A Characterization of the Vegetation Communities of Three Retrogressive Thaw Slumps on Herschel Island, Yukon Territory, Canada

by

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ABSRACT

Since vegetation exerts strong controls on local ecosystem processes, understanding the effects of disturbance on short-term and long-term revegetation patterns is a critical component of understanding the effects of climate change on the Arctic. Arctic landscapes underlain by massive ground ice and ice-rich permafrost are inherently unstable and often display evidence of past and present thaw subsidence. Retrogressive thaw slumps are permafrost thaw features which are progressively backwasting and tend to go through cycles of activity, resulting in dramatic changes to the landscape. The cyclic pattern of disturbance and stabilization related to these thaw slumps results in a patchy tundra landscape where there are easily identifiable geomorphic units reflecting the stage of stabilization and the time since disturbance. This thesis describes the vegetation and soil characteristic of these geomorphic units for three active, polycyclic retrogressive thaw slumps on Herschel Island, YT. Four geomorphic units were defined for each slump, and 60 m transects with six randomly placed 1 m x 1m plots were established at each of the geomorphic units. Species presence, diversity, and cover were used to define the plant community at each plot. Soil characteristics measured include pH, active layer depth, organic matter content, gravimetric water content, and soil temperature. Distinct vegetation communities are associated with the geomorphic units of each retrogressive thaw slump studied, representing their relative age and the degree of stabilization. Where unit overlap occurs, the tendency is for adjacent units to share species, and anomalies in this overall pattern of vegetation fidelity can be explained by the presence of vegetation remnants. It is these remnants which are likely responsible for part of the revegetation of retrogressive thaw slumps, although this thesis suggests that this process is scale dependent.

Key words: thermokarst, retrogressive thaw slump, Arctic vegetation, biogeomorphology, Herschel Island, Yukon Territory, Western Arctic

CHAPTER 1: INTRODUCTION

1.1 The Scientific Problem

Despite its ecological importance, there is surprisingly little literature characterizing the revegetation patterns following disturbance in permafrost environments. With few exceptions, (e.g. Lambert, 1976; Burn and Friel, 1989), most studies on this topic have tended to focus on anthropogenic disturbance (e.g. McKendrick, 1987; Forbes *et al*., 2001) or disturbance in forest ecosystems (e.g. Bartleman *et al*., 2000). Changes in arctic vegetation may have already begun as a result of the recent warming in the Arctic (Chapin *et al*., 1995; Stow *et al.*, 2004; Tape *et al*., 2006), and the problem could be further complicated by successional species changes resulting from climate warming (Lantz *et* al., 2009). Given the expected increase of permafrost thawing and the importance of the resulting thaw-related landscape features (thermokarst), it is especially important to characterize the ‘typical’ revegetation patterns following disturbance in order to understand the geomorphic history of an area and predict future changes in the landscape. Vegetation exerts strong controls on regional ecosystem processes, and since changes in the microenvironment following certain types of thermokarst can lead to reinitiation on multidecadal time scales, understanding the effects of disturbance on short-term and long-term successional trajectories is also a critical to understanding the effects of climate change on the Arctic (Lantz *et al*., 2009).

As a result of the recent advances in remote sensing technology, it is now possible to remotely survey large areas of the North. Given that each vegetation community has a distinct spectral signature, if vegetation proves a reliable indicator of geomorphic history then it may be possible to employ remote sensing to monitor changes in an area without the need for intensive fieldwork. Eventually, this could allow for a cost-effective, broad scale management and tracking system to be developed for the Canadian Arctic. This thesis argues that there are distinct vegetation communities associated with different stages of a stabilizing retrogressive thaw slump, and that the consistency of these vegetation patterns can be used to reconstruct a slump's geomorphic history and monitor future changes.

1.2 Study Aims

My research examines vegetation communities and corresponding soil properties associated with different geomorphic units which represent stages of stabilization surrounding retrogressive thaw slumps on Herschel Island. The goal of this thesis is to determine if distinct vegetation communities are related to current and previous episodes of disturbance in these ice-rich permafrost areas, and to understand how this type of landscape change affects vegetation and soil characteristics over time. I employ standard methods to characterize the plant communities: species' presence, diversity and cover. The following hypotheses were tested:

i) There are distinct, well-defined communities of vegetation within and surrounding retrogressive thaw slumps, which are directly related to the stage of stabilization (the geomorphic unit) and the amount of time that has passed since disturbance;

ii) Each of these geomorphic units has distinct soil characteristics, including pH, active layer depth, moisture content, and organic matter content;

iii) These geomorphic units and their associated vegetation community structures are consistent between different slumps in the same tundra environment.

The specific objectives of this thesis included:

a) To map out the chronology of landscape changes related to retrogressive thaw slumps at a series of sites on Herschel Island, Yukon Territory

a) To describe the vegetation community with each of landscape units marked by past and current thaw slump activity;

b) To characterize related soil characteristics for each geomorphic unit;

c) To determine the relative alpha diversity of the vegetation in each geomorphic unit;

d) To compare the similarity of corresponding geomorphic units across three retrogressive thaw slumps in three separate locations (beta diversity);

CHAPTER 2: BACKGROUND

2.1 Study Area

Herschel Island, or *Qikiqtaruk,* (69°36′N; 139°04′W) is located at the most northern point of the Yukon Territory, Canada (Figure 1). It is situated in the southern Beaufort Sea and lies 3 km off the north coast of the Yukon Territory. The rhombic-shaped island is approximately 108 km in area and has a maximum elevation of 183 m above sea level (Mackay, 1959; de Krom, 1990). Herschel Island is characterized by a rolling topography dissected by numerous streams and gorges (Mackay, 1959; de Krom, 1990). The island is composed primarily of deformed, fine-grained marine sediment dredged from the Herschel Basin and pushed into place by the Laurentide ice sheet during the Buckland Stage of the Wisconsinan Glaciation (Mackay, 1959; Lantuit and Pollard, 2008). The mean annual air temperature recorded on the island is approximately -11 °C with a mean annual precipitation of 160 mm (Pollard 1999; Couture *et al*., 2008). The climate of Herschel Island is Arctic maritime, characterized by long, cold winters and brief, cool summers reaching a daily high of 14.5 °C in July and 12.8 °C in August 2009 (Pollard, 2005; Environment Canada, 2009; Figures 2, 3). The closest weather station with reliable long-term weather records for the Yukon arctic coast is situated at Komakuk Beach approximately 50 km west of Herschel Island. The warmest month of the year according to these records is July, with a mean daily temperature of 7.8 °C, and the coldest is February at -25.3 °C (Environment Canada, 2009). Precipitation is strongly skewed toward the summer months when the Beaufort Sea is ice-free, with the highest annual precipitation occurring as rainfall in August (Environment Canada, 2009).

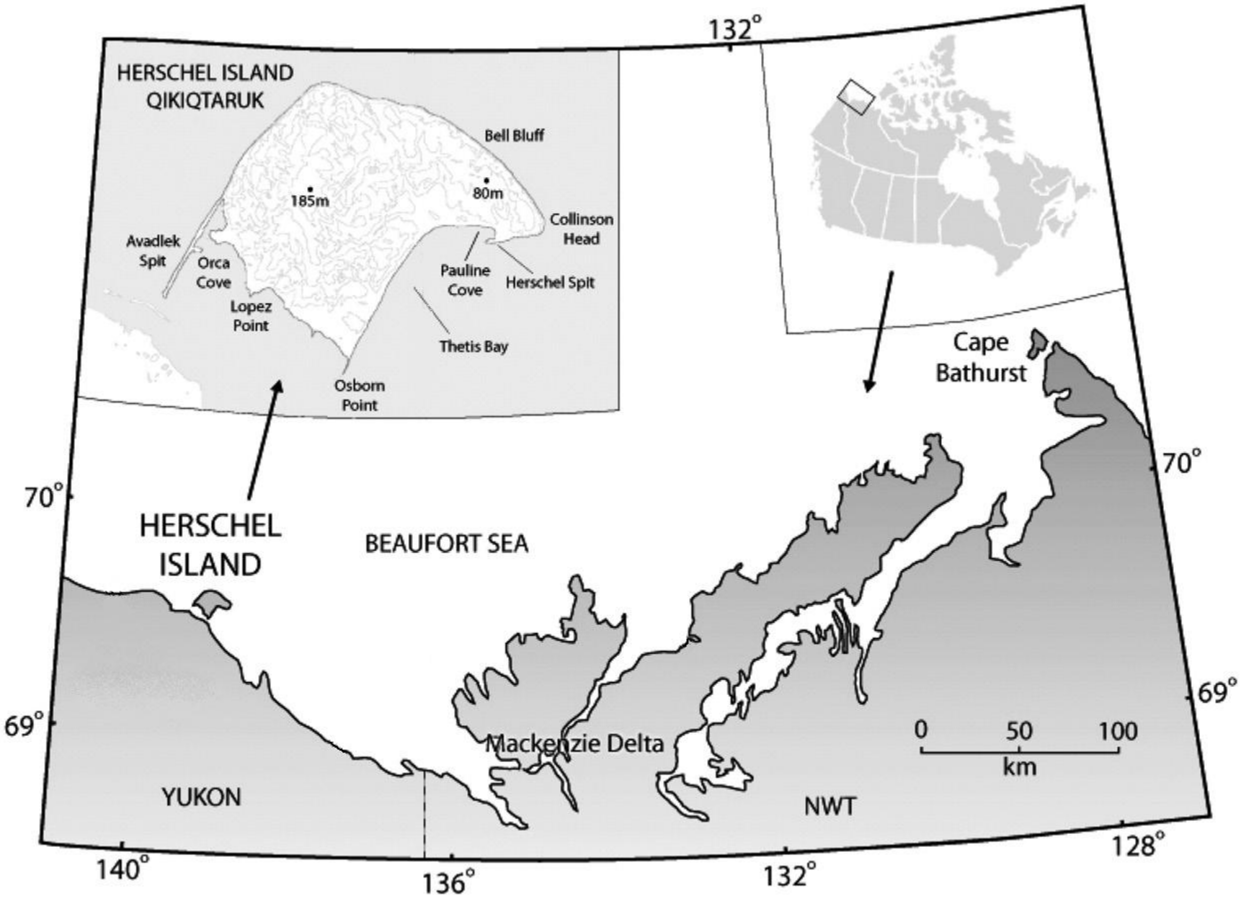


Figure 1 Herschel Island location in the southern Beaufort Sea. Top left hand inset: toponomy of the Herschel Island area (Lantuit and Pollard, 2008)

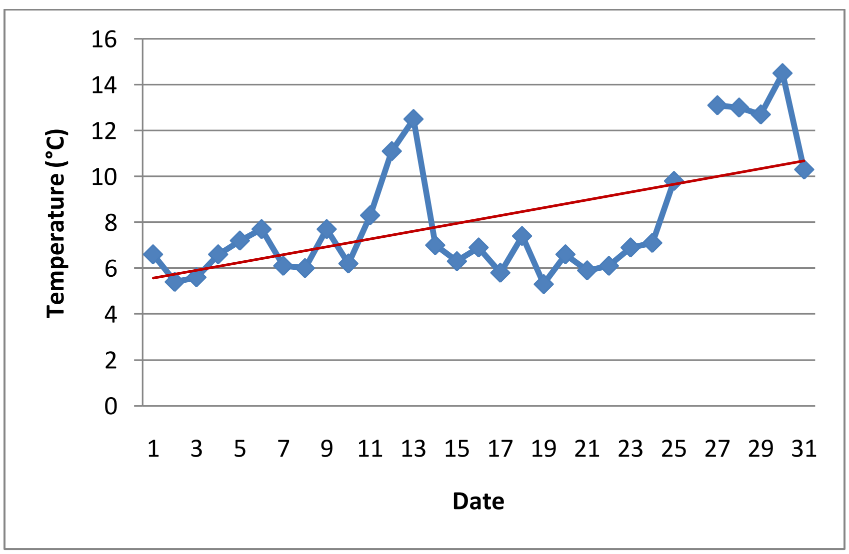


Figure 2 Mean daily temperatures recorded at the Herschel Island weather station for the month of July, 2009 (Environment Canada, 2009).

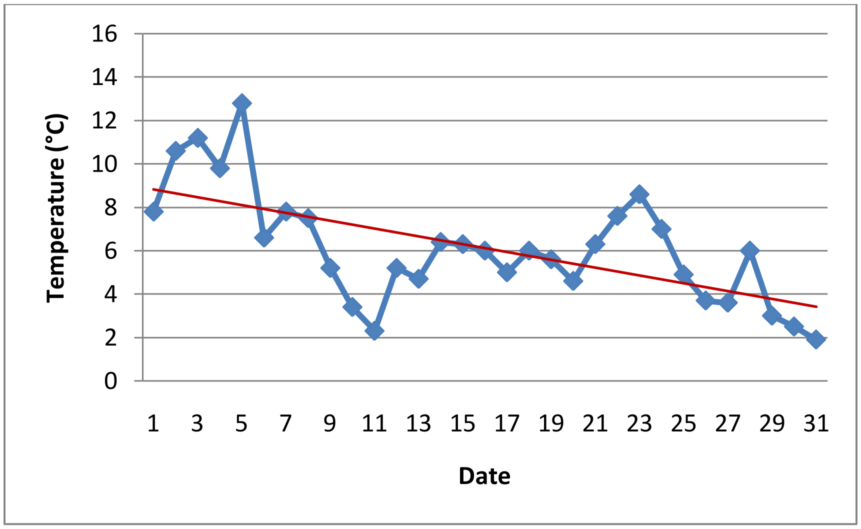


Figure 3 Mean daily temperatures recorded at the Herschel Island weather station for the month of August, 2009 (Environment Canada, 2009).

2.2 Permafrost and Ground Ice

Herschel Island is part of the Yukon Coastal Plain physiographic region located within the zone of continuous permafrost (perennially frozen ground) which on Herschel Island is at least 300 m deep (Rampton 1982; Pollard, 1999). The term permafrost refers to ground (i.e. soils, gravel, or rock) that remains at or below 0 °C throughout two consecutive years (French 1996; Anisimov, 2005). The upper layer of permafrost is subject to seasonal summer thaw; this thawed layer of soil is called the active layer (Anisimov, 2005). The active layer is highly variable in nature and its thickness is largely controlled by climate, meaning that the warm summer temperatures on Herschel Island cause a drastic increase in the depth of the active layer. The summer temperature regime is therefore the principal driver of thermokarst on the island, which directly affects the vegetation community composition. Active layer thickness is also influenced by snow cover, vegetation, and the presence of an insulating layer of organic matter at the surface (Anisimov, 2005). The active layer is shallower in the presence of organic materials due to their low thermal conductivity and capacity to reduce the heat flux between the atmosphere and the thawing ground (Anisimov, 2005). On the inland portion of Herschel Island, the active layer varies between 45 and 90 cm and is characterized by poorly sorted fine-grain sediment (Lantuit and Pollard, 2008).

Ground ice is widespread on Herschel Island and underlies most of the island in the form of ice wedges, pore ice, segregated ice lenses, intrasedimental ice, and buried snowbank/glacier ice (Pollard, 1990). It is the thawing of ice-rich permafrost and areas of massive ice which results in thermokarst, which is defined by the International Permafrost Association as “the process by which characteristic landforms result from the thawing of ice-rich permafrost and or melting of massive ice” (van Everdingen, 1998). The most spectacular thermokarst features on the island are its many retrogressive thaw slumps, landforms resulting from the thawing of ice rich permafrost (French 1996). Also known as retrogressive thaw flow slides (Rampton, 1982), or ground-ice slumps (Lewkowicz, 1987), they are initiated when ice-rich soil is exposed by disturbance and generally become stabilized within 30 to 50 summers (Burn and Friele, 1989; French 1996). Retrogressive thaw slumps consist of a relatively steep (20° –90°) headwall of exposed ground ice and a footslope of thawed material (Bartleman *et al.,* 2001; Lantz *et al.,* 2009). As the permafrost in the headwall melts, the headwall retreats upslope (retrogressively), and soil falls onto the footslope producing a zone of viscous mud (Bartleman *et al.*, 2001; Lantuit and Pollard, 2008; Lantz *et al.*, 2009). As the exposed ground ice melts, the overlying vegetation mat and active layer collapses into the slump and appear as islands of vegetation surrounded by liquid mud or water; these islands are often drowned and overtaken by successive mud flows (Lambert, 1976; Figure 4). As the distance from the headwall increases, pools of supersaturated sediment and standing water transition to plastic mud and finally to dry, desiccated mud (Lantuit and Pollard, 2008). In large slumps, the distance from the headwall to the dry area may be 30 to 40 m (Lantuit and Pollard, 2008). The resulting wet and dry bare soil surface is colonized by plants *ab initio* or from 'islands' (turf blocks) of vegetation which have survived the descent to the footslope (Lambert, 1976; Bartleman *et al*., 2001).

Retrogressive thaw slumps stabilize when exposed ground ice is either completely exhausted or has been covered by an insulating layer of debris (Burn and Friele, 1989). However, later erosion of the slump floor may trigger a new retrogressive thaw slump within the confines of an existing or stabilized slump, leading to polycyclic slumps – of which there are many on Herschel Island (Lantuit and Pollard, 2008). Between 1952 and 2000, the number of retrogressive thaw slumps on Herschel Island has increased both in areal extent and in terms of growth rates (Couture *et al*., 2008; Lantz *et al.*, 2009). Current slump retreat rates at Collinson Head and Thetis Bay are on the order of 10-15 metres/year, and this is expected to accelerate with continuing climatic warming in the arctic (Lantuit and Pollard, 2008).

Figure 4 Previously established vegetation islands being consumed by a fresh layer of headwall melt. Photo taken at the Collinson Head Slump July 30th.

2.3 The Tundra Ecosystem

The vegetation of Herschel Island is characteristic of the tundra biome, with diminished vascular flora diversity, simple plant community structure and a lower annual productivity than more southerly regions (Forbes *et al*., 2001; Forbes, 2005). Despite this, tundra ecosystems support large populations of migratory mammals and supply important nesting habitat for breeding populations of rare and endangered birds (Forbes *et al*., 2001). Herschel Island provides habitat for over 90 bird species, 40 of which breed on the island, and many of which are threatened species (Yukon Bird Club, 2000). It also provides habitat for barren ground caribou, wolves, grizzly bears, muskoxen, wolverines, cross and arctic fox, and polar bears (Environment Yukon, 2006). Herschel Island consists largely of tussock tundra, characterized by a thick, acidic organic layer and the presence of *Eriophorum vaginatum* (Forbes and Jefferies, 1999; Forbes, 2005). Although the principle macroenvironmental control on the gross distributions of vascular plants in the north is summer warmth, a mosaic pattern is more commonly observed at the local scale (Smith, 1989; Forbes *et al.*, 2001). At a microclimate scale, factors such as moisture, wind, aspect, and soil chemistry also become important (Forbes *et al.*, 2001).

Within the tundra environment, disturbances in the active layer result in both short and long-term changes in local vegetation patterns. Due to increasingly adverse conditions relative to southern latitudes, the number of competing taxa in the tundra has been reduced, and stress tolerance becomes a prime survival prerequisite for vegetation (Svoboda and Henry, 1987). In terms of vegetation succession, slow rates of colonization, a low resource base associated with low temperature, a short growing season, and slow rates of nutrient decomposition and nutrient turnover in the Arctic limit the potential for the regeneration of vegetation and increase the time scale of this regeneration (Forbes and Jefferies, 1998). In the case of small disturbances, rhizomatous graminoids and willow species can easily spread vegetatively, although recruitment from the seedbank may also occur (Forbes, 2005). When a large-scale disturbance occurs, however, the surface layer of organic material is removed and the seed bank contained within is destroyed, along with the possibility of lateral clonal growth from undisturbed patches (Forbes and Jefferies 1999). Plants adapted to the pioneering stage of disturbance will begin to colonize the site, having either been dispersed from elsewhere or having survived *in situ* as adult plants of viable propagules (Forbes *et al.*, 2001). Since only 60% of the 1,500 vascular plant species occurring in the Arctic are widespread, the species pool available for recolonization of a disturbed habitat is limited (Forbes and Jefferies, 1999). The degree of disturbance associated with a retrogressive thaw slump means that the seed bank is all but destroyed and pioneer species are often the first to appear. The exception to this rule is at the edges of the slump, or where "islands" of vegetation from the headwall have managed to survive the journey to a more stable area of the slump, where vegetative reproduction may be possible (Lambert, 1976; Figures 5,6,7).

Figure 5 Photo of a surviving vegetation island containing *Salix arctica* observed at the Collinson Head Slump August 8^{th} 2009 in the "Recent" zone.

