Investigation of permafrost degradation and coastal erosion at Sermermiut, 2024

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Investigations of permafrost degradation and coastal erosion at Sermermiut, Ilulissat Icefjord UNESCO World Heritage site, Avannaata Kommunia 15–19 July 2024

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1 August 2025

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Executive Summary

In recent decades, Arctic air temperatures have risen at an accelerated rate compared to the rest of the world (Rantanen et al. 2022), intensifying permafrost thaw and degradation, and endangering ecosystems, infrastructure, and cultural heritage (Hollesen et al. 2018). At the ancient settlement of Sermermiut, located within the Ilulissat Icefjord UNESCO World Heritage area, rapid erosion of the coastal bluffs is deteriorating one of Greenland's most significant cultural heritage sites. Erosion at Sermermiut is driven by a combination of hydrological, thermal, gravitational, and coastal processes, all enhanced by warming climate trends. Understanding these processes is important as warming air and permafrost temperatures in the Arctic will further threaten the stability of archaeological sites and communities in Greenland and beyond.

Field investigations and sampling in July 2024 characterized the erosional processes at Sermermiut and established a framework for monitoring future erosion and permafrost thaw. Continued monitoring and enhanced investigations at the site will be vital for management and decision-making going forward.

Kalaallisuuata naalisarnera

Ukiuni qulikkaani kingullerni nunarsuarmi sumiiffinni allanut sanilliullugu Issittumi silaannaap kissatsikkiartornera sukkaneroqaaq (Rantaen il.il 2022), tamatumalu kingunerivaa nunap qeriuaannartup aakkiartornera uukkaakkiartorneralu, tamassumalu aamma malitsigisaanik uumasoqassutsip, angallaveqarniarnerup taamatuttaaq kulturikkut kingornussat uloriarnartorsiortinneqalerput (Hollesen il.il 2018) Ilulissat Kanginani UNESCO-p allattorsimaffianut ilanngunneqarsimasumi inissisimavoq Kalaallit Nunaanni kulturikkut eriagisassaqarfiit pingaaarnersaasa ilaat - Sermermiut, taannalu silaannaap kissakkiartornerani uukkaakkiartorluni unitsitassaajunnaaleqqavoq. Sumiiffimmi Sermermiuni uukkaakkiartorneq sinerissami silaannaap nunallu pissusaasa unerisimannginnerannik pissuteqarpoq. Pingaaruteqarpoq pinngortitami allannguutit ilisimatusarnikkut misissugarissallugit paasissallugillu, tamakkumi ajornerulernermut allannguutit Kalaallit Nunaanni Issittoqarfimmilu allani itsarnisaqarfiit, inuiaqatigiillu unammilligassaqalernerannik kinguneqarsinnaavoq. Ukioq 2024 qaammat julimi Sermermiuni ilisimatusarnikkut suliaqarnermi misissugassanillu katersinermi sumiiffimmi susoqarneranik paasisanik nutaanik pissarsisoqarpoq, paasisallu aallaavigalugit siunissami nunap uukkaakkiartornera qeriuaannartullu aakkiartornera malinnaavigisussanngorneqarput, uuttuutit atortorissaarutit atorlugit. Summiiffiup ataavartumik misissugarinissaa malinnaavigineqarnissaalu siunissami sumiiffimmi isumaginnittunut pingaaruteqarluinnarpoq aammalu siusinaartumik periusissiassanut toqqammaviliisuusassallutik.

Danske resume

I de seneste årtier er lufttemperaturerne i Arktis steget med et accelereret tempo sammenlignet med resten af verden (Rantanen et al. 2022), hvilket intensiverer optøning og nedbrydning af permafrost og bringer økosystemer, infrastruktur og kulturarv i fare (Hollesen et al. 2018). Ved den gamle bosættelse Sermermiut, der ligger i Ilulissat Isfjord, som er på UNESCOs verdensarvsområde, forringer hurtig erosion af kystskrænterne et af Grønlands mest betydningsfulde kulturarvssteder. Erosionen ved Sermermiut er drevet af en kombination af hydrologiske, termiske, gravitationelle og kystnære processer, som alle forstærkes af opvarmende klimatendenser. Det er vigtigt at forstå disse processer, da opvarmning af luft og permafrosttemperaturer i Arktis yderligere vil true stabiliteten af arkæologiske steder og samfund i Grønland og andre steder. Feltundersøgelser og prøveudtagning i juli 2024 karakteriserede erosionsprocesserne ved Sermermiut og etablerede en ramme for overvågning af fremtidig erosion og optøning af permafrost. Fortsat overvågning og forbedrede undersøgelser på stedet vil være afgørende for forvaltning og beslutningstagning fremadrettet.

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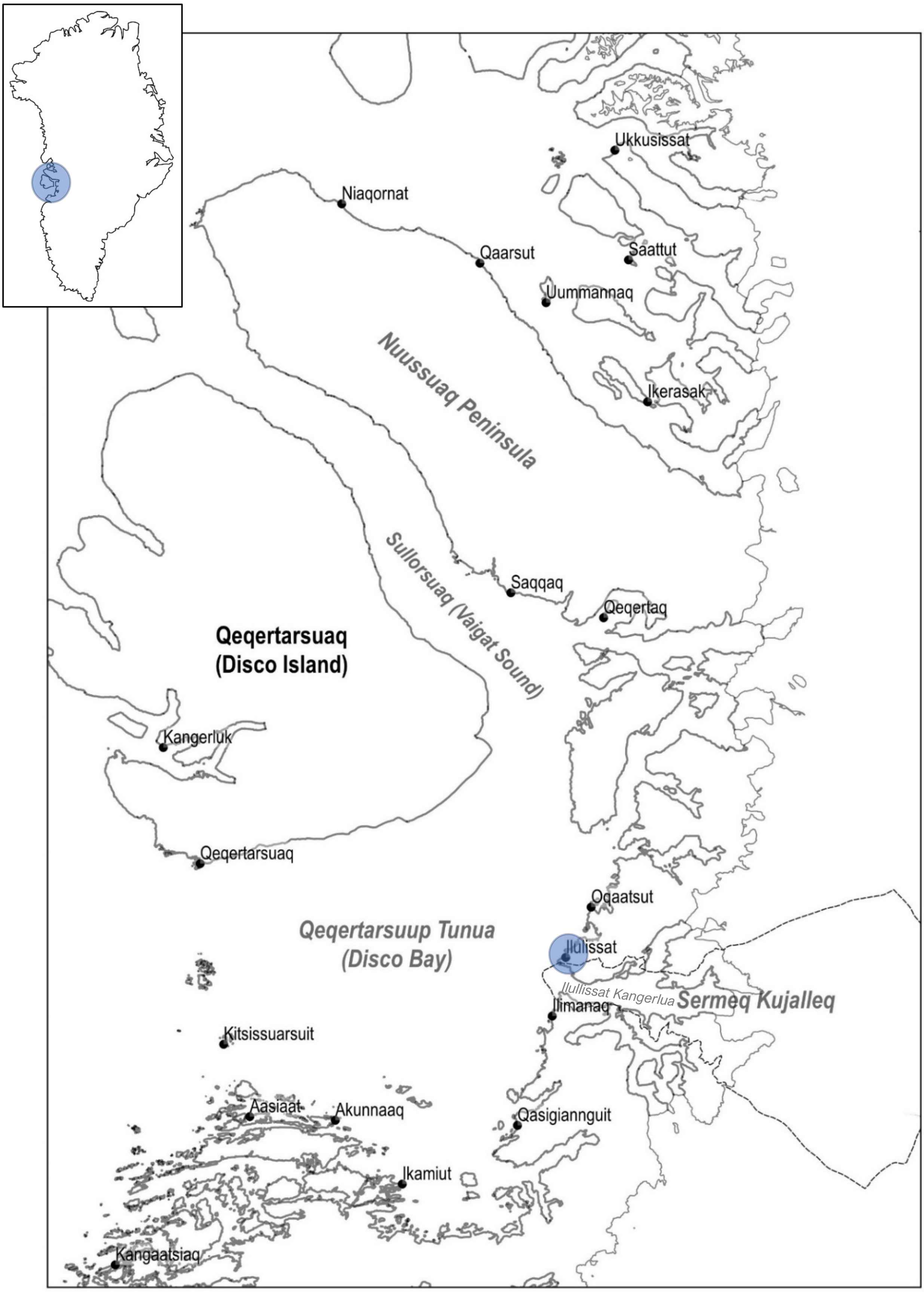

Figure 1. Map of the Disco Bay region. The Ilulissat Icefjord (Ilulissat Kangerlua) and the Sermeq Kujalleq glacier are located inside the Ilulissat Icefjord World Heritage area (indicated by the dashed line). The ancient settlement of Sermermiut is located a few kilometers to the southwest of Ilulissat (indicated by the blue circle).

Figure 2. Ilulissat and Sermermiut. Google Earth, 2024.

