

**Carbon-14 as a tracer of soil movement in earth hummocks:
a case study from northwestern Arctic Canada**

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Abstract

Involuted soil horizons and buried organic matter in the active layer and near-surface permafrost provide evidence that soil movement or cryoturbation is occurring within the active layer in hummocky terrain. Cryoturbation in the active layer of permafrost-affected soils could have significant implications in sequestering carbon, including trace metals and contaminants that are absorbed onto organic matter. Though several hummock development theories exist, there has thus far been limited evidence to support them; similarly, few studies have been able to establish hummock age. This study aimed to contribute radiocarbon-dated ages of buried organics in both the active layer and permafrost, as well as provide evidence for the convective cell/equilibrium model and the collapse model. Trenches were dug along a transect at two well-developed hummock sites in the Mackenzie Delta near Inuvik, NWT. Active layer and permafrost samples were analyzed for distribution of gravimetric water content (GWC), organic matter, inorganic carbon, and carbon-14 (C14). Results determined material ranged in age from the modern period (1959-1987AD) to 2300 yr BP with a generally normal distribution. Buried organics within the active layer ranged from 557-670 yr BP and 1023-1240 yr BP, with average displacement rates of 0.43 mm/yr and 0.16 mm/yr, respectively. These results suggest the convective cell/equilibrium and hummock collapse models can function simultaneously.

Résumé

Des horizons pédologiques et de la matière organique enfouis dans la couche active et dans le pergélisol près de la surface fournissent une preuve qu'il y a du mouvement ou de la cryoturbation qui se produit dans la couche active sur un terrain bosselé. La cryoturbation dans la couche active des sols affectés par le pergélisol pourrait avoir des implications importantes dans la séquestration du carbone, y compris les métaux traces et les contaminants absorbés dans la matière organique. Bien qu'il existe plusieurs théories reliées au développement du terrain bosselé, il y a peu de preuves qui les soutiennent. De plus, peu d'études ont été en mesure d'établir l'âge des hummocks. Cette étude visait à contribuer les âges radiocarbone de matières organiques enfouies dans la couche active et le pergélisol, ainsi que fournir des preuves pour le modèle de la cellule convective/à l'équilibre et le modèle de l'effondrement. Des tranchées ont été creusées le long d'un profil à deux sites de hummocks bien développés dans le delta du Mackenzie, près d'Inuvik, T.N.-O. Des échantillons de la couche active et du pergélisol ont été analysés pour la distribution de la teneur en eau gravimétrique (GWC), la matière organique, le carbone inorganique, et carbone-14 (C14). Les résultats ont démontré que le matériel était âgé de la période moderne (1959-1987 AD) jusqu'à 2300 ans BP avec une distribution normale. La matière organique enfouie au sein de la couche active variait entre 557-670 ans BP et 1023-1240 ans BP, avec des taux de déplacement moyen de 0,43 mm/an et 0,16 mm/an, respectivement. Ces résultats suggèrent que les modèles de la cellule convective/à l'équilibre et de l'effondrement des hummocks peuvent fonctionner simultanément

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LIST OF ACRONYMS

ARI	Aurora Research Institute (Inuvik, NT)
ARC	Advanced Research Centre (University of Ottawa, ON)
ACIA	Arctic Climate Impact Assessment
ALT	Active layer thickness
CALM	Circumpolar Active Layer Monitoring
CRREL	Cold Regions Research and Engineering Laboratory
DEM	Digital elevation model
GWC	Gravimetric water content
HTM	Holocene Thermal Maximum
IPCC	Intergovernmental Panel on Climate Change
IPY	International Polar Year
LIS	Laurentide Ice Sheet
MAAT	Mean annual air temperature
pmC	Percent Modern Carbon
PW	Pore water conductivity

1. INTRODUCTION

In permafrost regions, soil movement in the active layer typically occurs by cryoturbation, a process driven by ice segregation and differential frost-heaving and thaw settlement of frost-susceptible soils (French, 2007). Geomorphic evidence of cryoturbation includes patterned grounds, such as earth hummocks, frost boils, sorted and non-sorted circles. Earth hummocks are mounds up to 2 m in diameter and 60 cm in height and are a common landform in permafrost terrain (Tarnocai and Zoltai, 1978; Mackay, 1980; Kokej et al., 2007). Hummocks can be found in the landscape as well-developed, poorly-developed or collapsed. Due to varying vegetation and organic layer cover, the permafrost table of hummocks tends to mirror that of the surface topography, with the active layer typically being thicker in the hummock center and shallower in the inter-hummock depression (Tarnocai and Zoltai, 1978; Mackay, 1995). Thus far, ice segregation and differential frost heave and settlement have been invoked as processes leading to growth of hummocks (Mackay, 1980; Peterson and Krantz, 1998; Kessler and Werner, 2003; French, 2007; Woo, 2012). However, these models do not explain the collapsed form of hummocks. As such, Kokelj et al. (2007) proposed that the thaw of ice-rich near-surface permafrost might lead to soil instability and the sudden collapse of hummocks.

Involuted soil horizons and buried organic matter in the active layer and near-surface permafrost provide evidence that soil movement is occurring within the active layer in hummocky terrain (Mackay, 1976, 1980; Zoltai et al., 1978; Swanson et al., 1999). In winter, upward freezing from the base of the active layer and associated growth of ice lenses pushes the soils inward and upward, whereas in summer, thawing of the active layer and associated gravity-induced settlement transport the soils at depth towards the hummock center (Mackay, 1980; Peterson and Krantz, 1998; Peterson et al., 2003). Numerous freeze-thaw cycles gradually lead to hummock growth and this process also re-distributes the soils within the active layer of hummocks. Traditionally, cryoturbation and permafrost aggradation was considered the main process leading to the slow burial of vegetation in the inter-hummock trough (Crampton, 1977; Grab, 2005; Mackay, 1980; Tarnocai and Zoltai, 1978). However, the thaw of ice-rich permafrost near the trough and sudden collapse of hummock centers would lead to rapid burial of the organic matter occupying the inter-hummock depressions (Kokelj et al., 2007). Therefore, irrespective of the mechanism, the growth and collapse of hummocks in the low Arctic may be an effective mechanism to bury organic matter

in the active layer, which can potentially be preserved in an aggrading permafrost table (Kokelj et al., 2007). This could have significant implications in the sequestration of carbon, and active layer dynamics.

2. HYPOTHESES AND RESEARCH QUESTIONS

Despite the many studies on the development of hummocks and changes in hummock form over time, little is known regarding: 1) the rate of soil movement in this landform, and by consequence on the rate of cycling of organic carbon in the active layer; and 2) the time required to reach well-developed hummocks. The burial and re-distribution of organic carbon in the active layer and its preservation in aggrading permafrost could have significant implications in sequestering carbon, including trace metals and contaminants that are absorbed onto the organic matter (Olsen et al., 2011; Derksen et al., 2012; Vaughan et al., 2013).

The objectives of this thesis are to: i) determine if soil movement in hummocks occurs as cellular circulation due to differential heaving and settlement or by collapse of hummocks; ii) determine the rate of soil movement in hummocks; and iii) determine age of organic matter in inter-hummocks depression. This thesis uses the short-lived radioactive nuclide carbon-14 as a tracer of soil movement in hummocky terrain and to assess the time required to develop hummocks. These objectives will be achieved by analyzing the soil moisture, organic carbon content and organic matter content, measuring the $^{14}\text{C}_{\text{org}}$ (radiocarbon) of organic matter found in the active layer and near-surface of permafrost in a series of hummocks.

. The studied hummocks are situated in the Inuvik region, NWT, Canada, where hummocks range from well-developed to collapsed and where historical changes in active layer thickness in the hummock fields has been documented from the 1960's until present. Overall, this will be the first study that will measure $^{14}\text{C}_{\text{org}}$ of organic matter in hummocks to attempt to derive soil movement rates and determine the life-span of hummocks in the Inuvik region. As such, the findings of this project could be significant for several areas of Canadian research, including cycling of carbon in permafrost and stability of shallow permafrost for mineral exploration.

3. BACKGROUND

3.1 Permafrost and the Active Layer

Permafrost is defined as ground that is at or below 0°C for two or more years, and occupies approximately 22% of the land surface in the Northern Hemisphere (Brown et al. 1997; French, 2007). The distribution of permafrost (Figure 1) is primarily determined by climatic conditions and it can be classified based on the percentage of land mass it covers, which include continuous permafrost (>90%), discontinuous permafrost (≥50 to <90%), sporadic permafrost (≥10 to <50%) and isolated permafrost (0 to <10%) (Brown et al., 1997; French, 2007). The mean annual air temperature isotherm of -6°C to -8°C closely corresponds to the southern boundary of the continuous permafrost zone (Figure 1) (French, 2007; Burn, 2012). Subsea permafrost, such as in the Arctic Ocean, also exists as a relic from the last glaciation period when sea levels were much lower and cold air was able to penetrate the ground (Ritchie, 1985; French, 2007).

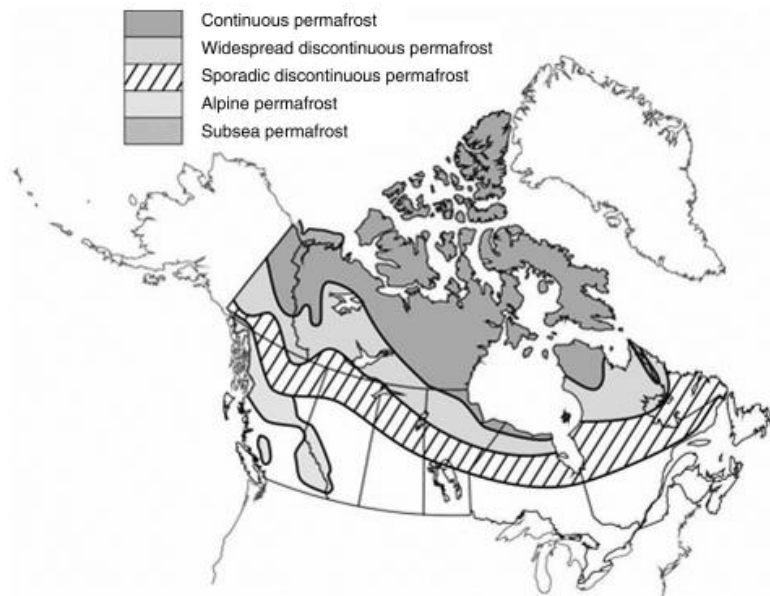


Figure 1: Permafrost distribution in Canada (Source: Burn, 2011)

The active layer has two contrasting definitions (Burn, 1998). It can be defined based on its thermal properties (surface layer that seasonally experiences temperatures above 0°C) or the physical state of water in the soil (surface layer that seasonally freezes and thaws) (Burn, 1998; French, 2007). The thermal definition of the active layer (Figure 2) is based on depth of penetration of the 0°C isotherm (Burn, 1998; ACGR, 1988). The definition based on the change of the physical

state of the water in soils often result in a thicker active layer due to a suppression of the freezing point below 0°C. This phenomenon occurs due to several factors, including the presence of dissolved solutes, pressure and especially soil grain size (French, 2007). These two contrasting definitions of the active layer indicate the complicated nature of soil profiles in permafrost environments, specifically that the exact depth of thaw can vary in space and time based on local factors: this is a dynamic measurement which can vary broadly. Determining the thickness of the active layer is a significant component when studying cryoturbation, as soil movement, as well as hydrological, biogeochemical and pedological processes have traditionally assumed to be restricted to this layer. Additionally, a “transient layer” exists in the upper section of permafrost, dividing it from the bottom of the active layer. This ice-rich transition zone can sometimes be observed, and acts as a buffer zone, protecting the permafrost below from degradation (Shur et al., 2005). It is the thaw of this near-surface ice-rich layer in inter-hummock depressions that can lead to their instability and collapse (Kokelj et al., 2007).

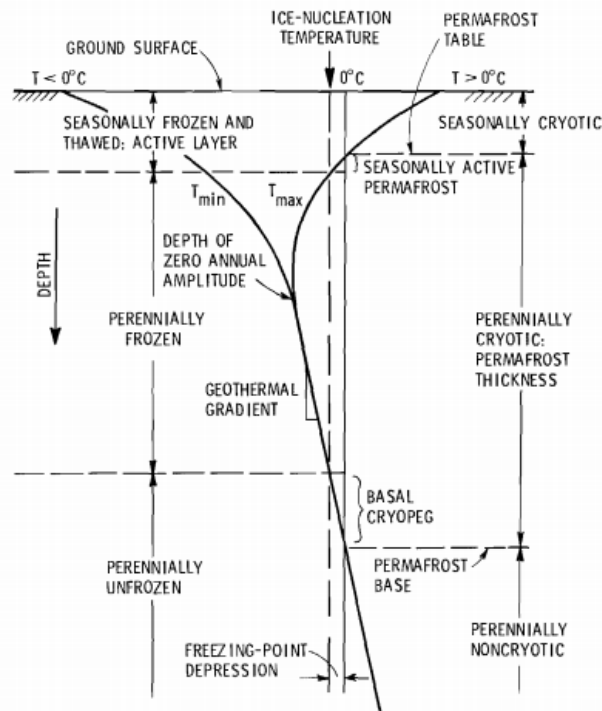


Figure 2: Diagram illustrating typical ground-thermal regime in permafrost. From: (ACGR 1988).

Active layer thickness (Z , in m) can be approximated with the Stefan Equation [1], where the ground surface temperature of the warmest month (T , in °C), the soil’s thawed thermal

conductivity (K , in $W/m \cdot K$ or $kcal/m \cdot ^\circ C \cdot h$), the thaw season period (t , in day/hour/second) and the volumetric heat of fusion (Q_i , in kJ/m^3) (French, 2007).

$$Z = \sqrt{2TKt/Q_i} \quad [1]$$

While active layer monitoring programs are relatively new and limited in temporal and spatial scope, the change in active layer thickness is an important characteristic of climate variability (Stocker et al., 2013). The Circumpolar Active Layer Monitoring program (CALM) demonstrates the fluctuation in active layer thickness from 25-120 cm from 1990-2013, as measured at a number of sites in Arctic Canada (Figure 3).

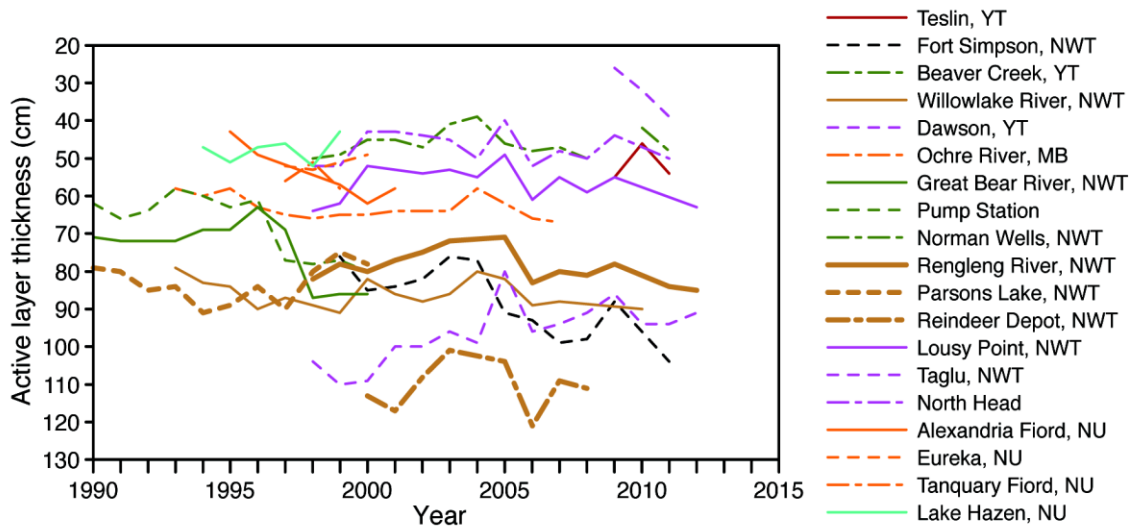


Figure 3: Active layer thickness (cm) measured at 19 sites in the Canadian Arctic. Data obtained from the CALM monitoring network.

While active layer thickness is primarily affected by variations in summer air temperature and snow cover thickness, several other factors play a role, including vegetation type and density, aspect, slope and thermo-physical properties of the soils (French, 2007). Overall, there is no clear active layer thickness trend, as only 6 of the 18 sites, such as Alexandria Fiord, NWT, have demonstrated an increase in active layer thickness. All others, such as Taglu, NWT, are experiencing a decrease in active layer thickness. The CALM sites closest to the study area are Rengleng River, Parsons Lake and Reindeer Depot (Figure 9). Rengleng River monitoring station registered a slight overall 10 cm increase in active layer thickness from 1998-2012, though there was a period of active layer thinning during the early 2000's. From 1990-1997, Parsons Lake recorded an increase in thickness from 80 to 90 cm, followed by thinning to 75 cm thickness until monitoring ceased in 2001. Reindeer Depot has the most variable measurements, thinning from

approximately 115 cm to 100 cm thickness during 2001-2003, stabilizing until 2005, and then increasing in thickness to 120 cm until 2007. There is an abrupt thinning from 2006-2007, after which there is a slight thickening before the end of monitoring. Overall, the active layer thinned by approximately 5 cm from 2000-2008.

