

**DISTRIBUTION, MORPHOLOGY AND CARBON STOCK OF EARTH
HUMMOCKS IN THE CHUCK CREEK TRAIL VALLEY, NORTHERN BRITISH
COLUMBIA, CANADA**

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Abstract

Cryoturbation translocates surface organic-rich horizons deeper in the soils and as such is an important process for carbon sequestration in the active layer (e.g., Kaiser et al., 2007; Van Vliet-Lanoë, 2004). Hummocks, which are non-sorted patterned ground, are sub-meter to meter-scale circular to oval-shaped mounds found in fine-grained frost susceptible sediments. This project examines the distribution, morphology and internal structure of hummocks in the sub-alpine region of the Chuck Creek Trail Valley in the Tatshenshini-Alsek Provincial Park, northern British Columbia. Morphological, sedimentological and geochemical analysis showed that the inter-field differences in hummock morphology of the Chuck Creek Trail Valley were dictated by the silt content within the soil. Hummock fields were found to have an average SOCC for a 1 m pedon of 16.3 kg/m^2 , 38 % situated in the B-horizon. For this pedon, hummocks fields contained 0.05 Pg – 0.2 Pg according to the distribution probability model. Dating of bulk sediments exhibited a cluster of radiocarbon dates around 2000 cal BP for cryoturbated intrusions, implying subduction rates ranging between 0.03 mm/yr to 0.10 mm/yr and coinciding with a period of climatic cooling (Viau, 2008). In conclusion, the differential frost heave model (Van Vliet-Lanoë, 1991) is the only hypothesis for hummock formation consistent with field evidence in the Chuck Creek Trail Valley.

Résumé

La cryoturbation agit comme agent d'enfouissement envers les horizons de surface riches en matière organique et se faisant, devient un processus important pour la séquestration du carbone dans la couche active (e.g., Kaiser et al., 2007; Van Vliet-Lanoë, 2004). Les hummocks, un type de sols polygonaux non triés, sont de petites buttes circulaires ou ovales d'environ un mètre qui se forment dans les sédiments susceptibles au gel. Ce projet examine la distribution, la morphologie et la structure interne des hummocks dans la région subalpine de la Vallée de Chuck Creek Trail, dans le Parc Provincial Tatshenshini-Alsek, au nord de la Colombie Britannique. Les analyses morphologiques, sédimentologiques et géochimiques ont démontré que les différences morphologiques entre les sites étaient dictées par la teneur en limon des sols. La teneur en carbone organique du sol a été évaluée à 16.3 kg/m^2 pour un pédon de 1 m, 38% situé dans l'horizon-B. Pour ce pédon, les champs de hummocks contenaient 0.05 Pg – 0.2 Pg de carbone selon le modèle de probabilité de distribution. La datation de sédiments a exhibé un groupement de dates au radiocarbone autours de 2000 cal BP pour les horizons cryoturbés, impliquant un taux de subduction entre 0.03 mm/an et 0.10 mm/an et coïncidant avec une période de refroidissement climatique (Viau, 2008). Pour conclure, le modèle de soulèvement différentiel dû au gel (Van Vliet-Lanoë, 1991) est la seule hypothèse cohérente avec les indices recueillis sur le terrain dans la Vallée de Chuck Creek Trail.

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List of Acronyms

AMRT: Apparent Mean Residence Time

AMS: Accelerator Mass Spectrometry

BP: Before Present

C: Carbon

C_{org}: Organic Carbon

CALM: Circumpolar Active Layer Monitoring program

CREEL: Cold Regions Research and Engineering Laboratory

DEM: Digital Elevation Model

GIS: Geographic Information System

GPS: Global Positioning System

HC: Hummock Center

HT: Hummock Trough

IRMS: Isotope Ratio Mass Spectrometer

LOI: Loss on Ignition

MAAT: Mean Annual Air Temperature

N: Nitrogen

NCSCD: Northern Circumpolar Soil Carbon Database

PCA: Principal Component Analysis

SOC: Soil Organic Carbon

SOCC: Soil Organic Carbon Content

SOCM: Soil Organic Carbon Mass

SOM: Soil Organic Matter

TDC: Thermal Conductivity Detectors

TGA: Thermogravimetric Analysis

UAV: Unmanned Aerial Vehicle

VPDB: Vienna Pee-Dee Belemnite

$\delta^{13}\text{C}_{\text{org}}$: Delta Isotope 13 for Organic Carbon

1. Introduction

Cryoturbation is an important long-term soil movement process that affects landscape development in high latitude and high elevation environments (e.g., Bockheim and Tarnocai, 1998; Van Vliet-Lanoë, 2004; Grab, 2005; French, 2007). The movement of water along thermal gradients in soils combined with repeated freezing and thawing leads to physical mixing of soils, including soil organic carbon and nutrients (e.g., Grab, 2005; Kaiser et al., 2007; Diochon et al., 2013). Cryoturbation translocates surface organic-rich horizons deeper in the soils and as such is an important process for carbon sequestration in frost susceptible soils (e.g., Van Vliet-Lanoë, 2004; Kaiser et al., 2007). Up to 55% of the SOC density in cryosols could be attributed to its redistribution by cryoturbation (Bockheim et al., 2007). Despite some recent studies on the role of cryoturbation for the sequestration of carbon, the carbon cycle in cryotic soils and the rate (mm to cm yr⁻¹) at which it may occur (e.g., Kaiser et al., 2007; Klaminder et al., 2014; Hjort, 2014), few studies have examined the distribution of organic carbon and the soil transport rates generated by cryoturbation for specific landforms. Patterned grounds derived from cryoturbation greatly affect pedogenesis and the complexity of soils on the micro-scale (Ping et al., 2015).

In Arctic, sub-Arctic and alpine regions, one of the most widespread landform indicative of cryoturbation is earth hummock. Hummocks, which are non-sorted patterned ground, are sub-meter to meter-scale circular to oval-shaped mound found in fine-grained frost susceptible sediments. Hummocks are known to display different morphological, sedimentological and geochemical characteristics depending on the properties of their environment. Although the hypotheses of this work for the origin of hummocks have been advanced (e.g., Kessler et al., 2001; Peterson et al., 2003), the implication of freeze-thaw processes and differential frost heave in their development is unequivocal (e.g., Ballantyne, 1986; Schunke and Zoltai, 1988; Lewis et al., 1993; Van Vliet-Lanoë, 2004). The implication of such processes in hummock formation affects the redistribution of organic carbon and nutrients and can sequester carbon for a very long time, by placing SOC in colder deeper soil layers where little or no biological

decomposition takes place.

This thesis examines the distribution, morphology and internal structure of hummocks in the sub-alpine region of the Chuck Creek Trail Valley in the Tatshenshini-Alsek Provincial Park, northern British Columbia. To describe the distribution pattern and morphology of hummock fields within the valley and explore environmental factors that control their distribution, seven transects were established along 4 different hummock fields. To describe the sedimentological, biochemical and mostly, the distribution of organic carbon and type of organic compounds in the hummocks, six soil cores (up to 1.35 m in depth) were collected from three different hummocks fields and analyzed for grain-size, moisture, organic matter and carbonates contents, and, C_{org} -N and $\delta^{13}C_{org}$ concentrations. A cross-section was also made to determine the age of soil organic carbon and to infer soil movement rates in hummocks. The results from this thesis will address the role of hummocky soils in the carbon cycle and their climatic implication.

1.1. Research Questions

- A. What is the distribution of earth hummocks in the Chuck Creek Trail Valley? What are their morphological characteristics? What information can the distribution and the morphology of earth hummocks provide on the environment of the Chuck Creek Trail Valley and how do they compare to other environments?
- B. What are the sedimentological and geochemical characteristics of the earth hummocks of the Chuck Creek Trail Valley? How do these parameters vary with depth and what is their relation with the environment of the valley and its carbon cycle?
- C. How do cryotubated organic matter intrusions differ from mineral horizons? What is the implication of cryoturbation processes in carbon sequestration within hummocks?
- D. What is the age of the soil organic carbon in the earth hummocks? Is it possible to infer soil movement rates within this environment?
- E. What hypothesis of hummock formation can be considered for the Chuck Creek Trail Valley? Do hummocks provide information on paleoclimates and what are their climatic implications?

2. Background

2.1. Permafrost and the active layer

The cold climate conditions in sub-Arctic and Arctic environments are favorable to the formation of permafrost, which is defined as ground (i.e. soil and/or rock) remaining at or below 0°C for at least two consecutive years (e.g., Brown and Péwé, 1973; French, 2007). Permafrost occupies 23 – 25% of the exposed land surface in the northern hemisphere, including 40 – 50% of Canada's landmass (Brown et al., 1997). Permafrost zones are classified upon percentage of landmass occupied by permafrost: continuous permafrost (90 – 100%), discontinuous permafrost (50 – 90%), sporadic permafrost (10 – 50%), or isolated permafrost (0 – 10%) (French, 2007). In North America, the presence of permafrost is strongly correlated with climate. In fact, the southern limit of continuous permafrost grossly coincides with the -6°C to -8°C mean annual air temperature isotherm (French, 2007). In the discontinuous, sporadic and isolated permafrost zones, site-specific factors like thermal conductivity and diffusivity of soils, vegetation, snow cover, topography, aspect and water bodies determine the presence of permafrost (French, 2007).

The soil layer above the permafrost table that experiences seasonal freezing and thawing is called the active layer (Figure 1) (French, 2007). The active layer has two contrasting definitions (Burn, 1998). It can be defined by the physical state of water in the soil or by the depth of penetration of the 0°C isotherm (French, 2007). This dual definition of the active layer is caused by the fact that the presence of dissolved solutes, pressure and especially grain size, can cause freezing point depression, or in other words, cause water to exist in a liquid state at temperatures below 0°C (French, 2007). The thickness of the active layer varies from year to year, depending on local factors like air temperature, vegetation, snow cover and water content (French, 2007). In general, the active layer tends to be thinner in high Arctic regions and thicker in sub-Arctic regions, varying from as little as 15 cm to more than 1 m (French, 2007).

Determining the thickness of the active layer is important since physical, hydrological, biogeochemical and pedological processes tend to be restricted to this

layer. The thickness of the active layer can be determined by frost probing in late summer or with thermistors to determine the position of the 0°C isotherm (Nelson et al., 1996). Further, the thickness of the active layer can be approximated with the Stephan Equation [1], where Z is the thickness of the active layer (m), T is the ground surface temperature during the thaw season (°C), K is the thermal conductivity in the thaw season (W/m), t is the duration of the thawing season, and Qi is the volumetric latent heat of fusion (kJ/m³) (French, 2007).

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

Recent modeling efforts have improved the Stephan equation to account for the influence of the soil heat capacity and non-zero initial temperatures. Kurylyk and Hayashi (2016) have elaborated correction factors, depending on the initial temperature and the nature of the phase change (i.e. freezing or thawing) by fitting polynomial function to the analytical results. These correction factors enable the Stephan equation to be implemented in more complex real-life scenarios with elements like different soil layers, variable surface temperatures and changing moisture conditions (Kurylyk and Hayashi, 2016). Williams et al. (2015) decided to use an approach that uses air temperature, net radiation and antecedent frost table position as driving variables of their model to minimize the inaccuracy of the 'n-factor' (function relating the relation between air and ground temperature). These proposed modifications to the traditional Stephan equation offer results that are closer to real-life physical processes.

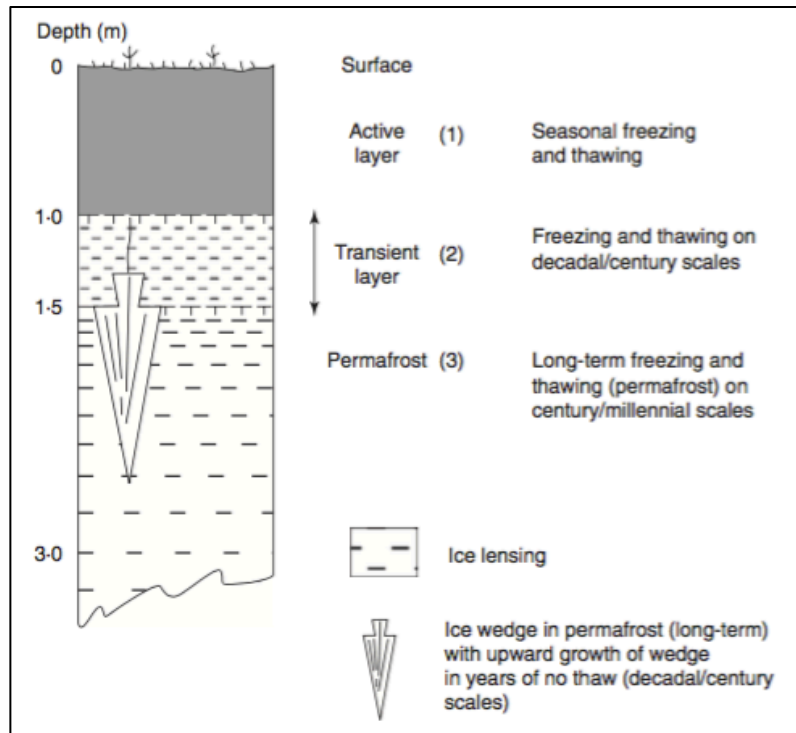


Figure 1: The classical three-layer model of the active layer-permafrost interface; (1) Active layer, (2) Transient layer, (3) Permafrost (French, 2007)

2.2. Cryoturbation and related processes

Cryoturbation is a term used to describe soil movements due to frost action (the repeated freezing and thawing of fine-grained frost-susceptible soils). It influences morphological, physical and even chemical properties of the soil and is therefore a major soil forming process (or set of processes) in Arctic and sub-Arctic environments (Bockheim and Tarnocai, 1998). Studies conducted in Arctic Canada indicated signs of strong cryoturbation in at least 79% of the sampled and observed soil profiles (Tarnocai, 2004). Irregular or broken horizons containing material incorporated from other horizons in soils are often evidences of cryoturbation (Tarnocai, 2004). These soil structures are generated by cryogenic processes like frost heave and cryostatic pressure explained in the following sections (Tarnocai and Bockheim, 2011). Other common cryoturbation features are involutions, swirl-like or tear-drop-like shape soil patterns, which are the result of the influence of cryostatic pressures and gravity on soil material (Bockheim and Tarnocai, 1998). Soils that have developed mainly in mineral material and that present evidence of cryoturbation are called *turbic cryosols* (Tarnocai,

2004). Although cryoturbation may occur in soils experiencing seasonal frost, cryoturbation occurs mostly in areas underlain by permafrost and is often marked by patterned grounds at the surface (Bockheim and Tarnocai, 1998). In fact, cryoturbation processes require moist soils during the freezing and the permafrost table acts as an aquiclude that favours moist soils (Bockheim and Tarnocai, 1998). As such, cryoturbation is driven by frost heave, thaw settlement, and all differential movements that include contraction and expansion due to thermal gradients associated water movements (French, 2007). It results in sorting, heaving, stirring, wedging and cracking of the soils (Washburn, 1980). Instead of being conceived as a single comprehensive process, cryoturbation is a set of multiple processes enacting upon different space and time scales, some of which have been included in models used to explain the genesis of hummocks.

2.2.1. Ice Segregation and Frost heaving

Ice segregation is a process associated with the formation of discrete lenses of ground ice of variable thicknesses in permafrost (French, 2007). Ice segregation occurs in moist frost susceptible soils, such as silty soils, during the freeze-back of the active layer. At this time, liquid water is removed to the ice phase (*at the freezing fringe*), creating a hydraulic gradient along which additional liquid water from depth can migrate toward the freezing front. As long as the total heat (sensible + latent) flux carried by liquid water from below can balance the diffusion of latent heat upwards to the surface, and cryosuction is maintained, the freezing front will remain stationary and ice lenses will develop in freezing soil. Once the soils beneath the freezing front is depleted of water, and the heat flux to the freezing front is no longer sufficient to balance conduction, the freezing front can again begin to move downward. This continues until another moist zone is reached, and another ice lens begins to form. The development of ice segregation results in the heaving of the ground surface as a result of the 9% volumetric expansion that occurs during the phase change from water to ice (French, 2007). Major ground displacement and various cryogenic landforms originate from frost heaving and associated thaw settlement.

2.2.2. Frost Sorting

Frost sorting is the natural upward movement of clasts within heterogeneous unconsolidated sediments by the freezing and thawing of the ground (French, 2007). The progressive upward movement of clasts can be explained by two hypotheses: the “frost-pull” and the “frost-push” hypotheses (French, 2007). The “frost-pull” mechanism assumes that the top of the clast or coarser particle is gripped by the advancing freezing plane and raised within the ground by the frost heave. Upon thawing, the space once occupied by the particle has been compressed by lateral soil movement, making it impossible for the particle to return to its original position. “Frost-push”, on the other hand, relies on the fact that larger clasts have greater thermal conductivity than smaller particles allowing the freezing plane to progress faster through it and form ice lenses preferentially around and beneath it (French, 2007). Upon thawing, the infill of finer particles prevents the clast from returning to its initial position.

2.2.3. Self-Organisation

While the previously discussed mechanisms explain the upward or *vertical* movement of clasts in heterogeneous sediments, it does not necessarily lead to the development of patterned grounds. In fact, frost sorting produces highly nonlinear and dissipative transport and lacks the lateral sorting required to develop pattern grounds (Kessler and Werner, 2003). The self-organisation theory is a mechanism that explains the separation of the heterogeneous material into fine and coarse domains and involves both the vertical and lateral sorting (Kessler and Werner, 2003). Lateral sorting can be explained by two feedback mechanisms. The first one, “lateral sorting”, is a direct product of the frost sorting mechanisms. The freezing front mimics sediment morphology and therefore descends faster in coarse-grained soils than in adjacent fine-grained soils (Kessler and Werner, 2003). Since frost heave acts normal to the freezing plane, in such context where the interface is inclined, fine particles are pushed towards the fine domain and coarser particles towards coarse domain (Kessler and Werner, 2003). The second mechanism, “lateral squeezing and confinement” stabilizes and promotes the organization of particles along their axes. This mechanism can be

explained by previously discussed laterally directed frost heave. The confinement vector resulting from lateral squeezing organizes the domains by inducing greater uplift along the stone domain axis (Kessler and Werner, 2003).

2.3. Earth Hummocks

Earth hummocks, or simply called hummocks, are defined as sub-meter to meter-scale bowl-shaped mounds that develop in seasonally frozen soils. The term *earth hummock* was first introduced and described by Sharp (1942) in the St Elias Mountains, YT. In Greenland and Iceland, the term *thufur* is used to describe bowl shaped mounds, whereas in Fennoscandia they are referred to as *pounus*; however, unlike hummocks and thufur, pounus are peat mounds that are linked to seasonal frost (Van Vliet-Lanoë and Seppälä, 2002; Luoto and Seppälä, 2002).

While several authors use the terms hummocks and thufur synonymously, such as Van Vliet-Lanoë (1998) who studied hummocky landforms in Iceland and considers thufurs to be hummocks of a minerogenic nature developing in loess deposits; other authors like Harris (1988) differentiate the terms hummock and thufur on the basis of the presence or absence of permafrost: earth hummocks are found in permafrost environments, whereas thufur are not restricted to permafrost regions (e.g., Zoltai et al., 1978; Harris, 1988; Schunke and Zoltai, 1988). In North America, almost all earth hummocks are underlain by permafrost, with the exception of those occurring in alpine areas and those that are in an inactive fossil form (Scotter and Zoltai, 1982; Tarnocai and Zoltai, 1978). This thesis will use the term *hummock*.

2.3.1. Distribution of hummocks

Earth hummocks are amongst the most common type of landforms in permafrost regions. Their presence has been reported in high-latitude regions (Iceland, Greenland, Russia, Scandinavia and Canada) as well as alpine environments. In sub-Arctic and Arctic North America, earth hummocks have largely been associated with permafrost regions like the Mackenzie Valley, the Yukon, the western and central Arctic and on the Arctic Islands (Figure 2) (Tarnocai and Zoltai, 1978). They have been found in active form from

around 60°N in the Mackenzie valley (Tarnocai and Zoltai, 1978) to 79°N on Ellesmere Island (Kojima, 1994).

In alpine areas, hummocks are typically found in the zone above the tree line (e.g., Lundqvist, 1962; Schunke, 1977; Ellis, 1983). While Thorarinsson (1951) suggested that hummocks become larger with increasing elevation, others (e.g., Pemberton, 1980; Schunke and Zoltai, 1988, Grab, 1997) have noticed that the duration of snow patches at higher elevation may insulate the ground, restricting frost penetration and therefore restricting the hummock formation processes. In other terms, in regions where the snow cover is particularly thick and melts later in the season, hummocks do not occur. Strict boundaries are not often applicable and the presence of earth hummocks is mostly dictated by parameters of microtopography such as slope, aspect, vegetation and snow.

Numerous studies examined climatic factors, such as mean annual air temperature (MAAT) on hummock distribution. It has been suggested that the upper limit for active earth hummocks to occur is between an MAAT of 3 – 5°C (e.g., Lundqvist, 1969; Karte, 1983). Karte (1983) also suggested that hummocks require gentle cooling and therefore are not as frequent in areas where the MAAT is less than -8°C; which contradicts their presence in active form in the mid to high Arctic. Zoltai and Tarnocai (1974) have added that hummocks are of rare occurrence in non-permafrost regions, and their presence in these regions is thought to be fossil or relict form. Yet, other studies suggest that hummocks may develop in regions where the MAAT is as high as 6°C and where permafrost is absent (e.g., Koaze et al., 1974; Grab, 1994; 1998). Gerrard (1992) concluded that earth hummocks are not limited to periglacial regions and thus cannot necessarily be used to suggest a particular climatic regime. However, this conclusion may be due to the interchangeable use of the terms *hummock* and *thufur*.

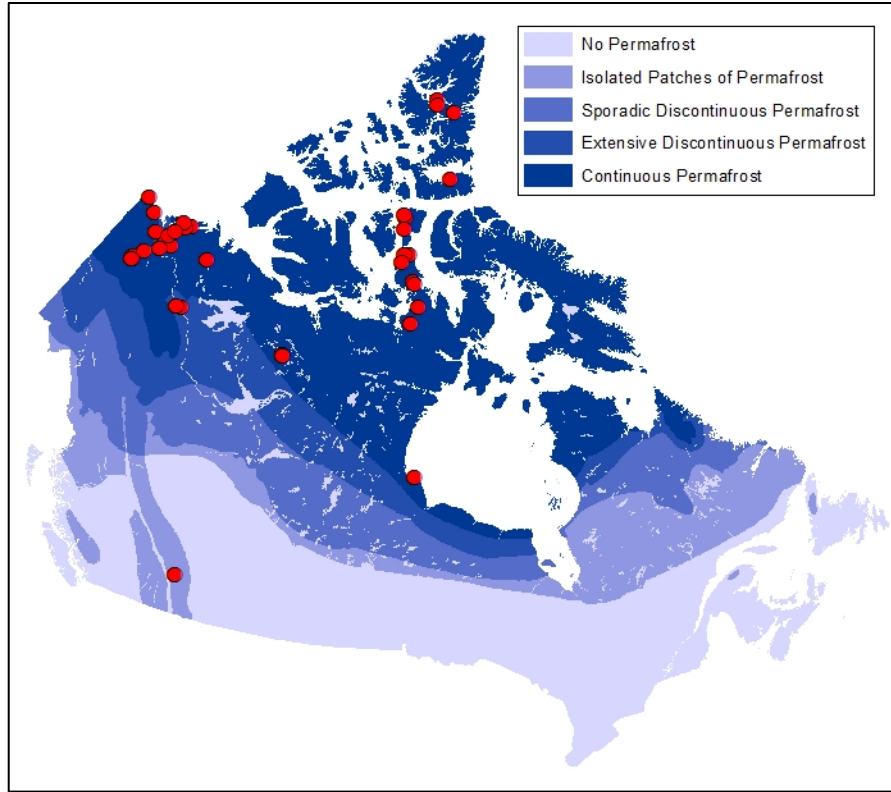


Figure 2: Map of permafrost and location of studied hummock sites in Canada (Table 1) (Permafrost Data derived from: Government of Canada, 2000)

Table 1: Studied hummock sites in Canada with references

Coordinate	Source	Coordinate	Source
68°55'N, 137°50'W	Bockheim & Tarnocai, 1998	68°08'N, 135°49'W	Zoltai et al., 1978
79°08'N, 80°30'W	Kojima, 1994	69°25'N, 139°59'W	Zoltai et al., 1978
68°23'N, 133°44'W	Kokelj et al., 2007	67°58'N, 132°43'W	Zoltai et al., 1978
80°00'N, 84°40'W	Lewkowicz, 2011	69°33'N, 131°35'W	Zoltai et al., 1978
79°42'N, 84°40'W	Lewkowicz, 2011	69°16'N, 132°20'W	Zoltai et al., 1978
68°22'N, 133.45'W	Main, 2016	65°10'N, 127°27'W	Zoltai et al., 1978
67°51'N, 133°38'W	Main, 2106	67°27'N, 133°50'W	Zoltai et al., 1978
51°04'N, 115°47'W	Scotter & Zoltai, 1982	66°05'N, 136°13'W	Zoltai et al., 1978
73°37'N, 94°50'W	Zoltai et al., 1978	68°22'N, 133°45'W	Zoltai et al., 1978
72°58'N, 94°57'W	Zoltai et al., 1978	69°26'N, 133°01'W	Zoltai et al., 1978
71°31'N, 94°10'W	Zoltai et al., 1978	66°10'N, 136°21'W	Zoltai et al., 1978
68°30'N, 92°52'W	Zoltai et al., 1978	66°05'N, 136°17'W	Zoltai et al., 1978
71°29'N, 94°52'W	Zoltai et al., 1978	66°50'N, 135°23'W	Zoltai et al., 1978
69°57'N, 93°30'W	Zoltai et al., 1978	73°46'N, 95°02'W	Zoltai et al., 1978
69°48'N, 93°22'W	Zoltai et al., 1978	67°32'N, 94°03'W	Zoltai et al., 1978
71°03'N, 95°20'W	Zoltai et al., 1978	68°21'N, 126°47'W	Zoltai, 1975
68°27'N, 132°27'W	Zoltai et al., 1978	65°17'N, 126°47'W	Zoltai, 1975

2.3.2. Morphology of hummocks

Earth hummocks are typically meter-scale dome-shaped circular or oval mounds (Schunke and Zoltai, 1988). Hummocks usually occur in groups on flat or gently sloping terrain ($<25^\circ$), although they can be found occasionally as scattered individuals (Schunke and Zoltai, 1988). Hummocks found on gentle slopes tend to be more circular with flatter tops whereas the ones found on steeper slopes tend to be more elongated, with low-angled sides (Schunke, 1977).