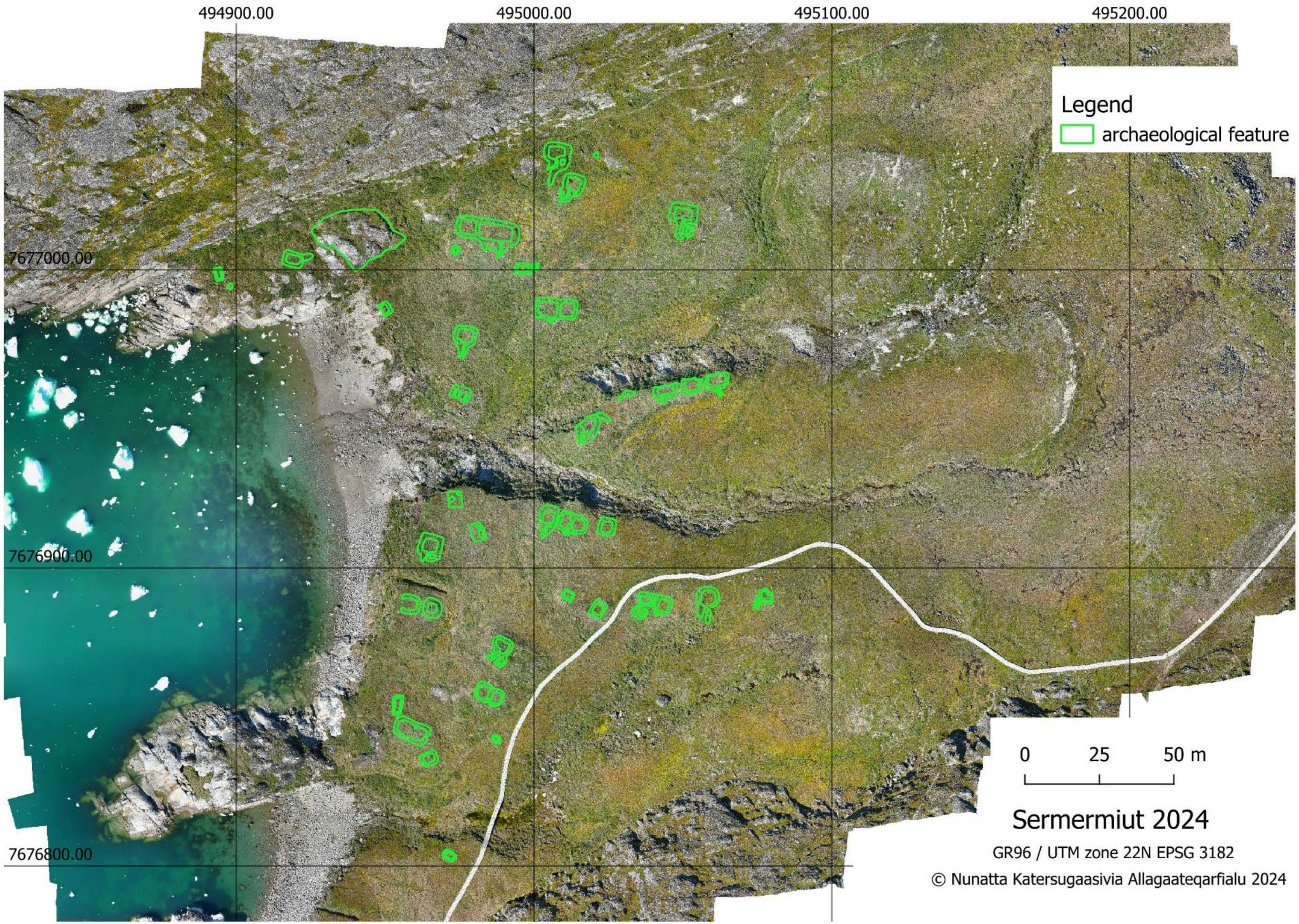

Figure 3. Sermermiut orthomosaic map with archaeological features outlined in green. H. Harmsen, 2024.

Figure 4. The ancient settlement of Sermermiut in the Ilulissat Icefjord World Heritage area, facing east. Photo: H. Lange, 2020.

Introduction

This report details the field activities conducted from 15–19 July 2024, as part of an ongoing effort to investigate permafrost loss and coastal degradation at Sermermiut, a UNESCO World Heritage Site within the Ilulissat Icefjord, Avannaata Kommunia, Greenland (Figs. 1–4). We additionally present preliminary observations made during the recent expedition, highlighting the immediate threats to the archaeological integrity of the site. Finally, we offer specific, actionable suggestions for future monitoring strategies at Sermermiut, emphasizing the necessity of sustained, interdisciplinary research to effectively safeguard this invaluable cultural heritage site.

Sermermiut is widely acknowledged as one of Greenland's most significant archaeological sites due to its record of human settlement spanning several millennia (Larsen and Meldgaard 1958; Mathiassen 1958; Møbjerg and Caning 1986). However, the site is now facing a critical challenge: intensified erosion driven by climatic warming is resulting in the collapse of large portions of the site near the beach. As sections of tundra soil detach, ancient house ruins and midden deposits are exposed. As a result, large quantities of freshly exposed artifacts and organic faunal remains migrate down the bluffs to the beach to be washed away by the tide.

In 2024, the U.S. Department of Interior's (DOI) International Technical Assistance Program (ITAP) initiated a collaborative project between experts from the United States and Greenland to explore this problem, including specialists from Nunatta Katersugaasivia Allagaateqarfialu (NKA). The initial phase of the project focused on gaining a comprehensive understanding of the thermal processes

Figure 5. UNESCO Site Manager Bo Albrechtsen consults with Claire Benton and Christina Bonsell on the beach below Sermermiut. Photo: C. Shields, 2024.

driving erosion at Sermermiut by working with local partners and establishing a comprehensive baseline of Sermermiut's current environmental conditions (Fig. 5). Crucially, the ITAP project aims to explore and develop practical steps that can be taken to remediate or, at the very least, significantly slow down the rate of erosion in future phases of the project. By combining scientific investigation with practical conservation strategies, the project seeks to safeguard the archaeological integrity of Sermermiut for future generations, ensuring that the valuable history contained within the site is not lost to rapid environmental change.

Data collection initiated during July 2024 encompassed geomorphology, soil dynamics, depth of permafrost, coastal erosion rates, and coastal dynamics (Fig. 6). Site analyses involved marine investigations, soil monitoring, and assessments of local micro-climate patterns and their impact on the terrain, with baseline measurements guided by six themes:

1. What environmental processes drive erosion at the Sermermiut archaeological site?
2. What is the current condition of frozen ground and permafrost?
3. What is the historical rate of erosion of the midden area?
4. What do soil characteristics indicate about vulnerability to future erosion?
5. What do coastal and ocean characteristics indicate about vulnerability to future erosion?
6. When are erosion events occurring, and how do they respond to warming temperatures?

Specific field activities addressed each of these themes as shown in table 1. In addition to observations and *in situ* data (Figs. 5 and 6), remote sensing is instrumental in understanding the broader context of Sermermiut's environmental changes at present and in the future. These analyses provide crucial insights into long-term trends and large-scale processes influencing the site.

Table 1. Correlated field activities and research themes.

Field effort or investigation	Theme
General site observations	1, 2, 3, 4, 5, 6
Mapping and photogrammetry	3, 6
Active layer thickness measurements	2, 6
Frost tube construction and installation	2, 6
Vertical soil profiles and vegetation surveys	1, 2, 4
Horizontal soil cores	2, 4
Soil temperature datalogger installation	2, 4, 6
Air temperature datalogger installation	5, 6
Coastal surveying	3, 5, 6

Figure 6. Claire Benton inspecting an exposed slope along the beach at Sermermiut. Photo: C. Shields, 2024.

Figure 7. The Sermermiut ITAP 2024 technical team. From left to right: Christina Bonsell, Mikkel Myrup, Bo Albrechtsen, Claire Shields, Hans Harmsen and Claire Benton. Photo: C. Shields, 2024.

The 2024 ITAP Technical Team

Our technical team (Fig. 7) is comprised of specialists from the United States and Greenland. Despite a condensed planning period of less than three months, beginning in April 2024, we successfully developed a plan for maximizing data collection in the field. A 5-day site visit in July 2024 yielded important baseline data. Subsequent site visits, designed to expand data collection and enhance long-term monitoring, will be vital for developing refined and actionable recommendations for the conservation of Sermermiut. Below is a list of all contributing project team members, their titles, and their home institutions and agencies.

- Aron Petersen — Park Ranger, Ilulissat Icefjord UNESCO World Heritage
- Bo Albrechtsen — Site Manager, Ilulissat Icefjord UNESCO World Heritage
- Christina Bonsell — Marine Ecologist, Bureau of Ocean Energy Management, U.S. DOI
- Claire Benton — Soil Scientist, Natural Resources Conservation Service, U.S. Department of Agriculture (USDA)
- Claire Shields — Project Manager, Asia, Pacific Islands and the Arctic, U.S. DOI ITAP
- Hans Harmsen — National Heritage Resources Manager, NKA
- Mikkel Myrup — Curator/Heritage Database, GIS, Remote Pilot (EASA A1/A3, A2), NKA

Figure 8. Early excavations of Sermermiut were conducted by Porslid and Osterman between 1912–1916. Photo: © Greenland National Museum and Archives.

Background

Archaeological significance

Sermermiut (NKAH 1817) is located on a raised valley overlooking a small bay just to the south of Ilulissat at the mouth of the Ilulissat Kangia (Ilulissat Icefjord), stemming from one of the northern hemisphere's most productive and fast-moving glaciers, Sermeq Kujalleq. The fjord and surrounding area possess a high degree of marine and terrestrial biodiversity, a factor that has made Sermermiut an attractive settlement by different cultural groups at different times over the last several thousand years. Early investigations at Sermermiut, conducted primarily by Danish archaeologists in the late 19th and early 20th centuries, focused on documenting the visible remains and chronological sequencing of cultural groups that had occupied the site.

One of the first documented investigations was conducted by Thomas Thomsen in 1909, followed by Morten Porsild and Hother Ostermann from 1912–1916 (Møbjerg and Caning 1986:178) (Fig. 8). Several decades later, Jørgen Meldgaard and George Nellemann conducted systematic excavations of the middens at Sermermiut in 1953 to gather evidence supporting a theory that the site possessed a deep history of human settlement beginning with the Saqqaq culture ca. 1500 BC, later followed by the Greenlandic Dorset, and lastly by the Thule culture until the site's abandonment ca. 1850 (Larsen and Meldgaard 1958). Therkel Mathiassen, Jørgen Troels-Smith and Svend Jørgensen would later expand the excavation area at Sermermiut and corroborate Larsen and Meldgaard's results, supporting a new theory of an early Paleo-Inuit migration to Greenland that predated the Thule culture Inuit (Mathiassen 1958). These conclusions marked an important revision of Greenland's cultural history and paved the way for an entirely new study of

Paleo-Inuit archaeological investigations in Greenland. In the decades that followed, researchers began to delve deeper into the intricacies of cultural change and adaptation in the region, exploring the relationships between Inuit groups and a changing Arctic environment. Radiocarbon dating further refined the chronology, providing a more precise timeline for the various cultural phases. These investigations at Sermermiut highlighted the site's significance as a key location for understanding the long-term history of human settlement and subsistence in Greenland.

