). Similarly, Aebly and Fritz (2009) found that the summers in the area were 5 days longer and 1°C warmer than today in this time interval and until 1250 CE. Furthermore, Aebly and Fritz (2009) estimate that the precipitation rate was 40 mm year⁻¹ higher than today in Kangerlussuaq, which is in agreement with our findings of a relatively lush vegetation (cf. *Sphagnum*, *Empetrum*, *Equisetum*, etc.). The timing of the MWP in our record is concordant with temperature reconstructions based on gas fractionation in GISP2 (Kobashi et al., 2017) and two centuries earlier than the MWP recorded in GRIP and Dye3 (Dahl-Jensen et al., 1998). This discrepancy is likely explained by the high, decadal resolution of the gas fractionation temperature reconstruction (Kobashi et al., 2017), whereas the borehole-reconstruction (Dahl-Jensen et al., 1998) is unable to capture rapid temperature fluctuations because of heat diffusion in the ice sheet (Vinther et al., 2010). After this warm period, we observe a gradual transition away from the warm, stable environment. We first detect the transition by the end of the ninth century as extended seasons of sea-ice cover. We observe a decrease in all proxies of organic productivity from c. 1100 CE, which marks the beginning of a new period characterized by a change to cool and arid conditions, coinciding with the Little Ice Age (as defined by (Kjær et al., 2022)). The development towards a cooler and drier climate is seen in the lowered organic production, more extensive sea ice conditions, and weakened stratification of the lake water. Our pollen record similarly indicates a change in hydrological regime towards cooler, more arid conditions and we detect a decrease in the relative abundance of caribou and lake level lowering from c. 1350 CE. The extremely dry conditions are likely to have promoted the risk of wildfires. This led to a severe local fire event that we observe at c. 1200 CE. The wildfire potentially caused the caribou to withdraw completely from the area for about 80 years until pre-wildfire vegetation conditions were reestablished. However, although the evidence for the renewed occurrence of this megafauna is continuous, it is clearly on a reduced scale. This attests to the presence of caribou either for a shorter annual residence period, or of a relatively reduced quantity of

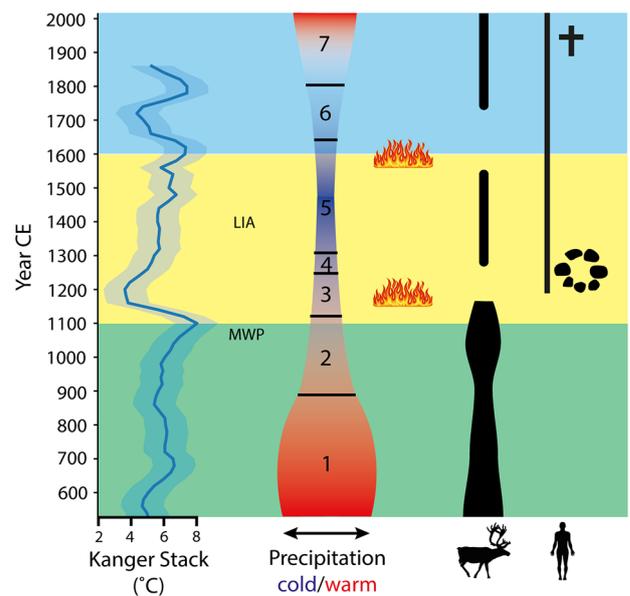


Figure 7. Timeline of climatic and environmental changes in Kangerlussuaq. From left: Kanger Stack lake water temperature reconstruction in nearby lake (D’Andrea et al., 2011). Relative cooling and warming (color grade) and precipitation amount (width) as reconstructed from multiproxy analyses and pollen (this study). Wildfires and caribou abundance (this study). Human presence at nearby Aasivissuit hunting ground (Inuit and European) (Grønnow et al., 1983).