In sub-Arctic and Arctic regions of Canada, the height of hummocks varies from 20 – 100 cm, averaging near 50 cm. Their diameter can reach as much as 320 cm, but most have diameters near 100 cm (e.g., Zoltai and Pettapiece, 1974; Tarnocai and Zoltai, 1978; Kojima, 1994; Schunke and Zoltai, 1988; Kokelj et al., 2007). The spacing between earth hummocks (inter-hummock spacing) is typically less than the diameter of the mounds (Grab, 1998). Based on the assumption that hummocks evolve from poorly to well developed form, the level of hummock maturity can be characterized by the relation between its diameter and height (Kokelj et al., 2007). Well-developed hummocks have a height:diameter ratio that is greater than poorly developed hummocks. However it is unclear if hummocks evolve from poorly to well-developed form, or if environmental and/or sedimentological properties control the level of maturity hummocks can reach. Furthermore, identifying whether hummocks are in active or fossil state remains a challenge. Dilation cracks on hummock tops, torn roots and organic matter around the perimeter are all indication of recent or relatively recent activity within hummocky terrain.

Hummocks are usually covered with vegetation and the vegetation is usually different between the hummock top and the hummock trough, causing a contrast in the soil thermal regime of the hummocks that will be discussed in the following section (Grab, 2005). In high latitude environments, vegetation in hummocky terrain consists mostly of meadow and sub-Arctic woodland (Schunke and Zoltai, 1988). In the boreal forest, hummocks can lead to the formation of *drunken forests*, where spruce trees growing on the sides of earth hummocks have tilted in response to the growth of

hummock (Kokelj et al., 2007). In high alpine environments, grasses and sedges are more dominant (Grab, 1994). A variation in the dominant vegetation types growing on hummocks top, within hummock troughs and on adjoining areas is not uncommon and is probably caused by moisture differences within the soil (e.g., Schunke, 1977; Crampton, 1977; Scotter and Zoltai, 1982). Scotter and Zoltai (1982) found that bryophytes were more frequently found in the interhummock depression zone and that few small bare patches occurred on hummock tops. Crampton (1977) also encountered these bare patches on the hummock tops.

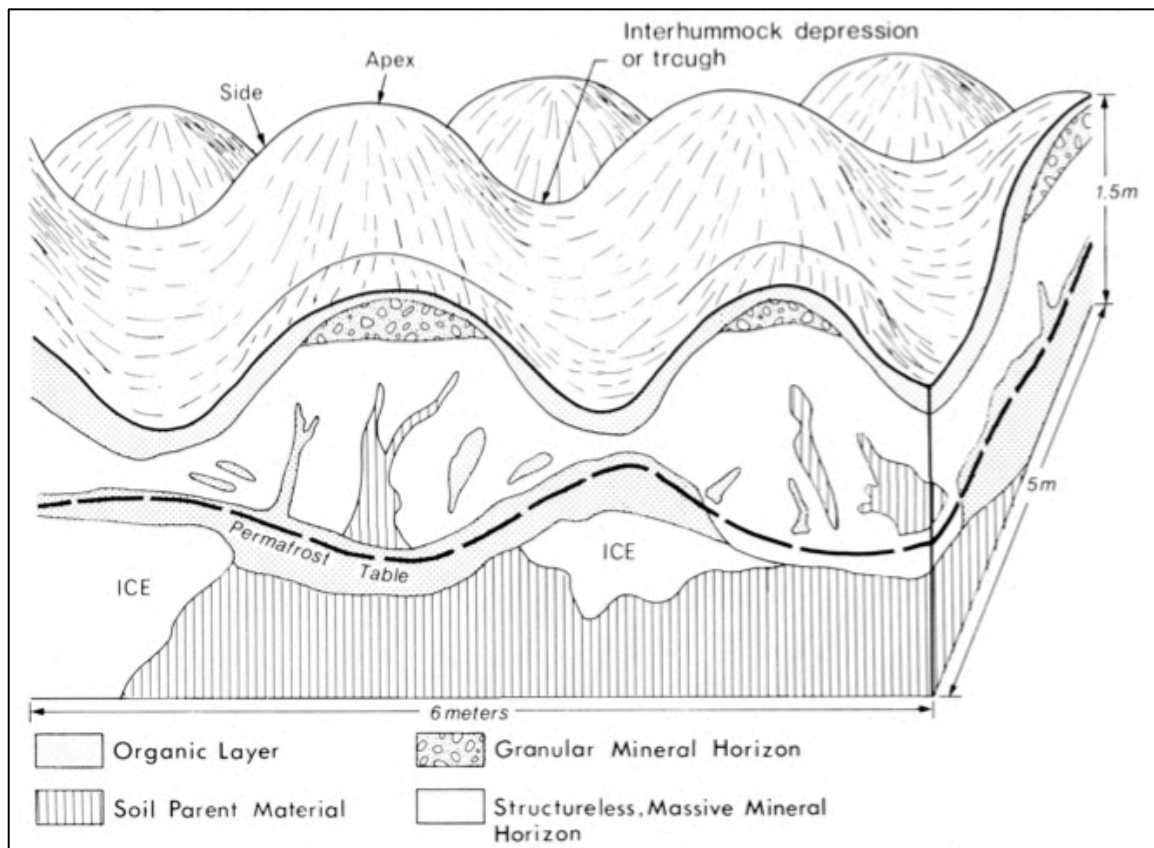


Figure 3: Schematic diagram showing the external and internal morphology of earth hummocks underlain by permafrost (Tarnocai & Zoltai, 1978)

2.3.3. Internal characteristics

2.3.3.1. Soil characteristics

Earth hummocks invariably develop in fine-grained and mostly stone-free frost

susceptible earth materials like volcanic-aeolian, lacustrine or glacial deposits (Schunke and Zoltai, 1988). Hummocks in parts of northern Canada contain an average fine sediment fraction of 58 – 99%, with the rest composed of sand (Tarnocai and Zoltai, 1978). The texture of the sediments within hummocks is mostly homogeneous but can present a slight increase of coarser particles along to top and sides of the mounds, and in the interhummock areas (Schunke and Zoltai, 1988). Mackay (1980) found oppositely that coarser sand was found at the top of the permafrost table and in the center of the mounds, indicating a cell-like circular pattern. Sectioned hummocks display an internal structure composed of buried surface soil horizons and strata of organic matter and ash, with a permafrost table mirroring the morphology of the surface (Figure 3).

2.3.3.2. Moisture content

Understanding the moisture content patterns within hummocky terrain may provide partial explanations to cryo-movements and frost susceptibility of soils. Hummocks tend to be found in well-drained areas with a deep water table although some moisture is necessary, as hummocks do not occur in completely dry sites (Van Vliet-Lanoë, 1991). The upper permafrost in hummocky terrain is ice-rich, being in excess of 100% by weight, and reflecting the imperfect surface drainage (Schunke and Zoltai, 1988). Zoltai et al. (1978) have found the pure ice layer or high ice content layer to be around 1 m thick in the top of permafrost. Main (2016) found in her study that the gravimetric water content within the active layer was greatest in the hummock troughs and lowest at the hummock tops, following a drainage pattern dictated by surface topography. Thermal gradients, which may be related to moisture content within hummocks have also been observed in a number of studies, though the long-term variations have not been studied. Tarnocai and Zoltai (1978) found the interhummock area to be the coldest part of the hummock topography.

2.3.3.3. Carbon content

The organic matter in hummocks is found in the form of continuous layers, intrusions or involutions and its burial is mainly attributed to the mechanism of

cryoturbation (Zoltai et al., 1978). A surface organic horizon around 15 cm thick usually develops on top of the hummock and can reach 20 – 25 cm in the trough (Tarnocai and Zoltai, 1978). Disseminated organic carbon is common within the active layer and reach concentrations of 2 to 5 % (Zoltai and Tarnocai, 1974). Main (2016) found that organic matter distribution was highest in the O-horizon and varied through the hummocks, measuring higher values in the troughs than within the tops. Grab (1994) observed that bulk density of the soil is strongly influenced by organic content while Tarnocai and Zoltai (1978) suggest that the range in bulk density within hummocks ($1.00 - 2.18 \text{ g/cm}^3$) is a sign of cryoturbation.

Gillespie et al. (2014) found the highest organic carbon concentrations (430 – 515 mg/g) in the surface organic horizons. Buried organic horizons within the active layers had lower concentrations ranging from 100 – 290 mg/g, while mineral soils only contained 10 – 49 mg/g. However, Kaiser et al. (2007) found the amount of carbon stored in the whole active layer of cryoturbated soil profiles to average 13.5 kg/m, from which approximately 50 % was stored in the B horizon. Diochon et al. (2013) estimate the carbon stock at 15 – 46 kg/m², with 16 – 78% contained in horizons with cryoturbation features. The importance of cryoturbation on carbon stock has been calculated by Michaelson et al. (1996); they found that the active layer of cryoturbated sites contained 62% higher carbon stores than non-cryoturbated sites.

2.3.4. Origin and development of earth hummocks

Several hypotheses for the origin of earth hummocks have been proposed over the last four decades, but they still remain ambiguous landforms. Many attempts to explain the formation of hummocks are based on mature hummock form and do not adequately explain the initial development phase. The involuted soil horizons, the grain-size distribution, and buried organic matter in the active layer indicated the presence of soil movement in hummocky terrain (Zoltai et al., 1978; Mackay, 1980). However, earth hummocks may have polygenetic origin and individual hummocks are likely to have been influenced by a synergistic set of processes (Grab, 2005). In the following sections, these hypotheses will be discussed.

2.3.4.1. Cryoexpulsion of clasts model

Péwé (1969) and Dionne (1966) were the first to propose that hummocks are the result of clasts migrating towards the surface through frost push and pull mechanisms (section 2.2.2) (Figure 4). Since the 0°C isotherm progresses more rapidly through the clast than through the adjacent soil, ice lenses forming below the clast are important attributes to the frost-push mechanism, causing the clast to move towards the surface. This mechanism is widely accepted for various types of patterned grounds, like sorted polygons. However, this hypothesis requires the presence of clasts, which contradicts the fact that hummocks develop in stone-free fine-grained soils. Therefore, the cryoexpulsion of clasts hypothesis seems more like an exception than an actual rule for earth hummock origin.

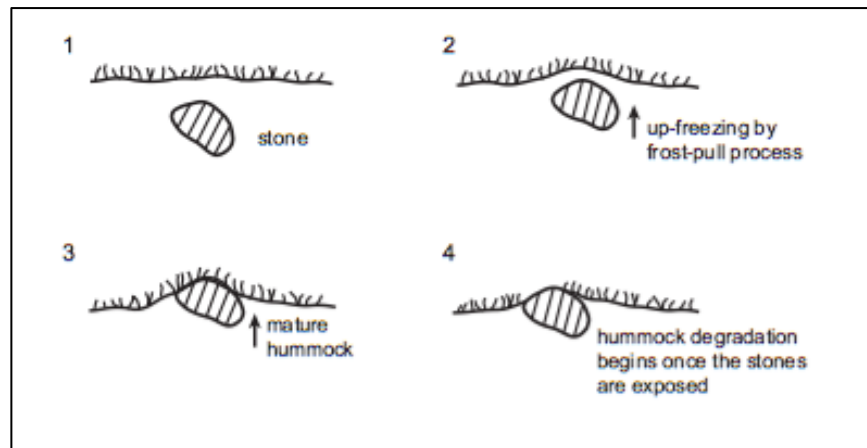


Figure 4: The cryoexpulsion of clasts model for hummock formation (Grab, 2005)

2.3.4.2. Hydrostatic and cryostatic pressure model

The hydrostatic pressure hypothesis entails that supersaturated fine-textured material experiences frost heave through a change in the water table (Lundqvist, 1969). Soil material at depth would be forced upward in response to thaw of the frozen layer from above (Figure 5). Similarly, the model for cryostatic pressure entails freezing from the surface downwards causing moisture to be trapped and frozen in parts of the active layer that were unfrozen (Grab, 2005). Material is then displaced into the zone of least

resistance, forming earth hummocks. However, Mackay (1980) suggests that hydrostatic and cryostatic pressures of such importance are very rare on the field. French (2007) supported this by adding that porewater in hummocks are often under tension rather than pressure. Moreover, this model is only applicable in supersaturated sites although hummocks can also occur in imperfectly to well-drained sites (Van Vliet-Lanoë, 1991). Therefore, hydrostatic and cryostatic pressure mechanisms are probably not of widespread significance for all circular type of patterns although they may influence other mechanisms like differential frost heave.

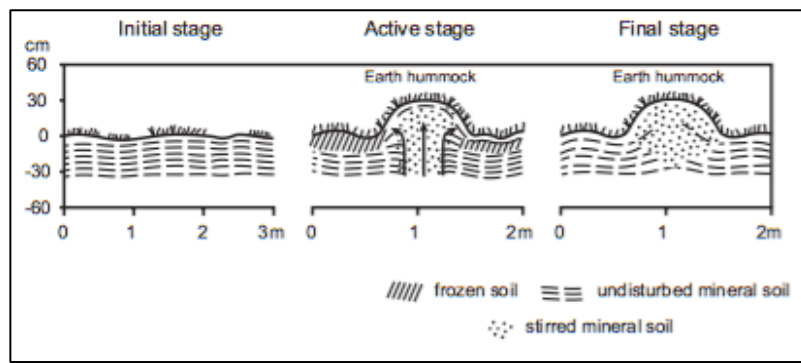


Figure 5: The Hydrostatic pressure model for hummock formation (Lundqvist, 1969)

2.3.4.3. Cellular circulation (Equilibrium Model)

First proposed by Nordenskjöld (1909), the equilibrium model is considered to be one of the least substantiated hypothesis to explain earth hummock formation (Van Vliet-Lanoë, 1988). It is based on the movement of Raleigh convection cells produced by thermally-induced density gradients within the soil. Mackay (1979; 1980) demonstrated that during the freeze-back period, in frost-susceptible soils, unfrozen porewater migrates towards the top of the active layer to form ice lenses, generating upward and radially outward frost heave. In areas with two-sided freezing, ice lenses will also develop at the base of the active layer creating a frost heave that is upward and radially inward (Mackay, 1980). During the thaw period, the active layer thaws downwards, melting ice lenses from the surface down generating a subsidence with a general downward and radially outward component. The melting of the ice at the bottom of the active layer then results in subsidence with a downward and radially inward component.

Given the mirror-like shape of the surface and the permafrost table, Mackay (1980) suggested that the driving forces supporting his cellular circulation model would be related to gravity and density rather than cryostatic pressure. However, Van Vliet-Lanoë (1991) evaluated that in order for the convection model to be possible it would need: a water content about 10% higher than the Atterberg liquid limit (critical water content of a fine-grained soil), a totally thawed profile, a cryogenic fabric which can reach a viscous state and an abrupt thermal gradient (Figure 6). Since those conditions are rarely met in periglacial environments, the cellular circulation model is unlikely to explain to genesis of all earth hummocks.

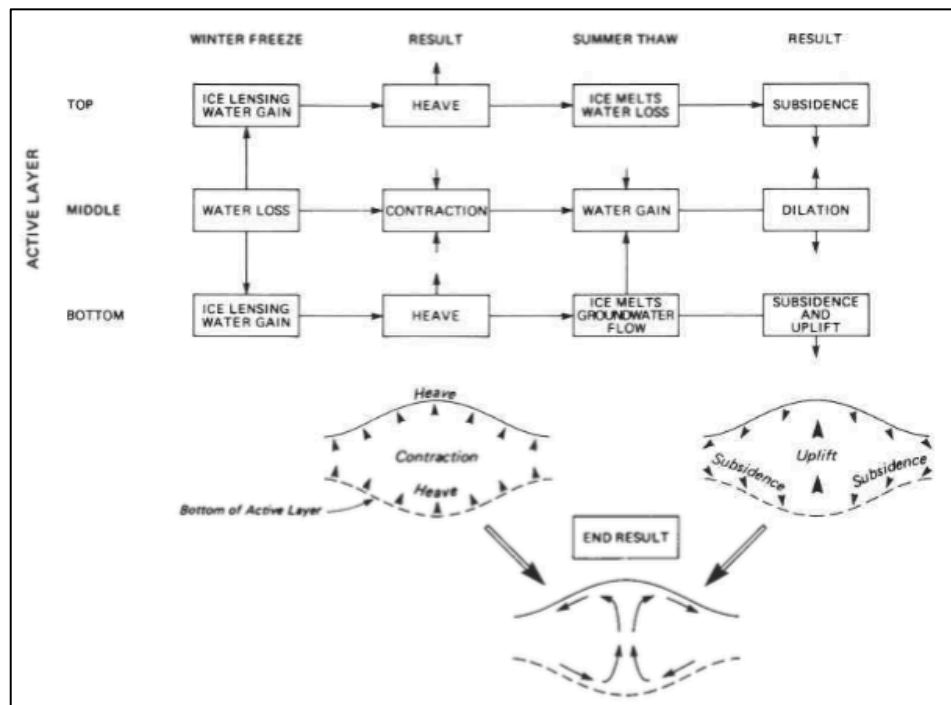


Figure 6: The equilibrium model for hummock growth (Mackay, 1980)

2.3.4.4. Differential Frost Heave and Cryoturbation

Cryoturbation, due to differential frost heave and helped by cryostatic pressures, by differential soil swelling and also by load casting, is the most widely accepted mechanism to explain earth hummock development (Van Vliet-Lanoë, 1991; Grab, 2005). Differential frost heave is induced through differences in ground temperatures or moisture conditions (Van Vliet-Lanoë, 1991). Frost susceptibility gradients of the soil can provide an explanation to the geometry of deformations. For example, the lowering of

the freezing plane through clays compared to less frost-susceptible sediments such as sand promotes cryostatic pressures and deformations in zones of mechanical weaknesses. If the surface sediment is less frost-susceptible than the underlying layer, the gradient is negative and allows for the underlying layer to be injected upwards (Van Vliet-Lanoë, 1991). The repetitive and cumulative actions of these deformations lead to the occurrence of cryoturbation and soil mixing (Van Vliet-Lanoë, 1991). Differential swelling could occur twice a year: (1) during the hydration consequent on spring thaw and (2) during the primary heave of the late fall (Van Vliet-Lanoë, 1991). The scale of the contrast in frost susceptibility would dictate the rate of growth of hummocks and therefore the rate at which the landform reaches its maturity (Van Vliet-Lanoë, 1991).

In the Canadian Arctic and sub-Arctic regions, all ingredients are available for cryoturbation to occur: heave-sensitive soil, high soil moisture content and seasonal frost penetration (Schunke and Zoltai, 1988). In fact, differential frost heave can occur both inside and outside of the continuous permafrost zone, and in supersaturated sites as well as in poorly to well-drained sites (Van Vliet-Lanoë, 1991). However, as for most hypotheses, the initiation of the formative process is the hardest to document.

Beskow (1930) first suggested that pre-existing uneven ground and vegetation cover would result in the differential frost heave. Schunke (1977) suggested that, once a small mound has formed, it is better drained than the surrounding topography and has a better vegetation insulation, and therefore loses heat more slowly. The freezing front penetrates faster in the areas surrounding the mound, causing lateral pressure towards the mound center and consequently causing hummock growth. However, on the field, not all hummocks have been found to have more vegetation on the apex (e.g., Mackay, 1980; Grab, 1998).

More recent studies have ascribed the formation of earth hummocks in regular patterns to thermal cracks or nets of polygonal desiccation (Figure 7) (e.g., Crampton, 1977; Schunke, 1977; Mackay, 1980; Kojima, 1994). Freezing may cause thermally induced desiccation and dilatation cracking of the soil resulting in differential frost heave (Van Vliet-Lanoë et al., 1998).

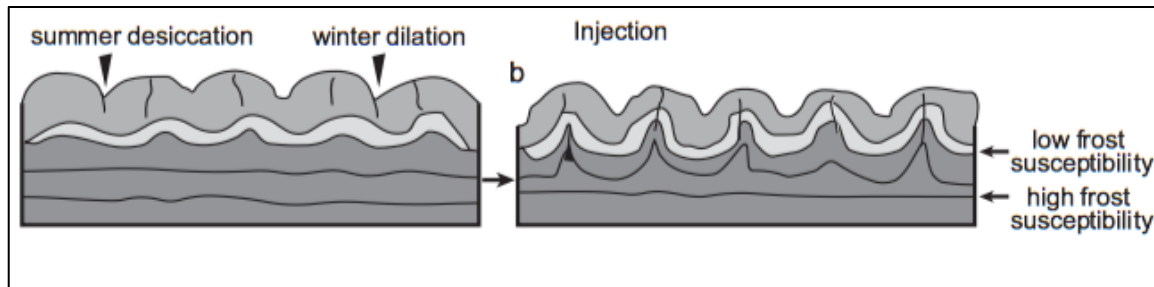


Figure 7: The differential frost heave (cryoturbation) model associated with thermal cracking (Van Vliet-Lanoë et al., 1998)

2.3.5. Role of hummocks in the carbon cycle

During the last decades, many efforts were made to estimate the quantity of carbon stored in cryosols. Values ranging from 400 – 9120 PgC stored in soils worldwide were obtained (Amundson, 2001). Amundson (2001) attributed the variance in the results to the amount of soils data, analyzed depth and summation methods. As more data of SOC became available, especially for cryoturbated pedons, estimates increased substantially. The Northern Circumpolar Soil Carbon Database (NCSCD), which was initially developed by Tarnocai et al. (2009), is now the largest spatially distributed soils data set for the northern circumpolar region. Hugelius et al. (2014) used an updated version of the NCSCD to calculate the more accurate estimate at present of 1307 PgC stored in 0 – 3 m depth permafrost region soils (along with carbon in the deeper Yedoma and deltaic deposits). However, the uncertainty associated with this value is still significant (ranging from 1140 – 1476 PgC). Low sampling density and significant data gaps associated with the remote access and vast extent of the circumpolar permafrost regions, along with the technical sampling challenges decrease confidence in SOC storage estimates (Ping et al., 2015). The lack of measured bulk density and variability in carbon stock calculations also contribute to increased variability (Ping et al., 2015). Furthermore, patterned ground features exhibit involutions in soil units that result in landscape heterogeneity. A number of studies have analysed the SOC content of patterned ground features like frost boils (Dyke and Zoltai, 1980; Walker et al., 2004; Kaiser et al., 2005; Michaelson et al., 2012), circles (Kimble et al., 1993; Hallet and Prestrud, 1986), stripes (Walmsley and Lavkulich, 1975; Horwath et al., 2008) and ice-

wedge polygons (Ping et al., 2014; Zubrzycki et al., 2013). SOC within hummocks has also been studied by Kimble et al. (1993) and Landi et al. (2004).

Cryoturbation may lead to the long-term storage of soil carbon by delaying the decomposition processes normally enacting upon organic material, by burying it and placing it under colder and slower microbial decomposition conditions (these conditions are even more extreme where permafrost is aggrading and organic material is *trapped*) (Kaiser et al. 2007). Little research has been conducted to understand the distribution, biochemical composition, and potential biodegradability of organic matter in turbic soil, though turbic cryosols contain almost 80% of the soil organic carbon in the Canadian Arctic (Diochon et al., 2013). Tarconai et al. (2009) have found organic soils (peatlands) and cryoturbated permafrost-affected soils to have the highest mean soil organic carbon contents (32.2 – 69.9 kg/m²).

As part of a broader research to study the interrelationships between patterned ground formation and vegetation zonation, Ping et al. (2008) measured SOC stores along a transect through five bioclimatic subzones from the High Arctic to the boreal region of North America (Walker et al., 2008). As the landforms transitioned from simple frost cracking in the high Arctic to well developed patterned grounds in the low Arctic, the vegetation transitioned from polar desert to tundra, and finally, to shrub tundra with increased dominance of vascular plants in the southern part of the transect (Walker et al., 2008). Ping et al. (2008) found a direct relationship between SOC stocks and biomass production, but the proportion of cryoturbated carbon didn't follow the same trend. Cryoturbated carbon stock was greater within the middle of the transect, where tussock tundra was dominant (Michaelson et al., 2008; Ping et al., 2008). This decrease in the low Arctic corresponds to reduced frost heave and cryoturbation associated with taller vegetation canopy, thicker ground moss and increased snowfall which provide greater thermal insulation (Rodionov et al., 2007; Kade and Walker, 2008; Walker et al., 2008).

The presence of organic matter within earth hummocks offers an opportunity to study the effects of cryogenic processes on soil movement and development (Zoltai et al., 1978). Radiocarbon dates from peat, wood and other organic material in convoluted

horizons provide an indication of the maximum possible time since their formation. Numerous studies have used radioactive nuclides as soil profile tracers (e.g., Yoo et al., 2011; Jelinski, 2013; Klaminder et al., 2014; Main, 2016). Zoltai et al. (1978) have conducted a study using radiocarbon indicating that most hummocks in North America originated 2500 – 5000 yr BP, with preponderance of dates from 3000 – 4000 yr BP, but have remained active since then. This may suggest a severe rate of cryoturbation in the initial phase of the earth hummocks, before they attained a state of “equilibrium” (Zoltai et al., 1978). Mackay and Mackay (1976) and Pettapiece (1975) both concluded from their study that earth hummocks in the Canadian Arctic and sub-Arctic are relatively stable features.