The active layer undergoes a significant amount of thermal and physical change on various time scales, due to multiple freeze-thaw cycles; this triggers a number of subsequent cryotic processes, some of which contribute to cryoturbation (French, 2007). The fall freeze-back of the active layer is a significant process in frost-susceptible soils (clays to fine sand) as it is associated with the growth of ice lenses; down-freezing and up-freezing both can occur, with down-freezing rates being more significant. However, through these freezing-fronts, high and low-pressure zones are created, allowing water to pool and ice lensing to occur (French, 2007; Woo, 2012). During the spring, thaw occurs rapidly from the surface downwards due to percolation of meltwater and heat transfer; latent heat is absorbed during thaw, but can also be released during refreezing of infiltrated water. There can also be a large increase in the water table until a progression of ground thaw causes it to drop again (French, 2007; Woo, 2012). The thaw period is also when resettling of material moved during frost heave, push and pull occurs (Mackay, 1984; Kokelj et al. 2007; Woo, 2012).

3.2 Cryoturbation

Cryoturbation is the *collective* term used to describe all soil movements due to frost action, and may also be referred to as “frost churning” (French, 2007). This process takes place only in the active layer where seasonal freezing and thawing occurs, and involves sorting, heaving, stirring, wedging, cracking, frost heave, thaw settlement, and all differential movements that include contraction and expansion due to temperature changes and the growth and disappearance of ice lenses (Washburn, 1980; Bockheim and Tarnocai, 1998; French, 2007). The term is also used in a plural sense to refer to irregular structures formed in soils by deep frost penetration and frost-action processes (Bockheim and Tarnocai., 1998; French, 2007). The most important factor necessary for observable cryoturbation is the cyclic freezing and thawing of frost-susceptible soils (ACGR, 1988; French, 2007). While this process can occur in any region where the ground undergoes freeze and thaw (including areas of seasonal frost), it is most commonly, extensively

and intensively found in permafrost regions, and is favoured where the active layer is < 2m thick, commonly observed in continuous permafrost (Bockheim and Tarnocai, 1998).

Though there are several hypotheses to account for cryoturbation, there is no comprehensive model, but instead it can be conceived of as a number of processes working at different durations, frequencies, intensities and times, to produce a variety of features (Washburn, 1980; French, 2007). Some of these have been developed into models to explain the formation of hummocks.

3.3 Cryoturbation: Contributing Processes

Cryoturbation occurs from the influence of several processes, including i) ice segregation, ii) frost heaving and thaw settlement and iii) frost sorting. These processes are briefly described below.

3.3.1 Ice Segregation

Ice segregation refers to the growth of ice lenses that form when water within frost-susceptible soils moves towards the freezing plane (French, 2007). Frost-susceptible soils are those with particle surface areas and pore spaces between particles that promote capillary flow and suction, such as fine silty and loamy soil textures (Van Vliet-Lanoë, 1988, 1991; French, 2007). The texture of frost susceptible soil allows moisture to migrate to the freezing front and form segregated ice lenses; if there is extensive ice lens development, this may lead to soil heaving, which is a major component of cryoturbation (Taber, 1930; Van Vliet-Lanoë, 1988; French, 2007; Woo, 2012). The controls associated with this process are the amount of water present in the active layer, specifically the effect of local drainage patterns, and the grain-size distribution: soils with smaller grain sizes favour the formation of segregation ice due to cryosuction (French, 2007; Van Vliet-Lanoë, 2010).

3.3.2 Frost Heaving and Settlement

Frost heaving refers to the raising of the ground surface as a result of the 9% volumetric expansion that occurs during the phase change from (pure) water to ice during the formation of

segregation ice (French, 2007). This process differs from normal freezing as the ice must first overcome resistance to its expansion caused by the strength of the overlying frozen soil (which usually only occurs with the formation of segregated ice) (Taber, 1930; Van Vliet-Lanoë, 1988; French, 2007). Frost heaving requires a frost-susceptible soil, a sustained supply of water and freezing temperatures to penetrate the soil. There are two types of heaving: primary heaving refers to heaving near the frost line, whereas secondary heaving occurs within frozen soil layers. Primary heaving occurs most often during autumn freeze-back of the active layer, and is related to the growth of segregation ice and volumetric expansion (French, 2007). Secondary heaving is important due to the large heaving pressures that may develop over time, though this process is not well understood (French, 2007). Major vertical ground displacements of over 30 cm can take place annually, producing a number of landforms unique to periglacial environments such as (Van Vliet-Lanoë, 1988).

Thaw settlement, or consolidation, is the settlement of soil particles during the thaw of the active layer in the summer season. Settlement occurs due to the melt of the segregation ice layers, and gravity-induced settlement transport material at depth. This results in compaction and resettlement of the soils under their own weight (French, 2007).

3.3.3 Frost Sorting: Frost Pull and Frost Push

Frost-sorting occurs when there is thermally-induced sorting within the active layer, whereby fine particles migrate under a larger range of freezing rates than coarser particles, over time sorting the material according to size (French, 2007). Frost sorting can occur through frost-pull and/or frost-push. Both processes assume that ice lenses grow on the cold (freezing) side of the object with water migration from the warm (unfrozen) side (French, 2007). Figure 4 best describes and compares these processes (Mackay, 1984).

The frost-pull process occurs when the freezing front penetrates into the soil, gripping the rock; along with the soil surrounding it, the rock is heaved and the space originally occupied by the rock has been compressed by the process (Mackay, 1984; French, 2007). During thaw, the space originally occupied by the pebble has been compressed by lateral frost heaving (frost thrusting); grains have also fallen into the slight depression left by this movement, and the boulder cannot move vertically down as far as before (French, 2007).

The frost-push process relies on the higher thermal conductivity of the stone than the surrounding soil matrix, such that when the freezing front approaches, it will propagate faster into the rock before the surrounding soil matrix. This results in the formation of ice preferentially around and beneath, thereby forcing the pebble upwards in comparison to the surrounding soil matrix. Upon thawing the infill of finer material beneath the stone prevents it from returning to its original position.

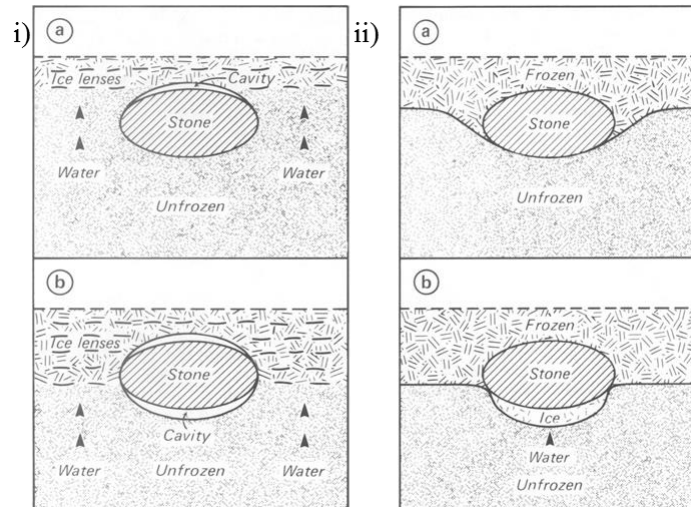


Figure 4: Diagram to illustrate the frost-push and frost-pull theories, from Mackay (1984).

i) Diagram to illustrate the frost-pull theory. (a) Ice lenses grow in a moist frost-susceptible soil by downward freezing. Heave from ice lens growth above the stone may leave a cavity above the stone. (b) Ice lens growth in the soil surrounding the stone uplifts the stone, together with the soil, to leave a cavity beneath the stone. When the ground thaws from the surface downward, the stone fails to return to its prefreezing position to give a net upward movement of the stone.

ii) Diagram to illustrate the frost-push theory. (a) The 0°C isotherm reaches the bottom of the stone faster than at the same level in the adjacent soil because of the higher thermal conductivity and/or diffusivity of the stone as compared to that of the soil. By implication, the soil is nonfrost-susceptible, because if the soil were frost-susceptible the stone would have been uplifted by ice lens growth as shown in Figure 4i. (b) Ice grows beneath the stone to push it up. Note that the theory requires frost-push of the stone into the super incumbent frozen ground. When the ground thaws from the surface downward, the stone fails to return to its prefreezing position

3.4 Related Landforms associated with Cryoturbation Processes

A number of landforms and soil features result from cryoturbation processes, and include micro-scale features associated with the soil structure, such as soil involutions, and mega-scale

features such as hummocks and sorted and non-sorted patterned ground (Bockheim and Tarnocai, 1998; French, 2007). Only features related to this study are discussed below.

3.4.1 Soil Involutions

Involutions are disturbed, distorted, and deformed structures in soils that are classified into two types: thermokarst involutions and periglacial involutions (French, 2007). Significant to this study, periglacial involutions are formed through repeated frost-action within the active layer and have been reported from both past and present permafrost environments (Sharp, 1942; French, 2007; Ogino, 2007). The dominant theory that explains periglacial involutions, diapirism, suggests that these soil structures are due to density and pressure differences caused by the variable water content in soil horizons, as demonstrated in Figure 5 (Swanson et al., 1999).

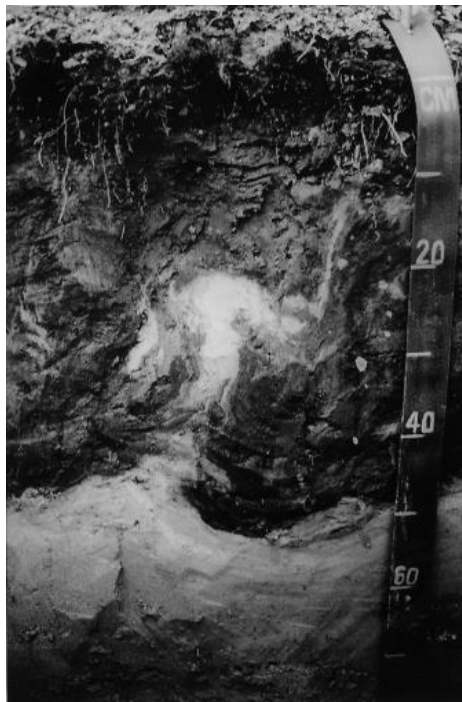


Figure 5: Diapiric form in a soil with permafrost near Tok, Alaska. A plume of light-coloured, loamy soil has risen into dark-coloured, organic-rich loamy soil. From Swanson et al., 2009

3.4.2 Non-Sorted Patterned Ground: Hummocks

Patterned ground exists mainly in areas where a combination of frost-action and mechanical weathering in the active layer develops sorted and unsorted accumulations of material at the ground's surface (French, 2007). This study examines one type of patterned ground: hummocks (Figure 6). Hummocks are considered to be non-sorted patterned ground and are defined as bare raised circular areas margined by troughs filled with vegetation (Mackay, 1976, 1980; French, 2007). They range in diameter from 0.5m to 3.0m and up to 0.5m in height, though there can be high variation in the size of individual hummocks at the same general site (Tarnocai and Zoltai, 1978; French, 2007). Beneath the well-developed hummock is a bowl-shaped permafrost table that typically mirrors the surface topography (Figure 6) (French, 2007; Kokelj et al., 2007). Hummocks are commonly formed of fine-grained, frost-susceptible soils, and their high centers vary in amount of vegetation, from bare to completely vegetated (Mackay, 1980; French, 2007).

French (2007) notes that the exact processes that produce patterned ground are not yet fully understood; they can be formed over short time periods, such as since the Little Ice Age (Haugland, 2006). This may indicate that less severe freeze-thaw cycles are required to produce features, or that these are not uniquely permafrost features, but are possible in soil that freezes and thaws a number of times annually (Ballantyne, 1996). Establishing a freeze-thaw index for the site may provide insight into the necessary thresholds for heave features to be present, however more extensive measurements, such as ground temperatures, snow depth and vegetation characteristics are necessary (French, 2007, Lewkowicz and Clark, 1998). Traditionally, the slow burial of vegetation in the inter-hummock trough or depression was considered as a main development of traditional theories of cryoturbation (Crampton, 1977; Grab, 2005; Mackay, 1980; Tarnocai and Zoltai, 1978). Kokelj et al. (2007) amended this view with the collapse theory, by considering how the aggradation or degradation of underlying ice-rich permafrost could influence hummock form. Through radioactive isotope dating of organic layers found within permafrost below inter-hummock depressions (troughs), this study may help to support Kokelj's (2007) theory, specifically if a linear age relationship can be detected in the troughs. At the same time, the

discovery of organic intrusions may support Mackey's (1980) cryoturbation and soil mixing theories, specifically if these materials are found within a younger soil matrix.

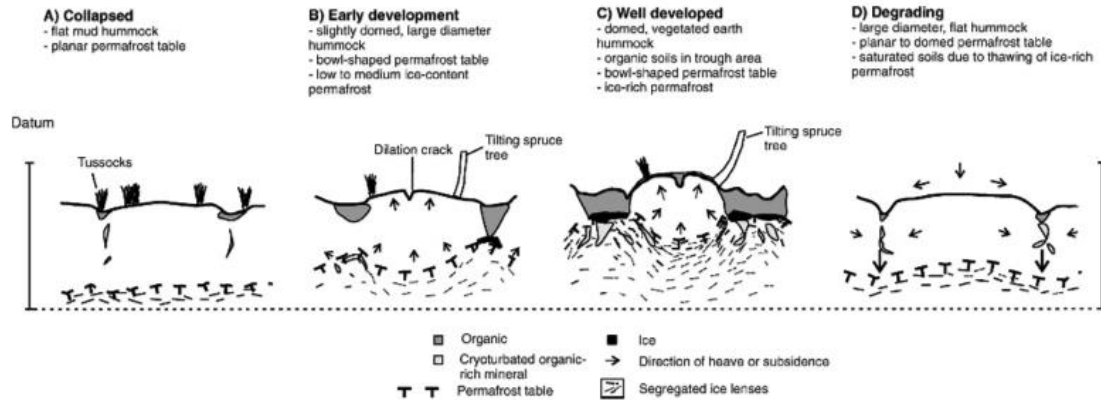


Figure 6: Diagram of hummock dynamics as a function of change in the configuration of the permafrost table and aggradation or degradation of ground ice; A) Collapsed: flat mud hummock, planar Permafrost table. B) Early Development: Slightly Domed, large diameter hummock, bowl-shaped permafrost table, low to medium ice-content permafrost. C) Well Developed: domed, vegetated hummock, with organic soils in the trough area and a bowl-shaped permafrost table, ice rich permafrost. D) Degrading: large diameter flat hummock, planar to domed permafrost table, saturated soils due to thaw of ice rich permafrost (Kokelj et al. 2007).

3.5 Existing cryoturbation and hummock development models

A number of hypotheses to explain cryoturbation and the resulting landforms have been advanced (Van Vliet-Lanoë, 1991; French, 2007). Two main models have been proposed to explain the process of hummock development due to cryoturbation: i) the convective cell equilibrium model, and ii) the differential frost heave and settlement model (Van Vliet-Lanoë, 1991; Bockheim and Tarnocai, 1998; Swanson et al., 1999).

3.5.1 Convective Cell (Equilibrium) Model

This theory was originally proposed by Nordenskjöld (1909), and while it has been reworked by modern permafrost scientists, it is considered one of the least substantiated theories (Van Vliet-Lanoë, 1988). In the convective cell or thermal convection theory, heave-subsidence cycles at the top of the active layer produce a net downward and outward movement of material,

whereas those at the bottom produce a net upward and inward movement, resulting in a slow upward cell-type circulation (Mackay, 1980).

Using the convective cell equilibrium theory as an alternative to the cryostatic theory, Mackay (1980) suggested that the formation of hummocks occurs through the formation of ice lenses and subsequent heaving (Figure 7). The ice lenses develop both at the top of the active layer and near the bottom of the active layer. Because the bottom of the active layer is typically saturated with water, the ice lenses will be large, and therefore will experience a higher degree of expansion. Frost heaving will occur both near the bottom and near the top of the active layer and is directed both upwards and radially outwards; this outwards heaving is significant as it leads to uneven heaving on the surface, allowing for subsequently uneven thaw subsidence (Mackay, 1980). The motion of these two processes in sequence over time creates a cell-type motion, and results in a positive feedback system (Mackay, 1980).

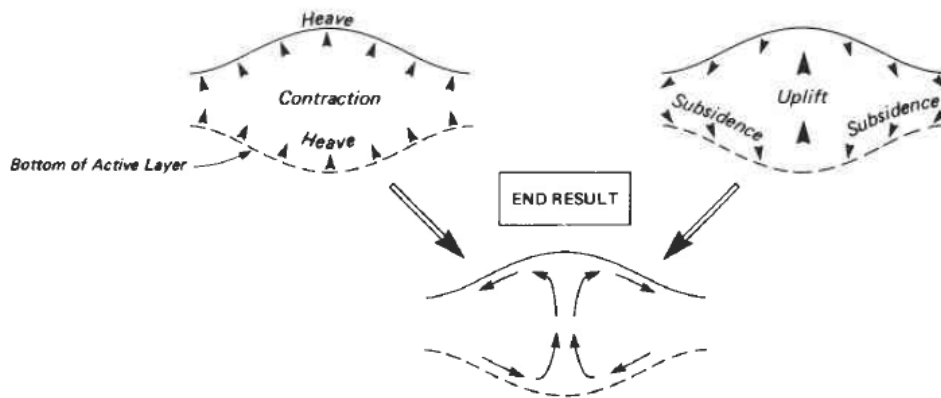


Figure 7: The equilibrium model for hummock growth. This is an example of how the convective cell equilibrium model would function in terms of cryoturbation; as mentioned previously, the motion is similar to the general convection model. From: Mackay, 1980.