animals. Both are attributable to the altered forage availability. Caribou are very selective, preferring food of quality over quantity (Grønnow et al., 1983; Klein, 1982; Lent and Klein, 1988; Spiess, 1979). As the preferred lush mosses, but for instance also *Equisetum*, are now much less abundant due to the increasing dryness, this climatic alteration ultimately affects animal behavior. People of the Thule culture began using the nearby caribou hunting site at Aasivissuit around 1200 CE (Grønnow et al., 1983), most likely after the wildfire, however the sequence of these events cannot be resolved as they occur within the few years of inaccuracy provided by calibrated radiocarbon ages. A second wildfire occurred at c. 1580 CE, after which the reestablishment of preceding vegetation conditions took more than 200 years, likely because low precipitation rates slowed down regrowth significantly.

The detected wildfires may not have affected the seasonal migration of caribou around Aasivissuit as adversely as suggested by the NM 1 lake core record, where the caribou appear to have disappeared. At least the early Thule dates of caribou bone from Aasivissuit demonstrate, that the Inuit hunted caribou in the area during the 13th and late 16th centuries when the terrain around NM1 was scorched by wildfires. There are no traces of wildfires in the sections recorded at Aasivissuit, but importantly, the midden accumulated in boggy terrain which assumingly would have remained moist even during dry summers.

Our findings of dry and cold conditions from 1100 to 1600 correspond well to observations of Aebly and Fritz (2009) who found the period from 1250 to present to be the windiest and driest time recorded in Kangerlussuaq throughout the Holocene. Similarly, the Kanger Stack displays a sudden temperature drop at c. 1150 CE, followed by low values until c. 1600, where temperatures rise (D’Andrea et al., 2011). In the ice core temperature reconstruction by Kobashi et al. (2017), the cooling trend starts at c. 1100 CE, fluctuates highly and continues until 1700 CE, whereas the GRIP and Dye-3 reconstruction by Dahl-Jensen et al. (1998) shows a cooling trend from c. 950 CE, which culminates c. 1550 CE. This discrepancy highlights the importance of

locally based climate reconstructions. We find that the cool and arid conditions in Kangerlussuaq prevailed until c. 1600 CE, where we see an increase in typical products of surface erosion due to increased runoff (Si and Ti) as well as a slow rise in organic productivity and moss growth, which similarly indicates more precipitation. We find that the latest period from c. 1600 to present is characterized by increasingly moister conditions, with temperatures approaching levels similar to today's. Furthermore, from 1600 onwards we see a decrease of sea-ice cover in the fjord, based on increased influx of Cl. Lake levels remain low in this period, as reflected by the pollen record, indicating that evaporation surpassed precipitation, as it does today. However, from 1800 to present, precipitation increased sufficiently to allow for more widespread growth of shrubs, which are visible in the modern landscape.

In summary, there is broad agreement between the multiple proxies used in this study to reconstruct climatic and environmental changes in Kangerlussuaq, which emphasizes the robustness of this approach. Furthermore, there are no observable lags between catchment changes observed from geochemical proxies and corresponding changes in the pollen record (Figure 7).

Conclusion

In this study, we make a reconstruction of climatic and environmental changes in close vicinity to the Aasivissuit summer hunting ground based on pollen and fungal spores, charcoal, and geochemical proxies from a lake core, covering the period from 560 CE to present. Our different proxies are in agreement regarding the observed environmental and climatological changes, and are also in agreement with other local climate reconstructions from the area. We see some disagreement when comparing to ice core-based temperature reconstructions, which highlights the importance and limitations of local reconstructions. We identify three distinct environmental regimes during the investigated period:

- c. 560 CE (base of record) to c. 1100 CE was characterized by stable climatic conditions that were relatively warm and humid (in sub-arctic context). Summer average temperature was 1.7°C warmer than today. Caribou were abundant in the area, however in smaller numbers from c. 830–930 CE.
- After a gradual change, 1100–1600 CE was a period of cooler and very arid conditions with more sea ice and we detect two wildfires. The wildfires cleared existing vegetation and forced away caribou for up to 200 years until reestablishment of vegetation.
- From 1600 CE to present we find increasingly warmer conditions with more precipitation and less extensive sea ice cover, gradually approaching the modern climate regime in Kangerlussuaq.