Zoltai et al. (1978) also noticed that the youngest material was found in the hummock troughs, close to the permafrost table. From there, moving towards the center of the hummock, the material appeared to become older (Zoltai et al., 1978). However, no clear pattern was found because both young and old dates were found within the center part of the hummocks (Zoltai et al., 1978). Ellis (1983) found similar dates of 3500 – 4000 yr BP in Central Scandinavia, while more recent dates (2000 yr BP) have been found on Svalbard (Van Vliet-Lanoë, 1998). Main (2016) found the youngest material (higher pmC values) near the surface and the older material (lower pmC values) at depth. Her study also showed inconsistencies within the troughs that may be due to contamination of the samples with surface material (Figure 8). Kaiser et al. (2007) have studied cryoturbated soil in the Siberian tundra, not specific to a landform, and found that the mean age of carbon in the buried layer was three times older (1300 yr BP) than in the parent horizon (400 yr BP). Since hummocks are thought to form through the process of cryoturbation, ages obtained from the active layer need to be treated with skepticism. Given that the type of the measured soil organic material in these studies varied from bulk material to humic fractions, and that cryoturbation results in an uneven displacement of soil materials and the juxtaposition of dates within hummock, using radiocarbon dating may present a challenge if the proper organic fraction is not dated.

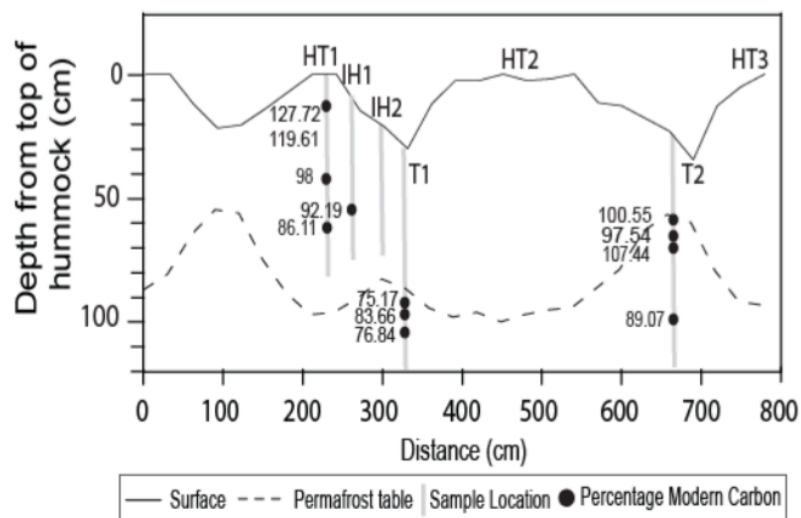


Figure 8: Distribution of percentage modern carbon (pmC) at Rengleng River (Main, 2016)

3. Study Area

The study area is situated in northwest British Columbia, in the Tatshenshini-Alsek Provincial Park (59°40'N, 136°37'W) (Figure 9). The Chuck Creek Trail valley is located in the Alsek Range (a subdivision of the Saint-Elias Mountains) near Samuel Glacier, west of the Haines Road (Highway 3). The area is in a rugged transitional mountain region with elevation varying from ca. 450 m (in the Tatshenshini River valley) to more than 2000 m (in the Alsek Range); the study sites are found between 1000 and 1200 m, which corresponds to the elevation of the treeline (Government of Yukon, 2013). Most of this area of the Alsek Range is drained by the Tatshenshini River into the Pacific Ocean, although there are numerous secondary rivers and creeks, like the O'Connor River and Clear Creek that flow through the valley.

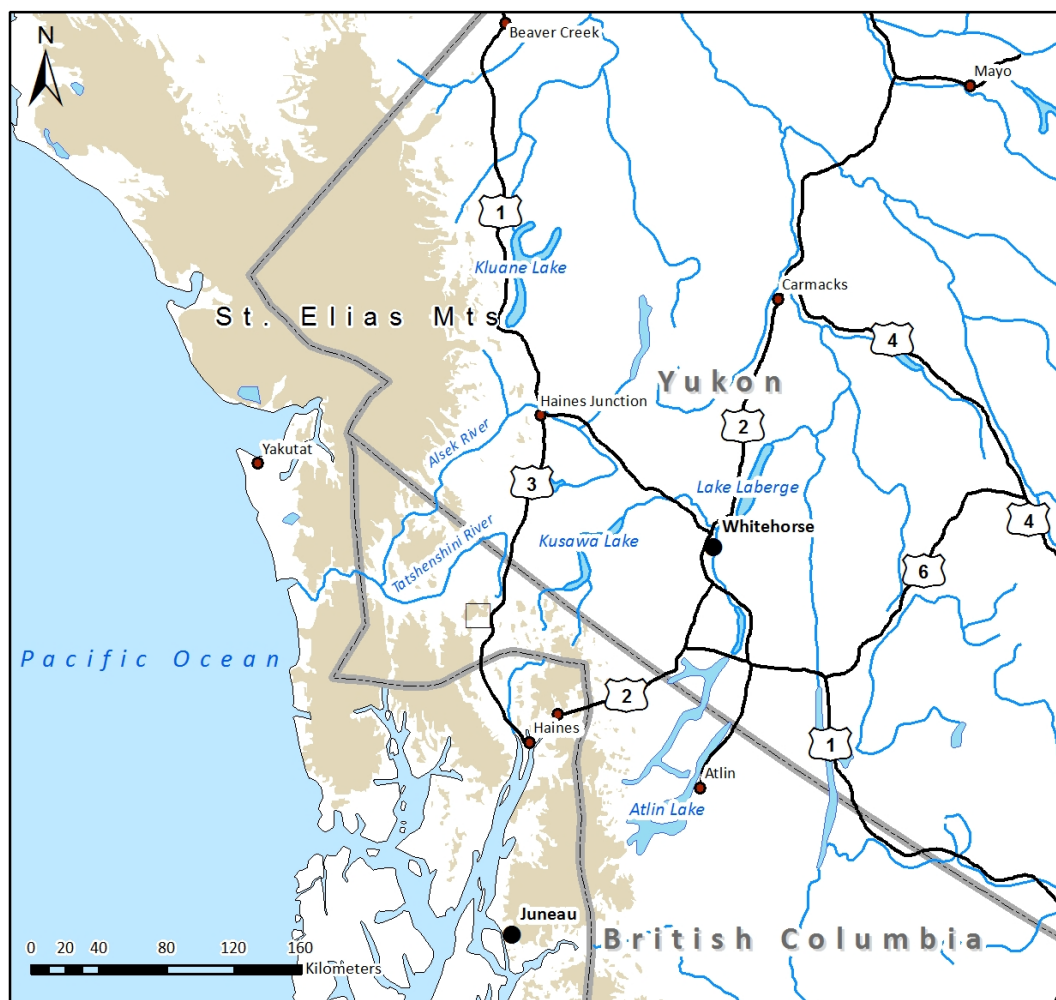


Figure 9: Map showing the study area, as indicated with the small black square. Detailed map in the following figure.

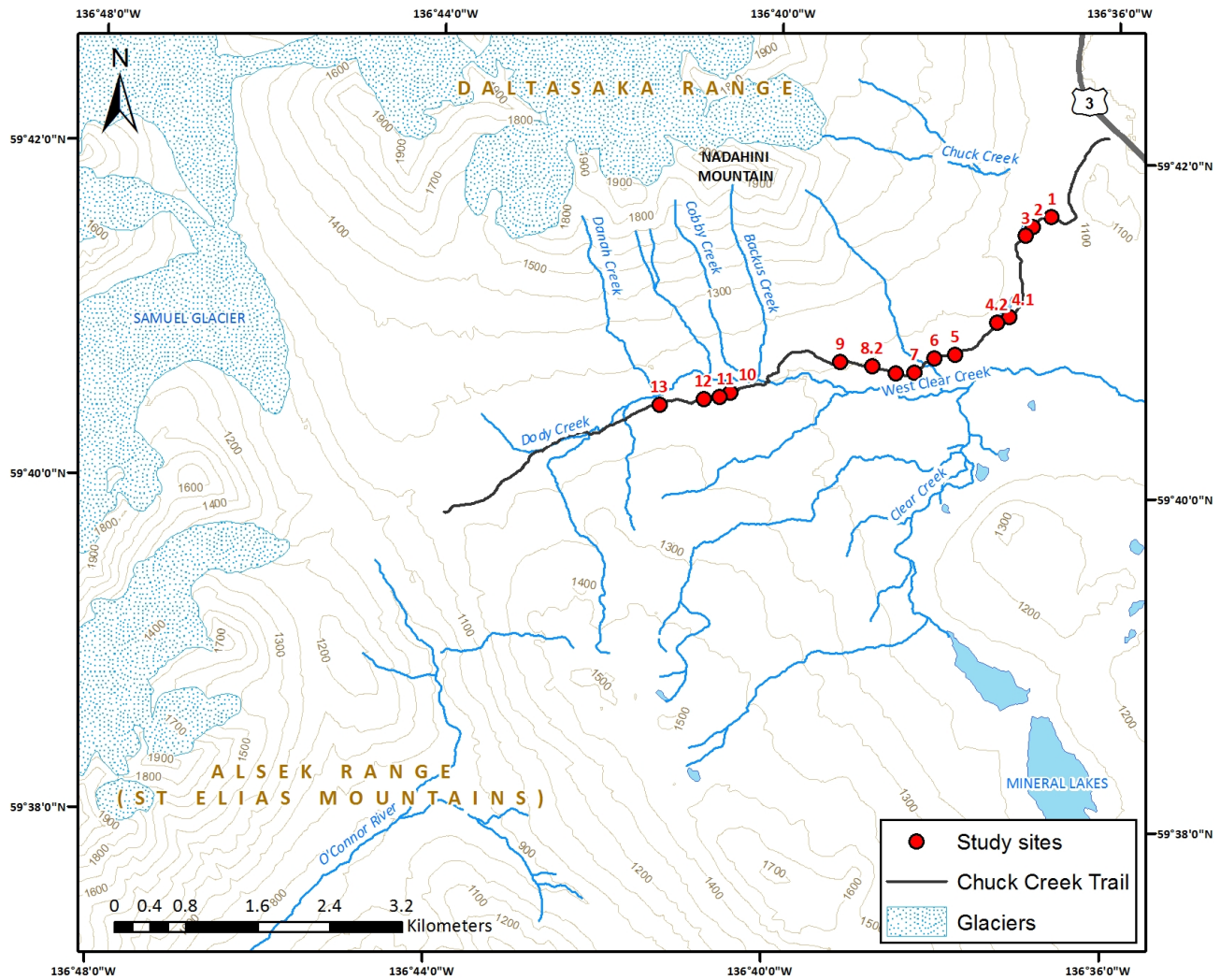


Figure 10: Detailed location map of the study sites, in the Chuck Creek Trail Valley



Figure 11: An overview of the Chuck Creek Trail Valley in the Tatshenshini Alsek Provincial Park, British Columbia

3.1. Climate and Permafrost Conditions

The regional climate is part of the northern boreal type and is under the influence of Pacific maritime weather systems (Government of British Columbia, 2016). The 1981 – 2010 mean annual air temperature recorded at the Blanchard River meteorological station (situated 34 km north of the study area) is -1°C ; mean July air temperature: 10.9°C and mean January air temperature: -14.6°C (Figure 12) (Government of Canada, 2015a). In winter, a temperature inversion is observed with January mean air temperatures of -25°C in the lower valleys to -18°C at higher elevations, while during the month of July, the warmest of the year, it varies from 12°C in the valleys to 5°C at higher elevation (Government of Yukon, 2013). According to the Haines Junction meteorological station (situated about 150 km north of the study area), between the mid-1940s and the mid-1970s, mean annual air temperatures showed a decreasing trend, but since then air temperatures have been increasing (Figure 13) (Government of Canada, 2015b).

Total precipitation at Blanchard River meteorological station reaches 500 – 600 mm annually (Government of Canada, 2015a). Moisture originates mainly from the Pacific Ocean and travels through the Alsek and Tatshenshini valleys (Government of British Columbia, 2016). Precipitation is lowest from February to June and highest in the fall and early winter months (Figure 12). From late September to early May, the precipitation usually falls as snow, as well as at elevations above 2000 m throughout most of the year (Government of Yukon, 2013). In an intermittent record since 1945, precipitation has been following an increasing trend (Figure 13).

Limited information characterizing permafrost conditions in southern Yukon and northern British Columbia is available. According to the probability model developed by Bonnaventure et al. (2012), the study area is situated in discontinuous permafrost, with permafrost likely occurring on north-facing slopes (Figure 14). Studies along the Haines Highway revealed the presence of sporadic permafrost (Brown, 1967; James, 2010). Where permafrost is present, the active layer is often very thick and patterned grounds and other periglacial landforms are common (Government of Yukon, 2013).

Monitoring the changes in active layer thickness is an important characteristic of climate variability. The Circumpolar Active Layer Monitoring program (CALM) compiled active-layer thickness fluctuations from 1990 – 2015 at a number of Canadian sites. In southwestern Arctic Canada, two sites are situated in proximity to the study area: Teslin, northern British Columbia, which is about 200 km east of the study site, at 823 m of elevation, and in Beaver Creek, Yukon, which is about 350 km north, at 695 m of elevation. At the Teslin site, the active layer depth was measured from 2009 to 2011 and varied from 55 cm to 54 cm; whereas, at Beaver Creek, the active layer thickness was only measured in 2010 and 2011 and varied between 42 cm and 48 cm. Along the Alaska Highway between Whitehorse, Yukon and Fort St. John, British Columbia, a preliminary survey of the active layer thickness has been conducted by James et al. (2008). The results indicate that the active layer has increased in thickness over four decades at most sites (James et al., 2008).

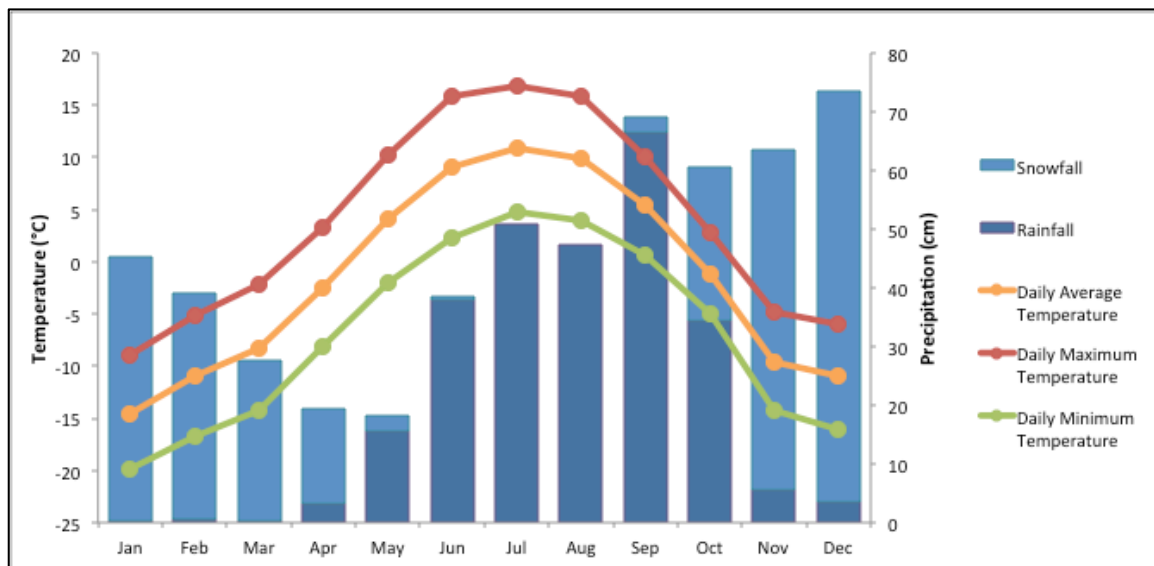


Figure 12: Temperature and Precipitation Chart for 1981-2010 Canadian Climate Normals for Blanchard River, 60°00'00"N 136°46'00"W, Elevation 836 m (Government of Canada, 2015a)

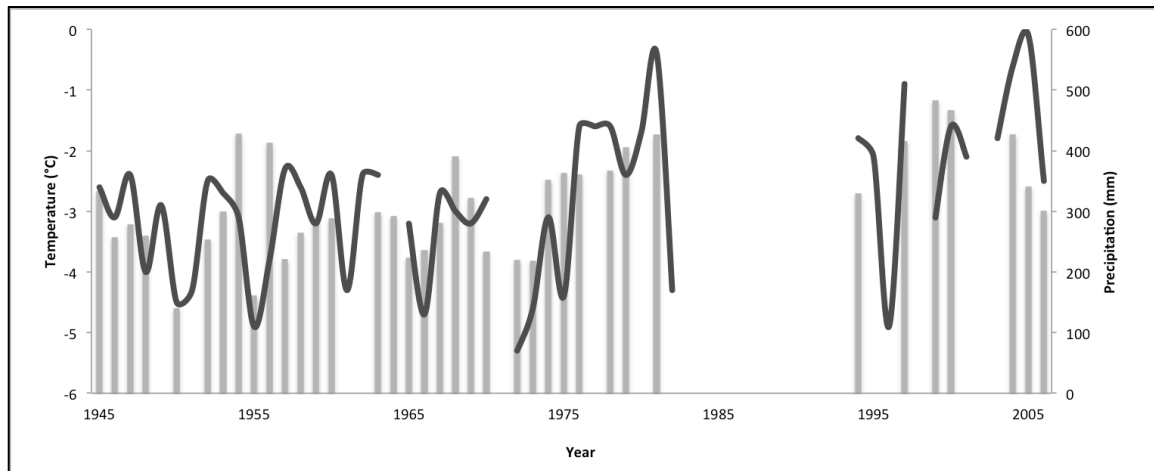


Figure 13: Historical Mean Annual Air Temperature and Precipitation Chart from 1945-2005 for Haines Junction, 60°44'58"N, 137°30'18", Elevation 596 m (Government of Canada, 2015b)

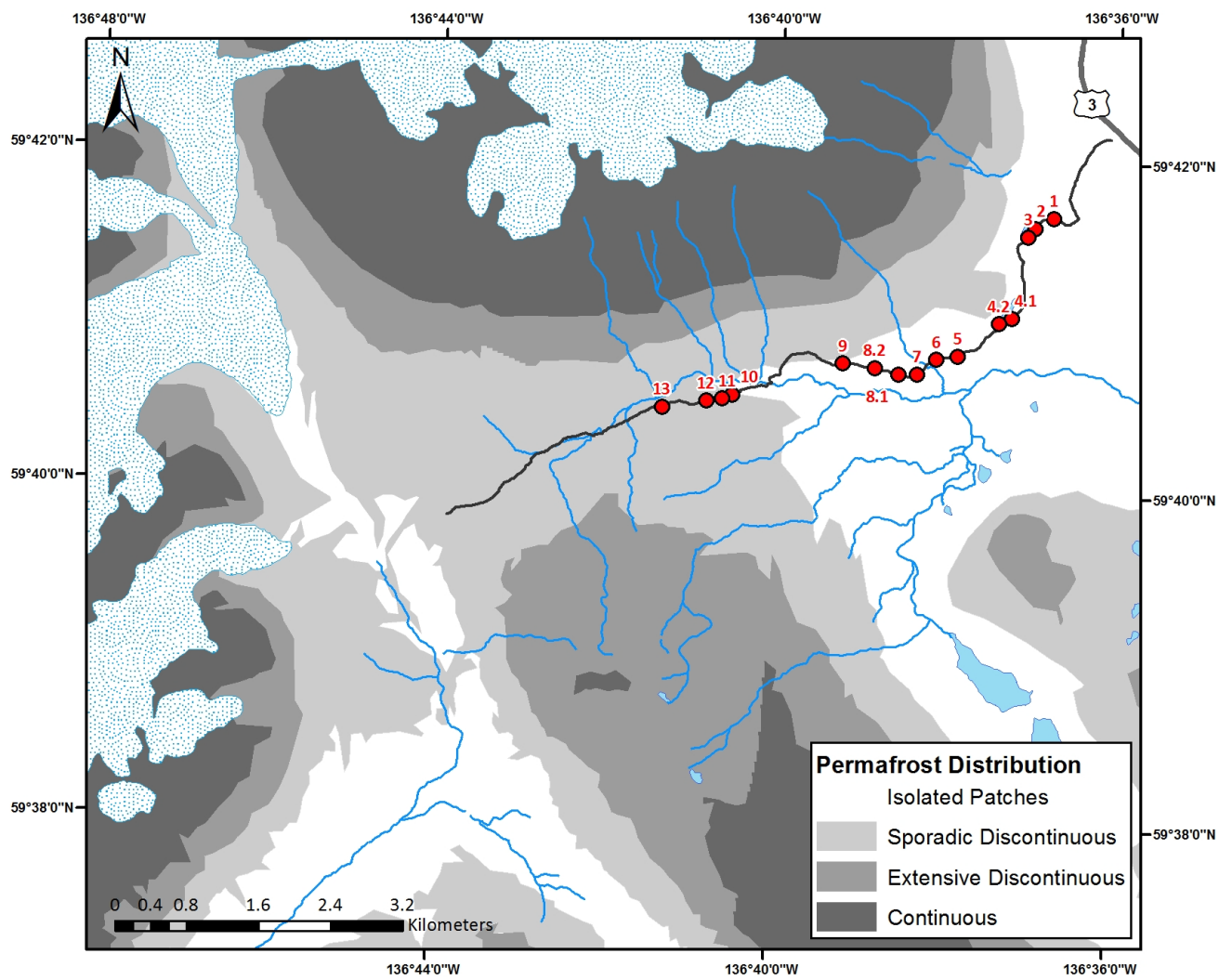


Figure 14: Permafrost distribution map in the Chuck Creek Trail Valley, according the Bonnaventure et al. (2012) model

3.2. Vegetation

The study area is situated within the Yukon-Stikine Highlands Ecoregion, more specifically in the Tatshenshini Basin Ecosection (Government of British Columbia, 2016). With the treeline found at around 1000 – 1200 m, the valley is considered to be in a transition zone between the subalpine and the alpine tundra zones (Pojar and Stewart, 1991). The valley floors and upper slopes are dominated by herbs (ex: *Festuca altaica*), graminoids (ex: *Carex microchaeta*, *Hierochloe alpina*), forbs (ex: *Polygonum viviparum*) moss (ex: *Polytrichum piliferum*), and lichen (ex: *Cetraria nivalis*, *Alectoria ochroleuca*), while clusters of prostrate deciduous shrubs, consisting mainly of birch and willow, dominate the leeward valley walls. Herb and grass vegetation is more dominant in the lower valley and becomes less frequent with elevation, where the cryptogamic layer is more developed. Unlike other studied hummock sites, the vegetation within the hummock troughs and on the hummock tops is comparable and dominated by *Cassiope stelleriana*. As in most alpine ecosystems, plants are typically small, close to the ground and strongly linked to microtopography; which can lead to variations in soil temperature, depth of thaw, wind effects, snow drifting and the resulting ability of plants to grow in such conditions (Pojar and Stewart, 1991).

3.3. Bedrock Geology

The Alexander Terrane, which consists of Cambrian to Triassic volcanic and sedimentary stratigraphy, underlies most of southeastern Alaska and Yukon, and western British Columbia (Caruthers and Stanley Jr., 2008). The terrane is thought to have evolved through three tectonic phases: 1) in the initial phase (Cambrian to Early Devonian), the terrane evolved along a convergent plate margin, 2) in the second phase (Middle Devonian to Lower Permian), accumulation occurred in a technically stable marine environment and 3) in the final phase (Triassic), the volcanic and sedimentary rocks formed in a rift environment (Gehrels and Saleeby, 1987).

The Alsek Range is composed mostly of amphibolite, siliceous and micaceous schist of the Carboniferous to Permian Kaskawulsh Group, intruded by the Alsek and Shaft Creek plutons (130 Ma) (Government of Yukon, 2013). More specifically, the

Chuck Creek Trail Valley has a sedimentary bedrock composed mainly of brown-green metagreywacke, commonly associated with tuff argillite and basalt flows (Government of British Columbia, 2015). Intrusive igneous rocks like granite and gabbro occur mostly along the slopes (Government of British Columbia, 2015). For the subject matter of this thesis, surficial geology is of greater significance than bedrock geology.

3.4. Glacial History and Surficial Geology

During the Pleistocene, at least six ice sheets have periodically covered the study area, the most recent and last being the Cordilleran Ice Sheet (Jackson et al., 1991). The Cordilleran Ice Sheet occupied the study area from 24 000 BP to ca. 10 000 BP (Jackson et al., 1991). Glaciation has strongly contributed to the range of surficial material in northwestern British Columbia. Widespread Pleistocene morainal deposits are found in the valleys and in the Chuck Creek Trail Valley along with Holocene fluvial deposits. Rampton (1982) has mapped the area to a 1:100 000 scale and identified the sediment of the valley floor mainly as silty/sandy Late Wisconsinian till (Figure 15). He also located glaciofluvial deposits, mostly composed of sand and gravel with veneer of fine sediments, undifferentiated till along with outcropping bedrock on the valley walls (Rampton, 1982). Landforms of glacial and neoglacial heritage like moraines, rock drumlins or fluted bedrocks and kames were also mapped in the Chuck Creek Trail Valley (Rampton, 1982). Active landforms that are commonly associated with periglacial environments, like ploughing blocks, are still present in the valley today (Figure 16).

The rugged and steep terrain in the study area results in an instability in which creep of surficial material hinders soil development. With the evidence of patterned ground and earth hummocks, frost shattering, colluviation, solifluction, nivation, cryoturbation and permafrost development are all processes that may be (or have been) active in the valley (Pojar and Stewart, 1991). Soils are strongly influenced by these processes, which can lead to mechanical sorting and displacement of soil particles. Pojar and Stewart (1991) have described the flat to gently sloping sites in the area to consist mainly of Cryic and Turbic Regosols, whereas the sloping sites with finer material tend to consist of Dystric and Sombric Brunisols.