3.5.2 Differential Frost Heave and Settlement Model

The differential frost heave theory refers to asymmetrical radial freezing and resultant lateral sorting which over time facilitate the production of hummocks (Van Vliet-Lanoë, 1988, 1991). These asymmetrical variations could be attributed to a number of micro-site non-uniformities, including moisture, vegetation or textural composition and non-planar permafrost

table (Van Vliet-Lanoë, 1988, 1991; Peterson, 2003; Matsuoka, 2003). Unlike many other cryoturbation theories, the differential frost heave and settlement model does not require saturated soils, because soil heaves mainly by upward movement of water from the unfrozen subsoil, and therefore is appropriate for the well-drained soils associated with hummocky terrain (Van Vliet-Lanoë, 1988; Matsuoka et al., 2003).

3.6 Methods Used To Determine/Measure Cryoturbation

One approach to finding evidence of cryoturbation is to utilize existing diagnostic landforms or small-scale experiments to infer data about the processes taking place (Van Vliet-Lanoë, 1988). Geomorphologists and permafrost scientists sometimes attempt to collect temperature, pressure, density, sediment size and water/ice content data in the active layer in an attempt to fit the parameters into models. The majority of the studies attempted to fit a model to the growth of sorted patterned ground (Ballantyne, 1996; Luoto and Hjort, 2004). Laboratory and field experiments have been undertaken with some success, such as Ballantyne's field reproduction of a miniature version of patterned ground in as little as eight freeze-thaw cycles (1996). Measurements surrounding the differential densities of soil horizons were undertaken by Swanson et al., (1999) to explain mudboils using involutions or periglacial diapirs. Past studies stressed the importance of seasonally high soil moisture in the cryoturbation process, and as such drainage patterns have been studied (Washburn, 1979; Van Vliet-Lanoë, 1991; French, 2007). It is not fully understood how changing permafrost conditions, especially increased moisture content and potential drawdown of the water table, could impact cryoturbation. Hummocks tend to correlate with well-drained sites and a deep water table; however, some moisture is necessary, as hummock landforms have not developed where sites are completely dry during the summer (Van Vliet-Lanoë, 1991).

3.6.1 Tracing Soil Movement in Hummocks with Radioactive Isotopes

The method of using radioactive nuclides as soil profile tracers is not unique to this study (Yoo et al, 2011; Jelinski, 2013; Klaminder et al., 2014). The basic premise of tracing soil movement is to use the fundamental theory of radioactive decay to establish the age of sediments and/or carbon in the soil profile. If the soil was laid down in a normal manner (from oldest at deepest depth to youngest at the surface), the decay profile should mirror this; however, if there

has been disruption or movement of the soil after it was laid down, this should also be visible in the soil profiles. Similarly, there should be significant spikes in the isotopes that correlate to known nuclear emission events in the recent past, specifically the 1963-1965 peak which corresponds to the highest period of nuclear weapons testing (Clark, 2015).

The basic method of determining age originates from the radioactive decay of a nuclide, which is governed by the following exponential law (Clark, 2015):

$$P(t) = P_0 \exp(-\lambda t), [2]$$

where P_0 is the initial concentration at time $t = 0$, and λ is the decay rate of the particular radionuclide.

Carbon-14 or ^{14}C refers to the radioactive isotope of carbon, which has a nucleus of six protons and 8 neutrons and a half-life of 5730 ± 40 years; through beta decay, carbon-14 decays into nitrogen-14 (Davis, 1977; Voges, et al., 2009). As the measurement of ^{14}C indicates the time since death of an organism, it is reasonable to infer that these values will indicate approximate burial time of organic matter in the inter-hummock troughs, therefore making it possible to estimate burial and hummock collapse rates (Voges, et al., 2009).

Due to unique physical properties, radioactive isotopes of specific elements have been used to quantitatively track the pathways and behaviours of systems (TCS, 2001). The radiocarbon dating method was developed by Libby et al. (1949). When ^{14}C is released into the biosphere, it is ingested or inhaled by most living organisms, making it then contained within these organisms (Davis, 1977). The post-mortem measurement of ^{14}C relies on the presence of organic carbon, and therefore is useful when dating plant material, such as the buried shrubs found in the troughs between hummock tops (Davis, 1977; Voges et al., 2009; Kokelj et al., 2007). Though ^{14}C is produced naturally through the reactions of secondary neutrons from the interaction of cosmic radiation entering the atmosphere and interacting with nitrogen (as well as to a lesser degree, oxygen and carbon) there was a significant increase during the nuclear testing periods from 1950-1980 (Davis, 1977; Voges et al., 2009). It is possible to use carbon-14 as a tracer in soil movement because this relies on the concept that soil is laid down sequentially, that is, that one would expect soil to have the oldest ages at a greater depth with younger age nearer to the surface. By comparing

relative ages, it may be possible to better understand soil movement and development of hummocks.

Studies that have used ^{14}C in an attempt to assess cryoturbation in hummocks include: Zoltai and Tarnocai, 1978, Dyke and Zoltai, 1980 and Klaminder et al., 2014. Klaminder et al. (2014) observed values ranging from 80.3 to 104.3 ± 0.4 percent modern carbon (pmC) in the hummock centres (0-7 cm depth,) and from 95.4 to 122.3 ± 0.4 pmC in intermediate hummock zones (0-10 cm depth). This correlates to an inferred estimated age range of 50 to 200 yr BP \pm 31 yr of soil layers between 0-10 cm depth across all hummock zones, and a downward transport rate of around 0.01 cm yr^{-1} (Klaminder et al, 2014).

Average hummock age determined by Tarnocai and Zoltai (1978) was 2700 yr BP, with a range of 490 ± 80 yr BP to $11,200 \pm 100$ yr BP. Ages were clustered between 3000 and 3500 yr BP, with the majority below 5000 yr BP. Based on this ^{14}C age distribution, they suggested that the majority of hummocks developed in the western Canadian arctic near Tuktoyaktuk during the severe cool climatic period since 5000 yr BP, up to 3000 yr BP. Interestingly, there was a large age gap between hummocks in close proximity, with one site dated to 2400 ± 80 yr BP, whereas others were significantly older; this indicates that these landforms are generally stable over time, as older and younger hummocks reach the same stage of morphological and pedological development tend to remain in a stable, self-renewing system. An example of radiocarbon dated material with calibrated ages from a hummock is shown in Figure 8 (Tarnocai, 2011).

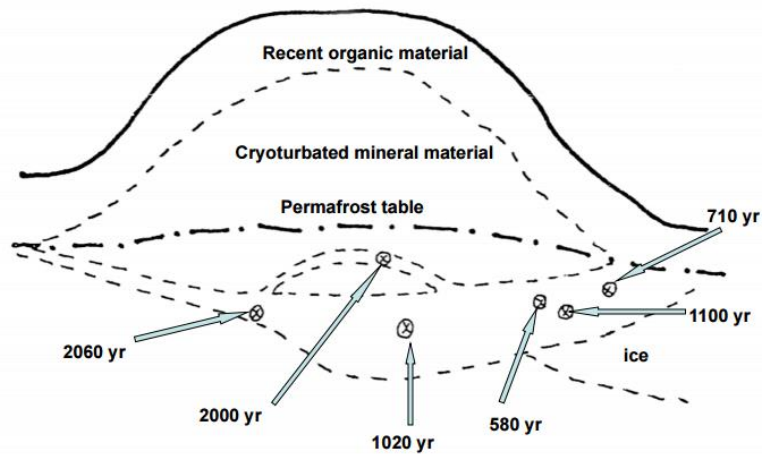


Figure 8: Ages of cryoturbated organic materials, from Tarnocai, 2011 (no scale provided).

4. STUDY AREA

The study area is situated the uplands east of the Mackenzie Delta near Inuvik, in the Northwest Territories (Figure 9). In this region, hummocks are common features in the landscape, with approximately 75% of the Mackenzie Valley is estimated to have hummocky microrelief (ECG, 2010). Hummocks in this region range from well-developed to collapsed (Zoltai and Pettapiece, 1974; Mackay, 1995, Kokelj et al., 2007). Two sites in the upland terrain were investigated: Navy Road and Rengleng River. The Navy Road site ($68^{\circ}22.988'N$, $-133^{\circ}45.241'W$) is located 2 km north of Inuvik and has been part of the long-term permafrost studies by J.R. Mackay (Mackay et al., 1976; Mackay et al., 1980; Kokelj et al., 2007; Lacelle et al., 2014). In 1968, a forest fire burned a section of this area and as such, hummocks in the burned area are collapsed and those in the unburned area are well-developed. The Rengleng River study site is situated along east side of the Dempster highway approximately 75 km south from Inuvik, and has well-developed hummocks ($67^{\circ}51.946'N$, $-133^{\circ}38.893'W$).

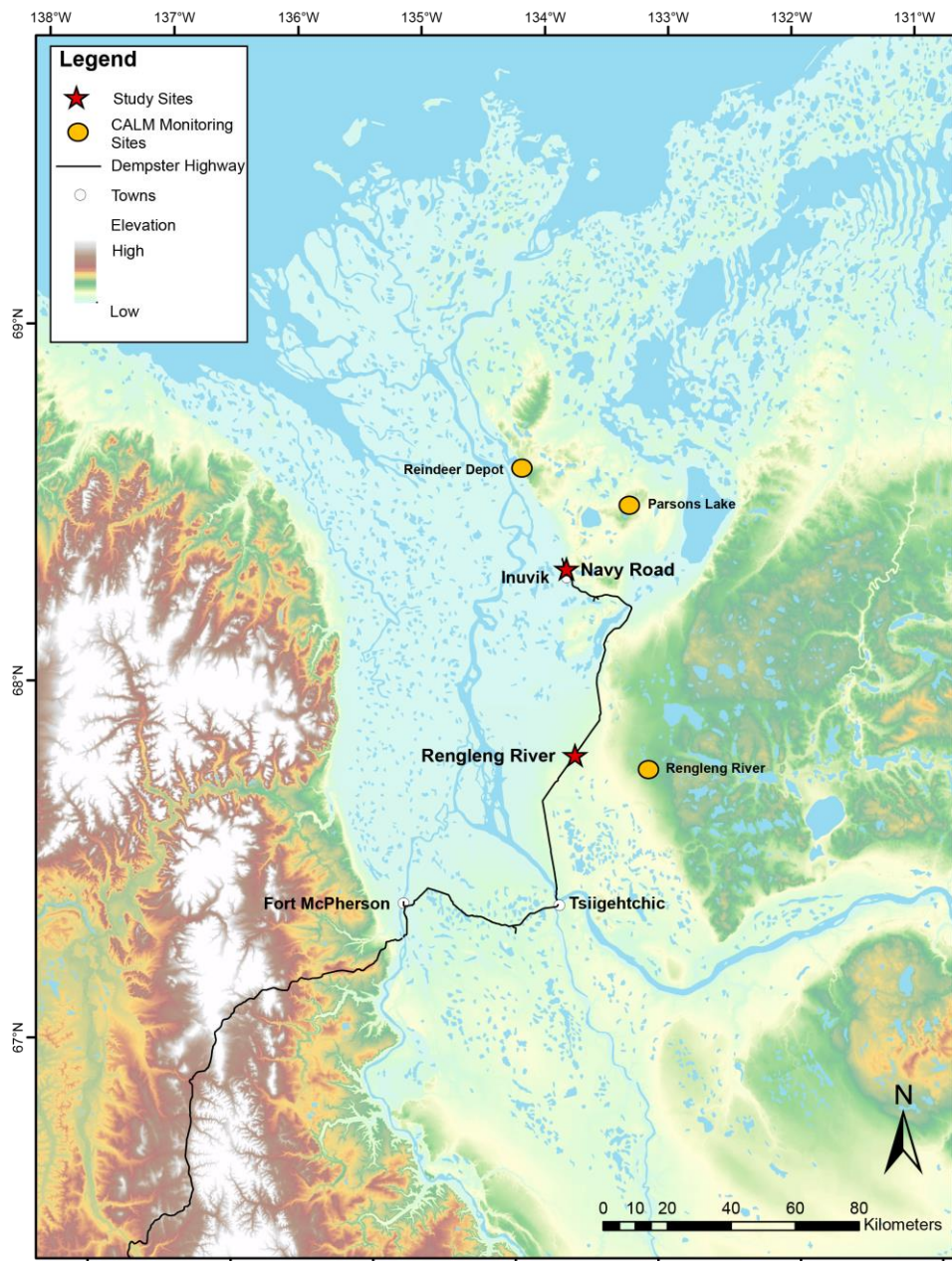


Figure 9: Location of study sites near Inuvik, NWT. Data obtained from Government of Canada, 2012, and CALM monitoring network.

4.1 Climate, Permafrost and Active Layer Conditions

The climate conditions in the Inuvik region can be described as high subarctic ecoclimate with very cold, long winters and cool short summers (Environment Canada, 1995; ECG, 2010). Figure 10 shows the mean annual air temperature (°C) and the total annual precipitation (mm)

from 1960 to 2014 (Environment Canada, 2015). The mean winter temperature is -26.5°C ; mean summer temperature is 8.5°C , with the mean annual air temperature is -9.5°C (Environment Canada, 2015). Since the 1960s, the MAAT has been increasing at a rate of 0.069°C per year (p-value: <0.001) (Brasseur, 2013).

As influenced by the climate conditions of the region, continuous permafrost exists in the study area. Permafrost thickness in the western Canadian Arctic varies from nearly 500 m near the coast of the Beaufort Sea, decreasing southward to around 100 m in Inuvik, NT. There is an increase to approximately 300 m in the northern Peel Plateau area (French, 2007; Burn and Kokelj, 2009). Thicker permafrost along the coastline was formed under lower sea level conditions than present, when it was exposed to cold air temperatures following deglaciation (Mackay, 1972).

Active layer thickness in the region can vary significantly in both time and space. Generally, the range on vegetated surfaces in fine-grain tills or in organic deposits is approximately 30-50 cm; however, in disturbed areas and gravelly floodplains thickness can reach more than 100 cm (Brown et al., 2000). CALM regional active layer monitoring indicates significant year-to-year variability and inconsistent long-term trends (Figure 3). In areas with stable vegetation conditions, the inter-annual variation in thickness of active layer is largely dependent on the thaw degree-days (Smith et al., 2009).

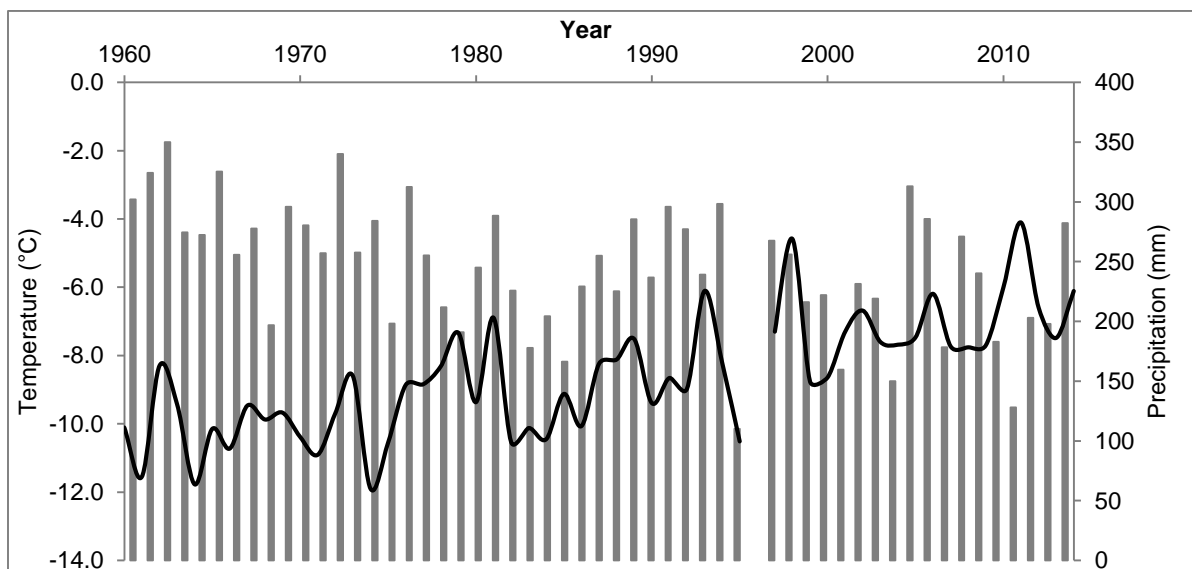


Figure 10: Total annual precipitation, in mm, and Mean Annual Air Temperature (MAAT) in $^{\circ}\text{C}$ in Inuvik, NWT between 1960 and 2014. Data obtained through Environment Canada <http://climate.weather.gc.ca>.

4.2 Vegetation

The present-day tree line is situated between Inuvik and Tuktoyaktuk. Vegetation in the eastern uplands is dominated by open, stunted stands of black spruce and tamarack with secondary quantities of white spruce, and a ground cover of dwarf birch, willow, ericaceous shrubs, cottongrass, lichen, and moss, as shown in Figure 11 (Environment Canada, 1995; ECG, 2010). Within the hummock zones, it is common to find significant shrubs and small vegetation within the troughs, while hummock tops are bare or thinly covered with grasses. Tilted spruce trees are found on the edges of hummocks, near the inter-hummock zone or close to troughs.



