PINPOINTING THE LOCATION OF BURIED WASTE ACROSS THE GREENLAND ICE SHEET

by

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THESIS ABSTRACT

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Military sites have historically become major point sources for environmental contamination. With globally changing climate patterns there is even higher potential than before for certain of these waste sites to become destabilized and cause human-ecological harm. During the Cold War, US strategy sought to turn the Arctic into a theater of war, which has resulted in an extensive network of military sites across its now changing land- and ice-scapes. Recent scientific investigations of the abandoned "city under the ice" at Camp Century, Greenland have analyzed the physical dimensions of the debris field, while various other scholars have articulated the historical and geopolitical dimensions that gave rise to this network of sites. We sought to expand existing discussions of pollution in Greenland by conducting an interdisciplinary and comprehensive analysis of military infrastructure in the ice sheet. We applied a mixed-methods approach that joins historical documents review, remote sensing analysis, and ice sheet modeling to expose the larger undiscussed extent of the US's ice sheet network. With this study, our specific goals are to: 1) determine the positions of all abandoned US military installations across the Greenland Ice Sheet; 2) draw attention to the history and present-day status of these other sites; and 3) introduce these sites within the framing of "waste colonialism" to better understand the threat they pose to ecological resilience.

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I. INTRODUCTION

1. Introduction

Military sites have historically become major point sources for environmental contamination. The scale of particularly US military operations is such that its network has become the largest institutional polluter in history through both liquid fuels consumption and greenhouse gas emissions (Bigger et al., 2021, Belcher et al., 2020; Crawford, 2019). Military sites have the potential to pollute significantly both through their day-to-day operations and through the contaminants left behind when unremediated. Studies examining the impacts of abandoned military sites have found that they have a high potential for contaminating environments with excess PCBs and heavy metals (Fonnum et al., 2012).

With globally changing climate patterns there is even higher potential than before for certain of these waste sites to become destabilized and cause human-ecological harm. Contaminated sites may have a higher risk of pollutant mobilization and degradation through a wide range of climate change stressors (Kibria et al., 2021); e.g., increasing water temperatures and higher precipitation rates increase pollutant mobility through intensifying erosion and surface runoff of excess nutrients (Xu et al., 2019), persistent organic pollutants (POPs) (Kallenborn et al., 2012), and heavy metals (Presley et al., 2006). The Arctic region has become centered in conversations about environmental contamination due to factors like the Northern up-concentration of POPs from hydrologic transport (Macdonald et al., 2005; Wöhrnschimmel et al. 2013) and legacy industrial contamination left behind in the increasingly destabilized ice and permafrost (Langer et al., 2023). The impact of climate change in this geopolitically unique region threatens to produce thousands of “unfunded environmental liabilities” (Langer et al., 2023; Colgan, 2018).

The United States’ Cold War strategy sought to turn the Arctic into a theater of war, which has resulted in an extensive network of military sites across its now changing land- and ice-scapes. Some of these sites have gained publicity around major remediation projects, such as the cleanup of the DEWLine (Distant Early Warning) Radar Chain

(Poland et al., 2001). The efforts of this project revealed the fiscal and logistical challenges associated with remediating contamination in remote polar landscapes (Eagles, 2012). Challenges in the physical extraction of waste and its financing are also central to the ongoing site investigation of Camp Century in Greenland (Kalaallit Nunaat). A 2016 ice sheet modeling study (Colgan et al., 2016) and various calls from Greenlandic government officials for the waste to be removed spurred political momentum around remediating hazardous waste in Greenland, resulting in the establishment of the Camp Century Climate Monitoring Programme (CCCMP est. 2017). The CCCMP aimed to assess the site's physical environmental conditions and report updated timelines for potential remobilization of this hazardous material. Thus far, reports have revealed Camp Century's present location, horizontal displacement, and vertical burial depth alongside updated firn modeling, which predicts a maximum percolation depth of 1.1 m– tens of meters away from the top of the debris field (Karlsson et al., 2019; Vandecrux et al., 2021; Colgan et al., 2022). Vandecrux et al. (2021) therefore finds it "extremely unlikely that meltwater interacts with military waste within this century" (Vandecrux et al., 2021)

Recent scientific investigations of the abandoned "city under the ice" at Camp Century, Greenland have analyzed the physical dimensions of the debris field, while various other scholars have articulated the historical and geopolitical dimensions that gave rise to this network of sites. We sought to expand existing discussions of pollution in Greenland by bridging these two perspectives. We apply a human-ecological perspective to this topic that leverages analysis of existing datasets of the ice sheet's physical properties to fill in the gaps of the historical record.

Furthermore, to address broadscale threats to ecological resilience, we argue here that understanding harm only through a physical lens (i.e., risk of environmental contamination by hazardous materials) is overly narrow. To deepen current conversations about the status of abandoned US waste in Greenland, we will dissect how unremediated waste both results from and upholds legislatively codified and ecologically destabilizing land relationships. As a component of this argument, we will draw attention to how the isolated scientific focus on Camp Century may obscure the full extent of the US's militaristic control of the ice sheet. Thus, we argue that we ought to approach Camp Century– and science-military sites more generally– through an understanding of both geopolitical and ecological relationships because that will emphasize the larger network of waste (and thus pollution) made additionally vulnerable by climate change.

With this study, our specific goals are to: 1) determine the positions of all abandoned US military installations across the Greenland Ice Sheet today; 2) draw attention to the history and present-day status of these other sites; and 3) introduce these sites within the framing of "waste colonialism" (Liboiron, 2021; Liboiron, 2018) to better understand the threat they pose to ecological resilience. The paper is structured as follows. First, we provide a brief history of Cold War era US military infrastructure in Greenland, then we describe our methods and the results of tracking the abandoned bases and finally conclude with discussions around the relationship between waste and ecological imperialism and the unsiliencing of military history.

II. HISTORICAL BACKGROUND

2. Historical background

As Cold War tensions grew post-WWII, the U.S. pursued The Polar Strategy which concentrated military command power at bases in the Continental U.S. while extending its operations deep into the Arctic (and thus geographically closer to the Soviet Union) through the construction of bases in Northern Greenland (Petersen, 2013). To make way for these plans, the American and Danish governments negotiated a protectorate agreement that expanded U.S. security interests into Greenland. What followed was the expansion of infrastructural planning and scientific research into ecologies otherwise unfamiliar to the United States Army Corps of Engineers (USACE). Building outward from the existing Thule Air Base (built in 1941)– the northernmost and then largest overseas US military base– they at first established five fixed camps on the ice sheet. Fundamental to their early interests were investigations of Earth processes in cold environments. These projects began under the early Snow, Ice, and Permafrost Research Establishment (SIPRE) in 1949, which later became the Cold Regions Research and Engineering Laboratory (CRREL) in 1961.

Of the sites that were constructed during this era, one in particular has accumulated notoriety. The famous Camp Century, the "city under the ice", was built in northwest Greenland through an extended network of tunnels on the ice sheet. Access to this site was made possible through ice roads beginning at the ice ramp at Camp Tuto (about 10 miles from Thule AB). The American people were filled with wonder upon hearing in news reports of this "fantastic" city (Nielsen et al. 2014), which was even depicted through illustrations in National Geographic Magazine. However, this quaint image was quashed when the camp closed, and the true intentions of the camp were revealed as the site for the experimental Project Iceworm, a program that would have produced a 2500-mile tunnel network in the ice sheet for storage and transport of hundreds of nuclear missiles. And yet, this never came to be. The snow and ice encapsulating Camp Century proved to be more dynamic than the engineers expected. Slowly warping ceilings and walls threatened to crush the base, its inhabitants, and the nuclear generator that powered the station. The site was evacuated and eventually closed permanently in 1967. Apart from the nuclear generator, which was removed in 1964, the debris from this site has remained trapped in the ice to this day (Nielsen et al., 2016).

The singular attention that Camp Century received as the "city under the ice" may create the illusion that it is the only one, but, in truth, Camp Century is just one piece of a larger network of US installations across the ice sheet. For example, Camp Century's design and construction process was tested out at three other "under ice camps". This handful of bases was supported by a larger subset of camps that were scattered around the greater Thule AB region to aid in scientific expeditions, supply, transport, and facilities upkeep at the subsurface bases (Figure 1). Outside of the programs in northwest Greenland, US military operations also extended to the southern half of the ice sheet. Two other networks of radar stations were constructed in the mid-1950s–the DEWLine chain (1957) and the Operation HIRAN stations (1956) (Figures 2 and 3, respectively). These two groups of facilities were constructed for wartime navigation and surveying of incoming (defensive) and outgoing (offensive) precision bombing. Ultimately, engineers designed and constructed stations above, on top of, and below the ice surface.

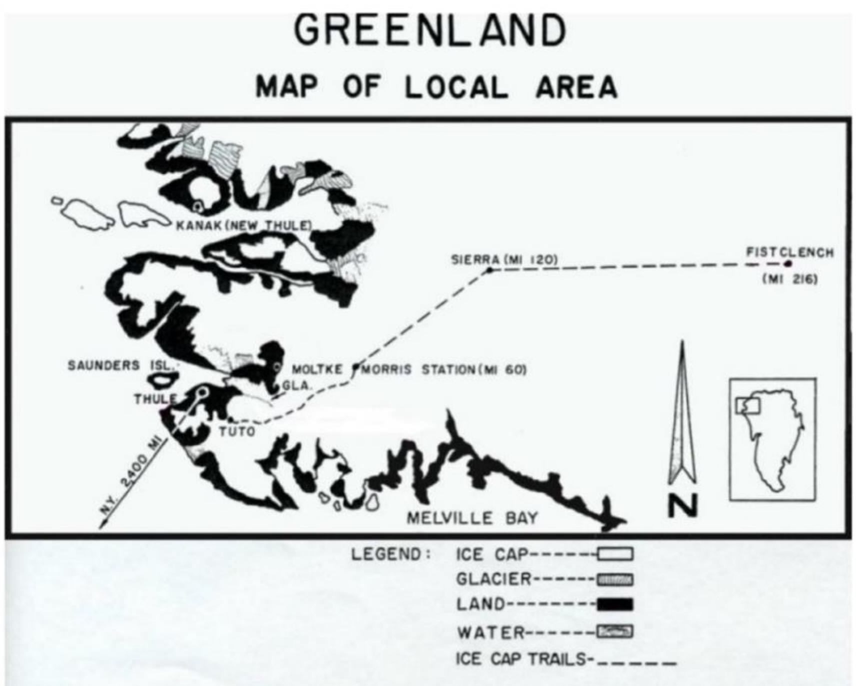

Figure 1: Early map of ice sheet bases extending outward from Thule AB and Camp Tuto.

Figure 2 & 3: Location of Greenland ice cap DEWLine stations (left) reproduced from Walsh &. Ueda (1998). Locations of HIRAN base camps (right) reproduced from Mock & Alford (1964).

Since these bases were to occupy permafrost and ice-covered landscapes, the military first needed to overhaul their prior understanding of construction and engineering, which was limited to the ecologies found further south of the Arctic. Reports from the SIPRE and CRREL programs detail the enormous efforts to manage snow and ice as a construction material (Abel, 1961; Butkovich et al., 1959). The research efforts of glaciologists, geophysicists, chemists, and engineers all worked together to understand how to maintain these bases on a fluid-dynamic foundation. Many styles of building were introduced that attempted to accommodate the continuous gravity-induced flow of ice above and beneath them. Jamesway huts (Figure 4), 12-story radome-towers on dynamic stilts (Figure 5), subsurface containers (Figure 6) with dormitories and cafeterias were installed across these networks to support long-term occupancy. Much like military towns elsewhere, they were equipped with research laboratories, monitoring equipment, construction machinery, waste disposal infrastructure, and entertainment spaces. The amenities of these bases resemble those of US cities to sustain morale for American soldiers and researchers while working in remote locations (Tangerman et al., 1958).

Figure 4: Example construction of a Jamesway Hut in Antarctica 1972-74. Photo Credit: Ralph Lewis. https://www.coolantarctica.com/Bases/OAE/RL-Misc-PICT0128.php

Figure 5: DYE-3, 1977. Example of radome-tower structure on column supports. Reproduced from Walsh & Ueda (1998).

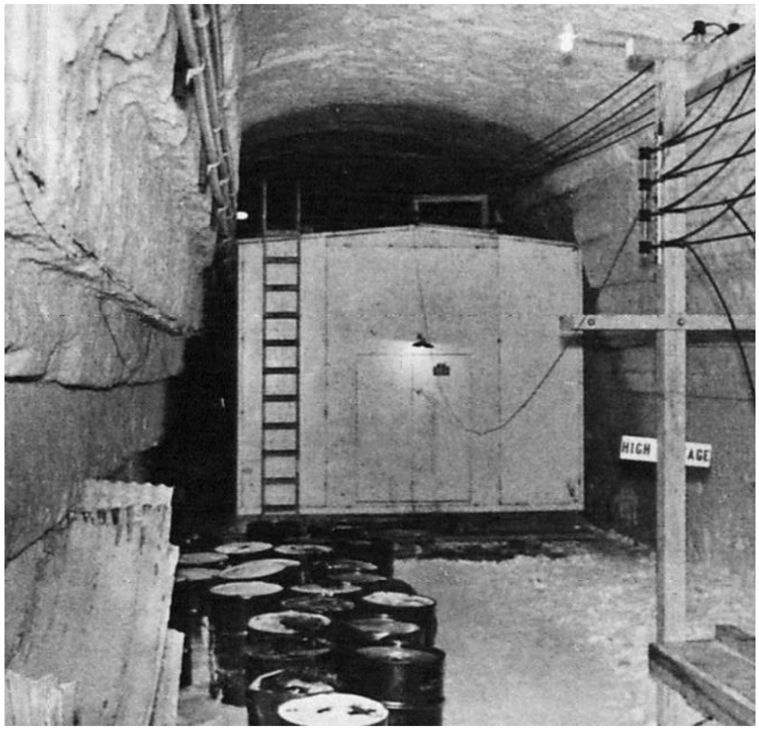

Figure 6: Example of prebuilt container structures in subsurface ice tunnels at Camp Century. Image credits: Austin Kovacs (1970).