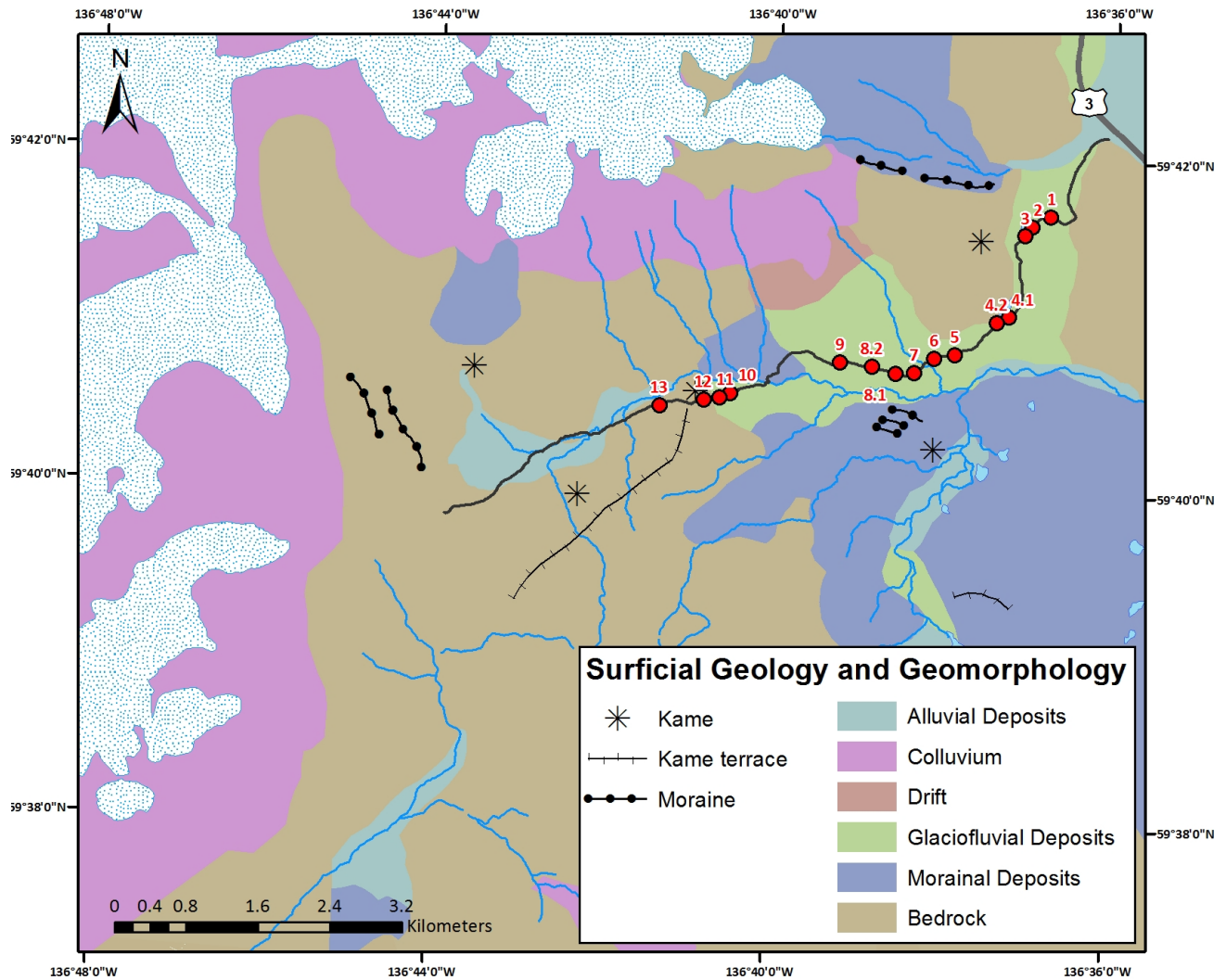


Figure 15: Surficial geology and geomorphology map of the Chuck Creek Trail Valley based on Rampton (1982)



Figure 16: Ploughing bloc in the Chuck Creek Trail Valley along the northern hill slope (Bjornson, 2016)

4. Methods

The chapter describes the methods and procedures used to address the different objectives and research questions. It is separated in three subsections: 5.1 Site Selection and Field Sampling, 5.2 Laboratory Measurements and Analyses, and 5.3 Remote Sensing and GIS Modelling.

4.1. Site Selection and Field Sampling

The first objective of this thesis is to characterize the distribution and morphology of hummocks and explore the environmental factors that control their distribution in the Chuck Creek Trail Valley. This site was selected because of its accessibility, and also for its presence of various hummock fields with different morphologies. The trail (which is an old mining road) was used as a focal axis for site selection; the location of all hummock fields along it was marked using a hand-held GPS. Hummock fields were considered distinct from each other if separated by non-hummocky terrain. A total of thirteen fields and two sub-fields (sections of hummock fields with substantial morphological differences: i.e. shape and size) were identified, totaling in 15 sites.

Four hummock fields that displayed different hummock morphologies (fields 1, 3, 8 and 12) were selected to undergo further studies (Table 2). Two 25 m transects were established along hummock tops in each selected field (except field 8, for which only a single transect was made). Topographical measurements were taken at 10 cm intervals to establish a detailed X-Y profile of the fields' morphology. This dataset was then used to extract the height and diameter of hummocks.

Soil samples were extracted from the hummock fields 1, 3 and 12, where a single *representative* hummock was selected. According to a study by Lacelle et al. (2014), where consecutive hummocks were cored on tops and troughs in the Inuvik area, there was around 70% of noise for non-soluble constituents and around 30% noise for soluble constituents. It is therefore important to keep in mind that there would be variability in the results due to micro-scale variations in the physical processes within the same hummock fields. Two cores were retrieved from each field: one from the hummock top and another from the hummock trough, totaling in 6 cores. These cores were made

using a 11.5 cm diameter Cold Region Research Engineering Laboratory (CREEL) core barrel with Viper power head (Figure 17). The depth of coring was dependent on the nature and size of the encountered material (large boulders prevented to core barrel from progressing further in the sediment). At field 1, a 25 cm core was retrieved from the hummock top (P1-HC) and a 35 cm core, from the trough (P1-HT). At field 3, an 85 cm core was retrieved from the top (P3-HC) and a 70 cm core, from the trough (P3-HT). The cores of field 12 reached down to 140 cm in the hummock top (P12-HC) and 125 cm, in the trough (P12-HT). The six cores were subsampled at approximately 5 cm intervals and placed in polyethylene plastic bags.

In addition, field 11 was also studied and sampled at an area where the trail cut through the hummocks. At that site, a soil cross-section was cleared using shovels and trowels in order to identify soil layers and structures. Ten additional samples, corresponding to distinct soil horizons, along with two coal samples, were retrieved from this site. Overall, a total of 125 soil samples were collected.

Table 2: Field sites and associated field procedures

Field Number	Geographic Coordinates	Elevation (m)	Field Procedures
1	N 59.69467°, W 136.61273°	1054	2 Transects 2 Cores: P1-HC (25 cm), P1-HT (35 cm)
3	N 59.69274°, W 136.61771°	1052	2 Transects 2 Cores: P3-HC (85 cm), P3-HT (70 cm)
8.1	N 59.67872°, W 136.64270°	1077	1 Transect
11	N 59.67591°, W 136.67741°	1035	1 Cross-section
12	N 59.67565°, W 136.68051°	1142	2 Transect 2 Cores: P12-HC (140 cm), P12-HT (125 cm)



Figure 17: Core drilling within the hummock top with the CREEL at field 12 (N 59.67565° W 136.68051°)

4.2. Laboratory Measurements and Analyses

The following subsections present the different laboratory analyses that the 125 soil samples underwent: 5.2.1 Grain-size Distribution, 5.2.2 Moisture, Organic Matter and Carbonates contents and 5.2.3 Organic Carbon and Type of Carbon. These analyses were undertaken to address the second objective of this research: to provide an extensive sedimentological and geochemical description of earth hummocks and to describe the distribution of organic carbon and type of organic compounds in hummocks of various morphologies. Section 5.2.4 Radiocarbon Dating addresses the third and fourth objectives of this thesis, which consist of locating cryoturbated horizons, dating SOC and inferring soil movement within hummocks.

4.2.1. Grain-size Distribution

A grain-size analysis was conducted in order to assess the frost susceptibility, or the potential for frost action within the soil (Carter and Bentley, 2016). Grain-size distribution can also indicate internal movement (Mackay, 1980; Kokelj et al., 2007). In fact, differential frost heave and ice segregation can lead to frost sorting of heterogeneous material, like the till-composed hummocks of the Chuck Creek Trail valley (French, 2007). Recent studies also show that particle size also influences the chemical composition and bioavailability of organic matter and therefore play a role in soil organic matter dynamics (Tisdall and Oades, 1982; Christensen, 1992; Xu et al., 2009).

Sample pretreatment consisted of placing a 5 mL subsample in a 50 mL falcon tube with 10 mL of deionized water. Three doses of 30 % peroxide (H_2O_2) were added to the solution to remove the organic material within the sample (5mL, 10 mL, 10mL). The remaining mineral soil sample was mixed with a 5% hexametaphosphate solution to disperse the particles and left for a week to react. Duplicates were analyzed for 5% of the samples to ensure the precision of the instrument. Primarily organic samples were excluded from this analysis because of their low mineral content. A Microtrac S3500 laser particle size analyzer, standardized with in-house sand, was used to determine the grain size of the mineral components of the samples. The Microtrac S3500 measured particle sizes from 0.02 to 2800 microns with a precision of approximately $\pm 1\%$. It, therefore, did not account for coarser material within the samples.

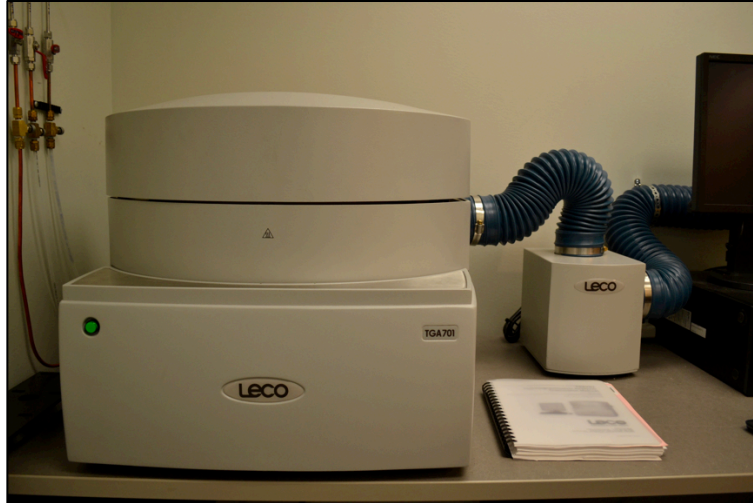


Figure 18: Leco TGA701 Thermogravimetric Analyzer used for LOI

4.2.2. Moisture, Organic Matter and Carbonate Contents

Moisture is an important parameter for understanding the potential of cryoturbation in cryosols (French, 2007). Along with grain-size, it affects frost susceptibility of soils. The bulk organic content is also an important parameter in pedological studies. It represents the fraction of organic matter that escaped mineralization of sedimentary processes, influenced by both initial biomass and subsequent degradation (Meyers and Lallier-Vergés, 1999). It often indicates changes in organic deposition and different sedimentary conditions and is key in understanding cryoturbation processes. Carbonates are often indicative of the soil parent material, influence soil biochemistry and provide additional context for carbon analyses. The loss on ignition method (LOI) is an accessible and recognized method that was used to determine the moisture, organic matter and carbonates contents in the samples (Heiri et al., 2001).

Approximately 3 – 5 g of each moist soil sample were placed in a crucible and positioned in the LECO thermo-gravimetric analyzer with an integrated balance (model TGA701) that determines the weight loss of material (Figure 18). Under ambient air conditions, the analyzer first reached a temperature of 105°C to dry soil, then rose to 550°C to combust the organic matter content and finally to 950°C to combust the carbonates content. The weight at each temperature step was recorded by the TGA

once its variation reached less than 0.1%. The moisture content, expressed as the percentage of water by mass of the dry sample, was determined from the wet and dry mass using the following equation [2]:

$$[2] \text{ Moisture}(\%) = \left(\frac{\text{Initial Mass (g)} - \text{LOI}_{105}(\text{g})}{\text{LOI}_{105}(\text{g})} \right) * 100\%$$

The organic matter and carbonates contents were determined using equation [3] and [4], respectively (Heiri et al., 2001):

$$[3] \text{ Organic matter}(\%) = \left(\frac{\text{LOI}_{105}(\text{g}) - \text{LOI}_{550}(\text{g})}{\text{LOI}_{105}(\text{g})} \right) * 100\%$$

$$[4] \text{ Carbonates}(\%) = \left(\frac{\text{LOI}_{550}(\text{g}) - \text{LOI}_{950}(\text{g})}{\text{LOI}_{105}(\text{g})} \right) * 1.36 * 100\%$$

where LOI₁₀₅ represents the weight of the sample after being dried at 105°C, LOI₅₅₀ is the weight after being combusted at 550°C and LOI₉₅₀ is the weight after being combusted at 950°C. In equation [4], the constant 1.36 represents the ratio between the molecular weights of CO₃ (60) and CO₂ (44) (Bengtsson and Enell, 1986). 5% of duplicate samples were also analyzed. The precision and accuracy of the analysis were determined from a calcium oxalate standard and an analytical error of $\pm 0.1\%$ was found.

4.2.3. Organic Carbon Content

In soils and sediments, there are three basic forms in which carbon may be present: (1) elemental, (2) inorganic and (3) organic. Elemental carbon forms include charcoal, soot, graphite and coal (Schumacher, 2002). Inorganic carbon forms are derived from parent material and are typically present in soils as carbonates (Schumacher, 2002). Calcite (CaCO₃) and dolomite [CaMg(CO₃)₂] are the two most common type of inorganic carbon minerals (Schumacher, 2002). Organic carbon forms are derived from the decomposition of plants and animals and range from barely

decomposed macroremains (e.g., leaves, twigs, branches) to highly decomposed material such as humus (Schumacher, 2002).

The concentration of bulk organic carbon and total nitrogen within the samples was determined using an Elemental VarioEL III analyzer. As a standard pre-treatment, the samples were first acidified with 5% HCl to remove all inorganic carbon (carbonates) content and to isolate the organic carbon fraction. Approximately 10 mg of dried samples, including 5% duplicates, were placed in tin capsules (8 x 5 mm) along with 25 mg of tungstic oxide (WO₃), a combustion catalyst, and were flash combusted at 1800°C, with the addition of oxygen. The resulting gases were carried by helium through columns of reducing and oxidizing chemicals in order to obtain N₂ and CO₂ and then separated through “purge and trap” method. A series of Sulfanilamide and Sulfanic Acid standards were performed each 40 samples to ensure the instrument remained calibrated. Gas concentrations were measured by thermal conductivity detectors (TDC) in their specific absorption columns with an analytical precision of ±0.1%.

Similarly, to obtain the $\delta^{13}\text{C}_{\text{org}}$ values, a DeltaPlus Advantage isotope ratio mass spectrometer (IRMS) coupled with the ConFlo III interface was used. Samples, with weight depending on their nitrogen concentration, approximately 100 µg of nitrogen per sample, were placed in tin capsules (with tungstic oxide) and flash combusted at 1800°C. The resulting gases were again carried by helium through columns of reducing and oxidizing minerals and separated through the “purge and trap” method. The results are expressed in δ notation, which corresponds to the parts per thousand difference of $^{13}\text{C}/^{12}\text{C}$ with respect to the Vienna Pee-Dee Belemnite (VPDB) standard. Analytical precision for this study was ±0.2%.

Following the determination of the bulk organic carbon, the values were converted to Soil Organic Carbon Content (SOCC, kg/m²) using equation (Tarnocai et al. 2009):

$$[7] \text{SOCC} = C * BD * T * (1 - CF)$$

where C is the organic carbon (C g/kg), BD is the bulk density (g/cm³), T is the soil layer thickness (m), and CF, the coarse fragment and/or ice content (%). Bulk density was determined using a simple mass and volume ratio. A standardized 2.5 cm³ cylinder was used to obtain a constant volume for the soil samples. The mass of each sub-sample was obtained using an electronic balance. Soil Organic Carbon Mass (SOCM) can then be computed by multiplying the SOCC of the specific soil by the area it covers (Tarnocai et al., 2009). The method used to obtain the area of hummock distribution is explained in section 4.3.

4.2.4. Radiocarbon dating

The basic premise of using radioactive isotope dating in the context of this project is to use ¹⁴C to determine the age of organic matter in hummocks as tracers of soil movement. In a regular context, soil material would be laid down according to the superposition principle (from newest to oldest from the surface down) and the decay profile would mirror this. However, if there had been a disruption in the depositional sequence, for example, due to cryoturbation, the radiocarbon dates should also show disruption.

¹⁴C is a radioactive atom, which contains 8 neutrons and 6 protons. It has a half-life of 5730 ± 40 years and decays into nitrogen-14 (Davis, 1977). Carbon-14 is passed onto the biosphere and can, therefore, be used as a dating method of organic matter (Davis, 1977). The radiocarbon dating method was instigated by Libby et al. (1949) and can be used to date vegetal macroremains and/or bulk sediments.

The samples extracted from Field 11 were chosen to undergo the radiocarbon analysis since a detailed profile was extracted from that field, providing additional details on the extent of each soil unit. For this study, bulk sediments were favoured over macroremains (twigs/roots, charcoal, leaves, etc.) because of the inability to locate and/or identify macroremains. To avoid the risk of dating roots, which lead to inaccurate results, the organic layer was excluded from this study. A total of 8 soil units were targeted, along with 2 additional coal samples collected along the profile, for a total of 10 samples.

The standard pre-treatment of the bulk sediments samples at the A.E. Lalonde AMS Laboratory are presented in Brock et al. (2010)'s protocol. It consisted of removing (1) plant macrofossils by manual extraction (2) carbonates during an acid wash (HCl, 1N, 80°C, 30 min.), followed by three rinses in MilliQ™ water. The samples were then freeze-dried overnight and combusted in a tin capsule with WO₃ using a Thermo Flash 1112 elemental analyzer. The analyzer was set in CN mode with an extraction line to capture the pure CO₂ in pre-baked 6 mm pyrex tubes. The samples then underwent graphitization, where the CO₂ collected during combustion was transferred to 10 mL rigs containing 2.0 – 2.5 mg iron catalyst that had been out-gassed with H₂. Hydrogen gas was then added to the sample in a 2:2 ratio of H₂:CO₂ to obtain a graphite target of 0.8 mg – 1.8 mg.

The radiocarbon analyses were performed using a 3MV accelerator mass spectrometer by High Voltage Engineering. Calibration was based on OxCal v.4.2.4 software using the IntCal13 calibration curve and results were presented with a 1 σ confidence limit (Bronk Ramsey, 2009). Oxalic II (F¹⁴C=1.34) was used as reference material and the age of the material was calculated using the Libby ¹⁴C half-life of 5568 years.

4.3. Remote Sensing and GIS Modeling

One of the objectives of this thesis is to understand the distribution of hummock fields within the Chuck Creek Trail Valley. As mentioned in section 4.1, single coordinates of each hummock field encountered along the trail were marked using a hand-held GPS. However, this method does not provide information about the area covered by hummocks within the valley. Hummocks, being meter-scaled landforms, could not be identified or located on neither aerial-photographs nor high-resolution satellite images. The unfavourable weather conditions during the fieldwork period also made UAV flights impossible. Therefore, remote sensing and GIS modeling were the best alternatives to obtaining an areal component for hummock distribution in the valley.

To model hummock distribution within the valley, three components were taken into consideration: 1) surface geology, 2) vegetation and land cover, and 3) slope. The 1:100 000 surface geology map developed by Rampton (1982) (Figure 15) was used to locate the different surficial geology units. As it has been widely accepted that hummocks occur in frost susceptible sediments (e.g., Schunke, 1977; Tarnocai and Zoltai, 1978; Mackay, 1980; Schunke and Zoltai, 1988; Van Vliet-Lanoë, 1991; Gerrard, 1992; Grab, 2005; French, 2007; Main, 2016) zones corresponding to units unfavourable to hummock development (colluvium, drift and bedrock) were excluded from the analysis. A maximum likelihood supervised image classification analysis was performed on a 1.84 m resolution DigitalGlobe WorldView-2 satellite image to identify the land cover classes and to isolate, more precisely, the class corresponding to alpine tundra vegetation. As previously discussed in section 2.3.2, hummocks in alpine and sub-alpine environments are dominated by sedges, grasses, mosses and lichen (Grab, 1994). Slope was derived using a 10-meters resolution DEM (Government of Canada, 2016). Since hummocks do not occur on terrain with slopes greater than 25°, areas exceeding this limit were excluded from the analysis (Schunke, 1977). The area corresponding to all three factors was identified as having a *moderate* probability of hummock. More severe thresholds were elaborated for the *high* probability class: 1) morainal deposits were also flagged as non-frost-susceptible sediments and 2) slopes greater than 15° were excluded from the analysis, based on the observations made by many studies (e.g., Tarnocai and Zoltai, 1978; Killingbeck and Ballantyne, 2012), in which the hummocks on these slopes are greatly elongated and vertical development rarely takes places. The resulting model is presented in the map of Figure 32.

5. Results

The results of this study are separated in four main sections: 6.1 Distribution of hummocks in the valley, 6.2 Morphology of hummock, 6.3 Hummock Sedimentology and Biochemistry and 6.4 Age of Organic Matter. The first section consists mainly of qualitative field observations. The second section presents the hummock morphological data derived from the transects described in section 5.1. The third section presents results obtained from the laboratory analyses described in section 5.2. (grain-size distribution, moisture, organics and carbonates contents, and elemental and isotopic analyses). The last section presents the radiocarbon ages of the organic matter in the active layer of hummocks.

5.1. Hummock Distribution

A total of 15 hummock fields (large clusters of earth hummocks) were identified along a 5 km segment of the Chuck Trail. The hummocks were found along the valley floor of the Chuck Creek Trail Valley, along gently sloping or flat terrain at elevation varying between 1049 and 1142 m (Table 3). They all occurred in areas of alpine tundra vegetation covering frost susceptible soils. Unlike in the low Arctic, the hummocks were fully covered by vegetation; their tops are not exposing mineral soils.

Table 3: Identified hummock fields along the Chuck Creek Trail with geographic coordinates

Field Number	Geographic Coordinates	Elevation (m)
1	N 59.69467°, W 136.61273°	1054
2	N 59.69361°, W 136.61630°	1055
3	N 59.69274°, W 136.61771°	1052
4.1	N 59.68458°, W 136.62053°	1052
4.2	N 59.68357°, W 136.62286°	1060
5	N 59.68068°, W 136.63112°	1049
6	N 59.68029°, W 136.63622°	1063
7	N 59.67880°, W 136.63908°	1063
8.1	N 59.67872°, W 136.64270°	1077
8.2	N 59.67934°, W 136.64735°	1085
9	N 59.67970°, W 136.65313°	1100
10.1	N 59.67635°, W 136.67535°	1126
10.2	N 59.67587°, W 136.67520°	1134
11	N 59.67591°, W 136.67741°	1135
12	N 59.67565°, W 136.68051°	1142
13	N 59.67496°, W 136.68915°	1142



Figure 19: Photos of the identified hummock fields along the trail in the Chuck Creek Trail Valley, British Columbia

5.2. Hummock Morphology

The morphology of hummocks, height and width, can be used to assess their extent of development. In the valley, hummocks range from 25 – 155 cm wide and 5 – 22 cm high, and generally shows a positive relation with wider and higher hummock (Figure 20). Hummocks in field 1 have a mean height of 10 cm and a mean width of 77 cm, with values ranging from 5 – 20 cm and 45 – 150 cm respectively. Field 3 has the greatest ranging values for hummock morphology. Height ranges from 5 – 22 cm, for an average of 11 cm, and width ranges between 30 – 150 cm, for an average of 77 cm. The hummocks of field 8 are substantially lower in height, ranging from 6 – 11 cm, averaging 8 cm, for a width of 50 – 100 cm, averaging 77 cm. Hummocks in field 12 have a mean height of 12 cm and mean width of 79 cm, with values ranging from 8 – 19 cm and 45 – 100 cm, respectively.

Hummock height:width ratios were calculated to determine their sphericity. Field 8 has the highest average height to width ratio of 9.1, followed by field 1, with 8.1, by field 3, with 7.3 and by field 12, with 6.4, making the hummocks of field 12 the most “rounded” (closer to a ratio of 1).

