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Quantifying Permafrost Extent, Condition, and Degradation at Eielson Air Force Base

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QUANTIFYING AND MONITORING PERMAFROST EXTENT, CONDITION, AND DEGRADATION AT EIELSON AIR FORCE BASE

THESIS

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THESIS

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Abstract

The DoD is executing over $500M in military construction on Eielson Air Force Base (AFB) within the next three years. This construction program will expand the footprint of facilities and change parts of the storm water management scheme, which may have second order effects on the underlying permafrost layers. These changes in permafrost will drive engineering decision, and help shape the overall strategy for military readiness in the Arctic. Little site-specific knowledge exists on the human caused effects to permafrost at this location. In 2016, the permafrost degradation rates at Eielson AFB were modeled using the Geophysical Institute Permafrost Laboratory (GIPL) 2.1 model and limited available geotechnical and climate data. To further refine an understanding of the permafrost at Eielson AFB and help engineers and commanders make more informed decisions on engineering and operations in the arctic, this project established two long term permafrost monitoring stations. The data generated by these stations are the first of their kind at Eielson AFB and represent the first modern systematic effort in the DoD to quantify permafrost condition before, during, and after construction activities. The data collected during this study indicates that there are permafrost losses occurring at this research site and the increased construction activities associated with the F-35 bed down are the likely cause of permafrost degradation.

Acknowledgments

I would like to thank my faculty advisor Major Steven J Schuldt for helping me overcome some of the unique challenges associated with the writing of this thesis. I truly appreciate your mentorship and guidance through this process. I would also like to thank the GEM faculty and my committee membership for their willingness and enthusiasm to help complete this undertaking. To my previous commanders, thank you for encouraging me to come to AFIT, complete my Master's Degree, and continue to grow as an officer. To my family, friends, and classmates, thank you for your continued love and support throughout this journey. I would also like to thank Capt Chris Edlund and Capt Alex Graboski for paving the road on which I now walk. Lastly, I would like to extend special gratitude to Kevin Bjella, Stephanie Saari, Zak Little, Jon Maakstad, CRREL, the 354 Civil Engineer Squadron Engineer Assistants, and all who braved the mosquitos with me to collect the data that made this thesis possible.

Ted Labedz

"I believe that in the future, whoever holds Alaska will hold the world."

- Brigadier General William "Billy Mitchell", 1935

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QUANTIFYING AND MONITORING PERMAFROST EXTENT, CONDITION, AND DEGRADATION AT EIELSON AIR FORCE BASE

I. Introduction

1.1 Background

The effects of the changing climate are being felt globally; however, the magnitude of these changes is greatly accelerated in the Earth's Polar Regions. With longer Arctic Summers and decreased Arctic Ocean sea ice pack, competition for control of this newly contested region and its resources is intensifying. The United States and our allies' interests in Arctic security are primarily focused on the state of Alaska, its surrounding waters, and the other nations vying for control of this newly navigable region. As a part of this surge in strategic focus on Alaska, the United States Air Force is spending over $500 million to bed down F-35s at Eielson Air Force base in addition to the F-22s bedded down and Joint Base Elmendorf Richardson. Furthermore, the Air Force is exploring investment at other arctic facilities. As the region warms, scientists are observing a degradation of permafrost soils which significantly reduces their load bearing capacity and stability. With this region's physical changes accompanying the United States' massive investment in Arctic infrastructure, it behooves the Air Force to study these changes to protect our built infrastructure, improve future investments, and understand any impact on our strategic goals for the Arctic.

1.2 Problem to be Investigated

Discontinuous permafrost is present on Eielson AFB and it presents a unique and expensive engineering challenge when developing infrastructure in the presence of these soils. The current engineering solution is to simply excavate the soil and replace it with more suitable building materials. However, the cost of the excavation is high and the excavated soil is often contaminated and requires additional expenditure to transport it to a hazardous waste disposal facility once disturbed. To better understand the implications of military construction activities on permafrost, specifically the expansion of Eielson Air Force Base along the south loop, I will investigate changes to the permafrost using a control point and an experimental point likely to be impacted by the construction activities. Additionally, the experimental point is located near a slough that will carry significant extra runoff from the newly impervious surfaces constructed in support of the F-35. This effect on the permafrost is unknown at this time; however, I hypothesize that the additional heat input into the ground via construction activity and storm water runoff will accelerate the warming already occurring due to climate or result in permanent thawing of the permafrost.

Given the changes that will be occurring on Eielson, the primary subject of inquiry is if in fact the construction activities on Eielson Air Force Base are effecting the behavior and thermal characteristics of the permafrost. I will compare the data from Station One (the bore hole close to the construction activities) with 2 (the bore hole much further away acting as a control point). Given the magnitude of investment occurring on Eielson, it would be prudent to expand the limited knowledge we have on how this build up will affect the permafrost long-term. This research will establish a baseline of permafrost condition prior to construction activities and determine if there is degradation. Furthermore, if degradation is observed that data can be used to inform engineers on the expected degradation rate associated with construction activities in the presence of discontinuous permafrost. In addition to the data collected from two bore holes, a weather station will be used to collect climatological data. By controlling for climate, the impact of thermal input from the construction activities is isolated as the unknown factor contributing to permafrost behavior. Since the “experimental’ borehole is near a slough that will be used for runoff discharge, thermal input via runoff may be an additional factor to consider at this site. This comparison between the two stations with as many factors controlled as possible in a natural system, should reveal if the construction activities in fact are effecting the permafrost.

1.3 Justification for Research

During the Arctic Science and Technology Symposium at the Cold Regions Research and Engineering lab in May 2018, Lieutenant General Reynolds Hoover, the Deputy Commander of United States Northern Command, delivered opening remarks highlighting the importance of the Arctic in the United States National Security Strategy. He outlined NORTHCOM’s four priorities for the Arctic: Domain Awareness, Communication, Presence, and Infrastructure. This research will increase the domain awareness by understanding the permafrost environment on which we construct and maintain our Arctic Installations. Also, in order for people and infrastructure to be present in the Arctic, permafrost must be understood and overcome using the appropriate engineering techniques. Lastly, the priority of infrastructure demands that we build, reinvest, and upgrade supporting infrastructure informed by the knowledge of how permafrost responds to construction activity.

The purpose of this inquiry is to observe discontinuous permafrost behavior changes when subjected to construction activities. Specifically, if there are any quantifiable changes between Station One and Station Two that can be associated with construction on Eielson Air Force Base. Capt Chris Edlund’s research initiative installed the initial permafrost monitoring equipment during the summer of 2017 to begin collecting data on these permafrost samples and thesis will refine this effort by observing the long term trends and potential changes to permafrost occurring at this location.

1.4 Assumptions

Current models are limited by several assumptions about permafrost behavior. My research and this thesis will collect field data which to validate or nullify their predictions. The comparison between the model and the field data will show if these were good assumptions or if they were an oversimplification of far more complex interactions. The two borehole sites we selected on Eielson are representative of the discontinuous permafrost on this installation. It is assumed that the soil in both of these locations is of similar composition and that any differences between them would be negligible. It is also assumed that the climatological effects of the permafrost can be accurately captured by our localized weather station and that any other differences in the behavior of the active layer could be attributable to either changing hydrology or increased heat transfer from facilities into the ground.

1.5 Scope

I will only be studying the permafrost on the South Loop of Eielson Air Force Base. Specifically, I'll be looking to understand the effects of construction activities on permafrost for Eielson Air Force base. The weather station I installed should serve as a means to account for the climatological degradation of the permafrost, but this is not a climate study. The focus of this study is to observe and changes to the permafrost due to the influence of construction activity or the associated storm water discharge.

1.6 Standards

The techniques used to monitor these boreholes are similar in practice to those used by the Cold Regions Research and Engineering Lab as well as the University of Alaska at Fairbanks. Additionally, the weather station, thermistor strings, and data loggers are configured to meet the manufacturers' recommendations. The Electrical Resistivity Tomography scans as well as frost probes were also conducted under the supervision of the Cold Regions Research and Engineering Lab (CRREL) who are subject matter experts on the standards associated with permafrost monitoring.

1.7 Methodology

The first step of this study will be to conduct an extensive literature review on permafrost degradation and explore the techniques utilized by researchers in order to monitor these changes. Secondly, I will modify and improve existing permafrost monitoring equipment, specifically the data logger and weather station. These will be used to collect data observing the behavior and thermal characteristics of the permafrost during the freeze and thaw cycles. Additionally, I will conduct two ERT scans as well as frost probes to compare the, with the baseline established in 2017. Using this baseline, I will then measure any changes that are occurring to the permafrost and try and isolate the source of the changes. I can then analyze this data for tends to inform engineers about how the permafrost is reacting to these changes. Lastly the installation of remote monitoring makes it possible to execute future data analysis should it be needed.

1.8 Research Questions

In order to focus this research to the problems at hand I will explore if the construction activities on Eielson AFB demonstrate any kind of relationship to permafrost degradation. If so, what time scale or rate is this degradation occurring at and does this align with the predictions from previous models? Should the model predictions and the data observed in the field diverge, what underlying assumptions need to be changed or what additional influencing variables need to be included in order to have increased fidelity on permafrost behavior due to construction activities?

II. Literature Review

2.1 Introduction

Global climate change has environmental, geopolitical, economic, and military implications for the United States and our allies, as well as our adversaries. The effects of climate change are global, but the magnitude of these changes has proved most dramatic in the Earth's Polar Regions [1]. While this may seem counterintuitive given the level of media coverage devoted to events such as the destruction of Tyndall Air Force base by a major hurricane on the Gulf of Mexico, the fact remains that the largest changes in climate trends are in the high Arctic and Antarctic. While violent, abrupt climate events such as hurricanes present a major vulnerability to the United States Air Force, the slow changes experienced by military installations at high latitudes merit thorough investigation so military leaders can shape our strategy in manner informed by scientific inquiry [29].

2.2 Strategic Context of the Arctic and Alaska

The Arctic's remoteness and low population density doesn't diminish it's strategic importance [29]. However, growing concerns over territorial claims in the Arctic Ocean, the opening up of new maritime shipping lanes, and environmental concerns are spurring interest in understanding the implications of the changing Arctic on the Department of Defense. For example, Under Secretary of Defense for Acquisition, Technology and Logistics recently stated in a formal memo to inquiring members of Congress that "Climate and other environmental effects are a national security issue and we are taking action with the components to enhance infrastructure resiliency by addressing identified vulnerabilities in each facility project [27] " Furthermore, 44 members of the House of

Representatives directed Secretary Mattis to "…assess the top ten military installations likely to be affected by climate change over the next 20 years and specific mitigations that may be necessary to ensure the continued operational viability and resiliency of the identified installations. [28]" This growing concern is resulting in increased investment in Arctic defense, specifically in the State of Alaska.

American interest in Arctic security is a relatively recent phenomenon. Alaska was admitted as the 49th state in the Union in 1959 and was a critical node of the American defense strategy from the end of the Second World War until the collapse of the Soviet Union. During that time, the expansion of communism and the Cold War between the United States and modern day Russian was an existential threat to the United States. Therefore, significant time and investment went into understanding the unique engineering challenges of construction and operations at high latitudes. While the United States has interests in the Arctic, it is not an Arctic Nation such as Canada, Russia, or the Scandinavian nations. This fact, coupled with the recent conflicts in Iraq and Afghanistan, resulted in a lapse in focus from Arctic security during the past two decades. As we refocus from counterterrorism and nation-building operations in warmer climates, there is once again renewed interest in Arctic security. Divisive, unresolved territorial claims, unpatrolled shipping lanes, as well as newly accessible, abundant natural resourses demand reinvestment in both Alaska and the arctic writ-large. While Arctic security has not been a top U.S. strategic priority since the end of the Cold War, some of our adversaries with Artic interests have not faltered in their resolve on matters of operating, securing, and building in the far North. In light of these disputes, the U.S.

interest in the Artic is comprised of two main elements: securing U.S. interests at extreme northern latitudes as well as understanding and protecting the changing global climate.

As a part of the surge in strategic focus on Alaska, the U.S. Air Force is spending over $500 million to bed down F-35s at Eielson Air Force base in addition to the F-22s already operating at Joint Base Elmendorf Richardson. This is a major step in securing the far North through the use of fifth generation fighters. However, building at far Northern latitudes requires overcoming unique engineering challenges. Specifically, these new facilities on Eielson Air Force base are being constructed and will exist on permanently frozen soils known as permafrost. The unique properties of permafrost, and specifically the ice it contains, is an emerging body of knowledge that is growing with our national interest in the Arctic [8]. This thesis weeks to better understand permafrost as an engineering problem and environmental concern in accordance with our national interests in the Arctic. Improved resolution of the behavior of permafrost with respect to how it affects our power projection platforms in the Arctic will lead to improved facility design and environmental stewardship. This chapter serves as a comprehensive review of literature investigating the body of knowledge utilized by major global institutions to study permafrost behavior as it interacts with an increasingly warm climate and increased human activity.

2.3 Permafrost Nomenclature

Permafrost is soil that remains at or below zero degrees Celsius for two or more years [1]. Most permafrost on earth is tens of thousands of years old [31, 35]. In fact, the U.S. Army Corps of Engineers permafrost research tunnel near Fox, Alaska has permafrost so old that mammoth bones deposited at the time of the permafrost's formation can be seen protruding the walls. The volume of permafrost is massive, as frozen soil underlays approximately twenty percent of the Earth's landmass [1]. Although frozen, the properties of the permafrost beneath the surface are not uniform, and there are anatomically specific attributes that must be understood in order to describe the behavior of permafrost. First, the permafrost can be divided into two primary sections: the active layer and the inactive layer. The active layer is shallow section of soil that seasonally freezes and thaws due to the influence of warm summers and cold winters [1]. Active layer depth depends on several variables, to include soil composition, vegetation, shade, and mean annual air temperature, but it typically varies from centimeters to a meter or two [1,3]. Beneath the active layer is the depth of zero amplitude where the summer thaw and the winter freeze no longer affect the temperature of the permafrost. This point demarcates the active layer from the inactive layer of permafrost [1]. At this point, the soil will warm at a thermal gradient as the soil increases in depth until the soil once again rises above zero degrees Celsius, which is at the base of the permafrost [1]. Graphical representations of these basic thermal properties that constitute permafrost soils are illustrated in Figure 2.1. Additionally, an example of the application of this nomenclature to a sample of field data from a borehole site near the University of Alaska Fairbanks is depicted in shown in Figure 2.2.

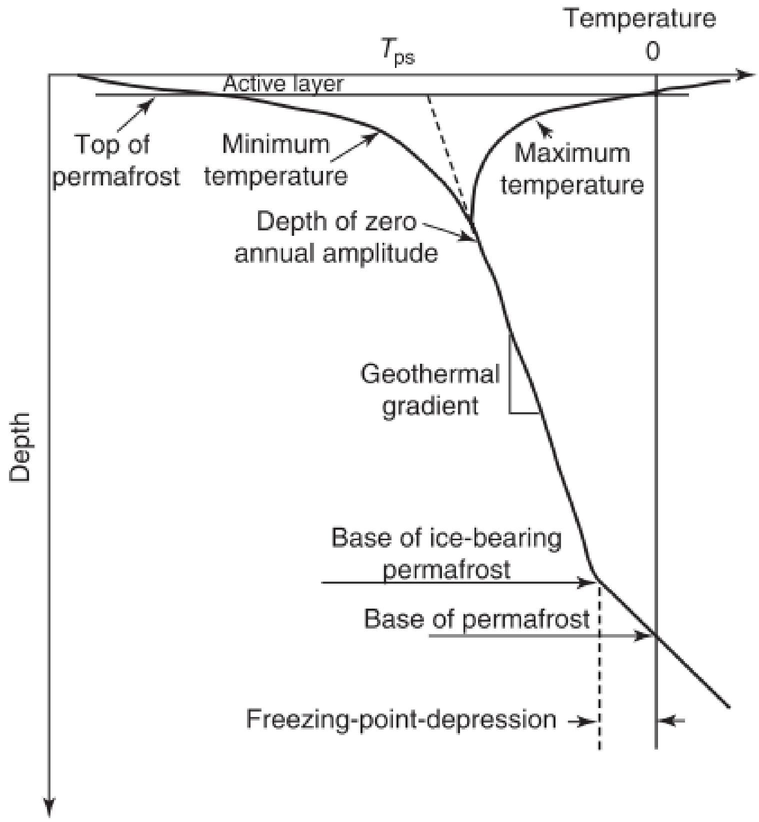

Figure 2.1: Basic Thermal Properties and Characteristics of Permafrost [1]

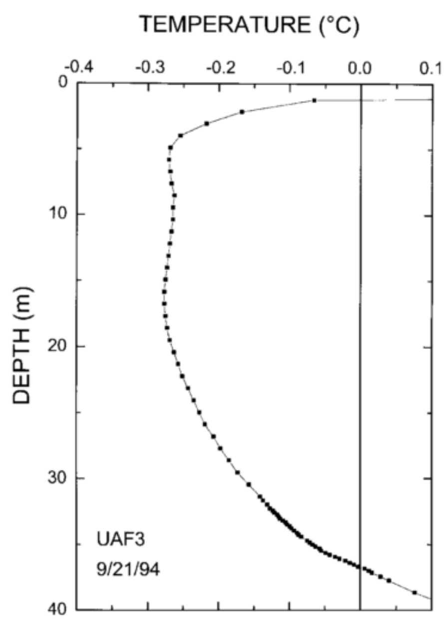

Figure 2.2: Example of Permafrost Temperature Variance with Depth [3]

While there are deep boreholes that monitor thermal behaviors in the inactive layer, the primary focus of permafrost study is on the active layer [3]. This near surface section is not only the most readily observable, but also the most vulnerable to the effects of climate change and human activity [3].

Permafrost also varies by the amount of ice it contains. Ice-Rich permafrost soils contain more water than they would in their non-frozen, saturated state [8]. The presence of more water than its saturated state is possible since the soil is fused by the crystalline structure of the ice [3]. Therefore, as additional water is deposited through precipitation or ground-flow, additional ice formations such as ice wedges form over centuries or millennia [16]. Ice-rich soils are particularly prevalent in areas where soils have large amounts of voids relative to their volume, such as prehistoric riverbeds. Sands and gravels often reflect these traits compared to silts, organics, or bedrock. As these voids fill with water through natural processes the soil accumulates far more water mass in the form of ice than it would otherwise in its thawed state [7]. The permafrost soils of the Tanana river basin near Eielson Air Force Base are ice-rich permafrost formations within the discontinuous zone as depicted in Figure 4.3 [30].

The formation of ice-rich permafrost is often discontinuous in central Alaska; furthermore, the characteristics of discontinuous permafrost can vary enormously over the course of only a few meters [35]. While there are a myriad of subterranean ice features found globally, the two most widely distributed and problematic for both scientists and engineers in interior Alaska are ice wedges (often called thermokarsts). When geologists and engineers refer to ‘ice-rich’ soils it is often because of the presence of these two features. Ice lenses are typically formed at the freezing face, which varies depending on the time of the year, the frost depth, and the depth of the active layer. These lenses are formed due to capillary action toward the freezing face [20]. Depending on season, capillary action can be toward colder ambient winter temperatures or downward toward the ice in the inactive layer [35]. This results in the formation of lenses of ice at variable and unpredictable depths throughout the soil column [35]. Ice lenses are famous for producing frost heaves, disastrous for pavements and foundations.

The second, and most dramatic, subterranean ice feature found in permafrost regions are called ice wedges. The best way to visualize the formation of these wedges is to imagine how freeze thaw cycles crack concrete. As water enters the voids, it freezes, expands, and creates additional voids that can be filled with additional water and ice. This same process happens on permafrost, but on a timescale of thousands of years. As these wedges migrate downward into the eather, they correspondingly increase in width [20, 35]. These formations can vary from millimeters to meters, as were witnessed during a site visit to the CRREL Permafrost Research tunnel in Figure 2.3. As these wedges form and grow they produce a polygonal shape to the overlaying landscape, which is indicative of the permafrost and ice wedges beneath. As the active layer of the permafrost warms and subsequently deepens, the top of the ice wedges melt and cause a depression in tundra when the melted ice drains [1]. This exacerbates the appearance of the polygonal or thermokarst terrain features [1]. The ice wedge behind Captain Labedz in Figure 2.3 is estimated to be approximately 33,000 years old. While remarkable, these formations and 'ice-rich' permafrost and are of increased concern for engineers because when they melt, the ice that was providing the bearing capacity in the soil column loses its crystalline structure resulting in a loss of load bearing capacity, settling, and terrain destabilization [1, 3, 33].

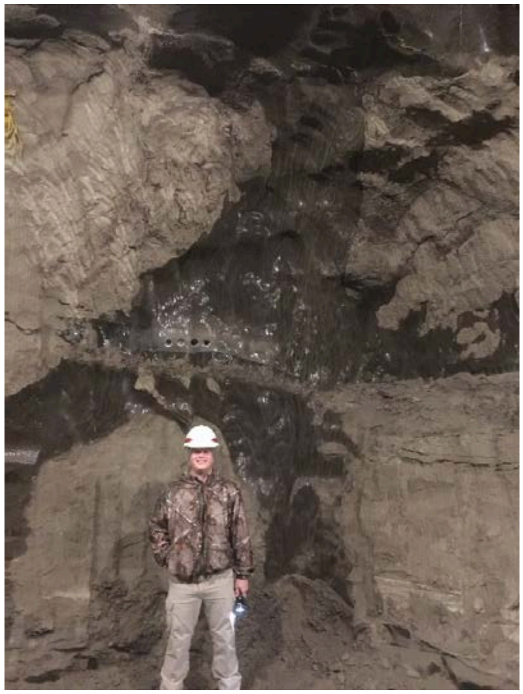

Figure 2.3: Ted Labedz Pictured with Ice Wedge at CRREL Tunnel near Fox, AK

Permafrost is present beneath approximately one fifth of the earth's landmass at the extreme northern and southern latitudes, and ambient atmospheric temperature is the causal factor. In order to maintain or form permafrost, there must be a mean annual air temperature (MAAT) of at least -8 degrees Celsius for continuous permafrost and -5 for discontinuous permafrost [3]. However, annual variations above and below that number as well as the presence of microclimates due to geographic variation result in a more discontinuous distribution of permafrost [1]. Once permafrost has fully thawed in discontinuous regions, it cannot be regenerated due to the difference in MAAT [9]. For example, there is a strong inversion in the Fairbanks, Alaska area where there can be double digit temperature differences within only a few miles [36]. There are several other strong inversions in interior Alaska, which is why microclimate monitoring and data needs to be incorporated into permafrost models as it can play a significant role in the thermal exchange of a given sample of permafrost [36].

Although permafrost is present in the circumpolar regions, I focus on permafrost in central Alaska as the military implications to permafrost changes in this reason affect infrastructure critical to maintaining U.S. national security interests. There are worldwide initiatives to better understand permafrost and its interaction with climate science; however, the primary focus will be on studying the discontinuous permafrost on or near Eielson AFB within the state of Alaska [4]. Figure 2.4 shows the distribution of permafrost across the state of Alaska. This map illustrates how Eielson AFB is located in the discontinuous region of central Alaska, which is highly effected by microclimates and inversions around the threshold of -5 to -8 degrees Celsius MAAT. This publication from the U.S. Geological Survey shows how permafrost is distributed across Alaska. It varies from being extremely isolated and sporadic at southern latitudes to discontinuous in this area of research interest. In the extreme north latitudes, primarily on the north side of the Brooks Range, the permafrost is completely continuous [2]. There is a strong correlation between latitude and temperature, which is primarily responsible for the increasing absence of permafrost at more southern regions of the state.