Figure 11: Vegetation characteristic of both sites; Photo taken August 2014 at Navy Road site.

4.3 Geology and Surficial Geology

The surficial geology of this region is shown in Figure 12. The surface geology at the two study sites consists largely of till blanket, though as boundaries are not exact, there is a possibility of till veneer cover in some areas. These deposits were laid down during the Late Pleistocene glaciation, and have left elongated drumlins and low-relief hills (Environment Canada, 1995; Fulton, 1995). To the west of these sites is a large area consisting of alluvial deposits, consistent with historical abandoned streambeds and the modern location of the Mackenzie River (Environment Canada, 1995). Underlying the surficial deposits, there are horizontal beds of various sedimentary rock, including limestone, shale, sandstone, and conglomerates. The

limestone deposits are of particular interest to oil and natural gas industries, due to their marine-environment genesis (Environment Canada, 1995; AANDC, 2012).

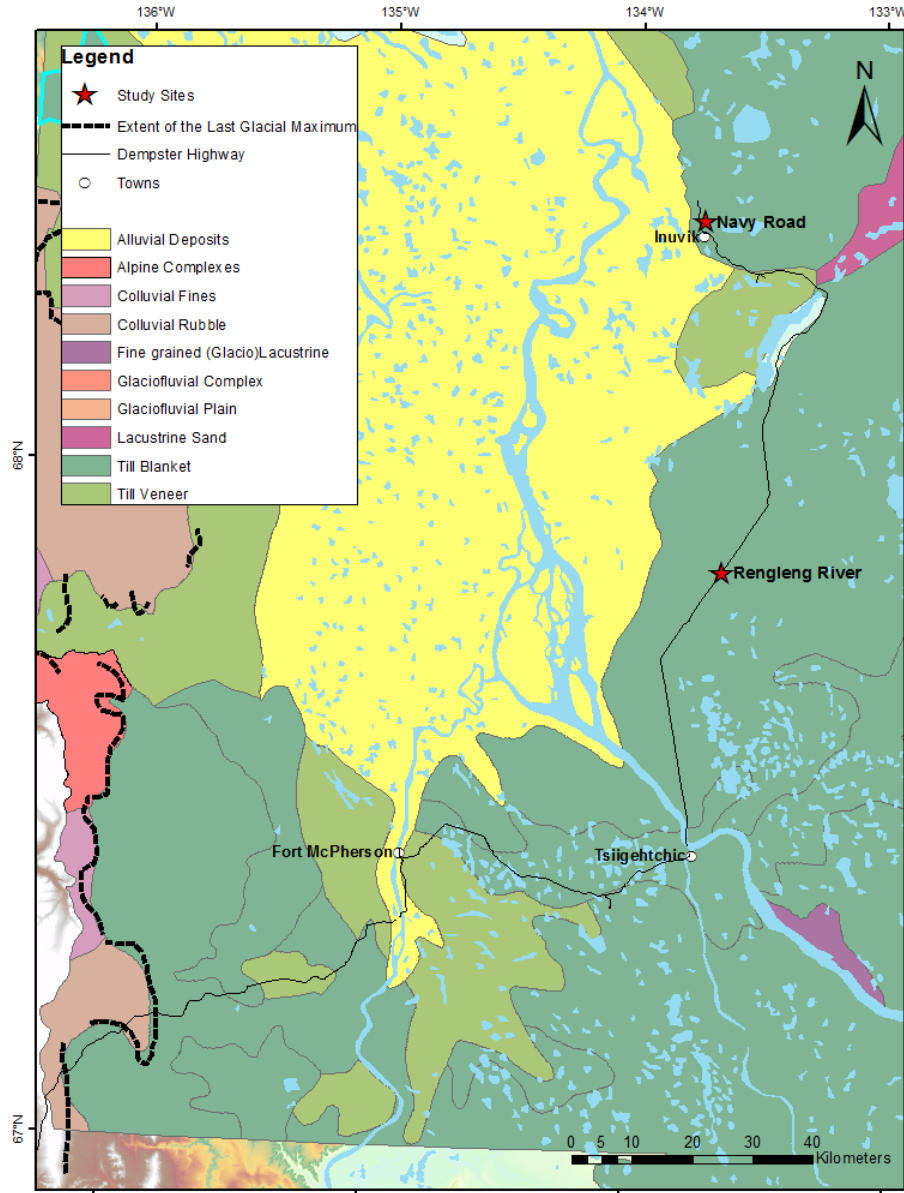


Figure 12: Surficial geology and study sites in the western Canadian Arctic. Data obtained from Côté et al., 2013, GSC Open File 7259

4.4 Soil Properties

The soils in the Inuvik region are classified as Cryosolic, as the permafrost table is observed within the uppermost 1 m of ground surface, or 2 m where soil has experienced significant cryoturbation (SCWG, 1998; Environment Canada, 1995). The general region is composed of Regosolic Static and Gleysolic Static Cryosols with Organic Cryosols developed on level fluvio-glacial, organic, and marine deposits (Environment Canada, 1995). Investigation of soils at Navy Road and Rengleng River sites suggest that it can be subdivided to Turbic Cryosols, as these are mineral soils experiencing cryoturbation as evidenced by cryogenic landforms such as earth hummocks (SCWG, 1998). Horizons are mainly composed of mineral soils below a thin organic layer consisting of mosses, shrubs (specifically Labrador tea) and woody materials (SCWG, 1998). Within hummock zones, there is a significant increase in the amount of organic material within troughs compared to the hummock tops. Tarnocai et al. (2011) estimated soil organic carbon content in the eastern Mackenzie Delta to be in the order of $>50 \text{ kg/m}^2$.

5. METHODOLOGIES

5.1 Site Selection, Active Layer and Permafrost Field Sampling

Active layer and permafrost samples were collected the Navy Road and Rengleng River sites in the upland terrain east of the Mackenzie Delta (Figure 9) in August 2014.

Table 1: The characteristics of the 2 sites where active layer samples and permafrost cores were collected in the western Canadian Arctic, including latitude and longitude (in decimal degrees), elevation (in m), active layer thickness (in cm), ecozone, and surficial geology.

Site	Latitude (N)	Longitude (W)	Elevation (m)	Active layer thickness (cm)	Ecozone	Surface Geology
Navy Road	68° 22.988'	-133° 45.241'	32	0 - >79	Taiga Plains	Till blanket
Rengleng River	67° 51.946'	-133° 38.893'	76	31 - >82	Taiga Plains	Till blanket

Table 1 provides a site characteristic summary, including geographical coordinates, elevation and surface geology. The sampling sites were selected based on accessibility and hummock development. Both Navy Road and Rengleng River sites are relatively well protected from wind, are situated in open woodlands with well-developed hummocks, and were located in upland regions as opposed to wetlands. Both sites fall within the Taiga Plain ecoregion and are located on till blanket surfaces (Figure 12). They are situated in the boreal forest near the limit of the tree-line within the Taiga Plains ecoregion, and vegetation in the area is comprised primarily of open, stunted black spruce forest with willows, alders, mosses and lichen composing the understory (Environment Canada, 1995; ECG, 2010).

Active layer samples were obtained from digging trenches traversing 2-3 well-developed hummocks from the soil surface to the top of permafrost, where accessible. The top of permafrost was not always reached within the centre of a hummock. A description with photographs and sketch of the soil texture and location of buried organic matter are included as Figures 13 and 14. Active layer samples were taken from the hummock centers, shoulders and inter-hummock depression at approximately 2 cm vertical intervals using a spade and placed in polyethylene bags. A particular emphasis was placed on locating buried organics within the soil matrix; those that fell outside of the vertical transect were also sampled.

Permafrost samples were collected from hummock troughs. The permafrost samples were obtained using a 5 cm diameter CRREL core barrel with Viper powerhead. The permafrost cores, up to 2 m in depth, were subsampled at approximately 3-5 cm intervals and placed in polyethylene plastic bags or sealed plastic jars.

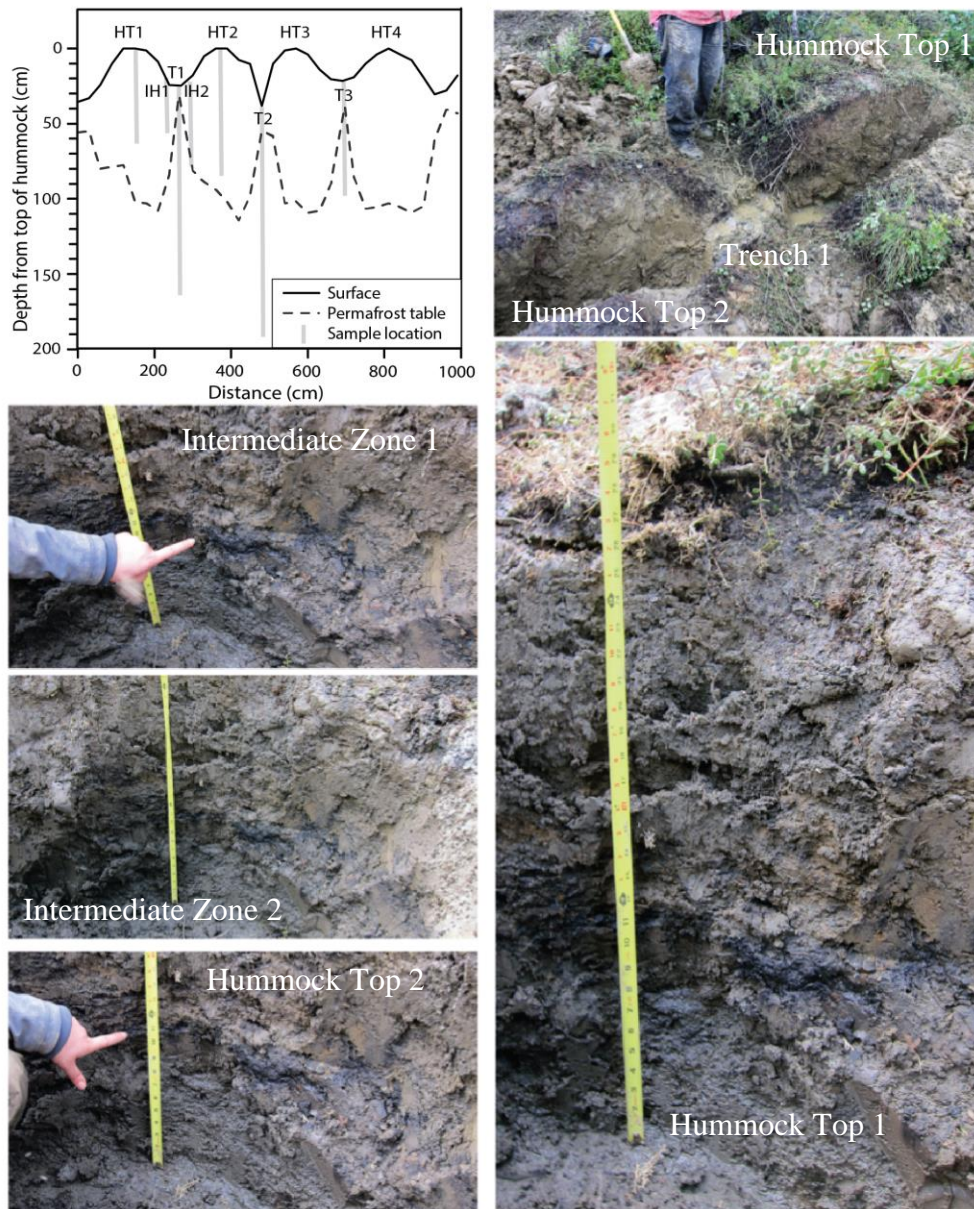


Figure 13: Active layer profile from Navy Road field site, showing sample locations in the hummock centre, inter-hummock and inter-hummock depressions (troughs). Permafrost table is indicated by the end of tape measure. Photos taken August 2014.

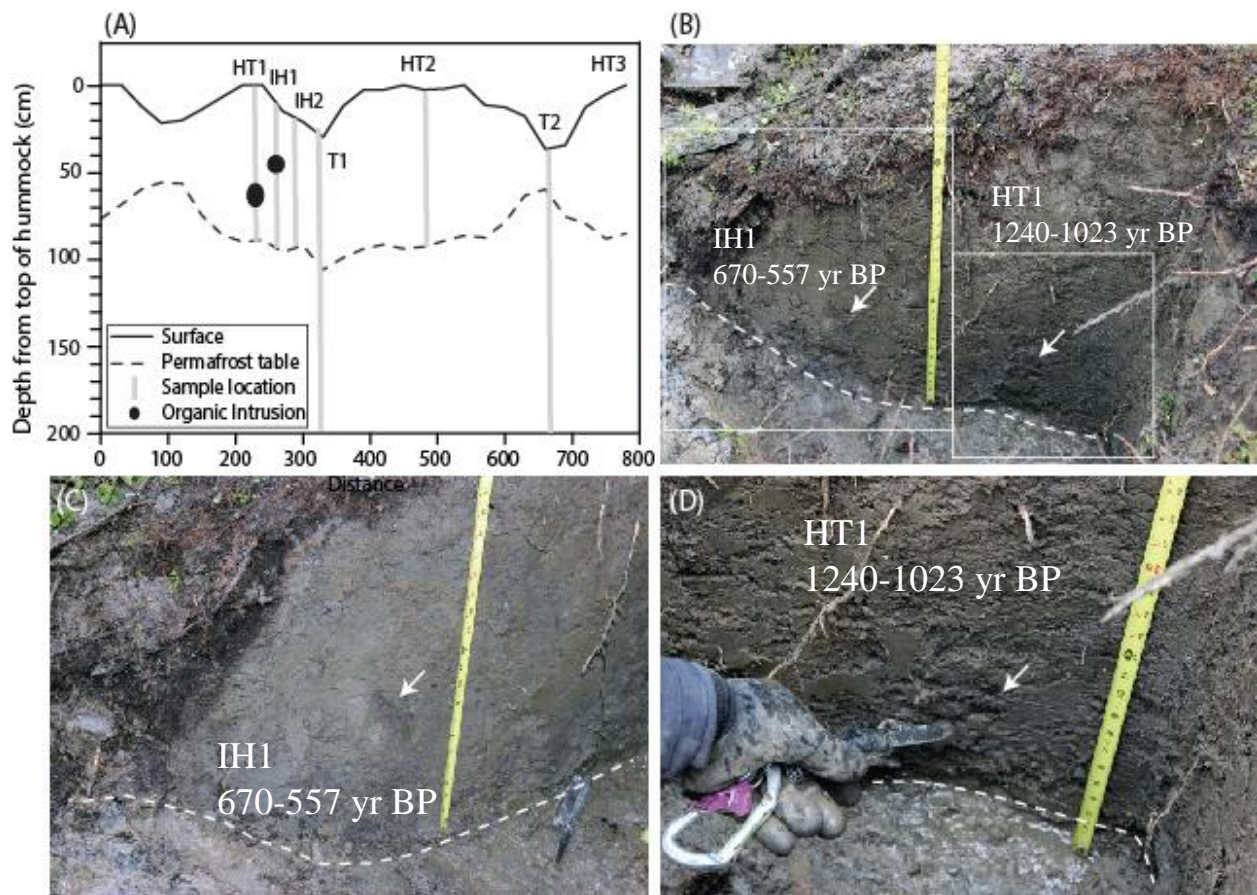


Figure 14: A) Active layer profile from Rengleng River field site, showing sample locations in the hummock centre, intermediate hummock, and inter-hummock depressions (troughs). Permafrost table is indicated by slashed line. Arrows indicate organic material and the direction of displacement. B) Location of organic intrusions in hummock top 1 (HT1) and intermediate hummock 1 (IH1) with ^{14}C calibrated ages. C) Organic intrusion 1 (R2-ORG-1) located in intermediate hummock zone 1 (IH1). D) Organic intrusion 2 (R2-ORG-2) located in hummock centre 1 (HT1). Photos taken August 2014.

5.2 Laboratory Analyses

5.2.1 Gravimetric water content

All active layer and permafrost samples were brought to Aurora Research Institute in Inuvik, NT, where they were analyzed for gravimetric water content (GWC). GWC was obtained

by measuring the wet weight, in g, before drying samples at 105°C for 24 hours; then the dry weight, in g was measured.

The equation below is used to determine GWC for each sample (van Everdingen, 1998):

$$\text{GWC (\%)} = \left(\frac{\text{Weight of moist soil (g)} - \text{Weight of dry soil (g)}}{\text{Weight of dry soil (g)}} \right) * 100\% \text{ [3]}$$

5.2.2 Grain size distribution

As initial observations found that the majority of samples were composed of fine sediments, a Microtrac S3500 laser particle size analyzer was used to determine grain size of mineral component of the soils. Prior to drying samples for GWC, a small subsample (ca. 5cc) of soil was removed and placed in a 50 mL falcon tube. The organic matter in the samples was removed with H₂O₂ (10% concentration) where necessary (>8%). The remaining mineral soil was placed in a 5% hexametaphosphate solution to disperse the soil particles.