In the end, each of these bases was deserted– left to succumb to the burial processes of the ice sheet. In the case of the northwestern sites associated with Thule AB, operations were halted at each camp by the structural hazards posed by the plasticity of the ice (Petersen, 2013). This factor deterred any further developments to subterranean programs on the ice sheet– most notably the famous Project Iceworm– and funding was cut off. On the other hand, the HIRAN camps were always intended to be temporary and were only occupied from April-August 1956. However, they were not removed at the end of the season. The Jamesway huts at each site proved to be effective catchment areas for snow drift, and they were quickly erased from the ice sheet surface. Lastly, the two stations associated with the DEWLine Radar Chain (DYE-2 and DYE-3) were maintained for three decades but ultimately replaced by the North Warning System in 1988. And so, each became obsolete and was abandoned. Here we will resurface them once again– albeit metaphorically. Further details about these sites will be discussed in our results under the section titled “Site Identification”.

III. STUDY DESIGN

1. Definitions

Since there is a wide variety of US military research and development (R&D) sites across the Arctic, we first define the scope of the locations included here before proceeding with this analysis. The sites of this study were limited to those confirmed to be “fixed camps”. In this context, that refers to any site with recorded documentation of a permanent shelter, likely indicated in records through site plans featuring plumbing, electrical, and waste infrastructure. Such long-term occupancy camps might be categorized together because in addition to being sites of technical and engineering research projects, they were also places that accommodated military personnel with site-managed overnight lodging, running water, generated power, and waste disposal. Like cities and towns elsewhere, these bases have their own food, water, power, and waste streams. Aside from these similarities, the sites vary in spatial extent, operating capacity, total operating duration, seasonal occupancy durations, and the types of research conducted.

2. Methods

A mixed-methods approach combining archival research, remote sensing analysis, and ice sheet modeling was used to retrace the history of the US Military’s fixed camps in Greenland. Several different techniques were used to determine past and present geolocations of each site as well as burial depth within the ice sheet. The methods here work to 1) identify the historical coordinates of each site location, 2) estimate present-day coordinates of each site location using projections ice flow velocity, and 3) determine burial depth of each site using the output of firn density modeling.

Past site positions were determined by a systematic review of digital and physical historic records published by the USACE. Digital records were accessed primarily on the USACE’s digital archive, the ERDC Knowledge Core (Accessible online at: https://erdc-library.erdc.dren.mil/jspui/), and physical reports were accessed in the Crary Science Library at McMurdo Station in Antarctica. Because most study sites were designed and constructed by the United States, the SIPRE/CRREL Special Reports from the ERDC serve as the primary source for historical record-keeping of early site geolocations. The documents compiled and studied here are the output of a systematic ERDC keyword search where publications are grouped by the following internally assigned terms and phrases: Camp Century; DEW Line; DYE-2; DYE-3; Early Warning Radar; Ice cap facilities; Greenland construction; Radar stations; Subsurface construction; Subsurface structures; Undersnow construction; Undersnow facilities. Once identified, each primary document was manually reviewed for geospatial references associating a site name with a coordinate pair. Other geospatial references noted during this review were maps and building and infrastructural site plans.

Because these structures were built on a flowing ice foundation, it is necessary that their geolocations be timestamped. For each site, coordinate pairs were obtained from the earliest published record making mention of the site. After compiling the literature base, site names (including secondary names), geospatial position as a coordinate pair, and the publication date (or year of expedition where relevant) were recorded. The site coordinates at the time of construction were used to determine present day geolocations through a series of time-driven models describing patterns of ice flow and firn densification.

The present horizontal positions of the sites were determined using rates of ice flow at each site from the MEaSUREs Multi-Year Greenland Ice Sheet Velocity Mosaic (Joughin et al., 2016). This dataset is derived from a combination of Interferometric Synthetic Aperture Radar (InSAR), Synthetic Aperture Radar (SAR), and Landsat 8 optical imagery data. The MEaSUREs Multi-Year Greenland Ice Sheet Velocity Mosaic provides an averaged representation of surface ice flow velocities for the entire ice sheet at a resolution of 250 m over the timeframe 1995-2015. Average ice flow velocity rates were extracted from this dataset for each site and projected starting at the year of construction and iterating through until the present day. Horizontal displacement is a calculated estimate of how much distanced was traveled since the site was constructed based on the ice flow velocity rate at that original point. The present vertical positions, i.e. burial depth, within the ice sheet were determined using outputs from the Community Firn Model (CFM) (Stevens et al., 2020). CFM is an open-source model that can simulate major processes occurring in accumulation zone of the ice sheet including firn densification, heat transport, and meltwater percolation and refreezing. Conveniently, each layer of the model is dated so the depth of each site can simply be identified if the number of years elapsed since the closure/abandonment of each base is known. Outputs from the CFM are tied to the MERRA-2 grid, so the nearest grid point to each camp location was used to determine firn compaction rates.

Table 1: Sites investigated using remote sensing and ice sheet modeling methods.

Name	Year Built	End Year	Horizontal Displacement (m)	Burial Depth (m)
Site I	**1953**	**1957**	**799.11**	**21**
Site II	**1953**	**1957**	**2582.23**	**46**
Camp Century	**1959**	**1967**	**324.68**	**42**
DYE-2	**1959**	**1988**	**2665.70**	**45**
DYE-3	**1960**	**1991**	**741.11**	**53**
HIRAN-26	**1956**	**1956**	**437.35**	**64**
HIRAN-27	**1956**	**1956**	**3310.46**	**55**
HIRAN-28	**1956**	**1956**	**290.51**	**33**
HIRAN-29	**1956**	**1956**	**1060.13**	**43**
HIRAN-30	**1956**	**1956**	**3470.77**	**51**
HIRAN-31	**1956**	**1956**	**1453.71**	**41**
Station Centrale	**1949**		**1453.71**	**71**

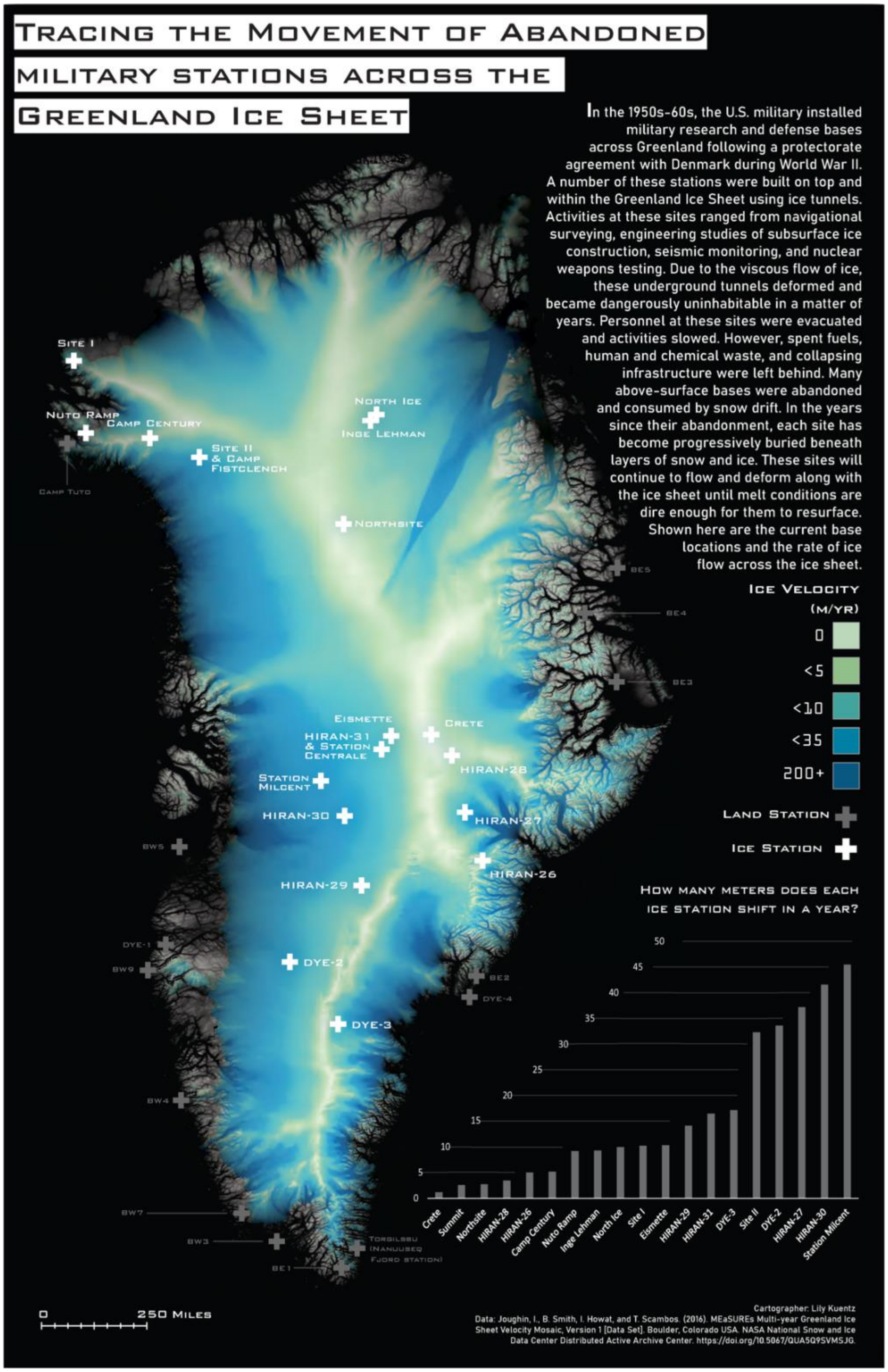

Figure 3: Site map indicating locations of ice-surface bases compared to ice flow velocity rates from Joughin et al. (2016).

IV. SITE IDENTIFICATION

We identified twenty-one fixed camp installations from a combination of archived SIPRE and CRREL reports. Of these, eleven had sufficient documentation to enable us to model the current locations. These sites are distributed across most of the ice sheet, and their movement patterns vary according to the ice properties at each site. In this section, we summarize the main sites and provide a present-day position in the ice sheet (Table 1).

1. Thule Air Base Sites

The SIPRE/CRREL R&D around Thule AB and Camp Tuto was supported by several fixed camps built on and off the ice sheet in northwest Greenland. At three of these sites there are subsurface stations– Camp Century being the largest and maintained the longest (8 years). In 1953, the identical Site I and Site II (at Camp Fist Clench) were outfitted as early proof-of-concept sites for constructing Camp Century, which was installed several years later (1959). These two camps, referred to as the "siblings" of Camp Century (Bierman & Schmidt, 2022), are similarly made up of subsurface ice tunnel networks lined with corrugated steel shells containing prefabricated buildings with indoor heating powered by diesel generators. They were originally constructed in 1953 and abandoned by 1957– Site II having "outlived its operational usefulness."

The history, operations, and legacy of Camp Century have been thoroughly reviewed in previous studies (Colgan et al., 2022; Vandecrux et al., 2021; Karlsson et al., 2019; Colgan et al., 2016; and Nielsen, 2014). Here, evidence about the installation and activities at Site I and Site II (Camp Fist Clench) is primarily drawn from three available U.S. Army Engineer Arctic Task Force "after operations" reports spanning 1957-1959. This evidence is supported by structural and environmental monitoring reports from SIPRE/CRREL with the following titles: Undersnow Structures: N-34 Radar Station, Greenland (Mellor, 1964); Excavations and Installations at SIPRE Test Site, Site 2, Greenland (Bader et al., 1955); Sewage Disposal at Ice Cap Installations (Small, 1955); and Instrumentation of Ice Cap Stations (Hansen, 1955). Hansen (1955) depicts near-identical site plans for Site I and Site II, however, the records reviewed here mainly describe Site 2.