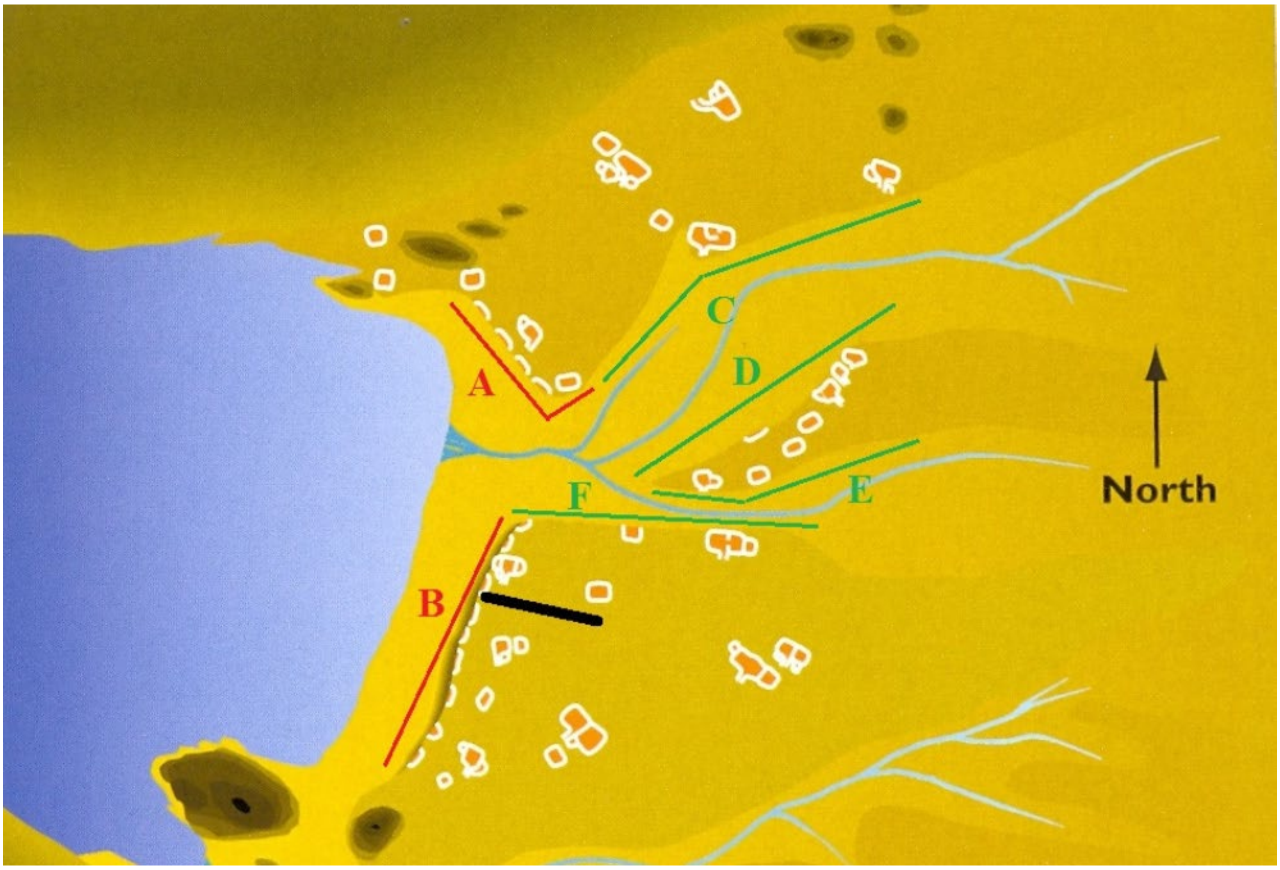

Figure 9. Sermermiut overview by David Barry. Barry only inspected coastal bluffs A and B but was convinced that erosion of cultural layers in bluffs C, D, E, and F was also occurring because large quantities of bones found in the watercourse. D. Barry (2004, modified from O. Bennike et al. 2004, "Ilulissat Icefjord" and T. Møbjerg, 1983).

In the late 1970s and early 1980s, reports of coastal erosion of the middens at Sermermiut inspired investigations by Bjarne Grønnow (Institut for Arkæologi og Etnologi), Morten Meldgaard (Zoologisk Museum, Copenhagen), Tinna Møbjerg (Forhistorisk Arkæologi, Aarhus), and Mogens Andersen (Jakobshavn Museum) that helped to build a foundation for a deeper environmental understanding of Sermermiut's ethno-history and archaeology (Møbjerg 1986). More research followed with Hans Kapel, Martin Appelt, and Niels Christian Clemmensen just prior to the Icefjord's inclusion on the UNESCO World Heritage List in 2004. This group completed a comprehensive mapping of the site's many house ruins while also measuring factors that they believed contributed to the degradation of the site because of the changing environment (e.g., settling in the ground surface, frost effect, meltwater erosion, erosion of the exposed coastal slope, and the effect of soil flow).

Around this same time, an in-depth report of the erosion at Sermermiut was provided by David Barry in 2004. Although the reporting consisted primarily of photo documentation, it was one of the first comprehensive attempts to establish a baseline for the progression of the erosion along the terrace slopes (Figs. 9 and 10). Barry concluded by proposing that the erosion at Sermermiut was the result of freshwater runoff and snowmelt. Erosion due to marine mechanics was assumed to be minimal, with only 3–5 meters of coastline retreat since 1995.

Figure 10. Erosion of the coastal slope visible from the air (green arrows), as well as the trench excavated by Meldgaard in 1953 and Mathiassen in 1955 (red arrow). D. Barry (2004).

Crisis in 2023

During an ITAP visit to Sermermiut in September 2023, the effects of rapid environmental change were starkly apparent. During the tour, the UNESCO Site Manager highlighted the accelerating erosion occurring at several areas along the bluff face, a concerning trend that appeared to be increasing due to the particularly heavy precipitation that summer. The ongoing detachment of turf along the upper bluffs and subsequent erosion resulted in the exposure of substantial amounts of faunal material that migrated down the slope towards the beach (Fig. 11). The loss of these materials not only diminishes the historical integrity of Sermermiut but also represents a loss of critical information about past human habitation in this region. This situation underscores the vulnerability of archaeological sites to the effects of climate change and the urgent need for measures to consider future scenarios for site conservation or mitigation of the erosion along the slopes.

Figure 11. Erosion documented at Sermermiut in September 2024. Photos: H. Harmsen, 2024.

Figure 12. Claire Benton and Christina Bonsell profiling one of the eroding slopes at Sermermiut. Photo: H. Harmsen, 2024.

Field activities

General observations

Over the course of our visit, we recorded careful observations, notes, and photos of the site (Fig. 12). Our focuses included: vegetation, soil surfaces, areas of active and past erosion, morphology of the beach and bluff system, and evidence of wave activity and coastal processes. Discussions with Park Ranger Aron Petersen provided valuable information, including insight on environmental iconditions that helped determine the placement of monitoring instruments and understand local oceanography.

The vegetation above the Sermermiut settlement is characterized by grass-dominated graminoid tundra ("GGT" per Scheer et al. 2023) with saxifrages colonizing cracks in the tundra and mosses and crustose lichens colonizing stabilized, bare organic soil. A mosaic of two graminoid species was observed on GGT: *Alopecurus magellanicus* (alpine foxtail) and a *Poa* sp.: presumably the same arctic bluegrass species that Bent Fredskild described as *P. arctica* in his botanical investigation of Sermermiut (Fredskild 1961). In the drainages and outside of the house ruins and middens, low and dwarf shrubs increase in cover, including several *Salix* spp. (willows), *Betula nana* (dwarf birch), *Empetrum nigrum* ssp. *hermaphroditum* (black crowberry), and *Vaccinium uliginosum* (bog blueberry).

At areas of steep slope gradient around Sermermiut, the ground is visibly failing in large volumes within the cultural layer (former structures and middens) of the soil by an erosion process called thermal denudation (Aré 1988). A high volume of coarse fragments, such as rocks and faunal bones, exists within the top 1 to 2 meters of soil; these coarse fragments are highly susceptible to thermal and gravitational erosion. The mineral subsoil below consists largely of fine-grained marine sediments and appears to seep out from underneath the cultural layer. While the fine-grained subsoil erodes out from underneath the cultural layer, the ground surface at Sermermiut responds to the weight of the unsupported cultural layer in expanding cracks that precede slumping or toppling erosion events (Fig. 13).

Figure 13. Cracks in the tundra at Sermermiut expose faunal bones in the middens as the ground begins to slump away. Photo: C. Benton, 2024.

Most materials observed eroding from the middens were a combination of midden waste and structural remains from earlier submerged house features, such as turf walls and large rocks. The midden waste material consisted largely of processed and discarded faunal remains, much of which appeared to be well-preserved.

The southern portion of the beach at Sermermiut is dominated by boulders and cobbles, while the outlet of the valley's stream is characterized by finer grains. This is consistent with the shape of the intertidal zone, which narrows in the southern portion and is widest at the stream outlet. This morphology indicates higher wave energy along the southern portion and may also indicate relatively large sediment inputs to the beach by the stream and a counterclockwise current in the bay. Highest high-tide water levels reach the very base of the bluff in the southern portion, as evidenced by deposited sand, dead vegetation on eroded tundra blocks, and observations during a time of near maximum annual tide height (Fig. 14). The scarcity of artifacts on the beach demonstrates that eroded material is removed quickly. Removal is likely done by a combination of waves, tidal motion, and ice motion or scour on the beach, in addition to accelerated decomposition upon exposure. The role of beach ice in transporting materials from the beach is an area for potential future inquiry.

Dense near-shore ice and pleasant weather led to calm water conditions in the Sermermiut Bay throughout our site visit, preventing any observations of site conditions (e.g., wave heights and run up) during wind events and storms.