5.2.3 Organic Matter, Organic Carbon and inorganic carbon content

Bulk organic matter and inorganic carbon contents were calculated using the loss on ignition method described by Heiri et al. (2001). After drying for GWC, the samples were ground finely with a mortar and pestle. Approximately 5-6 g of sample were placed in a crucible and dried at 105°C for 24 hours. The samples were weighed, in g, (LOI₁₀₅) and placed in a high temperature muffle furnace at 550°C for 6 hours, then weighed (LOI₅₅₀). They were returned to the furnace for an additional 6 hours at 950°C and weighed (LOI₉₅₀). These weights are used to complete the following equations and determine the organic matter and inorganic carbon contents:

The organic matter content is determined using the following equation:

$$\text{Organic matter (\%)} = \left(\frac{\text{LOI}_{105}(\text{g}) - \text{LOI}_{550}(\text{g})}{\text{LOI}_{105}(\text{g})} \right) * 100\% \text{ [4]}$$

The inorganic carbon content was determined using the following equation:

$$\text{Inorganic carbon (\%)} = \left(\frac{\text{LOI}_{550}(\text{g}) - \text{LOI}_{950}(\text{g})}{\text{LOI}_{550}(\text{g})} \right) * 100\% \text{ [5]}$$

5.2.4 Carbon-14 as a soil tracer

Sample selection for Carbon-14 analysis was determined from peaks in organic matter contents calculated through the Loss on Ignition method (Heiri et al., 2001). Due to relatively low organic matter, sample selection was limited. Site selection was limited to Rengleng River due to the organic intrusions that were discovered within hummock centre 1 and the intermediate hummock zone, as indicated in Figure 14. To determine the age of potential collapse events, priority was given to samples located within the troughs, as well as organic deposits found within the active layer. To separate the organic matter from the soil, a small soil sample was mixed with deionized H₂O and stirred. The organic material floated to the surface, and was then scraped off. Organics were separated into twigs/roots, charcoal, leaves and other organic material where possible to obtain. Wood was separated out where possible, as this material was more likely to have died before the surrounding organics, and therefore would not have provided an accurate approximation of burial.

The standard AAA pretreatment at the Andre Lalonde AMS Laboratory follows the protocol outlined in Brock et al. (2010). Briefly, sedimentary or other carbonates are removed during the first acid wash (HCl, 1N, 80°C, 30 mins), humic acid is removed during one or more alkali washes (NaOH, 0.2N, 80°C, 30 mins), and any CO₂ absorbed during the alkali step is removed with a second acid wash (HCl, 1N, 80°C, 30 mins). Each step is followed by three rinses in MilliQ™ water. Clean samples are freeze dried overnight and combusted in a tin capsule using a Thermo Flash 1112 elemental analyzer in CN mode interfaced with an extraction line to trap the pure CO₂ in a pre-baked 6 mm pyrex tube.

Where samples were too small for AAA pretreatment, an acid only treatment was used. If humic acid is not believed to be an issue, or the submitter does not wish for it to be removed, the sample will follow the AAA pretreatment protocol, omitting the alkali step and second acid wash. The cellulose extraction for wood at the Lalonde AMS Laboratory follows the protocol outlined in Staff et al. (2014). Briefly, the standard AAA pretreatment (Brock et al., 2010) is followed by a bleach treatment at 80°C. The samples are monitored and removed once the colour has turned white. After three rinses in MilliQ™ water, the samples are freeze dried overnight and combusted in a tin capsule using a Thermo Flash 1112 elemental analyzer in CN mode interfaced with an extraction line to trap the pure CO₂ in a pre-baked 6 mm pyrex tube.

Radiocarbon analyses were performed on a 3MV accelerator mass spectrometer (AMS) by High Voltage Engineering. Measurements were normalized with respect to the reference material Oxalic II ($F^{14}\text{C}=1.34$) and ages are calculated using the Libby ^{14}C half-life of 5568 years. The errors on ^{14}C ages represent 1σ confidence limits. Calibration was performed using OxCal v4.2.4 (Bronk Ramsey, 2009). Calibrated results are presented with 2σ confidence limits and greater than 90% of the calibrated age range under the calibration curve. For samples with an $F^{14}\text{C}$ less than 1, the IntCal13 calibration curve was used (Reimer et al., 2013). For samples with an $F^{14}\text{C}$ greater than 1, the post-bomb atmospheric curve was used (Hua et al., 2013).

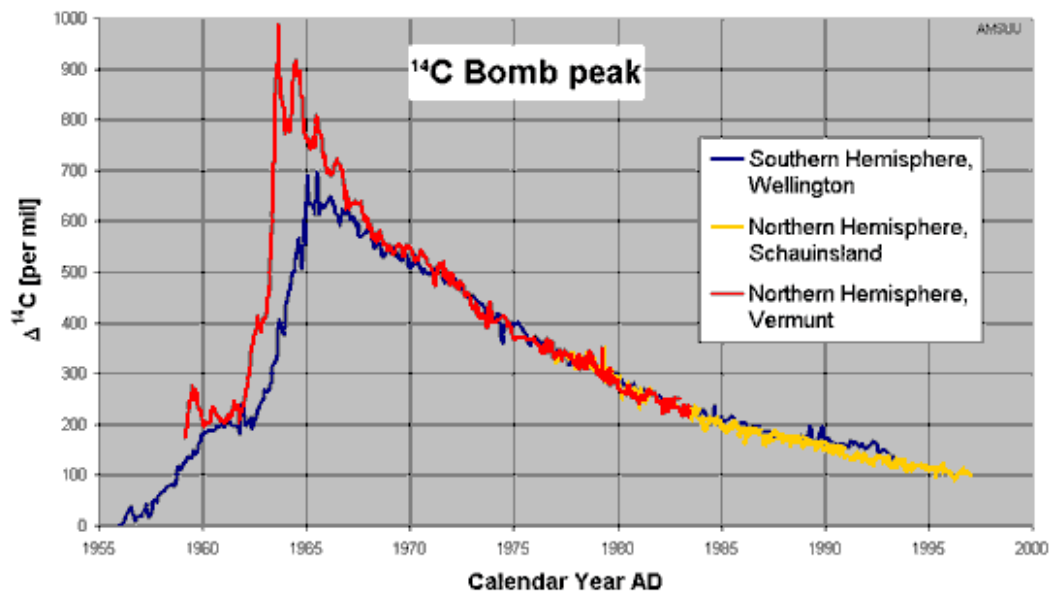


Figure 15: The bomb peak showing ^{14}C in the atmosphere in both hemispheres following nuclear testing from 1955-2000. From: Universiteit Utrecht, <http://web.science.uu.nl/AMS/Radiocarbon.htm>

6. RESULTS

The results are presented along the respective transects from left to right in the diagrams of sample location (Figures 13 and 14); however to compare troughs and intermediate zones together, some of the results have been described as a combination of the zones of each site. The vertical and horizontal scales are not uniform to allow results at individual sites to be presented simultaneously.

6.1 Relation between Gravimetric Water Content and sample location

At Navy Road and Rengleng River sites gravimetric water content (GWC) was lowest in the active layer at the hummock centres, increasing at the intermediate zones, and reaching highest values in the troughs. Active layer samples near the surface recorded high GWC content if samples were organic-rich. The highest variation occurred below the transient layer in permafrost zone.

6.1.1 Navy Road

The GWC results from hummocks at Navy Road are presented in Figure 16. In the centres of hummocks (HT1, HT2), GWC ranged from 36.1 to 41.1% with highest values in the O-horizon of the active layer at 40 and 60 cm depth respectively. In the intermediate zones (IH1, IH2), GWC ranged from 39.3 to 70.8% and remained relatively stable with depth. GWC in the troughs ranged from 48 to 652%, with no clear trend between the three cores. GWC ranged from 20 to 312% in trough 2 (T2), reaching a maximum at 352% at a depth of 71 cm; others have suggested that this indicates a relic active layer (Fontaine, 2015). Overall GWC is highest in the troughs (T1, T2, T3), below the transient layer in permafrost, although the organic-rich active layer samples recorded higher values compared to the intermediate zones or hummock centres.

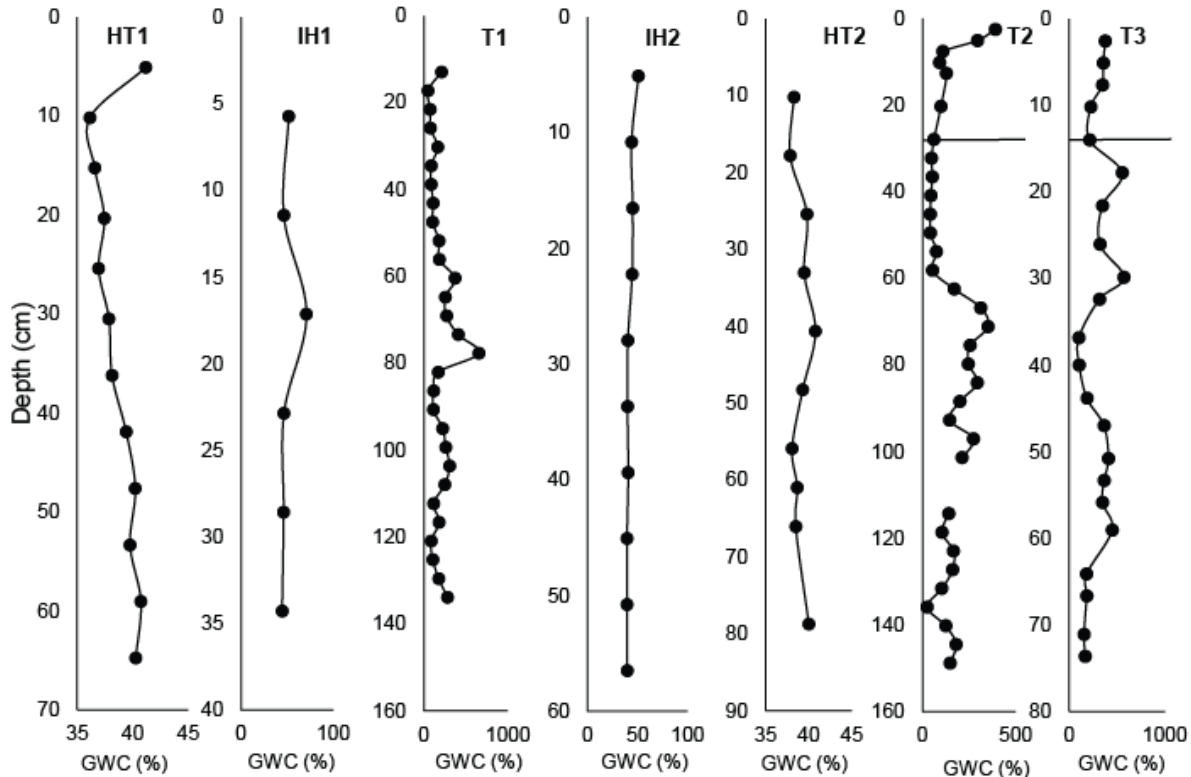


Figure 16: Gravimetric Water Content (%) at depth from samples at Navy Road site, organized according to location across transect. Note that vertical axis (depth) and horizontal axis are not standardized for all samples.

6.1.2 Rengleng River

The GWC results from hummocks at Rengleng River site are presented in Figure 17. GWC ranged from 7 to 520%. Samples in the active layer near the surface measured higher GWC values, corresponding to higher organic matter levels (Figure 19), and there is a decreasing trend with depth. Active layer samples in the hummock centre (HT1) ranged from 20.2 to 36.6%, reaching the maximum nearest the surface. The intermediate hummock zones (IH1, IH2) ranged from 7 to 279%, though the majority of the samples fell within the 27 to 56% range. The troughs (T1, T2) ranged from 23.5 to 520%, both reaching the maximum close to the transient layer and the top of permafrost. There is variability in GWC throughout the permafrost, with slightly higher levels though a decreasing trend overall. Trough active layer measurements are comparably low and do not measure above 35% aside from samples located near the surface in organic-rich zones.

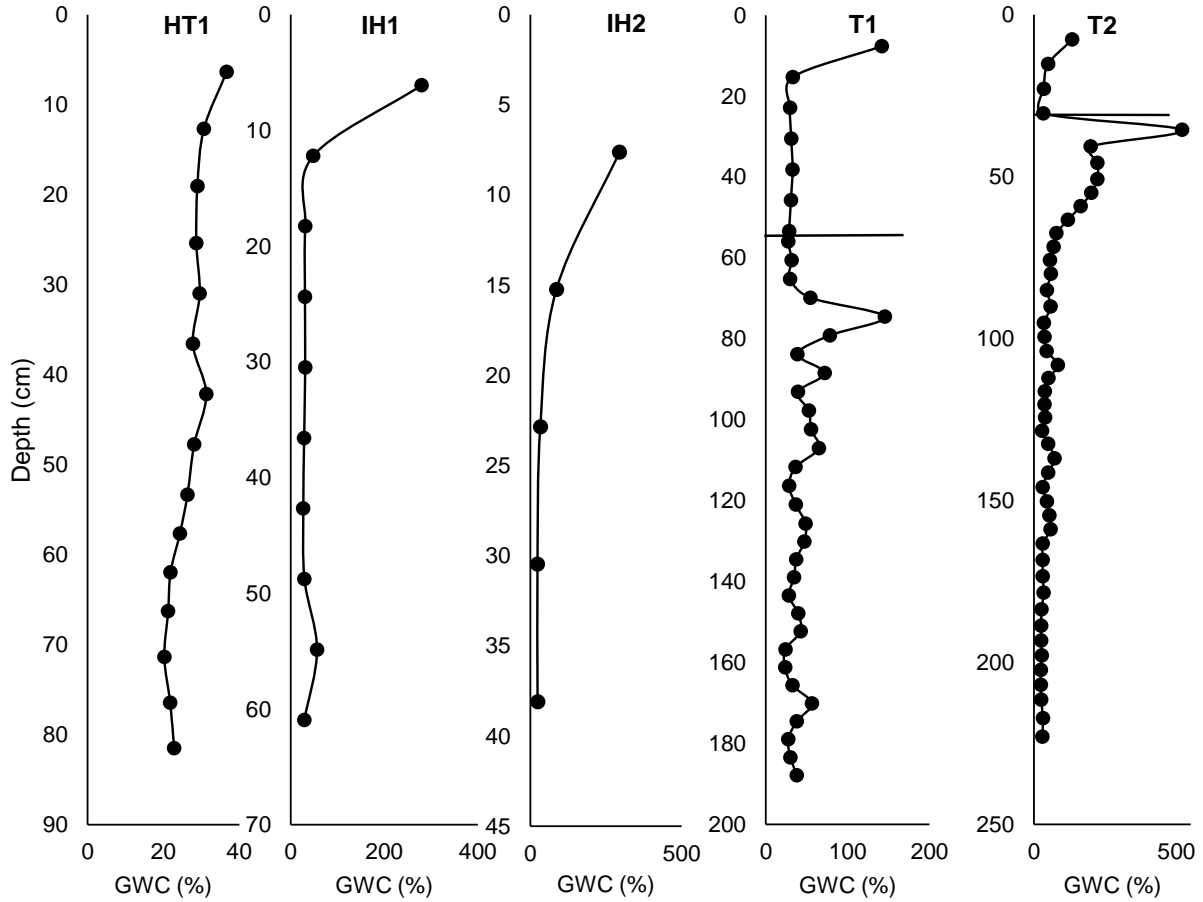


Figure 17: Gravimetric Water Content (%) at depth from samples at Rengleng River site, organized according to location across transect. Note that vertical axis (depth) and horizontal axis are not standardized for all samples.

6.2 Distribution of Organic Matter

The results of organic matter distribution are presented in Figures 18 and 19. Organic matter distribution was highest in the O-horizon, and otherwise varied across the hummock transect, generally measuring lower values within the active layer of the raised hummock tops followed by higher content in the samples taken from the troughs.

6.2.1 Navy Road

Results of organic matter concentration at Navy Road are presented in Figure 18. Organic matter ranged from 7 to 46%. In the hummock centres (HT1; HT2), low percentages of organic matter were measured, ranging from 6.2 to 10.4%, with maximum values found near the surface

in the O-horizon. Organic matter concentration in the intermediate hummock zones (IH1, IH2) ranged from 6.4 to 23.8%, generally decreasing concentrations with depth. The second intermediate zone recorded higher overall values, and reached a maximum at near the surface, while the first intermediate hummock zone reached a maximum at 11.4 cm depth; this also corresponds with the maximum GWC measurement (Figure 16). The intermediate zones (IH1, IH2) recorded a range of organic matter from 8 to 20%, reaching a maximum at 17.1 cm before decreasing with depth. Trough 1 and 2 (T1, T2) were similar in organic matter distribution with depth, compared to trough 3 (T3) which was much more variable. Trough 1 recorded organic matter in permafrost ranging from 6 to 19%. Trough 2 (T2) measured organic matter ranging from 7.2 to 46%, with the highest values at the surface in the organic-rich active layer; in the permafrost zone, the highest concentrations of ca. 25% are found at from 122 to 127 cm depth. Trough 3 (T3) has highly variable organic matter concentrations, ranging from 7-80%. Active layer measurements peaked near the surface at 73%, decreasing with depth to 29%. In the permafrost zone below the transient layer, values increased to 66%. Organic matter concentrations then decrease to 13% at 36 to 40 cm depth, before increasing from 27 to 80% from 43 to 59 cm depth. Concentration then decreases to 9% at the bottom of the core.