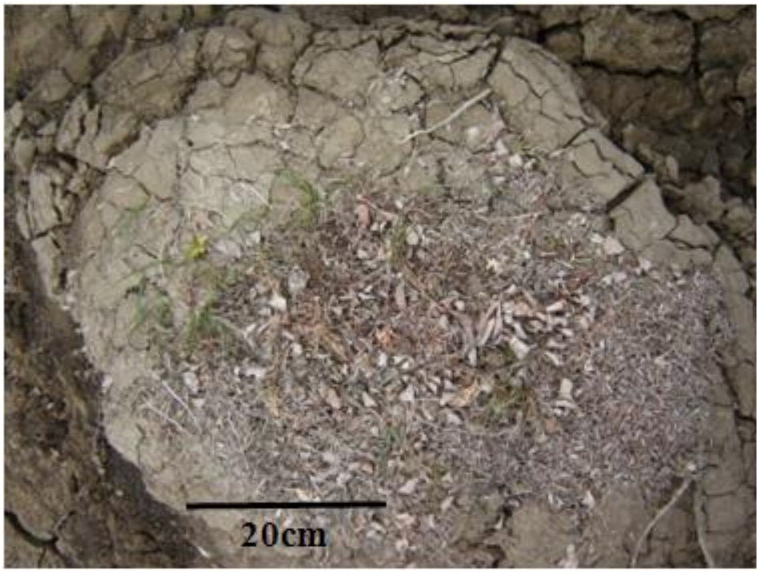


Figure 6   Vegetation island at the Collinson Head Slump containing deceased *Dryas integrifolia* and *Salix arctica*. Photo shows pioneer graminoid species beginning to establish where the original island species have died.

Figure 7   Photo showing the west side of the Collinson Head Slump, where there may be the potential for vegetative colonization between vegetation islands.

2.4 Community Structure

In order to classify and differentiate vegetation communities, it is important to recognize their biological diversity. Species diversity is an expression of community structure and a characteristic unique to the community level of biological organization (Brower *et al.,* 1997). While there are various measures of species diversity, the most useful are those which consider both the number of species (richness) and the distribution of individuals among the species (evenness), such as the Shannon Index and the Simpson Index (Brower *et al.*, 1997). A community has high species diversity when many equally or nearly equally abundant species are present, and low species diversity if the community is composed of few species or if only a few species are abundant (Brower *et al.*, 1997). The biodiversity within a particular community is known as alpha diversity (α-diversity) whereas comparing species diversity between ecosystems is known as beta diversity (β-diversity). Defining alpha diversity helps to describe the species richness of a specific community that is considered homogenous. Two of the most useful measures of alpha diversity are the Simpson index and the Shannon index, which are both calculated in this study.

The Simpson's index takes into consideration both the number of species present and the relative abundance of each species (Brower *et al.*, 1997). The Simpson index therefore expresses the probability of two randomly selected individuals belonging to different species (Brower *et al.*, 1997; Moreno, 2001). It can be calculated according to the following formula:

$$\mathrm{SIDI} = 1 - \sum_{i=1}^{N} pi \text{ x } pi$$

where N is the number of species and p_i is the relative abundance of each species (Nagendra, 2002). The Shannon index ranges in theory from 0 to infinity, and estimates the average uncertainty in predicting which species a randomly selected organism will belong to (Nagendra, 2002). It is calculated as follows:

$$\mathrm{SHDI} = 1 - \sum_{i=1}^{N} pi \text{ x } \ln pi$$

where N is the number of species and p_i is the proportional abundance of the *i*th type (Nagendra, 2002).

A proven technique for determining how close two communities are in their composition is calculating their coefficients of similarity (also called indices of similarity) and dissimilarity. For similarity indices, the higher the coefficient the more similar the two communities are, whereas dissimilarity measures calculate the differences between samples. The measure of beta diversity used in this study is the Bray-Curtis index of dissimilarity, which quantifies the compositional dissimilarity between two communities. When using the Bray-Curtis Index, possible values range between 0 and 1, with 1 representing no similarity between communities and 0 signifying absolute similarity between the two. It is calculated as follows:

$$\mathrm{BC} = \frac{\sum_{i=1}^{n} \mid S_{i1} - S_{i2} \mid}{\sum_{i=1}^{n} (S_{i1} - S_{i2})}$$

where S_{i1} is the cover value for each species in community 1, and S_{i2} is the cover value for each species in community 2. The Bray-Curtis Index is related to the Sorenson Index of similarity, where the Bray-Curtis value is equal to 1- the Sorenson Index, although depending on variations in calculating the Sorenson index the relationship may not be absolute.

One of the most useful forms of exploratory data analysis is cluster analysis, especially with large datasets where principal components analysis (PCA) is impractical. Cluster analysis uses similarity or distance measures to organize samples in a study. Cluster analysis can be either agglomerative or divisive, and the graphic result is a dendrogram showing the relative linkages and groupings calculated by the measure selected. In the case of agglomerative analysis, there are various ways to link or amalgamate different samples and clusters to one another. Complete linkage agglomerative cluster analysis, also called furthest neighbour sorting, is calculated by comparing clusters in terms of similarity at each step, with the two clusters that are most similar fused (Pisces Conservation, 2002). Centroid agglomerative clustering means that clusters are compared in terms of the similarity of their most similar samples (columns) at each iteration and the two clusters that hold the most similar samples are fused, and the average of the attributes of the fused group is calculated and the similarity between average properties are used in subsequent iterations (Pisces Conservation, 2002). Average linkage, also known as group-average sorting means that at each step, the clusters are compared in terms of the average similarity of their members and the two clusters that are most similar are fused (Pisces Conservation, 2002).

CHAPTER 3: METHODS

Field work for this project was undertaken between July 29th and August 8th, 2009. Vegetation surveys were conducted for three retrogressive thaw slumps on Herschel Island. For each thaw slump selected for study, four geomorphic landscape units reflecting distinct stages of recovery were visually delineated with the use of aerial photography and on-site assessment. A transect was established in each of the four geomorphic units, and six 1x1 m sample plots were randomly placed along each transect for a total of 24 plots per slump. At each sample plot, vegetation data collected included the estimated average height and percent cover of each species present. Voucher specimens were collected on-site to be identified later. Soil temperature was recorded at depths of 1 cm and 10 cm using a calibrated digital thermometer. Active layer depth was also measured at each plot using a 1.5 m permafrost probe, and soil grab samples were collected adjacent to each plot using the Environmental Protection Agency (EPA) grab sample protocol (American Society of Civil Engineers, 2000). Finally, a minimum of one digital photo was taken for each vegetation plot and the center of each plot was recorded using a Trimble 4700 differential GPS unit with a resolution of ±50 cm. The methods of each section of this chart are explained in detail in the sections that follow. Laboratory analyses of pH, gravimetric water content and organic matter content were preformed upon return to McGill and followed McKeague (1981). Vegetation data analysis included recalculating the species dominance values to exclude non-vegetation elements, calculation of the Simpson and Shannon indices of diversity, and using CAP software to perform ordination analyses. The voucher specimens of the vascular plants collected in this study are housed in the McGill Herbarium and at the Aurora Research Institute, Inuvik, NWT. For reference purposes, the full voucher specimen collection is also available in digital form upon request.

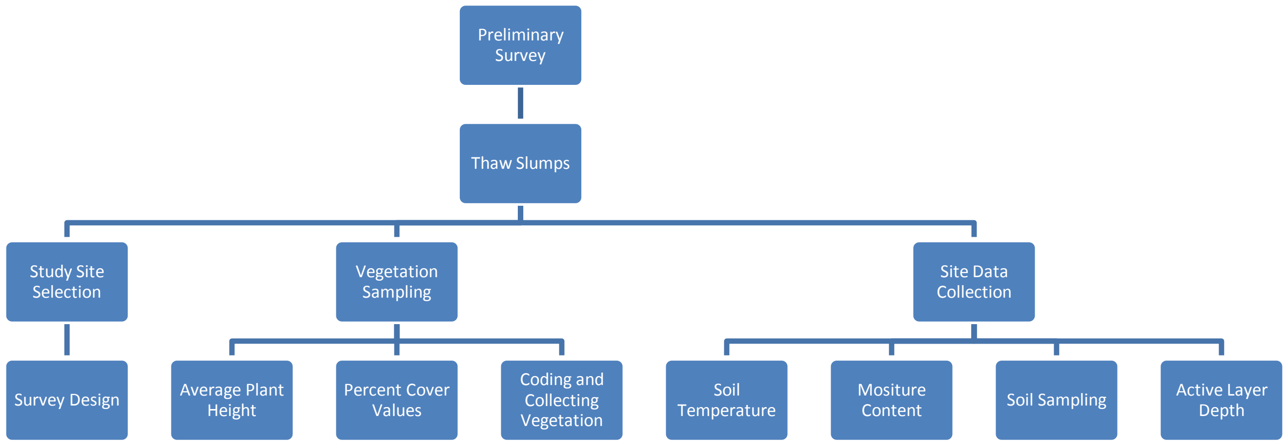


Figure 8 Field methodology flow chart illustrating the various relationships between each field methodology used in this study.

3.1 Survey Design

Methodology for this study was developed based on a synthesis of previous arctic vegetation studies including Johnstone and Kokelj (2008), Bartleman *et* al. (2001), Smith *et al.* (1989), and Lambert (1976). Based on annual surveys performed in the field and in the laboratory using satellite images, there are between 50 and 100 active retrogressive thaw slumps on Herschel Island, although not all of these slumps are active from year to year. The most spectacular thaw slumps on the island, however, are so large that they are self-sustaining and are reliably active each summer (e.g. "Slump A"). To identify particular retrogressive thaw slumps over time and between field seasons, the most studied and notable slumps have been identified with local names such as "Slump A," "Collinson Head Slump," Ranger's Slump" and it is important to note that these are not formally recognized names.

Many of the thaw slumps on Herschel Island, and particularly the larger slumps, are polycyclic, meaning that disturbance occurs repeatedly within the same boundaries. Within and surrounding each of these slumps, these stages of disturbance and recovery can be easily identified based on their topographic and morphologic expression, and their appearance is often enhanced due to contrasts in vegetation community (Figure 9). This means that from the air and from the ground, one can visually identify areas of common geomorphic condition related to current and previous episodes of slumping, where multiple stages of development and activity are reflected by different geomorphic units within one thaw slump. It is these discrete geomorphic zones which the methodology of this study was designed to characterize.

3.1.1 Study Site Selection.

Given the large number of active thaw slumps present on the island each year, finding a study slump is not a problem. Rather, for reasons of safety and time, the most practical study sites are those in relatively close proximity to the field camp. Before sites were selected, a preliminary mapping of the geomorphic units was performed for each possible study site. Air photos taken in previous years were first reviewed for each slump site, and distinct geomorphic zones were observed at “Slumps A,B,C,” the “Collinson Head Slump,” “Ranger’s Slump,” “Tina’s Slump” and “Hawk’s Slump” (Figure 10). Hawk’s slump was excluded due to its incredible complexity as a thaw slump matrix, and Tina’s slump was determined to be inaccessible for logistical reasons. Slump activity was determined using the Herschel Island Geographic Information System (GIS) slump headwall position data collected since 2004. An assessment of the headwall retreat in recent years demonstrated conclusively that Slump A, Collinson Head, and Rangers’ Slump are still active (Figures 11, 12, 13). In addition, these slumps provide variation in that they represent two coastal and one inland slump (Figure 10). These sites are also of long-term interest to other researchers (e.g Lantuit and Pollard 2008) meaning that not only is there available data from previous studies, but new information about these particular slumps will be of interest to the scientific community. In the case of the retrogressive thaw slump group referred to as “A, B, C” (Figure 11), Slump A was selected due to its similar shape and size to the Collinson Head and Ranger’s Slumps and also because the slump floor was firm enough to walk on. In addition, unlike Slump B, Slump A does not have a distinct vegetation “island” formed when two smaller slumps merged (Figures 9, 11). Because the transects within each geomorphic unit are intended to represent an approximate chronology of the slump, this irregularity may have interfered with transect data should a plot have been established there. At the Ranger’s Slump site, the more inland of the two Ranger’s Slumps was selected for this study based on field observations that it was more clearly still active.

Figure 9 Photo of Slump B showing the presence of an irregular steep-sided vegetation “island” (center) which is a remnant of the formation of this slump.

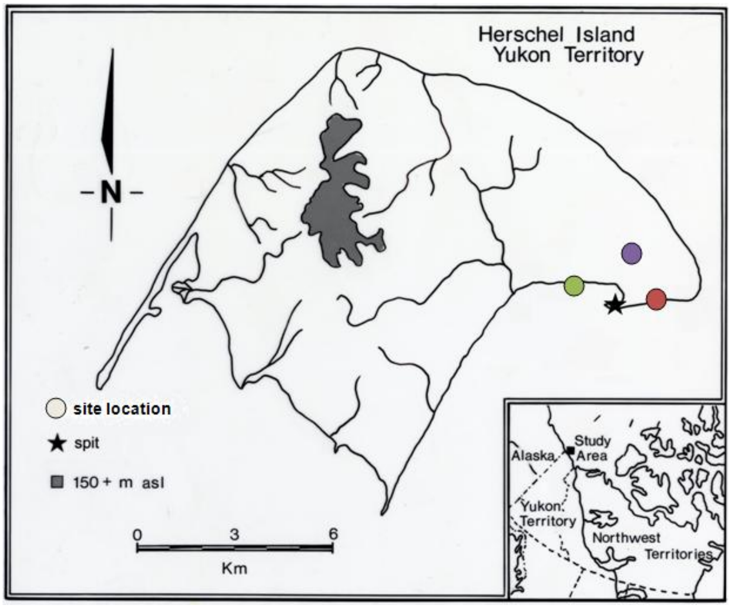


Figure 10 Map of Herschel Island showing the location of the spit (base camp) and slump site locations. Red icon represents the Collinson Head Slump, green represents Slump A, and the purple icon represents Ranger's Slump.

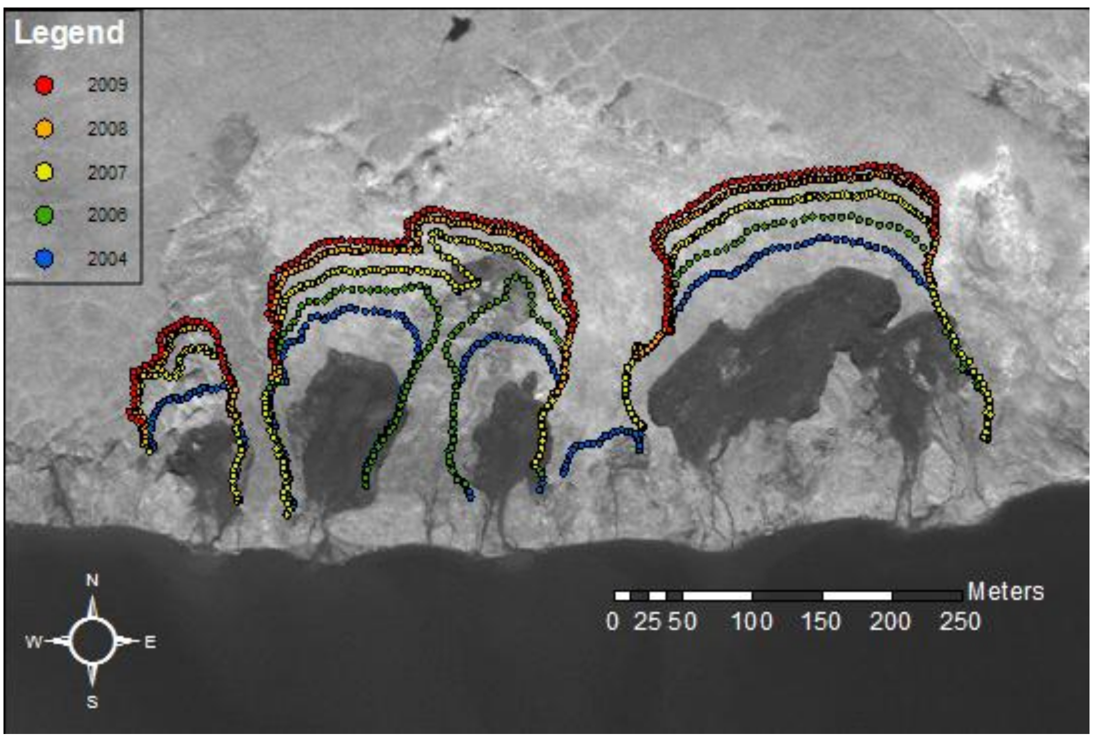


Figure 11 Headwall positions for slumps A (far right), B (center), and C (far left) from 2004 to 2009. For all years where the headwall location was recorded using differential GPS, a considerable change is observed. Base layer used is a 2001 IKONOS satellite image.

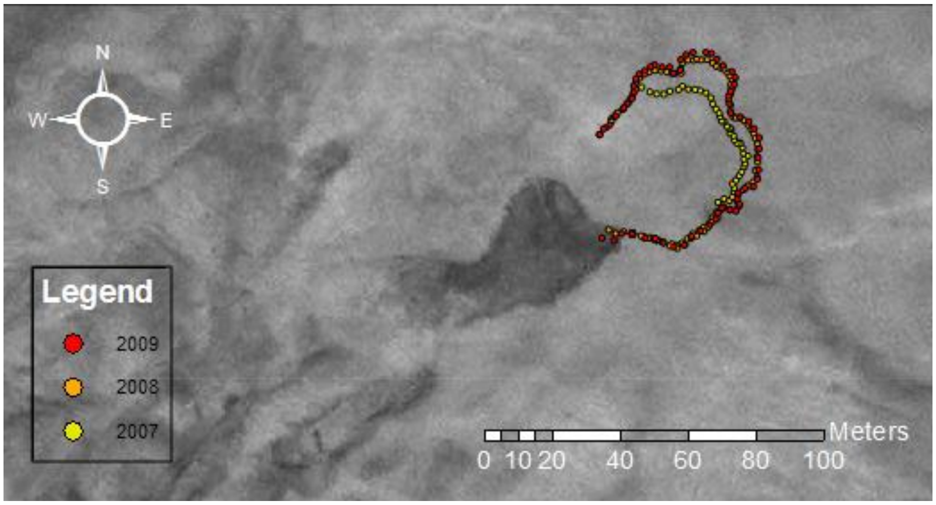


Figure 12 Headwall location of the Ranger's Slump between 2007 and 2009. The changing position of the headwall indicates that this slump is still active. Base layer used is a 2001 IKONOS satellite image.

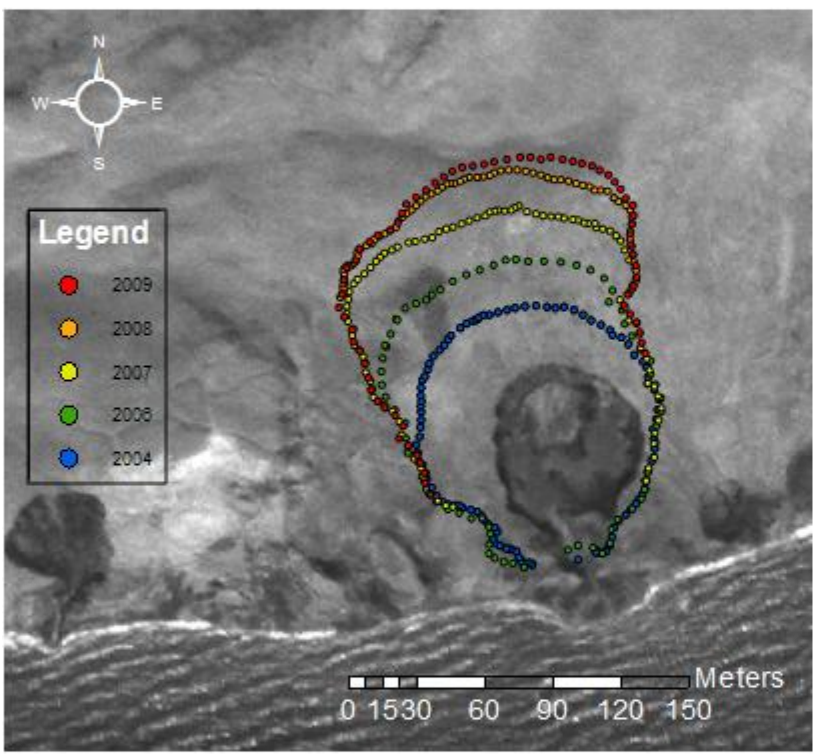


Figure 13 Headwall positions for the Collinson Head Slump between 2004 and 2009. The dramatic annual change in headwall location indicates that this slump is still active. Base layer used is a 2001 IKONOS satellite image.

3.1.2 Survey Design.

As mentioned above, prior to fieldwork four approximate geomorphic zones were visually delineated for each slump using air photos from previous years. Due to the dramatic annual change of the thaw slumps on Herschel Island, however, the exact position of the four geomorphic zones was established through on-site reconnaissance. Based on an analysis of air photos, three to four zones were initially expected, but it became clear once in the field that the composition of the vegetation community was different at the more established, drier portion of the slump floor (consequently named the “Intermediate” zone) than nearer to the headwall where the mudflow was more dynamic (labelled the “Recent” zone). Four geomorphic zones were therefore delineated, as illustrated in Figures 14, 15, 17, 18, 20, and 21. The zone labelled “Mature” can be clearly observed in aerial photos as a distinct region above the present headwall which is visibly different than the tundra beyond it (Figures 14, 15, 17, 18, 20, 21). It is likely that this area represents the headwall extend of a larger, older slump which has stabilized (Lantuit and Pollard, 2008). This assumption is in keeping with the polycyclic nature of the slumps of Herschel Island, and is supported by the fact that when observed from the ground the Mature zone lacks the irregularity that comes from having established grassy tussocks. The final distinct geomorphic area, called the “Undisturbed” zone, was identified beyond the furthest extent of the observable ancient headwall, and was in each case approximately parallel to the Mature transect line (Figures 14, 15, 17, 18, 20, 21). At all study sites, this geomorphic zone was easily delineated by the presence of slow forming tussock tundra and represents an area of long-term periglacial activity.