The changing climatic and environmental conditions have most likely been comparable at the investigated site and at the Aasivissuit summer hunting ground, 15 km away. However, we find no correlation between climatic changes and hunting intensity, indicating that the subsistence strategies and hunting types have been resilient to climatic variation. The first Inuit established the summer hunting ground simultaneously with initiation of Neoglacial cooling, and used the hunting ground regularly throughout the Neoglacial, with peak intensity close to the end of the Neoglacial detected at the coring site. Furthermore, the wildfires and resulting caribou abandonment observed at the coring site are very local events that had no impact on the summer hunting ground usage.

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Supplemental material

Supplemental material for this article is available online.

References

- Abram NJ, Wolff EW and Curran MA (2013) A review of sea ice proxy information from polar ice cores. *Quaternary Science Reviews* 79: 168–183.
- Aebly FA and Fritz SC (2009) Palaeohydrology of Kangerlussuaq (Søndre Strømfjord), West Greenland during the last ~8000 years. *The Holocene* 19: 91–104.
- Andersen TJ (2017) Some practical considerations regarding the application of ²¹⁰Pb and ¹³⁷Cs dating to estuarine sediments. In: Weckström K, Saunders KM, Gell PA et al. (eds) *Applications of Paleoenvironmental Techniques in Estuarine Studies, Developments in Paleoenvironmental Research*. Netherlands, Dordrecht: Springer, pp.121–140.
- Anderson NJ and Leng MJ (2004) Increased aridity during the early Holocene in West Greenland inferred from stable isotopes in laminated-lake sediments. *Quaternary Science Reviews* 23: 841–849.
- Appleby P (2001) Chronostratigraphic techniques in recent sediments. In: Last WM and Smol JP (eds) *Tracking Environmental Change Using Lake Sediments*. Springer, New York, pp.171–203.
- Bennike O, Anderson NJ and McGowan S (2010) Holocene palaeoecology of southwest Greenland inferred from macrofossils in sediments of an oligosaline lake. *Journal of Paleolimnology* 43: 787–798.
- Beug H-J (1961) *Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Gebiete*. G. Fischer, Stuttgart.
- Björk AA, Larsen NK, Olsen J et al. (2018) Holocene history of the Helheim Glacier, southeast Greenland. *Quaternary Science Reviews* 193: 145–158.
- Bos H (1998) *Aspects of the Lateglacial-Early Holocene Vegetation Development in Western Europe: Palynological and Palaeobotanical Investigations in Brabant (the Netherlands) and Hessen (Germany)*. LPP Contributions Series 10, Utrecht.
- Brock F, Higham T, Ditchfield P et al. (2010) Current pretreatment methods for AMS radiocarbon dating at the oxford radiocarbon accelerator unit (ORAU). *Radiocarbon* 52: 103–112.
- Ramsey CB (2021) OxCal v4. 4.4. Available at: <https://c14.arch.ox.ac.uk/oxcal.html> (accessed 2 December 2022).
- Dahl-Jensen D, Mosegaard K, Gundestrup N et al. (1998) Past temperatures directly from the Greenland ice sheet. *Science* 282: 268–271.