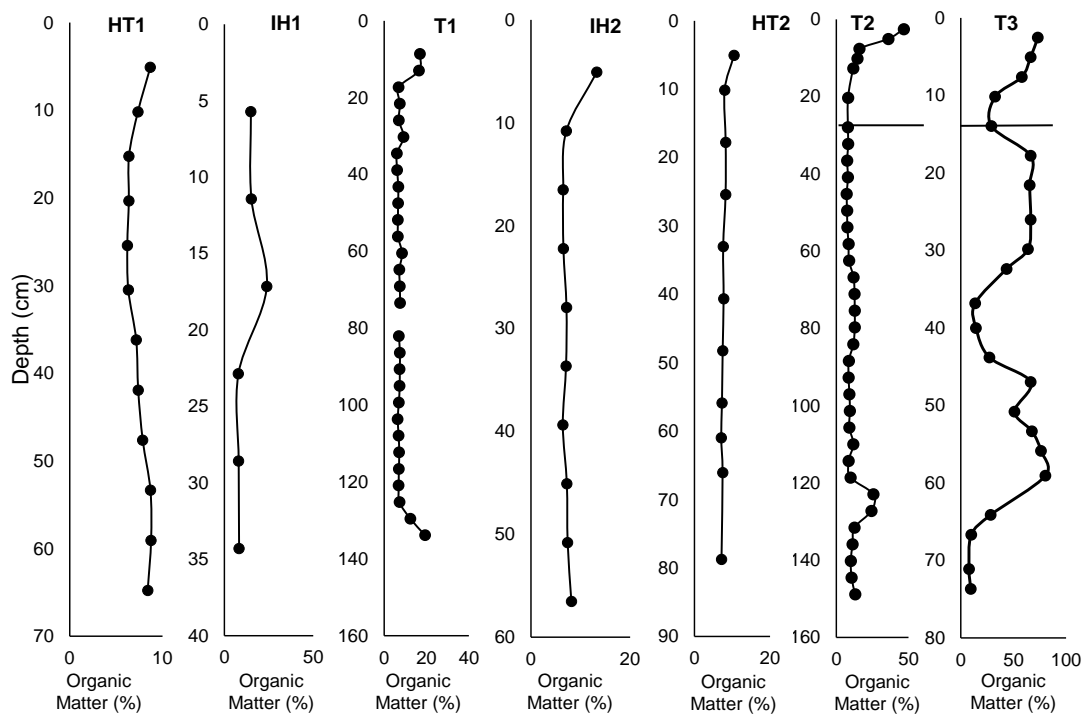


Figure 18: Organic matter (%) concentrations at Navy Road site determined using loss on ignition method (Hieri et al., 2001).

6.2.2 Rengleng River

Results of organic matter concentration at Rengleng River site are presented in Figure 19. Generally there are low percentages of organic matter found throughout the active layer samples (HT1, IH1, IH2), aside from the organic intrusions (indicated in Figure 14). Aside from the organic intrusion found at 55.8 to 71.12 cm depth, the hummock centre (HT1) recorded relatively low concentration of organic matter, with the highest values of 10% in the O-horizon near the surface, decreasing to 4% with depth. Both intermediate zones (IH1, IH2) recorded highest concentrations of organic material at the top of the active layer (67 to 71%), and decreased rapidly to below 10% with 8 cm, continuing to decrease or remain stable with depth. The second organic intrusion was found at 27.94 to 40.64 cm depth in the first intermediate hummock (IH1). Troughs (T1, T2) at Rengleng River site record highest concentration of organic matter in the active layer at the surface, ranging from 4.1-13.7%, decreasing until the transient layer, and increasing slightly in the upper permafrost. Below the transient layer, trough 1 (T1) reaches a maximum concentration of 6.5% at 60-75 cm depth, while trough 2 (T2) reaches a maximum concentration at 38% at 40 cm depth.

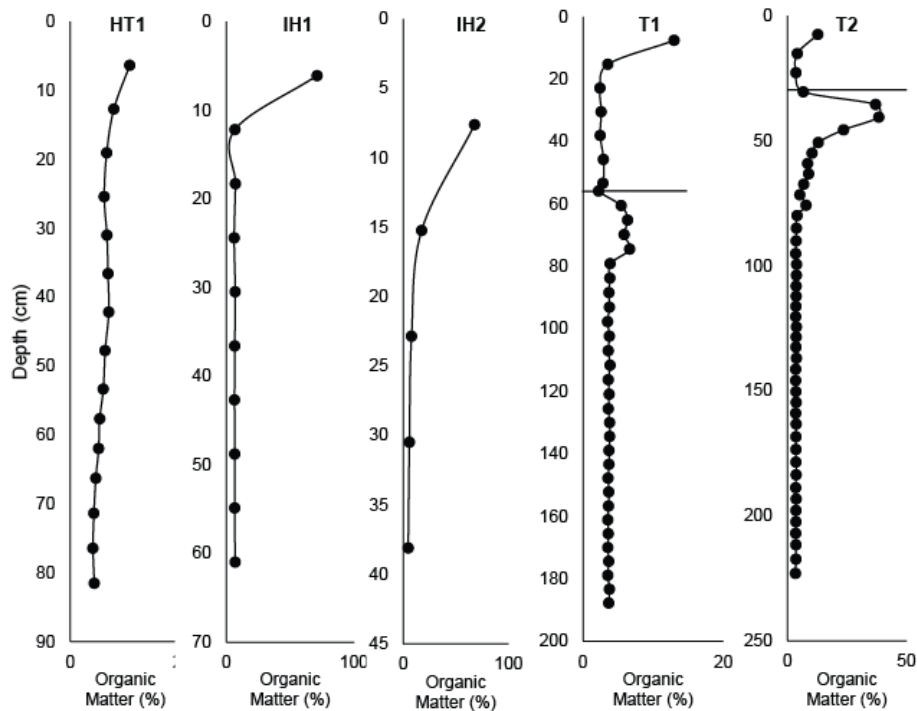


Figure 19: Organic matter (%) concentrations at Rengleng River site determined using loss on ignition method (Hierl et al., 2001)

6.3 Distribution of Inorganic Carbon

At both Navy Road and Rengleng River sites, inorganic carbon concentrations were relatively low throughout, ranging from 0.5 to 3.6%. Results are presented in Figures 20 and 21.

6.3.1 Navy Road

Results of inorganic matter content at Navy Road site are presented in Figure 20. Inorganic carbon ranged from 0.5 to 2.5%, demonstrating little change between the active layer and permafrost. The hummock centres (HT1, HT2) measured relatively consistent inorganic carbon measurements, ranging from 1.6 to 2.3%; with little change with depth. Intermediate hummock zones (IH1, IH2) recorded relatively low and consistent inorganic carbon concentrations, ranging from 1.0-2.3%. Inorganic carbon concentrations in the troughs (T1, T2, T3) ranged from 0.5 to 3.2%. Values were slightly higher than active layer samples, and were generally stable, with the maximum value recorded in T3 at a depth of 53 cm. Trough 2 reached a maximum of 2.6% at 114 cm depth.

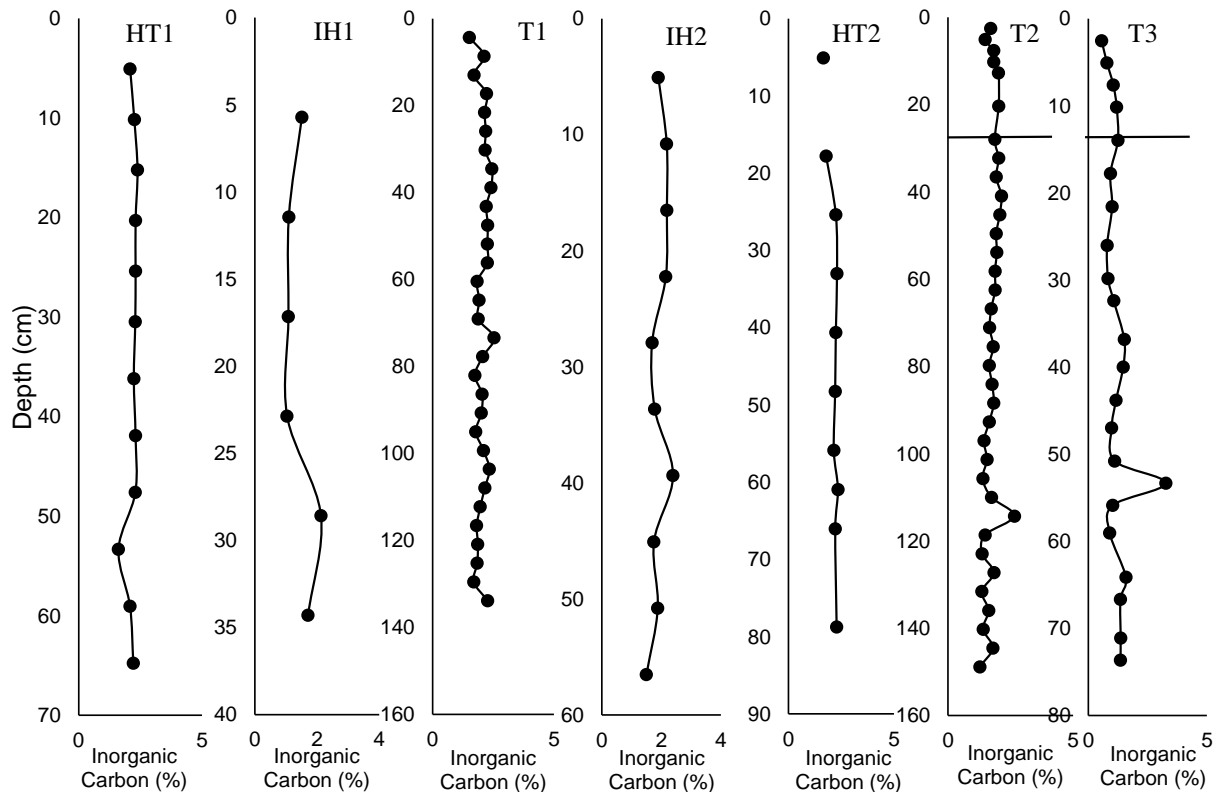


Figure 20: Inorganic carbon (%) concentrations at Navy Road site determined using loss on ignition method (Hieri et al., 2001)

6.3.2. Rengleng River

Results of inorganic matter content at Rengleng River site are presented in Figure 21. Inorganic carbon values in the active layer (HT1, IH1, IH2) range from 0.6 to 2.3%; HT1 and IH1 increase slightly with depth, while also decreasing slightly at the base of the active layer. The highest value in IH2 is measured near the surface at 1.1%, below which values are stable. Inorganic carbon concentration in the troughs (T1, T2) is low in the active layer, increasing in the permafrost zone, ranging from 1.0-3.6%. T1 reaches a maximum 83 cm depth, while T2 reaches a maximum at 108 cm depth; both record generally stable values around 2% with increasing depth after maximums

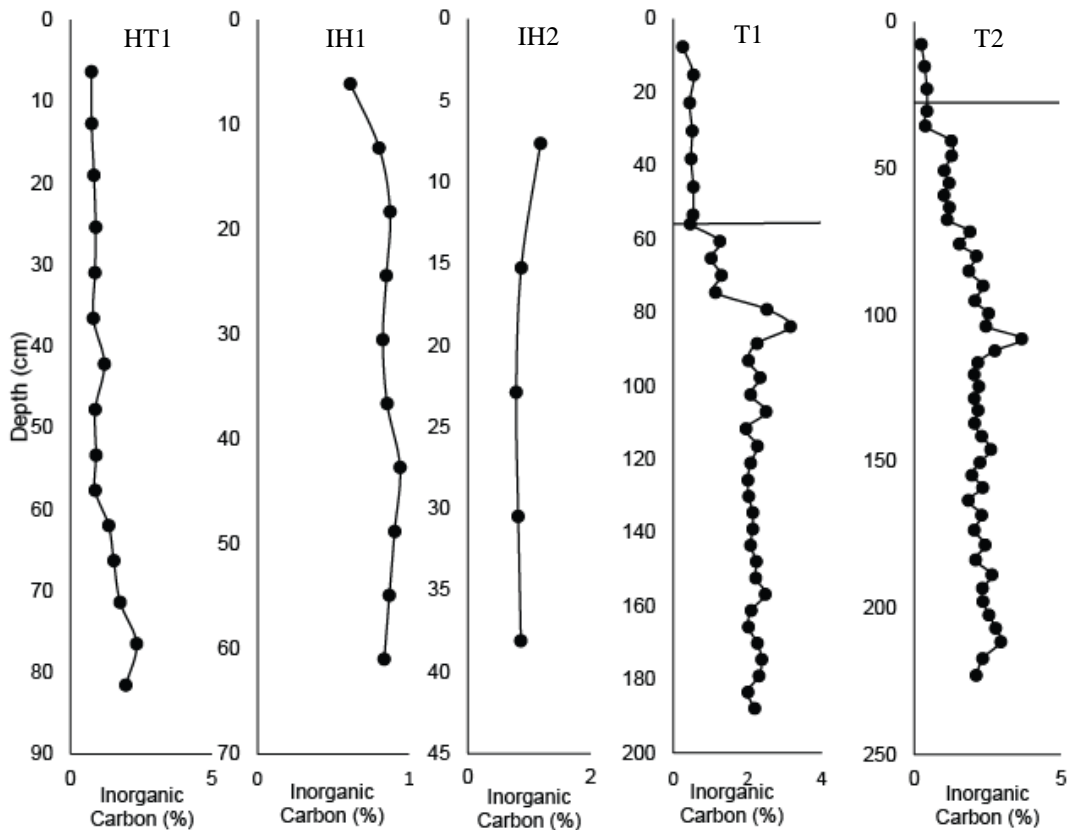


Figure 21: Inorganic carbon (%) concentrations at Rengleng River site determined using loss on ignition method (Hierl et al., 2001)

6.4 Grain Size Distribution

The soil texture at Navy Road and Rengleng River sites consist mainly of silty loam, though Navy Road (Figure 22a) recorded a slightly higher proportion of sand-sized particles than

Reng Leng River (Figure 23a). Average particle size at Navy Road is 16.5 μm , and 24.4 μm at Reng Leng River. Little variations in grain size distribution were observed across hummock transect or with depth.

6.4.1 Navy Road

Grain size distribution presented in the ternary graph in Figure 22a indicates that the soil is composed of a silty loam. Average grain size for the intermediate hummock cores and trough cores are represented in Figure 22b (IH1, T1, IH2 and T2). Intermediate hummock zone 1 (IH1) has an average grain size of 15.15 μm . In trough 1, grain size averages 14 μm and there are slight variations with depth, until 129 and 133 cm depths where average grain size reaches 24 to 49 μm . Intermediate hummock zone 2 (IH2) has an average grain size of 12 μm , and a range of 9.4 to 16.8 μm and shows little variation with depth. Trough 2 (T2) has an average grain size of 25 μm and a range of 14.3 to 48.8 μm . Average grain size reaches a maximum of 48.8 μm at 53.8 cm depth, after which average grain size decreases slightly to the 2 to -35 μm range.

Stacked area graphs in Figure 22c represent the percentage of clay, silt and sand for each sample set or core as it relates to depth. Overall average percentage for particle size throughout the site is as follows: 23.4% clay, 70.4% silt and 6.1% sand. The intermediate hummock zone 1 profile (IH1) demonstrates an increase in both silt and clay with depth. Trough 1 records slight variation in proportion of grain sizes with depth, though there is an increase in sand percentage at 133 cm depth. Intermediate hummock zone 2 (IH2) indicates a relatively similar profile of grain size with depth; there is a slight increase in sand percentage at both the top and bottom of the profile. Trough 2 records a spike in sand percentage at 53.8 cm depth as also indicated in Figure 22b, however percentages do not vary greatly in the overall profile.