In each geomorphic unit a 60 m transect was established and sample plots were located at random distances along them (Figures 16, 19, 22). Due to the homogeneity of the vegetation community within the geomorphic unit as assessed visually and as described by Smith *et al*. (1989), it was decided that six plots per transect would provide a representative sample to characterize relative vegetation abundances. To determine the location of the sample plots along each transect, random numbers were taken from a random number chart found in Brower *et al.*, (1997). These numbers were selected by horizontally reading the chart starting from different points for each transect and discounting any numbers that fell beyond the 0-60 range required to create random distances along the transects. So as not to disturb the vegetation within plots, every effort was made to walk on the downslope side of the transect lines. As a consequence of this precaution, it was not possible to establish repeat plots generated by the random number table on the opposite side of the transect as suggested by Brower *et al.* (1997). As a rule, duplicate random numbers generated for a transect were therefore disregarded and the next random number in the table was counted in its stead.

Each transect was laid out with a measuring tape, using the left side of the slump (as seen from the mouth of the slump) as a starting point. Once the tape was laid, it was pulled taut to create a straight line and gently lifted over any vegetation. Survey flags were then placed at the starting point of each transect as well as at each plot distance along it as determined by the random number chart. Wire survey flags were used because their small diameter allowed them to be inserted at the centre of each plot without disturbing the vegetation within it.

Figure 14 Air photo of Ranger's Slump and surrounding area, taken August 7th 2009.

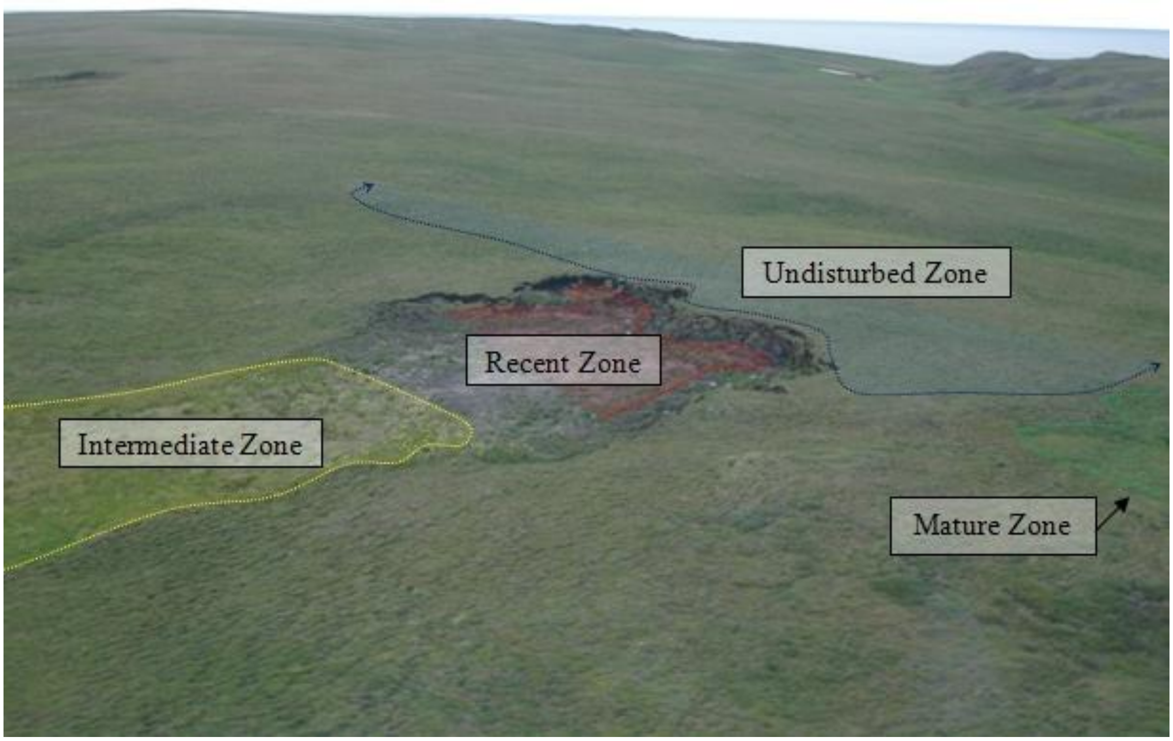


Figure 15 Delineation of the geomorphic zones at the Ranger's Slump. Background photo taken in August 7th 2008.

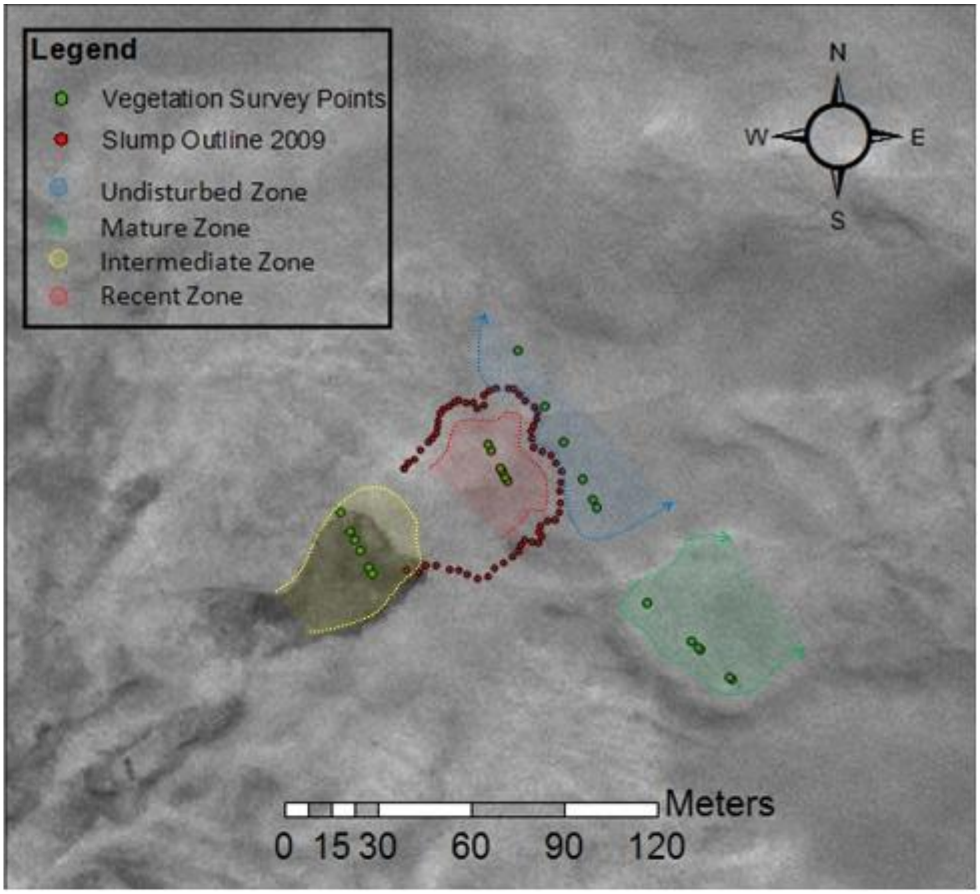


Figure 16 The Ranger's Slump geomorphic zones and the surrounding area, including the obvious stabilized headwall of the adjacent slump. The locations of each vegetation sample plot are shown in relation to the 2009 slump headwall. Base layer used is a 2001 IKONOS satellite image.

Figure 17 Air photo of Slump A (right) illustrating the clearly observable changes in vegetation in different areas within and surrounding the slump. Photo taken August 7th 2008.

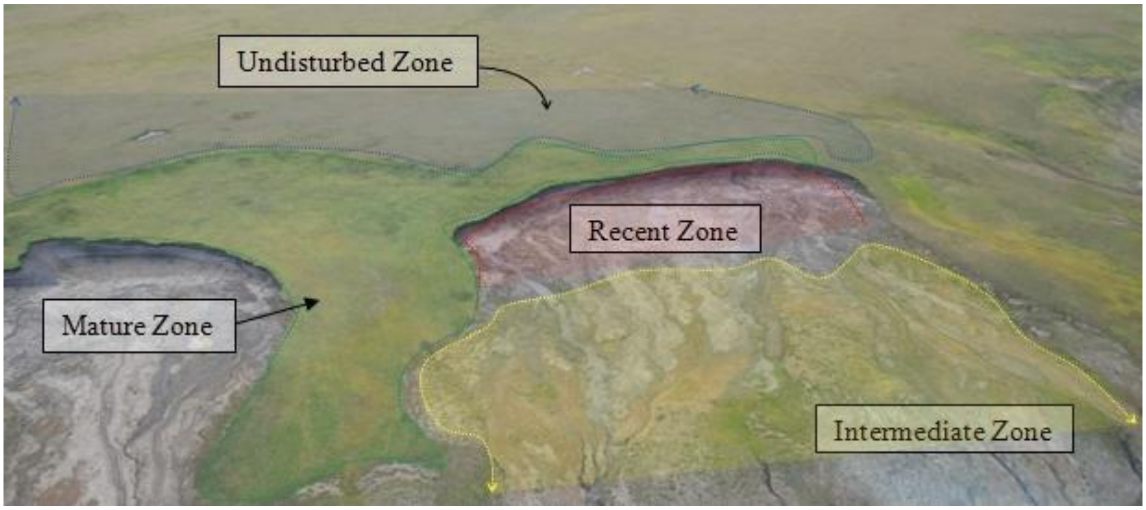


Figure 18 Delineation of the geomorphic zones at Slump A. Background photo taken on August 7th 2008.

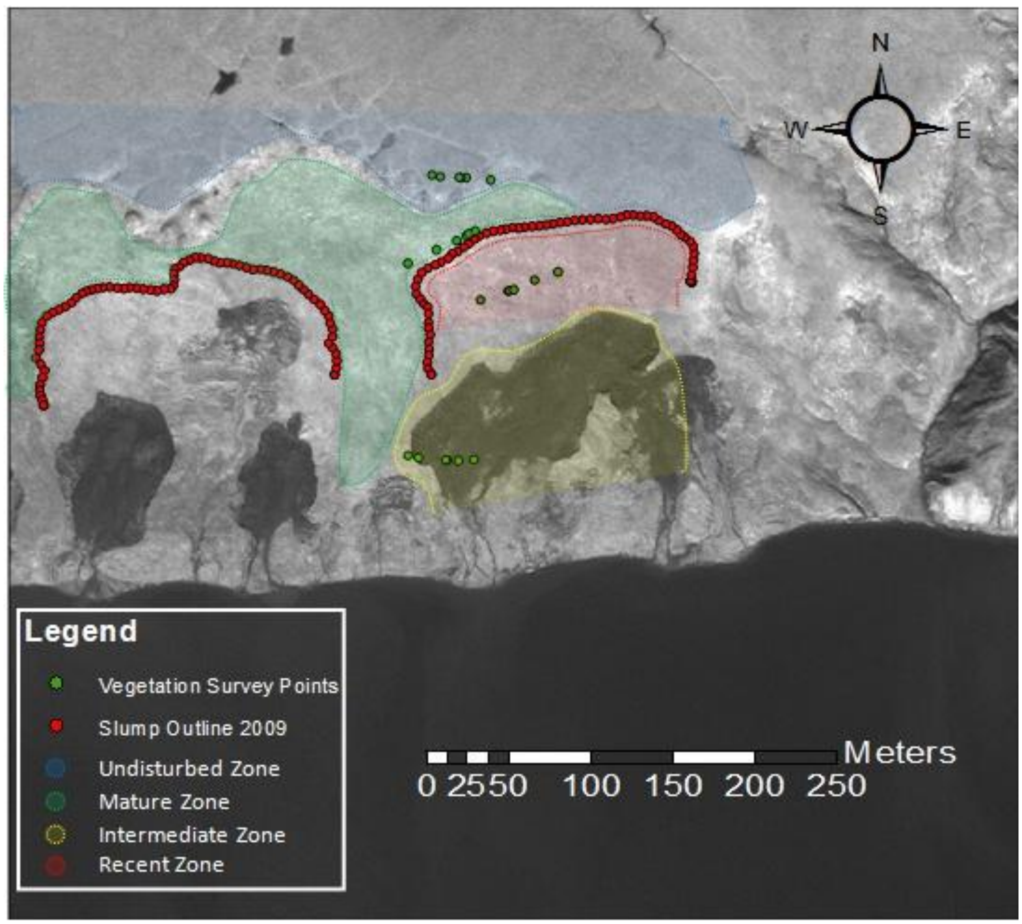


Figure 19 The geomorphic zoning and location of each vegetation sample plot for Slump A (right) in relation to the 2009 headwall position. Base layer used is a 2001 IKONOS satellite image.

Figure 20 Photo of the Collinson Head Slump taken on August 7th 2008

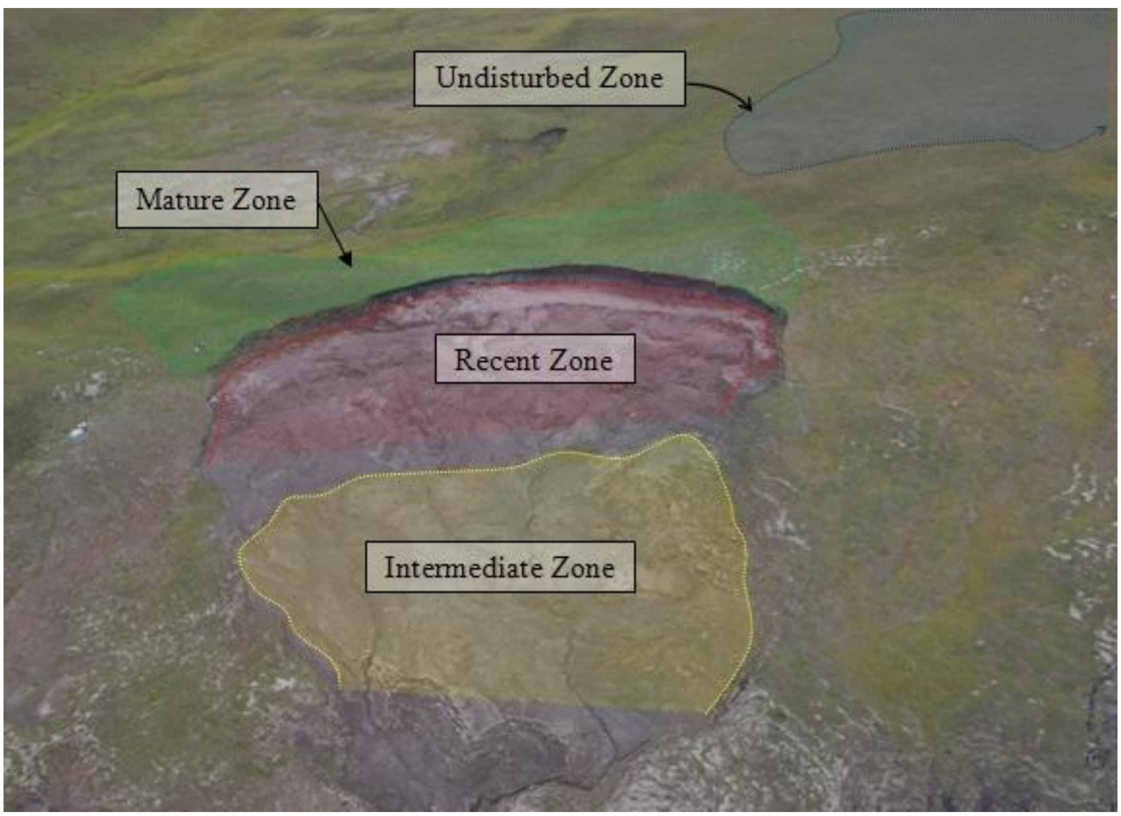


Figure 21 Delineation of the geomorphic zones at the Collinson Head Slump. Background photo taken on August 7th 2008.

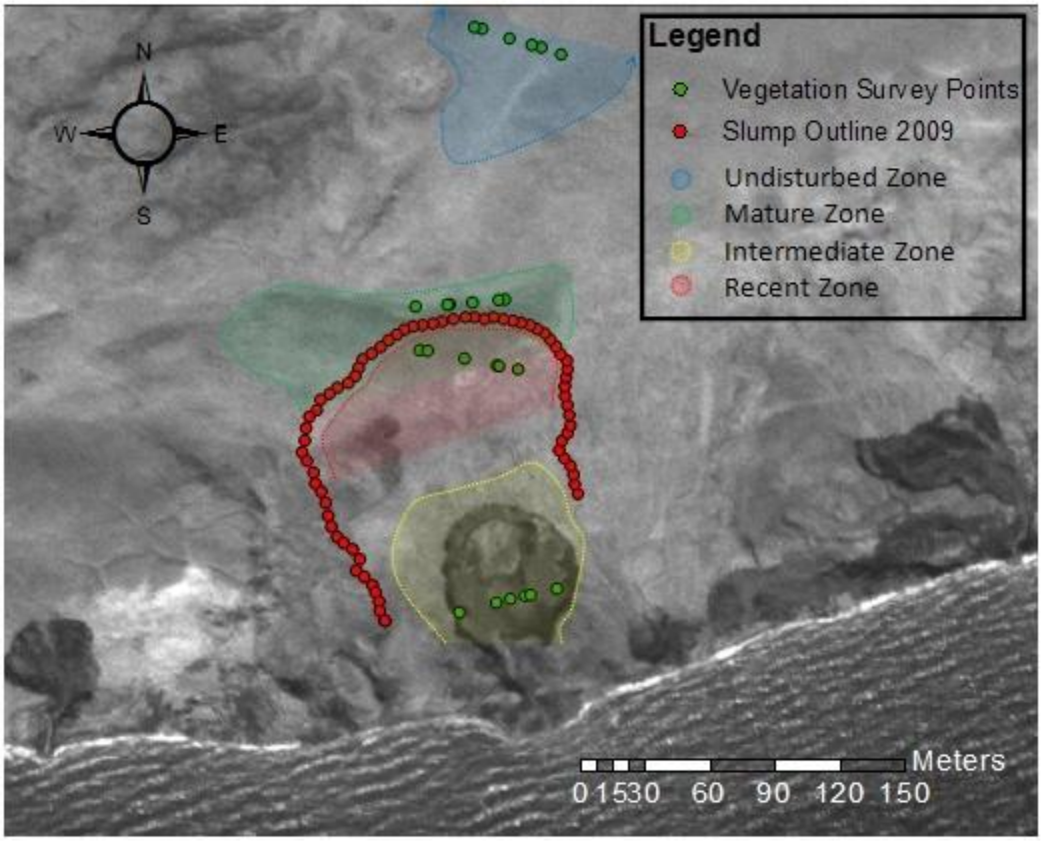


Figure 22 The locations of each geomorphic zone and sampling plot in relation to the 2009 headwall position of the Collinson Head Slump. Base layer used is a 2001 IKONOS satellite image.

3.1.3 Site-specific Methods.

Minor variations in the slope and character of the Mature zone were observed between slumps A and B and behind the 2009 headwall of Slump A. The transect in this zone was therefore located with its midpoint in the centre of this region so that the transect crossed both community variations/types and each species had an equal chance of being sampled (Figure 19). At the Rangers' Slump, the Mature and Undisturbed transects were completed as at Slump A and Collinson Head, using 60 m transects and six random number generated plots. However, the Recent and Intermediate transects were halved since the slump was not more than ~35 m across from wall to wall (Figure 16). The previously generated random numbers were therefore divided in half to maintain plot distancing. The number of sample plots was kept at six since decreasing the value would not have been representative nor in the interest of keeping the data consistent and being able to infer conclusions from the results. Since there was not a clearly observable headwall immediately behind the Ranger's Slump, the Mature transect was located in a stabilized slump immediately adjacent to the Ranger's Slump (Figures 14, 15, 16, 23). This area had the same characteristics of the Mature zones at the other sites, being of a noticeably different colour, having a clearly observable extinct headwall, and possessing a very regular surface (Figures 16, 23).

Figure 23 Air photo showing the location of the stabilized slump immediately adjacent to the Ranger's Slump. Arrows show the boundary of the stabilized headwall.

3.2 Vegetation Sampling

Once each transect at a particular slump was established, sample plots were revisited. Vegetation sampling methodology loosely followed Johnstone and Kokelj (2007). At each sample point, plant community composition was described by visually estimating the percent cover of each vascular plant species using a marked 1x 1 m quadrat (Figure 24). Bryophyte species were also included in the percent cover estimates by visually delineating species based on their physical characteristics. At each site, the quardrat was set-up so that the survey flag was at the exact centre of the plot (Figure 24). This ensured that plots located side by side would not overlap, and since all foot traffic was restricted to 0.5 m outside of each transect line, it also ensured that sample vegetation remained intact. Each species of vascular plant or bryophyte within the quadrat was then recorded using a unique code, or if know, its full latin name. Percent cover was visually estimated using the demarcation on the quadrat edges (Figure 24). The quadrat pole markings ensured that accurate estimates of percent cover could be quickly estimated with a consistent margin of error, since by simply visually assessing the plot and comparing a species cover to the area represented by the markings a reliable estimate was reached.