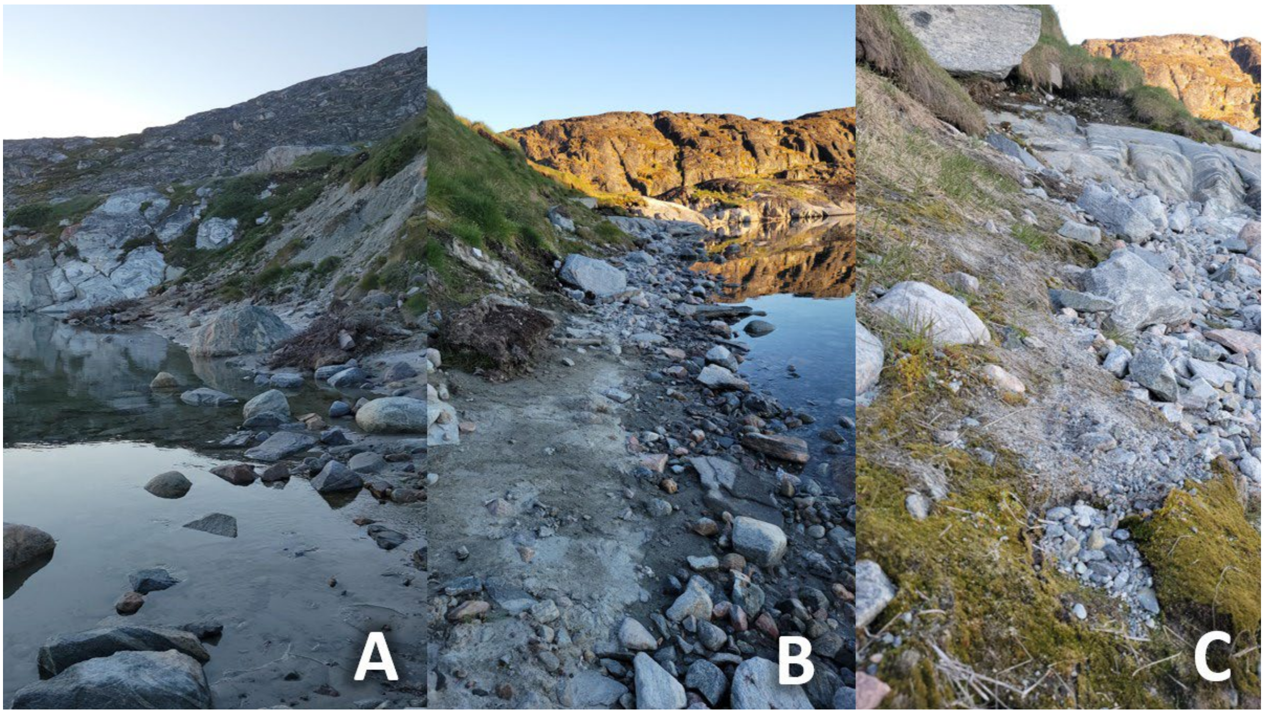

Figure 14. Beach conditions at Sermermiut. A) Approximately +2.7 m lowest astronomical tide (LAT) (annual high-high tide prediction is +2.9 m) at the north end of the beach, showing boulders and cobbles over soft sediment and apron features from bluff erosion in the background; B) Approximately +2.7 m LAT tide near the south end of the beach, showing the narrower profile and the transition to boulders and cobbles on the south end. Note that the base of the bluff is approximately where the +2.9 m water level would reach; C) Sand and pebble overwash at the base of the bluff demonstrating sediment movement from water and ice activity. Photos: C. Bonsell, 2024.

Mapping and photogrammetry

Prior to the arrival of the team on-site, Inuplan A/S was contracted by Avannaata Kommunia (Isfjordskontoret) and the NKA to establish seven ground control points (GCPs) at Sermermiut (Fig. 16). The GCPs will be used for future unmanned aerial vehicle (UAV) surveys of the area. The GCPs were surveyed using real-time kinematic global navigation satellite system (RTK-GNSS) equipment with an anticipated 3D accuracy of 20–30 mm relative to selected reference network (i.e., geodetic benchmarks). The coordinates are provided in GR96 UTM zone 22 (horizontally) and local MSL (vertically). These are the same reference systems used for most official technical and topographical maps of Ilulissat. The GCPs are marked with a 10 mm hole in the bedrock. All elevations are given relative to the surface and not the bottom of the hole.

In addition to the new GCPs, geodetic benchmark 31367 is also visible from the air and can be used as a GCP for future UAV surveys. All coordinates are listed in Table 2.

Table 2. Locations of geodetic benchmark 31367 and GCPs installed at Sermermiut.

Point ID	Northing	Easting	Elevation (m)
31367	7676835.968	494918.750	7.317
1	7676774.450	494887.175	6.868
2	7676858.668	494967.264	9.671
3	7676824.804	495078.713	20.651
4	7677017.646	494963.927	16.961
5	7677057.884	495068.040	30.807
6	7676991.761	494891.879	7.060
7	7676873.300	494937.349	2.133

UAVs and monitoring

Since 2020, the National Museum and Archives of Greenland has been acquiring drone imagery every summer, with the exception of 2023 (Fig. 15). The objective is to monitor changes using PPK (Post-Processing Kinematic) workflow and CORS (Continuously Operating Reference Station) data (Table 3). This approach is optimal for monitoring purposes using a fixed reference point — in this case, the Ilulissat permanent base station "ILUL," from which receiver independent exchange (RINEX) data is downloaded for correcting the acquired imagery. Processing drone imagery without a fixed reference point for corrections would not achieve the precision required for continuously monitoring the relatively minor changes at Sermermiut. The ILUL CORS is maintained by Dataforsyningen, the Agency for Climate Data’s distribution channel.

Table 3. Four years of drone imagery acquisition has yielded data of varying resolution. The lower resolution obtained in 2020 and 2022 is a function of area covered and flight altitude.

Data	2020	2021	2022	2024
Cm/pixel (orthophotomosaic)	3,31	1,41	2,9	1,33
Points/m³ (point cloud)	122	1278	167	1404

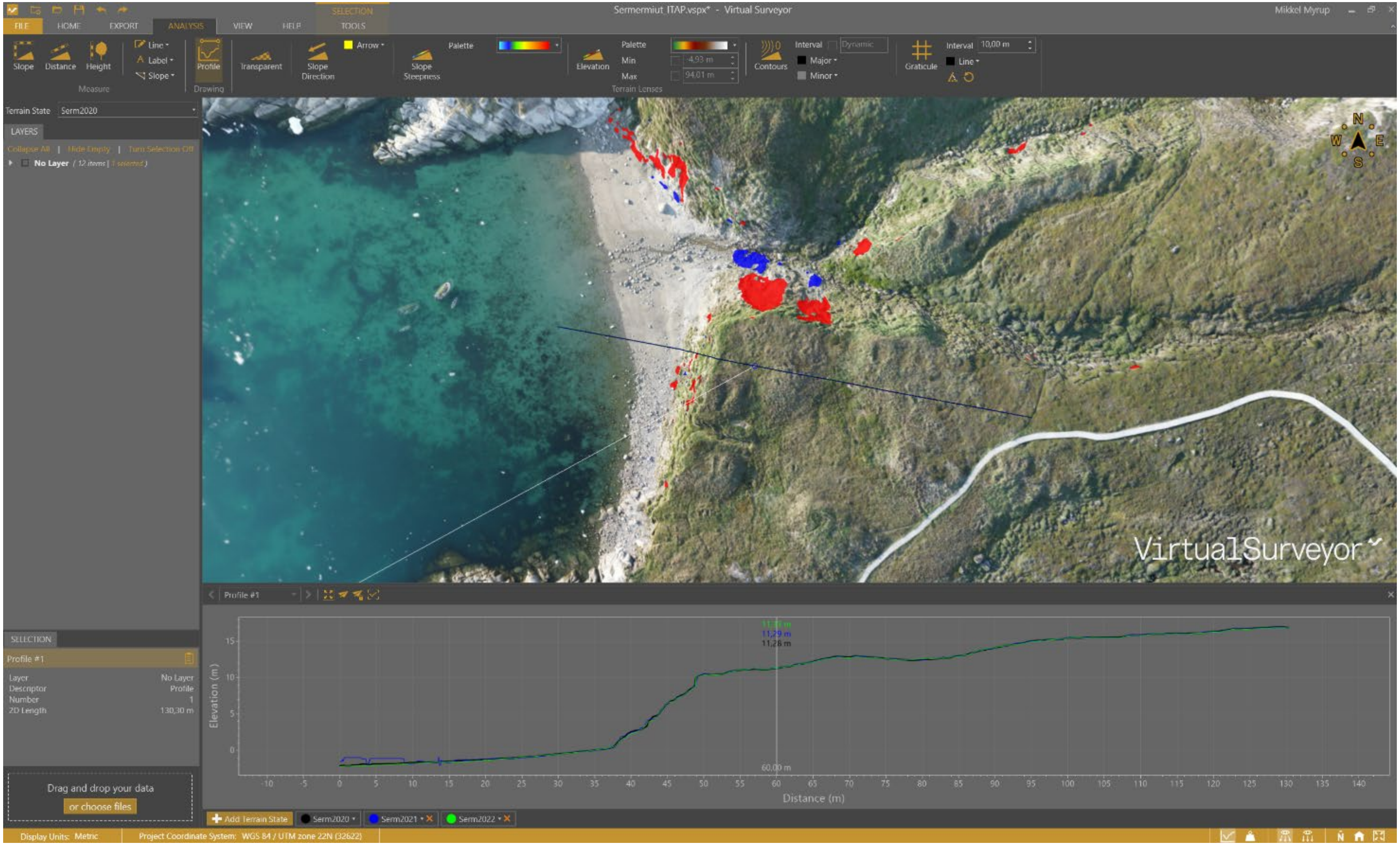

Figure 15. A comparison of datasets acquired in 2020 and 2022 reveals changes on the Sermermiut slopes. Red indicates fill (mobilized material) and blue indicates cut (accumulated material). Data source: Greenland National Museum and Archives, 2024.