The 1957 After Operations Report describes Site II as an “undersnow camp” with a 150-person capacity outfitted with a “kitchen, dining hall, snow melters, hot and cold water systems, a 150-kw power plant, 7000 sqft of covered storage space, a recreation hall, a third echelon Engineer and Ordnance equipment maintenance shop, a dispensary, radio communications and latrine facilities consisting of toilets, showers, lavatories, and laundry” (U.S. Army Engineer Arctic Task Force, 1957). The activities at these sites included research on permafrost core drilling, crevasse detection, snow compaction, building snow structures, avalanche control by means of explosives, snowdrift studies, ice tunnel construction, snow and ice trafficability, and building approach roads to the ice sheet (U.S. Army Engineer Arctic Task Force, 1957). Routine station support and maintenance also includes receiving and handling cargo shipments from the U.S., road maintenance, the use of dynamite to open ice crevasses, shoveling and hauling snow using heavy machinery, and transport between sites by plane and truck.

These sites were originally located meters below the surface in the 1950s and are now buried at depths in the ice sheet. Our analysis reveals that, in 2023, Camp Century is 42 m below the surface of the ice sheet, Site I is 21 m, and Camp Fistclench (Site II) is 46 m below the surface. Even though these sites were originally located on ice divides, these sites have also advected laterally in the ice sheet. In 2022, Camp Century is 324 m, Site I is 799 m, and Camp Fistclench (Site II) is 2582 m from their original positions.

2. DEWLine Sites

In its entirety, the DEW (Distant Early Warning) Line Radar Chain was constructed from 1955-1960 across the northern coasts of present-day Alaska, Canada, Nunavut, and through the southern half of Greenland. Of the five stations in Greenland associated with the DEW Line, two are located on the ice sheet (Figure 2). During the period of active operations, a series of CRREL reports were published (ten available on the ERDC Knowledge Core) that record measurements of structural stresses and snow properties, building performance studies, and structural recommendations for extending functionality that detail the history of these sites until their abandonment.

The two ice sheet sites, DYE-2 and DYE-3 were active from 1959-1988 and 1960-1991 respectively. Designed to perch atop the ice sheet on dynamic stilts, each site was routinely maintained until their closure. The structures at these two sites towered 40 m (about 12 stories) above the surface on four support columns connected to spread footing foundations buried tens of meters below the snow surface. The combined factors of snow accumulation, firn densification, and footing settlement were burying the structures at a rate of a couple feet each year (Tobaisson et al., 1973), so a jack-screw mechanism was used to raise each structure 6-7 times during their lifespan. To extend their structural lifespans even further after their original foundations became overstressed, both buildings were shifted laterally by 210 ft (64 m) onto new foundations in 1977 (DYE-3) and 1982 (DYE-2). While in use, DYE-2 and DYE-3 were raised 40 m and 49 m respectively (Tobaisson & Tilton, 1980; Tobaisson, 1979). Their experimental design and maintenance records exemplify the challenges of constructing permanent buildings on the ice sheet surface. Since their closures, DYE-2 and DYE-3 have been continuously buried for the last three decades.

The modeled results here estimate that DYE-2 has been displaced laterally by 2665 m SW and buried by 45 m. It is estimated that DYE-3 has shifted laterally by 741 m NE and buried by 53 m. These constructions once towered over the snowfield by 40 m. The top half of each building is still presumably visible above the snow surface. This is confirmed in recent 2017 visits to DYE-2, which is located adjacent to the active Camp Raven (Figures 7 & 8).

 

Figure 7 & 8: A recent visit to DYE-2 showing partial burial by snow (left). DYE-2 with adjacent figure demonstrating scale of building (right). Photo Credit: C. Max Stevens, 2017.

3. HIRAN Sites

Built as part of Operation HIRAN in 1956, six similarly outfitted camps are located in the southern half of the Greenland ice sheet (Fig. 3). Their original purpose was to bridge the gap between American and European geodetic datums as part of the High Intensity Radar Aids to Navigation (HIRAN) program conducted by the U.S. Air Force. Details about these camps are primarily recorded in CRREL report Installation of Ice Movement Poles in Greenland (Mock & Alford, 1964) and the USAF film "Operation Hiran, August 1956" recorded in the National Archives (Accessible online at: https://archive.org/details/342-USAF-23223OperationHiran08-1956).

At each of the six sites, a small configuration of Jamesway huts was constructed on the snow surface to house personnel and store equipment. Facilities included living quarters, an operations shelter, a shelter for diesel-based power generators, an emergency shelter, and, at five locations, a 50 ft aluminum pole to mark the location. Instead of a 50 ft aluminum pole at HIRAN Station 31, there is a 30 ft galvanized steel tower. Station 31 is unique from the other five sites in that the French Station Centrale is buried below and adjacent to the HIRAN shelters built on the surface. This base was constructed in 1949 using ice tunnels to join many corridors of living quarters, research facilities, and utilities infrastructure– much like the American Camp Century built nearly a decade later. In 1963, it was noted that this camp was buried about 30 ft below Station 31 (Mock & Alford, 1964).

Occupation of the HIRAN camps was temporary (April-August 1956), and they were promptly abandoned without revisitation until 1963. At this point, it was realized these sites had been quickly buried by snow and could serve as locations for a study of snow-accumulation given the place marking metal poles. A CRREL team conducted aerial surveys to relocate the six HIRAN camps, and only four were identified. At these four sites, a new 50 ft aluminum pole was erected, standing 35 ft tall above the 1963 snow surface. The remaining two sites could not be identified from aerial survey and were presumed to have been buried entirely by excessive snow drifting. Since this 1964 report, there has been no indication of any further revisitation, and all physical materials left behind (including Jamesway Huts and oil diesel barrels seen in Icecap, I. 1953 and presumably sewage and greywater) in 1956 are presumed to remain buried beneath the surface to this day.

The modeled results in this study estimate that Station 31 has shifted laterally by 1453 m SW and buried by 41 m, with Station Centrale buried by an additional 30 (ft) at 71 m below the surface. The remaining stations are estimated to have been displaced laterally and vertically respectively as follows: Station 26 shifting 437 m SW and buried by 64 m; Station 27 shifting 3310 m NE and buried by 55 m; Station 28 shifting 290 m NE and buried by 33 m; Station 29 shifting 1060 m SW and buried by 43 m; and Station 30 shifting 3470 m SW and buried by 51 m.

V. DISCUSSION

US military operations on the Greenland Ice Sheet were extensive. The locations of their built infrastructure vary based on project goals, resulting in a distributed count of bases– each interfacing with a different section of the ice sheet. Since ice deforms and accumulates at different rates across the landmass, the amount of deformation to each sites' debris field is highly place dependent. The estimated values reported here indicate considerable variation in ice movement between each of the abandoned sites. Based on these figures and the information available in the published records, we assume that the debris left behind at each site has become increasingly challenging to access as it has become further embedded in the ice. However, as alluded to at the start of this text, addressing the physical status of these sites alone does not capture the full scope of their ecological threat. In the following discussions, we will unravel the early geopolitical relationship between the US military and Greenland and explicitly define what waste is and how it results from said relationship to better understand the structural forces surrounding the topic of abandoned US military waste in Greenland.

1. Setting the precedent for waste

The physical materials that remain on the surface or subsurface of the Greenland Ice Sheet could be defined in many ways (e.g., "environmental hazard", "pollution", "unremediated infrastructures"). Colgan et al. (2016) use the term "abandoned wastes" to define these materials. In their definition, "waste" collectively encompasses "physical waste" such as buildings and railway, "chemical waste" such as diesel fuel and polychlorinated biphenyls (PCBs), "biological waste" such as sewage, and "radiological waste". For the purposes of this project, we also use the term "waste". However, we argue that "waste" is much more than just the physical materials left behind on the Greenland Ice Sheet and has several connotations. What follows is a critical reflection on the imperialistic relationship guiding the US military's expansion of polar science to respond to the question, "why waste?"

Early Arctic scientific research conducted by Western researchers was guided by US Cold War strategy, which involved weapons operation and defensive monitoring.

Realizing the strategic importance of the Arctic after WWII, the United States quickly began allocating military and university funding for polar base construction and research (Doel et al., 2014). Doel et al. (2016) summarizes the nature of the research questions investigated by the vast array of SIPRE/CRREL reports: "How would geomagnetic fluctuations and the aurora affect radio communications and navigational equipment? How would ocean currents influence ship movements and submarine operations? Was there evidence that the northern climate was indeed warming, requiring revised war plans? Did the ice cap mask seismic signals from Soviet nuclear tests?" Martin-Nielsen (2012) identifies control as the guiding principle behind the pre-1960s US approach to polar environmental science. This is plainly indicated in the 1961 Pentagon paper International Scientific Activities, which states that the "Department of Defense has a vital interest in the environmental sciences since the military service must have an understanding of, and an ability to predict and even to control the environment in which it is required to operate" (Doel, 2003).

In 1951 the United States coordinated with the colonial power of Denmark to get access to Greenland, thereupon opening the doors for their militaristic and scientific expansion onto (and into) the ice sheet (Petersen, 2013). At this time, Greenland was a Danish colony and without Parliament representation, the Indigenous Inuit were not included in these negotiations. Heymann et al. (2010) describe how the 1951 Defense of Greenland agreement established the basis for US military colonialism by granting permission to create "a small but powerful and isolated state of its own within the vast territory of Greenland"– i.e., the network of roads and military bases on Greenland's ice sheet and coasts. A control-rooted environmental relationship is evident in the many engineering and design approaches to assembling this military base network. Early structures were built on top and under the snow and ice surface. Prebuilt structures that could be cheaply and easily transported and deployed on the ice sheet or inside of tunnels carved within it were quickly found to be insufficient permanent shelters. The bases of Operation HIRAN or those associated with ice tunneling projects outside of Thule AB were partly overwhelmed by the challenge of managing excessive snow drift and accumulation and deformation in the viscous ice sheet. Later designs took a more adaptive and collaborative approach to the dynamic icescape (Martin-Nielsen, 2012); for example, the use of dynamic columns in the DYE sites' foundation forms the basis for modern day polar structures in Greenland and Antarctica (Weale et al., 2014). These early structures were abandoned partly due to the challenges in maintaining their inefficient designs– caused by the rapidly changing snow and ice and the incompatibility of "conventional building materials" with cold regions (Butkovich, 1962; Jacobson, 1964; Martin-Nielsen, 2012).

Turning our attention to the defense agreement, we identify the language that allows for the abandonment of waste by creating a remediation exemption for the United States. Article XI of the Defense of Greenland agreement states:

> All property provided by the Government of the United States of America and located in Greenland shall remain the property of the Government of the United States of America. All removable improvements and facilities erected or constructed by the Government of the United States of America in Greenland and all equipment, material, supplies and goods brought into Greenland by the Government of the United States of America may be removed from Greenland free of any restriction, or disposed of in Greenland by the Government of the United States of America after consultation with the Danish authorities, at any time before the termination of this Agreement or within a reasonable time thereafter. It is understood that any areas or facilities made available to the Government of the United States of America under this Agreement need not be left in the condition in which they were at the time they were thus made available. *Defense of Greenland: Agreement Between the United States and the Kingdom of Denmark, April 27, 1951 (Accessible online at: https://avalon.law.yale.edu/20th_century/den001.asp)*

As is stated, the physical materials remaining on the ice sheet are the property of the United States of America and may be removed at any time without restriction. However, disposal of these materials in Greenland requires the approval of the Danish Authorities, thereby falling under their responsibility. Though most relevant to the proceeding discussion, the final declaration of the article states that it is not expected of the US to return the land to its original state once projects are completed. So long as this agreement continues to guide the relationship between the US and Greenland, there is a legal window allowing for US military pollution to persist in Greenland. Beyond the potential environmental vulnerabilities in the current legal accountability structure, we argue that there are other fundamental reasons that the US military's operations in Greenland produced such extensive waste. These relationships will be further addressed in the following section.

2. A review of waste

The early ecological relationships between the United State and Greenland's physical geography were rooted in imperialism and military control of the environment. Here we will argue that the material incongruence resulting from this relationship produced the network of debris currently trapped in the ice sheet. The purpose of this section is to fundamentally unpack where waste comes from before we situate it in the US-military-Greenlandic context. We will do so first by unpacking various definitions for "waste" and "pollution" with regard to the materials left behind in the ice. Then, we will introduce the term "waste colonialism" which describes how the production, disposal, and management of waste is central to the colonial dispossession of land and ecosystems (Liboiron, 2021; Liboiron, 2018). We contextualize this framework within this imperialistic relationship by introducing evidence for how the US conceived of Greenland as a "wilderness" and "wasteland" that they could exploit. Finally, we apply this understanding of "waste colonialism" to frame our analysis of the imperial narratives that rationalize the historic and ongoing militaristic control of Greenland by the United States via the Kingdom of Denmark.

Early definitions for "waste" were limited in scope. Gourlay (1992) identified how the existing formal definitions of waste served only to create the legislative boundaries for its management. He cites the Oxford English Dictionary definition that waste– or "refuse matter"– is "unserviceable material remaining over from any process of manufacture; the useless by-products of any industrial process; material or manufactured articles so damaged as to be useless or unsaleable." In critiquing those early definitions, Gourlay (1992) revealed the innumerable forms of waste that are not captured within those formal definitions. For example, food waste can be created at points of both manufacturing and consumption. He specifies that even the simple act of putting too much mustard on your plate while eating a hotdog can result in waste during consumption (i.e., through the non-consumption). And so, Gourlay (1992) put forward the simpler working definition that “waste is what we do not want or what we fail to use.” This definition allows for fluidity in interpretation by the designator based on their perception of the matter’s function, value, or lack thereof. Recall the idiom, “one man’s trash is another man’s treasure.” That same dollop of mustard might not be considered waste to the raccoon that discovers it in the trash.