The same person performed all percent cover estimates, and for the purpose of these estimates an individual was considered to be within the plot if any part of it was within the quadrat (leaves, seed head, etc.). This eliminated problems associated with willows and other sprawling vegetation that may have root masses located at a distance from other plant parts. In dealing with tall grasslike plants in particular, there was the potential for skewed percent cover results, since placing quadrat edges inconsistently would cause more or less of a plant to be within the plot. To ensure a consistent percent cover estimate, quadrat edges were therefore always laid from directly above.

In addition to vascular and bryophyte species, percent cover estimates also included bare ground and litter categories, where litter included animal droppings and vegetation that was attached or fallen. Bare ground consisted of soil without any decaying organic matter (such as peat-hummock islands or willow roots). In contrast to Burn and Friele (1989), vegetation remnants from the original surface in the Recent zone were not ignored. Whereas Burn and Friele (1989) did this to clearly represent the nature of initial colonization, for the purpose of this study these vegetation islands are considered important sources of propagules (e.g. *Salix arctica* found in the Recent zone) and have been suggested by Lambert (1972) to have both a direct and indirect influence on the permafrost table.

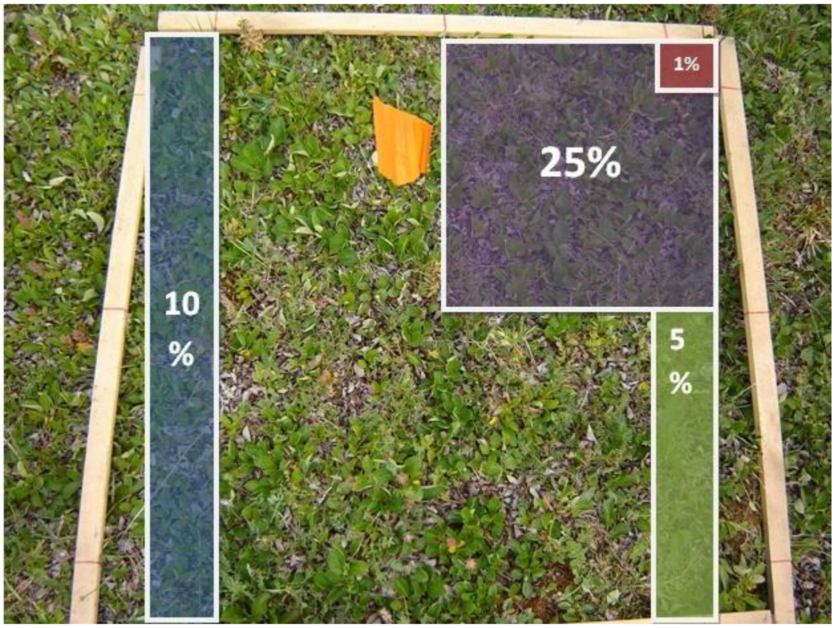


Figure 24 Photo of a sample plot at Slump A illustrating the percent cover methodology employed. As shown, different combinations of the quadrat markings provide consistent visual estimates of percent cover for each plot.

Certain easily recognized species were identified in the field, and for each a minimum of three voucher specimens of were collected to be identified at the field camp. These specimens were individually collected and stored in a sealed Ziploc© bag labelled with the date, slump, zone, plot, and the specimen's unique code. On the advice of Aurora Research Institute (ARI) vegetation specialist Annika Trimble, these reference samples were collected at locations separate from the transects whenever possible in order to identify species back at camp while not disturbing the vegetation of the sample plot. General habitat notes were recorded for each plot where pertinent, and for each transect notable plants not present in the sample plots but present at the site were recorded to give a richer view of plant community structure. A photo was then taken of each plot showing the position of the quadrat and the relative heights of a plot's vegetation, and each of these photos were labelled, sorted, and archived at the end of each day. Finally, the elevation and location of the centre of each plot was recorded spatially using a Trimble 4700 DGPS unit.

Vascular species nomenclature followed Cody (2000), and many plant identifications were verified in the field by Annika Trimble of the Aurora Research Institute or willow expert Ms. Isla Myers-Smith of the University of Alberta. Although bryophytes and lichens were not the focus of this study, they were included because evaluation on the basis of vascular plants alone in many cases overestimates the degree of vegetation recovery (Forbes *et al*., 2001). In this study, mosses and lichens were categorized based on visual assessment in the field and their percent cover value was recorded. This visual classification was repeated at the field camp once several samples had been collected, yielding distinct 'types' of mosses and lichens. Although these groups may indeed represent more than one species, bryophytes as a whole are only included in this study in a general way so that they may help characterize the community structure of the thaw slumps.

3.3 Site Data Collection

3.3.1 Soil Measurements.

Soil temperatures at the surface and at 10 cm were recorded at each sample plot using a calibrated digital thermometer. This was done by inserting the thermometer probe 1 cm into the soil and recording the temperature once it had equilibrated. A 10 cm soil depth temperature was then recorded by fully inserting the length of the probe into the ground and noting the temperature once the thermometer reading had stabilized. Due to the varying topography and presence of hummock islands (Recent zone), mud flows (Recent and Intermediate zones), and tussocks (Undisturbed zone), it was impractical to predetermine the point of soil measurement for each plot. Measurements were therefore recorded at an adjacent area within 20 cm of the plot location. Every effort was made to ensure that measurements were taken in an area as similar as possible to the average plot characteristics. After each use of the thermometer, the sensor prongs were wiped clean.

Active-layer depths were determined at each vegetation sampling point by inserting a steel 1.5 m permafrost probe into the soil to the depth of refusal, with the exception of certain points in the Recent zone where the soil density made further insertion impossible, in which case the value recorded was taken as the minimum depth to which the soil was free of permafrost. Every effort was made to ensure that the probe was inserted at soil a thickness representative of the vegetation plot area (e.g. not on a hummock island that only covered 10% of the quadrat area). In instances where the permafrost probe became difficult to insert into the ground, but had not likely hit the permafrost table, the measurement was attempted a second time.

3.3.2 Soil Sampling.

Following Burn and Friele (1989), soil samples were collected from the uppermost 10 cm for laboratory analyses to determine pH, gravimetric water content, and organic matter loss on ignition. Soil grab samples were collected using the United States Environmental Protection Agency guidelines set out for soil sampling (American Society of Civil Engineers, 2000). For each sample, the top layer of soil and organics was scraped off using a gardening knife before a trowel-full (200 to 700 g) of soil was collected, and placed into a pre-weighed Whirl-Pak® bag. After each use the trowel and knife were wiped clean to avoid contamination. Upon returning to the field camp, each soil sample was weighed on a digital scale set on a level surface, and the weight was recorded to 0.01 g. All samples were weighed within eight hours of their collection, and were kept out of direct sunlight in a cool warehouse until they could be transferred to the on-site ice house (max. 24 hours) where they were frozen to preserve their chemical traits for later analysis. Samples were then transported by air in a cooler while still frozen and placed in a McGill soils fridge within four hours of landing in Montreal. All soil samples were collected on days where no precipitation had occurred for over 24 hours for Slump A and Ranger's slump (August 3rd and 5th, respectively) and over eight hours for the August 8th Collinson Head Slump (Figures 25, 26).

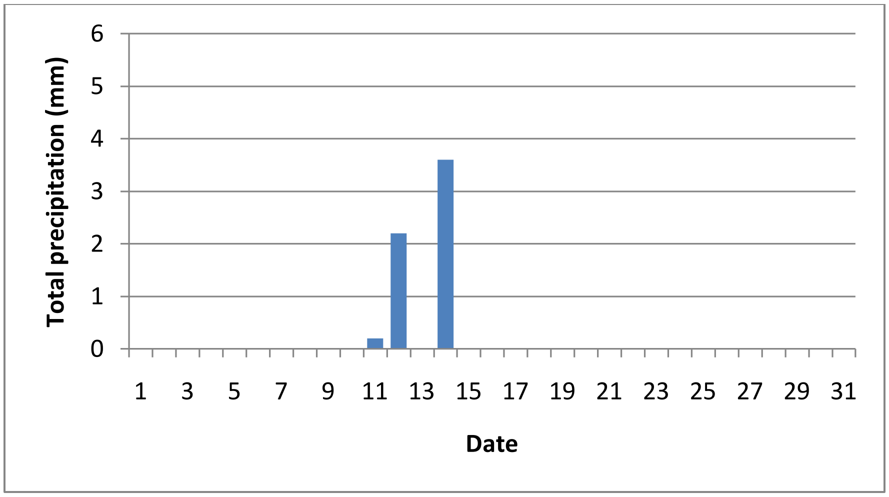


Figure 25 Total daily precipitation for the month of July 2009 recorded at the Herschel Island weather station on Herschel Island, YT, Canada (Environment Canada, 2009).

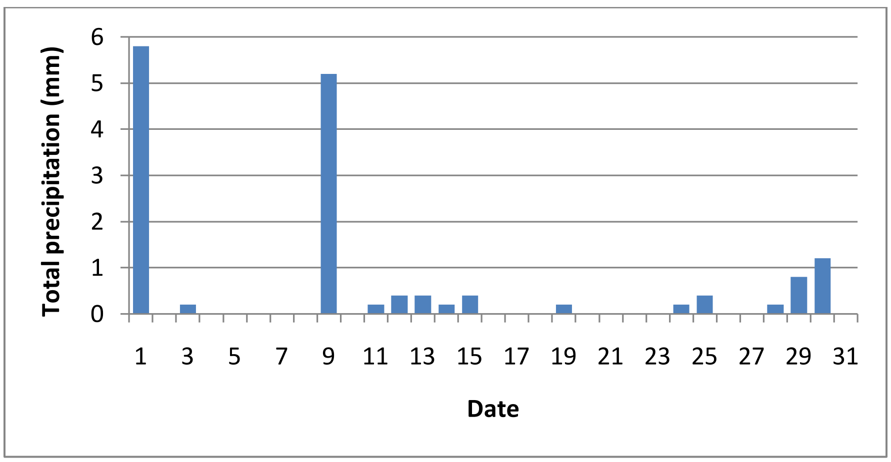


Figure 26 Total daily precipitation recorded for the month of August 2009 at the Herschel Island weather, Herschel Island, YT, Canada (Environment Canada, 2009).

3.4 Laboratory Methods

3.4.1 Soil Analysis.

Preparation for soil analysis at the McGill soils laboratory began with the sub-sampling of each of the 72 samples collected. To begin, each set of transect soil samples was thawed for

36 hours while still in their sealed Whirl-Pak® bags. Given that the grab samples had retained their cylinder-like structure, 27.0 g of soil was then removed from a mid-soil area from each grab sample – below any remaining roots or litter debris and above any colour-phase layer present- and placed in a pre-weighed, labelled pie plate containing the other 27.0 g samples from that transect. The resulting composite transect samples were then homogenized using a clean scoopula, and 43 g of this composite sample was placed in a smaller pre-weighed and labelled pie plate. The weights of each composite sample and subsample were recorded to two decimal places using a digital scale; the larger sample was air-dried to a constant weight, and the remaining material over-dried at 105 °C to a constant weight (~48 hours).

Testing for pH used the air-dried sample and followed McKeague's (1981) pH in water methodology. Soil moisture content was determined using McKeague's (1981) guidelines for "water content, weight basis" and the organic matter content of each composite sample was determined using the loss on ignition at 850 °C method described by McKeague (1981). To determine the initial weight of soil needed to ensure an appropriately large dry sample, it was assumed that each soil sample collected had a gravimetric water content of 90%.

3.4.2 Vegetation Data Analysis.

Alpha diversity was calculated for each plot using both the Shannon index and the Simpson index of diversity. Percent cover values were adjusted to exclude the litter and bare ground categories for statistical analyses. Beta diversity was calculated using the Bray-Curtis dissimilarity index using Community Analysis Package (CAP) software. Agglomerative cluster analyses were performed in CAP using the complete linkage option with the Bray-Curtis dissimilarity measure. Although there are various ways to cluster samples, the complete linkage method (furthest neighbour sorting) was used because it is calculated by comparing clusters in terms of similarity at each step and the two clusters that are most similar fused as opposed to the centroid method and average linkage method which generalize clusters with each iteration (Pisces Conservation, 2002). Two-way Indicator Species Analysis (TWINSPAN) and principal component analysis (PCA) were also calculated using the CAP software, but were not included in this study since the resulting plots containing 72 samples were extremely cluttered and visually inaccessible.

CHAPTER 4: RESULTS

Each geomorphic unit in this study had distinct soil characteristics, with pH, active layer depth, surface and 10 cm temperatures highest in the Recent (R) unit, followed by the Intermediate (I), Mature (M) and Undisturbed (U) units, while percent water content by weight and organic matter content following a U > M > R > I pattern. The average percent cover of bare ground was highest in the Recent zone, followed by the Intermediate and Mature zones, and was absent in the Undisturbed zone. Both litter and total average plant cover were higher in the Mature and Undisturbed zones than in the Intermediate and Recent zones. Alpha diversity as measured by species richness, the Shannon index, and the Simpson's index was highest in the Undisturbed zone, followed by the Mature zone, and was variable between the Intermediate and Recent zones. The results of the Bray-Curtis dissimilarity cluster analysis show that, with few exceptions, sample plots from the same geomorphic zone are more similar (regardless of the specific slump) than plots from different zones, and this distinction is greater between the zones which are furthest apart spatially and lesser between the Recent and Intermediate zones. Certain species such as *Senecio congestus* were found in only one geomorphic unit, and only three species, *Polygonum viviparum*, *Arctagrostis latifolia*, and *Salix arctica* occurred in all four geomorphic units. Most commonly, a particular species occurs in only one or two geomorphic units.

4.1 Soil Characteristics

There is a consistent trend in the pH values recorded at each geomorphic unit of each slump. In all cases, the lowest pH was recorded in the Undisturbed unit, followed by the Mature unit (Table 1). The pH values of the Intermediate and Recent units are similar to one another; at Slump A the pH is higher in the Recent unit whereas at Ranger's Slump and the Collinson Head Slump pH is higher at the Intermediate unit (Table 1). The organic matter content is highest at the Undisturbed unit of each slump, followed by the Mature unit (Table 1). At Slump A and Ranger's Slump the organic matter content at the Recent unit is higher than the Intermediate unit, and at the Collinson Head Slump the two are exactly equal (Table 1). The percentage of water by weight is highest at the Undisturbed unit for all slumps, followed by the Mature unit, the Recent unit and the Intermediate unit (Table 1). This pattern is also repeated in the air-dried samples (Table 1). The lower water percentage by weight value for the Intermediate unit than for the Recent unit is supported by field observations of dry, cracked terrain in the Intermediate unit versus the viscous mudflows which characterize the Recent unit.

Consistent with the existing literature concerning active layer depths at thaw slump sites, the active layer is at its greatest thickness at the Recent unit, followed by the Intermediate unit and the Mature unit, and is shallowest beneath the Undisturbed unit (Lambert, 1972; Lantz *et al.*, 2009) (Table 2). Temperatures recorded at a depth of 10 cm also follows this pattern, while surface soil temperature is highest at the Recent unit, followed by the Intermediate unit and the Undisturbed unit, reaching its lowest in the Mature unit (Table 2).

Table 1 Sample plot pH readings, organic matter loss on ignition (LOI) percentage, and percentage water by weight values for each slump site.

Slump	Transect	pH	Loss On Ignition (%)	% water by weight oven	% water by weight air dry
A	U	5.5	21.8	82.2	76.8
	M	6.9	13.3	62.6	35.3
	I	7.6	7.5	19.6	17.9
	R	7.8	8.3	21.3	19.7
Ranger’s	U	6.1	21.2	58.5	53.6
	M	7.5	13.0	32.6	28.4
	I	7.8	10.7	24.1	20.8
	R	7.4	12.9	31.0	28.2
Collinson	U	5.8	20.3	97.7	92.5
	M	7.3	12.2	35.5	33.6
	I	8.0	9.4	20.7	18.2
	R	7.7	9.4	25.9	24.3

Table 2 Average Active layer depth and soil temperatures, for each geomorphic unit.

Transect	Average active layer depth (cm)	Average temperature (°C) surface	Average temperature (°C) 10cm
U	33.5	11.1	5.3
M	53.0	10.3	5.8
I	>65.7	14.3	10.9
R	>88.7	15.1	11.1

4.2 Vegetation Data

4.2.1 Percent Cover.

There is a consistent pattern of cover within and between geomorphic units and across thaw slumps (Figure 28). The highest bare ground cover was observed in the Recent zone (Figures 27, 28) and the second highest in the Intermediate zone. The percent cover of bare ground is negligible in other units (Figures 27, 28). Deposits of an unknown precipitate were observed at all three slumps, and were most common in the Recent and Intermediate zones as well as the Mature zone of the Collinson Head Slump (Figure 27). Litter is most common in the Mature and Undisturbed zones, although values vary between individual sample plots and therefore slump transects; between the Intermediate and Recent zones, the percent cover of litter is highest in the Intermediate zone (Figure 28). Overall, total plant cover is highest in the Undisturbed zone, followed by the Mature, Intermediate, and Recent zones (Figure 28), but at Ranger's Slump, it is higher in the Intermediate zone than the Mature zone (Figure 28).

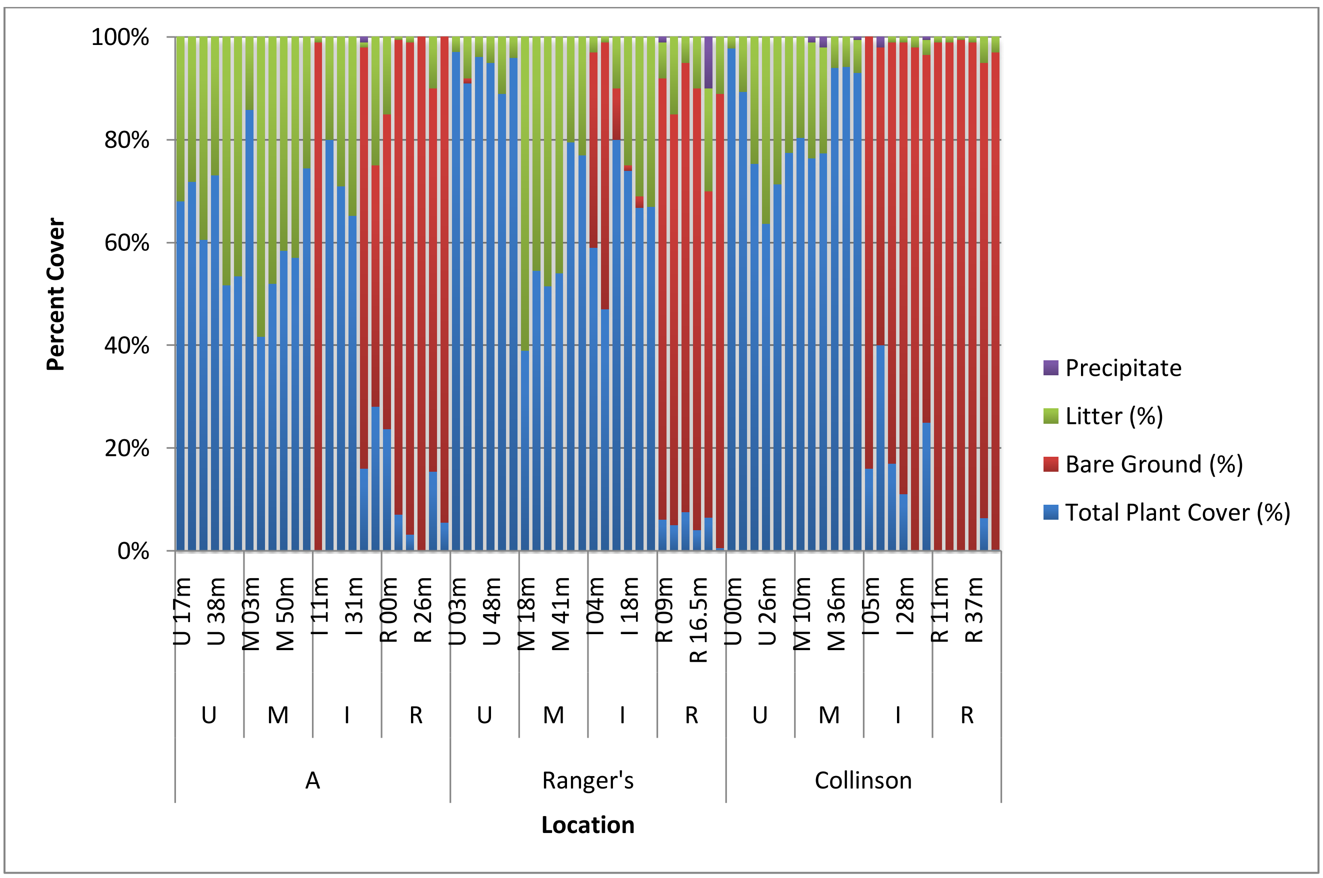


Figure 27 Percent cover values for each sample plot at each slump, organized by the transect established in the four geomorphic units of each slump: Undisturbed (U), Mature (M), Intermediate (I), and Recent (R).