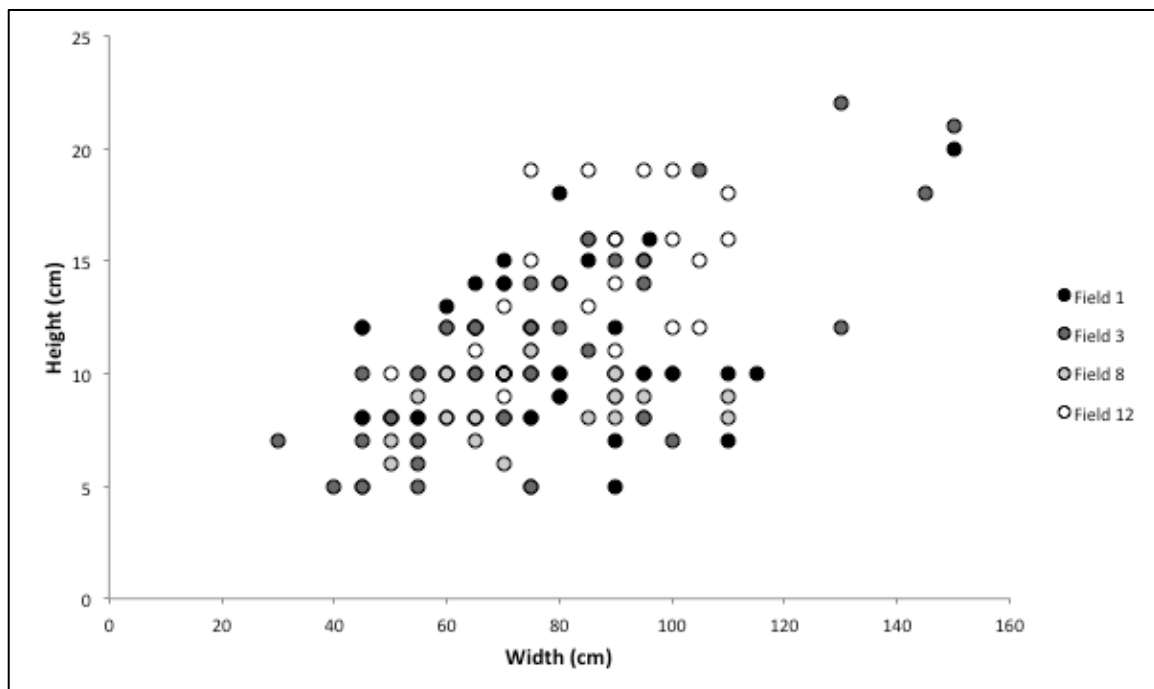


Figure 20: Width and height of hummocks along 25 m transects in fields 1,3, 8 and 12

5.3. Hummock Sedimentology and Biochemistry

The following sub-sections present the results from the laboratory analyses conducted on the cores obtained at fields 1, 3 and 12 (P1-HC, P1-HT, P3-HC, P3-HT, P12-HC, P12-HT) and subsampled at 5 cm intervals. Each core is presented on its individual profile, alongside the other coring sites with standardized horizontal and vertical axes to facilitate comparison (except Figure 22). Each data series is grouped by parameter: grain-size (Figure 22), moisture content (Figure 23), organic C content (Figure 25), cumulative SOCC (Figure 26), carbonate content (Figure 27), C:N ratio (Figure 28) and $\delta^{13}\text{C}_{\text{org}}$ (Figure 29). The last section presents the results associated with the description of the cross-section of field 11 and its different soil horizons.

5.3.1. Grain Size Distribution

Grain size distribution indicates that the soils of hummock fields 1, 3, 11 and 12 are composed of silt loam: dominant in silt, followed by sand and then clay (Figure 21). Field 12 has the highest silt content and field 3 has the lowest silt content, whereas fields 1 and 11 have intermediate silt contents. Sand-sized particles are more dominant in field 3, reaching up to 46% and least dominant in field 12, reaching down to 5%. Clay values always remain below 10%.

Grain size does not follow a particular trend in respect to depth (Figure 22). Average values correspond to 23% sand, 73% silt and 4% clay in P1-HC, to 32% sand, 64% silt and 4% clay in P1-HT, to 37% sand, 59% silt and 4% clay in P3-HC, to 33% sand, 62% silt and 5% clay in P3-HT, to 14% sand, 80% silt and 6% clay in P12-HC and, to 20% sand, 75% silt and 5% clay in P12-HT. There is no apparent difference between hummock troughs (P1-HT, P3-HT, P12-HT) and hummock tops (P1-HC, P3-HC, P12-HC). Clay experiences minimal variation throughout the profiles. Sand and silt have a more homologous relationship: when sand percentages increase, silt percentages decrease, and vice-versa. P1-HC experiences very little variations. P1-HT attains a sand peak at 15 cm (47%). P3-HC exhibits a sand maximum of 46% at 25 cm and a sand minimum of 25% at 70 cm. P3-HT also attains a sand maximum of 44% at 15 cm and a sand minimum of

23% at 50 cm. Field 12 experiences more variation. Its hummock top (P12-HC) reaches local sand maximums at 80 cm (24%), 95 cm (23%) and 130 cm (28%), while its hummock trough (P12-HT) reaches its sand maximum at 40 cm (36%), followed by minor fluctuations.

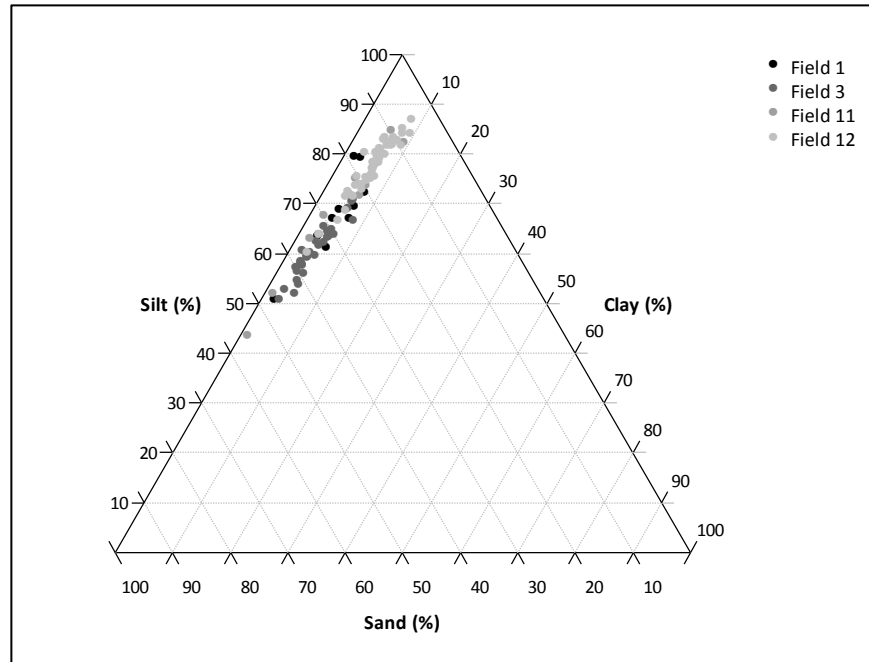


Figure 21: Ternary graph of grain size distribution in hummock fields 1, 3, 11 and 12 of the Chuck Creek Trail Valley

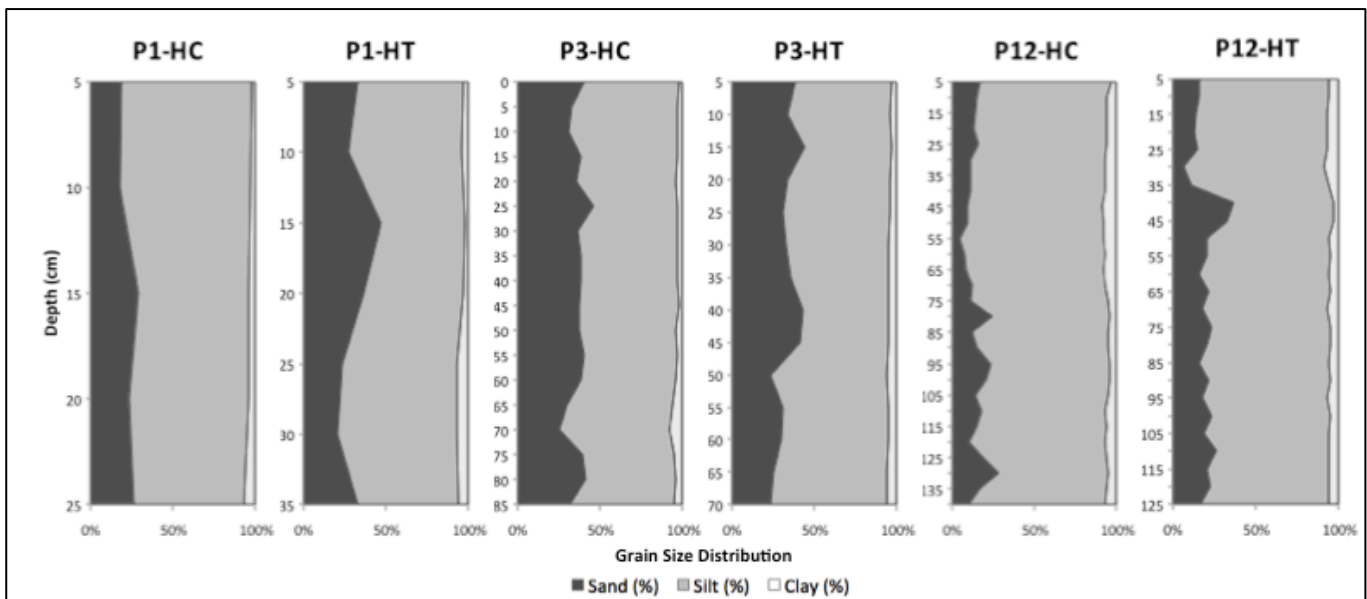


Figure 22: Percentage of grain size by percentage of sand (black), silt (grey) and clay (white) at depth for hummock fields 1, 3 and 12 of the Chuck Creek Trail Valley

5.3.2. Moisture content

Gravimetric moisture content within the profiles is higher near the surface and decreases with depth. Values range from 15.9 – 165.3% in P1-HC, from 14.8 – 221.9% in P1-HT, from 12.7 – 41.8% in P3-HC, from 14.5 – 214.4% in P3-HT, from 9.2 – 157.3% in P12-HC and from 15.9 – 121.6% in P12-HT. Hummock troughs (P1-HT, P3-HT, P12-HT) exhibit a sharper decrease within the first 5 cm than hummock tops (P1-HC, P3-HC, P12-HC). Fields 1 (P1-HC, P1-HT) and 3 (P3-HC, P3-HT) experience minimal variation beyond 20 cm of depth while field 12 experiences a more gradual decline until 80 cm for P12-HC and 40 cm for P12-HT. At these depths, all soil profiles reach a base value of approximately 15 – 25%.

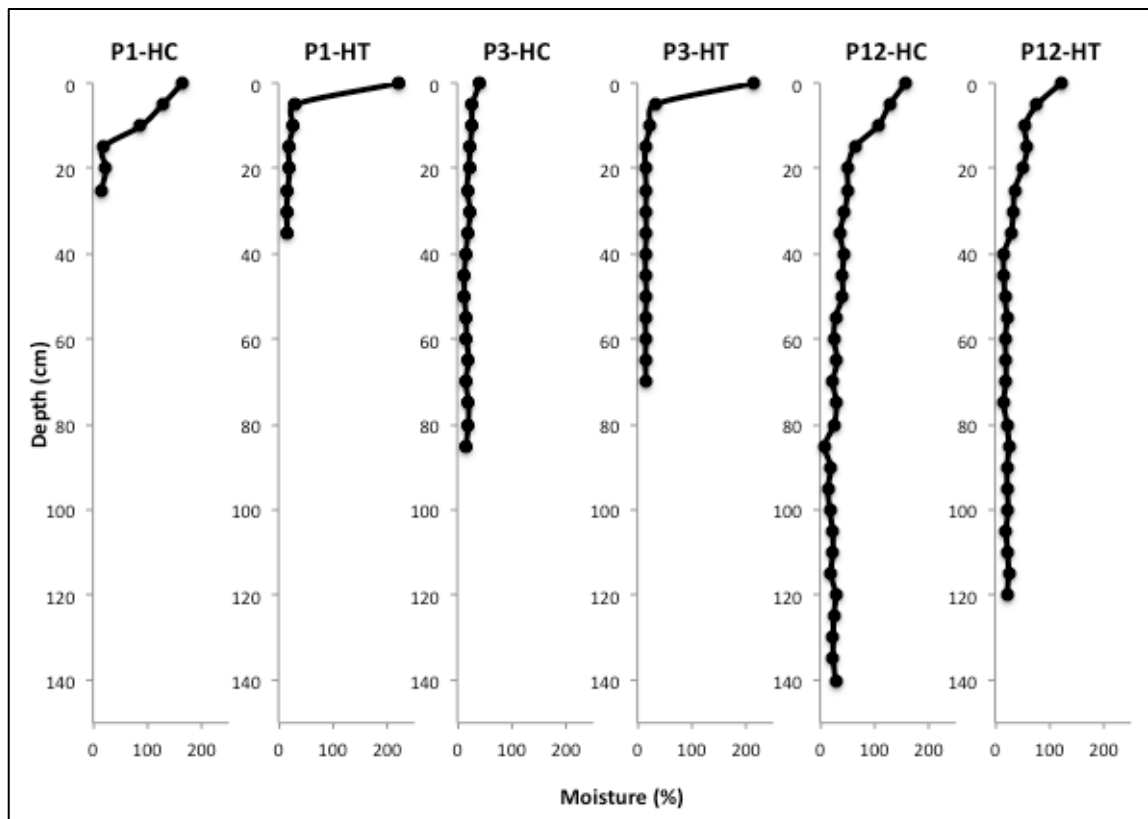


Figure 23: Moisture content (%) at depth from samples of hummock fields 1, 3 and 12 in the Chuck Creek Trail Valley

5.3.3. Organic matter and organic carbon contents

Organic matter and organic carbon contents were determined to establish the relation between both parameters and a positive relation was observed, with an r^2 value of 0.82 (Figure 24). A linear equation with a 0.3225 factor best describes this relation, which is lower than that reported from other studies (58% established by the Van Bemmelen factor of 1.724) (Van Bemmelen, 1890). Establishing the organic matter and organic carbon contents relation at the sites makes it possible to infer that both SOM and SOC behave similarly in respect to depth, with a p-value for the t-test < 0.05 (5.32×10^{-10}). Therefore, the following figure showing the SOM with respect to depth also implies similar SOC trends (Figure 25).

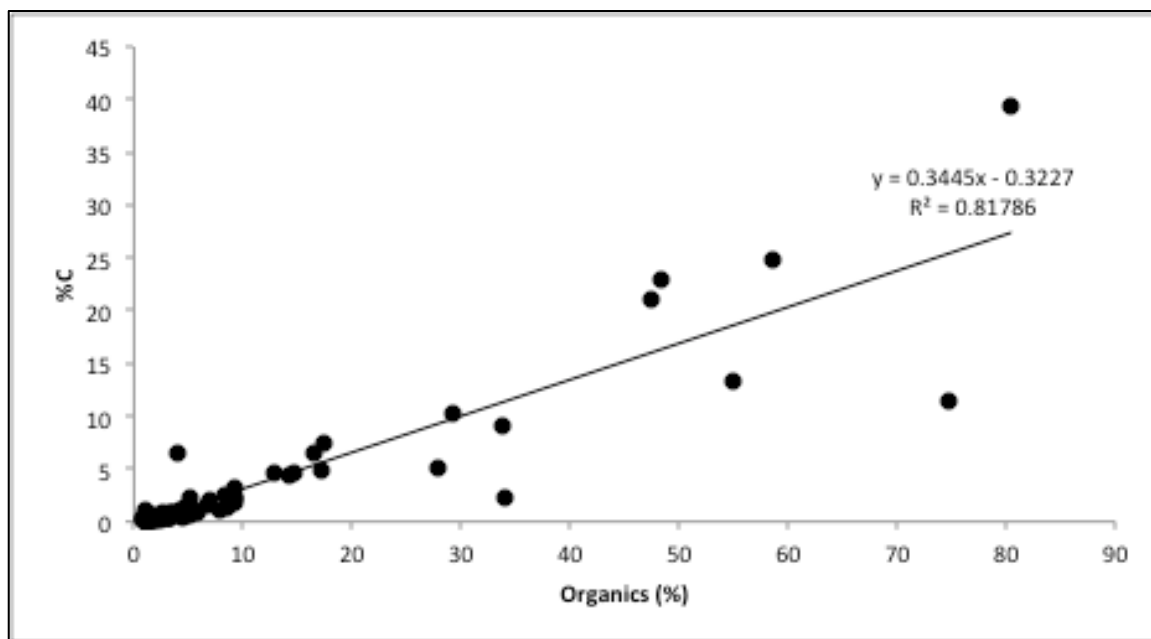


Figure 24: Relation between organic matter content (%) and organic carbon content (%) for all sampling sites

Organic matter content within the profiles is higher near the surface and overall decreases with depth. Values range from 2.3 – 74.6% in P1-HC, from 1.4 – 54.8% in P1-HT, from 1.1 – 7.0% in P3-HC, from 0.8 – 33.9% in P3-HC, from 0.9 – 80.4% in P12-HC and from 1.0 – 29.3% in P12-HT. There is no apparent difference in organic matter content between hummock troughs (P1-HT, P3-HT, P12-HT) and hummock tops (P1-HC, P3-HC, P12-HC). Profiles exhibit a sharp decrease within the first 5 – 15 cm. Fields 1 (P1-

HC, P1-HT) and 3 (P3-HC, P3-HT) experience minimal variation beyond 15 cm of depth while field 12 experiences small fluctuations, especially within the hummock top (P12-HC). At 40 and 50 cm of depths, local maximum of respectively 8.5% and 9.2% can be observed. The profiles all reach a base value of approximately 1 – 2%.

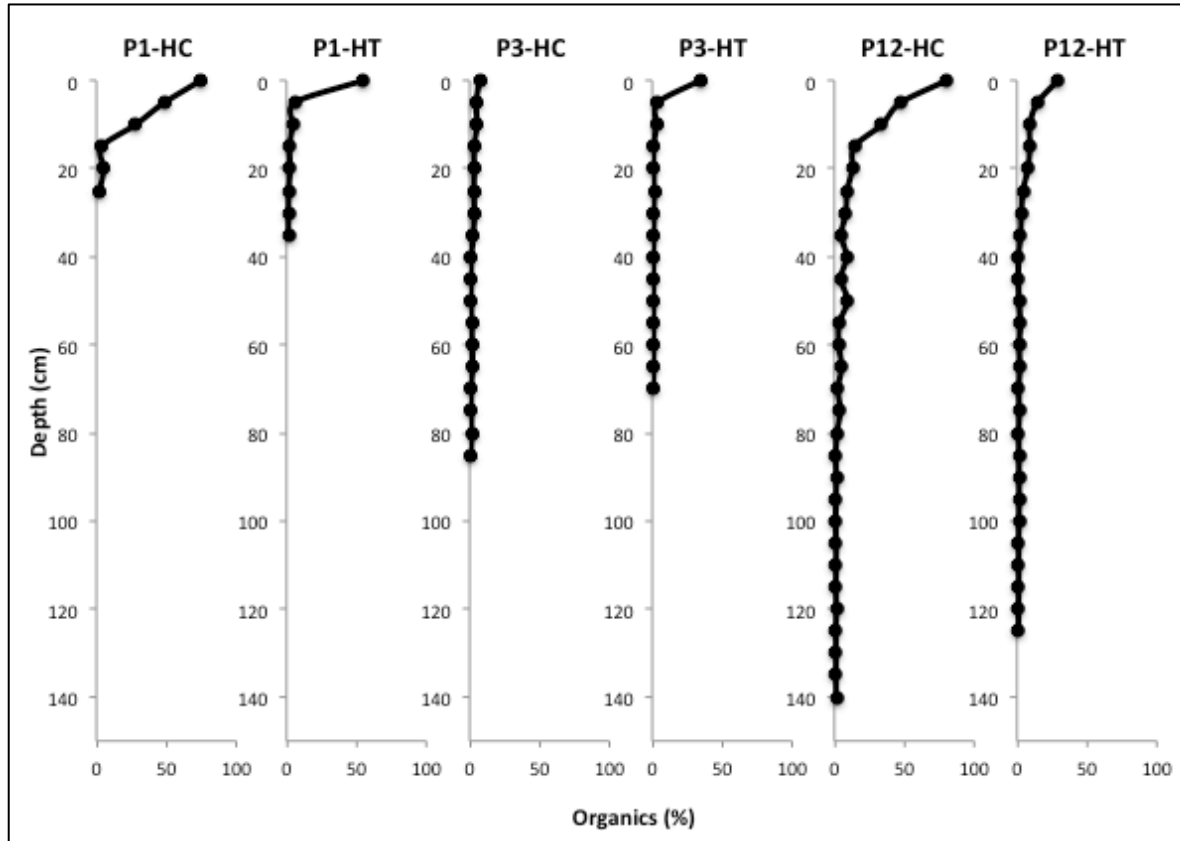


Figure 25: Organic matter content (%) at depth from samples of hummock fields 1, 3 and 12 in the Chuck Creek Trail Valley

Within the different soil profiles, cumulative SOCC values for the 0 – 25 cm interval vary from 18.6 kg/m² in P1-HC, to 6.3 kg/m² in P1-HT, to 4.6 kg/m² in P3-HC, to 2.5 kg/m² in P3-HT, to 20.0 kg/m² in P12-HC and to 8.9 kg/m² in P12-HT. In the 25 – 50 cm interval, reached by the hummocks at field 3 and 12, cumulative SOCC is lower than in the previous interval: 1.4 kg/m² in P3-HC, 1.2 kg/m² in P3-HT, 6.5 kg/m² in P12-HC and 1.6 kg/m² in P12-HT. For the 50 – 75 cm interval, P3-HC contains 1.7 kg/m², P3-HT, 1.1 kg/m², P12-HC, 3.7 kg/m² and P12-HT, 1.9 kg/m². The data for the following intervals is only available for field 12. For the 75 – 100 cm interval, cumulative SOCC is estimated at

1.1 kg/m² in P12-HC and 1.5 kg/m² in P12-HT. For the 100 – 125 cm interval, P12-HC is estimated at 1.3 kg/m² and P12-HT, at 1.7 kg/m². Hummock troughs (P1-HT, P3-HT, P12-HT) exhibit a more constant but weaker increase than their homologous hummock tops (P1-HC, P3-HC, P12-HC). At the highest comparative depth, field 1 has a cumulative SOCC of 1.87 kg/m² within its top while only 0.67 kg/m² within its trough (at 30 cm of depth). Similar results can be observed for field 3, with 0.80 kg/m² of cumulative SOCC within the top compared to 0.49 kg/m² within the trough (at 70 cm of depth) and for field 12, with 3.29 kg/m² of cumulative SOCC within the top and 1.59 kg/m² within the trough (at 125 cm of depth). Cumulative SOCC levels are therefore around twice as high in hummock tops than in hummock troughs.

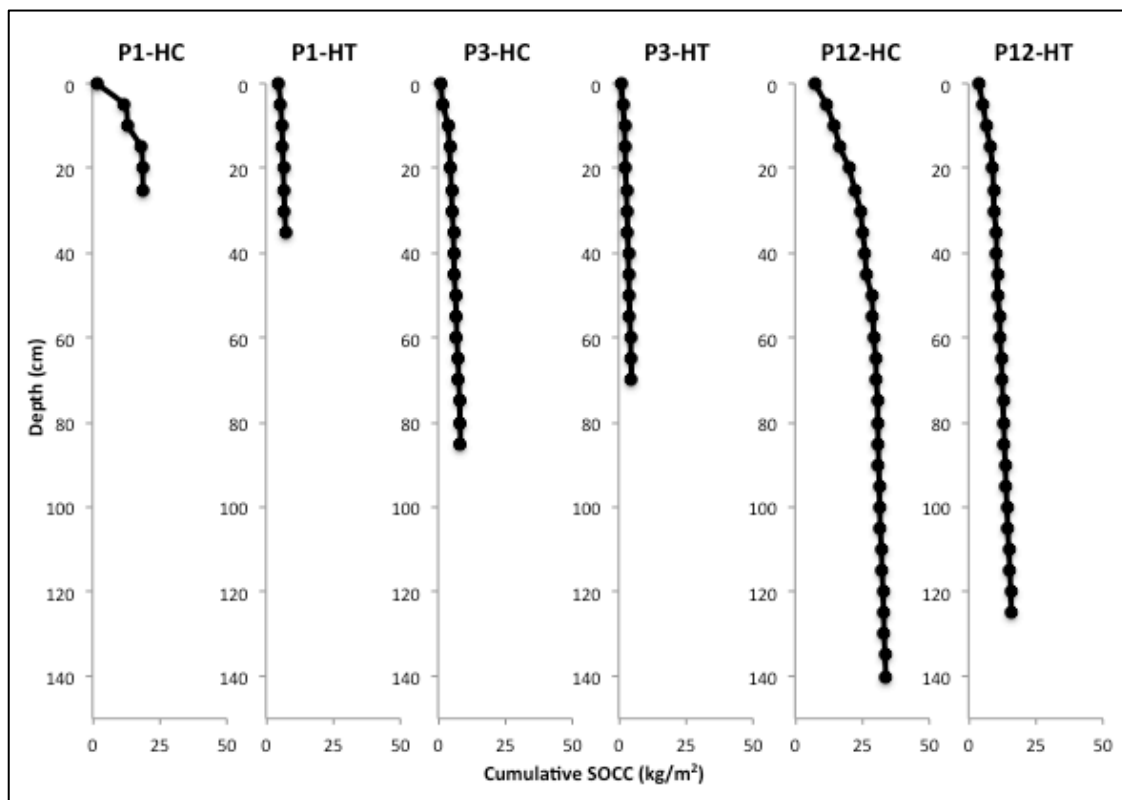


Figure 26: Cumulative SOCC (kg/m²) at depth from samples of hummock fields 1, 3 and 12 in the Chuck Creek Trail Valley

5.3.4. Carbonates content

Carbonates content within the profiles is overall constant with depth. Values range from 0.7 – 1.7% in P1-HC, from 1.0 – 2.4% in P1-HT, from 0.9 – 2.7% in P3-HC, from

1.2 – 7.7% in P3-HC, from 0.4 – 2.6% in P12-HC and from 1.0 – 2.6% in P12-HT. There is no apparent difference between hummock troughs (P1-HT, P3-HT, P12-HT) and hummock tops (P1-HC, P3-HC, P12-HC). The field 3 hummock trough (P3-HT) exhibits two anomalies at 65 and 70 cm of depth (5.0 and 7.7%). These are the only values exceeding 3.0% in all six profiles.