Later iterations on this topic further emphasize waste’s relativity. Strasser (1999) highlights how categories for identifying waste are dynamic throughout time and space and between individuals. She writes that “nothing is inherently trash,” and that instead, “trash is created by sorting.” These conceptions of waste draw attention to the fundamental processes by which waste is produced. It is the act or process of collecting and sorting materials as waste that makes them so. This explains why materials that are recycled or reused are not considered waste; after sorting, they are (according to Gourlay’s definition) reassigned function and thus value by the user. Presently, most waste infrastructure is oriented toward managing by-products from industrial processes, whereby waste can be created through short-sightedness, overestimation, negligence, or even catastrophe in the basic act of producing (e.g., excess plastic trimmed off and thrown away while manufacturing children’s toys, uncaptured CO2 emissions from oil refining, the remnants of a collapsed bridge, etc.). As in the earlier mustard example, defining waste outside of strictly industrial settings lets us consider the many scales across which it is produced.

Laid out so far, we have described the physical and relative characteristics of waste, but even in broadening what counts as waste and what processes produce waste, we are still limited in our understanding of how its comes to be and what it’s doing after it’s there. By focusing on the handheld, microscopic, and even molecular scales of waste, Max Liboiron (2011) pushes us to reconsider these 20th century models and instead consider waste from a global systems perspective. Drawing our attention to the bioaccumulation of molecular compounds like DDT and PCBs, they emphasize how the bodies of living beings store the burdens of pollution and waste. A focus on molecules and particulate matter expands the scale of our discussion of waste. Consider that when a single microscopic unit of pollution (like a CO2 molecule) is produced in excess, it has the potential to be massively dispersed through Earth's globally connected atmospheric processes. Through their work studying microplastics in the digestive tracks of marine animals, Liboiron questions the structures that gave rise to the global ubiquity of plastics. Namely, they discuss how colonial land relations are embedded in the processing, management, and disposal of waste through "waste colonialism".

Before introducing "waste colonialism", we should pause and reflect for a moment on definitions of "pollution" as they relate to "waste". Legal scholar Keith Hawkins (1984) suggested that working definitions for pollution are built around constructions for what is "tolerable" and around notions of whether it will have an "impact"– both of which involve highly subjective responses from enforcement authorities. A more concrete definition offered by economists Keeler, Spence, and Zeckhauser states that "pollution [is] any stock or flow of physical substances which impairs man's capacity to enjoy life." These definitions differ most significantly from those for "waste" through the added notion of material impact or even harm. Considering the subjectivity discussed by Hawkins, to create a working definition of "pollution" we must also understand the positionality of the power forming said definition. Hence, when Liboiron (2021) states that "pollution is best understood as the violence of colonial land relations rather than environmental damage", they are working away from forming top-down definitions for "pollution" that assert what is and is not harmful. Instead, they ask us to understand what "pollution" is through the colonial power relationships that are defining it.

Similarly, "waste" must also be understood through the power relationships that categorize it. The creation, disposal, and management of waste can all take the form of a colonial dispossession of land and ecosystem. Colonialism is "a practice of domination, which involves the subjugation of one people to another," often by the "dispossession of land, customs, and traditional history" (Kohn & Reddy 2023). In terms of managed waste, everything from municipal solid waste landfills to radioactive waste repositories is predicated on entitlement and access to land and ecosystem.

Thus, discussions of the processes that produce waste cannot be disentangled from discussions of power. Liboiron (2022) has pointed out how Mary Douglas's now classic definition of "dirt" as "matter out of place" (Douglas, 1966) has morphed uncritically into definitions for "waste". They argue for a more nuanced explanation of how power intersects with waste by identifying the numerous and compounding ways that waste/trash/rubbish is "kept in place". A process for managing waste after it is produced might be simplistically put as follows: label it as waste; relocate it for disposal or mechanical processing in a location designated for that waste; and then sometimes monitor it for its lasting impact on that location. This form of waste management creates a (potentially false) sense of security by implying a latent threat or hazard. Since waste management– even when well-intentioned– is also predicated on access to land, the inherent threat of waste lay not solely in the immediate potential for physical harm but also in the violent structures that are upheld. As Liboiron states, waste or "pollution is not a manifestation or side effect of colonialism, but rather an enactment of ongoing colonial relations to Land." And so, it is exactly within these modes of keeping matter "in place" that power is exerted.

3. From polar wastes to military wastes

In the context of the United States' imperialist expansion into Greenland, the power relationship between the US military and the unfamiliar geography they were encountering grew from a fundamental gap in their environmental knowledge. In the late 1940s to the early 1960s, the US military was only beginning to gain experience with the Arctic ecosystem. To understand this period of ecological naïveté, we build upon Di Palma's (2014) conception of a wasteland to articulate the relationship between the imperial power of the US military and the physical geography of the Greenland Ice Sheet.

Although the term "wasteland" may be used to describe a wide range of environments, the characteristics that unite ecosystems under this categorization are absence and hostility. By tracing the historical roots of the term to the Latin *desertus* or *solitudo*, Di Palma (2014) states that early conceptions of "wastelands" articulate them as "lands characterized by absence." She goes on to say that "the wasteland is a place, but even more it is a category of land, a category united not by consistent physical qualities… but rather, by their absence. The wasteland is defined not by what it is or what it has but by what it lacks: it has no water, food, or people, no cities, buildings, settlements, or farms." The reason for drawing attention to this absence or emptiness is that, for the person or entity describing a place as a "wasteland", their absence contributes to a sense of hostility within the landscape. A "wasteland" then, generally "stands in for any place that is hostile to human survival," and "…[its] lacks (of food and water, of cities and towns)… make it a threatening, challenging, and perilous place." Di Palma uses this foundation for what a wasteland is to unpack the relationships with land that formed out of the Enlightenment project of 17th and 18th century Great Britain. Here we will apply a similarly critical lens to the imperial project of the US's Cold War expansion into Greenland while developing the concept of a "wasteland" according to the definitions of "waste" laid out previously.

The basic terms of the compound word "wasteland" indicate clearly that it is a categorization for land that is characterized by "waste". Now, recall Gourlay's (1992) definition of waste, that it is "what we do not want or what we fail to use." Joining these two ideas, one's categorization of an environment as a "wasteland" draws attention to its function or use and thus value. To the person that perceives some place as a wasteland, its lacks make it void of usefulness, and so it is also not valuable. In her book, Di Palma furthermore suggests that the wasteland is hostile or inhospitable to its designator. This person or entity might then create value and usefulness of this land by transforming it. The landscape's supposed hostility is thus something that can be soothed or tamed by developing the land according to the needs of the designator.

Just as the scholars that sought to understand "waste" turned to identifying the underlying beliefs of the powers using this categorization, we must understand the powers that identify a place as "wasteland". It is though their lens and their relationships with land that we must unravel absolute claims over an environment's supposed hostility, lack of function, and lack of value. We argue here that the absence of a close connection or relationship with land, and thus an absence of experience and knowledge, can lead one to categorizing a place as "wasteland". Returning to the context of the Cold War expansion of the US into Greenland, this is clearly the case, as their arrival upon and continued presence within one such "wasteland" has resulted in a significant contribution to their body of scientific knowledge.

Starting in this early Cold War period, the public-facing media created by the United States Army devalued the Greenlandic ecosystem by portraying it as empty and hostile. The opening lines of one such film begin as follows: "The top of the world, the Greenland Icecap, for countless ages it has been a frozen expanse, feared by man, shunned by animals– a white, cold, empty place. But today, more than ever before there's been reason to invade this whiteness, to mark and explore it, for an urgent military purpose" (US Army Pictorial Service, 1953). These films depict the work of American soldiers on the ice sheet and coastal permafrost soils as they "[probe] the mysteries of the Arctic wastes", also referred to as "a total unexplored wilderness" (US Army Pictorial Service, 1965). These lines plainly articulate Greenland's Ice Sheet as both empty and hostile, but they also clearly allude to the potential for this land to be transformed into something (strategically) useful– an asset for defending North America from the Soviet Union. According to their narratives, overcoming the uncontrollable or untamable Arctic environment could only be achieved by the geotechnical expertise of American engineers and environmental scientists. And so, their architectural and engineering responses to the challenges they faced on the ice sheet were the result of their efforts to transform it into a functional space. The emphasis on Greenland as a vast "waste" (i.e. wasteland) serves to devalue the existing ecosystem. This devaluation creates a platform upon which, e.g., polar explorers or war-strategizing international actors, create value and usefulness within the ecosystem by forming it to their needs. In this case, this was an effort to control, exploit, and extract value from an unfamiliar physical geography. To transform this land to meet their needs, they needed to introduce materials from elsewhere in the world– i.e., from external ecologies. One source of trouble here is that the ecosystem these materials are brought into does not have the capacity to degrade and incorporate these pollutants, so without plans to remediate them, they remain trapped in the ice. Thus, the imperial conception of the Greenland Ice Sheet as a "wasteland" by the US military has given way to turning it into a site of waste production and disposal. For, if the land is already being perceived as empty and/or hostile, then the threat of or concern around pollution is minimized. This sentiment is particularly exacerbated by the misconception that waste in the Arctic will be “preserved for eternity” due to its low temperatures (Clark et al., 1962).

In summary, access to Greenland was granted by one colonial power to another in the name of global defense during WWII and again as the Cold War deepened. This access persisted long after the focus of the United States’ foreign affairs shifted out of the Arctic. The result of these agreements was a legal framework with a vague accountability structure for environmental remediation. For these reasons, the story of the remains of earlier American military infrastructure in Greenland has not ended. In the wake of the 20th century Cold War, most of these sites were abandoned– left behind as waste and a reminder of the duration of the United States’ militaristic presence in Greenland. As climate change progresses, new threats are emerging around the world. In the Arctic permafrost, abandoned industrial sites with legacy pollution are increasingly under threat of destabilization, risking widespread environmental disasters. This is true also of the Greenland Ice Sheet, whose unique history has allowed us to retrace the network of abandoned US infrastructure. By taking systems approach to understanding the relationship between the US and Greenland, we hope to reconsider the past, present, and future of polar pollution.

4. Unsiliencing US Military history in Greenland

Through this interdisciplinary study, we aim to build momentum around tracking and publicizing the full distribution of waste sites in Greenland as an active step toward identifying, deconstructing, and reimagining the structural relationships that create pollution in polar spaces. Our work resurfaces US military history within Greenlandic geography through publicly available SIPRE/CRREL records and open access glaciological datasets. It should be noted here that the archived records used to synthesize this history can contribute to a vital conversation around the importance of public records-keeping. One of the outcomes of the 1951 Defense Agreement was an extensive application and approval process whereby the US Army was required to seek permission from Denmark to conduct research outside of defense areas. Petersen (2013) points out that this requirement resulted in the over-exposure of Army activities in the region, hence the extensive collection of SIPRE and CRREL reports pertaining to Greenland (Langer, 2023). Even so, there were a few challenges to applying our methods that are necessary to describe here as they further emphasize the complexity of this history of waste.

Here we address the accuracy limitations of the estimates derived from both glaciological datasets and archived records. We produced estimates of both updated geolocations and values for horizontal and vertical displacement of eleven sites. Although the results here reflect our best efforts to be comprehensive in this study, there are a few limitations that could be addressed by developing more robust models and datasets for ice sheet processes and by expanding the availability of public records pertaining to the sites studied here and others alluded to by CRREL. These limitations are as follows: spatial heterogeneity in firn modeling; lack of recent ground-truthed data for sites other than Camp Century; uncertainty in original site location due to limited and inconsistent geospatial data keeping; absence of information around additional sites.

To meet the needs of the spatial scope of this project, data products covering the fullest spatial extent of ice sheet were used in this analysis. Horizontal displacements due to ice flow were obtained from an average of the MEaSUREs Greenland Ice Sheet Velocity Mosaic product which has a 200 m spatial resolution (Joughin et al., 2016). Burial depths are provided by the Community Firn Model with a spatial resolution of 0.625° x 0.500° which is 28 x 55 km at 60° N and 18 x 55 km at 75° N. There is likely significant spatial variability within these coarse grid cells due to variable snow accumulation over short distances (<25km), which is known to affect firn compaction rates (Dattler et al., 2019; Liston & Sturm, 1998). Based on these limits in spatial precision between coordinates, error in horizontal displacement is presumed to be within tens of meters and vertical displacement within several to tens of meters (Medley et al., 2022). This error range is reflected in comparisons between modeled output and measured values reported by the Camp Century Climate Monitoring Programme. Karlsson (2019) used ice-penetrating radar to demonstrate that Camp Century has shifted SWS by about 232 m as compared to the estimate derived from the ice velocity mosaic of

324 m. Some of this difference can also be attributed to the four-year time difference between measurement (2019) and estimate (2023). With respect to vertical burial, the same study found most subsurface reflectors at depths greater than 32 m (Vandecrux et al., 2021), suggesting this as an upper limit for the burial depth of the Camp Century debris field as compared to 42 m derived here from the Community Firn Model (Stevens et al., 2020). Given that recent ground truthing is constrained solely to the Camp Century debris field, the similarity between modeled and measured values is assumed to be consistent across other sites. However, only future visitations of other debris fields can reveal any potential over- or under-estimates reported here.