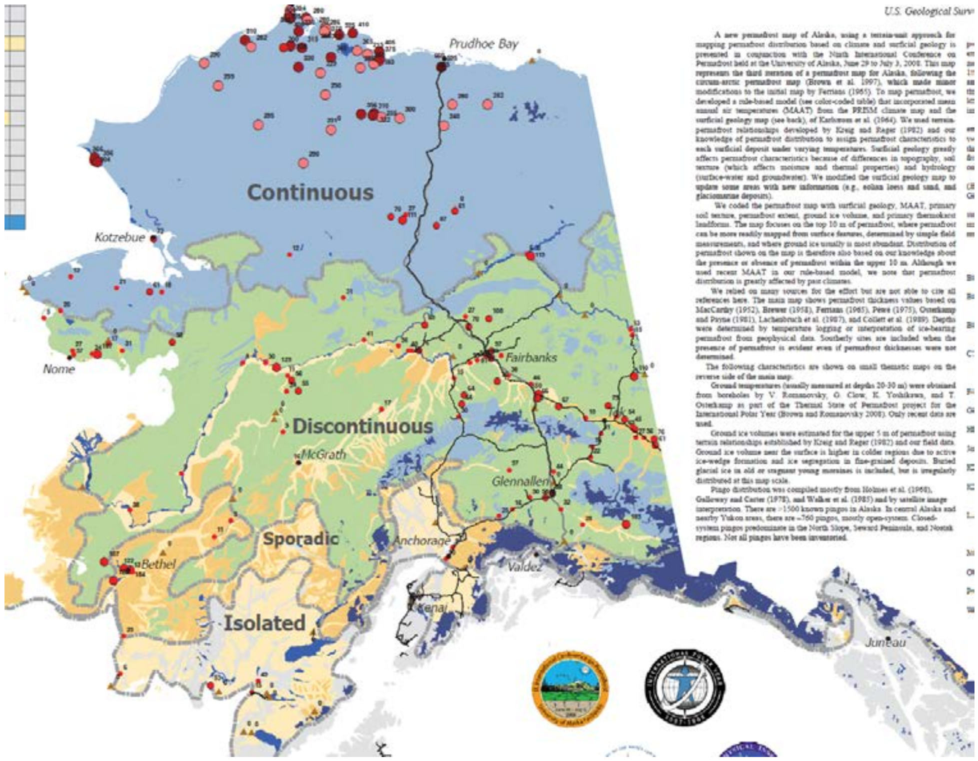

Figure 2.4: Permafrost Distribution Across the State of Alaska [11].

The distribution map in Figure 2.4 was based largely on extrapolating borehole data collected from research sites in the field. Those research sites are represented by the different shapes (mostly red dots) on the figure. With advances in remote sensing and permafrost modeling, the U.S. Geological Survey has improved mapping of permafrost distributions and developed a more probability-based permafrost distribution model, eliminating some of the uncertainty in the extrapolations used in previous research initiatives [11]. An application of this probability based model is depicted in Figure 2.5.

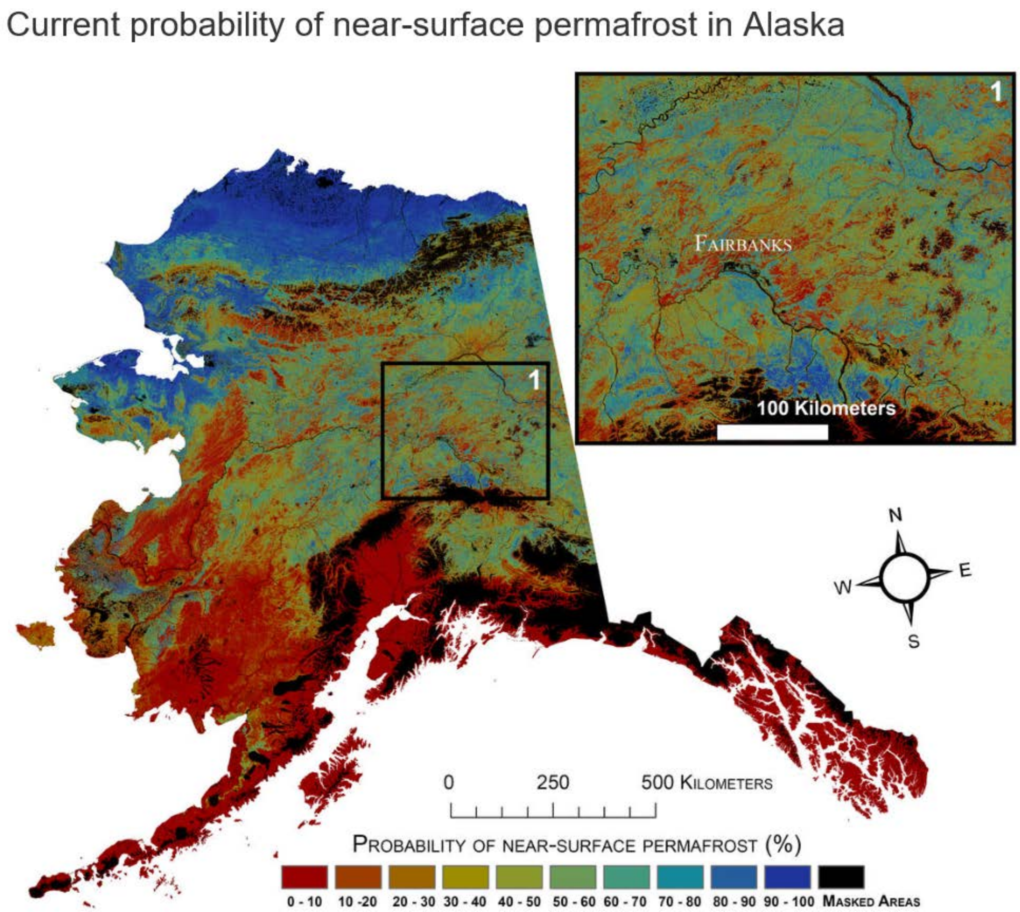

Figure 2.5: USGS Probabilistic Permafrost Distribution Model [11]

2.4 Permafrost Formation

The first permafrost on Earth was formed during the first ice age about 2.3 billion years ago, and its distribution and characteristics have varied in response to repeated ice ages and climate changes spanning Earth’s history [1, 13]. Much of the permafrost present on earth today is relatively ‘young’ by geological standards with most of it having formed to its current depths during the past two ice ages [32]. Forming during the Pleistocene and Wisconsin Ice Ages, much of Alaska’s shows evidence of being 12,000 to 160,000 years old [32]. While there has been natural formations and degradations of permafrost from natural climate changes spanning millennia, mankind’s impact to the permafrost is a recent phenomenon in Earth’s history. At present, there appears to be a positive correlation between industrialized human activity and permafrost degradation rates [7].

Permafrost can be formed in two ways. First, permafrost can be formed by freezing from the surface downward. If sufficiently cold climate is present, which is a MAAT of at least -8 degrees Celsius, there will be enough thermal extraction from the ground for the permafrost to grow downward [3]. This type of permafrost is known as epigenic, as it is formed in-situ [33]. The second type of permafrost formation is when the permafrost is formed as the material is deposited. This can happen in a variety of ways such as river sedimentation, wind-blown material, organic deposition, and any other natural mass transport process [33]. In these cases the permafrost is built upwards as frozen materials accumulate on top of one another [33]. These two processes often occur simultaneously the frozen material is deposited while the base of the permafrost drops deeper into the earth [1, 35]. The permafrost on Eielson AFB is mostly syngeneic as the materials in the area are all part of the ancient meanderings of the Tanana River [30].

2.5 Active Layer Permafrost Behavior

The active layer of the permafrost is the interface between the inactive layer and the atmospheric conditions. Consequently, its properties dictate the heat transfer between the atmosphere and the ground. Understanding this layer of the permafrost is crucial because this is the medium through which heat enters and leaves the deeper layers of permafrost during both the summer and the winter [5]. Water content, with its high specific heat, plays the largest role in permafrost active layer behavior [5]. Ice rich permafrost are more thermally stable since the heat of fusion needs to be overcame in order for the temperature to rise. Additional major factors that effect active layer behavior are local climate, hydrology, topography, and average winter snow cover [6]. Vegetation and its corresponding organics layer also play import roles as shields from the influence of solar radiation and insulating the ice below during the warmer summer months [7]. With the active layer serving as the medium for heat transfer, it experiences the largest temperature fluctuations in the soil column. These temperature fluctuations are often graphically represented as Trumpet Curves such as the one in Figure 2.5. Since the active layer is the heat conduit for the permafrost, changes to the permafrost – both expansion and degradation – are most easily observable at shallow depths in the active layer [7]. An example of how permafrost degradation results in temperature shift and deepening of the active layer is visible in figure 4.6. This shows how as temperature in the active layer increases it is often accompanied by a corresponding deepening of the active layer.

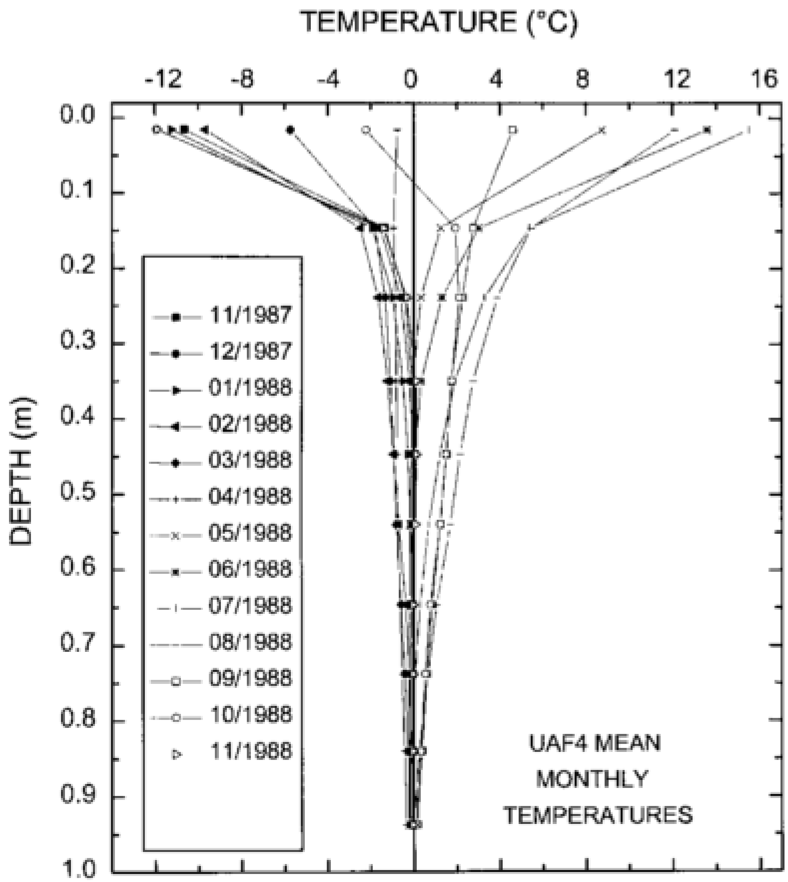

Figure 2.6: A Trumpet Curve for Active Layer Located at UAF's Site 4 Borehole [7].

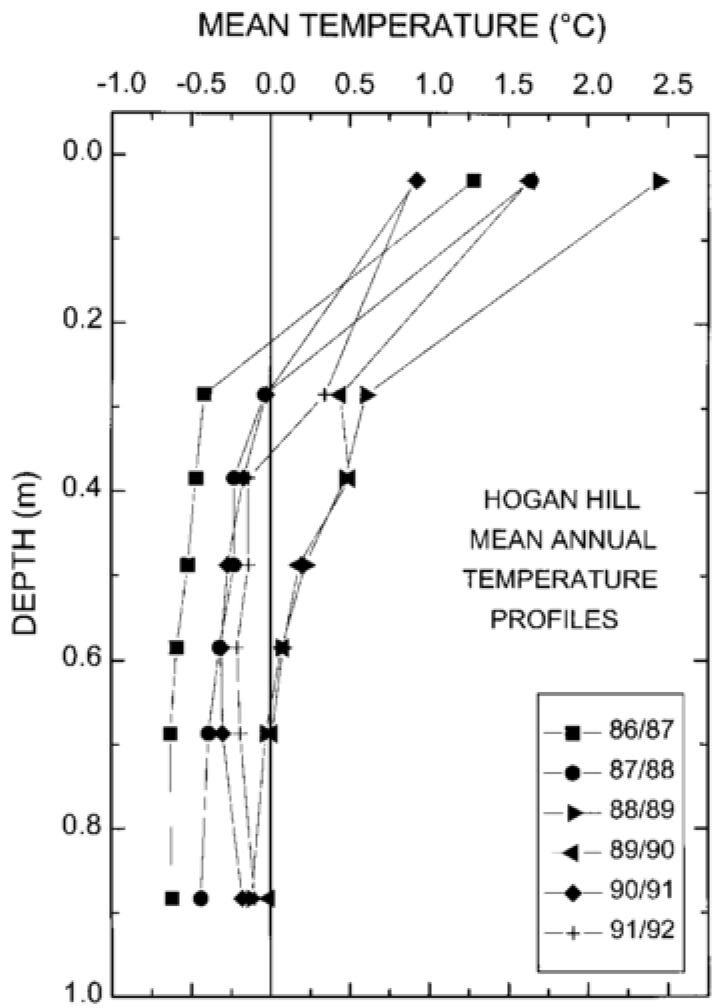

Figure 2.7: Example of Mean Temperature Migration at the Hogan Hill Research Site [7].

2.6 Significance of Research

There are permafrost boreholes located all over the northern cryosphere to include excellent coverage in the state of Alaska [3]. In attempt to provide better resolution on the global state of permafrost, there is a multinational initiative called the Global Terrestrial Network for Permafrost (GTN-P) and the Circumpolar Active Layer Monitoring (CALM) [4]. Despite the coverage throughout the state of Alaska, there is not yet any coverage of permafrost behavior on Air Force Installations in the Alaska. While the focus of this thesis will be to fill the gap in knowledge of permafrost behaviors in on Air Force installations in Alaska – specifically in the discontinuous permafrost zone – this initiative to monitor permafrost behavior is not the first of its kind in Air Force history. When the Air Force was experiencing failure of runway pavements at Thule AB, Greenland, they contracted with the Cold Regions Research and Engineering Lab, or CRREL, to study the behavior of the permafrost at this location [31, 45]. While the inquiry at Thule claims the title of first active monitoring of the permafrost in Air Force History, this inquiry will be the first of its kind on an Air Force base in Alaska, at Eielson Air Force base, and an Air Force Installation in the discontinuous permafrost zone [29, 30, 45]. This instrumentation and subsequent analysis will serve to improve understanding of permafrost behavior on military installations.

Permafrost monitoring in Alaska is not a new initiative, as data collection and modeling of permafrost has been conducted since the 1970's [5, 6]. The birth of this body of research was largely due to the construction of the Dalton Highway and subsequently after the construction of the Trans-Alaska Oil Pipeline [38]. The uniqueness contribution of this research thesis is not the monitoring of the permafrost, but rather the ability to study discontinuous permafrost before, during, and after a major anthropogenic alteration of the landscape [37, 39]. Past theses conducted initial analysis based on models used by the University of Alaska Fairbanks and the Alaska Geophysical Institute [39]. This pursuit is the third in a series of advancements made in furthering permafrost knowledge on Eielson AFB [39]. The first year was primarily analysis of the GIPL 2.1 model conducted by Captain Alex Graboski. The second year was site selection, the baseline Electrical Resistivity Tomography (ERT) ground scans, and the installation of Stations One and Two conducted by Captain Chris Edlund [37]. These will be described in much finer resolution in Chapter 3. This thesis will be using the initial round of data, a second set of ERT scans, and data collected from a weather station to examine any trends in the permafrost and examine the implications of changing groundwater hydrology and drainage discharge on the thermal profile of the ground.

The $550 million project on supporting the F-35 bed down required significant modification to the infrastructure and landscape on the south loop of Eielson Air Force Base. The clearing of ground cover, laying of new payments, excavation of new utlilidors, erection of new heated facilities, and increased stormwater runoff will all affect the energy transfer between the permafrost, surface activities, and the weather patterns [40]. These modifications will subsequently change thermal discharge into the ground through direct heat transfer as well as hydrological functions [6, 18, 20]. Given the expense associated with infrastructure investments in permafrost regions, understanding the permafrost changes as a consequence of human activities provides for more optimal engineering solutions, assists in making more informed risk decisions involving permafrost areas, and improves stewardship of the environment [6].

The current body of research demonstrates that much of the permafrost loss over the next century will be in the discontinuous permafrost zone because it is already much closer to zero degrees Celsius than the continuous zone [8, 39]. This increasingly vulnerable permafrost is collocated with this massive infrastructure investment, so understanding the long-term implications of thawing permafrost constitutes good stewardship of the installation, the mission, and the environment. For example, the permafrost on the North side of the Brooks Range can be as cold as minus 15 degrees

Celsius while permafrost on Eielson AFB can be as “warm” as minus .16 degrees Celsius [37]. Since this permafrost is so close to the freezing point, it is particularly sensitive to changes and thermal inputs [3, 7].

2.7 Permafrost Trends and Thermal Degradation

There is often an oversimplification of the changes occurring in the permafrost, specifically with respect to the terms “melting” and “warming”. Experts from across the globe have come to the general consensus that permafrost temperatures have risen in the last 20-30 years and are likely to continue rising [5-10, 12, 17]. In the continuous permafrost regions of central and northern Alaska, the temperature of the permafrost has risen an average of 2-4 degrees Celsius since record keeping began in the middle of the 20th century [1]. There was then a brief cooling trend in the 1980s followed by continual warming of approximately 3 more degrees to modern time [1]. The overwhelmingly common trend when analyzed over several decades remains to be a warming of the permafrost [7]. Like most trends, there are statistical outliers worth investigating in order to further understand or refute the perceived trend. Perhaps the greatest outlier is the permafrost sites in the Yukon that have slightly cooled. This is likely more correlated to the reduction in snowpack in the region in recent times [1]. Snow cover has insulating properties due to the large amount of void space present within the snowpack [5]. In areas that commonly reach temperatures of minus 40 degrees Celsius during the winter, deep snowpack can actually prevent the permafrost from becoming even colder. Therefore, a series of years or a trend of less snowpack could be highly correlated with a cooling of the permafrost due to the lack of the insulating effect of the snow at extremely cold temperatures [5, 7].

While all permafrost is frozen for at least two years, all permafrost is not equally frozen. Its temperature can vary widely from zero Celsius all the way down to minus 15 Celsius. This disparity has major implications for the manner in which it warms and subsequently melts. When permafrost research started, the use of boreholes and thermistors to measure subterranean temperature was the primary means of monitoring permafrost behavior. This was the widely accepted practice by Romanofski, Ostercamp, Bern, Hoelzle, and Mittaz [4-11]. Based on the warming trends observed from 1980-1996 it was estimated that the permafrost would begin to thaw at a rate of approximately 0.1 meters per year [7]. The grounds for this hypothesis were that since much of the discontinuous permafrost was only within a few degrees of melting that once it reached 0 degrees Celsius that they would begin to see increased thawing and ultimately disappearance of the permafrost [1]. While not overlooked, the difficulty of overcoming the latent heat of fusion in the process of permafrost degradation was underestimated [4-10]. In order for the permafrost to melt, the latent heat of fusion must be completely overcome; otherwise, the temperature will not continue to rise. Despite the trends of warming permafrost, there remains little evidence of significant permafrost loss [10].

As temperatures in permafrost increase to within a few degrees from freezing, the rising temperatures stall as they approach zero Celsius. Additionally, permafrost close to zero was observed to have no significant change in temperature. This trend was consistently observed across Alaska, Canada, and Siberia [8]. This stagnation of temperatures in ice-rich permafrost is likely due to ice needing to absorb the latent heat of fusion prior to complete melting [8].

The prevailing reason temperature was the primary tool for measuring permafrost changes was that it is relatively easy to do and worked well for temperatures below zero degrees Celsius [10]. However, the magnitude of change in the ground is indecipherable in soils where there is a large latent heat of fusion [10]. This is of most concern for warm, ice-rich permafrost regions in the discontinuous zone as those are the most vulnerable to degradation via the effects of climate change [10]. This is the case with the permafrost located on Eielson AFB. Using conventional techniques, it is difficult to observe where in the process of degradation this permafrost lies. It may have just stopped warming or it may be close to shedding the last of its latent heat of fusion and change phase. To complicate matters, the range of energy required to melt ice is the equivalence of raising water 162 degrees. Therefore, temperature as a sole indicator of permafrost health does not reveal where on the energy spectrum a given sample of permafrost exists in its current form. Additionally, soil properties, ice degradation rates, and heat transfer are not linear relationships nor are they consistent cross regionally as the properties of the soil can change depending on several input factors, namely volumetric water content [5]. Figure 2.8 demonstrates how these properties can vary.

Table 1. Thermal properties of the active layer and near-surface permafrost estimated from the model calibration

Depth (m)	Soil type	Volumetric water content θ (%)	Thermal conductivity K_t/K_f (W m^{-1} K^{-1})	Volumetric heat capacity C_t/C_f (MJ m^{-3} K^{-1})	Volumetric unfrozen water θ_u (%)
Barrow					
0.0–0.2	Peat	65	0.6/1.4	3.0/1.5	$2.6[T]^{-0.38}$
0.2–0.3	Silt	55	0.96/2.1	3.1/1.5	$12[T]^{-0.5}$
0.3–1.0	Silt	55	0.96/2.1	3.1/1.5	$6.4[T]^{-0.38}$
Bonanza Creek					
0.0–0.12	Living moss	5	0.1/0.13	1.7/1.5	$0.1[T]^{-0.1}$
0.12–0.35	Dead moss	3	0.3/0.71	1.7/1.6	$0.2[T]^{-0.1}$
0.35–1.25	Peat	65	0.5/1.70	2.6/2.4	$3.2[T]^{-0.38}$
1.25–6.0	Silt	45	0.9/2.20	2.9/2.0	$6[T]^{-0.35}$
University Farm					
0.0–0.24	Peaty silt	12	0.8/1.4	1.5/1.3	$2.2[T]^{-0.1}$
0.24–0.6	Silt	25	1.1/1.9	1.9/1.5	$3.6[T]^{-0.3}$
0.6–0.9	Silt	25	1.1/1.9	1.9/1.5	$3.6[T]^{-0.3}$
0.9–17.0	Silt	45	1.3/2.2	2.9/2.0	$3.6[T]^{-0.3}$

Figure 2.8: Thermal Properties Change Depending on Soil Composition [5].

2.8 History of Permafrost Construction and Research

Permafrost construction considerations were in their infancy as early as the 1800s as the Hudson Bay Company built primitive infrastructure along Hudson's Bay [1]. However, it was not until the construction of the Alaska-Canada Highway during the Second World War and later the construction of the Trans-Alaskan Oil Pipeline during the 1970s that more sophisticated Arctic-engineering techniques were born [42, 43]. The frost heave phenomenon and loss of soil bearing capacity due to melted permafrost required engineers to develop techniques that prevented or mitigated the heat transfer from their facilities into the permafrost. As facilities are heated, as is the case with buildings, some of that heat will inevitably be transferred into the ground which will in turn warm the permafrost and eventually overwhelm the heat of fusion, causing the permafrost to melt. Similar problems are encountered with pavements when the organic layers are removed and a much more thermally conductive pavement is overlain. The pavement will absorb the sun's energy and transfer it directly into the ground. This causes pavement failures due to a loss of the bearing capacity of the underlying soil.

The construction of the runway at Thule Air Base, Greenland during the 1950s is an example of a major engineering hurdle encountered by Air Force engineers building on permafrost. Despite the very cold continuous permafrost of minus 11 degrees Celsius, the presence of ice wedges beneath the pavement caused significant problems [45]. As the sun heated the pavement on the runway, the heat transferred to the ice wedges, resulting in differential settling. This caused significant repair costs and inoperability of this strategic hub during the Cold War [45]. The initial solution was to paint the runway white in order to reflect the solar energy, but this proved time to be expensive, labor intensive, and dangerous due to the loss of friction on the pavement [45]. In order to find a better solution, CRREL developed a method of using insulated panels beneath the pavement to prevent the destructive heat transfer. This technique is now widely used to prevent the premature degradation of pavements overlaying permafrost.

The largest oil reserves in the United States are found in the oil rich region of Northern Alaska called Prudhoe Bay [42]. In order to extract these reserves, oil companies and the State of Alaska launched large infrastructure projects in this ice-rich permafrost environment. Since their construction, scientists and oil companies alike have observed localized thermocarsting in addition to lakeshore and coastal erosion. Both of these observations are indicators of permafrost warming and degradation. The difficulty in analysis becomes separating the effects of local industrialized activities from the regional permafrost warming trend. Despite these difficulties, studies show that greatest negative impact to the permafrost at Prudhoe Bay is due to changing the natural hydrological flow in this ecosystem. Figure 2.9 shows how the construction of piping, roads, culverts, and facilities all leave lasting effects on the permafrost. The second order effect of changing hydrology and flooding in fact creates the greatest amount of damage to the permafrost at Prudhoe Bay [42].