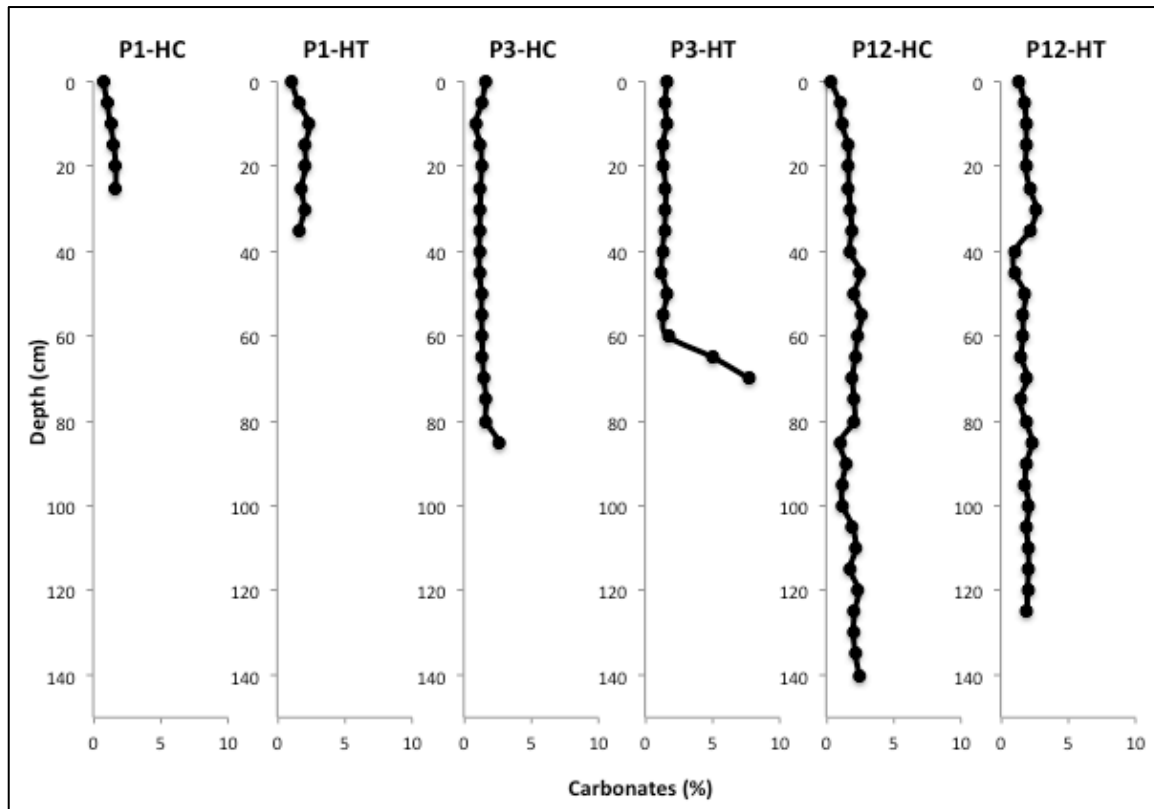


Figure 27: Carbonates (%) at depth from samples of hummock fields 1, 3 and 12 in the Chuck Creek Trail Valley

5.3.5. Elemental analyses

Organic carbon and total nitrogen ratio within the profiles follow different trends amongst different sampling sites. Overall, it seem to increase with depth in field 1 (P1-HC, P1-HT) and to decrease with depth in fields 3 (P3-HC, P3-HT) and 12 (P12-HC, P12-HT). Values range from 23.4 – 46.8 in P1-HC, from 19.5 – 105.1 in P1-HT, from 7.5 – 28.7 in P3-HC, from 9.1 – 23.8 in P3-HC, from 7.8 – 101.2 in P12-HC and from 19.2 – 58.5 in P12-HT. There is no apparent difference between hummock troughs (P1-HT, P3-HT, P12-HT) and hummock tops (P1-HC, P3-HC, P12-HC). Field 1 (P1-HC, P1-HT) experiences an abrupt increase around 20 cm. Field 3 (P3-HC, P3-HT) experiences minimal variation

except a local peak of 28.7 at 50 cm in the hummock top. Field 12 (P12-HC, P12-HT) experiences a more complex variation. The hummock top (P12-HC) is fairly constant from the surface down to 80 cm. Numerous local peaks are apparent beyond that: 1) 49.5 at 95 cm, 2) 53.9 at 115 cm and 3) 101.2 at 130 cm. The hummock trough (P12-HT) is fairly constant down to 35 cm. It then exhibits four local peaks: 1) 50.2 at 40 cm, 2) 48.7 at 60 cm, 3) 51.3 at 80 cm and 4) 58.5 at 105 cm.

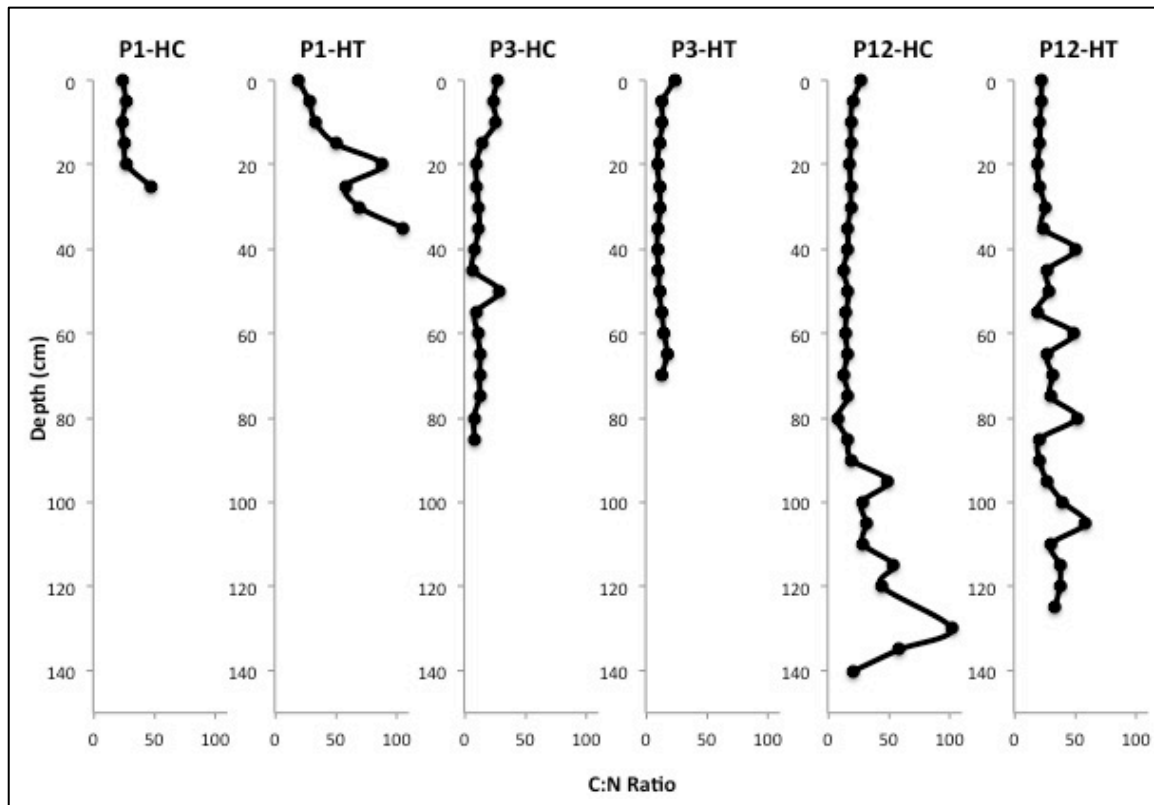


Figure 28: Carbon and nitrogen ratios at depth from samples of hummock fields 1, 3 and 12 in the Chuck Creek Trail Valley

Organic ^{13}C values within the profiles are lower near the surface and overall increase with depth. The $\delta^{13}\text{C}_{\text{org}}$ values range from -27.2 – -17.6‰ in P1-HC, from -26.7 – -14.3‰ in P1-HT, from -25.7 – -15.2‰ in P3-HC, from -28.7 – -15.9‰ in P3-HT, from -27.9 – -16.7‰ in P12-HC and from -27.4 – -16.9‰ in P12-HT. There is no apparent difference between hummock troughs (P1-HT, P3-HT, P12-HT) and hummock tops (P1-HC, P3-HC, P12-HC). The hummock trough at field 1 (P1-HT) experiences a local peak of -

14.3‰ at 15 cm, while its hummock top experiences it at 25 cm (although it is uncertain if the peak is attained since there is a sampling hiatus at that depth). Field 3 (P3-HC, P3-HT) also experiences its local peak higher in the trough profile than in the top. The local maximum of -18.1‰ is encountered at 15 cm in P3-HT while they are encountered at 50 cm (-15.2‰) and then at 70 cm (-17.3‰) in P3-HC. Field 12 (P12-HC, P12-HT) experiences most variation between 20 and 75 cm of depth. Local minimums and maximums are fairly synchronized in both the top and trough of the hummock. Both P12-HC and P12-HT exhibit a local peak around 45 cm (-21.6 and -17.6‰ respectively), around 60 cm (-20.1 and -18.3‰ respectively) and around 70 cm (-19.0 and -17.7‰ respectively). Variation remains minimal beyond 80 cm of depth. The overall median value for the soil profiles is -20.2‰.

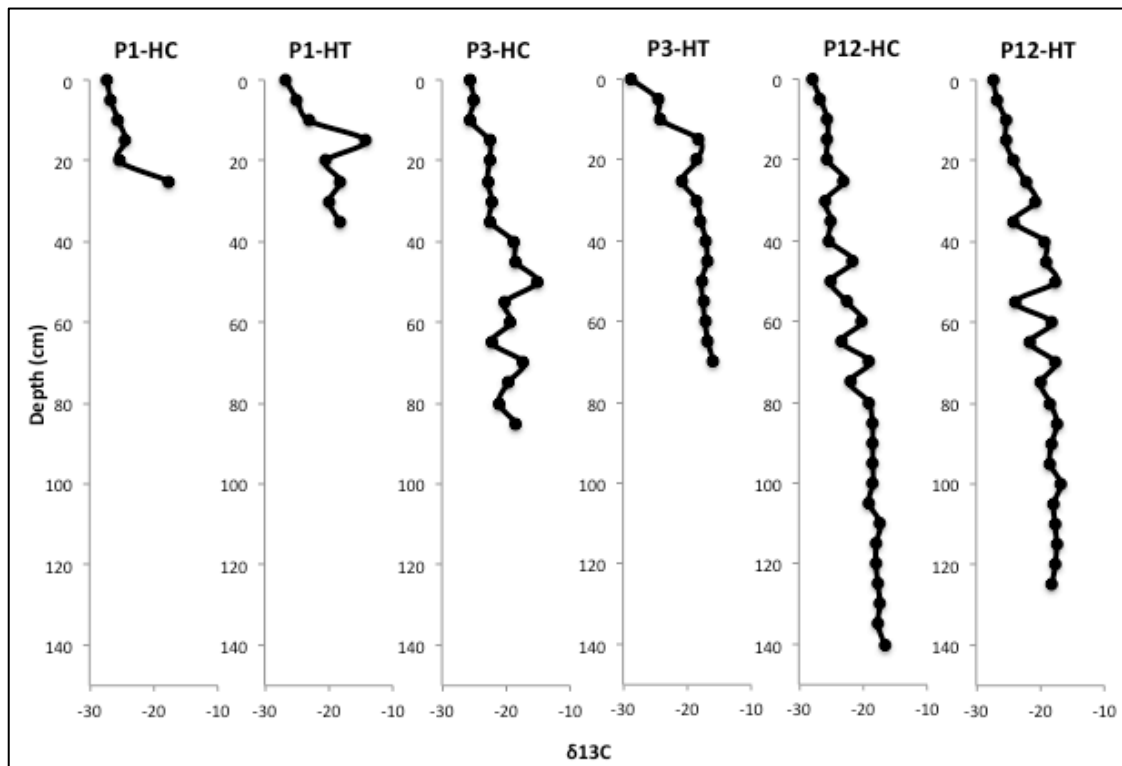


Figure 29: Carbon-13 values at depth from samples of hummock fields 1, 3 and 12 in the Chuck Creek Trail Valley

5.3.6. Field 11 cross-section and soil units

The description of the soil units of this cross-section are based upon the guide elaborated by Tarnocai in *Cryosols* (Kimble, 2004). The soil profile can be identified as a turbic cryosol: it consists of mineral soil and shows marked evidence of cryoturbation (disrupted, mixed and broken horizons, and/or displaced material). The presence of earth hummock as a surface evidence of cryoturbation also point towards a turbic cryosol (Figure 30).

The first horizon (0 – 20 cm) consists of a Mesisol (Omy) layer, which is an organic layer consisting mainly of moderately decomposed mosses, sedges and woody material. The material is partly altered physically and biochemically. It consists of 11% sand, 83% silt and 3% clay. It contains 104.8% gravimetric moisture, 58.6% organic matter and 0.8% carbonates. The horizon contains approximately 25.0% of organic carbon and 0.8% nitrogen, with a ratio of 30.6, and a $\delta^{13}\text{C}_{\text{org}}$ value of -26.5‰. SOCC associated with this layer is estimated at 21.4 kg/m². Two gray-colored organic-rich mineral horizons are intruded within the Omy layer: Bgy and Bghy1. The first is a 3 cm thick layer consisting of 10% sand, 84% silt and 6% clay and containing 40.3% moisture, 17.4% organic matter and 1.7% carbonates. Its C:N ratio is estimated at 20.5 and is has a $\delta^{13}\text{C}_{\text{org}}$ value of -26.4‰. SOCC is estimated at 1.3 kg/m². The second intruded horizon, Bghy1 is 5 cm thick and richer in clay than the other layers, consisting of 9% sand, 82% silt and 9% clay. It contains 40.2% moisture, 6.6% organic matter and 2.4% carbonates. Its C:N ratio is estimated at 13.7 and it has a $\delta^{13}\text{C}_{\text{org}}$ value of -22.5‰. SOCC is estimated at 0.8 kg/m².

The transition from the Omy layer and the Bmgy layer is marked by the absence of an A-horizon. The Bmgy layer is 25 cm thick and marked by both browning due to oxidation (m) and gleying due to reduction (g). It consists of 19.8% sand, 73.6% silt and 6.7% clay. It contains 28.7% moisture, 4.8% organic matter and 1.9% carbonates. The horizon contains approximately 0.7% of organic carbon and 0.1% nitrogen, with a ratio of 12.8, and a $\delta^{13}\text{C}_{\text{org}}$ value of -22.3‰. SOCC associated with this layer is estimated at 1.8 kg/m². A circular grey-coloured intrusion is present within this horizon (Bmgy2). It is

approximately 20 cm thick, consists of 21% sand, 75% silt, and 4% clay, contains 53.0% moisture, 16.6% organic matter, and 1.4% carbonates, has a C:N ratio of 26.7 and a $\delta^{13}\text{C}_{\text{org}}$ value of -26.4‰. SOCC associated with this layer is estimated at 8.5 kg/m².

A 15 cm thick B-horizon, characterized by its prominent gray color, (Bg) is situated below the Bmgy layer. However, it has not been sampled and therefore no data is available to make a complete description of this unit. It is underlain by two mineral horizons minimally affected by pedogenic processes (BCy1 and BCy2), which can be mainly differentiated by their color and high sand content. BCy1 is 15 cm thick and consists of 46% sand, 52% silt and 1% clay. It contains 15.0% moisture, 1.5% organic matter and 1.4% carbonates. The horizon has a C:N ratio of 20.3, and a $\delta^{13}\text{C}_{\text{org}}$ value of -18.4‰. SOCC associated with this layer is estimated at 0.7 kg/m². BCy2 is 5 cm thick and consists of 55% sand, 43% silt and 1% clay. It contains 9.0% moisture, 1.7% organic matter and 1.6% carbonates. The horizon has a C:N ratio of 18.6, and a $\delta^{13}\text{C}_{\text{org}}$ value of -17.8‰. SOCC associated with this layer is estimated at 0.3 kg/m². A small, oxidized intrusion, Bmy, is situated within BCy1. It is approximately 5 cm thick, consists of 35% sand, 63% silt, and 2% clay, contains 16.6% moisture, 2.8% organic matter, and 1.5% carbonates, has a C:N ratio of 12.92 and a $\delta^{13}\text{C}_{\text{org}}$ value of -21.6‰. SOCC associated with this layer is estimated at 0.4 kg/m².

The C-horizon is composed of mineral parent material, which in this case is glacier till. It lies below 60 cm of depth. It consists of 22% sand, 71% silt and 7% clay. It contains 15.5% moisture, 1.4% organic matter and 2.0% carbonates. The horizon has a C:N ratio of 16.8, and a $\delta^{13}\text{C}_{\text{org}}$ value of -16.7‰. Two coal samples were collected from the C-Horizon. The first one is situated at 70 cm of depth, has a C:N ratio of 185.3 and a $\delta^{13}\text{C}$ value of -9.3‰. The second one is situated at 100 cm, has a C:N ratio of 334.4 and a $\delta^{13}\text{C}$ value of -15.2‰.

To summarize, Field 11 consists of a silty loam. Horizons BCy1 and BCy2 have the highest proportion of sand, followed by Bmy. The other horizons all have >70% silt. All horizons contain <10% of clay. The bulk densities of the layers decrease with depth, ranging from 0.4 – 1.1 g/cm³. Gravimetric moisture content also seems to be decreasing

with depth, along with organic matter content, with the exception of the intruded horizons: Bghy1 and Bghy2. The carbonates content does not follow an apparent trend with depth. C:N ratios vary between 12.8 – 30.6 within the soil horizons but reach up to above 100 within the two coal samples. The $\delta^{13}\text{C}_{\text{org}}$ values range from -26.5 – -16.7‰ within the soil horizons, seemingly increasing with depth. The coal samples have the higher values of -9.3 and -15.2‰.

Table 4: Analyses of soil horizons of hummock cross-section at field 11

Soil Horizon	Depth (cm)	GRAIN SIZE				Bulk Density (g/cm ³)	Moisture (%)	Organics (%)	Carbonates (%)	ELEMENTAL COMPOSITION	
		MV (μm)	Sand (%)	Silt (%)	Clay (%)					C:N	δ ¹³ C
Omy	0-20	38	11	83	3	0.4	104.8	58.6	0.8	30.6	-26.5
Bgy	5-8	28	10	84	6	0.6	40.3	17.4	1.7	20.5	-26.4
Bghy1	5-10	26	9	82	9	1.0	40.2	6.6	2.4	13.7	-22.5
Bghy2	10-30	46	21	75	4	0.7	53.0	16.6	1.4	26.7	-26.4
Bmgy	10-35	43	20	74	7	1.0	28.7	4.8	1.9	12.8	-22.3
Bg	20-35	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Bmy	30-35	69	35	63	2	1.2	16.6	2.8	1.5	12.9	-21.6
BCy1	35-50	73	47	52	1	1.2	15.0	1.5	1.4	20.3	-18.4
BCy2	40-45	106	55	43	1	1.2	9.0	1.7	1.6	18.6	-17.8
C	45+	51	22	71	7	1.2	15.5	1.4	2.0	16.8	-16.7
Coal 1	70	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	185.3	-9.3
Coal 2	100	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	334.4	-15.2

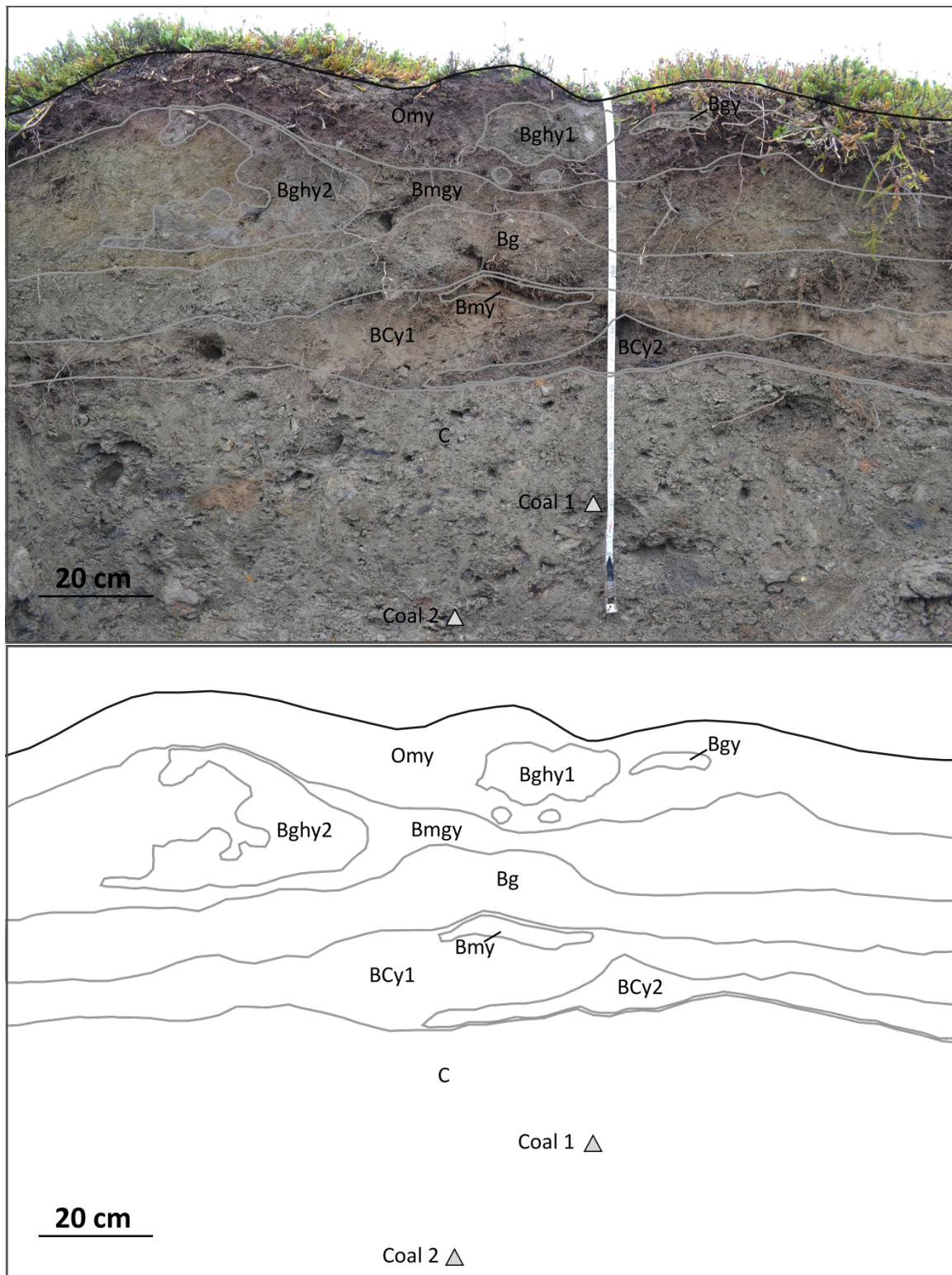


Figure 30: Cross-section of field 11 (N59.67591°, W136.67741°) associated with earth hummocks. “y” indicates a cryoturbated horizon.

5.4. Age of Organic Matter

Carbon-14 measurements were carried out on the field 11 profile and calibrated using the post-bomb Nh1 curve (Figure 31) (Hua et al., 2013). The Omy was not dated due to the predominance of roots, but the underlying regular horizons follow the principle of superposition. The Bmgy horizon yielded ^{14}C ages of 6026 – 5921 cal BP (73.7%), followed by the BCy1 horizon, 10,200 – 9916 cal BP (95.4%) and finally the C horizon, 18,160 – 12,820 cal BP (95.4%). Intruded horizons yielded a preponderance of dates around 2000 BP. The Bghy1 layer dates back to 2861 – 2766 cal BP (95.4%) and the Bgy layer, is qualified as modern (AD1957 or AD1996-2000). The Bghy2 intrusion dates back to 1706 – 1569 cal BP (95.4%). Within the BCy1 horizon, the Bmy intrusion dates back to 2809 – 2746 cal BP (85.8%), while the BCy2 broken horizon, back to 9821 – 9554 cal BP (91.0%). The coal samples within the C-horizon are more ancient than their parent material, dating back to 41,900 – 41,200 cal BP (95.4%) and 48,200 – 46,200 cal BP (95.4%).

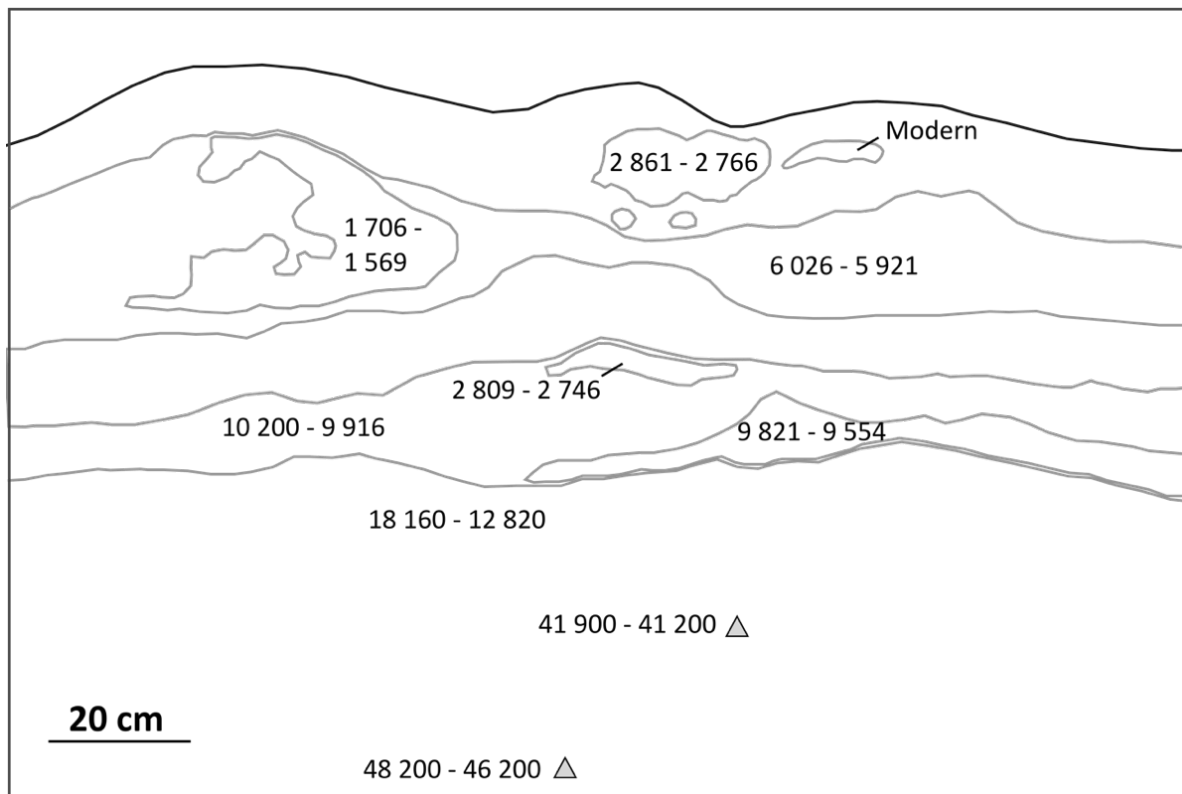


Figure 31: Radiocarbon dates in respect to soil horizons of field 11. Dates are expressed in cal BP.