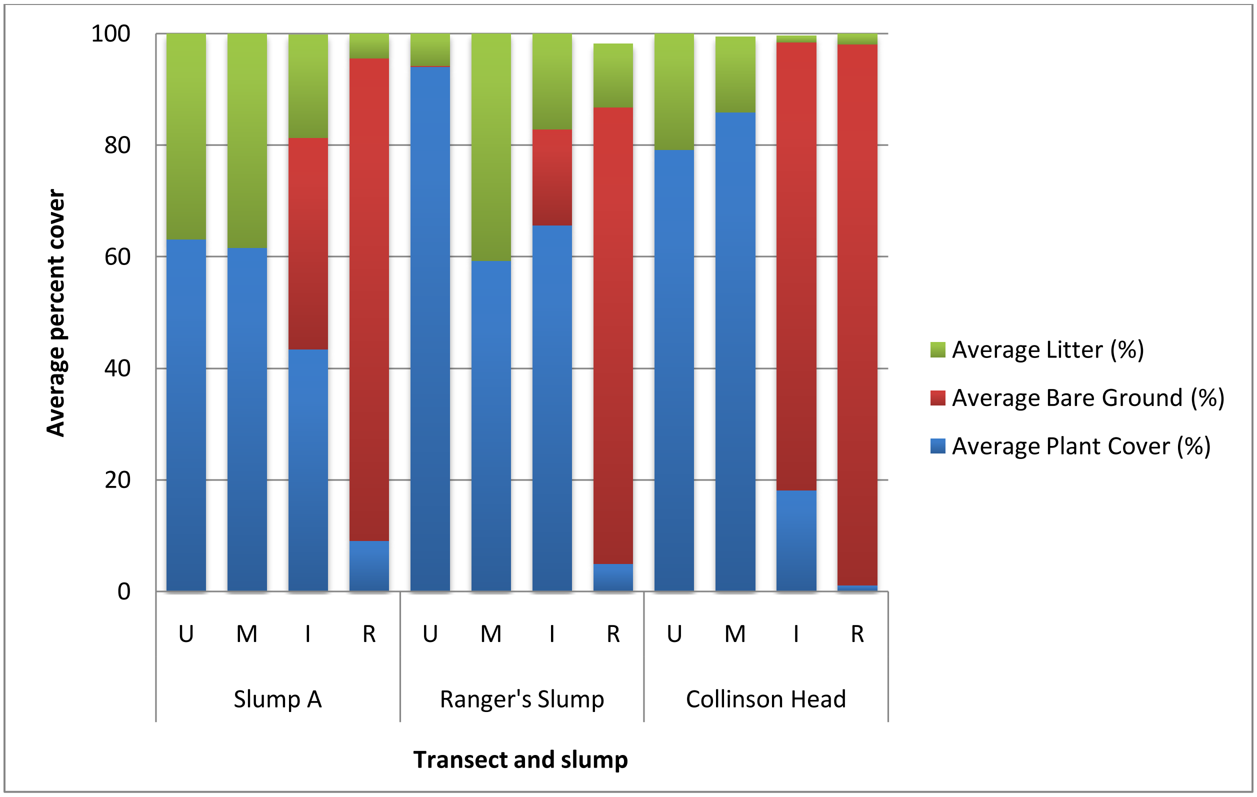


Figure 28 Graph shows a cross comparison of relative percent cover values of litter, bare ground and plant cover averaged for each transect of each slump, where transects are represented by the geomorphic zone they were established within: Undisturbed (U), Mature (M), Intermediate (I), and Recent (R).

4.2.2 Alpha Diversity.

The average total species richness is highest at the Ranger's Slump, followed by Slump A and the Collinson Head Slump (Table 3). At all three slumps, the Undisturbed zone has the highest average species richness, followed by the Mature zone (Table 3). The average species richness in the Intermediate zone is higher than the Recent zone at both Slump A and Ranger's Slump, but this is reversed at the Collinson Head Slump (Table 3). For all three slumps, there is a clear decrease in alpha diversity with disturbance as measured by both the Simpson Index and the Shannon Index, where it is highest in the Undisturbed zone, followed by the Mature zone (Figures 29, 30). Although the Shannon Index value is higher in the Intermediate zone than in the

Recent zone, the difference is negligible and as measured by the Simpson Index the alpha diversity of these zones is equal (Figure 29).

Table 3 Total average Species Richness by slump and transect area, where transects represent the Undisturbed (U), Mature (M), Intermediate (I), or Recent (R) geomorphic unit.

Transect	Collinson Head Slump	Slump A	Ranger's Slump
U	13	12	14
M	10	8	10
I	1	5	3
R	1	4	2.5
Average Total Species Richness	7	7	7

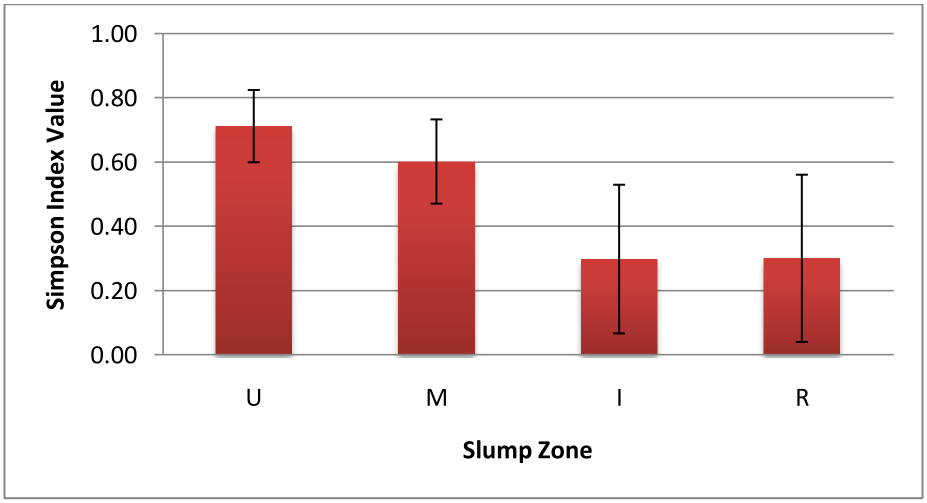


Figure 29 Average Simpson Index value and standard deviation displayed by geomorphic zone (Undisturbed, Mature, Intermediate, Recent) for all slump combined.

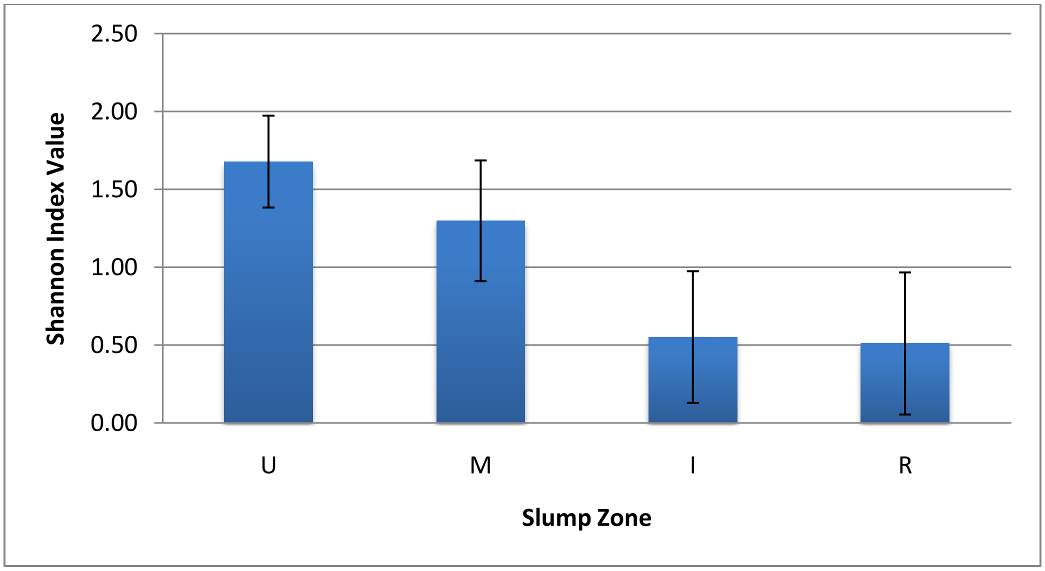


Figure 30 Average Shannon Index value and standard deviation displayed by geomorphic zone (Undisturbed, Mature, Intermediate, Recent) for all slump combined.

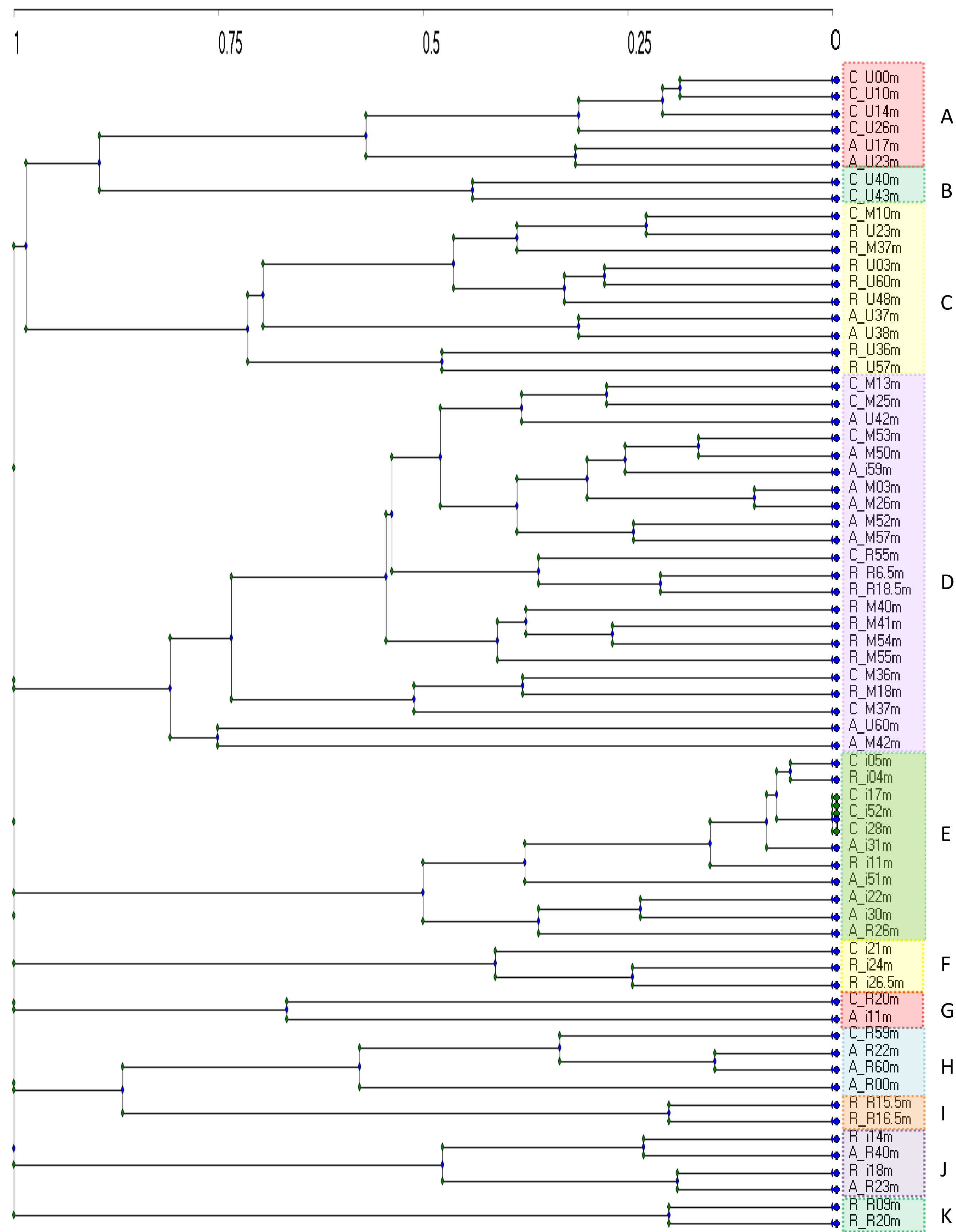
4.2.3 Vegetation Similarity.

The dendrogram presenting the Bray-Curtis dissimilarity matrix data calculated for each sample site is presented in Figure 31. For reference purposes, a complete Sorenson similarity matrix is also displayed in Appendix A. The first cluster of the dendrogram, cluster A (red) has a Bray-Curtis dissimilarity value of 0.57. Cluster A is exclusively composed of plots in the Undisturbed geomorphic unit. The exact breakdown if this group is: four plots in the Collinson Head Undisturbed zone, and two plots in Slump A's Undisturbed zone.

The B cluster (green) at the 0.44 level is comprised of two Undisturbed plots from the Collinson Head Slump. The C cluster (yellow) at the 0.71 level predominantly includes plots from the Undisturbed geomorphic units of all three slumps, with the exception of two Mature plots, the M 10m plot from the Collinson Head Slump and the M 37m plot from the Ranger's Slump. Cluster D (purple) is the largest cluster of the dendrogram and clusters at the 0.81 level. Cluster D includes sample plots from each slump and mainly represents the Mature geomorphic unit, with the exception of plot U 60m and U42m of Slump A, plot I 59m of Slump A, R 55m from the Collinson Head Slump, and plots R 6.5m and R 18.5m from the Ranger's Slump (Figure 31).

The E (green) cluster at the 0.5 level is composed almost entirely of Intermediate zone plots. Four of these plots are from the Collinson Head Slump, three are from Slump A and one is from the Ranger's Slump. There is also one Recent zone plot in this cluster, R 26m from Slump A. The F group (yellow) clusters at 0.41 and is made up of Intermediate zone plots from the Ranger's Slump and the Collinson Head Slump. Group G (red) clusters at the 0.67 level and contains one Recent zone plot from the Collinson Head Slump and one Intermediate zone plot from Slump A. The H group (blue), clusters at the 0.58 level and consists of Recent zone plots from Slump A and the Collinson Head Slump. Group I (orange) is composed of two Ranger's Slump Recent zone plots and clusters at the 0.2 level. The J cluster (purple) is grouped at the 0.48 level and is a mix of two Ranger's Slump Intermediate zone plots and two Slump A Recent zone plots. The final grouping, K (aqua), clusters at the 0.2 level and contains two Recent zone plots from the Ranger's Slump.

Figure 31 Dendrogram created using agglomerative cluster analysis and complete linkages and the Bray-Curtis dissimilarity index. The y-axis is the percent dissimilarity of each cluster (ranging from 0 to 1) and the x-axis shows each individual plot, where C stands for the Collinson Head Slump, A stands for Slump A, and R stands for the Ranger's Slump. The letter immediately following the underscore is the transect initial, which is followed by the plot ID (identified by the distance along the transect). The colour groupings represent the broadest clusters of sample plots, which are shown along the y-axis.


1
0.75
0.5
0.25
0
C_U00m
C_U10m
C_U14m
C_U26m
A_U17m
A_U23m
C_U40m
C_U43m
C_M10m
R_U23m
R_M37m
R_U03m
R_U60m
R_U48m
A_U37m
A_U38m
R_U36m
R_U57m
C_M13m
C_M25m
A_U42m
C_M53m
A_M50m
A_i59m
A_M03m
A_M26m
A_M52m
A_M57m
C_R55m
R_R6.5m
R_R18.5m
R_M40m
R_M41m
R_M54m
R_M55m
C_M36m
R_M18m
C_M37m
A_U60m
A_M42m
C_i05m
R_i04m
C_i17m
C_i52m
C_i28m
A_i31m
R_i11m
A_i51m
A_i22m
A_i30m
A_R26m
C_i21m
R_i24m
R_i26.5m
C_R20m
A_i11m
C_R59m
A_R22m
A_R60m
A_R00m
R_R15.5m
R_R16.5m
R_i14m
A_R40m
R_i18m
A_R23m
R_R09m
R_R20m
A
B
C
D
E
F
G
H
I
J
K

4.2.4 Species Occurrence.

Table 4 shows that very few species occur in every geomorphic zone, and the overall tendency is for overlapping species to occur in adjacent zones (e.g. Undisturbed and Mature, Mature and Intermediate, Intermediate and Recent). Only three species occur in all zones: *Arctagrostis latifolia, Polygonum viviparum,* and *Salix arctica* (Table 4). The most commonly occurring species in the Recent zone are *Senecio congestus* (9), *Poa sp.* (6), *Salix arctica* (6), "Moss 1" (6), and "Immature grass 1" (6); "Moss 1" and "Immature Forb 1" are the only species to occur solely in the Recent geomorphic unit (Table 4).

The most frequently occurring species in the Intermediate zone are: *Puccinellia sp.* (12), *Alopecurus alpinus* (8), and *Salix arctica* (6) (Table 4). *Achillea millefolium* and *Artemisia tilesii* occur exclusively in the Intermediate zone.

The most common plants in the Mature zone are *Salix arctica* (18), *Polygonum viviparum* (16), *Dryas integrifolia* (11), *Arctagrostis latifolia* (10), *Pedicularis lanata* (10), and *Astragalus umbellatus* (10) (Table 4). Eight species are found exclusively in the Mature zone: *Bupleurum americanum, Senecio cymbalaria, Oxytropis nigrescens, Oxytropis arctica, Saxifraga tricuspidata*, "Mushroom 1" and unidentified *Cetraria* and *Polytrichum* species.

The most commonly occurring plants in the Undisturbed zone are: *Dryas integrifolia*, *Cetraria cucullata*, *Polygonum viviparum*, *Salix arctica*, and *Pedicularis lanata* (12) (Table 4). Fifteen species (including bryophytes and vascular plants) are found only in the Undisturbed zone, most notably *Eriophorum vaginatum, Vaccinium vitis-idaea, Lupinus arcticus, Papaver radicatum, Polygonum bistorta,* and *Salix planifolia ssp. pulchra* and *Salix phlebophylla* (Table 4).

Table 4 Vegetation summary for the four geomorphic zones: Undisturbed (U), Mature (M), Intermediate (I) and Recent (R).

		U (*n*= 18)		M (*n*= 18)		I (*n*= 18)		R (*n*= 18)	
		F	*%C*	*F*	*%C*	*F*	*%C*	*F*	*%C*
Eriophorum	*vaginatum*	6	37						
Vaccinium	*vitis-idaea*	1	15						
Salix	*phlebophylla*	4	11						
Lupinus	*arcticus*	5	10						
Salix	*planifolia ssp. Pulchra*	7	8						
Equisetum	*arvense*	1	2						
Parrya	*nudicaulis*	2	1						
Hierochloë	*alpina*	1	1						
Polygonum	*bistorta*	6	1						
Saxifraga	*nelsoniana*	11	1						
Saussurea	*angustifolia*	4	+						
Myosotis	*alpestris*	1	+						
Papaver	*radicatum*	4	+						
Senecio	*atropurpureus*	4	+						
Luzula sp.		11	2	5	2				
Saxifraga	*hieracifolia*	1	1	1	1				
Salix	*reticulata*	10	16	2	5				
Valeriana	*capitata*	2	1	1	+				
Pedicularis	*lanata*	12	2	10	2				
Pedicularis	*capitata*	11	2	1	1				
Carex sp.		10	9	3	3				
Astragalus	*umbellatus*	9	1	10	4				
Dryas	*integrifolia*	17	22	11	11	1	1		
Oxytropis	*deflexa*	2	1	6	11	1	1		
Pedicularis	*verticillata*	2	+	5	2	4	2		
Stellaria	*longipes*	2	+	2	+	1	3		
Alopecurus	*alpinus*	1	1	8	5	8	12		
Oxytropis	*arctica*			4	12				
Oxytropis	*nigrescens*			4	6				
Bupleurum	*americanum*			1	1				
Saxifraga	*tricuspidata*			1	+				
Senecio	*cymbalaria*			1	+				
Castilleja	*elegans*			2	2	2	2		
Festuca sp.				8	2	1	0		
Artemisia	*tilesii*					3	1		
Achillea	*millefolium*					2	+		

	U (*n*= 18)		M (*n*= 18)		I (*n*= 18)		R (*n*= 18)	
	F	*%C*	*F*	*%C*	*F*	*%C*	*F*	*%C*
Senecio congestus					2	+	9	2
Puccinellia sp.					12	30	2	3
Matricaria ambigua					4	7	2	+
Petasites frigidus	1	10	2	+			1	+
Poa sp.	7	3	3	1			6	2
Arctagrostis latifolia	6	4	10	2	4	27	2	6
Polygonum viviparum	13	+	16	+	1	+	1	+
Salix arctica	13	8	18	34	6	10	6	4
Forb sp.	1	1						
Peltigera apthosa	2	+						
Moss 4	5	5	5	8				
Moss A	6	7	8	21				
Moss B	6	8	3	3				
Alectoria ochroleuca	1	1	1	1				
Cladonia sp.	2	+	1	+				
Thamnolia subuliformis	3	+	3	2				
Cetraria sp.			1	1				
Polytrichum sp.			1	6				
Mushroom 1			1	+				
Immature grass 1					1	+	6	+
Moss 1							6	2
Immature forb 1							2	+
Moss 2	1	2			4	9	2	+
Cetraria cucullata	16	1	8	+			2	+
Bare Ground						45		88
Litter		21		31		12		6

n, number of 1 x 1m quadrats placed in each geomorphic zone

F, frequency of occurrence in *n* quadrats, each 1 x 1m

%C, average percent cover in *n* quadrats; +, a value less than 1%

CHAPTER 5: DISCUSSION

Landscapes underlain by massive ground ice and ice-rich permafrost, such as those on Herschel Island, are inherently unstable and often display evidence of past and present thaw subsidence. Thermokarst and other forms of thaw induced erosion and mass wasting are naturally occurring processes on Herschel Island, and play an important role in the evolution of permafrost landscapes. Local variation within these landscapes is driven by topography, surface processes and vegetation. Given the cyclic pattern of disturbance, stabilization, and subsequent revegetation of stabilized surfaces, there exists a patchy landscape surrounding disturbed surfaces where the vegetation pattern is a reflection of geomorphic stage and time since disturbance. Particularly interesting are the revegeation patterns surrounding retrogressive thaw slumps on Herschel Island. These slumps are a progressive form of backwasting thermokarst that tend go through cycles of activity, frequently re-activating within the same area over the course of hundreds of years. Slumping and stabilization of the slump floor in these cases is a complex process involving a change in local slope, microtopography, soils, soil chemistry and microlimate. Chapters 3 and 4 summarize the systematic analysis and observation of several aspects of the changes observed around three retrogressive slumps on Herschel Island. The following provides an explanation of the vegetation patterns and soil characteristics observed in each geomorphic unit, and presents an analysis of the patterns of revegetation following large and small-scale slumping on Herschel Island.