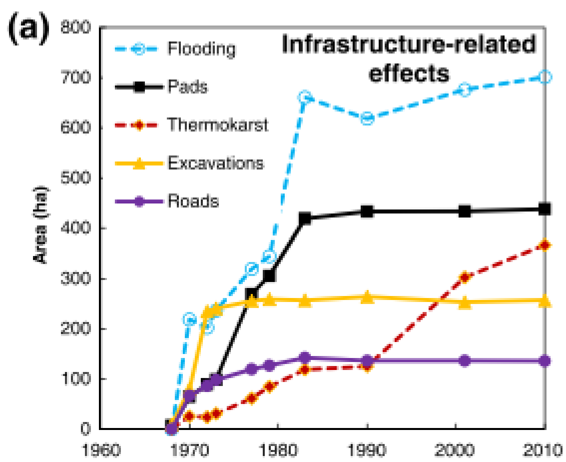

Figure 2.9: Infrastructure Development-Related Effects on Permafrost [42]

The Alaska Pipeline was constructed to transport the crude oil from the North Slope of Alaska to Valdez where it could be loaded onto tanker ships [38]. This required adapting the design to carry oil at a temperature of approximately 120 degrees across the continuous, discontinuous, and sporadic permafrost regions. The challenge presented in this scenario is that if the heat from the oil is transferred into the supporting superstructure, the supporting ice-rich permafrost would melt, settle, and ultimately fail [45]. This would be catastrophic to both the oil companies but also an environmental calamity to the fragile arctic ecosystem. In order to do so, engineers developed a technique utilized aluminum fan-like structures to dissipate heat rather than have it transferred into the ground. Furthermore, they insulated the footings to prevent any residual heat from being transferred. Lastly, they alternated between above-ground and below-ground construction, depending on the presence and composition of a given sample of permafrost [45]. This pipeline demonstrates a successful application of Arctic engineering technology to overcome the unique challenges of building on permafrost.

The construction of the 1,700 mile Alaska-Canada Highway during World War II connected the contiguous United States to the Alaska territory via Canada after the Japanese invasion of the Aleutian Islands and Bombing of Dutch Harbor [44]. Limited understanding of permafrost engineering techniques coupled with the required expediency of the war effort, resulted in the construction of the road without much knowledge of the long-term implications of building on these soils. The permafrost monitoring that began in 1964 along this corridor recorded a deepening of the active layer by 34% along the highway with a change in the depth of zero amplitude. This trend is similar to the long-term permafrost degradation observed across similar latitudes around the Northern Hemisphere. However, much like the study on the permafrost at Prudhoe Bay, it is once again difficult to distinguish between anthropogenic caused permafrost degradation and the effect of global climate change. An important observation of this study was the existence of permafrost in areas where the MAAT was 6-8 degrees warmer than the required minus 8 to maintain permafrost [43]. This consistent observation shows permafrost loss lags climate change due to the latent heat of fusion [5, 43]. The insulate properties of the organics layer and large presence of latent heat in ice-rich permafrost has resulted in a decades long heat transfer process despite increased MAAT. This heat exchange has manifested itself as a deepening of the active layer – which in fact constitutes permafrost degradation – rather than complete thawing [43]. While most sites witnessed degradation, there were sites toward the southern terminus of the road that experienced complete thawing of their permafrost, constituting a 25-75 km northward move of the southern permafrost limit since observations began in 1964 [43]. These observations largely employed the use of Electrical Resistivity Tomography in order to make precise observations about soil changes. These examples are highlights of the importance of understanding permafrost behavior when investing in infrastructure at northern latitudes. There and active and passive mitigating techniques available in order to preserve the ground's thermal equilibrium.

2.9 Borehole Research and the Global Terrestrial Network for Permafrost (GTN-P)

The primary means to study permafrost behavior across the northern latitudes is borehole drilling and monitoring [4]. Researchers take a drill rig and drill a narrow hole into the permafrost at depths varying from a few to hundreds of meters deep into the permafrost [4]. A distribution of these depths is depicted in Figure 2.10. A pipe may or may not be used as a casing for the borehole, depending on the properties of the soil, and a string of thermistors are calibrated and lowered into the casing at prescribed intervals to collect temperature readings at prescribed depths across the seasonal temperature fluctuations [30]. A thermistor is a highly sensitive, well-calibrated thermometer that records the temperatures of subterranean soils. A data logger then collects this data to be analyzed by researchers. The Onset Hobo Pro Data Logger is used at more than 100 of the sites and seems to be the preferred data logger for this application [3]. After the information is recorded, the data is analyzed year to year to look for any types of long-term trends.

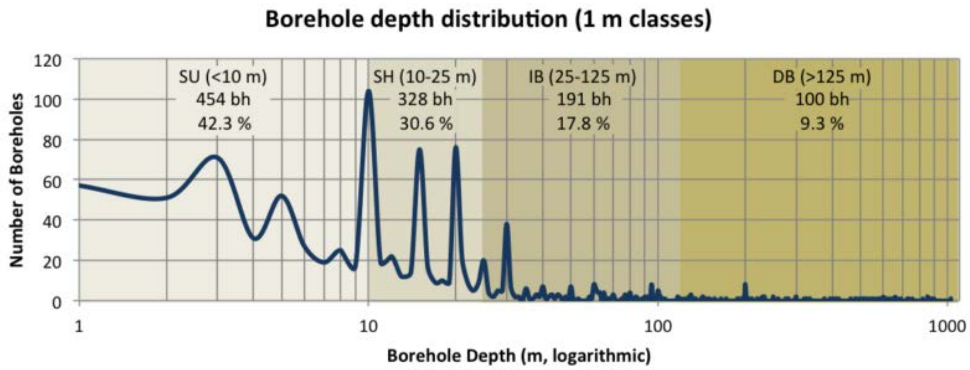

Figure 2.10: Borehole Depth Logarithmic Distribution [4]

While the data from an individual borehole is useful in monitoring a specific sample of permafrost, permafrost change is a global issue. In order to create a globalized network of data on permafrost, researchers came together to establish the Global Terrestrial Network for Permafrost or GTN-P. Currently there are 350 boreholes around the world collecting data for this database [3-4]. The purpose of the GTN-P was to establish an early warning system to detect changes within the permafrost as a response to climate change [4]. This research instrumentation often accompanies major infrastructure investments such as pipelines, roads, and airports [3]. These sites are spread across the discontinuous and continuous permafrost zones monitoring permafrost from zero degrees down to minus 15.8 degrees Celsius. With the recognition that most of the permafrost degradation takes place in the active layer, the GTN-P added a component to the network called CALM (Circumpolar Active Layer Monitoring).

The GTN-P's and CALM's measurements reveal that the temperatures of the permafrost at nearly all 350 boreholes have increased in the past 30 years. The greatest changes have been in the colder permafrost and the smallest changes have been in the permafrost less than -2 degrees Celsius [3]. This is due to the latent heat phenomenon discussed in section 2.5. Currently researchers believe that it will take decades to centuries for colder permafrost to reach thawing points given the heating rates observed across the network [3].

2.10 Alternative views

While there remains significant dispute among differing political factions about the occurrence or consequences of climate change, there is little conjecture in the field of Arctic climate study about the reality of changing atmospheric and subterranean temperatures in the Arctic. While the cause of this change remains disputed (specifically as to the causal factors driving the change in climate), little doubt remains among scientists due to the overwhelming amount of data indicating a warming trend. There is, however, uncertainty and differences of opinion as to how changing climate conditions will impact the permafrost. This is largely due to the complexity of the relationships among the factors that affect both permafrost behavior and degradation. However, collecting field data and seeing how it compares to the existing models will offer the opportunity to see if permafrost behaves in the manner prescribed by existing models or if perhaps there are erroneous assumptions or oversimplifications of these complex relationships. This data will verify or nullify the application of these models to the permafrost conditions on Eielson AFB and provide for increased awareness as to the impacts of both climate change and human activities on frozen soils at Eielson AFB.

The other major source of contention about permafrost is whether it should be treated as an undisturbed natural resource a burdensome obstacle of construction at extreme latitudes. As coastline erosion and the warming feedback loop become better documented, the preservation of permafrost should be done as a passive means of environmental protection becomes a compelling argument. This would require more comprehensive and restrictive siting and development strategies by not only the United States Government but by all public and private entities developing infrastructure in the Arctic and Antarctic.

2.11 Effects of Construction and Changing Hydrology on Permafrost

The most extreme and rapid form of change occurring to permafrost systems in the arctic is in the form of human construction activity. Pavements and buildings that are built on permafrost soils require special consideration to cope with the unique properties of permanently frozen soils. For example, when the trees and ground organics are cleared in preparation to build a roadway, the permafrost is readily exposed to heat transfer from the atmosphere as well as solar radiation. The pavement needs to either be insulated from the permafrost, otherwise it will rapidly deteriorate the underlying soil. Permafrost has sufficient bearing capacity for most construction applications so long as it remains frozen. This is especially true of areas in the discontinuous permafrost zone of interior Alaska. Upon melting, permafrost loses its bearing strength which results in dramatic and rapid pavement failure and differential settling to the point that the pavement will need to be replaced after only a fraction of its intended lifecycle. In a similar manner, facilities' and structures' foundations must be adequately insulated from the potentially damaging effects of degrading permafrost. This is especially true in the instance of heated facilities which inevitably transfer some of their heat to the frozen soils beneath. There are several widely practiced and proven construction techniques to mitigate these effects, but they are outside the scope of this thesis. The currently preferred method of coping with permafrost on Eielson AFB today is to simply excavate all of the soil out of the building footprint and replace it with virgin material to the specified compaction prior to constructing the facility for that site.

III. Methodology

3.1 Introduction

After a thorough review of the literature surrounding permafrost degradation in the discontinuous zone of Alaska and across the northern hemisphere, sufficient information was available to scope a methodology to investigate permafrost behavior on Eielson Air Force Base. This study was designed as the third round of investigation in a series of research projects surrounding this site. During the first study, Captain Alex Graboski and his advisor Dr. Dietrich Prigge analyzed the GIPL 2.1 model from 2016-2017. This modeled to the permafrost located on Eielson AFB and projected any permafrost changes that would result from global climate change over the next century. Captain Chris Edlund performed the second round of research advised by Dr. Dietrich Prigge where they installed permafrost-monitoring stations near the construction on the South Loop of Eielson AFB. The intended purpose of this inquiry was to install two boreholes and monitor the changes in the ground conditions close to the construction activities as well as at a control point further away. They also conducted an initial Electrical Resistivity Tomography scan of the ground to serve as a baseline for future monitoring. This research study collected both ground and climate data from this site in order to study human or climate caused changes to the thermal profile of this permafrost. Pursuant to these goals, the methodology associated with collecting ground temperature data from boreholes, climatological data from weather station instruments, and ground profile characterization using ERT will be outlined in this chapter.

3.2 Location Selection

The permafrost located on the South Loop of Eielson Air Force provides a unique opportunity to study permafrost on a military installation before, during, and after major anthropogenic modifications to the landscape. While there are numerous permafrost monitoring efforts being conducted across the Global Terrestrial Network for Permafrost, many of them are monitoring only the climate’s impact on permafrost behavior. There are far fewer sites that have monitored permafrost behavior as it interacts with infrastructure development in the arctic (such as the monitoring conducted along the Alaska Highway, the Trans-Alaska Pipeline, and the petroleum extraction facilities near Prudhoe Bay that were reviewed in Chapter 2). In 2017, Captain Edlund and Dr. Prigge identified the site that will be the focus of this research. This site has permafrost near the construction site and permafrost further away in an undisturbed wooded area. The permafrost bulb located closer to the construction activities served as the ‘experimental’ point and the point much farther away from the construction activities should be immediately unaffected – or at least the effects significantly buffered by geography – by the construction activities would serve as the control point for this site. Upon identification of these two locations in collaboration with CRREL, Captain Edlund’s team bored two, ten-foot-deep boreholes using direct push drilling, installed PVC casings, thermistor strings, data loggers, and conducted the initial baseline ERT scans in July 2017.

3.3 Existing Research on Eielson AFB

After taking over this research, I would be able to use the first year’s data collected from these two sites and upgrade the first year’s collection capabilities. Furthermore, I would be limited to conducting my research based on the site selection of my predecessors. During the initial site visit, Station 1 was found flooded, likely at some point during the spring thaw. Luckily, it had kept logging data and there was no interruption in the data despite the damage to the equipment. We inspected station 2 but it remained intact with no issues. The flooding in subsequent mitigation will be addressed in Section 3.7.

3.4 Date Selection

The field work portion of this research was conducted from 15-20 June 2018. While the dates for some of the field work tasks necessary during the summer 2018 research trip were inconsequential (such as upgrading the data loggers and the installation of the weather station) others would prove to have significant effects on our findings as will be discussed in Chapter 4. The purpose in selecting these particular dates were twofold. First, they coincided with AFIT’s summer break in coursework, allowing my advisor to accompany me with minimal impact to his course of instruction. Secondly, this was the time when the team from CRREL could outfit us with their ERT equipment and two technicians proficient in operating the highly sensitive package.

3.5 Methodology

With the selection and drilling of borehole one and borehole two completed in 2017, the question remained if there would be a significant divergence of behavior in the thermal profile of the soil during or after the completion of the construction required for the F-35 beddown. In order to see if there was a delta between station one and station two, I will employ both of the established means of permafrost monitoring by arctic researchers as outlined in Chapter 2.

The first method will be to use the boreholes themselves to collect data and see if there is a difference between the two stations as time progresses. I will accomplish this by collecting hourly temperature readings at specified intervals down to 10 feet. For the purposes of this study, I will have access to data from the initial installation of the data loggers in July 2017 through the data cutoff in January 2019. By maintaining two boreholes, I am able to observe the behavior of the soil in tandem. While I do expect to see a degradation of the permafrost in accordance with Captain Graboski's application of the GIPL 2.1 model and several other warming data trends from boreholes around the discontinuous permafrost zone of interior Alaska, this degradation due to climate should occur at approximately the same rate at station one as station two due to their close proximity and similar characteristics. The key indicator will be the difference in changes in behavior between station one and station two. By controlling for climate impacts to this permafrost, any change in behavior between the two boreholes could perhaps be attributed to the construction activities on the South Loop.

One of the limitations of the instruments installed in July 2017 was the fact that the data loggers were unable to transmit the data remotely. While the data loggers were not inferior in their capability to record the required information or durability (in fact one of the data loggers sustained significant damage due to ice damming and submersion but still kept recording), the only means of data collection were to manually download the data on the research site. Given the geographic separation between Wright-Patterson AFB, OH and Eielson AFB, AK this placed a major constraint on the accessibility of data. In order to improve the capabilities, part of this initiative was also to upgrade the data loggers to a more robust data logger package that is capable of remotely transmitting the borehole data so long as it maintains a cellular signal.

3.6 Weather Station Construction and Installation

In order to provide better resolution to the climate component of permafrost degradation, it is crucial to have highly calibrated weather instrumentation available directly above the permafrost soils in question. Interior Alaska is home to powerful temperature inversions that can cause significant differences in temperature within local regions separated by only a few miles. In order to control for this phenomenon and reduce any climatological uncertainty from being introduced into the analysis, I constructed and installed a weather station to provide localized data in the immediate vicinity of this research initiative. This provides a far more accurate depiction of the microclimate surrounding this permafrost system rather than simply relying on the temperature data from Fairbanks, North Pole, or even the installation's weather office.

The weather station package selected for this study was the Davis Pro 2 Weather Station. This package was within the allotted research budget for this project and provided the necessary capabilities. This package includes several important sensors that will provide the necessary climate data for this site. The primary capability is its ability to collect temperature data at a height of approximately 2 meters off the ground. The temperature sensor comes with a radiation shield to ensure that there is no undue influence from solar radiation on the ambient temperature. This is an important consideration for studying this type of permafrost as the organics layer at this site provide insolation properties from solar radiation penetrating into the permafrost layers below. Additionally, this package has a rain gauge, which is calibrated to measure down to 0.01

inches of precipitation. Since most of the research in this field is done in metric units, I installed a metric conversion device to the rainwater collection mechanism so that rainfall measurements would be measured in millimeters. The next device in the package was an anemometer which measures wind speed and direction at this site. The package also has the capability to measure many other weather parameters, such as length of day, relative humidity, dew point, and several other data points; however, these factors seem to be less influential to the behavior of the permafrost according the body of literature reviewed for this study. Nevertheless, this will be available in the event it later needs to be incorporated into the model.

In order for this weather station to function properly and in all seasons, it needed to be correctly configured and have an independent power source. The first consideration for the configuration was that the anemometer need to be oriented directly north in order to provide correct wind speed and direction values. This was fairly simple to achieve using a compass and magnetic north correction for this location. Furthermore I validated the orientation of the anemometer using a handheld Garmin GPS unit.

Much like the problem encountered with the data loggers, I needed to develop a way of relaying this data remotely from rural Alaska back to Wright-Patterson Air Force Base. This required two components be incorporated into the sensor package: a data logger and a transmitter. The data logger collects and compiles the information from the sensor array and then the transmitter is able to transfer the data via cellular signal to a software package called weatherlink. In order to reduce power consumption requirements, I hard wired the data logger directly to the transmitter so that it would not need to draw power to generate the cellular signal. However, that capability does exist as an auxiliary should the hardwire fail or should an additional sensor package be incorporated in the sensor array in the future.

It was imperative that the weather station be configured to function so that it would function during all seasons at high latitude. To achieve this capability, the weather station needed to be equipped with a continuous power source, the generation of which comes from a battery bank within the data logger and a smaller bank within the transmitter. Both are equipped with an independent solar panel that provides power and recharges these batteries so they can collect and transmit data. During the summer season there is almost continuous sunlight at Eielson AFB, so orientation of the solar panels is not of such extreme importance. However, during the winter there is only a few hours of sunlight and it is very low on the horizon. Providing sufficient power to the weather station during these winter months to ensure its operation is the greatest challenge of collecting year-round data from this site. In order to minimize the chances of the weather station receiving insufficient power, both solar panels needed a minimally-obstructed view of the south with minimal vegetation. This provides sunlight access as low to the southern horizon as possible. The most ideal placement of the weather station to meet these requirements was southwest of station two in the power line cut near the slough. The saturated nature of the slough prevented much tall vegetation from growing toward the southern horizon and was only 10 meters from transect one.

In addition to providing the required data, remote transmitting, and operability in the extreme Alaskan winters, the weather station also needed to be sufficiently compact to be flown via commercial airline luggage from Dayton, OH to Fairbanks, AK. In order to achieve this I initially constructed the weather station in my garage during the month prior to our scheduled departure date. In doing so, I was able to achieve two goals. First, I was able to fully configure the weather station and make sure that it was fully operational prior to departure. This allowed me to troubleshoot any issues while still at home station and familiarize myself with the nuances of the equipment. After I completely assembled the weather station I downloaded the software package to my computer and ensured that all of the sensors were operating, data was being logged, the signal was being transmitted, and that the data could be downloaded to both my personal computer and AFIT computers. I let the station run for 10 days to ensure that it was ready to be deployed to the field. I then began to strategically disassemble the weather station into pieces that would fit inside a Pelican case and require minimal re-assembly upon arrival to the field.

Selection of the type of tripod on which to mount the system was a tradeoff in meeting climate research standards with the application to permafrost and its transportability. Climate scientists capture their data at a standard height of 10 meters and above any local obstructions, but climate is only one piece of this research. The most important interaction between the climate and the permafrost happens at the boundary layer between the atmosphere and the earth. Therefore, it is far more important to get climate information closer to the ground than at a height of 10 meters. Furthermore, transporting a tripod of such a height would have proven much more difficult and potentially costly to deploy. There also would have been overhead safety consideration given the presence of power lines in the area and such a height could have potentially violated clear zone requirements for the airfield. The other extreme would have been to place the weather station as low to the ground as possible, but this would make the equipment vulnerable to trampling by wildlife and submersion by the winter snowpack. The purchase of a two-meter tripod was determined to be the ideal balance between protection height and proximity to the soil. Raising it up to this height would keep the sensors protected up off the ground, adequate access to the sunlight required for the solar panels, and not be unnecessarily far away from the permafrost. This height of tripod could also be readily acquired commercially from Davis as opposed to a custom fabrication.

One of the limitations of weather station as it exists today is that it does not have the capability to measure snowpack. As highlighted in Chapter 2, snowpack is an important consideration when studying permafrost behavior as it further insulates the permafrost from the climate above. Should this be deemed necessary to incorporate into future models, snowfall amounts are not nearly as variable as the temperatures in this region and this data could be pulled from base weather or from the town of North Pole. As it stands, this is a limitation of this sensor package.

Figure 3.1: Weather Station Assembly, Calibration, and Testing

Figure 3.2: Weather Station Deployment and Orientation

Once the site was selected for installing the weather station, all of the equipment and materials needed to be transported into the field. We were able to get the truck within approximately 100 meters from the site. The equipment had to be carried the remainder of the way through the forest in order to get there. Upon arriving, I set up the tripod and immediately was concerned about the stability of the ground. The organics layer in this area was thick and the stakes intended to fasten the tripod to the ground were far too flimsy to adhere the tripod to the ground in the event of high winds. Additionally, there was no effective way of leveling the weather station, an additional specification needed in order for it to function correctly.

In order to solve this problem, I drove to the Home Depot in Fairbanks, AK to see what readily available materials I could use to solve this problem. The solution I came up with was to use a combination of concrete blocks, all-thread, bolts, and washers. This system worked by placing the 36 inch all-thread through the hole at the center of the block and adhering it to the concrete block using a bolt and washer on both the top and the bottom of the block. This served two purposes. First, as the summer and winter freeze thaw cycles occurred in the active layer, this would prevent the concrete block from migrating from its installed position. Secondly, by having bolts on the top and the bottom I could adjust and loosen the three concrete bases in order to achieve a perfectly level base. This also allowed for approximately 30 inches of penetration by the all-thread into the ground, which affixed it more securely than the 6-inch alternatives. The completed assembly of one of the tripod bases is depicted in Figure 3.3. Upon achieving a level foundation, I bolted the tripod assembly on top of the base and ensured it was level, plumb, and properly oriented. The final assembly is shown in Figure 3.2.

Figure 3.3: Completed Tripod Foundation

3.7 Electrical Resistivity Tomography

During the summer of 2017, Captain Edlund and his team conducted the initial electrical resistivity tomography scans of this site. Two ERT scans were conducted during this time along two different transects. A transect in this case is a line of 84 individual points that create a subterranean profile image of the electrical resistance of the soils on that line. Figure 3.4 depicts the two transects that were surveyed at that time.

Each of the orange points represents a location where one of the ERT probes was placed into the ground and each gray points symbolize the location where we conducted a frost probe. Figure 3 also depicts how Station 2 is in the center of the two transects and station one is closer to the slough as well as the construction being conducted to beddown the F-35s.

Figure 3.4: ERT and Frost Probe Survey Points [37]

In order for there to be an accurate comparison of the 2017, 2018, and any future ERT surveys, the ERT probes need to survey the exact same transects in order to achieve a fair comparison. Inaccurately comparing different cross sections of ground would result in an inaccurate depiction of the resistivity of the ground over time. In order to ensure consistency, I acquired and used the same GPS points used during the 2017 survey. An example of the first five data points used to mark the points on the transects are depicted in Table 3.1.

Table 3.1: Selected ERT GPS Coordinates

Point Name	Latitude	Longitude	Elevation (M)
1	W 147° 2' 35.642"	N 64° 38' 55.602"	167.830
2	W 147° 2' 35.596"	N 64° 38' 55.541"	167.91
3	W 147° 2' 35.517"	N 64° 38' 55.485"	167.754
4	W 147° 2' 35.443"	N 64° 38' 55.428"	167.59
5	W 147° 2' 35.366"	N 64° 38' 55.374"	167.556

Additionally, the Engineer Assistants from the 354 Civil Engineer Squadron graciously offered to assist me in marking the points at the research site prior to conducting the ERT. It would have been difficult for me to generate this capability, as I did not have the ability or access to this specialized surveying equipment. Figure 3.5 shows the type of field conditions and equipment being used to generate the points used for the ERT surveys.

Figure 3.5: ERT and Frost Probe Point Survey

ERT scans are time and labor intensive and would take one whole day to complete each. The first day of ERT scans were 18 June 2018. I began the day by meeting staff from the Cold Regions Research and Engineering Lab (CRREL) on Fort Wainwright. After introductions, we loaded up their ERT equipment and convoyed out to Eielson AFB where we met up with the Engineer Assistants that were helping with the surveying portion of the study. After inspecting the transects and ensuring they had 2-meter intervals, we were ready to begin scans. However, the equipment required to conduct an ERT is quite heavy and cumbersome including: two deep-cycle batteries, the ERT console, 84 steel stakes with sledgehammers, eight 10-meter cables, 84 connection clips, and other miscellaneous tools. This equipment all had to be carried from our trucks into the woods approximately 200 meters. A sampling of this equipment is pictured in Figure 3.6.