The other significant source of error is due to the uncertainties in the original positions of the research stations based on the archived records. We assume that the coordinates recorded in the CRREL reports are timestamped and accurate at the time of publishing. However, geospatial data in these reports is shared in many different formats, and often lacks a consistent standard. For example, some camp site geolocations were recorded as latitude/longitude coordinate pairs with a precision in degrees and minutes or otherwise with two decimal places in decimal degrees, though they are more often recorded without decimal places/only in degrees. For other camp sites, only approximate distances were recorded; for example, in TR174, Site I and Site II are "respectively 96 miles NNW and 220 miles ENE of Thule" without further detail (Clark, 1965). The positions of other camp sites were simply recorded as points in a map figure. Without additional reports to corroborate the existence of a camp with a supporting geospatial reference, it is challenging to identify original site positions, and therefore present locations, using publicly available data. The lack of precise geographic positioning of US installations is confusing since other nations documented the positions of their camps much more effectively. As mentioned earlier, the French Station Centrale, built in 1949 below the surface of the ice sheet, contained similar set of tunnels and infrastructure. This camp has publicly accessible blueprints with construction and closure dates explicitly stated alongside site coordinates with a precision in degrees and minutes and a timestamp indicating the year the document was created (Accessible online: https://www.archives-polaires.fr/viewer/15078/?offset=4#page=1&viewer=picture&o=info&n=0&q=). This information makes it possible to track movements in these camps using the methods shown here much more accurately than the US research bases., and ultimately will be needed for planning a site cleanup.

A final limitation of our study is that there are at least several former research bases for which we were not able to provide an up-to-date location. While we strived to conduct this analysis as comprehensively as possible, it is not exhaustive for several reasons. The locations ultimately included here are only those fixed camps for which a timestamped coordinate pair and construction date could be obtained. There are several camps that we could not find sufficient geospatial records to include in this study. These are: Blue Ice Valley; Camp Red Rock; Camp Nuto / Nuto Ramp; Crete Station; Eismette Station; Milcent Station; Morris Station; North Site; Sierra Station; and Tuto East. It is likely that these sites contain unremediated waste.

There is one site with sufficient documentation that was not included in the ice sheet modeling because it is located at the ice sheet margin. The Camp Tuto Ice Tunnel was constructed at the edge of the ice sheet one mile outside of Camp Tuto (located 16 miles from Thule AB) and consists of two stretches of 1000 ft. long tunnels lined with cavernous rooms for housing personnel and storing equipment and fuel (Rausch, 1958). It was known during construction of this experimental site that the ice enclosing it moved on an order of magnitude of 300-500 m/yr (Abel, 1961). The rapidly shifting ice around this facility posed an immediate challenge, and it was observed that any opening to the ice tunnel began closing the moment it was made. Although Camp Tuto has since been decommissioned and from the view of satellite imagery, buildings appear to have been removed, there are no publicly available records indicating the timing or extent of the cleanup, nor if this decommissioning extended into the ice tunnels. Absent, missing, and/or undocumented site remediation records contribute to the already vague accountability structure around abandoned military waste sites in Greenland and poses an additional challenge to responding to and preventing environmental pollution.

Beyond those sites excluded due to absent USACE records, it must be noted that this analysis does not include actively maintained camps (which each manage their own waste streams), nor any non-military sites, nor any non-U.S. sites, nor does it include any sites (either active or abandoned) located off the ice sheet, of which there are many. Additionally, due to a lack of documentation, it was not possible to include sites of legacy contamination from temporary field camps (or tent camps) where activities like the use of explosives may have left behind toxic by-products. Presently, digitally available records of past U.S. military activities on the Greenland Ice Sheet on the ERDC Knowledge Core do not include documents related to field planning or research proposals. Thus, it will be a challenge to identify high precision coordinates for contaminated sites like these, however frequent references are made to these activities taking place in CRREL's scientific reports.

If there is one point that the limitations outlined here ought to emphasize, it is that there are considerable gaps in the records of waste left on the Greenland Ice Sheet, and that the volume and distribution of that waste is extensive. While the work here seeks to fill in some of those gaps, it will require additional tracing of historical records to uncover the full extent of this waste.

VI. CONCLUSION

Conclusion

The results revealed through this project have significant implications for polar science and geopolitics, particularly in Greenland. Through an interdisciplinary and mixed methods approach combining historical literature review, remote sensing analysis, and ice sheet modeling, we derived estimates for the present-day locations, horizontal displacement, and burial depth of eleven former fixed camps. The results here reveal significant variation in vertical and horizontal shifting between the debris fields at these sites. Finally, our critical analysis addressing the relationship between imperialistic power, land, and ecosystem articulates how sites of waste and pollution come to be, particularly in remote, Arctic settings like the Greenland Ice Sheet. Furthermore, this work builds on interdisciplinary work in critical physical geography and the emergent field of critical remote sensing. We demonstrate the necessity of approaching a complex topic like waste through a combination of historical, human-ecological, and physical-scientific perspectives. Gaps in both the historical and geospatial records can be addressed in part through a mixed-methods approach like the one used here. This work may also serve as an example of how existing physical datasets may be repurposed to expose and better understand topics with complex ecological and socio-political implications.

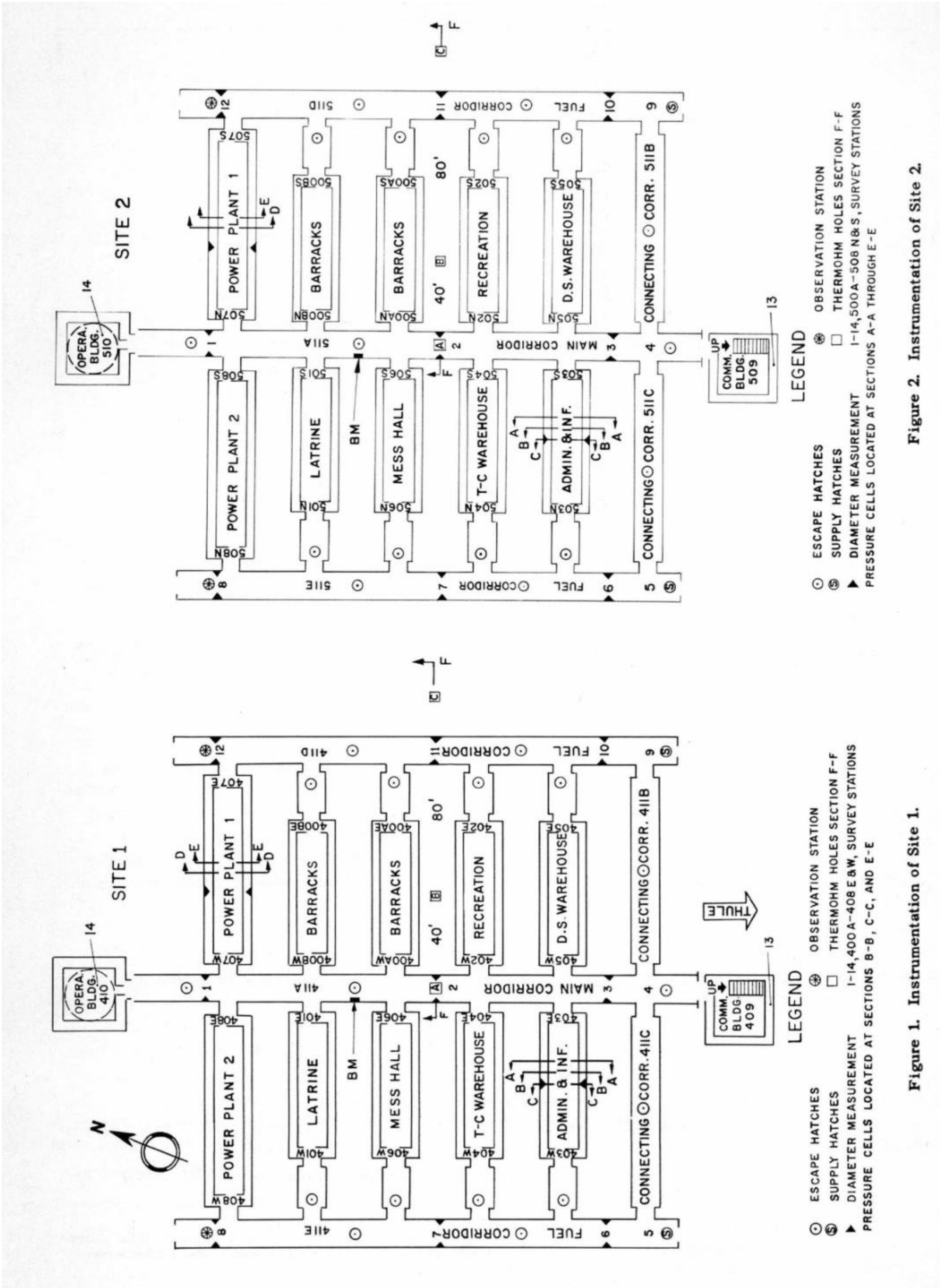

Figure 4: Site plans for Site I and Site II. Reproduced from Hansen, B. L. (1955). Instrumentation of ice-cap stations: Preliminary report. In This Digital Resource was created from scans of the Print Resource [Report]. U.S. Army Snow, Ice, and Permafrost Research Establishment. https://erdc-library.erdc.dren.mil/jspui/handle/11681/6011

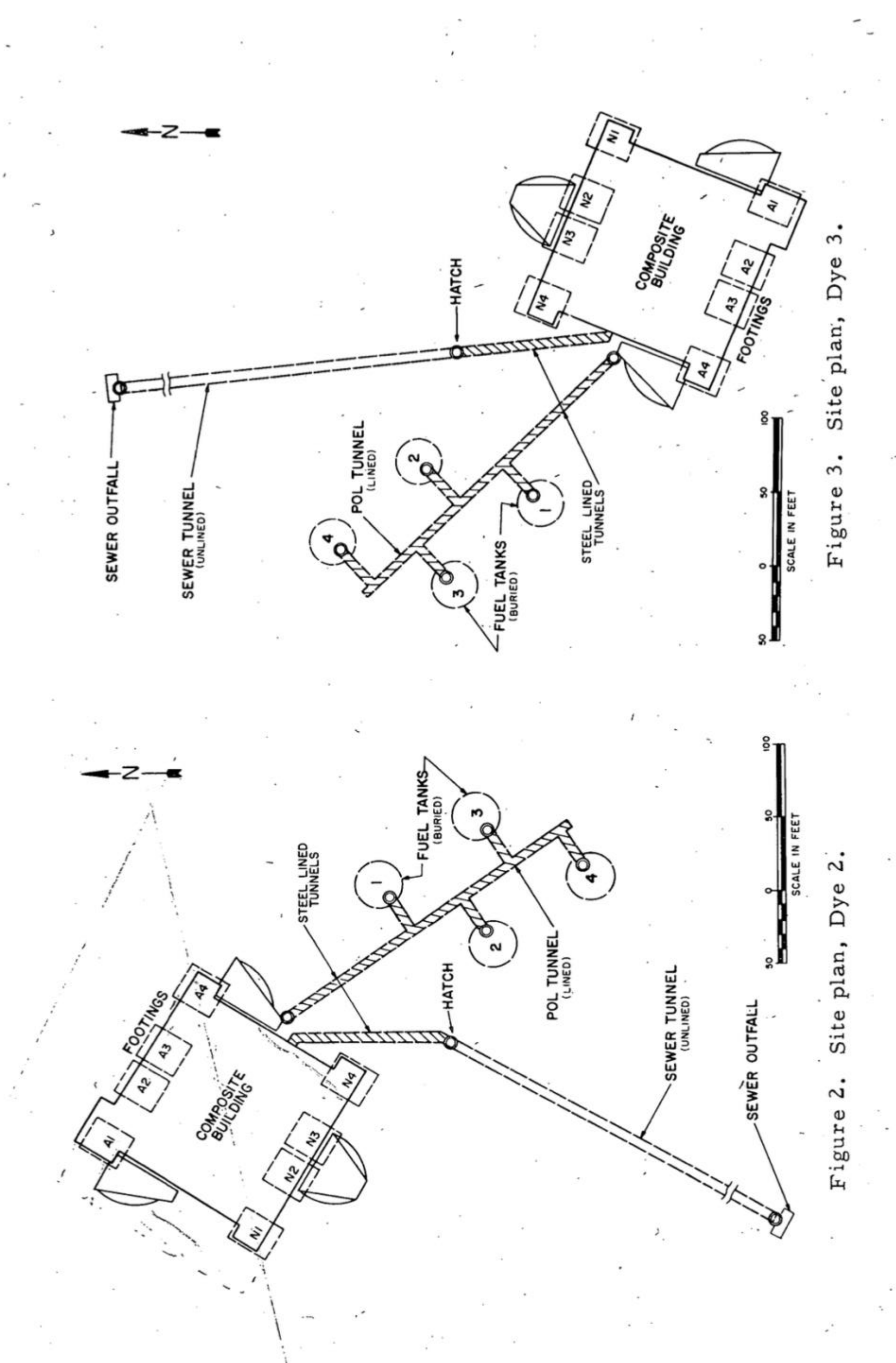

Figure 5: Site plans for DYE-2 and DYE-3. Reproduced from Reed, S. C. (1966). Performance study of the Dewline ice cap stations, Greenland, 1963. In This Digital Resource was created from scans of the Print Resource [Report]. Cold Regions Research and Engineering. https://erdc-library.erdc.dren.mil/jspui/handle/11681/11591