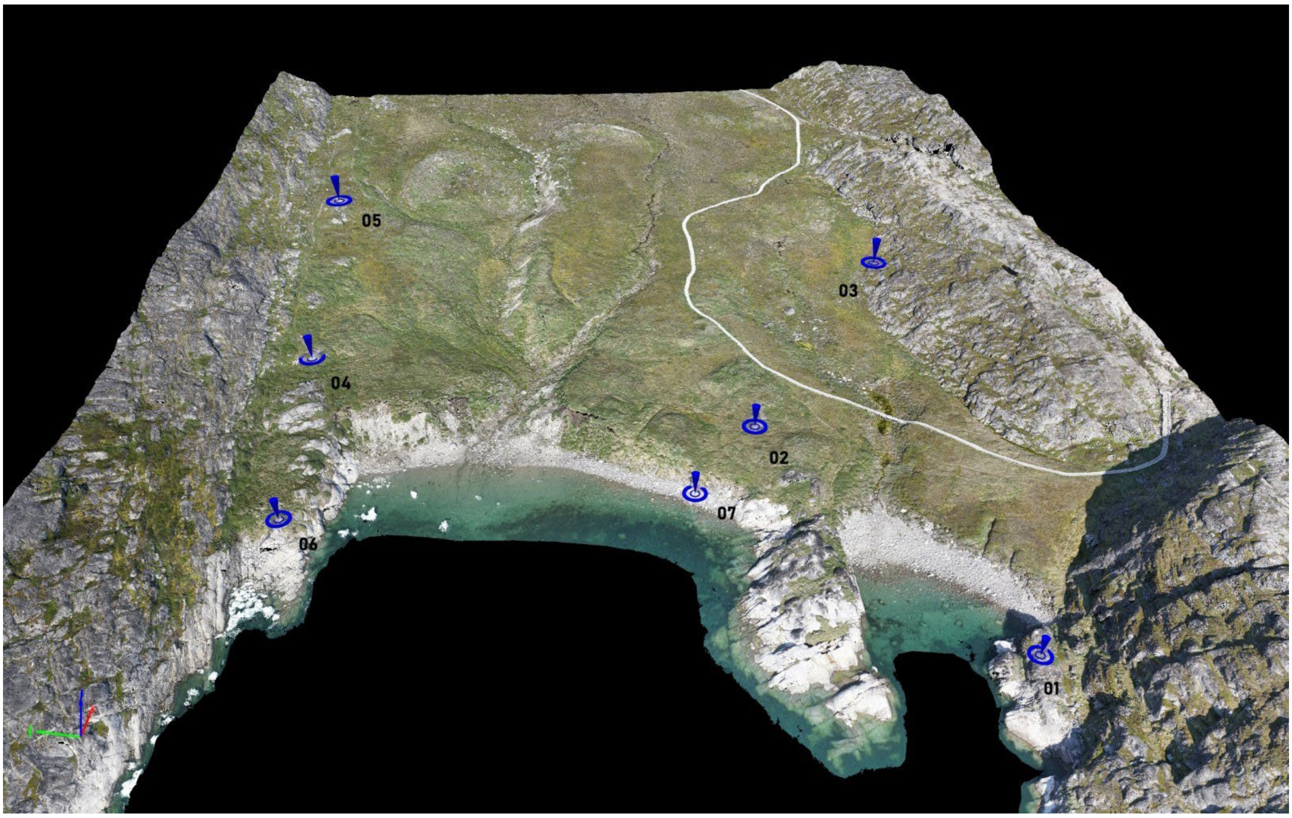

Figure 16. 2024 Sermermiut point cloud showing the newly established GCPs. Data source: Greenland National Museum and Archives, 2024.

Democratization of drone monitoring

The PPK-CORS workflow is an effective tool in a monitoring context, particularly for larger areas. However, it requires UAV equipment that is typically beyond the financial reach of the average consumer or hobby drone pilot. For instance, a minimum requirement is that the UAV is equipped with a PPK and RTK-GNSS module, which is not standard on consumer-grade drones. One way to enable layperson drone pilots to produce imagery suitable for monitoring purposes is to use GCPs in the post-processing, as we have now done at Sermermiut. This way the drone pilot could produce usable data by performing a grid flight with a suitable image overlap. The images would then be sent to the staff at the National Museum for post-processing and assessment. This is a model considered viable in different locations in Greenland where environmental change is threatening cultural heritage. The main hurdle would be the cost of hiring surveyors to establish GCP grids at the locations with heritage at risk. It will be interesting to see if the democratization of drone monitoring for layperson drone pilots is something that will gain traction in Sermermiut and other locations in Greenland.

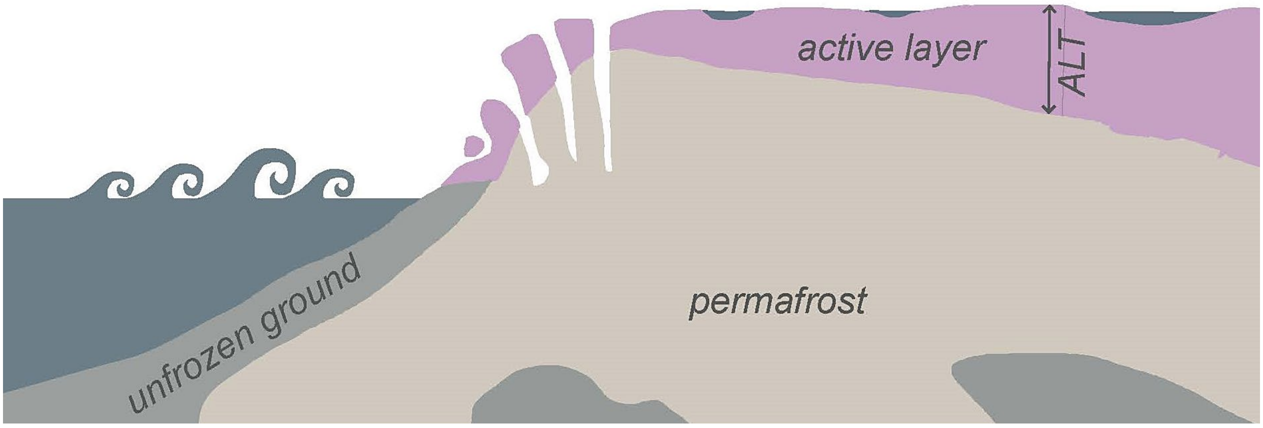

Figure 17. Diagram of the active layer and active layer thickness (ALT) over permafrost in an Arctic coastal environment. Adapted from Westerveld et al. (2023), © 2023 GRID-Arendal.

Active layer thickness measurements

The active layer is the portion of ground above permafrost that annually thaws and freezes with the warming and cooling of seasons. Active layer thickness (ALT) refers to the depth from the soil surface to frozen ground (Fig. 17). ALT reaches its minimum when the ground freezes during the winter and reaches its maximum when the ground has thawed to the top of the permafrost (ground that remains below 0° C for more than 2 years).

We recorded the depth to frozen ground at 29 different locations across the site with a steel tile probe with a pointed tip, following the methodology from Brown, Hinkel, and Nelson (2000). Depth to frozen ground was recorded to the nearest half centimeter for up to five measurements within a meter diameter, with the final measurement marked for coordinate collection by Differential Global Positioning System (DGPS). The date and time of data collection was noted for each ALT probing site. Slope, aspect, and vegetational functional groups were also recorded for each site.

Around Ilulissat, previous studies have shown that maximum ALT is expected around the months of September and October, when the warming front from summer sun has penetrated to its maximum depth (Olesen 2003; Scheer et al. 2023). Repeat ALT measurements have been suggested to capture the variation in ALT outside of the 5-day field effort.

The Sermermiut settlement site poses a unique challenge for ALT probing in its high volume of rock and bone fragments, in addition to a dense, ice-rich top of the active layer. While the active layer has a slightly different strike signature than that of bone or rock, it can be too similar to determine the ALT with certainty without digging a small hole or checking for frozen ground in a nearby surface soil crack. Despite this limitation, the data captured is beneficial to understanding the mechanics of the ground throughout the year.

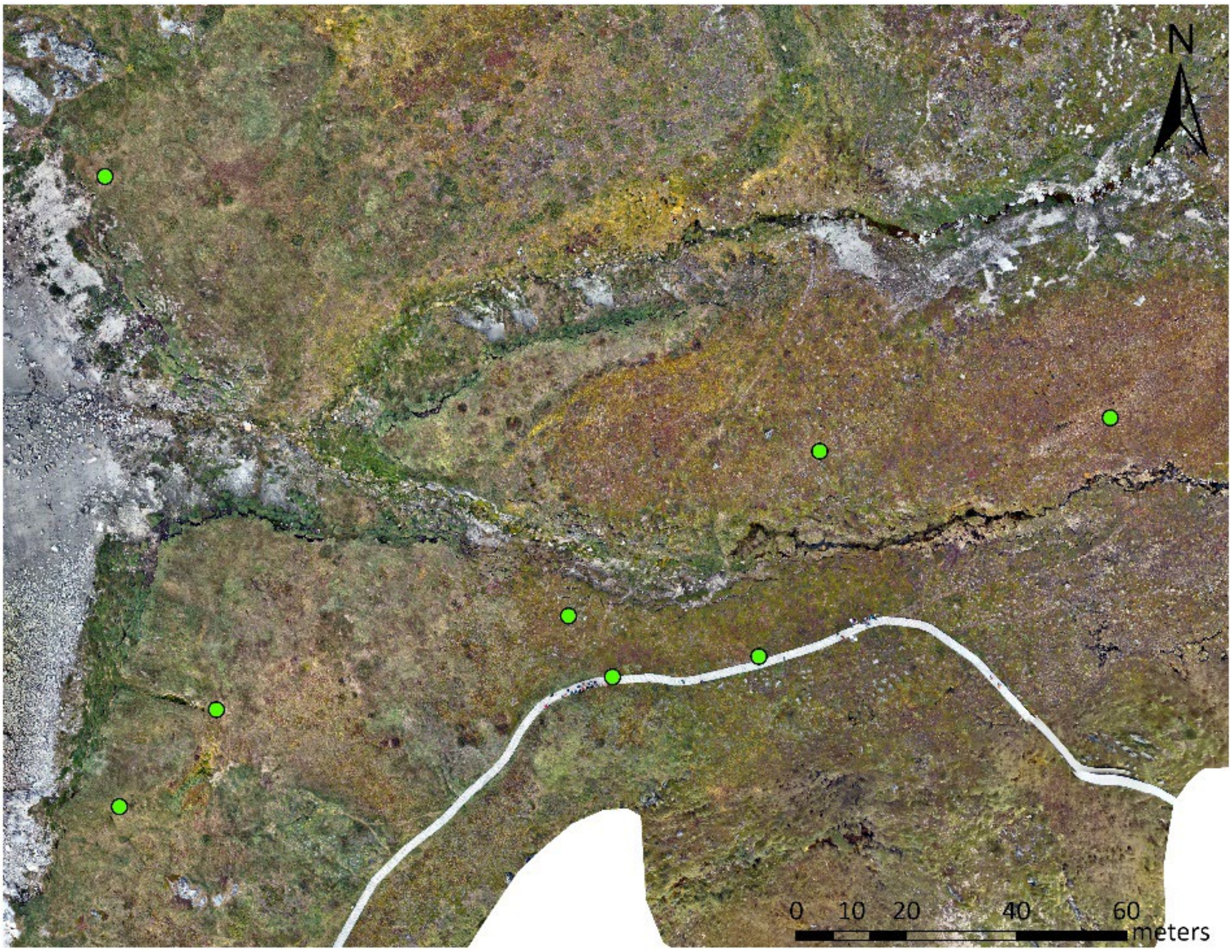

Figure 18. Frost tube locations (green points) at Sermermiut. C. Benton, 2024.

Frost tube construction and installation

We installed eight frost tubes to monitor the freezing and thawing of soil over the year and assess variation in the freeze-thaw cycle across the site (Fig. 18). Frost tubes are an analog method to measure the depth to frozen ground. They consist of a removable inner tube of colored liquid housed in outer polyvinyl chloride (PVC) tubes that are installed into the ground (Fig. 19).