Figure 3.6: ERT Field Equipment

Once we transported our gear into the field, we then pounded steel-stakes into the ground with sledgehammers and connected the electrical wires to the deep cycle batteries. The pounding of the stakes is conducted largely by feel. In order for the results to be accurate, the bottom of the stake needs to be in contact with the permafrost below. While hammering, there is a distinct feeling once the permafrost layer is reached as the stake penetrates much less into the ground with each blow as the frozen ground is far more impenetrable than thawed ground. Furthermore, we had two lengths of stakes available: short and long models. The short ones are nice for areas where the permafrost is shallow and much less weight to haul into the field. There were several occasions when short stakes needed to be replaced with longer ones when they did not strike frozen soil. Once complete, we then checked the conductivity of the ground and had to pour water on the stations that were unresponsive to improve the conductivity. This was indicated on the ERT module and would specify which stakes had insufficient conductivity with the ground. The configuration of the individual probes is depicted in Figure 3.7. The first ERT scan took several hours. During that time, while the electrical current was running, I elected to bring out the equipment that I would need the following day in order to upgrade the data loggers.

Figure 3.7: Standard ERT Probe Configuration

Once all the individual probes were installed they needed to be connected to the transmission cable in a very specific order. Each location on each cable has an individual conductor assigned to it within the cable. That way, the ERT module is able to know what information it is picking up from which probe. In this manner, the ERT sends the electrical current to two different probes along their specific conductors within the cable. The electrical current travels to the oppositely charged stake. By measuring the voltage and current properties between these points, the resistance of the ground is calculated by using Ohm’s Law. Figure 3.8 depicts how all the probes are connected to one another. The module runs its programs and bounces electrical currents between different probes for several hours and in doing so is able to map the resistivity of the soil at different depths and displacements from the module. This resistance will then be an indicator of how frozen the soil is underneath the ground as ice-rich permafrost soils are characteristically electrically resistive and thawed ground is far more electrically conductive. The results of these scans and the comparison between 2017 and 2018 will be in Chapter 4.

Figure 3.8: ERT Probes Along Transect One

On 19 June we once again met with the CRREL staff at Fort Wainwright and convoyed out to the site. We conducted the second ERT scan along transect two in the same manner as we had done the previous day on transect one. Additionally, we had several representatives from the 354 CES Engineering Flight come visit the site in order to see the research operations. Dr. Debu Misram a professor from the University of

Alaska Fairbanks, also visited our site as he studies permafrost at the UAF Department of Geophysics.

3.8 Frost Probes

A more rudimentary method used to collect data on permafrost conditions is called frost probing. This techniques uses a probe to find the the top of the permafrost layer. As mentioned in Section 3.5, the density and resistance of the ground varies from soft to nearly impenetrable as the probe passes through the thawed portion of the active layer and hits the top of the permafrost. By measuring the depth of the frost line using the frost probe, we are able to validate the ERT findings and use another means of comparing the downward or upward migration of the permafrost from year to year. In order to simplify documentation of the frost probes, they were conducted immediately next to the ERT probes at the same coordinates.

3.9 Station One Data Logger Upgrades

Prior to deploying to the field, I tested and configured the data loggers at home station to ensure they were fully operational. While setting up the weather station I also turned on both RX 3000s, activated their data transmission plans, and made sure they could transmit data to the Hobolink software program via cellular signal. They both worked as intended, but I also wanted to ensure they would work at low temperatures, so I placed them in my deep freezer at minus 23 Celsius to ensure they would work in the extreme arctic conditions. Once again they performed flawlessly.

After the completion of the ERTs, it was time to upgrade the data loggers. Upon inspecting Station One, we quickly discovered that both the data logger housing and the borehole were both flooded as shown in Figure 3.9. Many of the components in the housing were submerged as depicted in Figure 3.10. Even the data logger appears to have been submerged for an unknown period of time. These issues caused damage that would need to be addressed prior to making the planned upgrades to the data loggers. Specifically, corrosion was occurring on the data logger battery leads as shown in Figure 3.11.

Figure 3.9: Borehole One Flooded

Figure 3.10: Flooded Instrument Housing

Figure 3.11: Data Logger Damage from Corrosion

The first thing I needed to do was drain the water out of the borehole. My initial thought was to use a siphon; however, the siphons commercially available in the area were either too big to fit down the borehole or too short to drain it all the way to the bottom. The solution that proved to work was far more elementary. First, I gingerly removed the string of thermistors out of the borehole and placed them aside. Then, I used a ¼ inch piece of flex pipe and put it down to the hole to the bottom like a giant straw that would use for a drink. I then placed my finger over the top of the pipe so that the water collected within it could not escape and pulled the pipe out of the borehole. I then let took my finger off the top of the pipe and discarded the melt water I had collected. I repeated this process until the borehole was completely drained.

Since the cause of the intrusion remained unknown, I wanted to ensure that it was mitigated should it happen again. I spoke with the CRREL researchers and they said that when they experienced similar problems they backfilled their boreholes with sand. That way, if it did become saturated in the future, at least the soil and water would have similar thermal transport properties to the in situ soil versus a column of water. Therefore, I purchased fine-grained sand from Home Depot and hauled it back out to the research site. I then replaced the thermistor string back into the borehole casing and backfilled the borehole with the sand.

I then turned my attention to upgrading the data loggers. Before any work was to be conducted, I took my computer out and downloaded all the data to make sure that nothing would be lost while we did the work. Miraculously, even though it has been submerged and began corroding, it still collected data up until the moment I downloaded it on 18 June. The new RX3000 data loggers would be capable of transmitting the data remotely via cellular signal, much in the same manner as the weather station. Additionally, these data loggers would be powered and recharged by solar panels (once again they too would need to be oriented south in order to maximize their efficiency during the dark winter months.

I speculated that the cause of the water intrusion was the fact that it was laying directly on the ground in an area prone to deep snowfall. In the spring, during a period referred to by most Alaskans as breakup, ponding and ice damming is common on the surface that would lead to inundation of any instruments left directly at the surface. Therefore, I elected to elevate my instruments above the potentially harmful effects of this phenomenon. In order to accomplish, this I used a T-post driven into the ground by a sledgehammer. From there I was able to mount the RX 3000 and the solar panel responsible for charging both the data logger and transmitter batteries on the post. In order to add additional rigidity to the system against the elements, I also added three additional T-posts separated by 120 degrees around the primary support post. I also drove these into the ground and then affixed a guy wire comprised of 300-pound test cable from each of the support posts to the center post bearing the instrumentation. I used the corresponding guy wire clamps in order to achieve the proper tension on each cable. This rigidity was to serve two purposes. First, it would reinforce the primary post from high winds during the severe weather events that frequent the arctic. Second, it would help mitigate some of the frost heaving and soil displacements associated with both the annual freeze/thaw cycles and changes to the active layer of the permafrost.

After the construction of the post, I was able to begin rewiring the data loggers. First, in order for them to be protected from the elements and any curious rodents, I needed to run the wires through a PVC conduit. After completing that, I began the tedious task of plugging the sensors into the new RX 3000 data logger as shown in Figure

3.12. I was careful to wire the thermistors and other sensors in the same order that they were on the previous data logger, which corresponded to their sequential depth the in borehole. I then sealed any of the unused ports with rubber plugs in order to ensure that no moisture would be able to penetrate the data logger as had occurred on the previous data loggers. Additionally, I oriented the data logger in the upright position, which minimized exposure to any of the leads. Lastly, I mounted the solar panel on the top of the post and oriented it southward using my handheld GPS. I then made the power connection from the solar panel to the data logger in order to provide continuous, remote power.

Figure 3.12: Troubleshooting and Rewiring the Data Loggers

Table 3.2 lists the sensors that were placed in Borehole One during July 2017. Note that they are spaced much closer together near the surface than deeper down the borehole. This deliberate increase in sensor coverage near the surface because most of the permafrost changes initiate near the surface in the active layer. Therefore, the active layer and the top of the inactive layer need to be more closely monitored for changes than at deeper depths where changes will be subtle and may take longer than the lifespan of the equipment. Lastly, since Station One is closer to the construction associated with the F-35 beddown, my hypothesis is that Station One will be more affected initially than Station Two, which is further away. This hypothesis also merits additional instrumentation of Station One.

Table 3.2: List of Sensors and Depths

Depth (m)	Depth (ft)	Sensor Cable Length (m)	Sensor Information	Offset From 0°C
Ambient	Ambient	2	Temp, °C (LGR S/N: 20168199, SEN S/N: 20171362)	2.685
0.1524	0.5	2	Temp, °C (LGR S/N: 20168199, SEN S/N: 20160656)	-0.131
0.3048	1	2	Temp, °C (LGR S/N: 20168199, SEN S/N: 20160657)	0.024
0.4572	1.5	2	Temp, °C (LGR S/N: 20168199, SEN S/N: 20160655)	0.002
0.6096	2	6	Temp, °C (LGR S/N: 20168199, SEN S/N: 20182672)	0.108
0.762	2.5	6	Temp, °C (LGR S/N: 20168199, SEN S/N: 20168341)	-0.025
0.9144	3	6	Temp, °C (LGR S/N: 20168199, SEN S/N: 20168340)	0.081
1.0668	3.5	6	Temp, °C (LGR S/N: 20168199, SEN S/N: 20168339)	0.001
1.2192	4	6	Temp, °C (LGR S/N: 20168199, SEN S/N: 20168342)	-0.059
1.524	5	6	Temp, °C (LGR S/N: 20168199, SEN S/N: 20168343)	0.037
2.286	7.5	17	Temp, °C (LGR S/N: 20168199, SEN S/N: 20166912)	0.148
3.048	10	17	Temp, °C (LGR S/N: 20168199, SEN S/N: 20166913)	0.187

After completing all the installations and upgrades there was still several cables and connectors that would be vulnerable to the elements. The most expedient decision I could find was to place them all inside of a plastic five-gallon bucket and seal them against any kind of intrusions from weather or vermin. In case water did penetrate it somehow, I did place some small weep holes in the bottom of the bucket so it could drain. Figure 3.13 shows the completion of Station One.

Figure 3.13: Station One Upgrades

3.10 Station Two Upgrades

The instrumentation at Station Two was found to be in better condition than Station One. Figure 3.14 shows that the box was not compromised by any water. Prior to unplugging the instruments for the upgrade process, all of the data was downloaded and inspected for lapses. Station Two had performed well and collected all the data since July 2017.

Figure 3.14: Station Two Instrument Housing

Despite the fact that Station Two had not been compromised, to be safe and for the sake of uniformity, I elected to standardize Station Two with Station One. I pounded in the main support T-post and the three additional support posts the exact same way as I had done on Station One. I then connected the support posts to the main post using the same style guy wires and guy wire fasteners. Once again, I disconnected all of the sensors, extended the borehole housing and ran the cables through the PVC in order to protect them from the elements, and reconnected them to the new data logger. I also waterproofed this RX 3000 and ensured that the sensors were once again in the same order that they had been installed on the other data logger to ensure continuity. The process of conducting these upgrades can be seen in Figure 3.15. After the installation of the data logger, I installed an additional solar panel at this location (oriented south) and connected it the battery bank in the RX 3000.

Figure 3.15: The Process of Upgrading Station Two

Station Two is not as heavily instrumented as Station One. While this is not ideal, it should not be an impediment to the research. Since Station Two is acting as more of a control point, the changes at this station should be less substantial and be solely due to climate. There were funding restrictions in 2017 when the installation of these instruments occurred which disallowed the same instrumentation of both boreholes. As seen in Table 3.3, there are fewer instruments in the active layer and some of the interval lengths are increased. Again, the hypothesis surrounding this is that there should be less changes to both the active and inactive layers at Station Two due to increased geographic separation.

Table 3.3: Instrumentation and Depth in Borehole Two

Depth (m)	Depth (ft)	Sensor Cable Length (m)	Sensor Information	Offset From 0°C
0.152	0.5	2	Temp, °C (LGR S/N: 20177931, SEN S/N: 20177167)	-0.102
0.305	1	2	Temp, °C (LGR S/N: 20177931, SEN S/N: 20177163)	0.024
0.457	1.5	2	Temp, °C (LGR S/N: 20177931, SEN S/N: 20177166)	0.024
0.610	2	2	Temp, °C (LGR S/N: 20177931, SEN S/N: 20177165)	0.081
0.762	2.5	2	Temp, °C (LGR S/N: 20177931, SEN S/N: 20177164)	0.024
1.067	3.5	6	Temp, °C (LGR S/N: 20177931, SEN S/N: 20182674)	-0.004
1.372	4.5	6	Temp, °C (LGR S/N: 20177931, SEN S/N: 20182671)	0.079
1.524	5	6	Temp, °C (LGR S/N: 20177931, SEN S/N: 20182673)	0.104
3.048	10	17	Temp, °C (LGR S/N: 20177931, SEN S/N: 20166925)	0.135

Since the box on Station Two was not compromised, we elected to recycle it and use it to hold the additional cables and connectors. Unlike Station One, where I needed to replace the box with a bucket to house these items, we were able to simply leave these items in place. This is the only deviation in the upgrades that occurred between Station One and Station Two. The completed upgrades to Station Two can be seen in Figure 3.16.

After completing the upgrades at both sites and removing the last of our gear from the field, it was time to test their operability. In order to ensure they were transmitting data we returned to the main part of base to see if we could view the data collected by the new data loggers. Unfortunately, they were not transmitting, so we had to return to the site to see if we could troubleshoot the RX3000s. When I returned I was inspecting the data loggers and they did not have any of the channels or instruments loaded. I elected to restart both loggers and both populated all the channels that I had installed earlier that day. I once again returned to main base to see if the data was transmitting. I was able to pick up a Wi-Fi signal in the parking lot of the bowling alley and was able to verify that the data was indeed transmitting from both data loggers and the weather station.

Figure 3.16: Station Two Upgrades

3.11 Safety Considerations

Safety was always the priority during this field work. We wore safety toe boots, work gloves, and eye protection while using the sledgehammers. Additionally, the Arctic is famous for its mosquitos in the summer time, so we purchased and liberally applied DEET. We also supplied DEET to all others on site. While there was no threat of vector-borne illness on Eielson at that time, we wanted to prevent mosquito bites. We also purchased mosquito head nets to keep the mosquitoes off our faces and necks. Lastly, in the unlikely event of a hostile wildlife encounter, I purchased and carried bear mace, should we need to defend ourselves.

3.12 Permafrost Tunnel Site Visit

On the final morning of field work, the CRREL staff graciously treated us to a tour of US Army Corps of Engineers permafrost tunnel. The tour gave us an up-close subterranean view of the soil types present on Eielson AFB. This provided a great visualization tool of the underground ice formations that cause engineering problems for facilities constructed on permafrost. That afternoon we reconnoitered with Kevin Bjella on Fort Wainwright and drove down to Eielson AFB where Capt Chris Edlund gave us a tour of the construction occurring on that site. This visit provided additional insight and context for research into arctic soil conditions. An example of a large thermokarst, or permafrost bulb, similar to the ones observed on Eielson is in Figure 3.17.

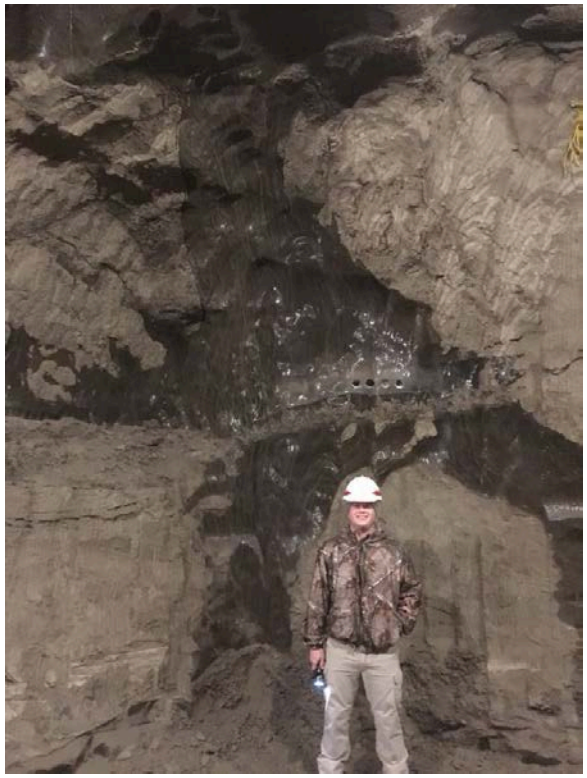

Figure 3.17: Ice Wedge Inside USACE Permafrost Tunnel

IV. Analysis and Results

4.1 Introduction

The methods utilized in Chapter 3 yielded two complete ERT scans, two sets of frost probe data, 16 months of borehole temperature data at Stations One and Two, and climatological data for the research site. The ERT scans provided a visual and numerical comparison between the conditions in the ground during July 2017 to June 2018. After this comparison is made, it will be possible to validate those changes with higher fidelity by using the frost probe data collected during both 2017 and 2018. Lastly, the data collected from the boreholes from July 2017 to December 2018 will be used to compare the behaviors of the permafrost at Station One to Station Two.

4.2 How to Read an Electrical Resistivity Tomography Scan

ERT technology uses pulses of electrical current through the ground between different probes to compute the electrical resistivity of the ground using Ohm’s Law. Ice rich permafrost is orders of magnitude more resistive than ground that has either thawed or never contained permafrost. This high correlation between electrical resistivity and the soil’s frozen water content is useful in comparing how permafrost changes over time. Using CRREL’s permafrost mapping software, we used the data collected by the ERT module in order to create a visual depiction of the permafrost contained within transect one and transect two. The darker colors such as reds, browns, and purples are all indicative of ice rich permafrost in its frozen state. The less resistive areas are represented by colors such as blues, greens, and yellows and indicate that permafrost is not present or is no longer present in that location. Figures 4.1 and 4.2 show the output of this software from the two ERT scans conducted during June 2018.

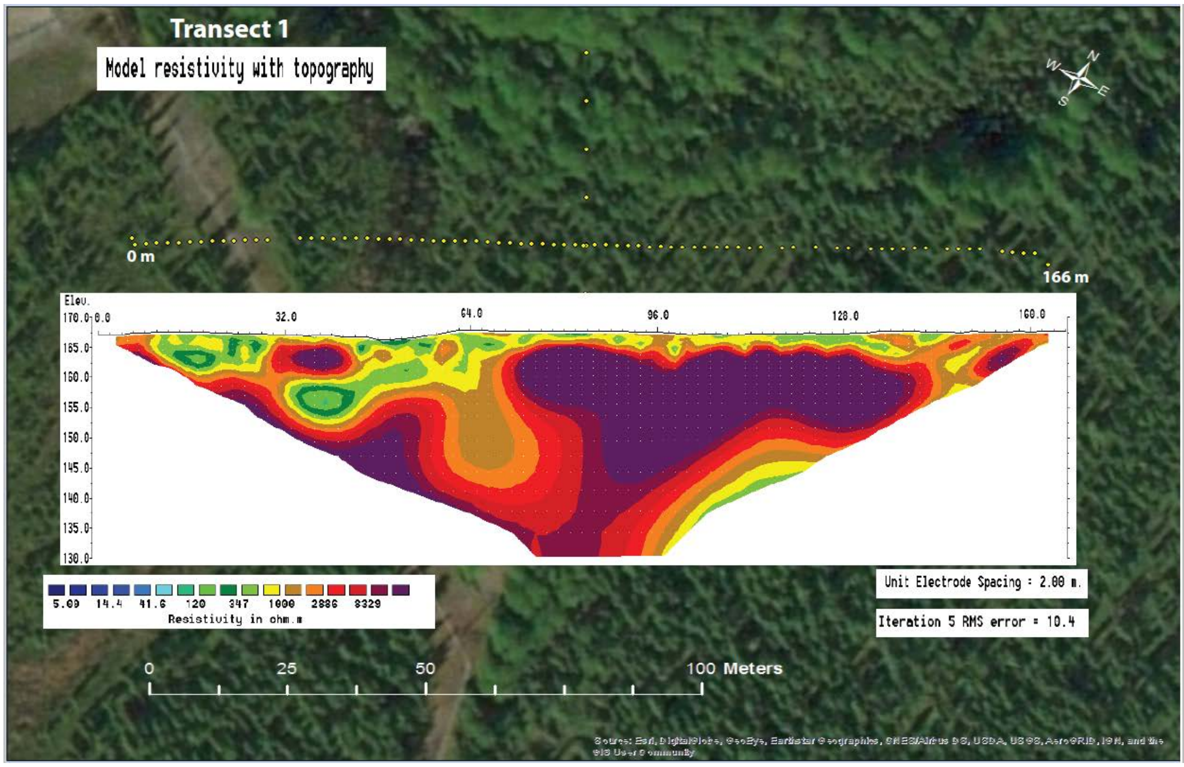

Figure 4.1: 2018 ERT of Transect One

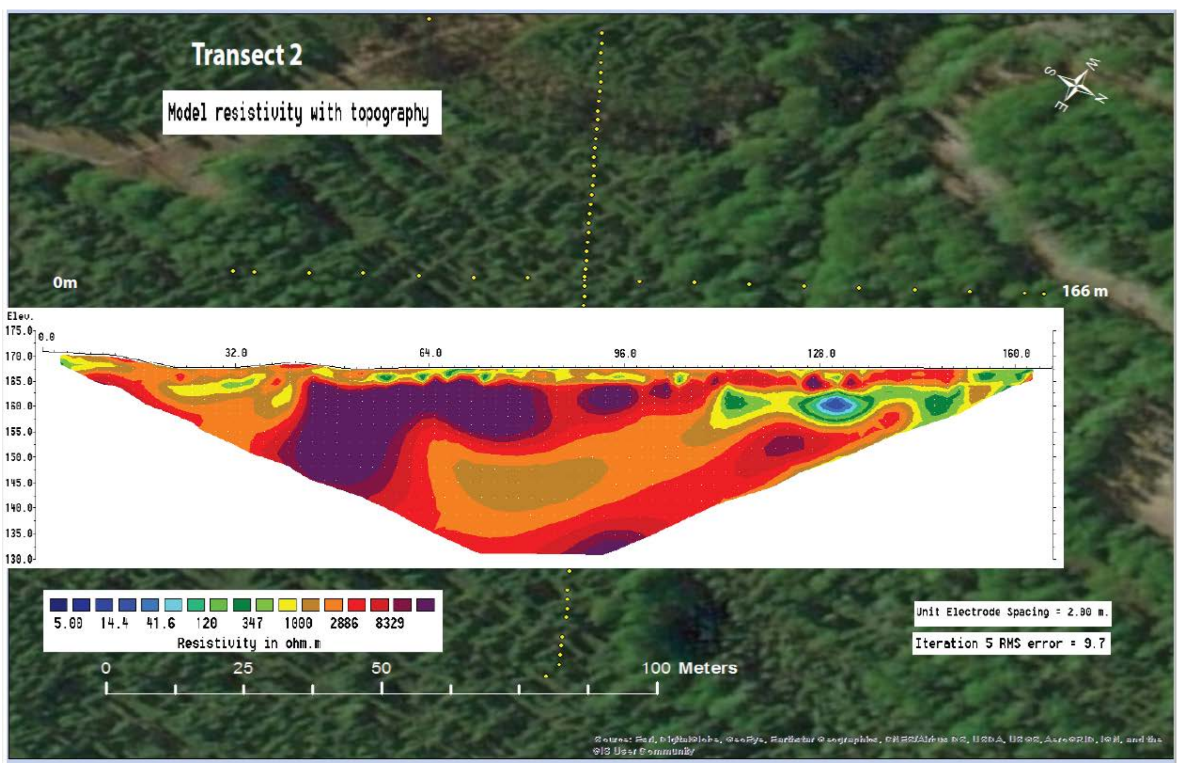

Figure 4.2: 2018 ERT of Transect Two

4.3 Comparison of ERT Scan Data from 2017 and 2018 for Transect One

One of the great advantages of applying ERT technology to permafrost applications is the fact that it provides a visual comparison of the same cross section of ground at a prescribed interval. Figure 4.3 depicts the ERT conducted on transect one as the baseline during July 2017. Beneath it is a scan of the exact same cross section conducted in June 2018. This comparison leads to some interesting insights about the behavior of this permafrost during this time period.