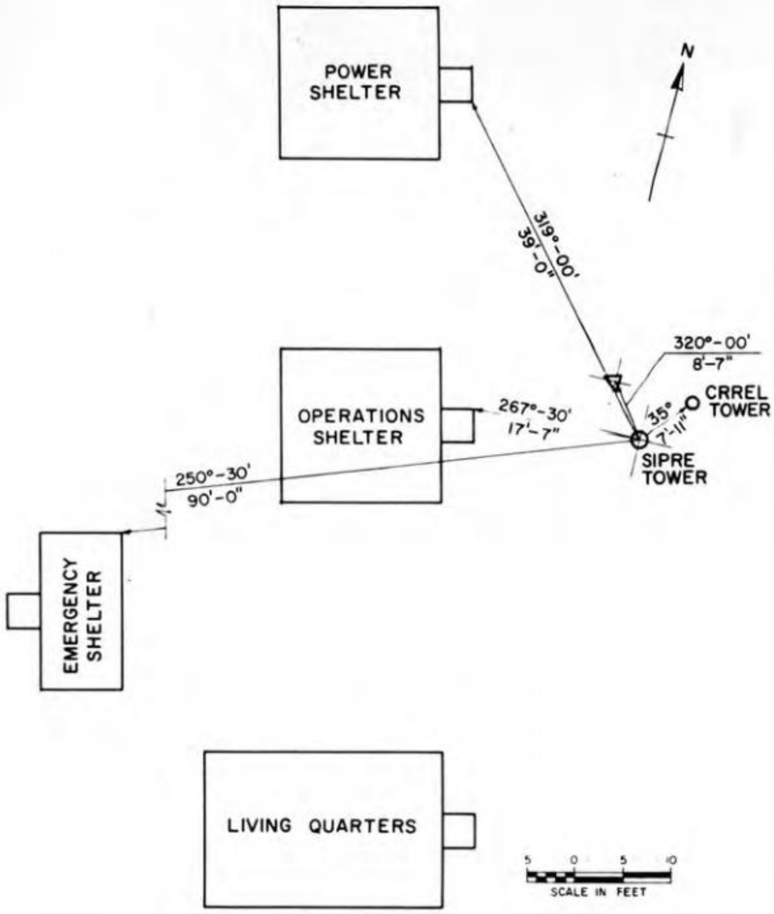

Figure C1. Sta. no. 26, HIRAN Camp. Approx. 68°-19' N. lat., 36°-21' W. long. Approx. elev. 9594 ft.

Notes:
1. HIRAN Camp is approx. 15 ft below 1963 surface.
2. SIPRE Tower extends 14 ft 8 in. above 1963 surface.
3. CRREL Tower extends 29 ft 1 in. above 1963 surface.

Figure 6: Site layout for HIRAN-26 camp. Reproduced from Mock, S. J., & Alford, D. L. (1964). Installation of ice movement poles in Greenland. In This Digital Resource was created from scans of the Print Resource [Report]. Cold Regions Research and Engineering Laboratory. https://erdc-library.erdc.dren.mil/jspui/handle/11681/11580

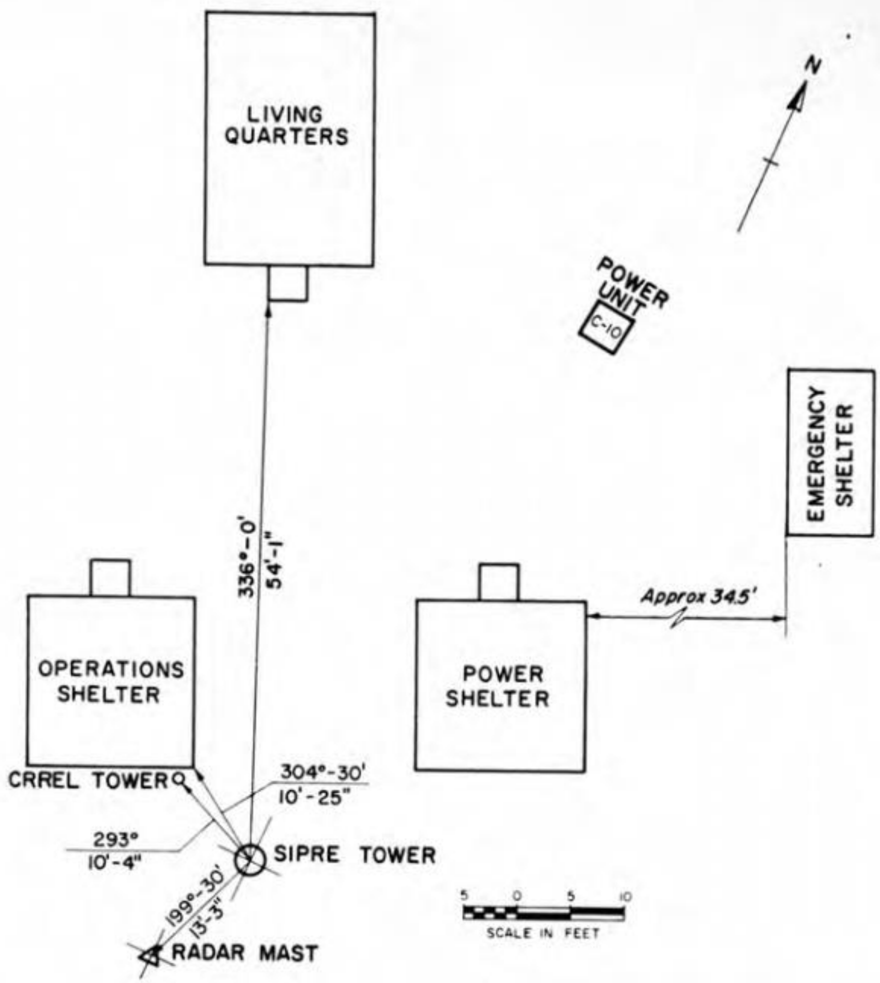

Figure Ç2. Sta. no. 27. Approx. 69°-23' N. lat., 35°-55' W. long. Approx. elev. 9049 ft.

Notes:
1. HIRAN Camp is approx. 26 ft below 1963 surface.
2. SIPRE Tower extends 9 ft 3 in. above 1963 surface.
3. CRREL Tower extends 30 ft 6 in. above 1963 surface.

Figure 7: Site layout for HIRAN-27 camp. Reproduced from Mock, S. J., & Alford, D. L. (1964). Installation of ice movement poles in Greenland. In This Digital Resource was created from scans of the Print Resource [Report]. Cold Regions Research and Engineering Laboratory. https://erdc-library.erdc.dren.mil/jspui/handle/11681/11580

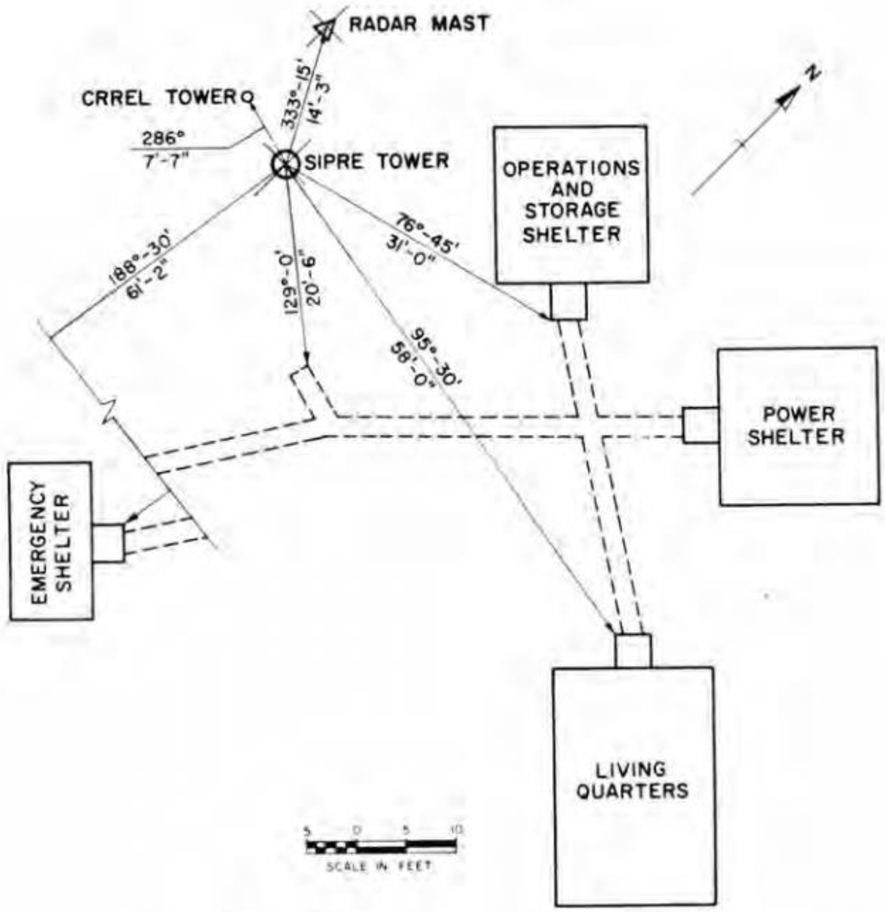

Figure C3. Sta. no. 28. Approx. 70°-37' N. lat., 36°-10' W. long. Approx. elev. 10, 298 ft.

Notes: 1. HIRAN Camp is approx. 16 ft below 1963 surface.

2. SIPRE Tower extends 16 ft 6 in. above 1963 surface.

3. CRREL Tower extends 31 ft 6 in. above 1963 surface.

Figure 8: Site layout for HIRAN-28 camp. Reproduced from Mock, S. J., & Alford, D. L. (1964). Installation of ice movement poles in Greenland. In This Digital Resource was created from scans of the Print Resource [Report]. Cold Regions Research and Engineering Laboratory. https://erdc-library.erdc.dren.mil/jspui/handle/11681/11580

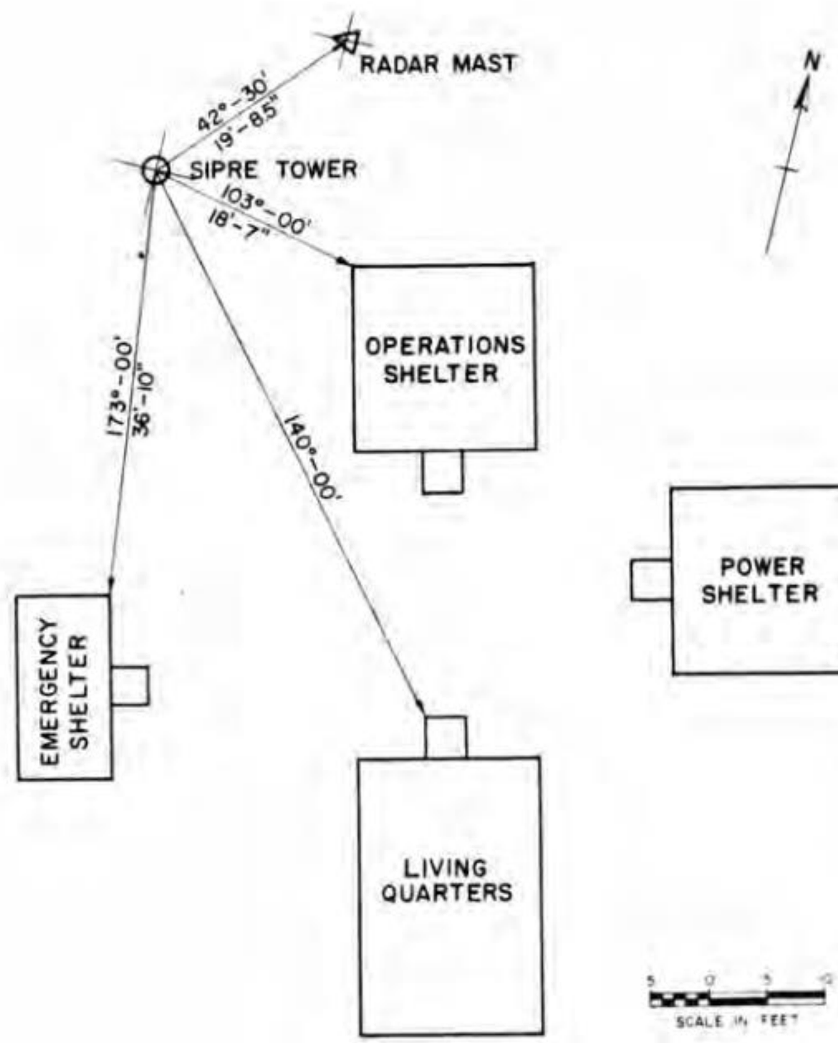

Figure C4. Sta. no. 29. Approx. 68°-04' N. lat., 42°-20' W. long. Approx. elev. 8506 ft.