- D'Andrea WJ., Huang Y, Fritz SC et al. (2011) Abrupt Holocene climate change as an important factor for human migration in West Greenland. *Proceedings of the National Academy of Sciences* 108: 9765–9769.
- Davies AL, Harrault L, Milek K et al. (2022) A multiproxy approach to long-term herbivore grazing dynamics in peatlands based on pollen, coprophilous fungi and faecal biomarkers. *Palaeogeography, Palaeoclimatology, Palaeoecology* 598: 111032.
- Davies SJ, Lamb HF and Roberts SJ (2015) Micro-XRF core scanning in palaeolimnology: Recent developments. In: Croudace IW and Rothwell RD (eds) *Micro-XRF Studies of Sediment Cores: Applications of a Non-Destructive Tool for the Environmental Sciences*. Springer, New York, pp.189–226.
- DMI (Danish Meteorological Institute) (2023) DMI Vejrarkiv. <https://www.dmi.dk/vejrarkiv/normaler-gronland/> (accessed 28 March 2023).
- Edwards KJ, Schofield JE and Mauquoy D (2008) High resolution paleoenvironmental and chronological investigations of Norselandnámat Tasiusaq, Eastern Settlement, Greenland. *Quaternary Research* 69: 1–15.
- Eisner WR, Törnqvist TE, Koster EA et al. (1995) Paleocological studies of a Holocene lacustrine record from the Kangerlussuaq (Søndre Strømfjord) region of West Greenland. *Quaternary Research* 43: 55–66.
- Erdman G (1960) The acetolysis method. *Svensk Bot Tidsskr* 54: 561–564.
- Forman SL, Marín L, Van Der Veen C et al. (2007) Little ice age and neoglacial landforms at the Inland Ice margin, Isunguata Sermia, Kangerlussuaq, west Greenland. *Boreas* 36: 341–351.
- Fredskild B (1988) Agriculture in a marginal area—South Greenland from the Norse landnam (985 AD) to the present (1985 AD). In: Birks HH, Birks HJB, Kaland PE et al. (eds) *The Cultural Landscape—Past, Present and Future*. Cambridge University Press, Cambridge, pp.381–393.
- Grønnow B, Meldgaard M and Nielsen JB (1983) Aasivissuit—the Great Summer Camp. Archaeological, ethnographical and zoo-archaeological studies of a caribou-hunting site in west Greenland. *Museum Tusulanum* 39: 96.
- Hasholt B and Søgaard H (1978) Et forsøg på en klimatisk-hydrologisk regionsinddeling af Holsteinsborg Kommune (Sisimiut). *Geografisk Tidsskrift-Danish Journal of Geography* 77: 72–92.
- Heiri O, Lotter AF and Lemcke G (2001) Loss on ignition as a method for estimating organic and carbonate content in sediments: Reproducibility and comparability of results. *Journal of Paleolimnology* 25: 101–110.
- Henriksen N (2005) *Grønlands geologiske udvikling: fra urtid til nutid*. København: Danmarks og Grønlands Geologiske Undersøgelse.
- Jensen JF, Appelt M, Grønno B et al. (2022) *Field Report 2021: WP 3.4: Dynamic Global Networks*. National Museum of Denmark, Copenhagen.
- Kjær KH, Bjørk AA, Kjeldsen KK et al. (2022) Glacier response to the Little Ice Age during the Neoglacial cooling in Greenland. *Earth-Science Reviews* 227: 103984.
- Klein DR (1982) Fire, lichens, and caribou Rangifer tarandus, ecological diversity, Eurasia, North America. *Rangeland Ecology & Management/Journal of Range Management Archives* 35: 390–395.
- Kobashi T, Menviel L, Jeltsch-Thömmes A et al. (2017) Volcanic influence on centennial to millennial Holocene Greenland temperature change. *Scientific Reports* 7: 1441.
- Kopec BG, Lauder AM, Posmentier ES et al. (2014) The diel cycle of water vapor in west Greenland. *JGR Atmospheres* 119: 9386–9399.