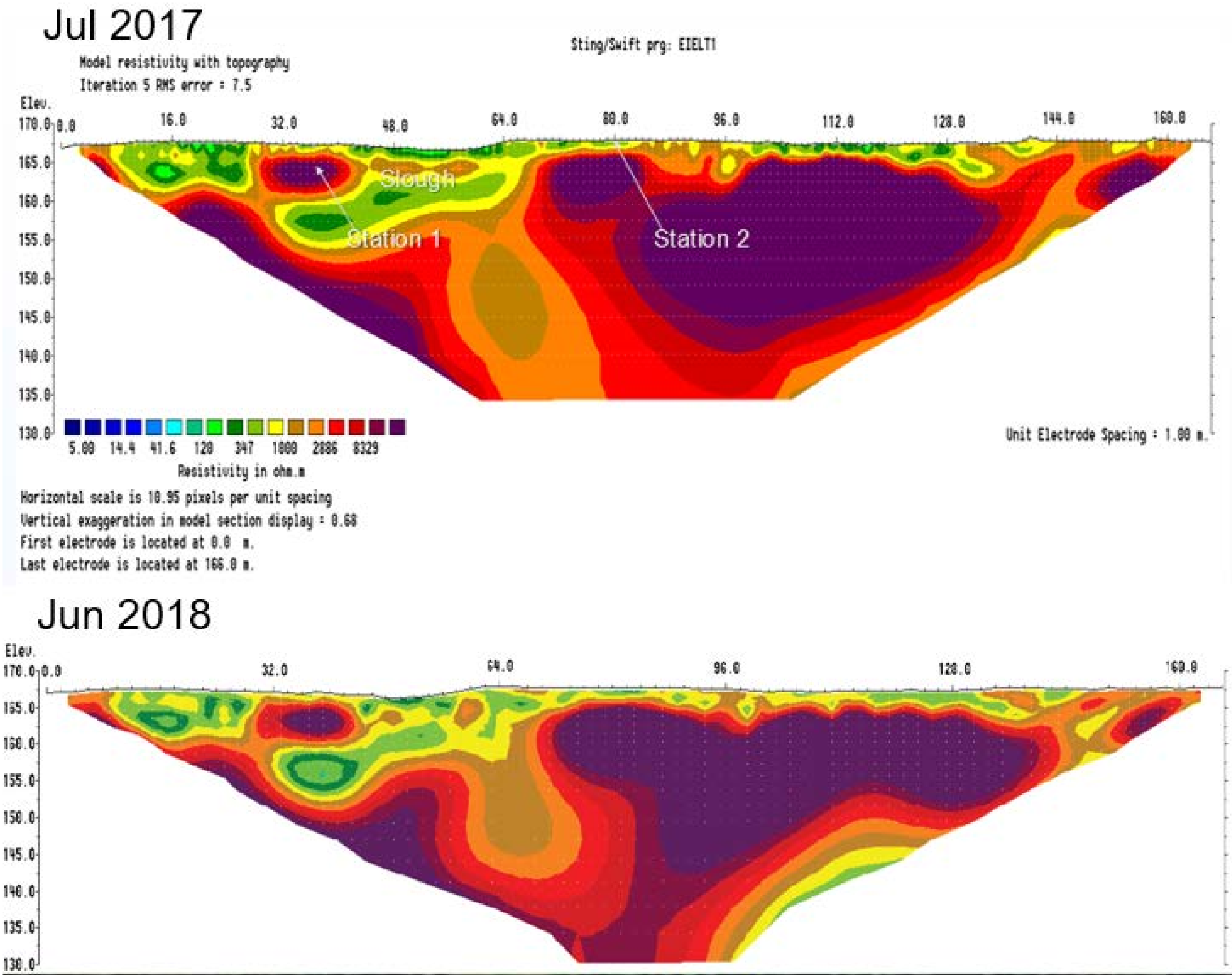

Figure 4.3: Transect One Comparison

The ERT conducted in July 2017 definitively shows permafrost on this transect and that there are two clusters, or bulbs, of permafrost beneath Stations One and Two. Station Two's permafrost bulb is surrounded by additional permafrost and the ground beneath it also appears to be frozen down to the depths visible by the ERT. Station One is unique in that there appears to be thawed ground beneath the permafrost as a shallow level. This is likely due to thermal energy carried by the water passing through the slough near it. As this water permeates into the ground, it carries the thermal energy with it and creates a pocket immune from permafrost. However, the shallower bulb at Station One still has enough exposure to the ambient climate in order to maintain the permafrost near the surface.

Up comparing the results from July 2017 to June 2018, it actually appears that in many instances along the transects that the permafrost table is actually shallower, indicating that the permafrost is colder and more widespread in June than it had been in the previous July. This observation would be highly inconsistent with the permafrost behavior witnessed at similar sites across interior Alaska. The most likely explanation for the shallower frost depth is that this permafrost is exhibiting behavior highly consistent with the expansion and degradation of the active layer of the permafrost. In July 2017, the active layer of the permafrost had an additional 5 weeks of thaw time prior to being evaluated. Since the scan conducted in 2018 was over a month earlier, it stands to reason that the permafrost would be shallower and more widespread given it did not have the opportunity to melt to the same conditions witnessed in July 2017. Therefore, making a definitive assessment as to the expansion or degradation of the permafrost at this site based on these scans is inconclusive. In order to make an accurate assessment as to the changes occurring in the permafrost over time, the scans would need to be conducted on the same day every summer in order to support consistent observations about the localized trends in those soils.

The one area that fails to conform to this behavior is the area in the slough and beneath the bulb at Station One. In this instance, it appears that little has changed in this area despite the fact that the second scan was a month early. If anything, there are indicators that this area contains less permafrost than the year prior despite the time difference. This could be due to multiple reasons. First, it could be due to the large heat carrying capacity of the water in this area and that it remained somewhat unaffected by the time difference. The second hypothesis is what the CRREL researchers and I maintain to be the cause. As part of the expansion on the south loop, engineers modified the storm water and snowmelt configuration of this part of the installation. There are more impervious surfaces due to facility expansions and additional paved surfaces; therefore, the water from these areas is being discharged as runoff. The slough that runs through this research site is one of the sloughs responsible for carrying this additional runoff. As this additional water flows through this slough, so to does the thermal energy carried by the runoff. Additional input of thermal energy into this permafrost system would upset the thermal equilibrium achieved naturally by these soils. Therefore, I think there may be a correlation between this anomaly beneath Station One and the increased thermal discharge into the slough. This hypothesis will be further evaluated by analyzing the thermistor data.

4.4 Comparison of ERT Scan Data from 2017 and 2018 for Transect Two

While the greatest changes to the permafrost are expected to be on Transect One, we conducted an additional ERT on Transect 2 during 2018 in order to see if any changes were readily apparent from the prior year. Similar to the Transect One, Figure 4.4 depicts that the soils on Transect 2 are in a more frozen state during June 2018 than July2017. Once again, this is likely due to the fact that the ERT was conducted more than a month earlier than the previous year. Again, in order for there to be a fair comparison, the ERTs would need to have been conducted on as close to the same date as possible one year apart. Despite the earlier timing, the permafrost on Transect 2 appears to be largely unchanged albeit slightly more frozen. This lack of significant change (despite the change in timing) does provide some reassurance that these more undisturbed permafrost specimens further from the impacts of the construction activities, are serving as an adequate control point against which we can compare changes at Station One.

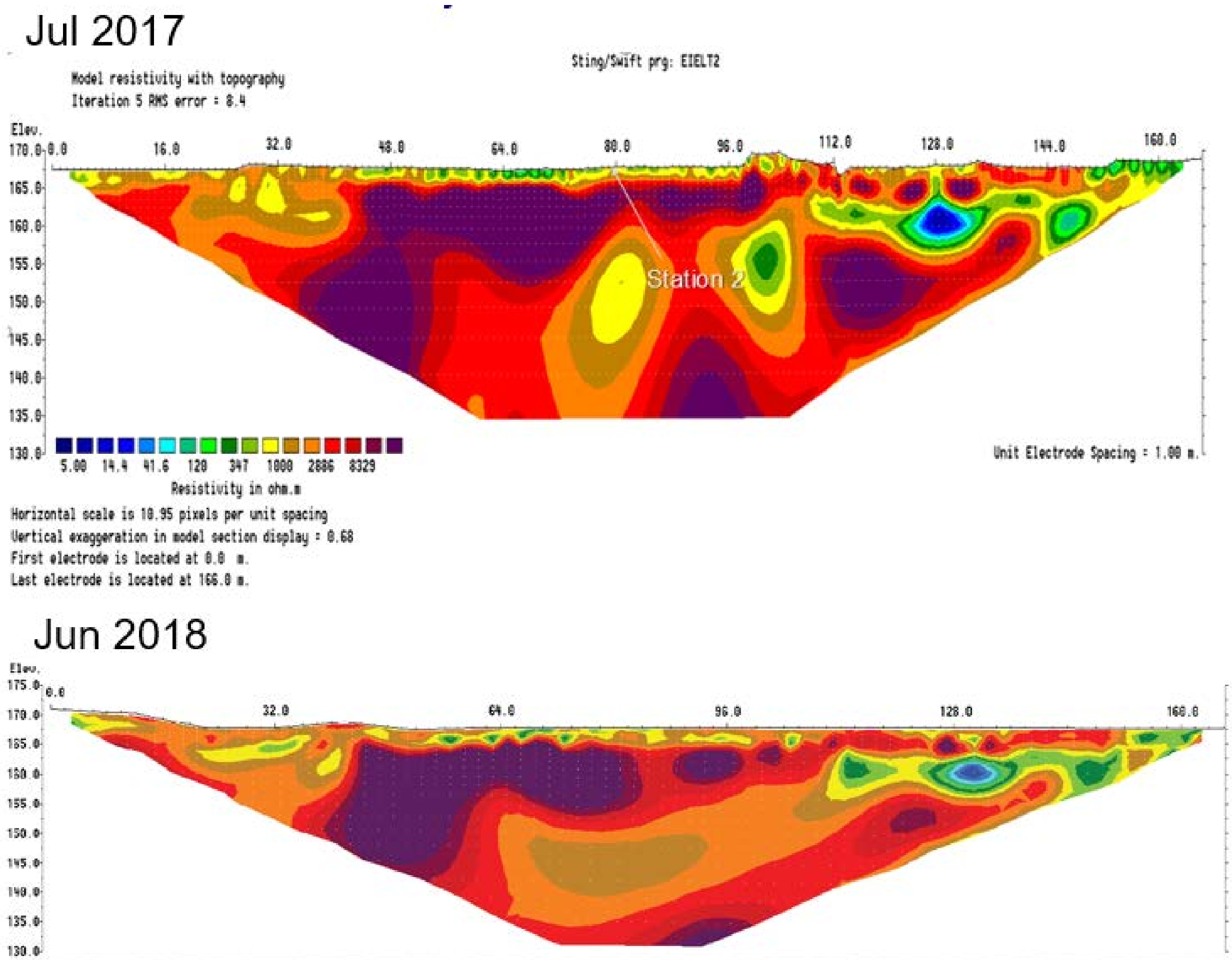

Figure 4.4: Transect Two Comparison. Note that despite the difference of one month in timing, the permafrost along Transect 2 appears to be largely unchanged from the previous year.

4.5 Comparison of Frost Probe Data from 2017 and 2018 for Transect One

While ERT provides large scale resolution about the condition of the permafrost, it is limited in its capability to provide numerical data on the depth of frost table. In order to overcome this uncertainty, we conducted frost probes along each transect to provide increased resolution about the frost table at this site. The frost probes were conducted adjacent to the ERT probes along each transect to ensure fidelity in comparing probe depth to the ERT. As I suspected from the ERT along Transect One, the frost depth in June 2018 was consistently shallower than the frost depth in July 2017. Figure 4.5 shows the depth of the frost probe between the two test dates and it clearly depicts a more frozen condition, likely due to the timing difference. This supports my hypothesis that conducting both the ERT and the frost probes at inconsistent dates does not provide accurate comparison from year to year. Once again, in order for there to be a fair comparison, the frost probes would need to be conducted on the same dates in order to provide conclusive evidence about the migration of the permafrost table.

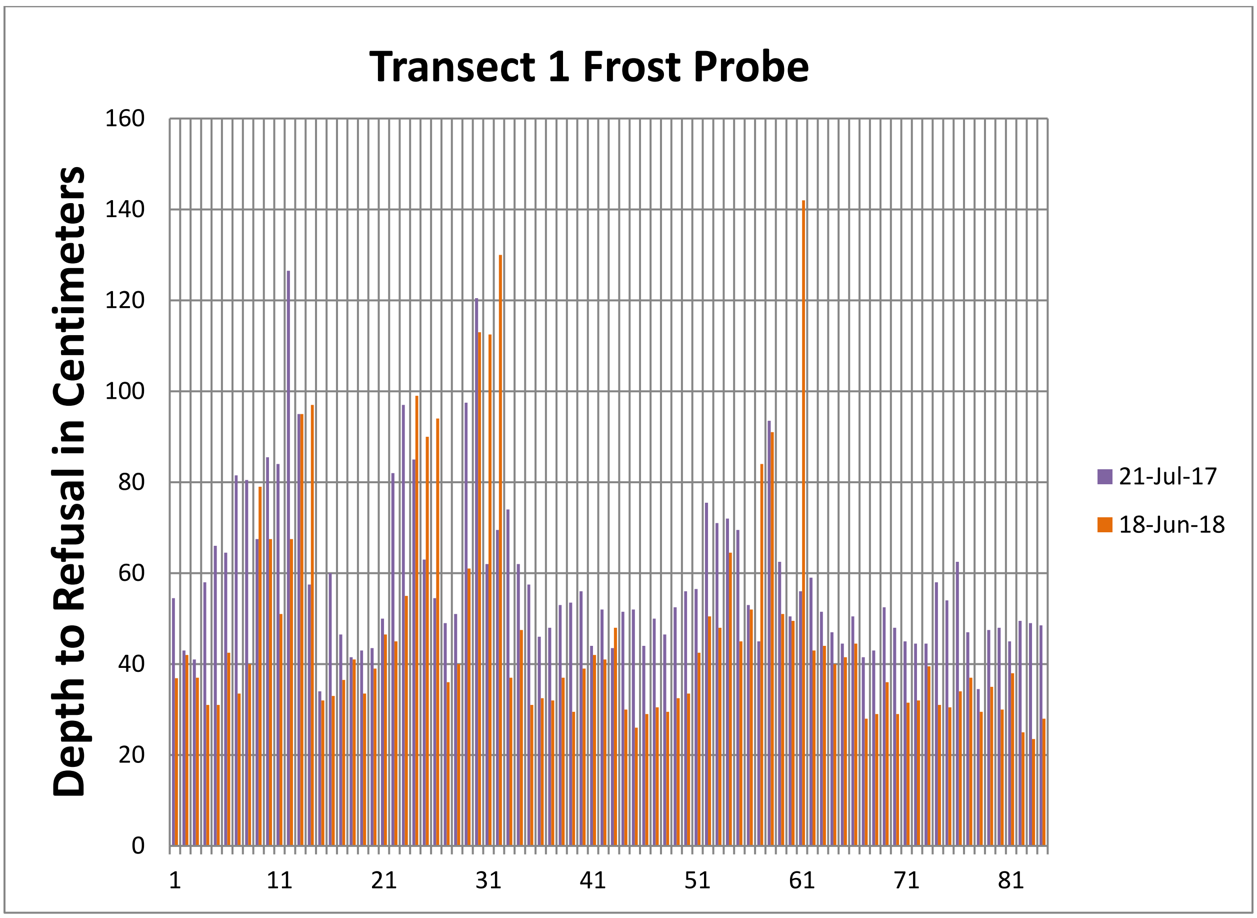

Figure 4.5: Transect One Frost Probe Depth Comparison

4.6 Comparison of Frost Probe Data from 2017 and 2018 for Transect Two

In order to provide fidelity for Transect 2 with the patterns observed in both the ERT comparison and the frost probe data collected on Transect One, I also elected to conduct a frost probe along Transect 2. Figure 4.6 demonstrates similar data patterns that I witnessed along Transect One. If anything, the decrease in frost depth from July 2017 to June 2018 is even more pronounced. This provides a fourth data point (in addition to ERT One and Two as well as the frost probe data from Transect One) that the conducting of these experiments early leads to an inaccurate comparison. This frost probe builds upon the body of evidence that the frost probes must be completed on as close to the same day as possible from year to year in order to be a credible and accurate comparison.

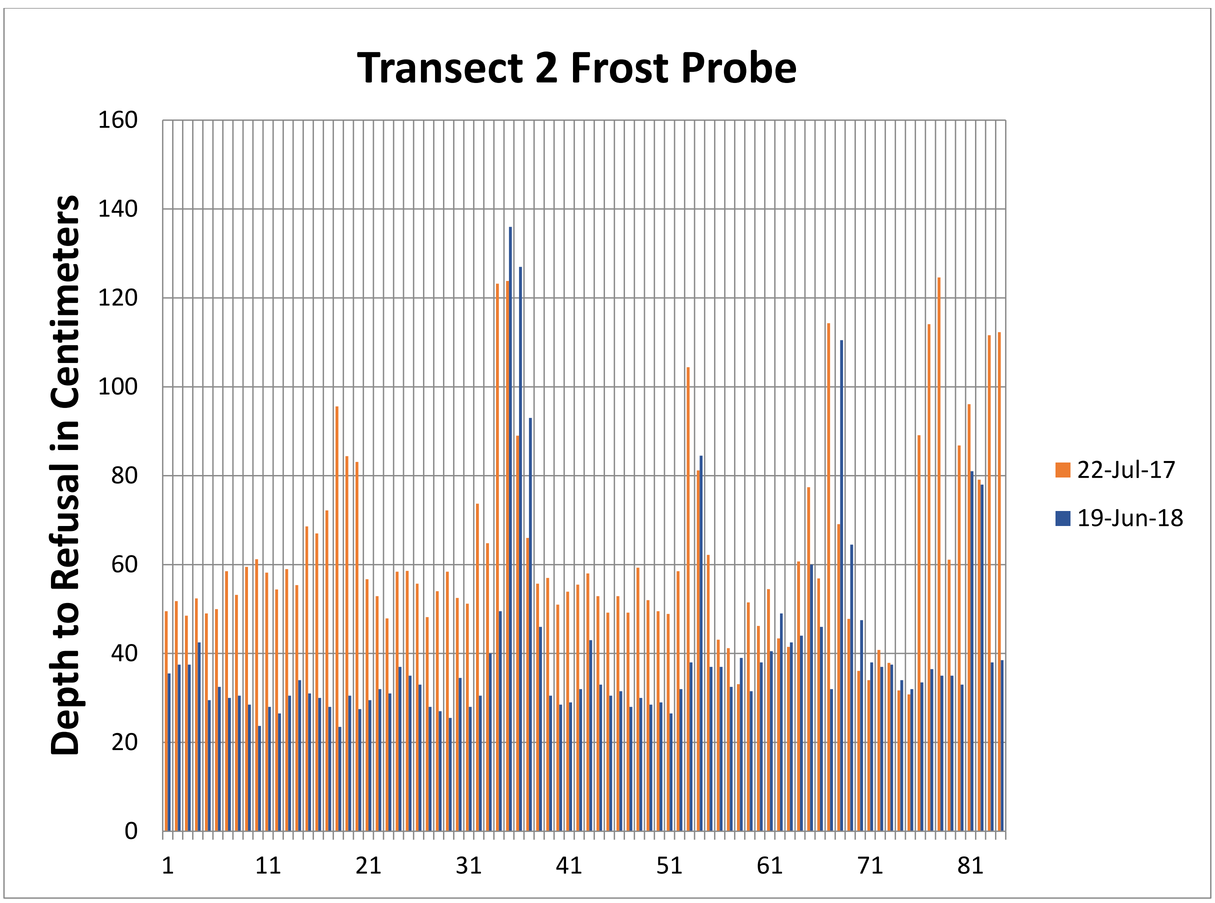

Figure 4.6: Transect Two Frost Probe Depth Comparison

4.7 Analysis of Temperature vs Time at Station One for All Depths

In order to visualize the temperature variations over time for the thermistor readings, I began by plotting the temperature readings at each depth over time in Figure 4.7. This shows the temperature fluctuations as the soils go through their annual freeze thaw cycle. By plotting the data in this way, it is possible to see how the temperature changes with both time and depth. The shallowest thermistors read the greatest temperature fluctuations while the deeper thermistors are less influenced by the season extremes of climate. At first glance, the deepest sensors appear to show no thermal variation at all; a behavior that is expected during permafrost observation. The other fluctuations are indicative of the formation and degradation of the freeze/thaw process in the active layer of the permafrost. As further analysis is conducted on this data, it will be possible to determine the depth of zero amplitude as well as compare the behaviors of Borehole One to Borehole Two.

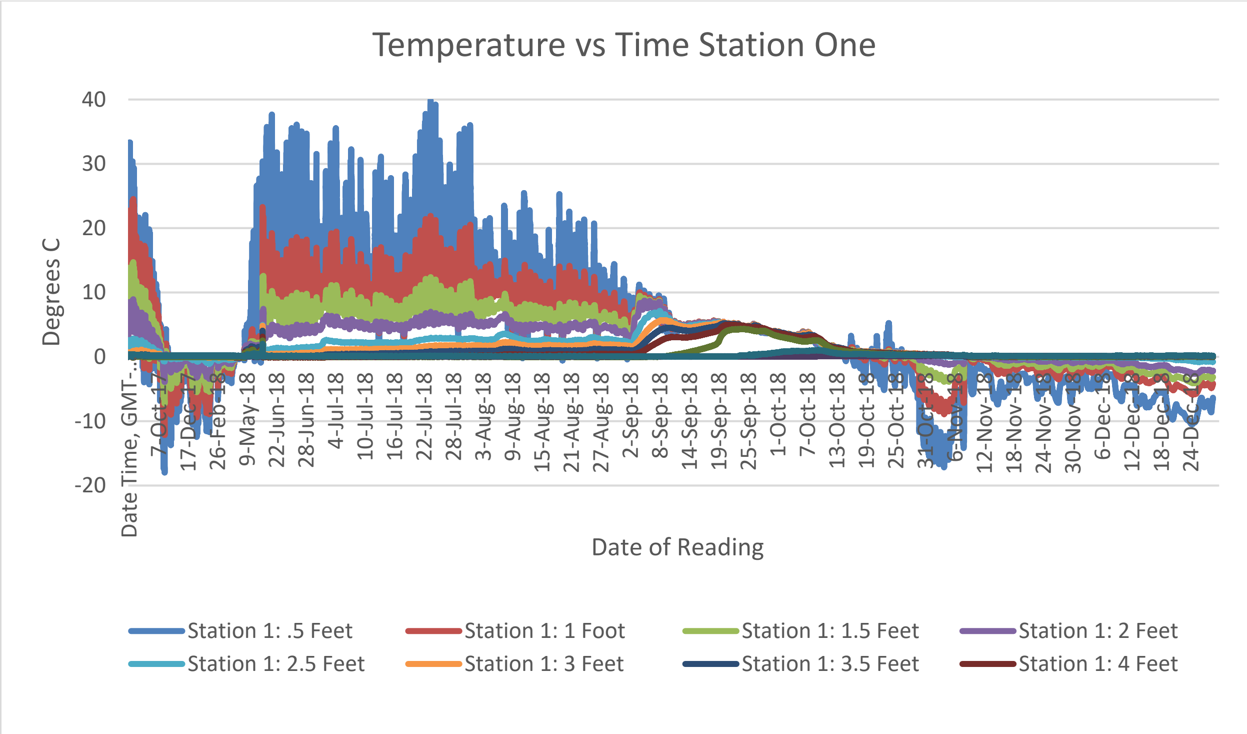

Figure 4.7: Temperature vs Time for Station One Depicting All Depths

4.8 Analysis of Temperature vs Time at Station Two for All Depths

In the same manner as Station One, I plotted the temperature at every depth versus time to see how it compared to the behavior at Station Two. It is immediately visible in Figure 4.8 that the amplitude of the temperature changes are significantly less than Station One, especially at the shallower depths. Specifically, the changes in the active layer are more indicative of typical permafrost active layer behavior whole the temperature swings at Station One are more extreme. This active layer appears to be shallower at Station Two, which is an indicator of healthier permafrost. Additionally, the depth of zero amplitude is also shallower, a second powerful indicator that the permafrost at Station Two is much healthier and cooler than at Station One. Given this initial analysis, it appears that there is something occurring at Station One that is causing a significant increase to the ground temperatures.