5.1 Zone Characteristics: Soil

As mentioned earlier, the temperature regime and permafrost table depths observed within the thaw slumps are consistent with observations reported in previous studies (Lambert, 1972; Lantz *et al*., 2009). The absence of vegetation cover and the prevalence of dark coloured mud surfaces in the Recent zone results in the highest surface and 10 cm temperatures recorded in this study, followed by the Intermediate zone. This difference can be explained by the higher litter and total percent plant cover values in the Intermediate zone, which would tend to reduce heating by insolation. As the ground surface revegetates, less heat is absorbed into the soil because the ground is shaded and the albedo increases: for example dark, bare soil has an albedo of 0.05 and tundra has an albedo of 0.18-0.25 (Budikova *et al.*, 2010). As would be expected, the depth of the permafrost table follows this general trend; as plant cover and canopy complexity increase following disturbance, the active layer depth decreases. Since the Mature zone lacks the diversity of vegetation canopy layers that are present in the Undisturbed zone, there is less microclimate variation and the lack of the insulating air pockets created by plant cover might explain the increase of temperature between the Mature and Undisturbed zones.

Kokelj *et al*. (2002) found that the soil organic matter content on Herschel Island was higher at disturbed sites than in the underlying permafrost. My study confirms those results, revealing a distinct trend in soil organic matter content from one zone to the next, and this is paralleled by the moisture content values observed in this study. In each case, the trend from highest to lowest values was U →M→R→I. The Undisturbed transect likely has the highest organic matter content because it possesses the highest overall percent cover of litter and the most established active layer and therefore root systems. Increased organic matter content, in turn, increases the water holding capacity of the soil. The Mature zone, with the second greatest level of plant cover, has greater drainage than the Undisturbed zone. The higher organic matter content of the Recent zone relative to the Intermediate zone is the result of the vegetation islands and the turnover of the active layer within the Recent zone, as compared to the settled environment of the Intermediate zone where very few vegetation islands were observed and most headwall vegetation had been buried by successive mud flows. These findings compliment the study by Kokelj *et al*. (2002) on Herschel Island, who found that the soil organic matter content was higher at disturbed sites than in the underlying permafrost. One would therefore expect the Mature zone to have a higher organic matter content than the reconstituted Intermediate and Recent zones, which are largely composed of soil from the underlying permafrost.

The pH values recorded in this study directly reflect the stages of slump maturity, where the most acidic soils are found in the Undisturbed zone, followed by the Mature, Intermediate and Recent zones. These findings are consistent with the study by Kokelj *et al*. (2002), who found that at disturbed sites the soluble cation concentrations in the active layer were greater than in the undisturbed active layer by 1-2 orders of magnitude, but that the concentration declined with the age of disturbance. Kokelj *et al.* (2002) found higher concentrations of soluble Ca^{++} in soils in the underlying permafrost than in the active layer at all study sites on Herschel Island, suggesting that cation leaching from the active layer occurs over time. This is supported in the present study by the observation of a mineral efflorescence within the slump floor, and is also consistent with Lambert's (1972) study of thaw slumps which concluded that the exposed soil of a mudflow is only moderately to slightly acidic compared to the strongly acidic condition of the surrounding climax community (pH 4.6). Interestingly, Kokelj *et al*. (2002) also found high concentrations of soluble Na^{+} within the permafrost on Herschel Island, and suggested that the degradation of permafrost may result in locally salinized or sodic soil which could be toxic to plants if in significant concentrations. This implies that the initial colonizers in the Intermediate and Recent zones may need to be adapted to sodic or saline soil conditions, since it is likely that the unknown precipitate recorded in this study is a form of salt.

5.2 Geomorphic Zone Characteristics: Vegetation

5.1.1 Undisturbed Zone.

The Undisturbed zone consists mainly of what has been described as *Eriophorum* tussock tundra, described by Smith *et al.* (1989) as the characteristic terrain of the oldest and most stable land surface on Herschel Island. This zone has the highest alpha diversity as measured by species richness, the Shannon index, and the Simpson index. This is consistent with the conclusions of previous arctic vegetation studies which found that species richness is typically lower at disturbed sites than undisturbed sites because low germination rates combine with reduced habitat heterogeneity at disturbed sites to decrease species richness (Ebersole and Webber, 1983; Forbes *et al.*, 2001).

This vegetation community is reflected in clusters A, B and C of the dendrogram in Figure 31. These are very distinct grouping, having only two exceptional plots between the three of them. One of these plots, M 37m at the Ranger's Slump, is dissimilar from the rest of the Mature zone plots due to the domination of *Dryas integrifolia*, which is more typical of the Undisturbed zone. Because this species is a slow-growing evergreen (Jones and Henry 2003), it is probable that this plot represents a vegetation island which became established during stabilization, allowing viable *Dryas* propagules to establish. Alternatively, it may also reflect a lower rate of removal of organic materials by mud flow in the slump floor. It is difficult to explain why the M 10m plot of the Collinson Head Slump belongs in this group, given that neither its elevation nor the surrounding topography make it exceptional within the Mature transect (Appendix D; Figure 20).

Smith *et al.* (1989) grouped the vegetation on Herschel Island into 11 classes which they called "vegetation types" based primarily on the dominance of species in each canopy strata. Dominance was determined by cover values, and the vegetation types were named to reflect their physiognomic structure by strata, where the dominant physiognomic feature of a stratum was generally the dominant species as determined by percent cover. Each of these zones were described in the study and illustrated in "Map 1" of the document, and upon matching the vegetation classes based on terrain units using the IKONOS 2001 slump images at the same scale, the Undisturbed geomorphic unit of each slump falls into the "Cottongrass/moss" and "Arctic willow/Dryas-Vetch" vegetation classes. Smith *et al.* describe the "Cottongrass/moss" community as a stable, climax community dominated by tussocks of cottongrass (*Eriophorum vaginatum*), interspersed with well-developed moss cover and scant lichen cover. They specify that this vegetation class contains sparse but ubiquitous low shrubs such as *Salix reticulata, Salix arctica,* and *Salix planifolia* and ericaceous shrubs such as *Vaccinium* spp. in addition to a variety of forbs present in low frequency, including *Dryas integifolia, Polygonum bistorta, Pedicularis capitata, Papaver spp., Sausserea angustifolia,* and *Valeriana capitata*. This type also includes a well developed moss layer and trace amounts of lichens including *Cetraria cucullata, Thamnolia subuliformis,* and *Alectoria ochroleuca*, all of which were found in the Undisturbed and Mature zones of the present study. The classification by Smith *et al.* (1989) is thus largely consistent with the results of this study, although there was only one instance of an ericaceous shrub, *Vaccinium vitis-idaea,* and the high frequency and percent cover of *Dryas* *integrifolia* observed in this study is not included in Smith *et al.*'s "Cottongrass/moss" vegetation class (Table 4).

The species absent from the "Cottongrass/moss" vegetation class but observed in the Undisturbed zone of this study are included in the "Arctic Willow/Dryas-Vetch" class. Smith *et al.*, describes this class as occurring on mesic sites associated with non-sorted patterned ground, or sites of moderately eroded terrain where vegetation cover is discontinuous and characterized by bare soil (up to 80%) interspersed with dense mats of *Dryas integrifolia* and bryophytes. This vegetation type was not observed in my study, and may be characteristic of degraded tundra associated with disturbances other than retrogressive thaw slumps. Indeed, Smith *et al.* (1989) identify this type as relatively stable for the sites at which it occurs being that these sites are often exposed and soil drainage is not impeded. In terms of specific species, however, there are some similarities between the "Arctic Willow/Dryas-Vetch" class and the Undisturbed zone as defined in this study. Smith *et al.* elaborate on the general description of the terrain by stating that on vegetated areas, *Salix arctica* is the dominant shrub, while *Salix reticulata* is present with a low percent cover. Forb species with a low percent cover but high frequency are said to include *Astragalus umbellatus, Alopecurus alpinus, Lupinus arcticus, Parrya nudicaulis, Myostis alpestris, Pedicularis capitata* and lichen species including *Cetraria cucullata, Thamnolia subliformis,* and *Alectoria ochroleuca,* all of which were found in the Undisturbed zone of this study with varying frequencies (Table 4). The fact that the Undisturbed zone sample plots form distinct clusters using the Bray-Curtis dissimilarity measure of beta diversity and that there is a diverse yet distinct vegetation composition of this geomorphic unit suggests that, as hypothesized, there is indeed an identifiable undisturbed community characteristic of sites unaffected by disturbance.

5.1.2 Mature Zone.

The alpha diversity of the Mature zone is lower than the Undisturbed zone in this study, having been disturbed at all sites by a previous cycle of slumping. This is not surprising, given that the altered abiotic conditions (e.g. pH, nutrient availability, ground thermal regime) observed in stable thaw slumps suggest that the effects of disturbance endure for decades to centuries and that vegetation is still developing (Lantz *et al*., 2009). Since this zone is a reconstituted slump scar, the irregular surfaces characteristic of the Undisturbed zone are absent, thus there are fewer microhabitats for species to inhabit and therefore reduced species diversity (Smith *et al.*, 1989). In the case of thaw slump scars specifically, the residual concave morphology can likely be sustained for centuries, meaning that elevated snow accumulation (which inhibits ground heat loss and delays freezeback compared to the undisturbed tundra) and distinct abiotic conditions also persist (Lantz *et al*., 2009). Visually, the colour and texture of the Mature zone is distinct and the boundaries are easily discernable on the ground or from the air even to those unfamiliar with the polycyclicity of these thaw slumps (Figures 14, 17, 20). The specific vegetation community repeats at each stabilized slump scar in this study and many others observed on Herschel Island. This consistency is likely due in part to the fact that in arctic environments, a shortage of efficient colonizers means that many of the same species occur repeatedly in disturbances of different ages and origins (Forbes *et al.*, 2001).

This geomorphic unit is represented by dendrogram cluster D (Figure 31). Where exceptions to the dominance of Mature zone plots occur, their physical location can usually explain the discrepancy and the hypothesis of a uniform zone of vegetation is still upheld. It is especially revealing to examine the exceptions to the overall trend of Mature zone plots in cluster D. The Intermediate zone sample plot in this cluster, Slump A plot 59m, is the furthest west of all of the plots in this transect and is the only plot which falls outside of the 2001 boundaries of this slump (Figure 19; Appendix D). As such, it is likely that the level of disturbance at this site has been less than that of the adjacent plots, and its proximity to the Mature zone (Figure 19) has allowed a greater dispersion of propagules from nearby vegetation, which is supported by the dominance in this plot of *Salix arctica* in this plot. The other anomalous plots in this cluster are from the Recent zone of the Ranger's Slump and the Collinson Head Slump. Surviving vegetation islands occur in all three exceptional plots, making them floristically more similar to the Mature zone from which they originated than the rest of the Recent zone.

The presence of two Undisturbed unit plots in cluster D is particularly interesting. The Undisturbed zone plot 60m from Slump A is the furthest west of all of the Undisturbed transect plots and is in close proximity to the broken terrain resulting from a previous episode of slumping (Figure 19; Appendix D). It is likely that dissimilar drainage conditions at this site have affected the vegetation community, which would explain the variation between this plot and the rest of the Slump A's Undisturbed plots which fall into clusters A and B. Both plot M 37m and M 36m at the Collinson Head slump are located in an area of the Mature zone which, based on the 2001 IKONOS image, appears to have been within the limit of a previous disturbance (Appendix D) and likely distinct for the same reason as the Undisturbed 60m plot of Slump A. Continuing this pattern, the M 18m plot from the Ranger's Slump Mature zone is exceptional within that transect since it is the closest to the old headwall area and is located just downslope of an unevenly textured area which could affect its microclimatic conditions differently than the rest of the transect plots (Appendix D). The presence of the U 42m of Slump A's Undisturbed zone in this grouping is difficult to explain. Being of average relative elevation for this transect

(Appendix B) and not having significant anomalous landscape features surrounding it (Figure 19; Appendix D), the difference may be attributed simply to natural variation within the zone.

The location of this zone corresponds to the "Arctic Willow/Dryas-Vetch," "Arctic Willow/Lupine-Lousewort," and "Willow/Saxifrage-Coltsfoot" vegetation types described by Smith *et al*. (1989). As described above, the "Arctic Willow/Dryas-Vetch" zone is not entirely consistent with the results of this study, although many of the forbs identified are indeed present and *Salix arctica* is the dominant shrub. It has been suggested that *Salix arctica* is well adapted to areas with drier, older terrain due to its high below: aboveground biomass ratio and the fact that is has ectomycorrhizae (a symbiotic relationship between a fungus and the plant's roots which facilitates nutrient transfer)(Jones and Henry 2003; Cripps and Eddington, 2005). Interestingly, ectomycorrhizae has also been observed with *Polygonum viviparum* and *Salix reticulata,* which are also observed in this zone (Jones and Henry 2003; Cripps and Eddington, 2005).

Smith *et al*.'s description of both the "Willow/Saxifrage" and "Arctic Willow/Lupine-Lousewort" vegetation classes, also included in the Mature zone, is similar in many ways. Both classes are described as continuous and established on moderately eroded, unstable terrain where *Salix arctica* is the dominant shrub and *Salix reticulata* also occurs. A well developed moss layer is also a common feature of both classes, although it is considered ground cover in the "Willow/Saxifrage" class but occurs in depressions between hummocks in the "Arctic Willow/Lupine-Lousewort" class. Lichens are said to be scarce in the "Willow/Saxifrage" class and scattered throughout in the "Arctic Willow/Lupine-Lousewort" class, and whereas graminoids are sparse or absent in the "Willow/Saxifrage" class they include *Carex* and *Luzula* spp. in the "Arctic Willow/Lupine-Lousewort" class. It therefore appears as though the Mature zone of the slumps studied are most closely related to the “Arctic Willow/Lupine-Lousewort” class, although given the diversity of forbs that Smith describes in both classes and the lack of hummocks in the Mature zone there is clearly some overlap between the “Willow/Saxifrage” class and the Mature zone vegetation as well.

5.1.3 Intermediate and Recent Zones.

The least differentiated vegetation classes are found in the Intermediate and the Recent geomorphic units, although there are distinct clusters that include only Intermediate and Recent zone plots and there are abiotic conditions particular to each zone (Appendix A). Total plant cover is higher in the Intermediate zone than the Recent zone, where bare ground predominates. Species richness varies marginally by slump, and is highest in the Intermediate zone and sections of the Recent zone containing vegetation islands, although other measures of diversity show no notable difference. The higher than expected diversity in the Recent zone can be explained by the presence of vegetation islands which contain species from the Mature zone. These islands are not generally present in the Intermediate zone, since further away from the headwall the unstable nature of the substrate combined with seasonal burial under a layer of liquid mud tend to envelop the islands (Lambert 1976); the almost identical Shannon index and Simpson index values for the Recent and Intermediate zones are likely a result of this as well.

The decreased differentiation of the Intermediate and Recent zones is principally due to the complex nature of the abiotic site characteristics of the slump floor (e.g. moisture, time since disturbance). These differences in slump floor stability have been attributed to cross-slump differences in headwall elevation, where mud in the slump floor more frequently covers lower portions of the slump headwall, decreasing the rate of ablation and resulting in a slower rate of headwall retreat at these locations (Lewkowicz 1986). In some slumps, headwall sections with low ice contents tend to stabilize while retreat continues in adjoining areas that are ice rich, creating a dynamic pattern of slump floor stability which may leave one area of ground undisturbed long enough for plants to colonize (Lewkowicz 1986). This phenomenon is especially evident at the sides of Slump A and Ranger's Slump as well as at the headwall of the Collinson Head Slump. Based on a Ground Penetrating Radar (GPR) study of the Collinson Head Slump, the higher portion of the headwall is ice rich whereas the lower west side of the headwall appears to be exhausted and shows early signs of stabilization (Figures 7, 12, 20; Angelopoulos *et al. in preparation*). Thus, diversity may vary with location within the slump floor, and for future studies it may be more informative to examine the specific vegetation communities as a whole as opposed to relying on alpha diversity measures.

Based on the dendrogram dissimilarity clusters, there are several clear patterns that emerge between the zones. Cluster E is the second largest cluster, and contains only one exceptional plot interrupting the dominance of Intermediate zone plots: R 26m of Slump A. In addition to being one of the drier Recent zone plots, the small *Puccinellia* and *Marticaria* sprouts identified in this zone put it closer along the floristic spectrum to the Intermediate zone than the Recent zone (Appendix D). From this and the remaining clusters, one begins to appreciate the complex nature of the slump floor and how individual plots can be affected differently by mud flow disturbances depending on their unique location. Although cluster F is composed of only Intermediate zone plots, it contains only three sample plots. Clusters G and J are mixed, whereas clusters H, I and K are composed only of Recent zone plots. This Intermediate and Recent zone variation notwithstanding, it is interesting to note that these clusters include plots from each slump, and despite a few notable exceptions are impressively homogeneous by geomorphic unit.

In terms of individual species occurrence, one of the two species occurring only in the Recent zone, "Moss 1," is a bryophyte found only in the moist cracks of the slump floor. This is consistent with Lambert's (1976) finding that areas of the slump floor not covered by *S. congestus* supported colonies of *Bryum* sp. moss and the Smith *et al.* (1989) study on Herschel Island which found bryophyte species in the moist surface fissures of disturbed areas. The unidentified species "Immature Forb 1" is almost certainly a juvenile form of one of the other grasses found in the slump floor environment. Despite the potential advantage that ectomycorrhizae gives to *P. viviparum* and *S. arctica*, these species only occur on vegetation islands in the Recent zone, which also true where *P. viviparum* occurs in the Intermediate zone.

A key distinction of the Recent zone versus the Intermediate zone is the presence of *Senecio congestus* in the Recent zone versus *Arctagrostis latifolia* and other grasses in the Intermediate zone, and previous studies of vegetation succession on thaw slumps support this differentiation. In particular, *Senecio congestus* has been noted as a prominent first colonizer of actively eroding silty outwashes on Alaska's North Slope (Hok, 1969), in Inuvik (Hernandez, 1973a), on Garry Island (Lambert, 1976), and on Herschel Island itself (Smith *et al.*, 1989). *Arctagrostis latifolia* is a major component of plant cover in disturbed areas but only minimally present in undisturbed communities (Hernandez, 1973a). Lambert (1972; 1976) has suggested that when stabilization progresses and the soil dries out, seeds of *A. latifolia* are able to germinate and compete with *S. congestus*, and the frequency of *A. latifolia* increases as the dominance of *S. congestus* decreases (Bartleman *et al*., 2001). Indeed, Lambert (1976) found a strong negative correlation between *A. latifolia* and *S. congestus*, (r = -0.793) and the relationship was highly significant with decreasing surface moisture and increasing age of the site. Eversole and Webber (1983) also found that reworked permafrost soils were colonized by *A.*

latifolia, and Lantz *et al*. (2009) observed that on Herschel Island active slumps were generally dominated by both *A. latifolia*, and *S. congestus*. Within the Mackenzie Delta, both *Artemisia. tilesii* and *S. congestus* were found uniquely in active slumps (Lantz *et al*., 2009; also McKendrick, 1987). Whereas *S. congestus* requires a water-logged mineral substrate, *A. latifolia* establishes on mineral soil with free drainage (Lambert, 1976). The process of succession between these two species has been described by Lambert (1976) as follows: "*S. congestus*, being the initial pioneer, lacks competition, and with its short, compact root system (less than 10 cm penetration) it is well adapted to the unstable, liquid mud substrate" of the Recent zone (Lambert, 1976: 1756). *Arctagrostis latifolia*, on the other hand, has a higher root: shoot ratio (Lambert, 1976). Lambert (1976) has suggested that the increase in root biomass of later colonizers reflects the increased stability of the substrate, and competition from neighbouring species for essential moisture and nutrients; these are precisely the conditions which characterize the Intermediate geomorphic unit. Although slower to establish and more susceptible to competition as a seedling, *A. latifolia* grows quickly and can flower by the second year (Younkin 1973). As soil pH and plant available nutrients (Ca^{2+} and SO^{-}_{4}) decrease with leaching and the water source (ice-rich headwall) retreats further upslope, *A. latifolia* gains the advantage (Lantz *et al*., 2009).