Frost tubes were constructed following methodology developed for the Globe Learning and Observations to Benefit the Environment (GLOBE) Program (GLOBE, 2019). While frost tubes are ideally installed into the top of the permafrost at the end of the thaw season, the field work window in July constrained the installation to the shallower active layer depth at the time.

We determined frost tube locations (Table 4) based on vegetation functional groups, their distributions, and microclimates within Sermermiut (Fig. 20). We aimed to measure frost conditions at a variety of vegetation communities while ensuring feasible access during winter months (i.e., not in locations of substantial snow accumulation), limited disturbance to the cultural heritage site, and facilitated public outreach and engagement with the project. To that end, two frost tubes were placed directly next to the boardwalk that winds through Sermermiut valley. Albrechtsen and Petersen will regularly measure the depth to frozen ground, as conditions and equipment integrity allow, and upload results and observations to the shared project site.

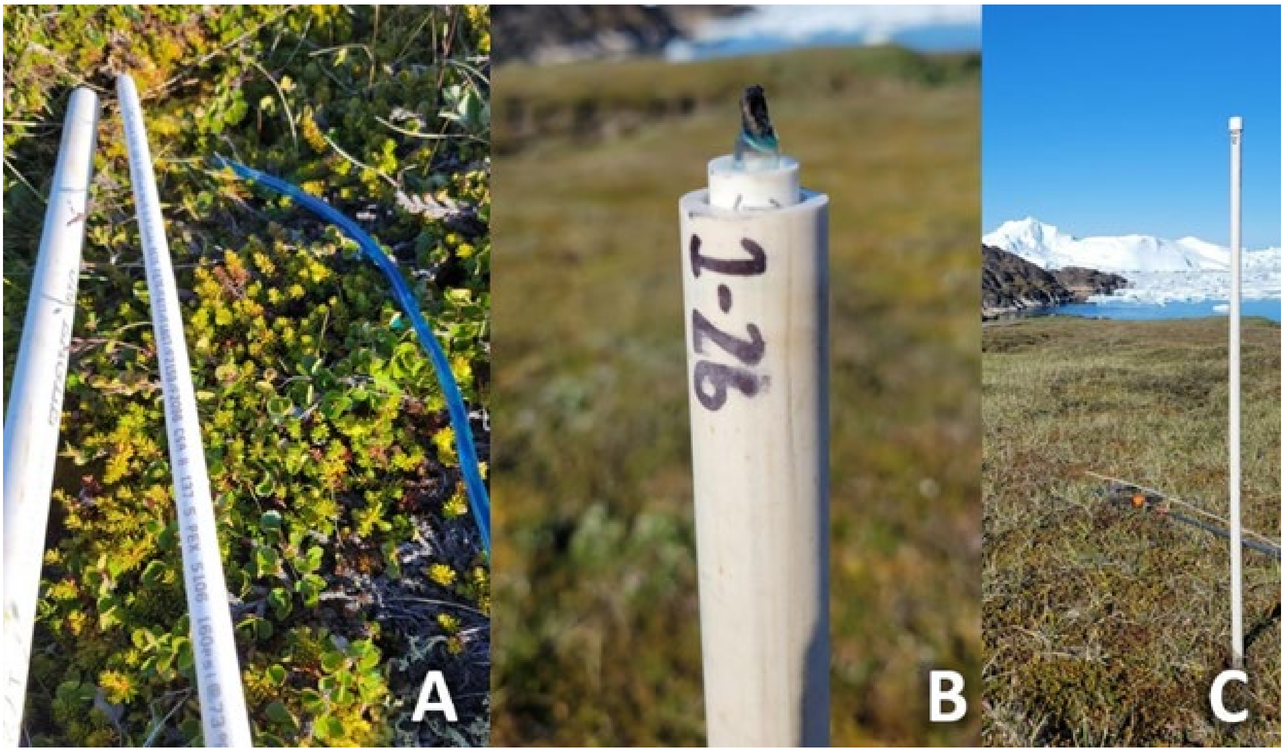

Figure 19. Frost tube construction. From left to right, A) the outer PVC tube, middle cross-linked polyethylene (PEX) tube, and inner vinyl tube filled with colored water; B) Components nested inside each other; C) Typical installation. Photos: C. Bonsell, 2024.

Table 4. Frost tube locations and corresponding vegetation communities.

Frost tube ID	Northing	Easting	Vegetation community
1-03	7676989.532	494951.501	Willow-dominated tundra
1-16	7676909.396	495035.862	Crowberry, dwarf birch, and moss-dominated tundra
1-23	7676874.545	494954.283	Grass-dominated tundra
1-25	7676892.412	494971.823	Grass-dominated tundra
1-26	7676939.485	495081.459	Crowberry, dwarf birch, and moss-dominated tundra
1-27	7676945.535	495134.313	Crowberry, grass, and moss-dominated tundra
1-28	7676902.047	495070.433	Crowberry and dwarf birch-dominated tundra
1-29	7676898.371	495043.859	Dwarf birch, willow, and crowberry-dominated tundra

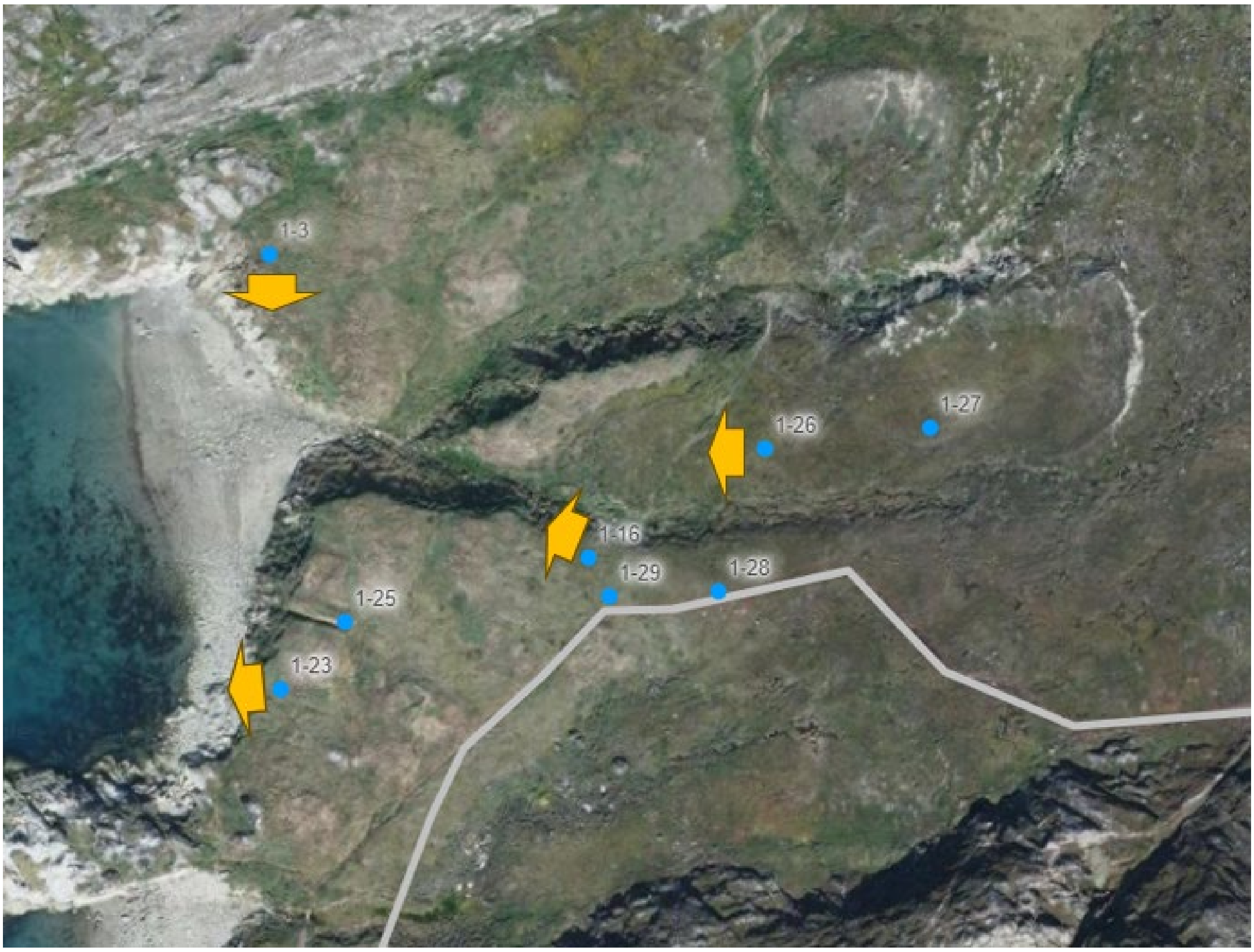

Figure 20. Frost tube locations (blue points), with locations for and direction of framing for repeat photography indicated by yellow arrows. Google Earth, 2024.

Vertical soil profiles and vegetation surveys

Five soil profiles were surveyed to document physical, chemical, and thermal aspects of the soil, which can be correlated with and supplement historic descriptions of the soil (Fredskild 1961; Larsen and Meldgaard 1958). A modified Pedon Description Form from the USDA Natural Resources Conservation Service (NRCS) was used to document soil (pedon) and site data (Soil Survey Staff 2024). Soil profiles were prepared and extracted using minimally invasive shovel slices, knife cuts, and hand-operated augers on the bluffs (Fig. 21) and using hand-operated augers in the thawed active layer and a Shaw Backpack Drill in frozen layers. Soils were described following NRCS standards (Soil Survey Staff 2024), with additional data collected for depths greater than two meters, ice volume, and cryostructures.

Figure 21. A soil profile exposed along the bluff face, with white markers indicating transition zones. Photo: C. Benton, 2024.

Figure 22. Pin flags marking the corners and center of a 1 m^2 vegetation quadrat. Photo: C. Benton, 2024.

Site, pedon, and vegetation plot data (Fig. 22) is stored in the USDA's National Soils Information System database. PDF copies of all datasheets will be stored on the team's DOI Sharepoint web page.

Soil samples were collected from each soil profile and transported to the Geologic Survey of Denmark and Greenland (GEUS) Sediment Lab in Copenhagen by Benton and Bonsell, where they were analyzed for total organic carbon content and mineral particle size by GEUS staff. Results from the lab analyses were made available in November 2024. These results will provide a more precise documentation of the soil at Sermermiut, inform a better understanding of soil formation and dynamics, and allow for comparison to historic soils data from previous investigations as well as to data from other studies around Ilulissat. Vegetation plot data can similarly be referenced in comparison to legacy data, primarily Bent Fredskild's "Floristic and Ecological Studies near Jakobshavn, West Greenland" (1961). Soils and vegetation data will be analyzed in conjunction with remote sensing data, ALT data, and frost tube results to generate interpretations of erosion susceptibility and future erosion scenarios.