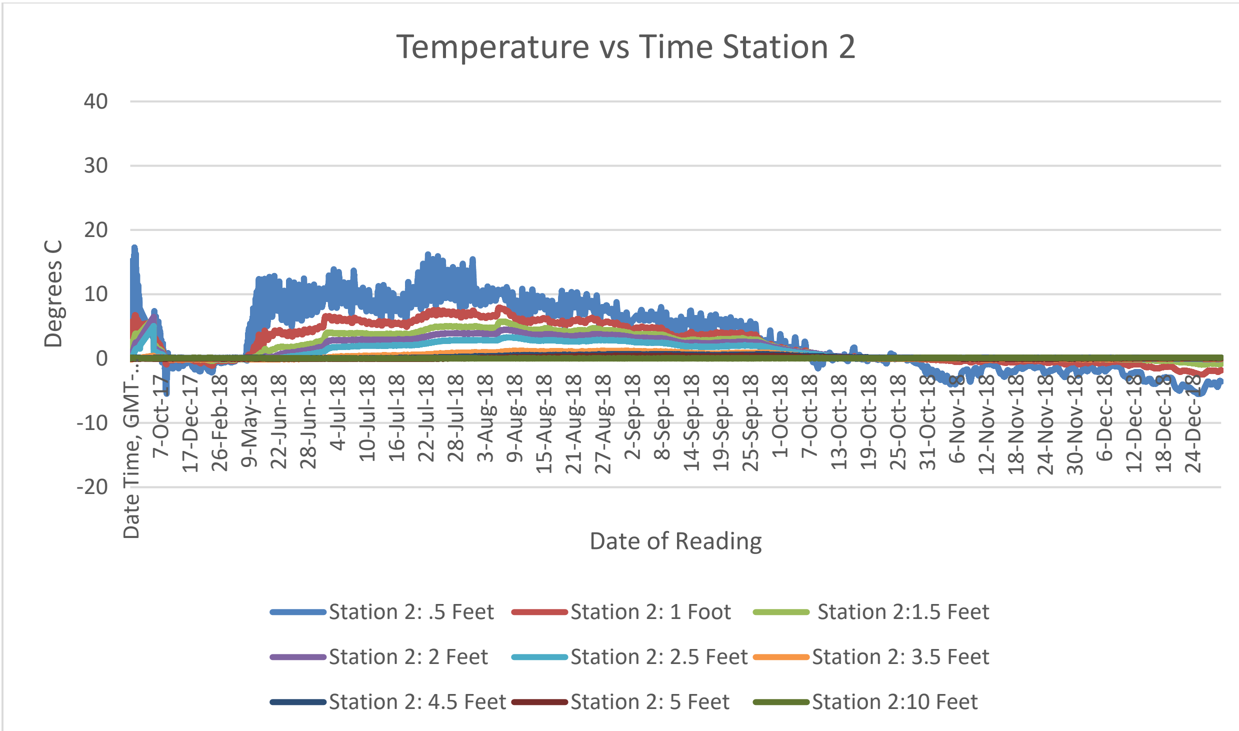

Figure 4.8: Temperature vs Time for Station Two Depicting All Depths

4.9 Analysis of Temperature vs Time at Stations One and Two at Depth of 0.5 Feet

While temperature at a depth of only six inches is not the best indicator of the health of the permafrost, it is a first glimpse into the behavior of the active layer. Figure 4.9 indicates that the temperature variations at Station One are much greater in amplitude and also significantly higher during the summer months and cooler during the winter months. This is an initial indicator that at the surface level there is less thermal buffer in the form of latent heat from the permafrost. Station Two's temperature is more indicative of permafrost behavior in that its fluctuations are far more tempered than Station Two and they are significantly less in magnitude. These both indicate that the permafrost depth is either much deeper at Station One or that there permafrost degradation at this site.

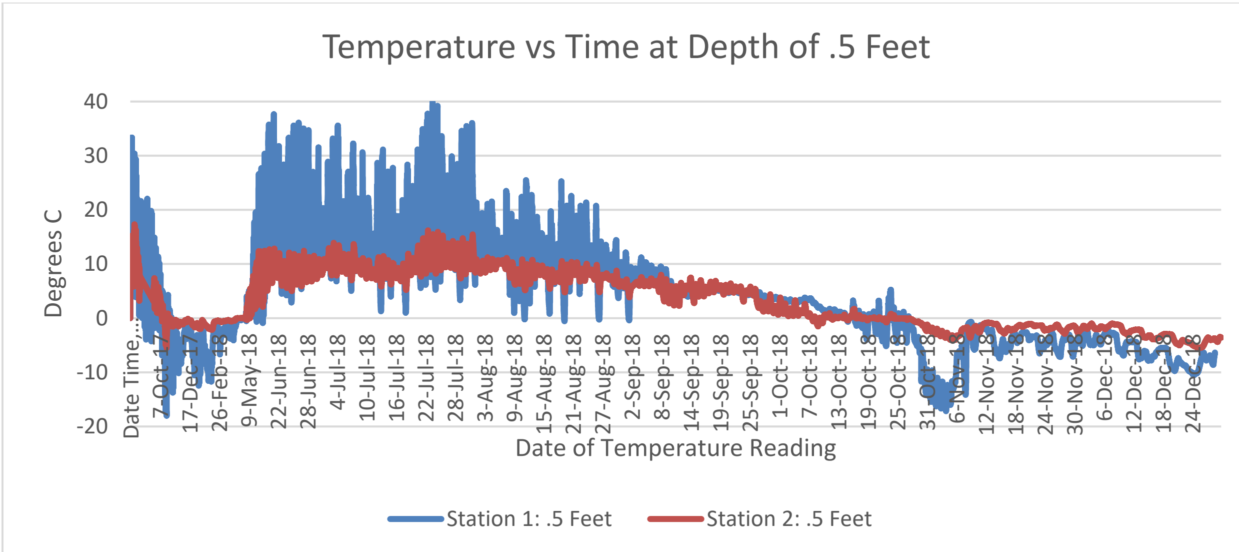

Figure 4.9: Temperature vs Time at Depth of 0.5 Feet

4.10 Analysis of Temperature vs Time at Stations One and Two at Depth of 1 Foot

Moving deeper into the active layer, similar patterns are visible at a depth of 1 foot. Figure 4.10 shows the fluctuations at Station One are much more dramatic and higher in temperature than Station Two. This is true of both the summer and winter months as once again Station One is warmer in the summer on average and colder on average than Station Two. Again this could indicate healthier permafrost at Station Two or permafrost degradation at Station One.

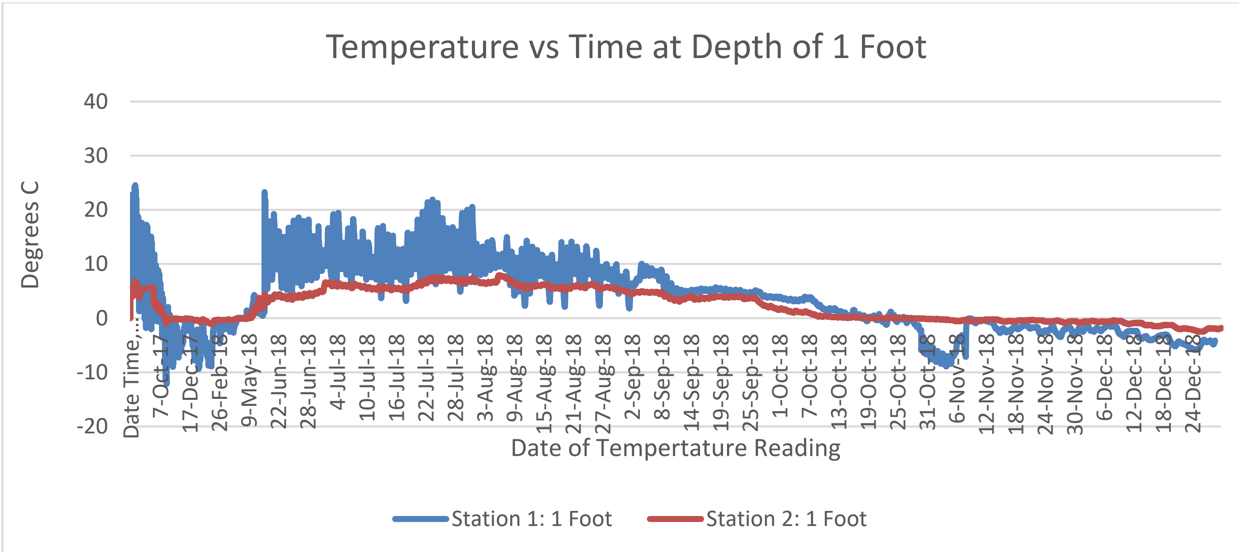

Figure 4.10: Temperature vs Time at Depth of 1 Foot

4.11 Analysis of Temperature vs Time at Stations One and Two at Depth of 1.5 & 2 Feet

The behavior at depths of 1.5 Feet and 2 Feet in Figures 4.11 and 4.12 show progressively cooler temperatures with depth as suspected. The behaviors again suggest seasonal formation and degradation of the active layer at both Stations with Station One continuing to show warmer temperatures as well as larger temperature fluctuations in both warm and cold seasons. Also note the thaw date is later and the freeze date is sooner as depth increases toward the depth of zero amplitude.

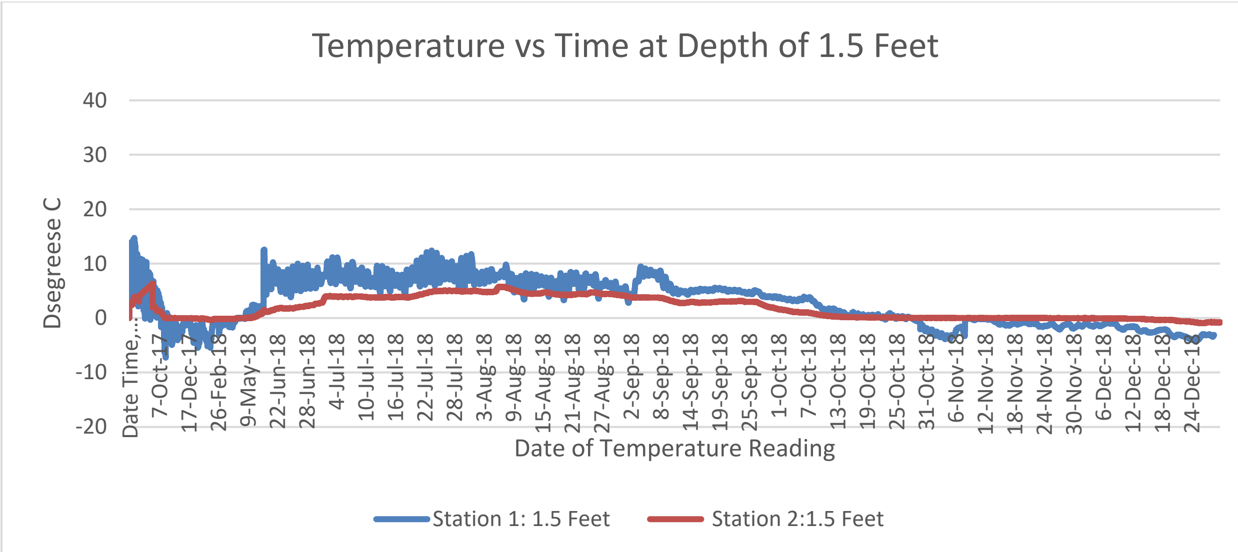

Figure 4.11: Temperature vs Time at Depth of 1.5 Feet

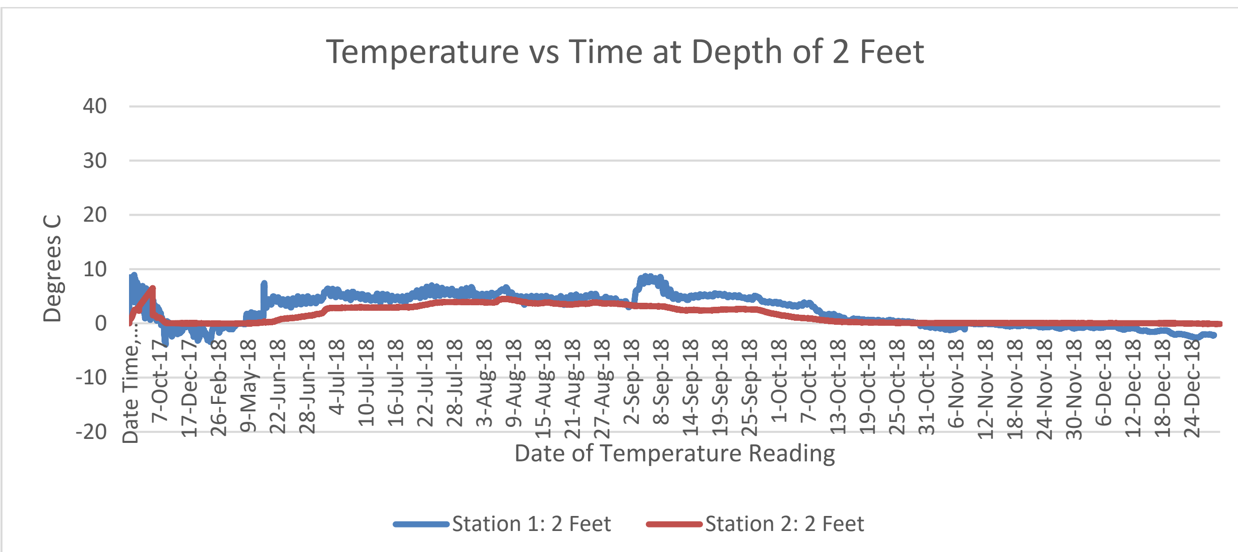

Figure 4.12: Temperature vs Time at Depth of 2 Feet

4.12 Analysis of Temperature vs Time at Stations One and Two at Depth of 2.5 Feet

Figures 4.13 depicts how the temperature difference between the two boreholes begins to diminish with depth. Additionally, the large temperature fluctuations present near the surface at Borehole One are reduced to a smoother curve, behavior more consistent with what we would expect with soil influenced by latent heat within ice.

However neither of these is yet in the permafrost since they still thaw out during the summer months. Of particular interest are the significant deviations in temperature between the two boreholes from early September to late November as well as an isolated peak in June. These trends also continue and will be summarized in Section 4.11.

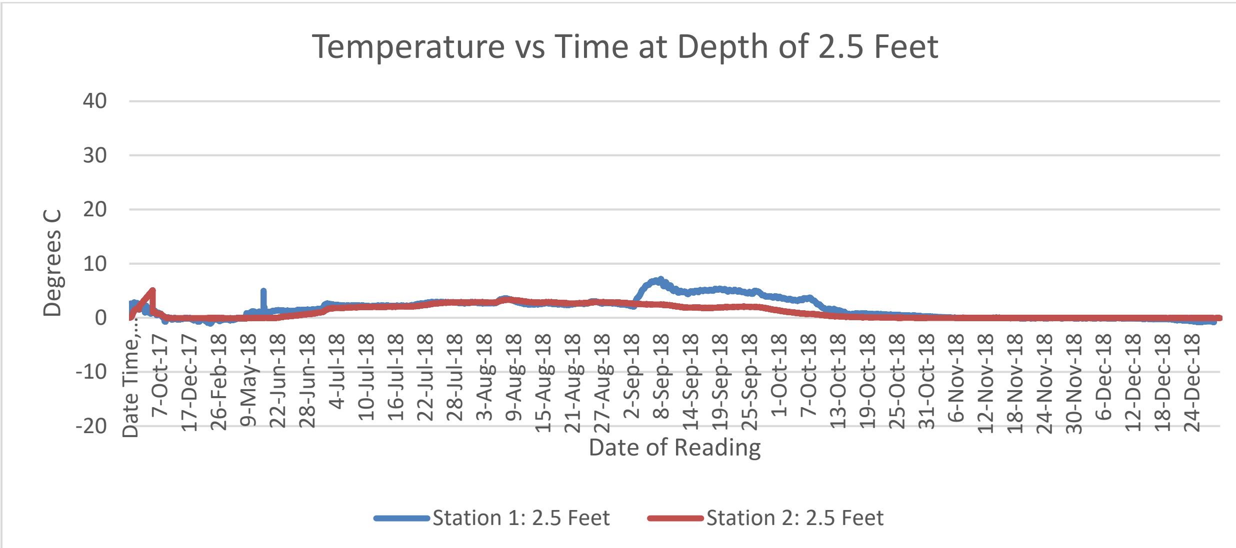

Figure 4.13: Temperature vs Time at Depth of 2.5 Feet

4.13 Analysis of Temperature vs Time at Stations One and Two at Depth of 3 Feet

The curves continue to flatten as they approach zero degrees Celsius, or the depth of zero amplitude of the permafrost. However, they still are slightly above freezing during the summer months and still cannot be considered permafrost. Once again there is a noticeable rise in temperature in late summer where the temperature in Station One significantly rises. Additionally, there is a localized spike in temperature still present from April through June. This is most likely due to the flooded condition of Borehole One. Since the borehole was filled with water, thermal energy flowed freely through the water column and brought heat down to the lower layers where it would not have otherwise been found naturally. This inaccurately recorded warmer temperatures than likely were actually present at that time. After the hole was drained during the June 2018 research trip and backfilled with sand to prevent the same anomaly in the future, the temperature appears to have re-stabilized to conditions more accurately reflective of their depth.

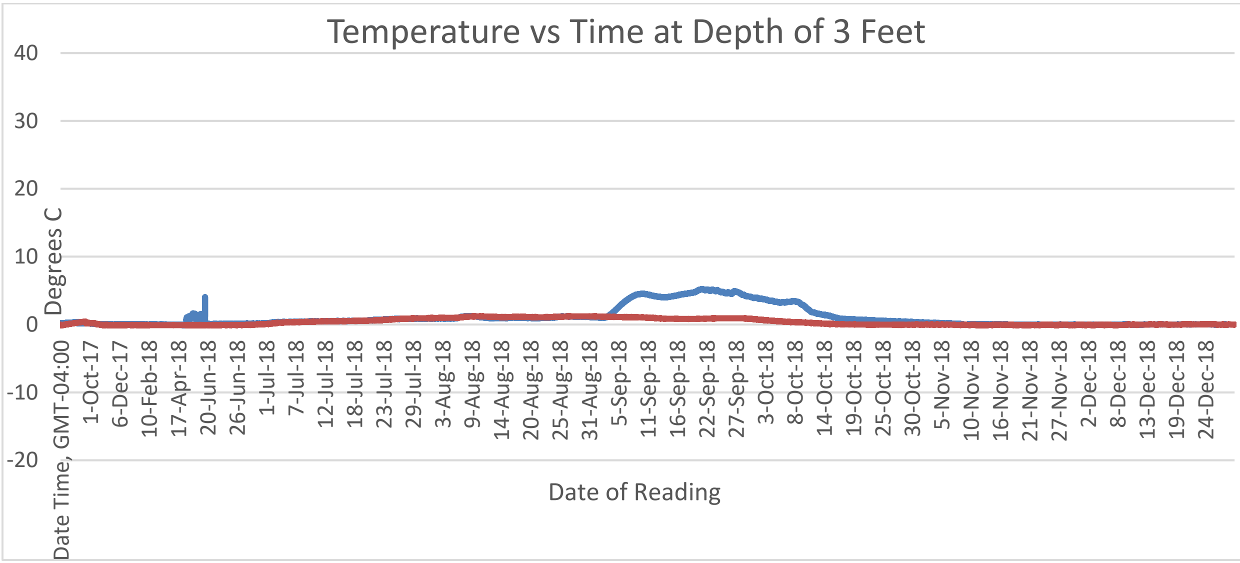

Figure 4.14: Temperature vs Time at Depth of 3 Feet

4.14 Analysis of Temperature vs Time at Stations One and Two at Depth of 5 Feet

Figure 4.15 shows Station Two is likely at or very near the depth of zero amplitude at this depth. The readings do show temperatures slightly above zero degrees Celsius, so the zero amplitude depth may in fact be slightly deeper. Regardless, there is very little thermal deviation present at Station Two for this depth, indicating that it is likely somewhere along the line of its latent heat of fusion. This indicates that it is vulnerable permafrost, but it is not possible to determine the amount latent heat remaining in those soils. Station One once again has a localized spike when the borehole flooded, and the same localized temperature delta in late summer is present in a similar fashion as at a depth of 3 feet.

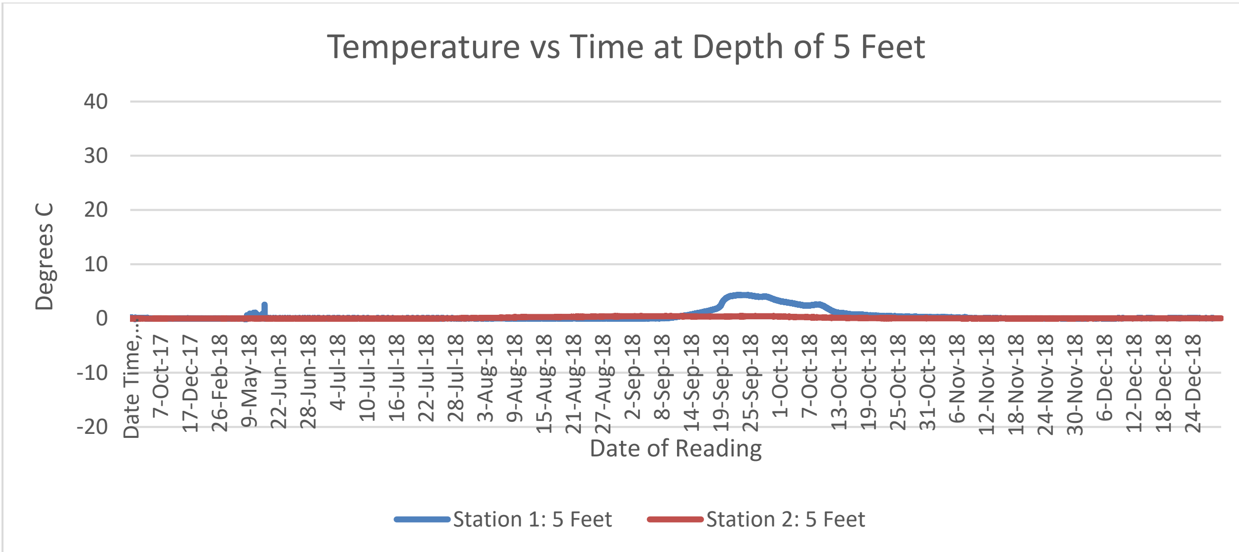

Figure 4.15: Temperature vs Time at Depth of 5 Feet

4.15 Analysis of Temperature vs Time at Stations One and Two at Depth of 10 Feet

With the given scale, there appears to be hardly any difference between either Stations with both hovering right around zero degrees. The localized peak from the flood is still slightly visible and there is a slight delta in late summer consistent with the shallower depths. Section 4.14 will take a closer look at those localized anomalies.

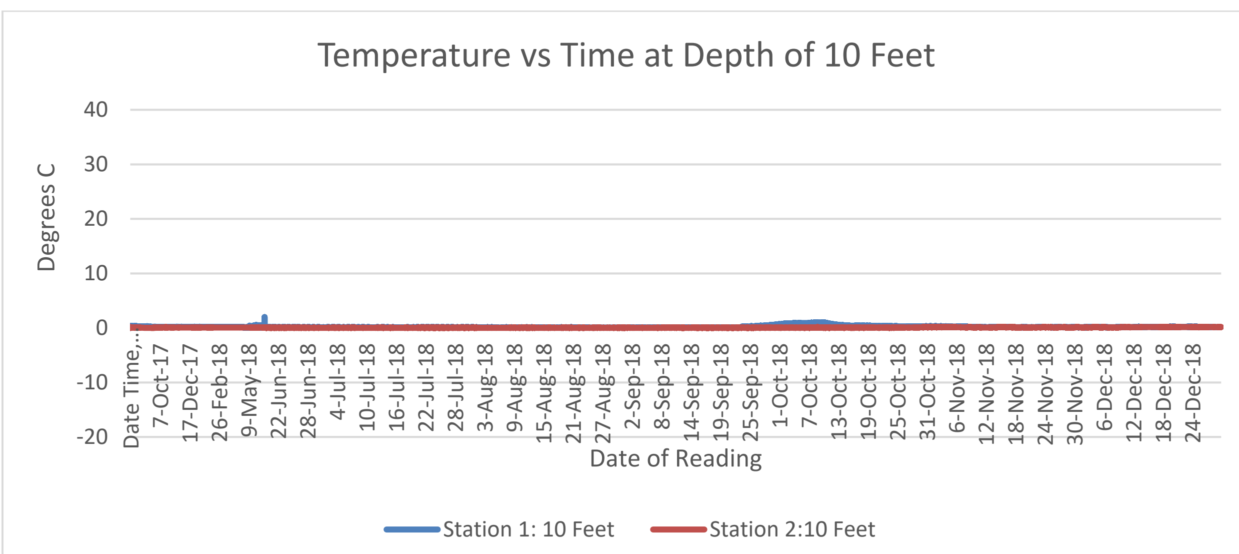

Figure 4.16: Temperature vs Time at Depth of 10 Feet

4.16 Small Scale Analysis of Temperature vs Time at Stations and Two at Depths of 3, 5, and 10 Feet

Figures 4.14-4.16 are the same as Figures 4.17-4.19 with the exception that the Y axis scale has been truncated in order to observe the temperature deltas, specifically the one from late August through November. This truncation serves to show the influence the flooded pipe had on the temperature from April through June. This spike was immediately abated by the draining of the water from Station One and resumed normal, characteristic behavior.