6. Discussion

6.1. Hummock Distribution

Hummock fields in the Chuck Creek Trail Valley occupy mostly the valley floor, in a zone, according to the model by Bonnaventure et al. (2012), underlain by isolated patches of permafrost, except fields 12 and 13, which are situated in the sporadic discontinuous zone. Based on surface sediments, vegetation and land cover, and slope, a model of probability of hummock distribution in the valley was developed. Areas with favourable surface sediments (i.e. frost susceptible), land cover (i.e., sedges, grasses, mosses, and lichen) and slopes (i.e., $< 15^\circ$) were classified as likely to hummock development. The model concurs with the location of 13 out of 15 field sampling sites (86.6%).

Based on the model, hummocks have a high probability of covering an area of $3,086,469 \text{ m}^2$ ($\sim 3.1 \text{ km}^2$) and a more moderate probability of covering $13,221,300 \text{ m}^2$ ($\sim 13.2 \text{ km}^2$) in the Chuck Creek Trail Valley (Figure 32). However, the model is likely an over-estimate of the actual area occupied by hummock fields and is a probabilistic model that is not quantitatively assessable since it is based on unweighted descriptive thresholds. The high probability class is simply characterized by stricter thresholds than the moderate probability class. It should therefore only be considered tentative and represent a gross overview of hummock distribution within the valley.

Hummocks in the Chuck Creek Trail Valley appear to be controlled by the existence of a sufficient thickness of fine-grained frost susceptible sediment. The surficial geology component of this model is based on a large-scale map (Rampton, 1982) with a qualitative soil unit classification. Frost susceptibility is a quantitative parameter, based on silt content. A more detailed sedimentological analysis of the surficial deposits within the valley would therefore provide a more precise output, not to mention moisture content and topographic position also play a role. These factors control not only the presence and position of the hummocks within the valley, but also the morphology of the hummock fields, as discussed in the following sections.

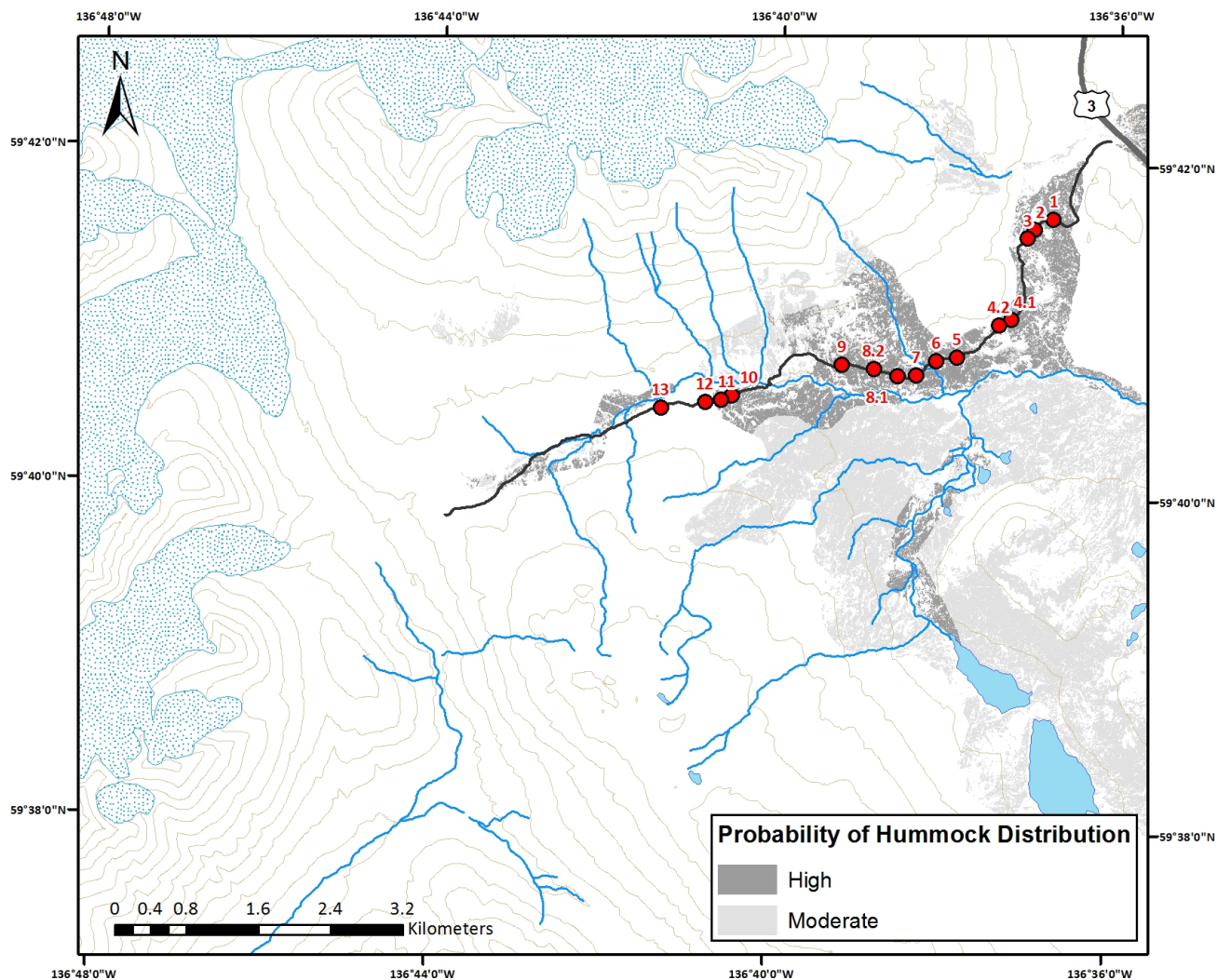


Figure 32: Map showing moderate (light grey) and high (dark grey) probability of hummock distribution within the Chuck Creek Trail Valley

6.2. Morphological, Sedimentological and Geochemical Characteristics of Hummocks

In the Chuck Creek Trail Valley, hummock diameter ranges from 25 – 155 cm and hummock height ranges from 5 – 22 cm. A Mann-Whitney *U*-test was conducted on the height (Table 5) and diameter (Table 6) measurements of the hummocks of the four studied fields (P1, P3, P8, P12) to assess if they are statistically similar with a threshold p-value of 0.05. The diameter measurements were found to be not significantly different between sites; however, the heights between sites were found to be statistically different. Therefore, there are two distinct scales of differences in hummock

morphology that need to be discussed: (1) the *inter-site variability* (ex: sub-Arctic vs. Arctic environments) and (2) the *inter-field variability* in the Chuck Creek Trail Valley.

First of all, the dimensions of hummocks in the valley are significantly smaller to those found elsewhere in permafrost regions of Arctic and sub-Arctic Canada. For example, in the western sub-Arctic near Willowlake River, hummocks measuring up to 440 cm were found, averaging at 320 cm (Tarnocai and Zoltai, 1978). In the Mackenzie Valley (sub-Arctic), hummock diameter ranged from 110 – 160 m and their height ranged from 40 – 78 cm (Tarnocai and Zoltai, 1978). In the central Arctic, the diameter of hummock averaged at 117 cm, ranging from 80 – 140 cm and the height of hummock varied between 22 – 40 cm (Tarnocai and Zoltai, 1978).

The dimensions of the hummocks in the valley are more similar to those in regions of seasonal frost. Grab (2005) suggested that high-latitude regions produce larger hummocks than mid-latitude alpine regions where permafrost is absent and the ground thermal regime would dictate the size of hummocks. In the Drakensberg, southern Africa, hummocks size ranged from 7 – 37 cm in height, averaging 18 cm, and from 20 – 98 cm in diameter, averaging 49 cm (Grab, 1994). Slightly larger sized hummocks were measured in England (Killinbeck and Ballantyne, 2012) and in Japan (Ogata, 2007). The overall distribution of hummocks in England had a median value of 114 cm in diameter and a 15 cm height (Figure 33), whereas in Japan hummocks had a mean value ranging between 54.8 – 60.5 cm for diameter and between 30.6 – 35.1 cm for height (Figure 33). It has been hypothesised that smaller hummocks in seasonal frost regions may reflect the brief freezing period that permits only shallow frost penetration (Grab, 1994). The resemblance between the morphology of the hummocks of the Chuck Creek Trail Valley and those found in regions of seasonal frost suggests that the morphology of the hummocks in the Chuck Creek Trail Valley may not be influenced directly by the permafrost table, which was not encountered up to depths of 1.5 m.

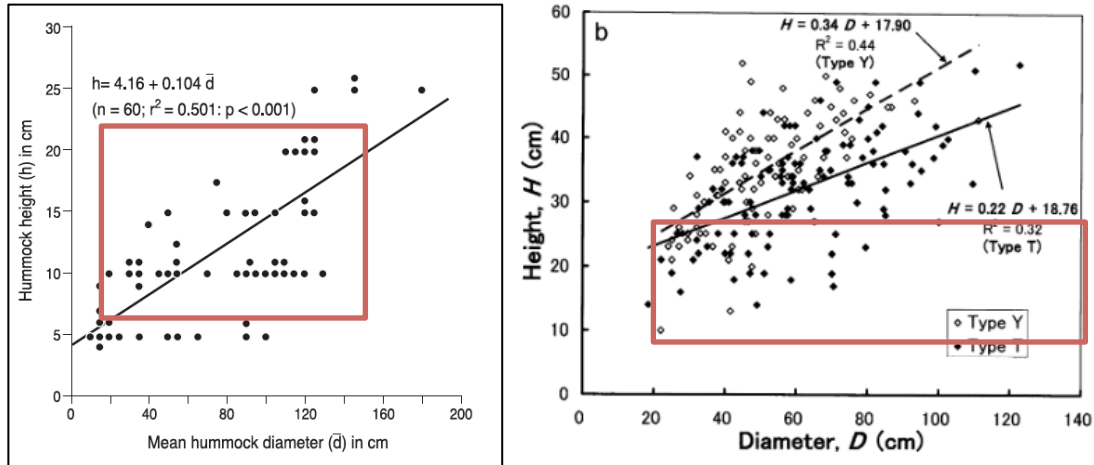


Figure 33: Relationship between hummock height and hummock diameter for (A) a sample of 60 hummocks surveyed along transects in West Dartmoor, SW England (Killinbeck and Ballantyne, 2012) and (B) a sample of 205 hummocks surveyed along transects in the Nemuro Peninsula, northern Japan (Ogata, 2007). Hummock distribution range in the Chuck Creek Trail Valley represented in red box.

Besides permafrost, many studies have found other local physiographic factors to have important control on hummock morphology. For example, slope does not favour hummock development as the downslope movement of soil elongates hummocks on slopes (e.g., Ballantyne 1986, Krantz et al. 1988; Ballantyne and Harris, 1994; Mark, 1994). In addition, hydrological factors seem to control the hummock spacing. Hummock formation likely requires a shallow water table, that results from imperfectly drained ground, to enable effective frost heave and cryoturbation (Van Vliet-Lanoë, 1998). Grab (1994)'s hummocks were more closely-spaced in shallow water-table areas than in areas with deeper water tables. Ogata (2007) found a similar trend regarding hummock spacing and changes in the hydrological environment. In the Chuck Creek Trail Valley, no distinction in spacing was found between sites, implying that the water table and soil drainage is not significantly different within the hummock fields of the valley.

The significant differences between the heights of hummocks within this study are therefore a product of other field properties. The possible sedimentological controls on hummock morphology in Chuck Creek Trail Valley were investigated with a principle component and a multiple regression analyses. The PCA analysis indicates that the

greatest loading in the first principal component (which is accountable for 49.8% variance) is attributed to hummock diameter, closely followed by silt and height, all of which are positively correlated, although the silt arrow is positioned slightly below the 0 x-axis (Figure 34). This anomaly could be explained by the silt component having a weak loading for PC2 and being more dominant in PC4. Field 12 is predominant in the height, diameter and silt components, but also slightly more dominant in the depth component (which is only due to the fact that the cores at field 12 attained greater depth). Moisture and organics parameters seem to slightly favour the P12 group, but are overall in conjunction with all groups, suggesting no or little difference between the groups. Fields 1 and 3 seem to overlap meaning their components are not significantly different. The moisture and organics parameters are positively correlated, but negatively correlated to depth, suggesting that as depth increases, moisture and organics content decrease. These relations are expected given that moisture and organic matter content are typically higher near ground surface. Kaiser et al. (2007) also found moisture soil content to generally decrease with depth. Biasi et al. (2005) and Main (2016)'s hummocks displayed significantly higher moisture contents within hummock troughs than for hummock tops. Similarly, in this study, surficial moisture was higher in the hummock troughs than on the hummock tops (Figure 23). This is likely due to the surface morphology of the hummocks, which favours drainage at the surface from the hummock top towards the lowered hummock trough. Hummocks examined by Tarnocai and Zoltai (1978) displayed very homogeneous moisture content at depth. This is also the case for the hummocks of this study, which also experience minimal variance beyond the first 20 cm.

According to the multiple regression analysis (Figure 35), the height and diameter show a distinct correlation of $r^2=0.92$. However, this analysis is based on mean values for each field, limiting the input of outlying values in the initial distribution. The silt content correlates strongly with the morphological parameters (i.e. height and diameter). The moisture and organics parameters are also strongly correlated with an r^2 value of 0.96. Soil moisture strongly influences soil carbon storage, but also indirectly

alters soil thermal and hydraulic properties (Falloon et al., 2011). Thus, soil moisture content is an important parameter in understanding cryoturbation, but also subsequent carbon cycling, which is explored in the following section.

In the Chuck Creek Trail Valley, silty-loam soils were predominant at the study sites, indicating high frost susceptibility and potential for cryoturbation. Within the different sites, field 12 had the highest silt content and also showed the most rounded and overall largest hummocks. According to the statistical analyses, hummock morphology is dependant on sedimentological properties. Silt content is therefore the principal component explaining inter-field morphological differences within the Chuck Creek Trail Valley.

However, the inter-site variability and the effects of global-scale environmental factors are not fully understood. The morphology of the hummocks of the Chuck Creek Trail Valley is more similar to hummocks found in regions of seasonal frost than those found elsewhere in Arctic and sub-Arctic Canada. Therefore, the deep permafrost table (at more than 1.5 m) in the Chuck Creek Trail Valley may suggest shallow frost penetration resulting in smaller hummocks, as encountered in seasonal frost areas. The inter-site differences in hummock morphology may therefore be explained by ground thermal regimes, as suggested by Grab (2005). A more complete statistical analysis, implicating climatic, sedimentological, hydrological and micro-topographical parameters would be required to explain the differences in hummock morphology between sites, which is outside the scope of this project.

Table 5: Mann-Whitney U test comparison of the width of hummocks. P-values are presented above the diagonal; bold values represent significant differences (p-value < 0.05) in width measurements. W values are presented below the diagonal.

	P1	P3	P8	P12
P1	-	0.720	0.936	0.547
P3	879	-	0.814	0.337
P8	366	363	-	0.574
P12	660	660	293	-

Table 6: Mann-Whitney U test comparison of the height of hummocks. P-values are presented above the diagonal; bold values represent significant differences (p-value < 0.05) in height measurements. W values are presented below the diagonal.

	P1	P3	P8	P12
P1	-	0.447	0.021	0.006
P3	758	-	0.008	0.073
P8	495	540	-	1.43e-5
P12	459	578	89	-

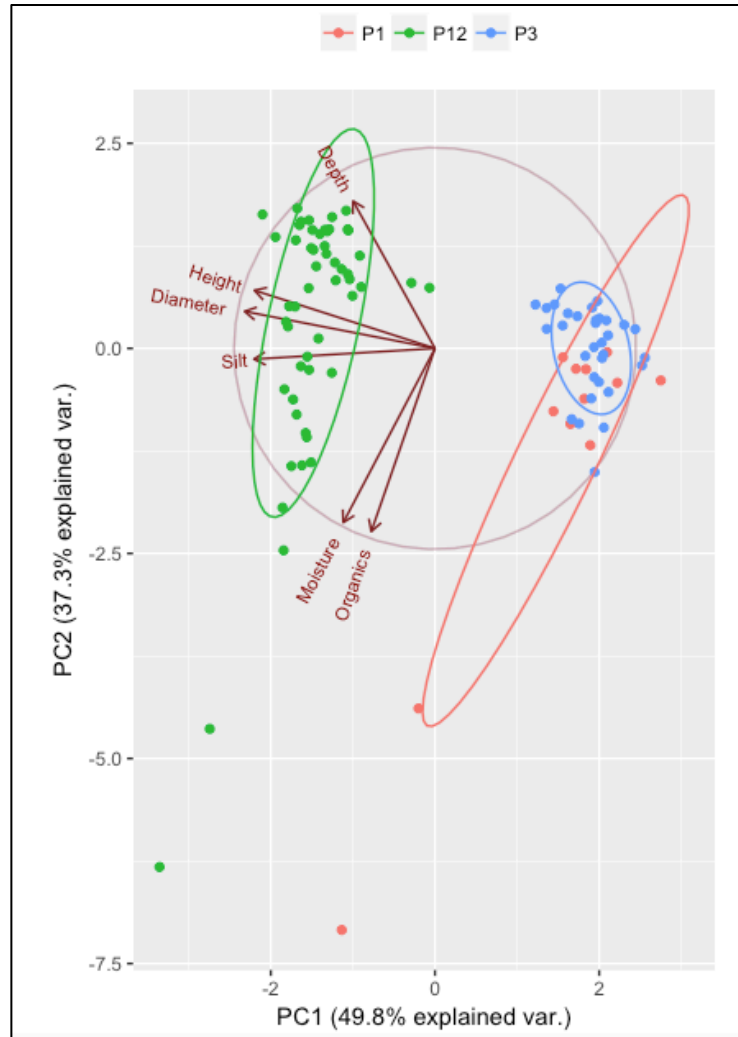


Figure 34: Biplot of the (scaled) first two principal components of the PCA analysis on P1, P3 and P12 hummock fields

Table 7: The loadings from the principal components of all samples and variables at the study sites

	PC1	PC2	PC3	PC4	PC5	PC6
Silt	-0.520	-0.036	-0.202	-0.803	0.202	0.040
Moisture	-0.264	-0.580	0.228	0.129	0.101	-0.718
Organics	-0.183	-0.609	0.361	0.067	-0.089	0.672
Depth	-0.236	0.490	0.832	-0.086	-0.017	-0.062
Diameter	-0.548	0.123	-0.224	0.211	-0.767	-0.040
Height	-0.519	0.193	-0.182	0.532	0.593	0.156
Standard deviation	1.729	1.497	0.651	0.509	0.250	0.162
Proportion of Variance	0.498	0.373	0.071	0.043	0.010	0.004
Cummulative Proportion	0.498	0.871	0.942	0.985	0.996	1.000

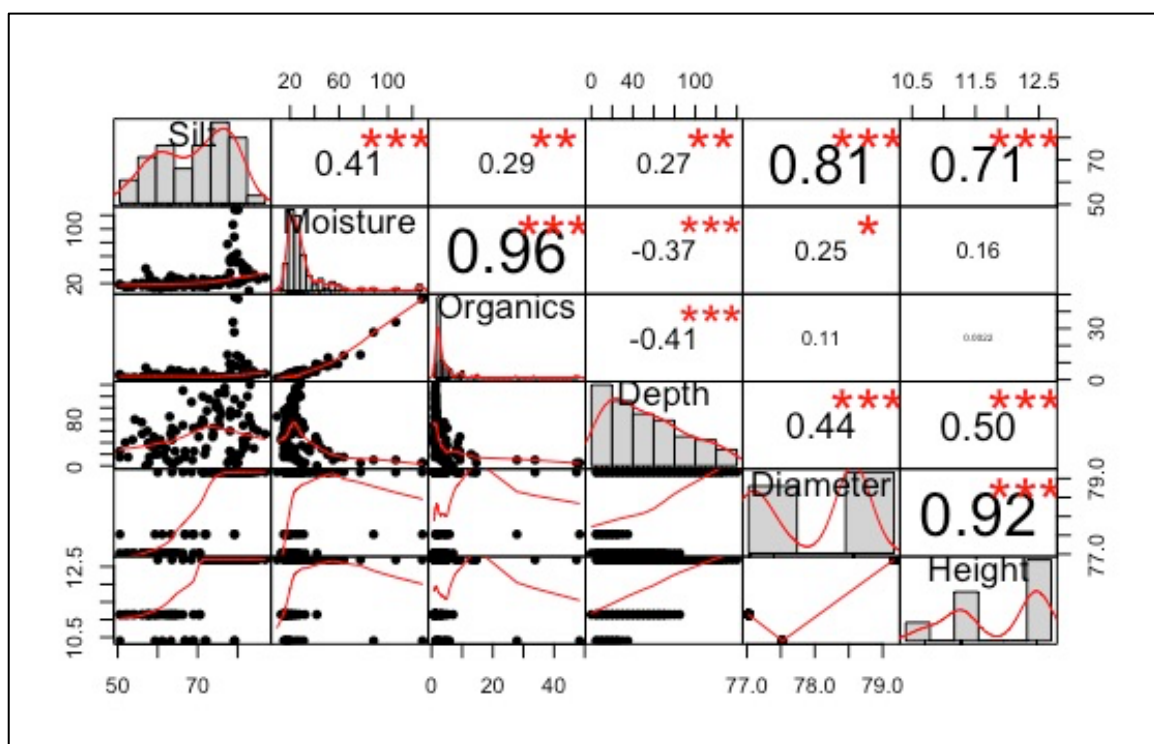


Figure 35: Multiple regression analysis performed on the silt, moisture, organics, depth, diameter and height parameters on the P1, P3 and P12 hummock fields

Table 8: Correlation matrix for the multiple regression analysis

	Silt	Moisture	Organics	Depth	Diameter	Height
Silt	1.0	0.41	0.29	0.27	0.81	0.71
Moisture	-	1.0	0.96	-0.37	0.25	0.16
Organics	-	-	1.0	-0.41	0.11	0.00
Depth	-	-	-	1.0	0.44	0.50
Diameter	-	-	-	-	1.0	0.92
Height	-	-	-	-	-	1.0

6.3. Carbon Stock, Stable Carbon Isotopes and Effects of Cryoturbation in Hummocks

One of the main objectives of this thesis is to understand geochemical parameters within hummocks, leading to a more comprehensive overview of soil organic carbon. In general, older or highly degraded soil organic matter has lower C:N ratio than younger, less degraded, soil organic matter (Ping et al., 1998). This is due to

the loss of CO₂ during degradation of organic matter. In Biasi et al (2005)'s hummocks, C and N contents appeared to be higher within hummock trough than within hummock tops, but no significant differences were observed for C:N ratios. The C:N ratios of the Chuck Creek Trail Valley also displayed similar trends in the hummock trough and hummock top cores, except for a few peaks at depth. These peaks may be associated with allochthonous coal fragments within the C-horizon, composed of till, as observed in the field 11 cross-section. Coal C:N ratio is usually approximately 100 (Campbell and Claridge, 1987).

Hummock fields of the Chuck Creek Trail Valley have an average SOCC for a 1 m pedon of 16.3 kg/m². The first depth interval (0 – 25 cm) contained an average of 10.2 kg/m², the second depth interval (25 – 50 cm), 2.7 kg/m², the third depth interval (50 – 75 cm), 2.1 kg/m² and the fourth depth interval (75 – 100 cm), 1.3 kg/m². The depth interval beyond 1 m (100 – 125 cm) contained slightly more SOCC than the overlying interval, 1.5 kg/m² (Figure 36). Zubrzycki et al. (2013) found the overall SOCC estimated for a reference depth of 1m for their study to be approximately 25.7 kg/m². Johnson et al. (2011) found the Alaska Range Transition zone, which is similar to the study site ecozone, to have an SOCC for a 1 m pedon of approximately 210 Mg/ha, which is approximately 23.15 kg/m². Tarnocai et al. (2009)'s large-scale study of soil organic pools in the circumpolar permafrost regions found Turbels to have an average of 32.2 kg/m², ranging from 1 – 126 kg/m². Overall, the value found at the Chuck Creek Trail Valley is therefore slightly smaller than average, but still within the range of other studies.

The present study found that for field 11, the SOCC averaged at 3.53 kg/m², 38% situated in the B-horizon (Figure 37). Kaiser et al. (2007) found the amount of carbon stored in the whole active layer of cryoturbated soil to average 13.5 kg/m², from which approximately 50% was situated in the B-horizon. Using equation [7] and multiplying the resulting SOCC by the area occupied by hummocks in the Chuck Creek Trail Valley (Section 6.1) enables the calculation of Soil Carbon Mass (SOCM). Hummocks fields

contain 0.05 Pg using the high probability model and 0.2 Pg using the moderate probability model for a 1 m pedon (0-100 cm depth).