Notes: 1. HIRAN Camp is 35 + ft below 1963 surface.

2. SIPRE Tower extends 35 ft above 1956 surface.

Figure 9: Site layout for HIRAN-29 camp. Reproduced from Mock, S. J., & Alford, D. L. (1964). Installation of ice movement poles in Greenland. In This Digital Resource was created from scans of the Print Resource [Report]. Cold Regions Research and Engineering Laboratory. https://erdc-library.erdc.dren.mil/jspui/handle/11681/11580

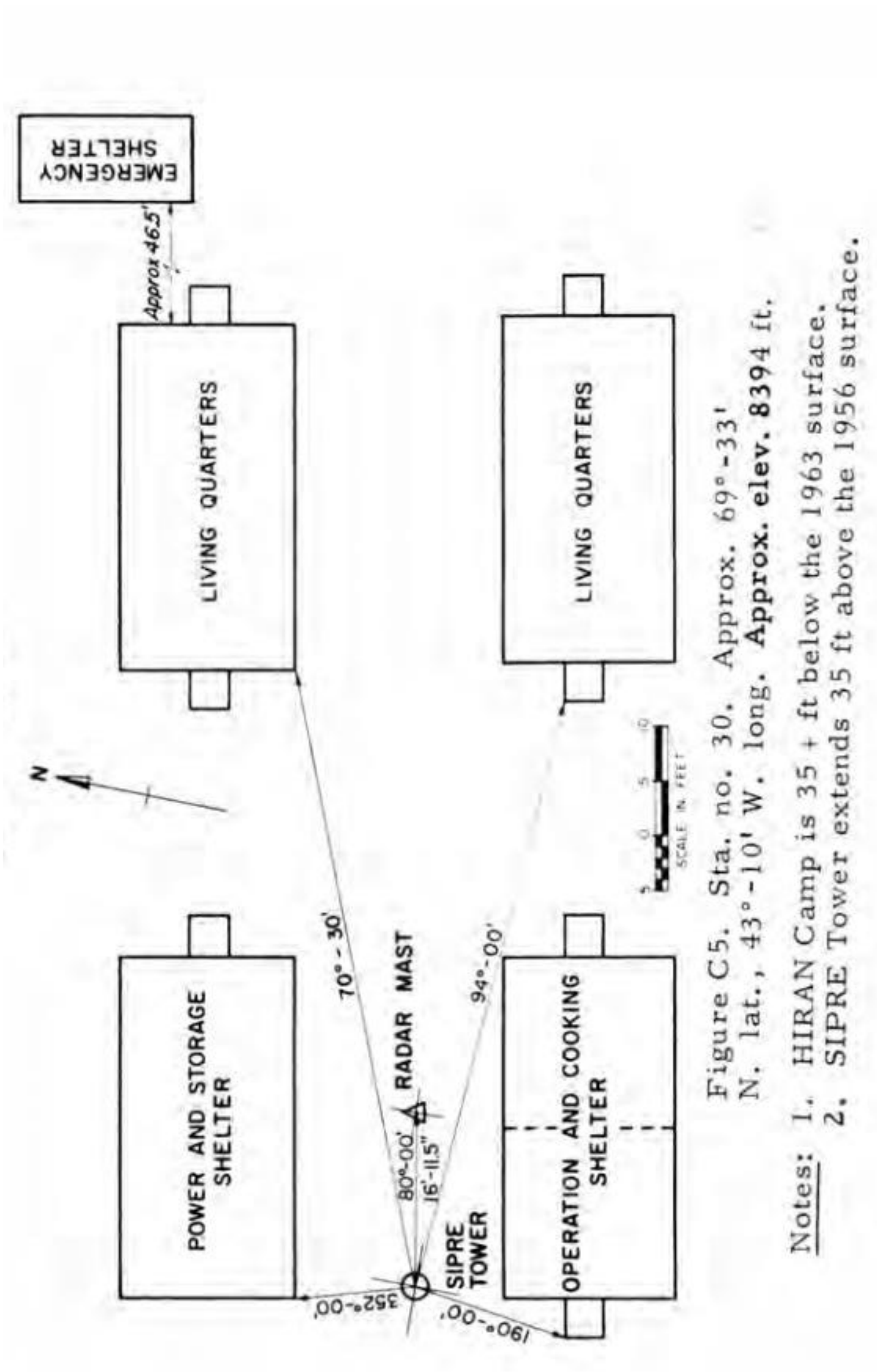

Figure 10: Site layout for HIRAN-30 camp. Reproduced from Mock, S. J., & Alford, D. L. (1964). Installation of ice movement poles in Greenland. In This Digital Resource was created from scans of the Print Resource [Report]. Cold Regions Research and Engineering Laboratory. https://erdc-library.erdc.dren.mil/jspui/handle/11681/11580

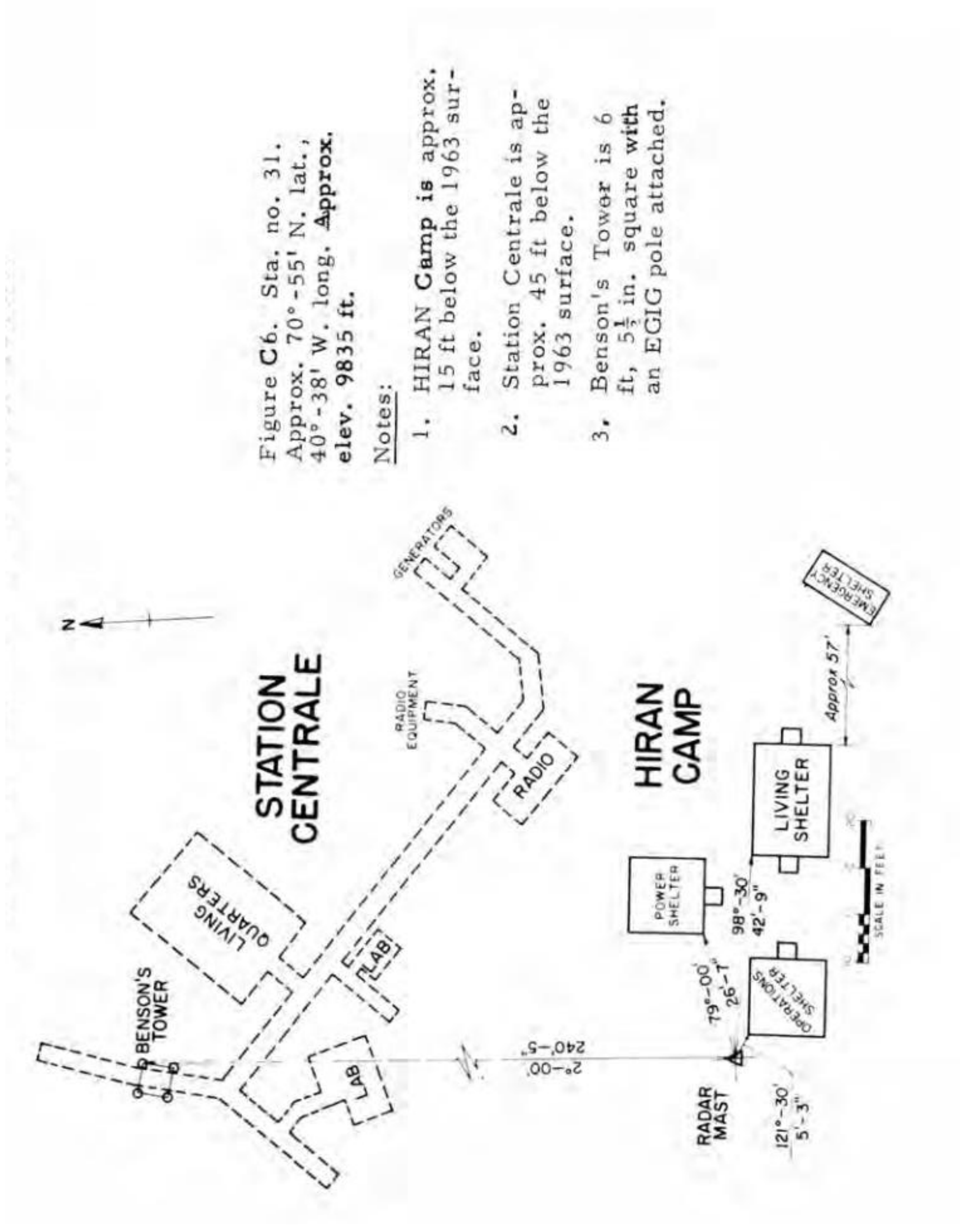

Figure 11: Site layout for HIRAN-31 camp and Station Centrale. Reproduced from Mock, S. J., & Alford, D. L. (1964). Installation of ice movement poles in Greenland. In This Digital Resource was created from scans of the Print Resource [Report]. Cold Regions Research and Engineering Laboratory. https://erdc-library.erdc.dren.mil/jspui/handle/11681/11580

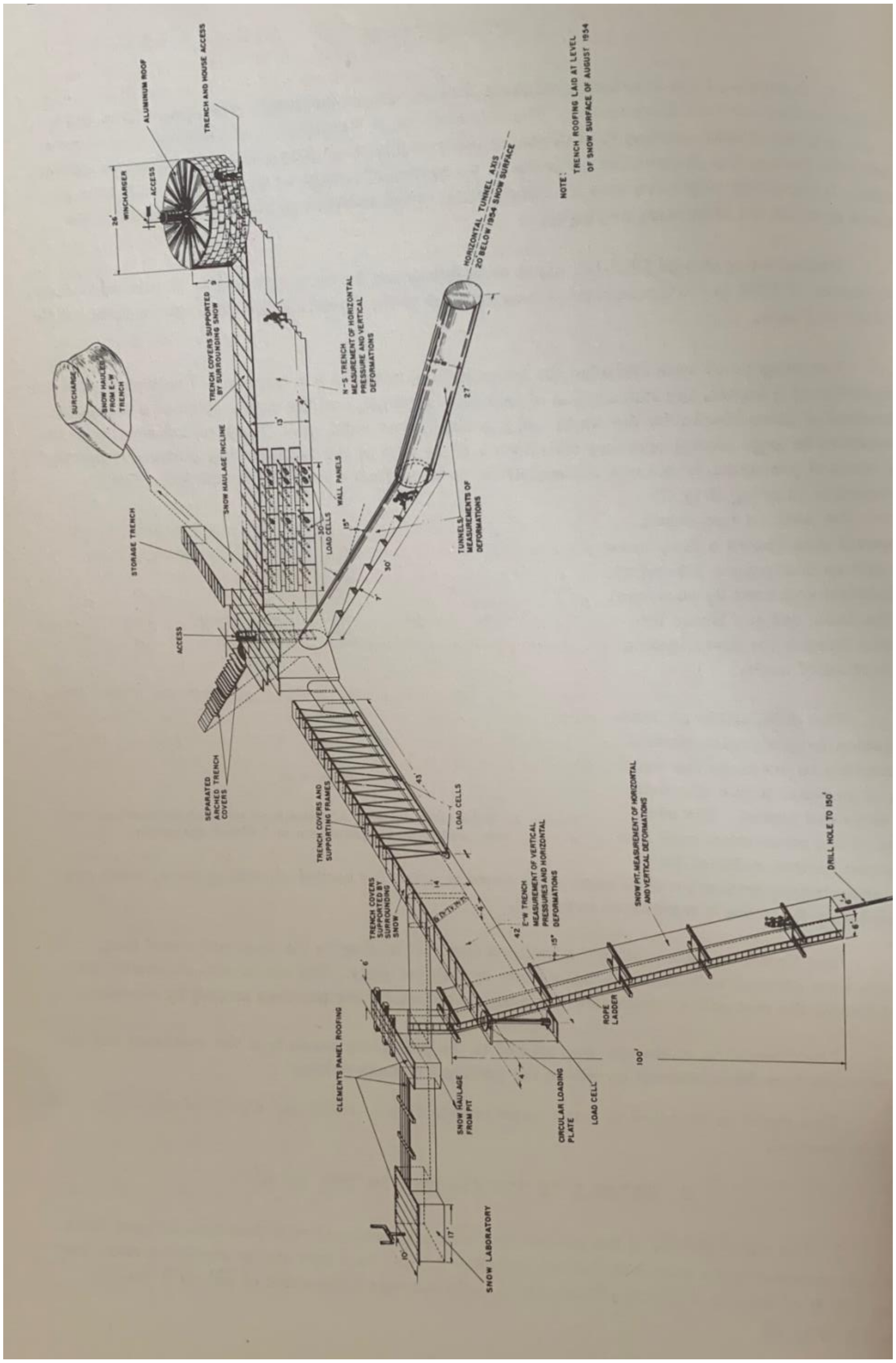

Figure 12: Three-dimensional layout of subsurface ice construction at Site II. Reproduced from Waterhouse, R. W. (1955). Structures for snow investigations on the Greenland Ice Cap. Snow, Ice and Permafrost Research Establishment, Corps of Engineers, U.S. Army. Accessed at Crary Science Library at McMurdo Station, Antarctica.