The temperature delta at the depths of 3, 5, and 10 feet between Station One and Station Two represent an interesting anomaly. At the depth of the feet the temperatures very closely mirrored one another until the beginning of September and then there was a rapid warming at this depth until freeze up in late November when they once again shared similar characteristics, At three feet, the temperature difference achieved a maximum delta of 4 degrees Celsius, a significant divergence in permafrost behaviors in such a short period of time. This pattern presents itself again at the depth of 5 feet. In this instance, Station One was indicating permafrost behaviors until once again there was a massive temperature increase in late September of 2018. Station Two indicated that it broke zero degrees during the summer, which is an indicator that it is also part of the active layer at this location but Station One appeared to be in permafrost until September 2018 at the depth of 5 feet. This same trend also occurred at a depth of 10 feet where, during the same time period, the thermistors registered a temperature of 1 degree prior to the winter freeze at Station One while Station Two is clearly within a healthy layer of permafrost.

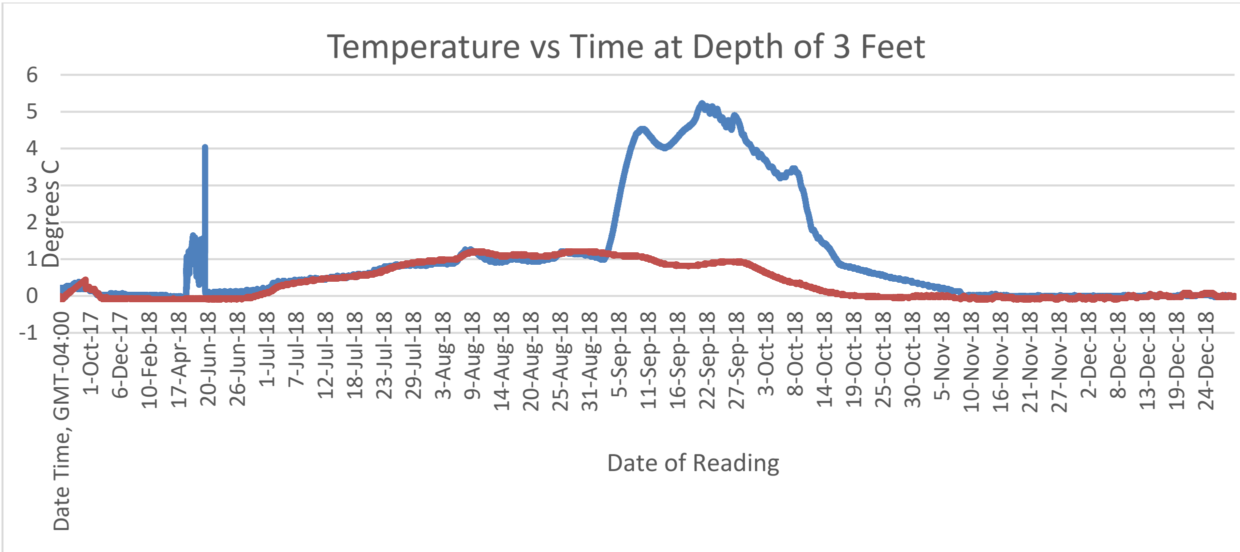

Figure 4.17: Small Scale Temperature vs Time at Depth of 3 Feet

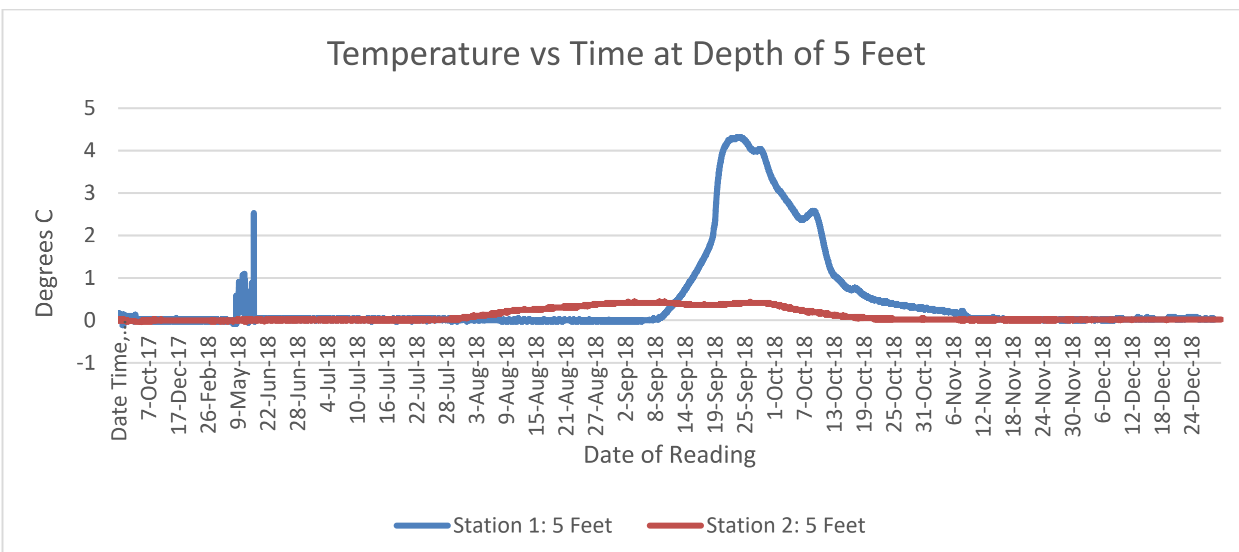

Figure 4.18: Small Scale Temperature vs Time at Depth of 5 Feet

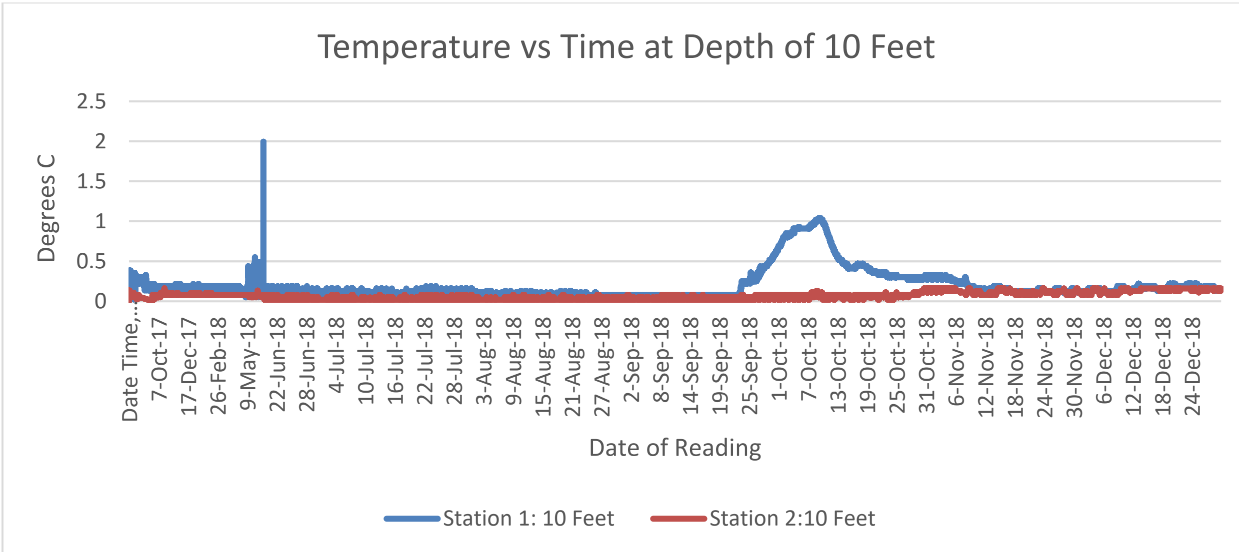

Figure 4.19: Small Scale Temperature vs Time at Depth of 10 Feet

4.17 Application of Thermodynamic Properties of Ice to Permafrost Behavior

Figure 4.20 depicts why scientists and this research initiative are witnessing a stalling of temperature changes in permafrost near zero degrees Celsius [40]. In order for one gram of ice in permafrost to raise in temperature by one degree Celsius, the ice must absorb 2.06 joules of thermal energy. However, in order for the same one gram of ice to completely melt, it must absorb 334 joules of thermal energy. Since the energy it takes to melt the permafrost is two orders of magnitude larger than to warm it, it makes sense that they are observing a stagnation in temperatures near the freezing point. For example, at some of the sites in the discontinuous zone, there was a fairly consistent observation of an increase in temperature of approximately 1.5 degrees during the 1980s and 1990s. This constitutes a thermal input of approximately 3.09 joules per gram of ice over the span of two decades. When compared with the heat of fusion required to melt that gram, it is revealed that the amount of energy needed to melt that gram of ice 108 times higher than the energy needed to raise it by 1.5 degrees. Although a significant oversimplification, it would take approximately 2160 years for the same permafrost system to completely deteriorate given that level of thermal input. The use of temperature as a mechanism for measuring changes to the permafrost is excellent for very cold permafrost that are not yet approaching the freezing point. However, the use of temperature as the only indicator of permafrost change breaks down as the temperature approaches the freezing point as temperature alone is not an indicator of absorption and consumption of the latent heat of fusion within the ice. In cases such as these, temperature alone becomes an ineffective indicator, and the measurement of unfrozen versus frozen water content becomes a better metric of how much heat of fusion is being absorbed [8]. Despite the warming climate, the permafrost temperature in ‘warm’ permafrost appears unaffected due to the latent heat of fusion [3].

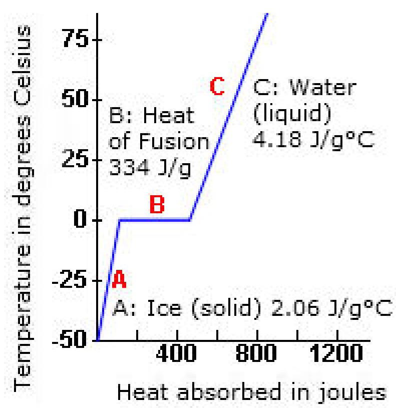

Figure 4.20 Energy Required for Ice Phase Change [40]

4.18 Analysis of Temperature Trends for Station One

Permafrost by definition soils that remain at or below zero degrees for more than one year. By this definition, there is no longer permafrost present at Station One down to a depth of 10 feet. At all depths down to 10 feet at Station One during 2018, the temperature rose to at least 1 degree above zero. This means that all of the permafrost at this location was likely melted after the June 2018 ERT. This claim is supported by the thermal data given at all depths, especially during the period of late September through early November 2018.

Additionally, I speculated that perhaps the melting would occur from underneath with the unfrozen ground beneath the bulb demonstrating expansion. This theory does not gain much support given this data set as temperatures decreased with depth even during the melting period at Station One. For example, during the melting period the peak temperature was 5, 4, and 1 degree at depths of 3, 5, and 10 feet respectively. If the bulb had melted from the bottom up, we would have seen the inverse of this phenomenon as thermodynamics dictates heat moving from warm to cold. Given this temperature trend, the preponderance of evidence indicates that the melting occurred from the top down, not the bottom up.

4.19 Analysis of Temperature Trends for Station Two

The data for Station Two indicates that there is still healthy permafrost at this location but that it is at the latent heat of fusion. The depth of zero amplitude for Station Two appears to be somewhere between 5 and 10 feet, but does indicate characteristic behavior indicative of permafrost at Station Two. Given the lack of large temperature swings as depths progress that were observed at Station One, the permafrost at Station Two is likely quite healthy. These smooth lines indicated continual influence of the permafrost's latent heat acting as a heat sink, which stabilizes the influence of climate on the permafrost below. However, if these lines begin to demonstrate increased changes in amplitude, I predict that the latent heat of fusion at this location to be degrading similarly to Station One. These rapid changes in amplitude demonstrate insufficient latent heat to temper the effect of climate and are likely to increase prior to the melting period witnessed in late summer like at the depths of 5 and 10 feet at Station One.

V. Conclusions and Recommendations

5.1 Significance of Timing on Studying Permafrost Active Layer

Near surface permafrost behavior varies with seasonal fluctuations as seen in the temperature trends in Chapter 4. These trends are an expected behavior of the active layer and in order to compare them accurately from year to year it needs to be done on or as close as possible to the same exact date. As was shown with both the ERT scans and the frost probes, it is not possible to make any meaningful comparisons by doing the two scans over a month apart, with the first having been done in July and the second being conducted in June. As the data in chapter 4 showed, the greatest changes to the permafrost occur during the summer months and improper timing will lead to improper conclusions. In order to mitigate this in future years, should this research be continued, the ERT scans and frost probes need to be conducted on the same date. Furthermore, I would recommend that this agreed upon date be in late summer, preferably August or September, which would reveal the greatest changes after the impact of the annual thaw cycle has run its course.

5.2 Overcoming Challenges in Measuring Latent Heat of Fusion

Chapter 3 analyzed the magnitude of the latent heat of fusion compared with the amount of energy required to raise the temperature of the ice with the former being two orders of magnitude larger. Consequently, it takes far less energy to raise the temperature of the ice than to initiate the phase change. The data collected using the ERT scans and the frost probes are a non-temperature-based mechanism by which we can monitor permafrost degradation activities. Even though, the timing was off to make a fair comparison between the state of the active layer between 2017 and 2018, it did serve the purpose of demonstrating that non-thermal measuring could be effectively used to monitor changes to the permafrost.

The thermistor strings at Stations One and Two provided accurate data useful in monitoring the permafrost at this site, but the trends in the data highlighted a key limitation of relying too heavily on temperature-based permafrost monitoring. In soils where latent heat is not present in the form of ice, temperature serves as an accurate means of measuring the thermal condition of the soil. This is substantiated by the temperature fluctuations observed at both Stations One and Two in the active layers. Input or extraction of energy into the ground in these instances contributed directly to an increase or decrease in temperature correspondent to that materials specific heat. However, in the deeper, and inactive portions of the permafrost at this site, temperature begins to break down as an indicator of permafrost condition.

Given the data for this site, the permafrost at this location is at or very near zero degrees Celsius. This poses a unique challenge in monitoring the permafrost at this site using temperature. Since this permafrost is already at the temperature of fusion, there can be significant input or loss of energy into this system without triggering any kind of temperature indication. Depending on how much additional heat of fusion capacity is available, there could be significant thermal changes in one season and they would go undetected since the temperature reading would still read zero degrees Celsius. Because of this characteristic of permafrost at zero degrees, boreholes alone become an ineffective means of monitoring permafrost health, as they are incapable of measuring the latent heat remaining in a specific soil sample.

Take for example the temperature at both stations at the depth of 10 feet, the deepest thermistor on each string at both boreholes. At this depth the temperature changes should be the most subtle as they are the most insulated from the seasonal effects of climate. The temperature of the permafrost at both Station One and Station Two early in the study both read approximately zero degrees. However, without any indication, Station One began reading above zero in September 2018. This indicates that at this time, thermal inputs into the soil at this depth overcame the heat of fusion and caused the permafrost to undergo a phase change, melting it down to a depth of 10 feet at this site. While this permafrost melted, the temperature at Station Two remained constant and frozen at this depth.

Due to this challenging characteristic associated with permafrost at the freezing/thaw temperature, additional mechanisms need to be employed in order to accurately monitor permafrost changes (in this instance being ERT and frost probing). While temperature is a good indicator of when the permafrost melts, it does not inform researchers well as to the health of a given sample of permafrost at zero degrees. There could be significant changes occurring, and these changes would not trigger a change in temperature reading. In order to overcome this challenge, I recommend continuing to monitor temperatures at these two Stations but ERT and frost probing would need to be employed at this site in order to further understand how this permafrost is changing.

5.3 Thermal Impact of Localized Hydrology Changes on Permafrost Condition

The permafrost at Station One melted significantly faster than previously hypothesized. There are likely two explanations for this rapid change. The first is that the permafrost at Station One was already dangerously close to undergoing its phase change and this phase change happened due to climatological influence during September 2018. While this would constitute a very well-timed coincidence, it cannot be excluded as a possibility. The second possibility is what I believe to be the more likely explanation. The slough near Station One previously was unaffected by construction activities or military operations on Eielson AFB. However, due to the expansions on the south loop associated with the F-35 beddown, there was an increase in the amount of impervious surfaces in that portion of the installation. Therefore, there was increased storm water runoff and discharge that would have occurred during the summer of 2018. This specific slough was a part of this storm water runoff plan and likely began to experience an increased flow of water through this system during the summer months. This storm water would have collected energy from the atmosphere as it fell to the ground and further increased in energy as it came into contact with pavements or buildings and their associated storm water systems prior to being discharged into this slough. This thermal input into this system would be greater than the naturally experienced thermal equilibrium achieved by this system over time and could have led to the accelerated degradation of the permafrost at Station One.

5.4 Recommendation of Introduction of Hydrological Monitoring

Currently, ERT, frost probes, and borehole thermistor strings are being used to monitor the permafrost at this location. In order to investigate the impact of localized changes in surface hydrology and its potential impact on the permafrost along the slough, I recommend including hydrological monitoring on this slough in order to more accurately understand the influence of storm water discharge on permafrost on Eielson AFB.

5.5 Equipment and Procedural Upgrades for Future Studies and Lessons Learned

Should this research be continued, there are several lessons learned and improvements that could be made moving forward. The first and most pressing would be the necessity of purchasing additional data plans for both Station One and Station Two as well as for the weather station. These current one-year plans will expire in June and the data would only be able to be accessed via manual download at the sensors on Eielson AFB. The second lesson learned would be to reduce the amount of data collected to one data point per day at a specified time. The current collection interval of 5 minutes proved more cumbersome than useful in modeling the permafrost behavior. This would also be in line with other similar research initiatives by other institutions studying permafrost. This would create a far more analytically friendly data set. Additionally, I recommend configuring the thermistor strings by their numerical serial number in future studies, as this is how Hobolink records the data. This would reduce data formatting time as the data would be recorded in the appropriate order as sensors increased in depth. The final recommendation would be to repair the weather station in order to more accurately investigate the significance of climate on this permafrost. The weather station was installed in June 2018 and no longer transmitted data after October, giving me only 5 months of weather data, which is insufficient to meaningfully include into this study. Of primary interest would be seeing if the MAAT is indicative of permafrost formation, permafrost maintenance, or permafrost degradation and comparing that information to what is occurring at Station One and Two. Should this information become necessary, I could substitute in the weather data for North Pole, AK until the weather station can be repaired.

5.6 Recommendation of Inclusion of Permafrost in Environmental Impact Statement

As with any military construction project, there is a difficult balance between being good stewards of the environment and successfully executing the missions with which we have been entrusted. Going forward, I recommend including permafrost disturbance and degradation in environmental impact surveys for military construction projects in the Arctic. Changes to permafrost are most often irreversible and can result in increased carbon and methane emission, erosion, differential settling, and the loss of real estate's suitability for future development. In order to better understand the implication of construction on permafrost, I recommend including permafrost into the planning considerations for a construction project. Not only is it a challenging engineering obstacle to overcome, but something that needs to be considered in the long-term health of our military infrastructure and the impact our military operations have on the environment. One of the means of mitigating the effects witnessed in this study would be to divert storm water runoff into areas that do not contain permafrost when configuring runoff plans for areas located in discontinuous permafrost.

5.7 Station Two Permafrost Monitoring and Addition of Third Station

The data collected in this study points to the conclusion that the permafrost at Station One has degraded to a depth of ten feet. However, I recommend continuing monitoring at this station to see if there are any long-term trends associated with the depth at 10 feet. Specifically, if the thaw point becomes earlier and the freeze point becomes later. This would point to continue degradation and deepening of the active layer. Also long-term monitoring of depth of zero amplitude at Station Two would show if the permafrost in that area is stable or if in fact it is degrading as well. Given the fact that Station One degraded sooner than anticipated, there could be an addition of a third station along Transect One, which would make Station Two the new experimental station and Station Three the new control if we expect a continued thermal impact from the slough and South Loop activities outward from those sites. Continued understanding of permafrost and its impact to our infrastructure and environment will lead to more informed engineering decisions in the Arctic, more effective infrastructure, and improved mission readiness for the Air Force at high latitudes.

5.8 Collaboration with University of Alaska Fairbanks

During his site visit, Dr. Debu Misra from UAF expressed interest in partnering with AFIT to analyze this data. UAF is also collocated with the Alaska Geophysical institute, which also specializes in permafrost research. By partnering with these institutions, we can leverage their expertise on this subject matter in order to conduct more detailed analysis of the existing data set and any data collected in the future. Given the fact that hydrology is likely playing an important role in the degradation of the permafrost at this site, partnering with Dr. Misra could improve our understanding of the changes happening at Station One. He proposed using this data set as a capstone for one of his classes he teaches at UAF. Through this cooperation, I can achieve improved data analytics from these experts at zero cost.

5.9 Groundwater Contaminant Tranport via Permafrost Degradation

There are contaminated soils located across Eielson AFB, an unfortunately common occurance across Air Force installations. During the excavations conducted for F-35 beddown construction, there are piles of contaminated soils located across the installation awaiting transport to a hazardous waste disposal facility, illustrating the prevalance of contamination. As permafrost warms and the water it contains changes phase, groundwater will begin to flow in places where it was previously frozen. This creates an opportunity for contaminants that were perhaps previously locked in ice an avenue for transport and disposition via groundwater transport. This remains only a hypothesis at this time, but given the prevalance of contaminants and strong evidence of permafrost degredation, it merits investigating if permafrost melting could create a mode of transport for groundwater bourne contaminants.