- Kramer FE (1996) The Paleo-Eskimo Cultures in Sisimiut District, West Greenland: Aspects of Chronology. In: *Presented at the The paleo-eskimo cultures of Greenland: A new perspective in Greenlandic archaeology: Papers from a symposium at the institute of archaeology and ethnology, University of Copenhagen*, 21–24 May 1992, pp. 39–63. Danish Polar Center.
- Krüger S (2020) Of birches, smoke and reindeer dung – Tracing human-environmental interactions palynologically in sediments from the Nahe palaeolake. *Journal of Archaeological Science: Reports* 32: 102370.
- Krüger S, Dörfler W, Bennike O et al. (2017) Life in Doggerland – palynological investigations of the environment of prehistoric hunter-gatherer societies in the North Sea Basin. *E&G Quaternary Science Journal* 66: 3–13.
- Krüger S, Schnetger B, Strunk A et al. (2023) Potential critical sources of error in the analysis of microcharcoal in Greenlandic palynological samples—an initial study. *Journal of Quaternary Science* 38: 139–145.
- Larsen NK, Strunk A, Levy LB et al. (2017) Strong altitudinal control on the response of local glaciers to Holocene climate change in southwest Greenland. *Quaternary Science Reviews* 168: 69–78.
- Lasher GE, Axford Y, Masterson AL et al. (2020) Holocene temperature and landscape history of southwest Greenland inferred from isotope and geochemical lake sediment proxies. *Quaternary Science Reviews* 239: 106358.
- Lasher GE, Axford Y, McFarlin JM et al. (2017) Holocene temperatures and isotopes of precipitation in Northwest Greenland recorded in lacustrine organic materials. *Quaternary Science Reviews* 170: 45–55.
- Law AC, Anderson NJ and McGowan S (2015) Spatial and temporal variability of lake ontogeny in south-western Greenland. *Quaternary Science Reviews* 126: 1–16.
- Lecavalier BS, Milne GA, Simpson MJR et al. (2014) A model of Greenland ice sheet deglaciation constrained by observations of relative sea level and ice extent. *Quaternary Science Reviews* 102: 54–84.
- Lent PC and Klein DR (1988) Tundra vegetation as a rangeland resource. In: Tueller PT (ed) *Vegetation Science Applications for Rangeland Analysis and Management*. Kluwer Academic Publishers, Dordrecht, pp.307–337.
- Lesnek AJ, Briner JP, Young NE et al. (2020) Maximum South-west Greenland ice sheet recession in the Early Holocene. *Geophysical Research Letters* 47: e2019GL083164.
- Levy LB, Kelly MA, Howley JA et al. (2012) Age of the Ørkendalen moraines, Kangerlussuaq, Greenland: Constraints on the extent of the Southwestern margin of the Greenland Ice Sheet during the Holocene. *Quaternary Science Reviews* 52: 1–5.
- Lund-Hansen LC, Hawes I, Holtegaard Nielsen M et al. (2018) Summer meltwater and spring sea ice primary production, light climate and nutrients in an Arctic estuary, Kangerlussuaq, west Greenland. *Arctic, Antarctic, and Alpine Research* 50: S100025.
- Mayewski PA, Meeker LD, Whitlow S et al. (1994) Changes in atmospheric circulation and ocean ice cover over the North Atlantic during the last 41,000 years. *Science* 263: 1747–1751.
- Meldgaard M (1986) *The Greenland Caribou-Zoogeography, Taxonomy, and Population Dynamics*. Museum Tusulanum Press, Charlottenlund.
- Müller R (1906) *Vildtiet og jagten i Sydgrønland* [The game and the hunt in South Greenland]. København: Universitetets Bogtrykkeri, pp.1–519.
- Olsen J, Anderson NJ and an Knudsen MF (2012) Variability of the North Atlantic Oscillation over the past 5,200 years. *Nature Geoscience* 5: 808–812.