Horizontal soil cores

Five horizontal soil cores were removed from two different sites along the coastal bluff at Sermermiut. The two sites were selected for their similar landform position and aspects but differing erosion stability: the first site, 001, is amid an actively eroding portion of middens, while the second site, 005, is amid an area of eroded but stabilized tundra blocks, with little bare exposed soil. Four soil samples were collected for total organic carbon and mineral particle-size analyses at the GEUS Sediment Lab in Copenhagen. Horizontal depth to frozen ground was documented for each core, and various photographs and notes were captured on the characteristics of the soil.

Soil and air temperature datalogger installation

Temperature dataloggers (HOBO Pendant MX2201) were affixed to PVC pipe and installed at various horizontal depth intervals at the same locations as the horizontal soil cores (Table 5, Fig. 23). These dataloggers will collect soil temperature data throughout the year to assess variation among sites and depths. They will be retrieved from the bluffs, and the data will be downloaded at the end of summer 2025.

An additional temperature datalogger (HOBO MX2301A) was installed at frost tube site 1-03 to collect air (approximately 60 cm above surface within the mounting tube) and surface soil (approximately 2 cm depth) temperature over the year (Fig. 24). The data from this datalogger can be downloaded any time using the HOBOConnect cell phone application.

Figure 23. Soil temperature datalogger array showing three different dataloggers set to be installed at different depths. Photo: C. Bonsell, 2024.

Table 5. Deployment information for soil temperature dataloggers. Times given in West Greenland Time (WGT).

Site ID	Planned horizontal depth (cm)	Serial number	Time of instrument launch
005-1	5	21854620	7/18/2024 17:56
005-1	15	21854619	7/18/2024 17:51
005-1	25	21854622	7/18/2024 17:54
005-1	33	21854624	7/18/2024 17:53
005-1	40	21854608	7/18/2024 17:55
005-2	5	21854628	7/18/2024 17:17
005-2	30	21854614	7/18/2024 17:18
005-2	60	21854612	7/18/2024 17:19
005-2	71	21854627	7/18/2024 17:20
001-3	5	21854603	7/18/2024 15:12
001-3	50	21854604	7/18/2024 15:15
001-3	90	21854602	7/18/2024 15:17
001-3	128	21854611	7/18/2024 15:18
001-1	5	21854609	7/18/2024 16:06
001-1	15	21854615	7/18/2024 16:07
001-1	30	21854623	7/18/2024 16:09
001-1	42	21854600	7/18/2024 16:11
001-2	5	21854613	7/18/2024 14:06
001-2	35	21854625	7/18/2024 14:02
001-2	45	21854610	7/18/2024 14:04

Figure 24. Air and surface soil temperature datalogger at site 1-03. Photo: C. Bonsell, 2024

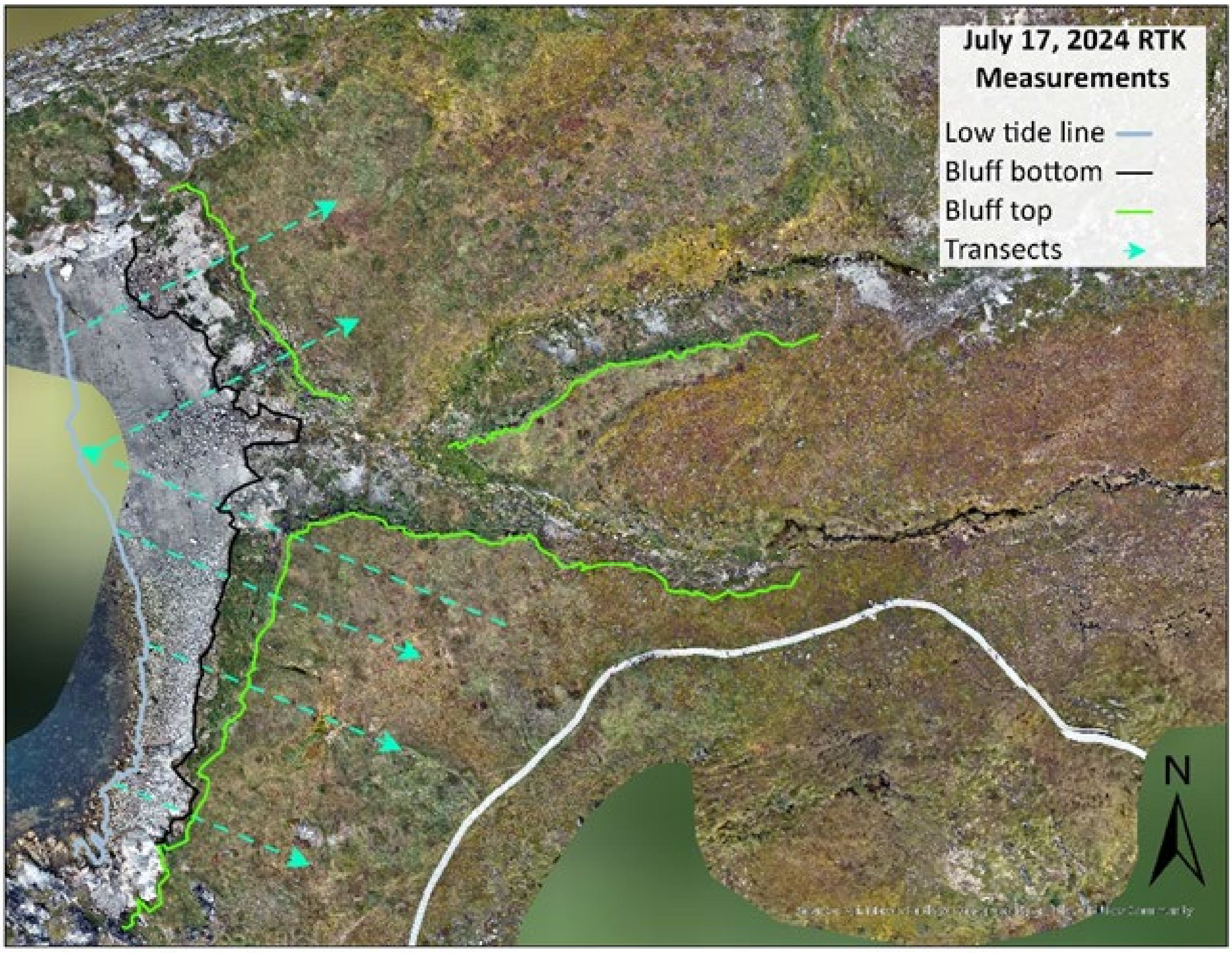

Figure 25. Map of RTK survey lines by Inuplan A/S 17 July 2024. C. Benton, 2024

Coastal surveying

RTK surveying was conducted by Inuplan A/S along cross-shore and along-shore transects (Fig. 25). The along-shore transects capture the top edge of the bluff (i.e., the seaward edge where the horizontal tundra or tundra block ends), the base of bluff (i.e., where beach substrate begins), and the low water line at the time of the survey. For the top edge of bluff areas where there was tundra mat detachment, the surveyed points mark the end of the contiguous, near-horizontal tundra mat. For the base of bluff where there was apron material, points were taken at the seaward edge of the apron.

Figure 26. Seal skin recovered from eroding slope at Sermermiut. Most likely from a kayak. Photo: H. Harmsen, 2024.

Surface artifact recovery

A significant portion of our fieldwork in July was dedicated to documenting the substantial amount of archaeological material eroding from the middens along the bluff edges and cascading down the slope to the beach. This material comprised a mixture of midden waste and structural remnants from submerged house features, including turf walls, cobbles, and flagstones that would have formed dwelling floors. The non-structural component primarily consisted of processed and discarded faunal remains, many of which exhibited remarkable preservation. However, the sheer volume of these remains scattered across the newly eroded slopes and beach necessitated a selective approach to artifact collection. We limited our retrieval to three objects: (1) a large section of seal skin, most likely part of a kayak (Fig. 26); (2) a small piece of worked wood (Fig. 27); and (3) an ivory fragment, likely once part of a harpoon shaft (Fig. 28). These artifacts are now securely stored at the Greenland National Museum in Nuuk.

Figure 27. Worked wood fragment from Sermermiut. Possibly part of a toy paddle or oar. Photo: H. Harmsen, 2024.

Figure 28. Ivory fragment from Sermermiut. Most likely part of a harpoon shaft. Photo: H. Harmsen, 2024.

Figure 29. Erosion event recorded in October 2024. Photo: B. Albrechtsen, 2024.

Next steps

Ongoing monitoring and data collection

Photographs are a useful tool to understand erosion rates. Five locations were chosen for repeat photography from August 2024 to September 2025 to monitor environmental conditions and potential erosion events at areas with hypothesized high likelihoods of future erosion (see Fig. 20). Photographs will be taken during visits to collect data from the frost tubes over the coming year.

On 3 October 2024, a recent erosion event was noted during a visit for repeat photography. This event occurred between the 30 August and 3 October site visits. A block of soil with an approximate surface area of 13 m^2 and volume of 5.9 m^3 detached from the bluff edge in one cohesive unit (Fig. 29). The detachment occurred above site 001 and buried sensor 001-2 (Figs. 30–32). This block slid partway down the slope, exposing and displacing multiple artifacts from the bluff. No visible ice was present on the newly exposed face.

Figure 30. Main failure unit from fall 2024 erosion event. Photo: B. Albrechtsen, 2024.

Figure 31. October 2024 erosion zone (hatched orange polygon) and 001 thermistor tube locations (blue points). Map imagery from August 2024, prior to the erosion event. Orthoimagery source: A. Koeppel and C. Edwards, 2024.