Appendix A: ERT and Frost Probe GPS Points

Point Name	Latitude	Longitude	Elevation (M)
1	W 147° 2' 35.642"	N 64° 38' 55.602"	167.830
2	W 147° 2' 35.596"	N 64° 38' 55.541"	167.91
3	W 147° 2' 35.517"	N 64° 38' 55.485"	167.754
4	W 147° 2' 35.443"	N 64° 38' 55.428"	167.59
5	W 147° 2' 35.366"	N 64° 38' 55.374"	167.556
6	W 147° 2' 35.291"	N 64° 38' 55.317"	167.502
7	W 147° 2' 35.217"	N 64° 38' 55.264"	167.607
8	W 147° 2' 35.145"	N 64° 38' 55.206"	167.494
9	W 147° 2' 35.068"	N 64° 38' 55.149"	167.454
10	W 147° 2' 34.998"	N 64° 38' 55.093"	167.356
11	W 147° 2' 34.919"	N 64° 38' 55.038"	167.464
12	W 147° 2' 34.844"	N 64° 38' 54.983"	167.546
13	W 147° 2' 34.769"	N 64° 38' 54.928"	167.687
14	W 147° 2' 34.698"	N 64° 38' 54.871"	167.671
15	W 147° 2' 34.628"	N 64° 38' 54.815"	167.646
16	W 147° 2' 34.550"	N 64° 38' 54.756"	167.668
17	W 147° 2' 34.484"	N 64° 38' 54.699"	167.8
18	W 147° 2' 34.413"	N 64° 38' 54.643"	167.774
19	W 147° 2' 34.332"	N 64° 38' 54.588"	167.75
20	W 147° 2' 34.260"	N 64° 38' 54.531"	167.757
21	W 147° 2' 34.189"	N 64° 38' 54.476"	167.904
22	W 147° 2' 34.109"	N 64° 38' 54.420"	167.812
23	W 147° 2' 34.038"	N 64° 38' 54.364"	167.953
24	W 147° 2' 33.957"	N 64° 38' 54.310"	167.956
25	W 147° 2' 33.886"	N 64° 38' 54.253"	168.031
26	W 147° 2' 35.719"	N 64° 38' 55.640"	167.966
27	W 147° 2' 35.831"	N 64° 38' 55.703"	167.726
28	W 147° 2' 35.926"	N 64° 38' 55.778"	167.917
29	W 147° 2' 35.972"	N 64° 38' 55.809"	167.948
30	W 147° 2' 35.974"	N 64° 38' 55.815"	167.867
31	W 147° 2' 36.046"	N 64° 38' 55.867"	167.825
32	W 147° 2' 36.132"	N 64° 38' 55.921"	167.916
33	W 147° 2' 36.208"	N 64° 38' 55.976"	168.026
34	W 147° 2' 36.443"	N 64° 38' 56.074"	172.628
35	W 147° 2' 36.389"	N 64° 38' 56.110"	169.545
36	W 147° 2' 36.456"	N 64° 38' 56.107"	170.81
37	W 147° 2' 33.804"	N 64° 38' 54.200"	168.101

38	W 147° 2' 33.732"	N 64° 38' 54.142"	168.129
39	W 147° 2' 33.655"	N 64° 38' 54.087"	168.18
40	W 147° 2' 33.520"	N 64° 38' 54.023"	171.531
41	W 147° 2' 33.502"	N 64° 38' 53.965"	167.482
42	W 147° 2' 33.198"	N 64° 38' 53.826"	171.032
43	W 147° 2' 41.061"	N 64° 38' 54.314"	167.302
44	W 147° 2' 41.003"	N 64° 38' 54.307"	167.341
45	W 147° 2' 40.875"	N 64° 38' 54.332"	167.424
46	W 147° 2' 40.758"	N 64° 38' 54.372"	167.444
47	W 147° 2' 40.628"	N 64° 38' 54.402"	167.671
48	W 147° 2' 40.501"	N 64° 38' 54.438"	167.75
49	W 147° 2' 40.371"	N 64° 38' 54.470"	167.752
50	W 147° 2' 40.248"	N 64° 38' 54.503"	167.851
51	W 147° 2' 40.124"	N 64° 38' 54.533"	167.729
52	W 147° 2' 39.978"	N 64° 38' 54.569"	167.757
53	W 147° 2' 39.857"	N 64° 38' 54.600"	167.738
54	W 147° 2' 39.719"	N 64° 38' 54.635"	167.738
55	W 147° 2' 39.588"	N 64° 38' 54.666"	167.696
56	W 147° 2' 39.462"	N 64° 38' 54.696"	167.674
57	W 147° 2' 39.214"	N 64° 38' 54.764"	167.47
58	W 147° 2' 39.173"	N 64° 38' 54.783"	167.43
59	W 147° 2' 39.077"	N 64° 38' 54.798"	167.474
60	W 147° 2' 38.953"	N 64° 38' 54.826"	167.314
61	W 147° 2' 38.816"	N 64° 38' 54.861"	167.352
62	W 147° 2' 38.688"	N 64° 38' 54.893"	167.447
63	W 147° 2' 38.550"	N 64° 38' 54.922"	167.34
64	W 147° 2' 38.429"	N 64° 38' 54.949"	167.176
65	W 147° 2' 38.291"	N 64° 38' 54.984"	167.077
66	W 147° 2' 38.149"	N 64° 38' 55.011"	166.974
67	W 147° 2' 38.024"	N 64° 38' 55.045"	166.997
68	W 147° 2' 37.897"	N 64° 38' 55.077"	166.685
69	W 147° 2' 37.766"	N 64° 38' 55.105"	166.748
70	W 147° 2' 37.630"	N 64° 38' 55.142"	166.733
71	W 147° 2' 37.500"	N 64° 38' 55.170"	166.706
72	W 147° 2' 37.381"	N 64° 38' 55.199"	166.884
73	W 147° 2' 37.245"	N 64° 38' 55.231"	167.284
74	W 147° 2' 37.108"	N 64° 38' 55.264"	167.729
75	W 147° 2' 36.982"	N 64° 38' 55.291"	167.994
76	W 147° 2' 36.844"	N 64° 38' 55.322"	167.968
77	W 147° 2' 36.704"	N 64° 38' 55.352"	168.06
78	W 147° 2' 36.580"	N 64° 38' 55.382"	168.001

79	W 147° 2' 36.438"	N 64° 38' 55.415"	167.911
80	W 147° 2' 36.306"	N 64° 38' 55.444"	167.92
81	W 147° 2' 36.176"	N 64° 38' 55.477"	167.903
82	W 147° 2' 36.043"	N 64° 38' 55.505"	168.066
83	W 147° 2' 35.915"	N 64° 38' 55.534"	168.005
84	W 147° 2' 35.782"	N 64° 38' 55.565"	168.06
85	W 147° 2' 35.668"	N 64° 38' 55.596"	167.923
86	W 147° 2' 35.613"	N 64° 38' 55.606"	167.996
87	W 147° 2' 35.521"	N 64° 38' 55.635"	168.004
88	W 147° 2' 35.392"	N 64° 38' 55.663"	167.949
89	W 147° 2' 35.256"	N 64° 38' 55.694"	167.951
90	W 147° 2' 35.122"	N 64° 38' 55.726"	167.785
91	W 147° 2' 34.990"	N 64° 38' 55.756"	167.735
92	W 147° 2' 34.858"	N 64° 38' 55.792"	167.638
93	W 147° 2' 34.736"	N 64° 38' 55.820"	167.754
94	W 147° 2' 34.604"	N 64° 38' 55.854"	167.626
95	W 147° 2' 34.473"	N 64° 38' 55.885"	167.423
96	W 147° 2' 34.342"	N 64° 38' 55.916"	167.398
97	W 147° 2' 34.213"	N 64° 38' 55.947"	167.48
98	W 147° 2' 34.072"	N 64° 38' 55.977"	167.59
99	W 147° 2' 33.950"	N 64° 38' 56.016"	167.541
100	W 147° 2' 33.818"	N 64° 38' 56.043"	167.419
101	W 147° 2' 33.681"	N 64° 38' 56.076"	167.496
102	W 147° 2' 33.549"	N 64° 38' 56.110"	167.398
103	W 147° 2' 33.418"	N 64° 38' 56.144"	167.454
104	W 147° 2' 33.294"	N 64° 38' 56.171"	167.478
105	W 147° 2' 33.157"	N 64° 38' 56.202"	167.519
106	W 147° 2' 33.014"	N 64° 38' 56.234"	167.534
107	W 147° 2' 32.902"	N 64° 38' 56.259"	167.583
108	W 147° 2' 32.759"	N 64° 38' 56.286"	167.576
109	W 147° 2' 32.621"	N 64° 38' 56.316"	167.511
110	W 147° 2' 32.490"	N 64° 38' 56.345"	167.631
111	W 147° 2' 32.346"	N 64° 38' 56.370"	167.624
112	W 147° 2' 32.217"	N 64° 38' 56.388"	168.313
113	W 147° 2' 32.082"	N 64° 38' 56.428"	167.93
114	W 147° 2' 31.950"	N 64° 38' 56.457"	167.941
115	W 147° 2' 31.808"	N 64° 38' 56.481"	167.927
116	W 147° 2' 31.688"	N 64° 38' 56.514"	167.955
117	W 147° 2' 31.544"	N 64° 38' 56.543"	167.93
118	W 147° 2' 31.407"	N 64° 38' 56.568"	167.781
119	W 147° 2' 31.268"	N 64° 38' 56.593"	167.797

120	W 147° 2' 31.130"	N 64° 38' 56.622"	167.807
121	W 147° 2' 30.853"	N 64° 38' 56.680"	168.115
122	W 147° 2' 30.723"	N 64° 38' 56.701"	168.038
123	W 147° 2' 30.589"	N 64° 38' 56.728"	167.821
124	W 147° 2' 30.451"	N 64° 38' 56.758"	167.955
125	W 147° 2' 30.317"	N 64° 38' 56.788"	167.802
126	W 147° 2' 30.188"	N 64° 38' 56.817"	168.005
127	W 147° 2' 30.038"	N 64° 38' 56.841"	167.904
128	W 147° 2' 30.929"	N 64° 38' 56.663"	167.802
129	W 147° 2' 36.502"	N 64° 38' 56.203"	168.778
130	W 147° 2' 36.580"	N 64° 38' 56.257"	168.189
131	W 147° 2' 36.653"	N 64° 38' 56.307"	168.431
132	W 147° 2' 36.813"	N 64° 38' 56.366"	166.638
133	W 147° 2' 36.797"	N 64° 38' 56.430"	167.76
134	W 147° 2' 36.897"	N 64° 38' 56.498"	167.801
135	W 147° 2' 36.951"	N 64° 38' 56.541"	167.742
136	W 147° 2' 37.026"	N 64° 38' 56.595"	167.718
137	W 147° 2' 37.100"	N 64° 38' 56.651"	167.885
138	W 147° 2' 37.178"	N 64° 38' 56.707"	167.798
139	W 147° 2' 37.176"	N 64° 38' 56.767"	168.135
140	W 147° 2' 37.326"	N 64° 38' 56.819"	168.009
141	W 147° 2' 37.475"	N 64° 38' 56.926"	167.993
142	W 147° 2' 37.550"	N 64° 38' 56.982"	168.617
143	W 147° 2' 37.614"	N 64° 38' 57.034"	168.217
144	W 147° 2' 37.695"	N 64° 38' 57.097"	167.931
145	W 147° 2' 37.767"	N 64° 38' 57.150"	167.815
146	W 147° 2' 37.832"	N 64° 38' 57.210"	167.803
147	W 147° 2' 37.910"	N 64° 38' 57.267"	167.812
148	W 147° 2' 37.975"	N 64° 38' 57.320"	167.866
149	W 147° 2' 38.049"	N 64° 38' 57.381"	167.854
150	W 147° 2' 38.120"	N 64° 38' 57.432"	167.771
151	W 147° 2' 38.207"	N 64° 38' 57.490"	167.747
152	W 147° 2' 38.210"	N 64° 38' 57.537"	168.74
153	W 147° 2' 38.286"	N 64° 38' 57.598"	168.765
154	W 147° 2' 38.369"	N 64° 38' 57.657"	168.66
155	W 147° 2' 38.429"	N 64° 38' 57.710"	168.639
156	W 147° 2' 38.503"	N 64° 38' 57.766"	168.597
157	W 147° 2' 38.574"	N 64° 38' 57.822"	168.72
158	W 147° 2' 38.649"	N 64° 38' 57.872"	168.904
159	W 147° 2' 38.785"	N 64° 38' 57.938"	167.778
160	W 147° 2' 33.419"	N 64° 38' 53.913"	Unknown

161	W 147° 2' 33.344"	N 64° 38' 53.857"	Unknown
162	W 147° 2' 33.269"	N 64° 38' 53.801"	Unknown
163	W 147° 2' 33.195"	N 64° 38' 53.745"	Unknown
164	W 147° 2' 33.120"	N 64° 38' 53.689"	Unknown
165	W 147° 2' 33.045"	N 64° 38' 53.633"	Unknown
166	W 147° 2' 32.970"	N 64° 38' 53.577"	Unknown
167	W 147° 2' 32.895"	N 64° 38' 53.521"	Unknown
168	W 147° 2' 32.820"	N 64° 38' 53.464"	Unknown
169	W 147° 2' 32.745"	N 64° 38' 53.408"	Unknown
170	W 147° 2' 32.670"	N 64° 38' 53.352"	Unknown
171	W 147° 2' 32.595"	N 64° 38' 53.296"	Unknown

Appendix B: Transect One Frost Probe Data

	18-Jun-18		
	2 M spacing		
	Frost probe		
	depth to refusal		
	measured to the top of the vegetative layer		
electrode	**depth cm**	**note**	
1	36.9	Moss	
2	42		
3	37		
4	31		
5	31		
6	42.5		
7	33.5		
8	40	Edge of powerline	
9	79	gravelly	Powerline
10	67.5	gravelly	Powerline
11	51	gravelly	Powerline
12	67.5	gravelly	Powerline
13	95	gravelly	Powerline
14	97	gravelly	Powerline
15	32	moss	
16	33		
17	36.5		
18	41		
19	33.5		
20	39		
21	46.5	Hobo	slope edge
22	45		
23	55		
24	99		
25	90	top of gully edge	
26	94	muck	
27	36	mud	
28	40	tussock	
29	61		
30	113	edge of gully	
31	112.5		south facing slope
32	130	moss	

33	37	""	
34	47.5	""	
35	31	""	
36	32.5	""	
37	32	""	
38	37	""	
39	29.5	""	
40	39	""	
41	42	""	
42	41	""	
43	48	""	
44	30	""	
45	26	""	
46	29	""	
47	30.5	""	
48	29.5	""	
49	32.5	""	
50	33.5	""	
51	42.5	""	
52	50.5	""	
53	48	""	
54	64.5	""	
55	45	""	
56	52	""	
57	84	gravelly	
58	91	gravelly	
59	51	gravelly	
60	49.5	gravelly	
61	142	gravelly	
62	43	moss	
63	44	moss	
64	40	moss	
65	41.5	moss	
66	44.5	moss	
67	28	moss	
68	29	moss	
69	36	moss	
70	29	moss	
71	31.5	moss	
72	32	moss	
73	39.5	moss	

74	31	moss	
75	30.5	moss	
76	34	moss	
77	37	moss	
78	29.5	moss	
79	35	moss	
80	30	moss	
81	38		
82	25		
83	23.5		
84	28		

Appendix C: Transect Two Frost Probe Data

19-Jun-18			
AFIT T2	2 M spacing		
Eielson AFB			
	depth to refusal		
	measured to the top of the vegetative layer		
electrode	depth cm	**note**	
1	35.5	Black spruce and moss	
2	37.5	Black spruce and moss	
3	37.5	Black spruce and moss	
4	42.5	Black spruce and moss	
5	29.5	Black spruce and moss	
6	32.5	Black spruce and moss	
7	30	Black spruce and moss	
8	30.5	Black spruce and moss	
9	28.5	Black spruce and moss	
10	23.7	Black spruce and moss	
11	28	Black spruce and moss	
12	26.5	Black spruce and moss	
13	30.5	Black spruce and moss	
14	34	Black spruce and moss	
15	31	Black spruce and moss	
16	30	Black spruce and moss	
17	28	less dense tree cover	
18	23.5	less dense tree cover	game trail

19	30.5	less dense tree cover	game trail
20	27.5	less dense tree cover	game trail
21	29.5	less dense tree cover	game trail
22	32	less dense tree cover	game trail
23	31	less dense tree cover	game trail
24	37	less dense tree cover	game trail
25	35	less dense tree cover	game trail
26	33	less dense tree cover	game trail
27	28	less dense tree cover	game trail
28	27	less dense tree cover	game trail
29	25.5	less dense tree cover	game trail
30	34.5	less dense tree cover	game trail
31	28	less dense tree cover	game trail
32	30.5	less dense tree cover	game trail
33	40	less dense tree cover	game trail
34	49.5	less dense tree cover	game trail
35	136	less dense tree cover	game trail
36	127	less dense tree cover	game trail
37	93	less dense tree cover	game trail
38	46	less dense tree cover	game trail
39	30.5	less dense tree cover	game trail
40	28.5	less dense tree cover	game trail
41	29	less dense tree cover	game trail

42	32	less dense tree cover	game trail
43	43		
44	33		
45	30.5		
46	31.5		
47	28		
48	30		
49	28.5		
50	29		
51	26.5		
52	32		
53	38	embankment toe	
54	84.5	top	
55	37	toe	
56	37	thin moss	
57	32.5		
58	39		
59	31.5	gravelly	
60	38	gravelly	
61	40.5	gravelly	
62	49		
63	42.5		
64	44		
65	60		
66	46	Fence line	
67	32	embankment toe	
68	110.5	top	
69	64.5	toe	
70	47.5	gravelly	
71	38		
72	37		
73	37.5		
74	34		
75	32		
76	33.5	gravelly	near road
77	36.5		near road
78	35		
79	35		

80	33		
81	81		
82	78	gravelly	
83	38		
84	38.5		

`

Appendix D: Borehole One Sample Data

Date Time	Surface	0.5 Feet	1 Foot	1.5 Feet	2 Feet	2.5 Feet	3 Feet	3.5 Feet	4 Feet	5 Feet	7.5 Feet	10 Feet
7/27/2017 14:09	15.414	16.296	14.026	8.866	6.179	2.209	0.577	0.163	0.079	0.163	0.273	0.329
7/27/2017 15:09	20.436	23.016	16.511	10.345	6.864	2.343	0.605	0.19	0.107	0.163	0.329	0.356
7/27/2017 16:09	21.581	23.28	18.057	11.175	7.268	2.396	0.605	0.19	0.107	0.163	0.329	0.356
7/27/2017 17:09	25.04	24.339	18.794	11.662	7.469	2.423	0.605	0.218	0.107	0.163	0.329	0.384
7/27/2017 18:09	23.569	23.232	18.509	11.71	7.544	2.45	0.632	0.218	0.107	0.163	0.329	0.384
7/27/2017 19:09	24.315	27.875	21.557	13.281	8.295	2.557	0.66	0.218	0.107	0.163	0.329	0.384
7/27/2017 20:09	21.461	18.509	17.51	11.565	7.619	2.503	0.632	0.218	0.107	0.163	0.329	0.356
7/27/2017 21:09	20.984	19.793	17.415	11.394	7.469	2.423	0.605	0.19	0.107	0.163	0.329	0.356
7/27/2017 22:09	20.388	18.889	16.868	11.248	7.419	2.423	0.605	0.19	0.107	0.163	0.329	0.356
7/27/2017 23:09	18.794	16.892	15.461	10.638	7.192	2.396	0.605	0.19	0.107	0.163	0.329	0.356
7/28/2017 0:09	18.271	16.868	15.031	10.369	7.066	2.343	0.605	0.19	0.107	0.163	0.329	0.356
7/28/2017 1:09	17.296	15.39	14.266	10.051	6.94	2.343	0.605	0.19	0.107	0.163	0.329	0.356
7/28/2017 2:09	15.915	13.69	13.161	9.485	6.712	2.316	0.605	0.19	0.107	0.163	0.301	0.329
7/28/2017 3:09	14.146	11.565	11.807	8.792	6.408	2.236	0.605	0.19	0.107	0.163	0.301	0.329
7/28/2017 4:09	12.292	9.657	10.394	8.07	6.026	2.209	0.605	0.19	0.107	0.163	0.301	0.329
7/28/2017 5:09	10.81	8.344	9.262	7.444	5.719	2.155	0.605	0.19	0.079	0.163	0.301	0.329
7/28/2017 6:09	9.46	7.167	8.27	6.889	5.437	2.101	0.577	0.19	0.107	0.163	0.301	0.329
7/28/2017 7:09	8.394	6.382	7.444	6.382	5.154	2.047	0.577	0.19	0.107	0.163	0.301	0.329
7/28/2017 8:09	7.318	5.462	6.687	5.924	4.921	2.021	0.577	0.19	0.107	0.135	0.301	0.329
7/28/2017 9:09	6.56	4.947	6.077	5.539	4.688	1.967	0.577	0.19	0.107	0.163	0.301	0.329
7/28/2017 10:09	6.458	5.565	5.949	5.334	4.532	1.94	0.577	0.19	0.107	0.163	0.301	0.301
7/28/2017 11:09	9.015	10.149	8.095	6.204	4.844	1.967	0.577	0.19	0.079	0.163	0.301	0.301
7/28/2017 12:09	11.127	12.727	9.657	6.864	5.128	2.021	0.577	0.163	0.079	0.163	0.301	0.301
7/28/2017 13:09	15.031	17.582	12.847	8.319	5.77	2.101	0.605	0.19	0.107	0.163	0.301	0.329

Appendix E: Borehole Two Sample Data

Date and Time	0.5 Feet	1 Foot	1.5 Feet	2 Feet	2.5 Feet	3.5 Feet	4.5 Feet	5 Feet	10 Feet
7/27/2017 14:30	8.494	4.298	2.128	0.577	0.051	-0.06	0.079	0.024	0.079
7/27/2017 15:30	9.04	4.376	2.128	0.577	0.024	-0.088	0.107	-0.004	0.107
7/27/2017 16:30	10.247	4.558	2.155	0.577	0.024	-0.06	0.107	-0.004	0.107
7/27/2017 17:30	12.05	4.869	2.209	0.577	0.024	-0.06	0.079	0.024	0.135
7/27/2017 18:30	12.558	5.102	2.262	0.605	0.051	-0.06	0.079	0.024	0.135
7/27/2017 19:30	12.268	4.973	2.209	0.577	0.024	-0.06	0.107	0.024	0.107
7/27/2017 20:30	12.122	4.921	2.209	0.577	0.024	-0.06	0.107	0.024	0.107
7/27/2017 21:30	12.847	5.179	2.262	0.577	0.024	-0.06	0.107	-0.004	0.107
7/27/2017 22:30	12.243	5.102	2.236	0.605	0.024	-0.06	0.107	-0.004	0.107
7/27/2017 23:30	11.637	5.024	2.236	0.577	0.024	-0.06	0.107	-0.004	0.107
7/28/2017 0:30	11.492	5.05	2.262	0.605	0.024	-0.06	0.107	-0.004	0.107
7/28/2017 1:30	10.883	4.999	2.262	0.605	0.024	-0.06	0.107	0.024	0.107
7/28/2017 2:30	10.296	4.921	2.262	0.605	0.024	-0.06	0.107	-0.004	0.107
7/28/2017 3:30	9.583	4.818	2.262	0.605	0.024	-0.06	0.107	-0.004	0.107
7/28/2017 4:30	8.891	4.714	2.262	0.605	0.024	-0.06	0.107	0.024	0.107
7/28/2017 5:30	8.319	4.61	2.236	0.605	0.024	-0.06	0.107	0.024	0.107
7/28/2017 6:30	7.745	4.506	2.236	0.605	0.024	-0.06	0.107	0.024	0.135
7/28/2017 7:30	7.242	4.428	2.236	0.632	0.024	-0.06	0.107	0.024	0.135
7/28/2017 8:30	6.788	4.324	2.236	0.632	0.024	-0.06	0.135	0.024	0.135
7/28/2017 9:30	6.382	4.22	2.209	0.632	0.024	-0.06	0.135	0.024	0.135
7/28/2017 10:30	6.281	4.141	2.209	0.632	0.024	-0.06	0.135	0.024	0.135
7/28/2017 11:30	6.839	4.194	2.209	0.632	0.024	-0.06	0.107	0.024	0.107
7/28/2017 12:30	7.318	4.22	2.209	0.632	0.024	-0.06	0.107	0.024	0.107
7/28/2017 13:30	7.895	4.298	2.209	0.632	0.024	-0.088	0.107	-0.004	0.107

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Vita

Captain Theodore Joseph Labedz is currently enrolled at the Air Force Institute of Technology completing his Master's Degree in Engineering Management. In the course of his studies, he's focused his research on the unique challenges associated with military construction in the Arctic. For his thesis, he studied the soils on Eielson Air Force Base, Alaska to understand the effect of the F-35 beddown on the permafrost.

His interest in Arctic studies began in 2014 while assigned at Joint Base Elmendorf-Richardson near Anchorage, Alaska. Since then he's made 5 trips north of the Arctic Circle on various expeditions and climbed Denali in 2017. These experiences infused him with a passion for the Arctic and a desire to better understand its intricacies.

Captain Labedz was born in Omaha, Nebraska, commissioned in May of 2011, and has been privileged to serve as an officer for the past 8 years. He has held a myriad of positions including two times as an Emergency Management Flight Commander, deputy, operation support officer, project engineer, and Wing Executive Officer. His most recent deployment was commanding an 84 member bi-national construction of a school in Central Luzon, Philippines for over 2300 children.He has been selected to PCS to OSAN AB, ROK to serve with the 51st Civil Engineer Squadron beginning in May 2019.

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14. ABSTRACT

The DoD is executing over $500M in military construction on Eielson Air Force Base (AFB) within the next three years. This construction program will expand the footprint of facilities and change parts of the storm water management scheme, which may have second order effects on the underlying permafrost layers. These changes in permafrost will drive engineering decision, and help shape the overall strategy for military readiness in the Arctic. Little site-specific knowledge exists on the human caused effects to permafrost at this location. In 2016, the permafrost degradation rates at Eielson AFB were modeled using the Geophysical Institute Permafrost Laboratory (GIPL) 2.1 model and limited available geotechnical and climate data. To further refine an understanding of the permafrost at Eielson AFB and help engineers and commanders make more informed decisions on engineering and operations in the arctic, this project established two long term permafrost monitoring stations. The data generated by these stations are the first of their kind at Eielson AFB and represent the first modern systematic effort in the DoD to quantify permafrost condition before, during, and after construction activities. The data collected during this study indicates that there are permafrost losses occurring at this research site and the increased construction activities associated with the F-35 bed down are the likely cause of degradation.

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