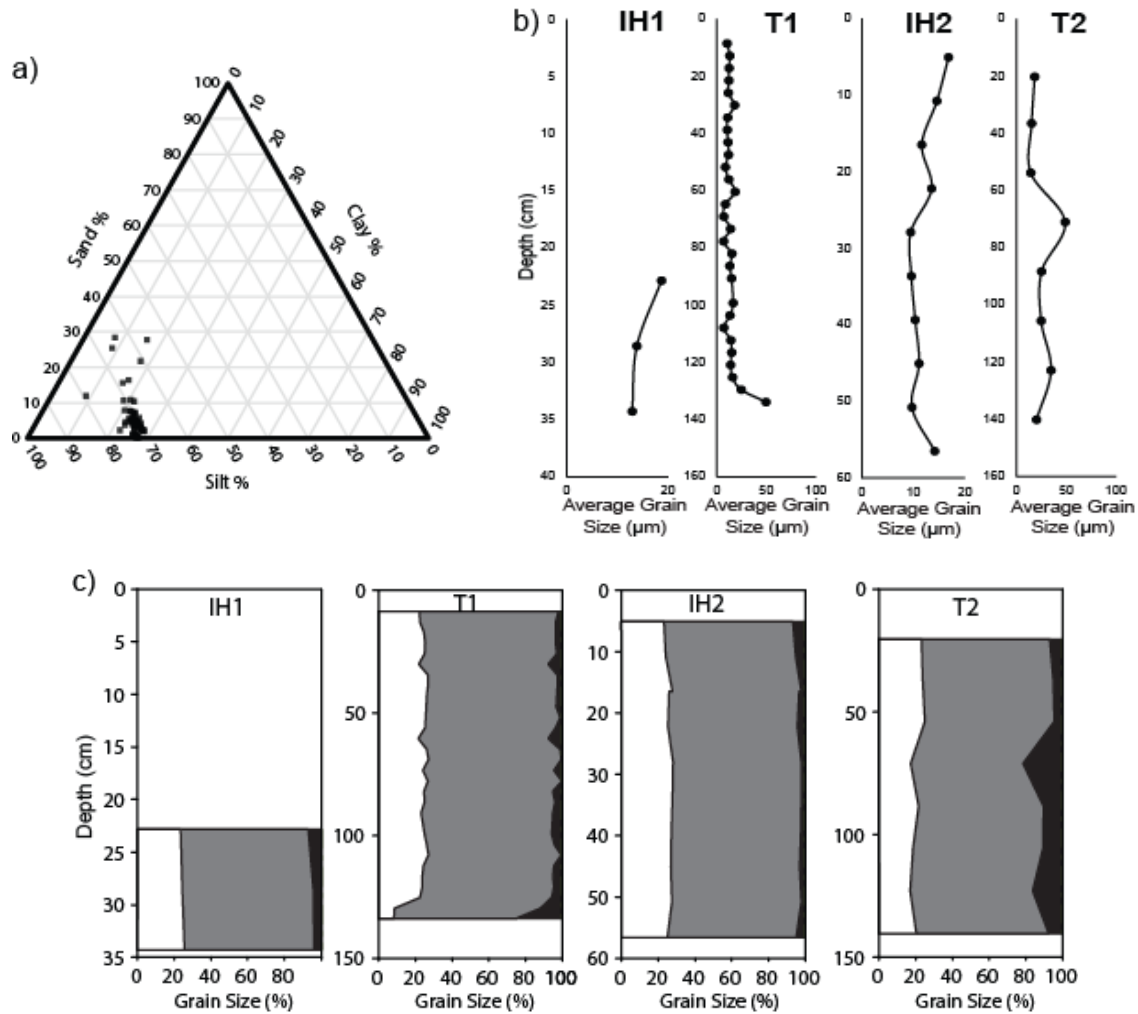


Figure 22: Distribution of grain size at Navy Road site as determined using the Microtrac S3500 laser particle size analyzer a) Ternary graph of grain size distribution b) Average grain size distribution (μm) c) percentage of grain size by percentage of clay (white), silt (grey), and sand (black) at depth

6.4.2 Rengleg River

Grain size distribution presented in the ternary graph in Figure 23a indicates that the soils are composed of a silty-loam. These samples are tightly clustered with minimal variation between 10-20% differences in particle size variation.

Average grain size for all Rengleg River samples is $24.5 \mu\text{m}$. Grain size in hummock centre 1 (HT1) is mainly consistent, ranging from 18 to $25.5 \mu\text{m}$, with an average of $22.3 \mu\text{m}$. There is a slightly higher grain size at the top of the active layer near the surface, measuring $25.5 \mu\text{m}$, as well as a peak of $25 \mu\text{m}$ from 36.5 to 53.3 cm depth, below which particle sizes decrease

slightly to 20 μm . The first intermediate hummock zone centre (IH1) ranges from 18.7 to 28.5 μm , with an average grain size of 24.5 μm . The largest change in size occurs from the 18 to 24 cm depth with an approximate 7 μm increase in particle size, after which values range from 22 to 28 μm . The second intermediate hummock zone (IH2) grain size ranges from 23 to 30.5 μm with an average particle size of 26.5 μm ; there is a slight decreasing grain size trend with increasing depth.

Stacked area graphs in Figure 23c represent the percentage of clay, silt and sand for each sample set or core as it relates to depth. Overall average percentages for particle size throughout the site are as follows: 12.7% clay, 78.7% silt and 8.5% sand. Hummock centre 1 indicates a slightly higher percentage of sand in the top of active layer nearest the surface, however variations are minimal. The first intermediate hummock zone shows a slight increase in grain size with depth, which is also indicated in the average particle size values found in Figure 23b. There is a slight increase in percentage of sand in the second intermediate hummock zone (IH2) with depth.

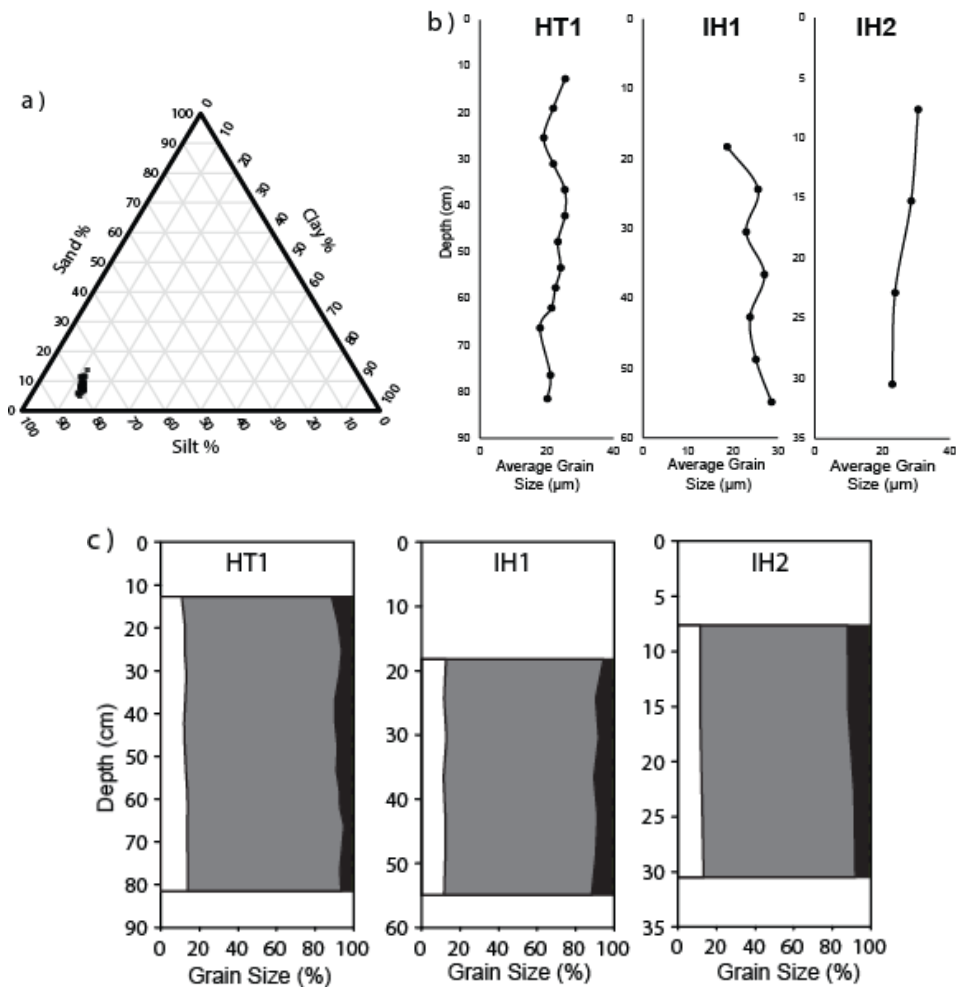


Figure 23: Distribution of grain size at Rengleng River site as determined using the Microtrac S3500 laser particle size analyzer a) Ternary graph of grain size distribution b) Average grain size distribution (μm) c) percentage of grain size by percentage of clay (white), silt (grey), and sand (black) at depth.

6.5 Distribution of Carbon-14

Carbon-14 measurements were done only for the Rengleng River site (Figure 24 and Table 2). The highest values of percentage modern carbon (pmC) are found near the surface of the active layer in the hummock centre whereas the lowest values are found in near the top of permafrost in the troughs. Within hummock center 1 (R2-H1-2A), a value of 127.72 pmC (119.61 pmC for duplicate sample) was measured at 12.7 cm depth and pmC values progressively decrease with depth. In both troughs, there is a mixed age sequence. In T1, pmC measurements vary from 75.17, 83.66, 76.84 at 65.2 cm, 69.9 cm, and 74.5 cm depths, respectively In T2, pmC measurements vary from 100.55, 97.54 and 107.44 at 35.56 cm, 40.64 cm and 45.72 cm depths, respectively

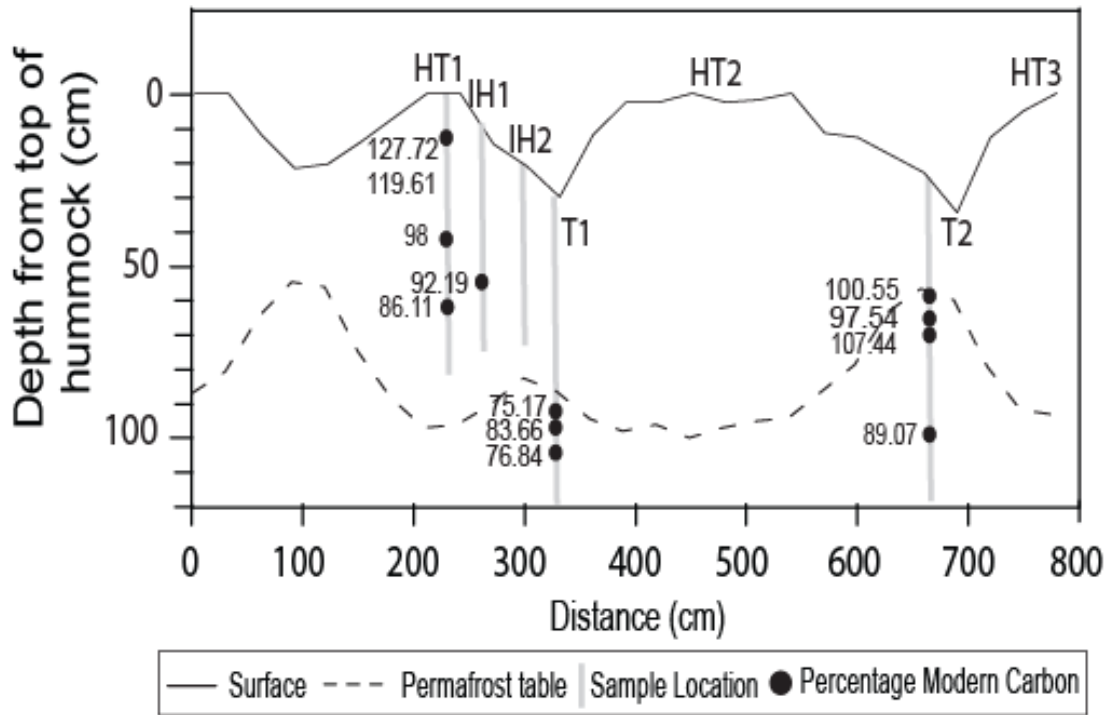


Figure 24: Distribution of percentage modern carbon at Rengleng River. Where two carbon-14 values are available, only those with exclusively twigs and leaves are used. Wood samples are included in Table 2

Table 2: Summary of carbon-14 samples from Rengleng River, including various materials obtained from the same sample.

Sample ID	Core	Depth (cm)	Material	pM Carbon	±	cal BP
R2-ORG-1	IH1	27.94-40.64	twigs	92.19	0.0031	670-557
R2-ORG-2	HT1	55.8-71.12	twigs	86.11	0.0035	1240-1023
R2-H1-2A	HT1	12.7	leaves, twigs	127.72	0.0036	AD1959-1962 or AD1979-1981
R2-H1-2B	HT1	12.7	leaves, twigs	119.61	0.0035	AD1958-1961 or AD1984-1987
R2-H1-7	HT1	42.164	leaves, twigs	98	0.0031	285-0+
14-R2-2	T1	65.1764	leaves, twigs	75.17	0.0026	2354-2183
14-R2-3	T1	69.8246	leaves, twigs	83.66	0.0032	1379-1294
14-R2-4	T1	74.4728	leaves, twigs, charcoal	76.84	0.0035	2299-1992

14-R2-38A	T2	35.56	twigs	100.55	0.0031	AD1954-1956
14-R2-38B	T2	35.56	wood	96.45	0.0027	435-294
14-R2-39A	T2	40.64	wood	94.99	0.0031	517-333
14-R2-39B	T2	40.64	twigs	97.54	0.0031	299-0+
14-R2-40	T2	45.72	twigs	107.44	0.0032	AD1956-1957 or AD 2002-2005
14-R2-47	T2	75.79	leaves, twigs	89.07	0.003	920-790

7. DISCUSSION

7.1 Gravimetric Water Content Variation in Hummocks

Ground ice and water contents, as measured by gravimetric water content (GWC) is constrained by several factors, including moisture availability/migration, soil porosity and texture, all of which affects frost susceptibility of soils (French, 2007). It is commonly noted that gravimetric water content is lowest in the active layer (except in the O-horizon when present) compared to underlying permafrost (Kokelj and Burn, 2005). The highest GWC measurements occur in the active layer of the troughs, which is likely related to the high organic matter found in these layers. Some studies have noted the variation of moisture distribution over short distances within the active layer, likely due to the capability of water to migrate in the active layer and permafrost (Kokelj and Burn, 2005; Lacelle et al., 2014). In this study, active layer measurements determined GWC was lowest at the hummock centres, increasing at the intermediate zones, and reaching highest values in the troughs (Figures 16 and 17). An increase in GWC at the troughs can be explained by the surface morphology of the hummocks whereby water drains at the surface towards the lowered area of the trough. Less vegetation on the hummock centres and increased vegetation in the troughs would also impede surface water migration, storing water more effectively and creating a positive feedback to allow more vegetation to develop (French, 2007). This is consistent with the soil moisture profiles described by Tarnocai and Zoltai (1978), which also demonstrated a decrease in moisture at the hummock centre, increasing towards the troughs.

In hummocky terrain, Kokelj et al. (2007) observed 0.5-3 cm thick ice lenses distributed perpendicular to the direction of heat flow (no depth provided). It was possible to observe ice lenses within the Rengleng River and Navy Road sites trough permafrost cores, similar to those described in Kokelj et al. (2007). Growth of ice-lenses beneath the aggrading bowl-shaped permafrost table can heave soils up and towards the hummock centre (Kokelj, et al., 2007).

An ice-rich transition zone, termed the “transient layer”, at the top of permafrost and base of the active layer, has been attributed to the formation of segregated ice within upper permafrost over decades to centuries (Cheng, 1983; Mackay 1983; Shur et al. 2005). It is generally accepted that this layer acts as a physical boundary or buffer zone, preventing water migration and protecting permafrost at depth from degradation due to the increased energy input required to melt higher ice contents (Cheng, 1983; Osterkamp and Burn, 2003; French, 2007). In this study, some of the

troughs such as Navy Road trough 3 (NR-T3), and NR-T1 (no active layer sampled) appear to indicate the presence of a transient layer with high GWC immediately below the permafrost table; however, this was not observed in NR-T2. Similarly at the Rengleng River site, high GWC was found in the top of permafrost in Trough 2 (RR-T2), whereas ice-rich layer was not observed in the top of permafrost in trough 1 (RR-T1). Similar observations of ice-rich near-surface permafrost, with excess ice contents of 20-40% below well-developed vegetated hummocks were observed by Kokelj et al. (2007) at Navy Road site. The development of the ice-rich transient layer can contribute to the collapse theory as a partial or complete thaw leads to instability in the troughs and surface lowering from melting of excess ice. The transient layer thus denotes the boundary which constrains the soils in the hummock centres, and thawing leads to the collapsed form of hummocks (Kokelj et al. 2007). Dyke and Zoltai (1980) indicated that samples below the frost table had natural moisture contents considerably in excess of the liquid limit, which would favour a collapse of hummock centers when thawed.

7.2 Grain Size Distribution in Hummocks

Hummocks tend to develop in frost susceptible soils, which are mainly composed of fine- to medium- textured sediment, as this favours the formation of segregation ice and ice lenses (Tarnocai and Zoltai, 1978; Mackay 1980; Tarnocai and Zoltai, 1981; French 2007). Conversely, a study from Dyke and Zoltai (1980) investigated the development of hummocks in a more sandy soil texture, where sand fraction reached 79%. They noted that the active layer was saturated and prone of liquefaction at the time of excavation, leading to questions surrounding water migration capability. Segregated ice lenses can only form under certain conditions, many of which are associated with fine-grained sediments. Due to smaller pore sizes, clay and silt-size particles are comparably more cohesive, thus enabling and sustaining higher negative pressures, or cryosuction, to develop in soil during the transformation from water to ice during freezing (French, 2007). These pressures allow water to migrate through capillary action, and sustain the development of ice lenses parallel to the surface. As shown in Figures 22 and 23, silty-loam soils were recorded at both sites, indicating high susceptibility to cryoturbation activity (French, 2007). Due to a lack of suitable evidence of variations in grain size in the hummocks, visual observations from the soil pits provided more insight into potential cryoturbated material, as shown in Figures 13 and 14.

Since clasts were not observed in the soil pits at both sites, there is almost no evidence for frost push or pull processes (Figures 22 and 23). This is similar, though on a smaller scale, to the diapirs or plumes that Shilts (1978) documented in the hummock centres, which spread laterally at the surface.

7.3 Organic Matter Concentration in Hummocks

One of the primary objectives of this study was to determine distribution of organic matter in hummocks. Distribution of organic matter within the active layer of hummock centres has been studied for several decades (Dyke and Zoltai, 1980; Lacelle et al., 2014; Kokelj et al., 2007). Notably, Dyke and Zoltai (1980) observed elongated layers of organic material, which were smeared into the mineral soil. Similar layers of organic material were observed in the active layer of hummock centers at Rengleng River (Figure 14), but were not observed at Navy Road site. The presence of organic material at Rengleng River provides evidence for cryoturbation, as these are distributed parallel to the permafrost table. During freeze-back of the active layer, the organic inclusions are pushed further inward toward the hummock center as ice lenses form. Radiocarbon dating of these organic inclusions should therefore provide insights into the rate of movement.