- Olsen J, Anderson NJ and Leng MJ (2013) Limnological controls on stable isotope records of late-Holocene palaeoenvironment change in SW Greenland: A paired lake study. *Quaternary Science Reviews* 66: 85–95.
- Olsen J, Kjær KH, Funder S et al. (2011) High-Arctic climate conditions for the last 7000 years inferred from multi-proxy analysis of the Bliss Lake record, *North Greenland*. *Journal of Quaternary Science* 27: 318–327.
- Olsen J, Tikhomirov D, Grosen C et al. (2017) Radiocarbon analysis on the new AARAMS 1MV tandemtron. *Radiocarbon* 59: 905–913.
- Pasda C (2004) Hotel Grønland. BAR. *International Series* 1309: 4.
- Patterson WA, Edwards KJ and Maguire DJ (1987) Microscopic charcoal as a fossil indicator of fire. *Quaternary Science Reviews* 6: 3–23.
- Ramsey CB (2008) Deposition models for chronological records. *Quaternary Science Reviews* 27: 42–60.
- Ramsey CB and Lee S (2013) Recent and planned developments of the program OxCal. *Radiocarbon* 55: 720–730.
- Raper D and Bush M (2009) A test of *Sporormiella* representation as a predictor of megaherbivore presence and abundance. *Quaternary Research* 71: 490–496.
- Räsänen S, Froyd C and Goslar T (2007) The impact of tourism and reindeer herding on forest vegetation at Saariselkä, Finnish Lapland: A pollen analytical study of a high-resolution peat profile. *The Holocene* 17: 447–456.
- Reimer PJ, Austin WEN, Bard E et al. (2020) The IntCal20 northern hemisphere radiocarbon age calibration curve (0–55 cal kBP). *Radiocarbon* 62: 725–757.
- Renberg I (1991) The HON-Kajak sediment corer. *Journal of Paleolimnology* 6: 167–170.
- Rhodes AN (1998) A method for the preparation and quantification of microscopic charcoal from terrestrial and lacustrine sediment cores. *The Holocene* 8: 113–117.
- Scherjon F, Bakels C, MacDonald K et al. (2015) Burning the land: An ethnographic study of off-site fire use by current and historically documented foragers and implications for the interpretation of past fire practices in the landscape. *Current Anthropology* 56: 299–326.
- Spieß AE (1979) Reindeer and caribou hunters: An archaeological study. Academic Press, New York.
- Stockmarr J (1971) Tables with spores used in absolute pollen analysis. *Pollen et spores* 13: 615–621.
- Thomas EK, Hollister KV, Cluett AA et al. (2020) Reconstructing arctic precipitation seasonality using aquatic leaf Wax $\delta^2\text{H}$ in lakes with contrasting residence times. *Paleoceanog and Paleoclimatol* 35: e2020PA003886.
- Tipping R (1996) Microscopic charcoal records, inferred human activity and climate change in the Mesolithic of northernmost Scotland. In: Pollard T and Morrison A (eds) *The Early Prehistory of Scotland*. Edinburgh University Press, Edinburgh, pp.39–61.
- Van Geel B (1978) A palaeoecological study of holocene peat bog sections in Germany and The Netherlands, based on the analysis of pollen, spores and macro- and microscopic remains of fungi, algae, cormophytes and animals. *Review of Palaeobotany and Palynology* 25: 1–120.
- Van Geel B, de Lange L and Wieggers J (1984) Reconstruction and interpretation of the local vegetational succession of a Lateglacial deposit from Usselo (The Netherlands), based on the analysis of micro-and macrofossils. *Acta Botanica Neerlandica* 33: 535–546.
- Van Tatenhove FGM, Van Der Meer JJM and Koster EA (1996) Implications for Deglaciation Chronology from New AMS Age Determinations in Central West Greenland. *Quaternary Research* 45: 245–253.
- Vinther BM, Jones PD, Briffa KR et al. (2010) Climatic signals in multiple highly resolved stable isotope records from Greenland. *Quaternary Science Reviews* 29: 522–538.
- Willemse NW (2002) *Holocene sedimentation history of the shallow Kangerlussuaq lakes, west Greenland*. Museum Tusulanum Press, Charlottenlund.