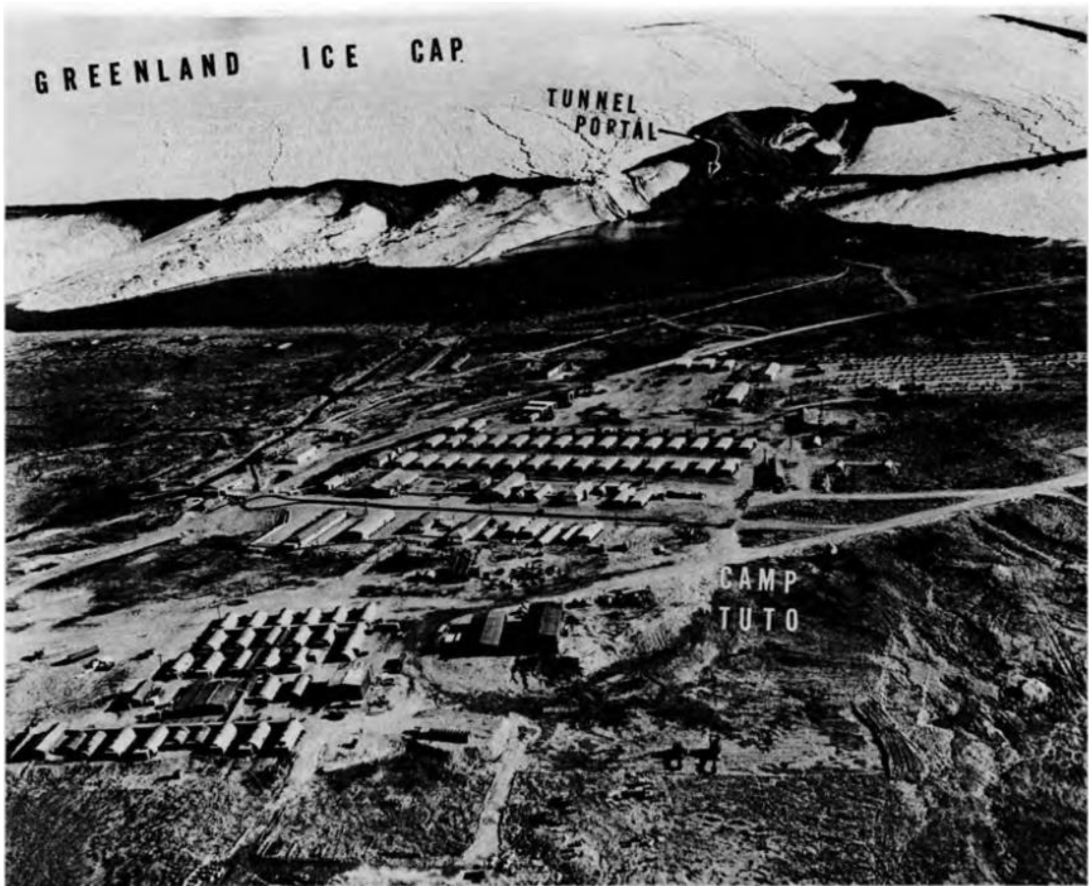

Figure 13: Aerial view of Camp Tuto, Lake Tuto, access road, and portal of ice tunnel. Greenland Ice Cap in background. (Original caption) Reproduced from Russell, F. L. (1961).

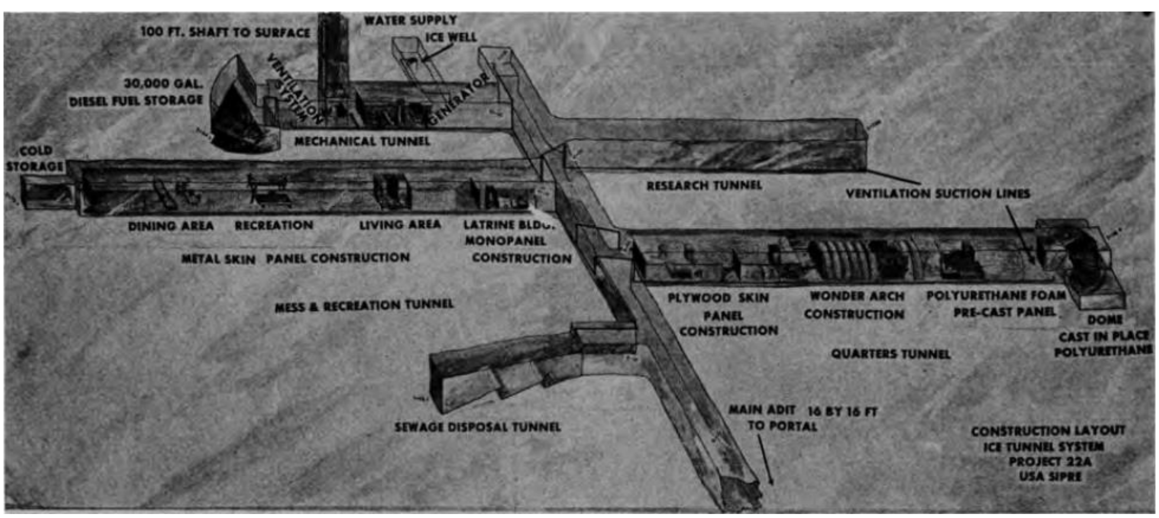

Figure 14: Isometric view of tunnel complex showing location of structures and utilities (Original caption). Reproduced from Russell, F. L. (1961).

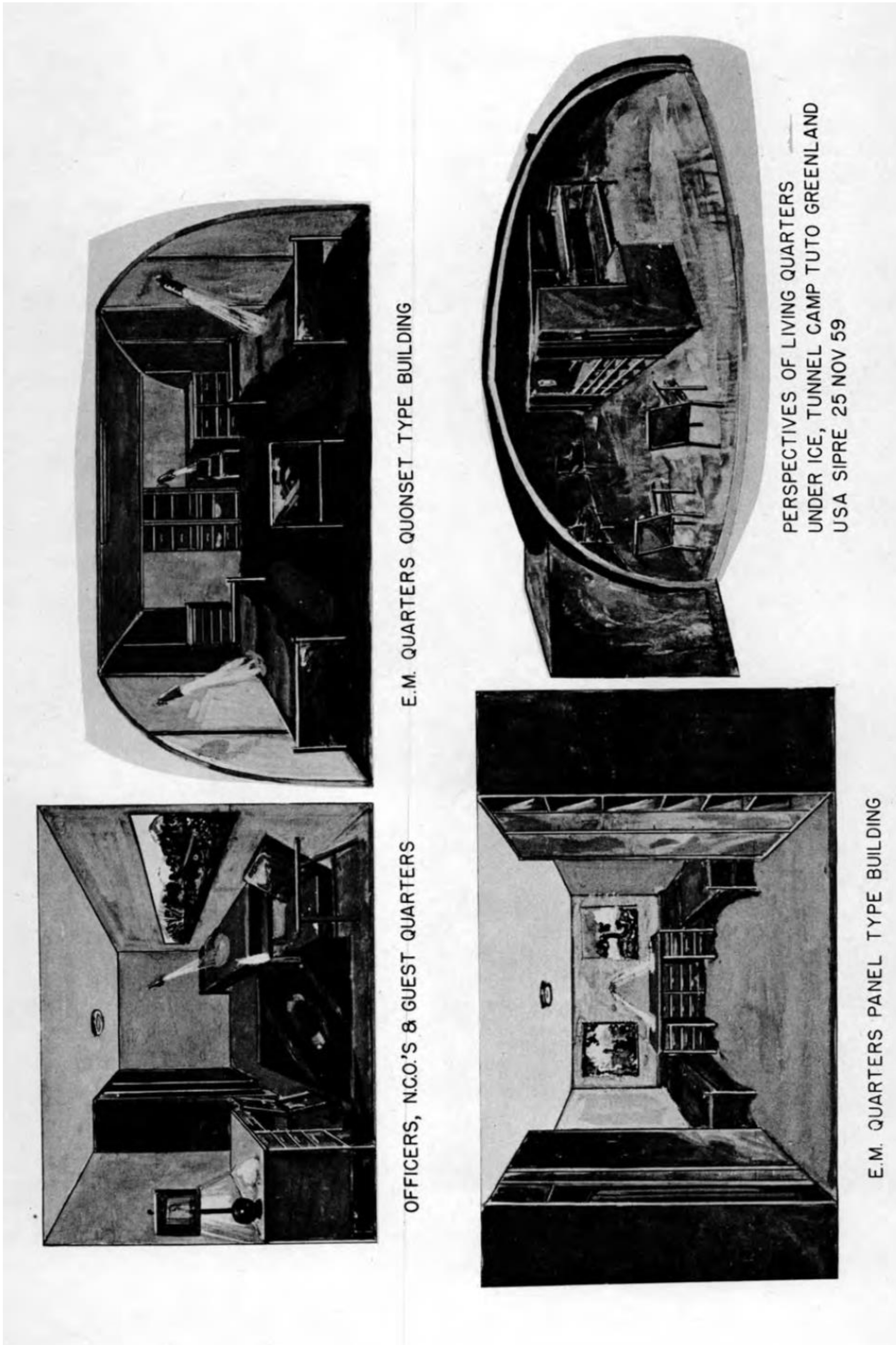

Figure 15: Architectural sketches of dormitory rooms in the various structures (Original caption). Reproduced from Russell, F. L. (1961).

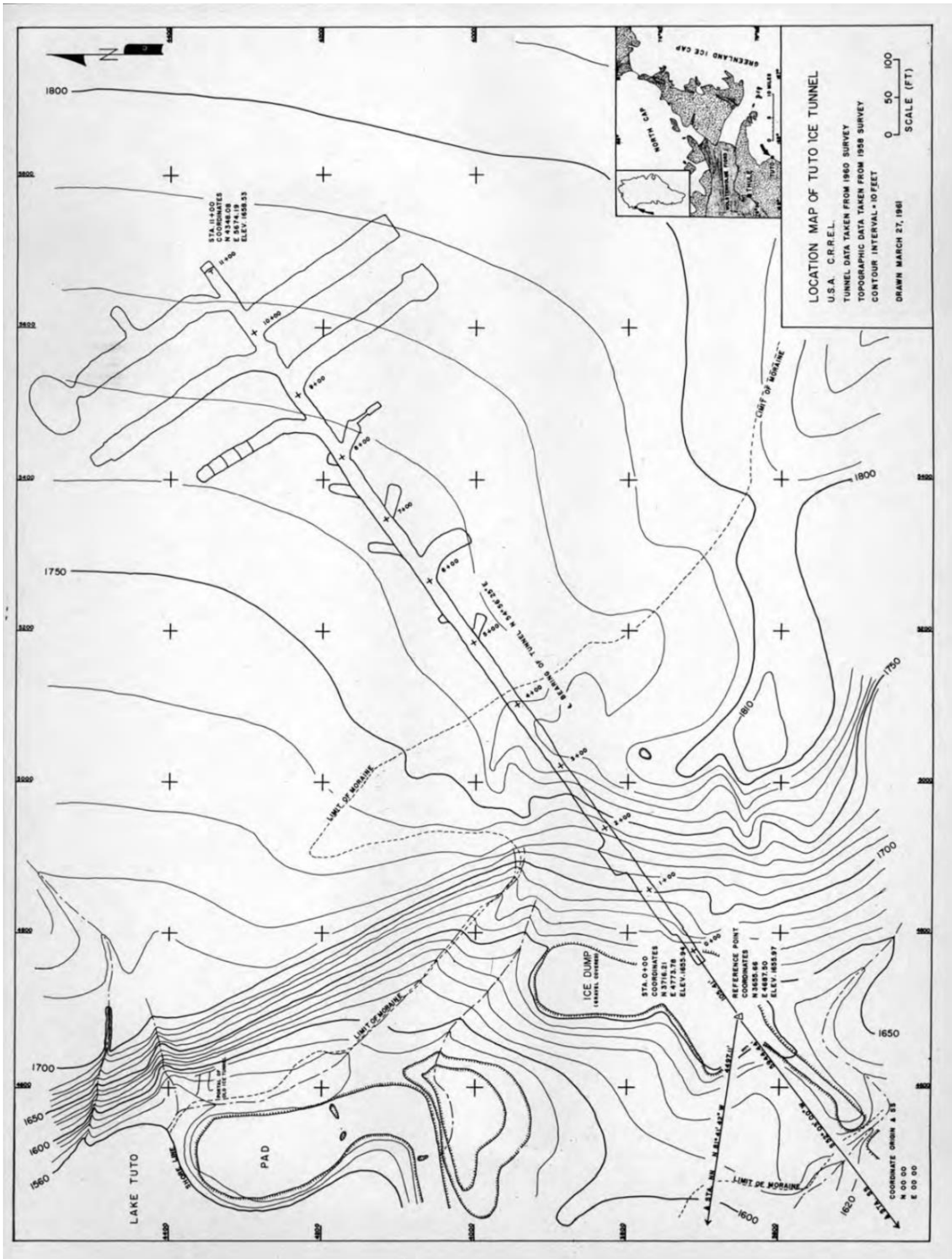

Figure 16: Location map of Camp Tuto Ice Tunnel. Reproduced from Russell, F. L. (1961).

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