Organic matter contents from hummock troughs were found to vary with depth both between sites, and along the transects. At Navy Road, organic matter content showed high variation with depth in trough 3, where there were several organic-rich layers below the permafrost table; however troughs 1 and 2 had relatively stable organic matter content below the active layer. Organic-rich layers were also measured at both trough 1 and 2 below the permafrost table at Rengleng River. Dyke and Zoltai (1980) also noted organic rich layers immediately below the permafrost table, as well as a subsequent organic layer 20 cm below the permafrost table.

7.4 C14 Variations in Hummocks

Tarnocai and Zolati (1978) described the difficulty in determining the age of a hummock, as well as the cryoturbation process in 1978, and since then several studies have utilized radioactive tracing methods to date organic material in hummocks (Dyke and Zoltai, 1980; Jelinski, 2012; Klaminder et al., 2014). However difficulty remains in using this technique to trace the

cryoturbation process as a comprehensive method. In this study, the ages derived from ^{14}C testing are used to infer the approximate burial time of plants in the inter-hummock troughs during collapse events, which were theorized in Kokelj et al., (2007). Specifically, small shrubs buried during collapse events were assumed to be represented by leaves and twigs found within the permafrost cores taken from troughs between hummock centres. Wood was tested in some cases, but was considered inappropriate for the dating of collapse events: a tree could fall significantly earlier than is buried in a low-productivity environment, therefore providing an older date, and not that of the actual collapse event. These dating difficulties were explained in detail in Tarnocai and Zoltai (1978), and are still relevant in this study. In addition, organic intrusions found within intermediate hummock zones were tested to determine if cryoturbation could be determined within the hummock active layer. Figure 24 demonstrates the relationship between radioactive carbon testing and location of samples taken throughout the hummocks.

There have been limited studies using carbon-14 as a tracer for hummock ages and cryoturbation rates (Tarnocai and Zoltai, 1978; Dyke and Zolati, 1980; Kalminder et al., 2014). Ages determined by Tarnocai and Zoltai (1978) range between 3000 and 3500 yr BP, with the majority below 5000 yr BP; this is similar to the ages presented in Figure 24 and Table 2. The majority of Rengleng River radiocarbon dated samples found a normal distribution of percentage modern carbon (pmC) (Figure 24), whereby youngest material, represented by higher pmC values is located at the top of the column nearest the surface, and with older material (relatively lower pmC) at depth; however, there are slight inconsistencies within the troughs.. Specifically, in trough 1 (T1), there is a mixed age sequence where pmC values vary from 75.17, 83.66, 76.84 at 65.2 cm, 69.9 cm, and 74.5 cm depths, respectively. In trough 2, pmC measurements vary from 100.55, 97.54 and 107.44 at 35.56 cm, 40.64 cm and 45.72 cm depths. Using bomb-peak calibration, it is possible to estimate age. In trough 1, the sample ages are calculated from the surface downwards at 2354-2183 yr BP, 1379-1294 yr BP and 229-1992 yr BP, displaying distinct ages with no overlap. A similar pattern exists in trough 2, where the age sequence from surface to depth is calibrated as modern (AD1954-1956), 299-0+ yr BP, and modern (AD1956-1957 or AD2002-2005). As the samples from trough 2 are impacted by the Suess effect, it becomes more difficult to calibrate values due to the flat portion of the calibration curve caused by the burning of fossil fuels. While inconsistencies in measured pmC and calibrated ages exist in both of the trough permafrost cores, these are most likely caused by contamination the samples with rootlets which

would add a significant amount of young carbon at depth, thereby impacting overall C¹⁴ percentages.

Dyke and Zoltai (1980) utilized organic material to calculate subduction rates in upper permafrost samples: the distance that any piece of organic material has travelled along the column, divided by its radiocarbon age provides the rate of subduction. Their measurements found that the age of material at the base of the active layer was between 1035-2150 yr BP, and subduction rates ranged from 0.46 mm/year to 0.92 mm/year. These displacement rates are about one order of magnitude higher to those estimated by Klaminder et al., (2014) (0.01 cm yr⁻¹).

In addition to rate of subduction of material in the hummock centre, upward displacement of material parallel to the permafrost table can be estimated from buried organic intrusions (R2-ORG-1, R2-ORG-2) found near the base of the active layer (Figure 25). The organic inclusions (R2-ORG-1, R2-ORG-2) buried within the soil matrix were dated between 670 to 557 yr BP and 1240 to 1023 yr BP, respectively. By dividing the median displacement from the permafrost table by the median calibrated age, the rate of displacement of R2-ORG-1 was calculated at 0.43 mm/year and R2-ORG-2 at 0.16 mm/year.

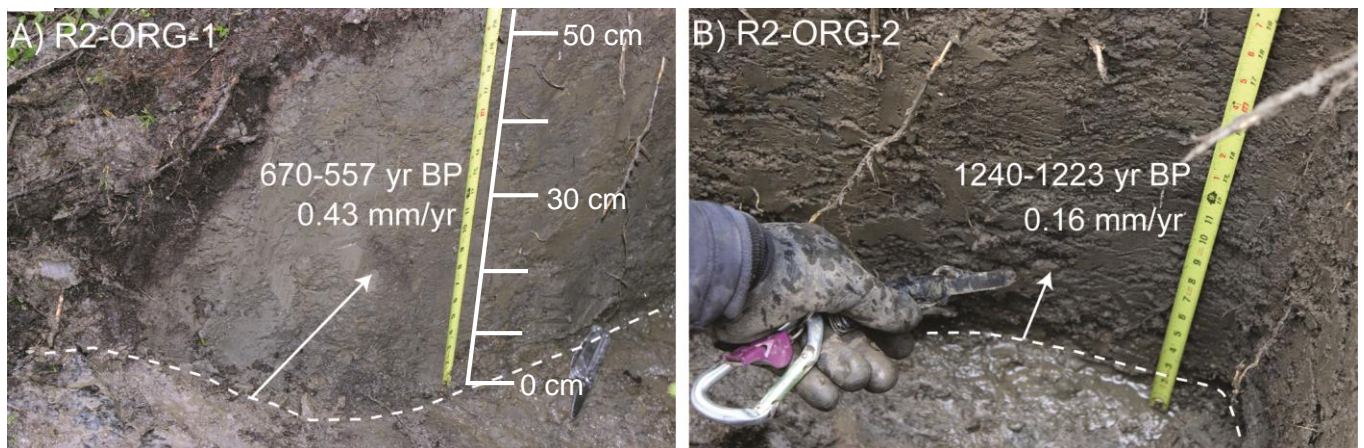


Figure 25: Calibrated ¹⁴C ages and estimated displacement rates of buried organics from Rengleng River site. A) R2-ORG-1 located in the intermediate hummock zone 1 (IH1). B) R2-ORG-2 located in the hummock centre 1 (HT1). Displacement of organics indicated by arrow, permafrost table indicated by dashed line.

As this is the first study of its kind to use radiocarbon dating to look for burial events within troughs, there were several lessons learned when establishing a methodology, and in many ways

this thesis serves as a testing phase for longer-term studies. With a more robust sampling and sub-sampling system in place, this could be a valid method for dating hummock movement, and for understanding the complex processes associated with these landforms. This is discussed in more detail in future work.

7.5 Comparisons to Existing Models

The observations obtained through this study can support two main models of hummock development: the convective cell/equilibrium model proposed by Mackay (1980) and the collapse model proposed by Kokelj et al. (2007).

7.5.1 Convective Cell/Equilibrium Theory

The observations in this study support the convective cell/equilibrium model, as the organic intrusions observed displayed evidence of displacement parallel to the frost table, as demonstrated in Figures 14, 24 and 25. Mackay (1980) proposed surface material displacement of hummock centres towards the neighbouring troughs due to the formation of segregated ice and resultant frost heave during winter, followed by thaw settlement in the spring. Frequent seasonal freeze-thaw cycles over long time periods could gradually restructure soil within the hummock (Mackay, 1980; Peterson and Krantz, 1998; Kokelj et al., 2007). This model was expanded by Dyke and Zolati (1980), who argued that hummocks are essentially closed sediment systems, where sediment must move downward at or near the edges: as hummocks are outlined by vegetation or turf, these organic materials are carried under by the sub-ducting sediment. It was initially theorized that material could be carried deeper than the permafrost table, which marks the base of the active layer. However, organic matter can also then be brought along the permafrost table, cycling into the hummock centre, due to frost heave and upward injection, which is evident by organic intrusions (Van Vliet-Lanoë, 1991). Displacement of cryoturbated organic-rich material in the active layer is also observed at the Caribou Creek field site in Kokelj et al.'s (2007) study: as the hummock begins to collapse outwards, there is an increased rate of organic material distributed within the soil profile, suggesting that a bowl-shaped permafrost table acts as a constraint on the inclusion of organic material into the active layer.

7.5.2 Kokelj's Collapse Theory

Kokelj's model was influenced by studies such as Mackay (1979, 1980), Tarnocai and Zoltai (1978), Peterson and Krantz, (1998), and Kessler et al., (2001). Similar to Tarnocai and Zoltai's observation that young and old hummocks are at the same stage of morphological and pedological development (1978), it is suggested from the radiocarbon results (Figures 24, 25) that the ages of material in troughs that are close together can yield unexpectedly different ages. This is observed in calibrated age differences between troughs 1 and 2 at roughly the same depth of 75 cm (2299 to 1992 yr BP and 920 to 790 yr BP respectively). It can be suggested that these hummocks reach late stage development and continue cycling and expansion in the hummock centres, but do not change the morphology of the landform itself, due to the eventual collapse of intermediate zones into the troughs, bringing the landform back to a state of equilibrium. A crucial factor which none of the previous hummock development models considered was the opportunity for material to aggrade into permafrost due to seasonal changes, such as active layer thaw and refreezing (Kokelj et al., 2007). Kokelj and others' (2007) observations found that the main cause of hummock growth is an increase of near-surface ground ice, connected with an aggrading bowl-shaped permafrost table. These processes thrust soils inward and upward causing hummock growth, whereas thaw subsidence may cause outward spreading and hummock collapse (2007). In addition, experimental results from Kokelj et al. (2007) indicated a slight increase in hummocky relief was associated with upward aggradation of the permafrost table below the troughs by up to 35 cm. Heave was on the order of 1-3 cm in the active layer, however the hummock top heaved by 7.5 cm. In relation to thaw and subsidence, it was observed that in the trough between two well-developed hummocks, near-surface organic matter content was up to 80%; this is compared to only 30% between two collapsed hummocks, supporting the constraining capability of the frost table, and suggesting buried organics are aggraded into permafrost within stable troughs.

Observations from this study support Kokelj's theory of hummock development, whereby due to heave and subsidence of the hummock centres, the intermediate hummock zone collapses onto the trough, burying organic matter. The organic material then aggrades into the permafrost table which is supported by the observations a linear or normal age sequence of organic material found at similar depths in the trough. Displacement of cryoturbated organic-rich material in the active layer is also observed at the Caribou Creek field site in Kokelj et al.'s (2007) study: as the hummock begins to collapse outwards, there is an increased rate of organic material distributed

within the soil profile, suggesting the convective cell/equilibrium and hummock collapse models can function simultaneously.

8. CONCLUSIONS

This thesis examined active layer and near-surface permafrost characteristics of two sites in the Mackenzie Delta region near Inuvik, NWT, to contribute to the ongoing discussion of hummock development dynamics. This study also provided evidence in support Mackay's (1980) convective cell/equilibrium theory, as well as for Kokelj and others' (2007) collapse theory. Additionally, this thesis provided radiocarbon dated ages and displacement rates for organic matter within the hummock active layer and near-surface permafrost. The main findings were:

1. Carbon-14 dating is a valid method for dating hummock collapses.
2. Normal or linear age sequences of radiocarbon dated organic matter were found within both Rengleg River site troughs, providing evidence for Kokelj's hummock collapse theory.
3. Calibrated ages of organic matter range from to 2354 yr BP to the modern era. Soil ages within hummock centres were modern, ranging from 1959-1987 AD, while buried organics were considerably older, from 670 to 1240 yr BP.
4. Displacement of buried organic matter provides evidence for Mackay's convective cell or equilibrium theory: material is moved along the permafrost table, eventually cycling into the hummock active layer. This is indicated by the age of buried organics R2-ORG-1 and R2-ORG-2, 670 to 557 and 1240 to 1023 yr BP, respectively, found in the hummock intermediate zone and centre. The oldest material is located nearer to the hummock centre, while the younger material is located closer to the permafrost table. Average displacement rates were calculated at 0.43 mm/year and 0.16 mm/year respectively. There is considerable difficulty in dating modern-era organic matter and hummocks using ^{14}C due to a long half-life, and it is suggested that this method is paired with dating of radioactive isotopes of a shorter half-life such as tritium or caesium-137.

9. FUTURE WORK

9.1 *Framework: Radioactive Isotope Tracing of Hummocks*

As with any study, there are improvements which could be suggested for future work in active layer dynamics and hummock dating. Specifically, the number of samples tested for C14 should be increased, and be more evenly distributed throughout the sampling region (Figure 26). The following is a summary of the lessons learned and improvements that should be made for future work using this or a similar method.

1. Increase the number and uniform distribution of samples available for ^{14}C testing
2. Remove organic matter, such as twigs and leaves before crushing samples for organic matter and inorganic carbon analysis. This will limit potential contamination of samples with rootlets (source of young carbon), and will also provide a larger amount, as well as the most viable material for C^{14} dating.
3. Combine ^{14}C testing with additional radioactive tracers which have a shorter half-life to increase resolution when dating modern aged samples, such as tritium or caesium-137.
4. Due to the uniformity of grain size throughout hummocks, a detailed analysis of grain size is not recommended due to redundancies.

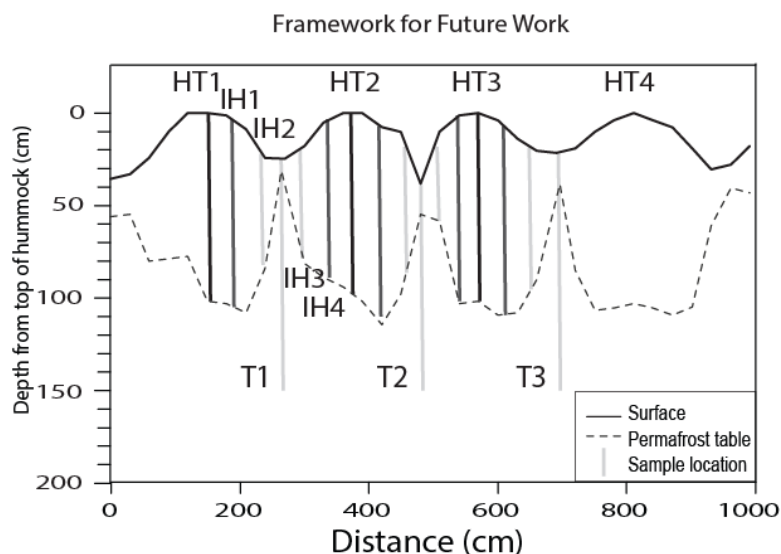


Figure 26: Framework for future hummock development studies: it is recommended that more samples be collected and analyzed for ^{14}C , with a particular emphasis on the location of buried organics.

9.2 Future of Cryoturbation Studies

While a number of studies have been undertaken to study cryoturbation processes, there are still large gaps in scientific understanding of these theories. A disproportionate percentage of studies centred on the formation of patterned ground, which due to differences in soil texture provide little overlap in sorting processes. Additionally, studies of earth hummocks have been mainly limited to the western Canadian Arctic, providing opportunity for further research across a variety of moisture conditions such as in the Canadian high Arctic or Antarctic Dry Valleys.

Methods associated with measuring cryoturbation have involved mainly small-scale experiments and measurements which are difficult to extrapolate to large-scale terrain, both temporally and spatially. Surprisingly, limited permafrost coring and active layer transects have been conducted in hummocky terrain, and as demonstrated by the results of this study and those by Tarnocai and Zoltai (1978), large variation across small distances is common. An increase in long-term experiments and monitoring could yield valuable data and processes change with changing conditions; one such example is expressed at the Navy Road permafrost site in Inuvik (Mackay, 1980; Kokelj et al., 2007). Innovative approaches such as future radioactive isotope dating could help to fill in the gaps associated with hummock age variability. The application of remote sensing in the analysis of historical aerial photos could be utilized to quantify the hummocky terrain across the region.

A deeper understanding of cryoturbation is important for numerous reasons, one being that these processes have an impact on several other periglacial and arctic processes and landforms. Increased understanding of micro-scale processes is significant in regards to furthering understanding of sediment, water flow and vegetation processes. In particular, mixing of surface organics into the subsoil and aggradation into permafrost could have important implications for carbon sequestration, including trace metals and contaminants that are absorbed onto the organic matter (Olsen et al., 2011; Derksen et al., 2012; Vaughan et al., 2013). Understanding cryoturbation can also be used to determine past climates systems and environmental conditions (Van Vliet-Lanoë, 1988). Similarly, much of what can be learned about cryoturbation processes from the Arctic can also be applied to other planetary work, particularly in analyzing the patterned ground structures that have recently been found on Mars. Aside from the scientifically significant gains that would occur from clarifying cryoturbation processes, there are also numerous pragmatic

implications that result from these studies, including more accurate models for permafrost-affected infrastructure, a particularly challenging aspect of settlement in the Arctic.

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