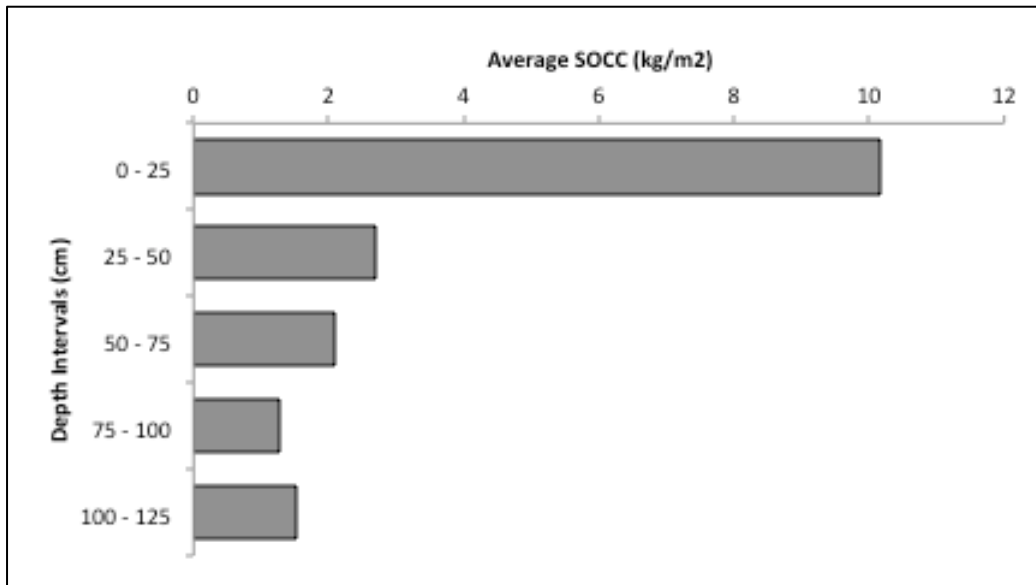


Figure 36: Average SOCC in respect to depth intervals: from 0-25 cm (n=6), from 25-50 cm (n=4), from 50-75 (n=4), from 75-100 cm (n=2) and from 100-125 (n=2)

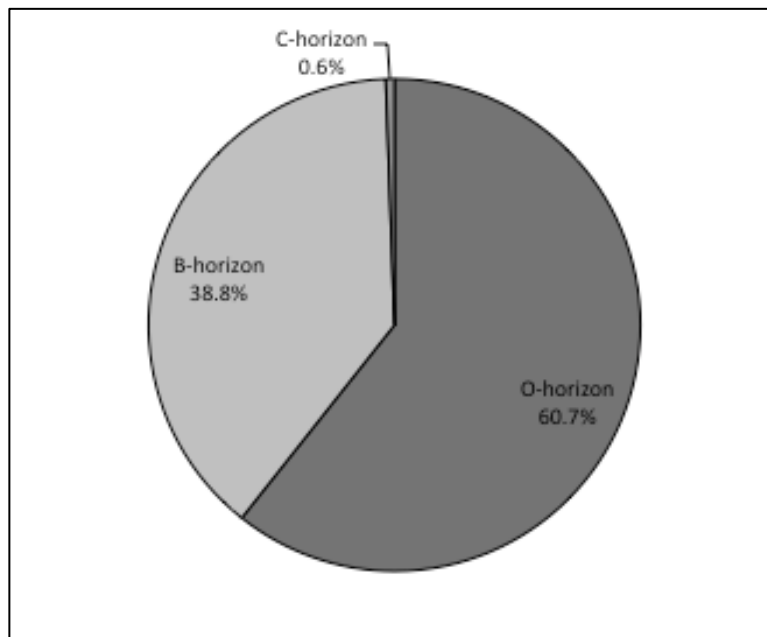


Figure 37: Distribution of SOC along different soil horizons in hummock field 11

Regarding carbon stable isotopes, the $\delta^{13}\text{C}$ signal of plants depends on the ratio of leaf-internal to external CO_2 concentration, which is dictated by stomatal conductance and carboxylation efficiency (Von Caemmerer and Farguhar, 1981). $\delta^{13}\text{C}$ values of plants is, in simple terms, highly dependent on the preferential consumption of ^{12}C versus ^{13}C (Farquhar et al., 1980). The more negative the ratio, the less ^{13}C there is. There are three biochemical pathways of carbon acquisition used by plants leading to three distinct groups: C3 plants, C4 plants and CAM plants (Keeley, 1991). Carbon isotopic ratios are a good indicator of the photosynthetic pathway at use, and consequently of the plant group in question (Keeley, 1991).

In terrestrial plants, carbon isotopes ratios vary from -20 to -35 per mil in C3 plants and from -8 to -15 per mil in C4 plants (Keeley, 1991). CAM plants may range from C4-like to C3-like ratios. Preferential uptake of the lighter CO_2 justifies why plant $\delta^{13}\text{C}$ values are lower than those of the surrounding air. C3 plants sustain a more pronounced discrimination against carbon 13, although the main difference in carbon isotope ratio results from the carbon fixation processes (Keeley, 1991). The results of this experiment clearly show that $\delta^{13}\text{C}$ values rise with depth. With surface values ranging from -28.71 to -25.69 per mil, the soil samples evidently belong to the C3 plant group, which is often the case for alpine plants (Korner et al., 2016). Jelinski et al. (2017) found similar $\delta^{13}\text{C}$ values averaging -25.9 per mil and becoming more enriched with depth (less negative).

Within soils, $\delta^{13}\text{C}$ values are initially directly related to their respective plant groups. However, the increasing values with depth may be explained by the three processes: (1) Suess effect (global phenomenon, which describes the decrease in $\delta^{13}\text{C}$ values in atmospheric CO_2 due to fossil burning) (2) Differential loss of components with different isotope ratios, (3) Progressive ^{13}C -enrichment of SOM due to respiratory loss of ^{12}C -enriched CO_2 (e.g., Keeling, 1979; Cerling and Quade, 1993; Boström et al., 2007). The last factor is often considered the most important: $\delta^{13}\text{C}$ values at surface are more related to the atmospheric ratios, whereas deeper soils reflect the respiration processes (Cerling and Quade, 1993). Typically, the differential loss component is considered

minimal since most carbon gets digested by microbes, leaving minimal carbon in deeper SOM. However, cryoturbation could lead to disruption in the regular microbial regime. This can be observed in the field 11 cross-section, where the $\delta^{13}\text{C}$ values of the cryoturbated horizons differ from the parent horizon: the Bghy1 horizon is greater (less negative) than the parent horizon while the Bghy2 horizon is smaller (more negative) than the parent horizon. The Bghy2 horizon having similar $\delta^{13}\text{C}$ values to that of the surface horizon may suggest that the deep SOM is cryoturbated from the surface, as observed by Xu et al. (2009). It is also visible in the profiles of Figure 29, where local peaks of $\delta^{13}\text{C}$ values could represent cryoturbated horizons with more degraded material than the parent horizons. The difference in the alignment of peaks within hummock tops and troughs could be due to sampling heterogeneity but are most likely due to the microtopography (profiles are aligned in respect to surface, instead of actual spatial positioning).

As previously discussed, cryoturbation causes soil horizons to be warped, broken or discontinuous, resulting in a redistribution of carbon stores (Ping et al., 1998). Complicated patterns of redistribution, migration, accumulation and cryoconservation of SOM are implemented during pedogenesis (Lupachev et al., 2017). These processes disturb the paragenetic connection of soil horizons and can lead to the alteration of soil profiles (Lupachev et al., 2017). The potential alteration of SOM, under changing climate conditions, is highly dependant on its stabilization. Understanding the composition and quality of SOM and SOC contained in cryoturbated material is therefore very important. Cryoturbated organic material is typically kept within mineral horizons, where it remains relatively stable in a low temperature regime, with a lack of free oxygen and low microbial activity (Lupachev et al., 2017). Many studies have observed intrusions of organic matter within hummock tops (e.g., Dyke and Zoltai, 1980; Kokelj et al. 2007; Main, 2016). Most of these intrusions were found within mineral soil horizons at varying depths. Within the field 11 cross-section, organic-rich intrusions were observed, providing evidence for cryoturbation. These intrusions were found from depths of 5 – 35 cm, mostly within the B-horizons, although present within the O-horizon.

The cryoturbated horizons that are incorporated in the Omy horizon, Bgy and Bghy1, display a lower C:N ratio and greater (more positive) $\delta^{13}\text{C}$ values. This would suggest that the horizons are incorporated from older or more degraded horizons. On the opposite side, the Bhgy2 and Bmy horizons display greater C:N ratios (except for Bmy, which displays a lower C:N ratio) and smaller (more negative) $\delta^{13}\text{C}$ values than their parent material, suggesting that they are composed of younger and less degraded SOM. This would concur with the ^{14}C dates.

6.4. Age of Cryoturbated Material and Rate of Soil Movement

Determining the exact age of a hummock can be challenging since radiocarbon dates do not necessarily indicate neither the time at which cryoturbation took place nor the time at which hummock development began (Tarnocai and Zoltai, 1978). Based on the premise that the oldest cryoturbation date may provide an estimate for the initiation of hummock formation, it could be inferred that the process in the Chuck Creek Trail Valley initiated around 2 800 cal BP. However, it is important to take into consideration that the buried organic material would have had a certain residence time prior to burial, with the modern organic horizon being around 20 cm thick (Scharpenseel and Schiffmann, 1977). This would mean that the resulting ^{14}C age would be greater than the burial event. Since it is very difficult to estimate the apparent mean residence time (AMRT), there has been a great deal of controversy over using radiocarbon dating for interpreting soil movement.

Interpretation of the radiocarbon dates at the field 11 can therefore only be tentative. The logical sequence of events would be: (1) The Chuck Creek Trail Valley was glaciated between 24 000 yr BP to ca. 10 000 yr BP by the Cordilleran Ice Sheet (Jackson et al., 1991), (2) Following deglaciation, the C-horizon, composed of glacial till (including allochthonous coal fragments) was deposited between 18 160 - 12 820 cal BP, (3) A succession of soil horizons subsequently formed between 10 200 and 5 921 cal BP (BCy1, BCy2, Bg and Bmgy in order), (4) Around 2 800 cal BP, cryoturbation became more dominant and soil intrusions occurred until around 1 500 cal BP, trapping layers Bmy and Bghy2 within older soil horizons in place and (5) Cryoturbation processes seem

to remain active during the modern period with soil intrusion, Bghy1 and Bgy, within the modern organic layer.

The study conducted by Tarnocai and Zoltai (1978) also found the average uncalibrated age to be approximately 2700 ^{14}C yr BP, with the oldest date being 11 200 ^{14}C yr BP. The study did not identify any morphological and pedogenic difference between relatively young (2 400 ^{14}C yr BP) and much older hummock (8 780 ^{14}C yr BP) dated at nearby sites (Tarnocai and Zoltai, 1978). Pettapiece and Zoltai (1974) also dated subsurface organic material that ranged from 1500 to 3200 ^{14}C yr BP. Similar dates were also found in Leirdalen, Norway, where the hummocks would have been in early stages around 1200 – 3000 cal BP (Ellis, 1983). Jelinski et al. (2017) also measured dates of 1860 – 1990 cal BP and 2350 – 2680 cal BP, converging with other subducted material in non-sorted circles. Main (2016) also found similar dates for the hummocks at Rengleng River, though many inconsistencies occurred in her date series. A study conducted by Kaiser et al. (2007) in Siberia cryosols also revealed substantially older radiocarbon dates within cryoturbated horizons (800 cal AD) than parent horizons (1640 cal AD), suggesting that decomposition processes were delayed.

Although the physical and chemical characterisation of cryoturbated material is well established, the empirical quantification of rates of material displacement has been scarcely studied (Jelinski et al., 2017). Many studies (e.g., Zoltai, 1975; Mackay and Mackay, 1976; Tarnocai and Zoltai, 1978) indicate that earth hummocks in the Canadian Arctic and sub-Arctic have been relatively stable features in the past decades. However, these observations remain mostly qualitative.

In order to quantify soil movement, Dyke and Zoltai (1980) used radiocarbon dating to calculate subduction rates by dividing dates with depth. Their study estimated subduction rates ranging between 0.44 mm/yr to 0.92 mm/yr. Klaminder et al. (2014) found subduction rates to be considerably higher, at approximately 0.01 cm/yr. Main (2016) found displacement rates to be between 0.16 mm/yr to 0.43 mm/yr. Using the same calculation of depth divided by time, the present study displays subduction rates ranging between 0.03 mm/yr to 0.10 mm/yr, which is significantly smaller than other

sites. However, this result does not take into consideration the lateral movement required for the formation of patterned grounds. A study led by Jelinski et al. (2017) provided unique empirical insights into different aspects of material movement, using multiple radionuclides and elemental tracers. By using a compilation of published material involving non-sorted and sorted circles their study exposes a more holistic approach of soil movement by including four types of movements: centre upward movement, surficial lateral movement, subduction/subsurface movement and surface exposure history (Jelinski et al., 2017). This approach may lead to a more complete understanding of hummock genesis discussed in the following section.

6.5. Hypotheses of Hummock Formation

As discussed in Chapter 2, many distinct hypotheses of earth hummocks formation have been proposed, most of which relate to freezing and thawing of frost susceptible soil (Grab, 2005). The characteristics of the hummocks within the Chuck Creek Trail Valley are incompatible with most of these hypotheses. The cryoexpulsion of clast model, where updoming of soil occurs above frost-heaved boulders (Harris and Matthews, 1984; Hanvey and Marker, 1992; Van Vliet-Lanoë and Seppälä, 2002), can be ruled out from the absence of boulders within hummocks of this study. All hypotheses that explicitly require a permafrost table can also be discounted, as no permafrost table was observed in the field, up to depths of 1.5 m. This includes: cryostatic pressure operating in pockets of saturated unfrozen soil during freezing of the active layer (Lundqvist, 1969; Crampton, 1977; Tarnocai and Zoltai, 1978, Gerrard, 1992), circulatory movement of soil during active layer thaw (Mackay, 1980) and permafrost aggradation (Kokelj et al., 2007). The lack of evidence for soil injection within the excavated soil hummocks also excludes the hypothesis proposed by Van Vliet-Lanoë to explain thufur development in Iceland (1998). All hypotheses requiring peat (Billings and Mooney, 1959, Seppälä, 1988) can also be ruled out since the hummocks of the Chuck Creek Trail Valley are composed of mineral material. Any formation by slopewash (Bennett et al., 1996) or by selective erosion (Ballantyne, 1986) can also be ruled out since the hummock fields occur on level ground.

Only the differential frost heave model (Van Vliet-Lanoë, 1991) seems to be consistent with field evidence. It is applicable to patterned grounds occurring both outside the permafrost zones as in well-drained permafrost sites (Van Vliet-Lanoë, 1991). Numerical models have shown that within moist silty soils, a uniform one-dimensional frost heave develops into a laterally non-uniform heave with a wavelength dependant on local conditions (soil texture, freezing regime and moisture content) (Peterson and Krantz, 2003). Peterson and Krantz (2003) found that differential frost heave is favoured by silt-rich soil, small non-uniform surface heat transfer and abundant moisture to feed the growth of ice lenses, all of which are applicable to the Chuck Creek Trail Valley. Local liquefaction, differential swelling, refreezing ice, and possibly load casting, could also interact positively on differential frost heaving, though they are not the leading processes in all hummock fields (Van Vliet-Lanoë, 1991). The differential frost heave model would allow the local environmental parameters such as texture, drainage and vegetation, and their variation throughout the climatic and sedimentological evolution of each site, to explain the wide range of patterned grounds and morphologies (Van Vliet-Lanoë, 1991). As discussed in the previous sections, silt content (and possibly drainage) dictates hummock size and spacing, supporting the finding that the modal wavelength of differential frost heave depends on initial boundary parameters and conditions (Peterson and Krantz, 2003).

6.6. Climatic Implications

Numerous studies have described cryoturbation features and their relation with Holocene climate variations (e.g., Zoltai et al., 1978; Scotter and Zoltai, 1982; Van Vliet-Lanoë, 1998). Although not calibrated as the dates of the present study, the results from other studies regarding radiocarbon dating can still be used for relative comparison of climatic changes in their respective environments. Tarnocai and Zoltai (1978) found the majority of the dates for buried organic material to be less than 5000 ^{14}C yr BP, with a relatively high cluster of dates from 3000 to 3500 ^{14}C yr BP (Tarnocai and Zoltai, 1978). As climatic conditions became colder in northern Canada around 5000 ^{14}C yr BP, Tarnocai and Zoltai assumed hummocks probably developed in this area between 5000

and 3000 ^{14}C BP (Tarnocai and Zoltai, 1978). Scotter and Zoltai (1982) came to similar conclusions about hummocks in the Sunshine Area of the Rocky Mountains, which are now only present in relict form; implying the need for cooler conditions for hummock formation to be initiated.

However, many other studies suggest that cryoturbation was particularly active during mid-Holocene warming periods in the Arctic. In a study in Abisko, northern Sweden, Becher et al. (2013) measured radiocarbon dates using 12 buried organic horizons in non-sorted circles. Bockheim (2007) compiled published ages from organic inclusions beneath patterned ground in North America. Both studies concluded that the ages of buried organic material coincided loosely with periods of climatic warming (Table 9). They both hypothesized that moderate warming could lead to an increase in cryoturbation activity. Jellinski et al. (2017) found dates of cryoturbated parcels to roughly coincide with the inferred warming period in Scandinavia (based on reconstructions of glacial advances) (Becher et al., 2013). In the Chuck Creek Trail Valley, a cluster of radiocarbon dates around 2000 cal BP for cryoturbated intrusions would coincide with a period of cooling (Viau et al., 2008) and a westward shift and weakening of the Aleutian Low (Anderson et al., 2005) (Figure 38). However, the initiation of hummock development and cryoturbation climax activity may not require the same climatic implications. In other words, different environments could behave differently to climatic cooling or warming depending on their thermal regimes pre-sets.

Using cryoturbation intrusions as an indicator of paleoclimate may only be tentative. Not only are radiocarbon dates of soil organic matter widely controversial (as discussed in section 6.4) but changes in climate also have consequences on cryoturbation rates, which have been only scarcely studied. However, rising temperatures in the Arctic and sub-Arctic will affect soil thermal regime and therefore soil organic matter decomposition by increasing plant primary production and thus the input of plant-derived organic compounds into the soil (Wild et al., 2014). The allocation of such compounds can alter the decomposition of older SOM. In an experiment conducted by Wild et al. (2014), with a slight increase in temperature, SOM

decomposition rates increased by a factor of two or three in the mineral subsoil horizons and by two in the cryoturbated horizons. Therefore, even if the effects of climatic warming on cryoturbation or not fully understood, it is widely accepted that it will affect soil carbon cycling.

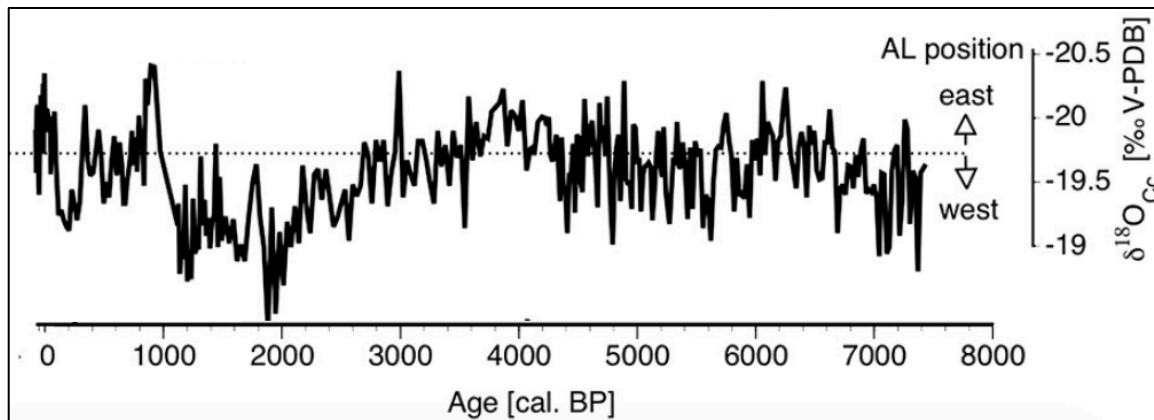


Figure 38: Jelly bean Lake $\delta^{18}\text{O}$ Holocene record with Aleutian Low reconstruction. Derived from Clegg and Sheng Hu (2010) and Anderson et al. (2005)

Table 9: Compiled data of age in ^{14}C yr and proposed climate during periods of active cryoturbation (Bockheim, 2007)

Area	Event	Timing	Change in climate	Reference
		^{14}C yr		
Swedish Lapland	increased cryoturbation	7800–7580, 6300–4080, 2450–2000, 1170–740	warming	Hormes et al. (2004)
Bylot Island, NWT	increased ice-wedge polygon growth and cryoturbation	1230–240	warming	Fortier and Allard (2004)
Finnish Lapland	increased earth hummock growth and cryoturbation	1000–330	cooling	van Vliet-Lanoë and Seppala (2002)
Arctic, subarctic Canada	increased earth hummock growth and cryoturbation	3500–1000	cooling	Zoltai et al. (1978)
North Slope Alaska, USA	high peat accumulation rate, increased cryoturbation	6900–4800	warming	Marion and Oechel (1993)
Svalbard	increased earth hummock growth, cryoturbation, patterned ground formation	6000–4500, 1000–550	cooling	van Vliet-Lanoë (1998)
Mayo, Yukon Territory, Canada	thaw-lake unconformity, permafrost aggradation	8870	warming	Burn et al. (1986)
Tuktoyaktuk, Canada		10,000–8000	warming	Burn (1997)

7. Conclusions and future work

Earth hummocks have been largely documented since the 1950s. The interest in their research can be explained by the variable conditions in which they occur and by their widespread presence in both permafrost and seasonally frozen regions (Grab, 2005). A number of environmental parameters required for hummock formation, such as the necessity for frost susceptible sediments, prolonged seasonal freeze and moisture availability have been largely studied and confirmed by this study. The Chuck Creek Trail Valley offered a great study site to understand the factors implicated in hummock distribution since the presence of hummocks is sporadic and displays different morphologies. This study also provided additional knowledge regarding the distribution of organic carbon and type of carbon within hummocks and, rate of soil movement within the landform. The main findings of this study can be listed as:

1. Hummocks occur sporadically in the Chuck Creek Trail Valley, in sporadic to discontinuous permafrost and in frost susceptible sediments.
2. The hummocks of the Chuck Creek Trail Valley exhibit a positive relation between height, diameter and silt content. The size of the hummock is comparable to that of hummocks in mid-latitudes and seasonal frost regions, but the morphological differences in the valley seem to be dictated by the silt content within the soil.
3. Hummock fields of the Chuck Creek Trail Valley have an average SOCC for a 1 m pedon of 16.3 kg/m^2 , 38 % situated in the B-horizon. For this pedon, hummocks fields contain 0.05 Pg using the high probability model and 0.2 Pg using the moderate probability model in the Chuck Creek Trail Valley.
4. The present study displays subduction rates ranging between 0.03 mm/yr to 0.10 mm/yr.
5. The differential frost heave model (Van Vliet-Lanoë, 1991) is the only hypothesis for hummock formation consistent with field evidence in the Chuck Creek Trail Valley.

6. In the Chuck Creek Trail Valley, a cluster of radiocarbon dates around 2000 cal BP for cryoturbated intrusions would coincide with a period of cooling (Viau et al., 2008).

However, other factors regarding the distribution, morphology, genesis, maintenance and degradation of hummocks remain to be researched. There are still large gaps in scientific knowledge regarding cryoturbation processes. Additionally, studies of hummocks in North America are mainly limited to the western Canadian Arctic: hummocks in sub-Arctic Canadian environments have never been extensively studied, along with those occurring in alpine areas.

Larger-scale studies may be a key to improving our understanding of the processes operating on morphologically similar landforms in dissimilar conditions and environments. As proposed by this study, the application of remote sensing and/or aerial photographs or UAV flights could be utilized to quantify the hummocky terrain across the region. Limited coring has been done on hummocky terrain and as demonstrated by the results of this study, large variations occur across small distances. Additional coring would better explain the variability of the results obtained in the context of this study.

Research in the dynamics of periglacial processes and their trends in the near future will become more important with the changing climate. Cryogenic and periglacial processes affect slope movements, soil formation and degree of hazards at construction and operation of large engineering work (Kalvoda, 2005). The results of this work are also significant in the in the context of climate change and potential sequestration of organic carbon in cryosols.

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Appendix 1: Radiocarbon Results

Appendix 1A: Radiocarbon results. Calibration was performed using OxCal v4.2.4 (Bronk Ramsey, 2009) and the IntCal13 calibration curve (Reimer et al., 2013). Material codes are described in Crann et al. (2016).

Lab ID	Submitter ID	Material	Material Code	14 C yr BP	±	F14C	±	Cal BP
Coal 1	UOC-3823	Charcoal	AAA	36898	194	0.0100	0.0002	41900 – 41200 (95.4%)
Coal 2	UOC-3824	Charcoal	AAA	44003	372	0.0042	0.0002	48200 – 46200 (95.4%)
Bghy2	UOC-3825	Bulk Sediment	A	1733	26	0.8059	0.0026	1706 – 1569 (95.4%)
Bghy1	UOC-3826	Bulk Sediment	A	2722	24	0.7126	0.0021	2861–2766 (95.4%)
Bmgy	UOC-3827	Bulk Sediment	A	5243	29	0.5207	0.0019	6176 – 6152 (6.5%) 6117 – 6077 (12.6%) 6065 – 5921 (73.7%)
BCy1	UOC-3828	Bulk Sediment	A	8929	36	0.3290	0.0015	10200 – 9916 (95.4%)
C	UOC-3829	Bulk Sediment	A	14786	52	0.1587	0.0010	18167 – 17820 (95.4%)
Bgy	UOC-3830	Bulk Sediment	A	Modern	22	1.1018	0.0031	*AD1957 or AD1996 – 2000
BCy2	UOC-3831	Bulk Sediment	A	7826	33	0.3775	0.0016	9821 – 9554 (91.0%)
Bmy	UOC-3832	Bulk Sediment	A	2667	26	0.7175	0.0023	2844 – 2816 (9.6%) 2809 – 2746 (85.8%)

* Calibrated using the post-bomb NH1 curve (Hua et al., 2013)

Appendix 1B: Calibration Plots