With further drainage and competition, other grasses such as *Poa arctica* (Lambert, 1976; Bliss, 1979), *Puccinellia* spp. (Ovenden, 1986; Forbes and Jefferies, 1998), and *Alopecurus alpinus*, invade the disturbed slump floor (Bliss, 1979). Additionally, Ebersole and Webber (1983) have suggested that grasses and willows are preadapted as colonizers of bare soil based on their abundant, wind-dispersed seeds, and that once established these high-turnover species quickly form dense stands due to the favourable nutrient regimes created by disturbance (Forbes and Jefferies, 1998). These species-specific characteristics would suggest that the findings of this study are in keeping not only with similar arctic vegetation disturbance studies but also with the expected successional patterns of disturbed tundra. The vegetation community characteristic of the Intermediate zone has been found to persist over medium (<30 years) periods of time since colonizers inhibit the establishment of other species, especially the slower-growing dominants of the undisturbed tundra (Ebersole and Webber, 1983). Ebersole and Webber (1983) suggest that these communities will persist for several hundred years, until the nutrient regime is no longer enhanced by the rapid decomposition created by good drainage and higher soil temperatures of the Intermediate zone.

The location of the Intermediate and Recent geomorphic units at all sites corresponds to the "Grass/Chamomile-Wormwood" vegetation type, described by Smith *et al*. as establishing downslope from retrogressive thaw slumps and having a high percentage of exposed soil and a permafrost table >50 cm below the surface. Smith *et al.* consider this an early successional stage maintained by the frequent deposition of fine-grained sediment, with flora originating from wind-borne propagules of typical pioneer species (e.g., *Matricaria spp.*), and strongly nitropholous grasses (e.g. *Alopecurus alpinus*), in addition to remnants of mature vegetation (e.g., *Salix arctica*) which have sloughed off the adjacent terrain and headwall. *Smith et al.* suggest that as slump stabilization occurs, steep slopes will evolve into the arctic "Willow/Lupine-Lousewort" type while gentle slopes will develop into the "Willow/Saxifrage-Coltsfoot" type.

5.3 Successional Patterns

Whereas Forbes *et al.* (2001) found that early-successional communities occupying many disturbed patches are self perpetuating, my results suggest that there is a progressive recolonization dynamic. On natural silty tundra mudflows, it has been suggested that succession proceeds in a two-step process (Lambert, 1972; Hernandez, 1973b). The first step is an initial colonization of the bare surface by species such as *Senecio congestus* and *Arctagrostis latifolia*, followed by an increase in plant cover through the gradual expansion of vegetation islands which survived the fall from the headwall (Hernandez, 1973b). Based on the results of my study, however, there appears to be a relationship between the scale of a landscape disturbance and the pattern of revegetation. In the case of smaller retrogressive thaw slumps such as the Ranger's Slump, the presence of *S. arctica* follows the pattern of succession outlined by Lambert (1972) and Hernandez (1973b). For these slumps, the relatively small height of the headwall means that the mechanical process of melting and repositioning of vegetation islands is different than that of larger slumps. Less ice in the headwall means that there is a comparatively shallower pool of liquid mud at the base of the headwall capable of drowning out the vegetation island, as well as less mud volume overall to envelop established vegetation islands in the slump floor. Also, the smaller headwall means that vegetation islands will tend to slide down the face of the headwall and land right-side-up as opposed to tumbling down it, which is the case in larger slumps.

In larger slumps, the scale of disturbance is such that surviving vegetation islands in the Intermediate zone are extremely rare. This suggests that the pattern of succession of Slump A and the Collinson Head Slump is a multistage process. The first step consists of initial colonizing plants establishing themselves from propagules, followed a series of indistinct stages thereafter where vegetation expands from surviving sections at the side of slumps or lower portions of the headwall. Eventually, the stabilized slump scar is covered by the Mature zone vegetation community found at the Ranger's Slump and behind the headwall at Slump A and the Collinson Head Slump (Figures 14, 17, 20). The decreasing annual rate of headwall retreat of the Collinson Head Slump and the static nature of the entire west side of its headwall suggests that the stabilization and revegetation process is likely already underway (Figures 7, 12, 20). The existence of two divergent patterns of slump revegetation suggests that given reference studies, it would be possible to assess how and when revegetation will occur based on the size of a slump and if it is known to be polycyclic.

In terms of a successional time frame for Herschel Island, it is clear that the revegetation process proceeds over a long period of time, and though the Mature zone vegetation community may otherwise achieve the physical and floristic characteristics of the Undisturbed zone, this is interrupted by the polycyclic nature of these slumps. Indeed, Kokelj *et al.* (2002) attribute the high floristic diversity of Herschel Island in part to the cycle of permafrost degradation, resulting soil salinization and cation leaching from the active layer created by polycyclicity. To give an idea of the time scale of succession, in a study of the vegetation succession in drained thermokarst lakes on the coastal plain of northern Alaska, Forbes and Jerreries (1998) suggested a time scale of the order of 1000 years or more. They justified this estimate by citing the rates of colonization and frequent physical disturbance at micro- and meso-scales, as well as the low Arctic resource base associated with low temperature, a short growing season and slow rates of decomposition and nutrient turnover. Although Lambert (1972) suggests that slumps stabilize when the overhanging vegetation collapses over the exposed permafrost and that colonization of mud surfaces occurs only once the slump becomes inactive, the study sites on Herschel Island show that in all cases an Intermediate zone was established over a large portion of the slump floor while the slump was still active. Based on the results of this study, it would seem that once gullying has established channels of mud flow, certain areas of the slump become stable and are colonized quickly while other areas continue to experience disturbance. While the tundra ecosystem is known for its lengthy disturbance recovery time, the time necessary for each slump studied to establish the Intermediate geomorphic zone was only eight summers. This is clearly evident from Figures 16, 19, and 22, where the Intermediate transects of each slump are completely encompassed in the 2001 extent of the slumps, each in sections that would most probably have been active mudflow areas at that time. This suggests that slump floor recolonization may proceed in a staggered manner, where initial colonization of wet, still active mud floors by early colonizers like *S. congestus* occurs very quickly (Recent zone), and within 10 years portions of the slump have stabilized sufficiently to allow a relatively stable community of grasses and forbs (Intermediate zone). This gradually transforms into the Mature zone vegetation community over a very long period of time. Even in the medium term (>75 years), Forbes *et al.*, (2001) found that none but the smallest, wettest patches of disturbance recovered unassisted to anything close to their original vegetation cover, implying that although the establishment of initial plant cover occurs surprisingly rapidly, further species replacement proceeds at a much slower rate due to the decrease in moisture and nutrient availability. This theory is reflected in the conclusions of Forbes *et al.* (2001) who found that surface moisture limits both short- (20-year) and medium-term (20-75 year) recovery, and that vegetation regeneration is generally fastest in wet sites and slowest in dry sites.

5.4 Implications for Restoration

In his study on Garry Island in the Mackenzie Delta, Lambert (1976) found that human-initiated mud slumps appear to follow a similar pattern of recession and gradual stabilization as naturally occurring slumps. Based on this, Lambert suggests that attempts to artificially revegetate mud slumps before stabilization has occurred would be impractical since "if native species can establish as rapidly as they appear to… then it seems far more sensible to allow nature to follow its own course" (Lambert, 1976: 1758). In saying this, however, Lambert implicitly assumes that the climate and physical environment that these native species are adapted to is static. As we are observing in this century, climate is not a stable phenomenon and its slightest aberrations are responded to very strongly in marginal environments (Svoboda and Henry, 1987). Based on previous research, it is also known that in the Arctic these aberrations have had a profound impact on vegetation in the past (Svoboda and Henry, 1987) and that tundra vegetation is responding to rapidly to currently warming circumpolar temperatures (Chapin *et al*., 1995; Stow *et al.*, 2004; Tape *et al*., 2006). The impact of disturbance on arctic vegetation communities is likely to increase as the Arctic warms further and the frequency of thermokarst features such as retrogressive thaw slumps increases (Lantz *et al*., 2009). In their study of the relative impacts of disturbance and temperature on persistent changes in the microenvironment and vegetation in retrogressive thaw slumps, Lantz *et al*. (2009) assert that disturbance caused by warming has a larger and more immediate impact on Low Arctic ecosystems than temperature increases alone, and as the number and extent of these slumps increase these disturbances will have an increasing influence of the vegetation communities of the Low Arctic. Understanding the current and past rate and composition of vegetation sequences during succession is therefore an important direction for future research both for managing the restoration of artificially disturbed sites and for predicting what future community structure will be, since the exposed substrate created by disturbance provides unique opportunities for the rapid colonization and movement of species beyond their present geographic ranges (Bartleman *et al*., 2001; Lantz *et al*., 2009).

CHAPTER 6: CONCLUSION

This thesis has argued that there are distinct vegetation communities associated with the geomorphic units surrounding a retrogressive thaw slump, representing their relative age and the degree of stabilization. At all slumps studied, there are clear differences in the soil conditions in the Undisturbed, Mature, Intermediate, and Recent geomorphic units, including the organic matter content, pH, water content, active layer depth, and soil temperatures. However, there is less distinction between Intermediate and Recent geomorphic units than between any other unit, since the nature of Intermediate and Recent unit plots can vary depending on individual site characteristics (e.g. moisture, recentness of disturbance). In terms of vegetation, there is also less differentiation between the Intermediate and Recent units than the other units, likely due to the variability of the slump floor. Overall, many individual species occur in only one geomorphic unit, and could therefore be used as indicator species. Where unit overlap takes place, the tendency is for adjacent geomorphic units to share vegetation; very few species encountered in this study occurred in all units. A detailed analysis of the beta diversity results has shown that anomalies in this overall pattern of vegetation fidelity can be explained by the presence of vegetation ‘islands’ (surviving remnants of the headwall vegetation) in the Recent and (rarely) Intermediate units. It is these ‘islands’ which are likely responsible for part of the revegetation of retrogressive thaw slumps, although this thesis suggests that this is scale dependent.

Although this thesis suggests that the consistency of vegetation patterns within and surrounding slumps can be used to reconstruct a slump’s geomorphic history and monitor changes, there is growing evidence that tundra vegetation is responding to rapidly warming circumpolar temperatures. Since vegetation exerts strong controls on local ecosystem processes, understanding the effects of disturbance on short-term and long-term revegetation patterns is a critical component of understanding the effects of climate change on the Arctic. The examination of tundra plant diversity is a field of study that has not been extensive, and if we are to assess vegetation change in the future, reliable species lists and classification studies are critical. Suggested subjects for further research therefore include a comparison between the revegetation patterns of ‘old’ versus ‘new’ slumps to assess the ongoing effects of climate change in the Western Arctic, and a comprehensive vegetation study examining the vegetation associated with different types of thermokarst.

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APPENDIX A

Sorensen Index similarity matrix showing the similarity score for each sample plot. Plot created using the binary no double zero method of Community Analysis Package software. Reading the axes, C stands for the Collinson Head Slump, A stands for Slump A, and R stands for the Ranger's Slump. The letter immediately following the underscore is the transect initial, which is followed by the plot ID (identified by the distance along the transect).

COLLISON SLUMP

	C_U00	C_U10	C_U14	C_U26	C_U40	C_U43	C_M10	C_M13	C_M25	C_M36	C_M37	C_M53	C_i05	C_i17	C_i21	C_i28	C_i52	C_R20	C_R55	C_R59
C_U00																				
C_U10	0.6																			
C_U14	0.6	0.7																		
C_U26	0.6	0.7	0.6																	
C_U40	0.6	0.5	0.6	0.6																
C_U43	0.6	0.7	0.7	0.6	0.7															
C_M10	0.3	0.3	0.3	0.5	0.5	0.4														
C_M13	0.2	0.2	0.2	0.2	0.4	0.2	0.5													
C_M25	0.4	0.3	0.4	0.5	0.5	0.5	0.6	0.4												
C_M36	0.3	0.4	0.2	0.3	0.3	0.2	0.4	0.2	0.5											
C_M37	0.2	0.3	0.2	0.3	0.4	0.2	0.4	0.1	0.4	0.7										
C_M53	0.3	0.3	0.3	0.5	0.5	0.3	0.7	0.4	0.7	0.7	0.6									
C_i05	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.3	0.3	0.2								
C_i17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7							
C_i21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.3	0.3	0.2	1.0	0.7						
C_i28	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	1.0	0.7					
C_i52	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	1.0	0.7	1.0				
C_R20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0			
C_R55	0.2	0.1	0.1	0.2	0.3	0.1	0.4	0.2	0.3	0.2	0.2	0.3	0.0	0.0	0.0	0.0	0.0	0.0		
C_R59	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.3	
R_U03	0.3	0.3	0.3	0.4	0.6	0.4	0.6	0.4	0.5	0.3	0.3	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0
R_U23	0.3	0.2	0.3	0.5	0.5	0.3	0.6	0.3	0.4	0.4	0.4	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0
R_U36	0.6	0.4	0.5	0.6	0.8	0.6	0.6	0.4	0.5	0.3	0.3	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0
R_U48	0.5	0.4	0.4	0.5	0.7	0.6	0.5	0.3	0.5	0.3	0.2	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0
R_U57	0.5	0.3	0.4	0.6	0.7	0.6	0.5	0.3	0.5	0.4	0.3	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0
R_U60	0.5	0.4	0.4	0.5	0.7	0.6	0.6	0.3	0.5	0.4	0.4	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0
R_M18	0.5	0.5	0.5	0.6	0.7	0.6	0.5	0.4	0.6	0.6	0.5	0.6	0.1	0.0	0.1	0.0	0.0	0.0	0.2	0.0
R_M37	0.3	0.2	0.4	0.4	0.5	0.4	0.4	0.4	0.6	0.5	0.4	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
R_M40	0.3	0.3	0.3	0.4	0.4	0.3	0.4	0.3	0.4	0.5	0.5	0.5	0.2	0.0	0.2	0.0	0.0	0.0	0.1	0.0
R_M41	0.2	0.3	0.3	0.4	0.5	0.3	0.5	0.3	0.3	0.6	0.7	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0
R_M54	0.3	0.3	0.4	0.4	0.5	0.5	0.5	0.4	0.6	0.4	0.5	0.5	0.1	0.0	0.1	0.0	0.0	0.0	0.2	0.0

	C_U00	C_U10	C_U14	C_U26	C_U40	C_U43	C_M10	C_M13	C_M25	C_M36	C_M37	C_M53	C_i05	C_i17	C_i21	C_i28	C_i52	C_R20	C_R55	C_R59
R_M55	0.0	0.0	0.1	0.1	0.2	0.1	0.3	0.2	0.4	0.3	0.5	0.5	0.3	0.0	0.3	0.0	0.0	0.0	0.2	0.0
R_i04	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.4	0.3	0.3	0.8	0.5	0.8	0.5	0.5	0.0	0.0	0.0
R_i11	0.0	0.0	0.0	0.0	0.1	0.0	0.2	0.1	0.1	0.3	0.3	0.2	0.5	0.7	0.5	0.7	0.7	0.0	0.3	0.0
R_i14	0.1	0.0	0.0	0.0	0.2	0.0	0.2	0.2	0.3	0.6	0.4	0.4	0.3	0.0	0.3	0.0	0.0	0.0	0.2	0.0
R_i18	0.1	0.0	0.0	0.0	0.1	0.0	0.2	0.1	0.3	0.6	0.4	0.4	0.7	0.4	0.7	0.4	0.4	0.0	0.2	0.0
R_i24	0.0	0.0	0.0	0.1	0.2	0.0	0.1	0.2	0.2	0.4	0.4	0.3	0.3	0.0	0.3	0.0	0.0	0.0	0.4	0.3
R_i26.5	0.0	0.0	0.0	0.0	0.1	0.0	0.2	0.1	0.2	0.5	0.6	0.3	0.5	0.0	0.5	0.0	0.0	0.0	0.3	0.0
R_R6.5	0.3	0.1	0.1	0.2	0.3	0.1	0.5	0.3	0.3	0.2	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0
R_R09	0.1	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.1	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0
R_R15.5	0.1	0.0	0.0	0.1	0.2	0.0	0.3	0.1	0.2	0.2	0.2	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.3
R_R16.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.5
R_R18.5	0.1	0.0	0.0	0.1	0.2	0.0	0.3	0.1	0.2	0.2	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0
R_R20	0.2	0.0	0.0	0.1	0.1	0.0	0.2	0.0	0.1	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0
A_U17	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.2	0.3	0.4	0.2	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0
A_U23	0.4	0.3	0.5	0.3	0.4	0.4	0.3	0.2	0.4	0.3	0.2	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
A_U37	0.3	0.2	0.4	0.2	0.4	0.4	0.3	0.2	0.4	0.4	0.3	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
A_U38	0.2	0.3	0.4	0.2	0.4	0.3	0.4	0.3	0.4	0.4	0.3	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0
A_U42	0.3	0.4	0.3	0.3	0.4	0.5	0.4	0.3	0.4	0.5	0.4	0.5	0.2	0.0	0.2	0.0	0.0	0.0	0.3	0.0
A_U60	0.3	0.5	0.4	0.2	0.4	0.3	0.4	0.3	0.3	0.4	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0
A_M03	0.3	0.2	0.2	0.2	0.3	0.2	0.4	0.2	0.4	0.4	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0
A_M26	0.1	0.0	0.1	0.2	0.3	0.2	0.4	0.3	0.3	0.3	0.3	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0
A_M42	0.0	0.0	0.1	0.2	0.3	0.2	0.4	0.3	0.3	0.2	0.3	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0
A_M50	0.3	0.3	0.3	0.3	0.5	0.3	0.6	0.4	0.4	0.5	0.4	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0
A_M52	0.2	0.1	0.2	0.2	0.3	0.2	0.4	0.2	0.3	0.3	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0
A_M57	0.4	0.3	0.3	0.3	0.5	0.4	0.6	0.4	0.6	0.4	0.4	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0
A_i11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.3	0.8
A_i22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.3	0.1	0.8	0.5	0.8	0.5	0.5	0.0	0.0	0.0
A_i30	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.4	0.3	0.4	0.4	0.0	0.0	0.0
A_i31	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.2	0.1	0.0	0.0	0.1	0.3	0.3	0.3	0.3	0.3	0.0	0.0	0.0
A_51	0.1	0.0	0.0	0.0	0.1	0.0	0.1	0.2	0.1	0.2	0.0	0.1	0.2	0.3	0.2	0.3	0.3	0.0	0.0	0.0
A_i59	0.0	0.1	0.2	0.2	0.3	0.2	0.5	0.3	0.4	0.5	0.5	0.5	0.3	0.0	0.3	0.0	0.0	0.0	0.2	0.0
A_R00	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.1	0.1	0.2	0.2	0.1	0.3	0.3	0.3	0.3	0.3	0.3	0.5	0.5
A_R22	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.2	0.7
A_R23	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.2	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.3	0.2	0.6
A_R26	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.7	0.5	0.7	0.7	0.0	0.0	0.0
A_R40	0.1	0.0	0.0	0.0	0.1	0.0	0.1	0.1	0.2	0.4	0.2	0.3	0.0	0.0	0.0	0.0	0.0	0.3	0.4	0.6
A_R60	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.7