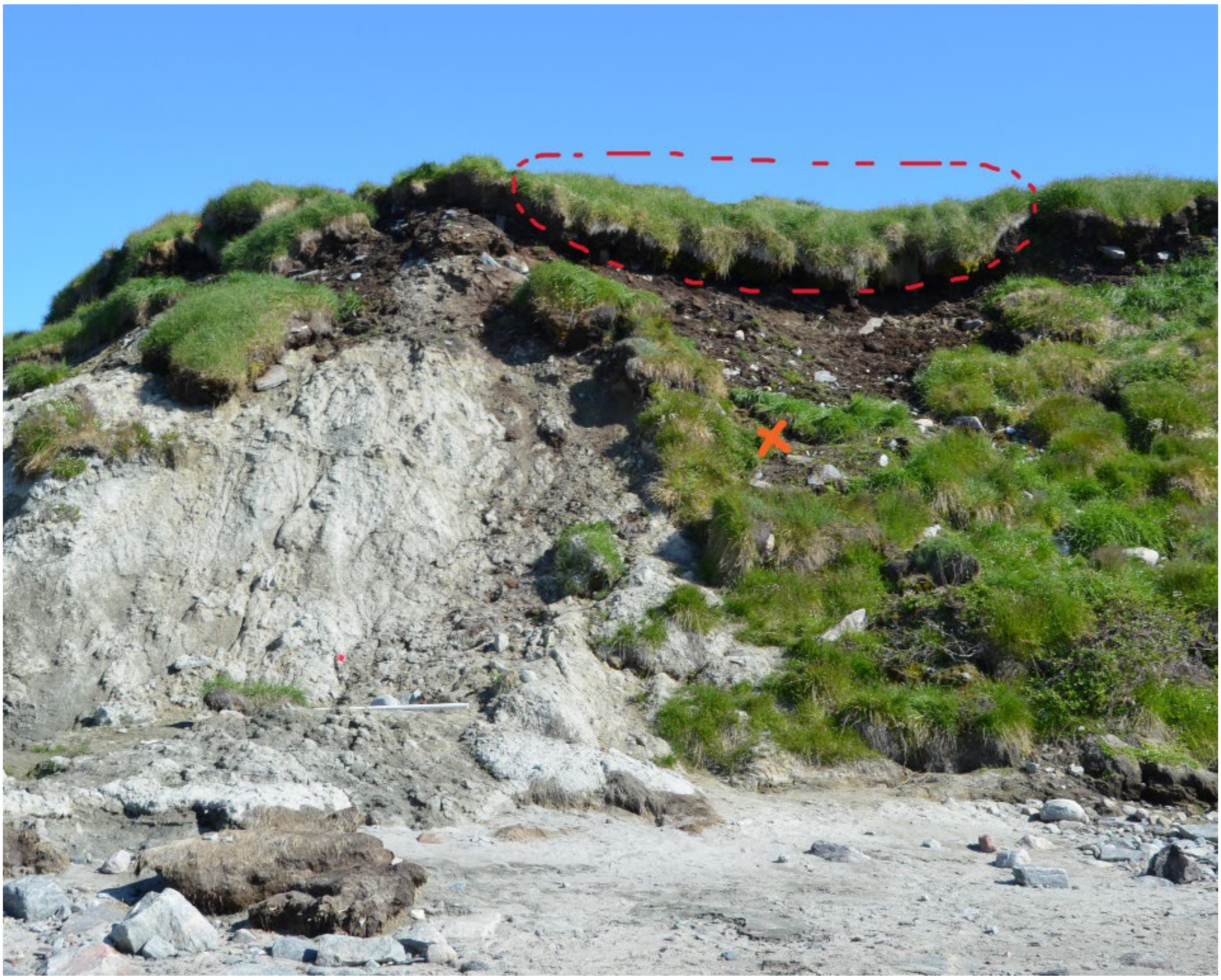

Figure 32. Photo of overhanging block from July 2024, with approximate section that eroded in October 2024 circled. The orange X indicates approximate location of thermistor array 001-2. Photo: C. Benton, 2024.

Benton and Bonsell plan to analyze data during the winter and spring of 2024–2025 and upon retrieval of the temperature dataloggers in September 2025. Using field data, temperature and photo monitoring data, GEUS Sediment Laboratory results, and external datasets, we will propose a hypothesis for the mechanism of current and historic erosion at Sermermiut and provide interpretations and risk indices for future erosion potential. External data will include meteorological data from the Danish Meteorological Institute, Ilulissat borehole data, historic aerial imagery, historic Sermermiut datasets, and other peer-reviewed research.

Products

The team plans to create a small online dissemination project about our findings and hypotheses in Kalaallisut, Danish, and English using ESRI's StoryMaps. This format will allow for easy public access, engaging visuals, and integrated maps. The intended audience is the resource managers of the Ilulissat Icefjord UNESCO World Heritage Site and Avannaata Kommunia municipality, the community of Ilulissat, and the public. We will provide recommendations for immediate or long-term actions, as applicable, and assist with the identification of additional studies or subject area experts needed.

Mitigation

After data analysis and reporting, the technical team will expand to include experts in erosion engineering, rescue excavations, and tourism to address possible mitigation steps for Sermermiut going forward. The results from our reporting will help to inform the feasibility of different scenarios, from engineering to stop or slow the erosion, to archaeological excavations to preserve remaining artifacts, to methods to prevent visitors from entering the eroding areas and collecting artifacts and bones.

Conclusion and recommendations

The Arctic is experiencing some of the most dramatic effects of global climate change, with rapidly rising temperatures, thawing permafrost, and increased coastal erosion (Hollesen et al. 2019). These changes pose a significant threat to the region's rich archaeological heritage, particularly those sites located along vulnerable coastlines. Coastal archaeological sites, like Sermermiut, hold important records of past human adaptations and cultural practices but are increasingly exposed to the negative influences of a rapidly warming Arctic. Accelerated coastal erosion, driven by rising sea levels and intensified storm surges, is damaging these sites. The thawing of permafrost further exacerbates this problem, destabilizing the soil and making sites more susceptible to solifluction (Ballantyne 2018), thermal abrasion, and thermal denudation (Aré 1988) erosion events.

The loss of the archaeological remains at Sermermiut represents a significant loss of culture and history. It is imperative that efforts continue to keep visitors from treading on the sensitive ground near Sermermiut's bluffs and that site monitoring continues via datalogger and UAV deployments. Future considerations for site and cultural heritage preservation could include nature-based solutions for erosion mitigation and locally based decision making with input from descendants of Sermermiut's inhabitants. In an increasingly warming Arctic, the vulnerability of coastal archaeological sites underscores the urgent need for proactive conservation efforts and collaborative research to document, protect, and preserve these irreplaceable cultural and scientific resources.

Works Cited

Aré, F. E. 1988. "Thermal abrasion of sea coasts (part I)." *Polar Geography and Geology* 12 (1).

Barry, D. I. 2004. Erosion af Sermermiut-bopladsen: En ikke-faglig vurdering Sammenfatning. Kalundborg Arkæologiforening.

Ballantyne, C. K. *Periglacial Geomorphology* (pp. 195-212). John Wiley & Sons, 2018.

Brown, J. H., K. M. Hinkel, and F. E. Nelson. 2000. "The circumpolar active layer monitoring (CALM) program: research designs and initial results." *Polar Geography* 24 (3):166-258.

Fredskild, B. 1961. *Floristic and ecological studies near Jakobshavn, West Greenland*. Vol. 163, Kommissionen for videnskabelige undersøgelser i Grønland: CA Reitzels.

Global Learning and Observations to Benefit the Environment (GLOBE) Program. "Instrument Construction and Installation: Instructions for Making and Installing a Frost Tube to Measure Depth of Frozen Ground." The GLOBE Program, 2019. https://www.globe.gov/documents/352961/c8514dca-1eb9-4a24-9f0c-08202b68faeb.

Hollesen, J., M. Callanan, T. Dawson, R. Fenger-Nielsen, T. M. Friesen, A. M. Jensen, A. Markham, V. V. Martens, V. V. Pitulko, and M. Rockman. 2018. "Climate change and the deteriorating archaeological and environmental archives of the Arctic." *Antiquity* 92 (363):573-586.

Hollesen, J., H. Matthiesen, R. Fenger-Nielsen, J. Abermann, A. Westergaard-Nielsen, and B. Elberling. 2019. "Predicting the loss of organic archaeological deposits at a regional scale in Greenland." *Scientific Reports* 9 (1):9097.

Larsen, H., and J. Meldgaard. 1958. *Paleo-eskimo cultures in Disko Bugt, West Greenland*. Vol. 161, *Meddelelser om Grønland*. København: C.A. Reitzels Forlag.

Mathiassen, T. 1958. *The Sermermiut excavations 1955*. Vol. 161, *Meddelelser om Grønland*. Copenhagen.

Møbjerg, T. 1986. "A contribution to paleoeskimo archaeology in Greenland." *Arctic Anthropology* 23 (1/2):19-56.

Møbjerg, T., and K. Caning. 1986. "Sermermiut in the Middle of the Nineteenth Century." *Arctic Anthropology* 23 (1/2):177-198.

Olesen, O. B. 2003. Shallow Borehole Temperatures, Ilulissat, Greenland (GGD631, Version 1). Edited by Greenlandic Geological Survey (GEUS). Copenhagen, Denmark.

Rantanen, M., A. Y. Karpechko, A. Lipponen, K. Nordling, O. Hyvärinen, K. Ruosteenoja, T. Vihma, and A. Laaksonen. 2022. "The Arctic has warmed nearly four times faster than the globe since 1979." *Communications Earth and Environment* 3 (1):168.

Scheer, J., R. Caduff, P. How, M. Marcer, T. Strozzi, A. Bartsch, and T. Ingeman-Nielsen. 2023. "Thaw-Season InSAR Surface Displacements and Frost Susceptibility Mapping to Support Community-Scale Planning in Ilulissat, West Greenland." *Remote Sensing* 15 (13):3310.

Soil Survey Staff. 2024. *Field book for describing and sampling soils, version 4.0*. U.S. Government Printing Office: USDA, Natural Resources Conservation Service.

Westerveld, L., T. Kurvits, T. Schoolmeester, O. B. Mulelid, T. S. Eckhoff, P. P. Overduin, M. Fritz, H. Lantuit, B. Alfthan, A. Sinisalo, and F. Miesner, L.-K. Viitanen, and the NUNATARYUK consortium. 2023. *Arctic Permafrost Atlas*. GRID-Arendal, Arendal.

Appendix A. Surface artifacts collected from Sermermiut in 2024

X-number	Date collected	Context	Artifact or sample type	Material type	Quantity (*n*)	Is the artifact diagnostic?	Preservation quality of artifacts (poor, good or excellent)	Does the object need to be conserved? (Y/N)	If yes, what conservation measures to be taken
X0001	15-Jul-2024	Surface	Fragment, possible toy paddle or oar	wood	1	N	Good	N	None
X0002	15-Jul-2024	Surface	Possible section of harpoon shaft	Ivory	1	N	Good	N	None
X0003	15-Jul-2024	Exposed midden layer	Kayak skin	Seal skin	1	Y	Good	Y	Freezer