RANGER'S SLUMP

	R_U03	R_U23	R_U36	R_U48	R_U57	R_U60	R_18	R_37	R_40	R_41	R_54	R_55	R_i04	R_i11	R_i14	R_i18	R_i24	R_i26.5	R_R6.5	R_R09	R_R15.5	R_R16.5	R_R18.5	R_R20
R_U23	0.7																							
R_U36	0.6	0.7																						
R_U48	0.5	0.5	0.8																					
R_U57	0.5	0.6	0.8	0.8																				
R_U60	0.6	0.5	0.8	0.7	0.8																			
R_M18	0.6	0.6	0.6	0.5	0.6	0.6																		
R_M37	0.5	0.6	0.4	0.3	0.5	0.5	0.8																	
R_M40	0.5	0.7	0.6	0.4	0.6	0.5	0.6	0.5																
R_M41	0.6	0.6	0.4	0.3	0.4	0.4	0.7	0.7	0.6															
R_M54	0.5	0.7	0.6	0.5	0.5	0.5	0.7	0.6	0.7	0.5														
R_M55	0.4	0.5	0.3	0.2	0.3	0.3	0.4	0.5	0.6	0.5	0.6													
R_i04	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.2	0.1	0.0	0.1	0.2												
R_i11	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.1	0.3	0.4											
R_i14	0.2	0.1	0.1	0.1	0.2	0.3	0.4	0.4	0.3	0.4	0.3	0.4	0.6	0.3										
R_i18	0.1	0.1	0.1	0.1	0.2	0.3	0.3	0.3	0.3	0.2	0.3	0.4	0.9	0.7	0.8									
R_i24	0.2	0.1	0.1	0.1	0.1	0.1	0.3	0.3	0.3	0.3	0.2	0.4	0.3	0.3	0.7	0.4								
R_i26.5	0.1	0.2	0.1	0.1	0.1	0.1	0.3	0.2	0.3	0.2	0.3	0.5	0.4	0.5	0.7	0.7	0.6							
R_R6.5	0.4	0.3	0.4	0.3	0.2	0.3	0.2	0.2	0.1	0.2	0.3	0.2	0.0	0.4	0.3	0.3	0.3	0.4						
R_R09	0.1	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4					
R_R15.5	0.2	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.2	0.0	0.3	0.3	0.3	0.4	0.3	0.6	0.7				
R_R16.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.5	0.7			
R_R18.5	0.2	0.3	0.2	0.2	0.1	0.1	0.1	0.2	0.1	0.2	0.1	0.2	0.0	0.4	0.3	0.3	0.3	0.4	0.7	0.8	0.9	0.4		
R_R20	0.1	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.7	0.4	0.0	0.5	
A_U17	0.3	0.3	0.4	0.4	0.4	0.5	0.4	0.3	0.3	0.3	0.2	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.3	0.0	0.1	0.0	0.1	0.0
A_U23	0.2	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.2	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.0	0.1	0.0	0.1	0.0
A_U37	0.3	0.4	0.4	0.3	0.5	0.4	0.5	0.5	0.4	0.3	0.3	0.2	0.1	0.2	0.3	0.3	0.1	0.2	0.1	0.0	0.1	0.0	0.1	0.0
A_U38	0.4	0.3	0.3	0.2	0.4	0.5	0.5	0.4	0.3	0.4	0.4	0.3	0.2	0.2	0.3	0.3	0.1	0.2	0.3	0.0	0.1	0.0	0.2	0.0
A_U42	0.4	0.3	0.4	0.3	0.5	0.5	0.6	0.4	0.4	0.3	0.4	0.4	0.3	0.2	0.4	0.4	0.3	0.3	0.3	0.0	0.1	0.0	0.1	0.0
A_U60	0.5	0.3	0.4	0.4	0.3	0.5	0.4	0.2	0.3	0.4	0.3	0.1	0.0	0.2	0.1	0.1	0.1	0.2	0.3	0.0	0.1	0.0	0.2	0.0
A_M03	0.4	0.3	0.4	0.3	0.4	0.5	0.4	0.4	0.3	0.4	0.2	0.4	0.2	0.2	0.3	0.3	0.2	0.2	0.2	0.0	0.2	0.0	0.2	0.0
A_M26	0.4	0.3	0.3	0.2	0.4	0.4	0.5	0.6	0.2	0.4	0.3	0.3	0.2	0.2	0.5	0.4	0.3	0.2	0.2	0.0	0.2	0.0	0.2	0.0
A_M42	0.3	0.3	0.3	0.2	0.3	0.3	0.3	0.5	0.2	0.3	0.3	0.5	0.0	0.2	0.2	0.2	0.2	0.2	0.2	0.0	0.2	0.0	0.2	0.0
A_M50	0.4	0.4	0.4	0.3	0.5	0.6	0.5	0.4	0.4	0.5	0.4	0.3	0.2	0.2	0.3	0.3	0.1	0.2	0.3	0.0	0.2	0.0	0.2	0.0
A_M52	0.4	0.3	0.3	0.2	0.4	0.4	0.4	0.4	0.2	0.3	0.3	0.3	0.2	0.2	0.4	0.4	0.2	0.2	0.4	0.0	0.2	0.0	0.2	0.0
A_M57	0.5	0.4	0.5	0.4	0.5	0.7	0.5	0.5	0.3	0.4	0.4	0.4	0.2	0.2	0.3	0.3	0.1	0.2	0.3	0.0	0.2	0.0	0.2	0.0
A_i11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.3	0.4	0.0	0.0
A_i22	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.1	0.2	0.7	0.4	0.3	0.6	0.3	0.4	0.0	0.0	0.0	0.0	0.0	0.0
A_i30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3	0.0	0.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
A_i31	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.2	0.2	0.3	0.0	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0

	R_U03	R_U23	R_U36	R_U48	R_U57	R_U60	R_18	R_37	R_40	R_41	R_54	R_55	R_i04	R_i11	R_i14	R_i18	R_i24	R_i26.5	R_R6.5	R_R09	R_R15.5	R_R16.5	R_R18.5	R_R20
A_51	0.2	0.1	0.0	0.0	0.1	0.1	0.3	0.4	0.1	0.3	0.1	0.2	0.4	0.2	0.4	0.4	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
A_i59	0.3	0.4	0.3	0.2	0.3	0.3	0.4	0.4	0.5	0.5	0.4	0.5	0.2	0.3	0.4	0.4	0.4	0.5	0.2	0.0	0.2	0.0	0.2	0.0
A_R00	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.2	0.2	0.5	0.2	0.4	0.4	0.3	0.2	0.3	0.6	0.5	0.4	0.0
A_R22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.3	0.3	0.0	0.0
A_R23	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.3	0.0	0.2	0.2	0.4	0.0	0.0	0.0	0.2	0.3	0.0	0.0
A_R26	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.5	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
A_R40	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.1	0.2	0.1	0.2	0.3	0.3	0.4	0.4	0.4	0.3	0.3	0.0	0.4	0.3	0.3	0.0
A_R60	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.4	0.7	0.0	0.0

SLUMP A

	A_U17	A_U23	A_U37	A_U38	A_U42	A_U60	A_03	A_26	A_42	A_50	A_52	A_57	A_i11	A_i22	A_i30	A_i31	A_51	A_i59	A_R00	A_R22	A_R23	A_R26	A_R40	A_R60
A_U23	0.7																							
A_U37	0.7	0.7																						
A_U38	0.6	0.5	0.8																					
A_U42	0.6	0.5	0.7	0.8																				
A_U60	0.5	0.2	0.5	0.6	0.6																			
A_03	0.4	0.3	0.4	0.4	0.4	0.4																		
A_26	0.3	0.3	0.4	0.5	0.4	0.2	0.7																	
A_42	0.2	0.2	0.3	0.4	0.3	0.4	0.7	0.7																
A_50	0.5	0.4	0.4	0.5	0.5	0.4	0.6	0.5	0.4															
A_52	0.4	0.3	0.4	0.6	0.6	0.5	0.5	0.6	0.6	0.5														
A_57	0.5	0.3	0.4	0.5	0.5	0.5	0.8	0.6	0.6	0.6	0.6													
A_i11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0												
A_i22	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3											
A_i30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.6										
A_i31	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.2	0.1	0.0	0.1	0.2	0.4	0.6									
A_51	0.1	0.1	0.1	0.1	0.1	0.0	0.1	0.3	0.0	0.1	0.1	0.1	0.0	0.2	0.4	0.3								
A_i59	0.2	0.3	0.4	0.4	0.5	0.3	0.3	0.3	0.3	0.4	0.3	0.3	0.0	0.2	0.2	0.0	0.3							
A_R00	0.1	0.1	0.1	0.1	0.1	0.3	0.1	0.2	0.3	0.1	0.3	0.1	0.4	0.2	0.2	0.2	0.2	0.2						
A_R22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.3	0.2	0.0	0.0	0.4					
A_R23	0.1	0.1	0.1	0.1	0.1	0.0	0.2	0.2	0.0	0.1	0.2	0.1	0.5	0.0	0.2	0.2	0.2	0.0	0.4	0.9				
A_R26	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.8	0.7	0.5	0.2	0.0	0.3	0.0	0.0			
A_R40	0.2	0.2	0.3	0.3	0.3	0.1	0.3	0.3	0.2	0.3	0.3	0.3	0.8	0.3	0.2	0.2	0.2	0.2	0.5	0.4	0.6	0.3		
A_R60	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.3	0.4	0.3	0.0	0.3	

APPENDIX B

Coordinates and elevations of each sample plot where voucher specimens were collected.

Slump	Transect	Location	Northing	Easting	Elevation (Ellipsoidal for Lat Long)	Ortho Height	LatLong
Slump A	U	U 17m	7720204.421	580087.542	47.7		UTM 7N (WGS84): 580087.542E, 7720204.421N
		U 23m	7720203.150	580093.501	46.9		UTM 7N (WGS84): 580093.501E, 7720203.15N
		U 37m	7720202.636	580107.214	47.8		UTM 7N (WGS84): 580107.214E, 7720202.636N
		U 38m	7720202.412	580108.379	47.7		UTM 7N (WGS84): 580108.379E, 7720202.412N
		U 42m	7720202.528	580112.351	47.3		UTM 7N (WGS84): 580112.351E, 7720202.528N
		U 60m	7720200.618	580130.078	45.6		UTM 7N (WGS84): 580130.078E, 7720200.618N
	M	M 03m	7720139.735	580069.860	38.5		UTM 7N (WGS84): 580069.86E, 7720139.735N
		M 26m	7720149.584	580090.710	41.0		UTM 7N (WGS84): 580090.71E, 7720149.584N
		M 42m	7720156.337	580105.235	42.1		
		M 50m	7720159.853	580112.351	42.5		
		M 52m	7720161.266	580114.223	43.1		
		M 57m	7720163.452	580118.775	43.2		
	I	I 11m	7719995.838	580117.791	19.7		UTM 7N (WGS84): 580117.791E, 7719995.838N
		I 22m	7719995.026	580106.616	19.1		UTM 7N (WGS84): 580106.616E, 7719995.026N
		I 30m	7719995.511	580098.661	19.0		UTM 7N (WGS84): 580098.661E, 7719995.511N
		I 31m	7719996.937	580097.922	20.3		UTM 7N (WGS84): 580097.922E, 7719996.937N
		I 51m	7719997.424	580077.652	19.1		UTM 7N (WGS84): 580077.652E, 7719997.424N
		I 59m	7719998.806	580070.135	20.6		
	R	R 00m	7720112.842	580122.658	31.9		UTM 7N (WGS84): 580122.658E, 7720112.842N
		R 22m	7720120.513	580143.216	32.5		UTM 7N (WGS84): 580143.216E, 7720120.513N
		R 23m	7720119.716	580143.818	31.2		
		R 26m	7720120.436	580146.678	30.8		
		R 40m	7720127.365	580161.899	33.1		
		R 60m	7720133.372	580178.917	34.0		
Ranger’s	U	U 03m	69.582	-138.899	65.1	68.0	UTM 7N (WGS84): 68.582°N, 138.899°W
		U 23m	69.582	-138.898	64.0	67.0	

Slump	Transect	Location	Northing	Easting	Elevation (Ellipsoidal for Lat Long)	Ortho Height	LatLong
		U 36m	69.582	-138.898	63.4	66.0	UTM 7N (WGS84): 68.582°N, 138.898°W
		U 48m	69.582	-138.898	63.1	66.0	UTM 7N (WGS84): 68.582°N, 138.898°W
		U 57m	69.582	-138.898	62.7	65.0	UTM 7N (WGS84): 68.582°N, 138.898°W
		U 60m	69.582	-138.898	62.5	65.0	UTM 7N (WGS84): 69.582°N, 138.898°W
	M	M 18m	69.581	-138.898	59.7	62.0	UTM 7N (WGS84): 69.581°N, 138.898°W
		M 37m	69.581	-138.897	58.4	61.0	UTM 7N (WGS84): 69.581°N, 138.897°W
		M 40m	69.581	-138.897	58.2	61.0	
		M 41m	69.581	-138.897	58.2	61.0	
		M 54m	69.581	-138.897	58.0	61.0	
		M 55m	69.581	-138.897	58.0	61.0	
	I	I 04m	69.582	-138.900	56.0	59.0	
		I 11m	69.581	-138.900	55.9	58.0	
		I 14m	69.581	-138.900	55.6	58.0	
		I 18m	69.581	-138.900	55.5	58.0	
		I 24m	69.581	-138.900	55.1	58.0	
		I 26.5m	69.581	-138.900	54.9	57.0	
	R	R 6.5m	69.582	-138.899	61.6	64.0	
		R 09m	69.582	-138.899	61.4	64.0	
		R 15.5	69.582	-138.899	61.5	64.0	
		R 16.5	69.582	-138.899	61.3	64.0	
		R 18.5	69.582	-138.899	61.3	64.0	
		R 20m	69.582	-138.899	61.1	64.0	
Collinson	U	U 00m	7719764.071	582976.452	64.4		UTM 7N (WGS84): 582976.452E, 7719764.071N
		U 10m	7719767.415	582967.062	64.8		
		U 14m	7719768.620	582962.459	62.5		UTM 7N (WGS84): 582962.459E, 7719768.62N
		U 26m	7719771.813	582951.609	64.5		
		U 40m	7719776.443	582938.439	64.4		
		U 43m	7719777.244	582934.728	62.1		UTM 7N (WGS84): 582934.728E, 7719777.244E
	M	M 10m	7719646.469	582949.339	54.9		UTM 7N (WGS84): 582949.339E, 7719646.469N
		M 13m	7719646.209	582946.433	55.3		UTM 7N (WGS84): 582946.433E, 7719646.209N
		M 25m	7719645.014	582933.815	51.3		UTM 7N (WGS84): 582933.815E, 7719645.014N
		M 36m	7719644.046	582922.932	50.5		
		M 37m	7719643.907	582921.909	50.4		
		M 53m	7719643.094	582906.426	53.0		

Slump	Transect	Location	Northing	Easting	Elevation (Ellipsoidal for Lat Long)	Ortho Height	LatLong
	I	I 05m	7719507.622	582974.591	36.9		
		I 17m	7719504.007	582961.972	33.0		
		I 21m	7719504.143	582959.171	36.8		
		I 28m	7719502.583	582952.234	36.3		
		I 34m	7719500.797	582945.365	33.2		
		I 52m	7719496.242	582927.538	34.1		
	R	R 11m	7719612.790	582955.802	52.2		
		R 20m	7719613.897	582945.861	48.3		
		R 21m	7719614.736	582945.626	52.6		
		R 37m	7719618.089	582930.118	51.3		
		R 55m	7719621.767	582912.319	51.7		
		R 59m	7719622.118	582908.414	51.7		

APPENDIX C

List of species collected as part of this study.

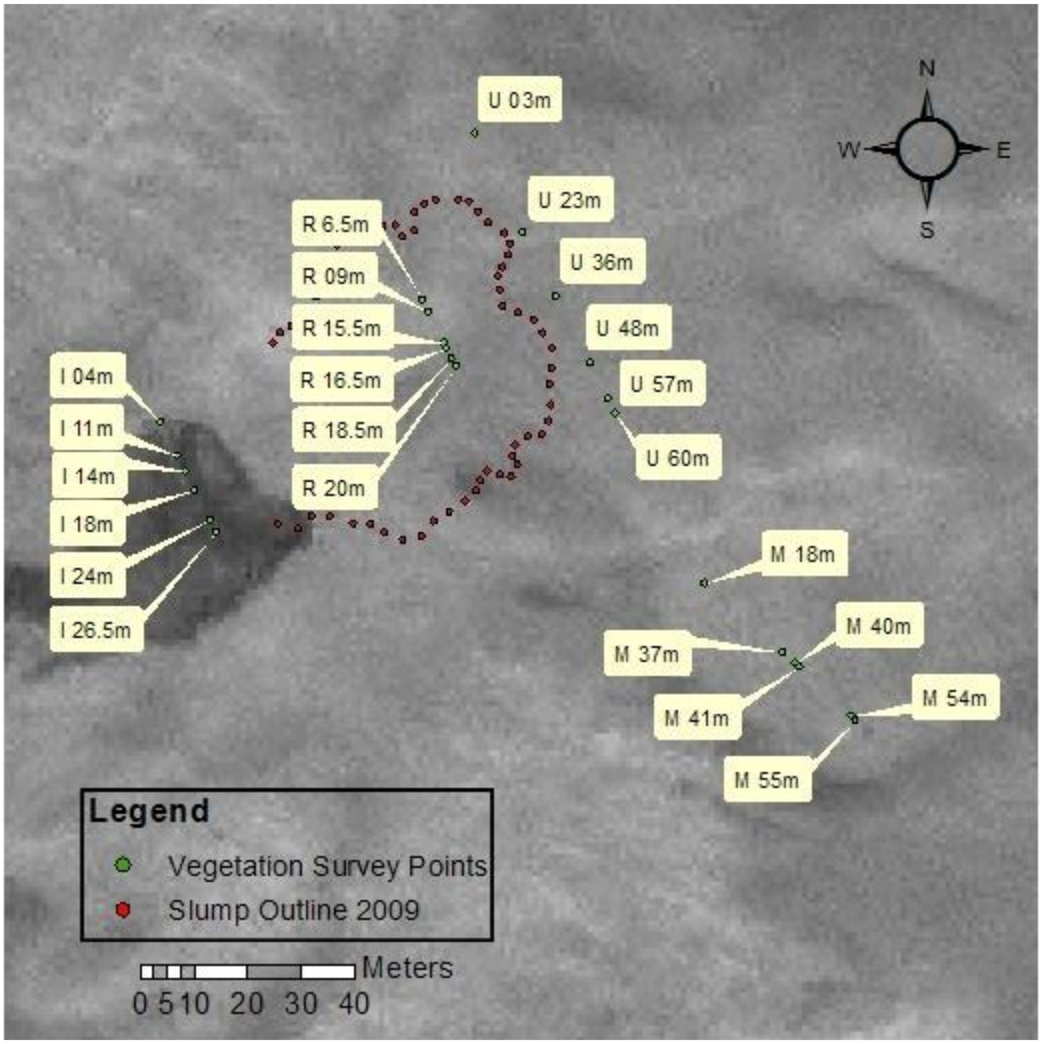
Family	Genus	Species
Apiaceae (Umbelliferae)	*Bupleurum*	*americanum*
Asteraceae (Compositae)	*Artemisia*	*tilesii*
Asteraceae (Compositae)	*Matricaria*	*ambigua*
Asteraceae (Compositae)	*Petasites*	*frigidus*
Asteraceae (Compositae)	*Saussurea*	*angustifolia*
Asteraceae (Compositae)	*Senecio*	*atropurpureus*
Asteraceae (Compositae)	*Senecio*	*cymbalaria*
Asteraceae (Compositae)	*Senecio*	*congestus*
Boraginaceae	*Myosotis*	*alpestris*
Brassicaceae (Cruciferae)	*Parrya*	*nudicaulis*
Caryophyllaceae	*Stellaria*	*longipes*
Cyperaceae	*Carex*	
Cyperaceae	*Eriophorum*	*vaginatum*
Ericaceae	*Vaccinium*	*vitis-idaea*
Equisetaceae	*Equisetum*	*arvense*
Fabaceae (Leguminosae)	*Astragalus*	*umbellatus*
Fabaceae (Leguminosae)	*Oxytropis*	*nigrescens*
Fabaceae (Leguminosae)	*Oxytropis*	*deflexa*
Fabaceae (Leguminosae)	*Oxytropis*	*arctica*
Fabaceae (Leguminosae)	*Lupinus*	*arcticus*
Juncaceae	*Luzula*	
Papaveraceae	*Papaver*	*radicatum*
Poaceae (Gramineae)	*Alopecurus*	*alpinus*

Family	Genus	Species
Poaceae (Gramineae)	*Arctagrostis*	*latifolia*
Poaceae (Gramineae)	*Festuca*	
Poaceae (Gramineae)	*Hierochloë*	*alpina*
Poaceae (Gramineae)	*Poa*	
Poaceae (Gramineae)	*Puccinellia*	
Polygonaceae	*Polygonum*	*viviparum*
Polygonaceae	*Polygonum*	*bistorta*
Rosaceae	*Dryas*	*integrifolia*
Salicaceae	*Salix*	*reticulata*
Salicaceae	*Salix*	*planifolia*
Salicaceae	*Salix*	*arctica*
Salicaceae	*Salix*	*phlebophylla*
Saxifragaceae	*Saxifraga*	*nelsoniana*
Saxifragaceae	*Saxifraga*	*hieracifolia*
Saxifragaceae	*Saxifraga*	*tricuspidata*
Scrophulariaceae	*Castilleja*	*elegans*
Scrophulariaceae	*Pedicularis*	*lanata*
Scrophulariaceae	*Pedicularis*	*capitata*
Scrophulariaceae	*Pedicularis*	*verticillata*
Valerianaceae	*Valeriana*	*capitata*
Parmeliaceae	*Cetraria*	*cucullata*
Parmeliaceae	*Cetraria*	
Cladoniaceae	*Cladonia*	
Icmadophilaceae	*Thamnolia*	*subuliformis*
Polytrichaceae	*Polytrichum*	
Peltigeraceae	*Peltigera*	*apthosa*
Parmeliaceae	*Alectoria*	*ochroleuca*
	Mushroom 1	
	Moss 1	
	Moss 2	
	Moss 4	
	Moss A	

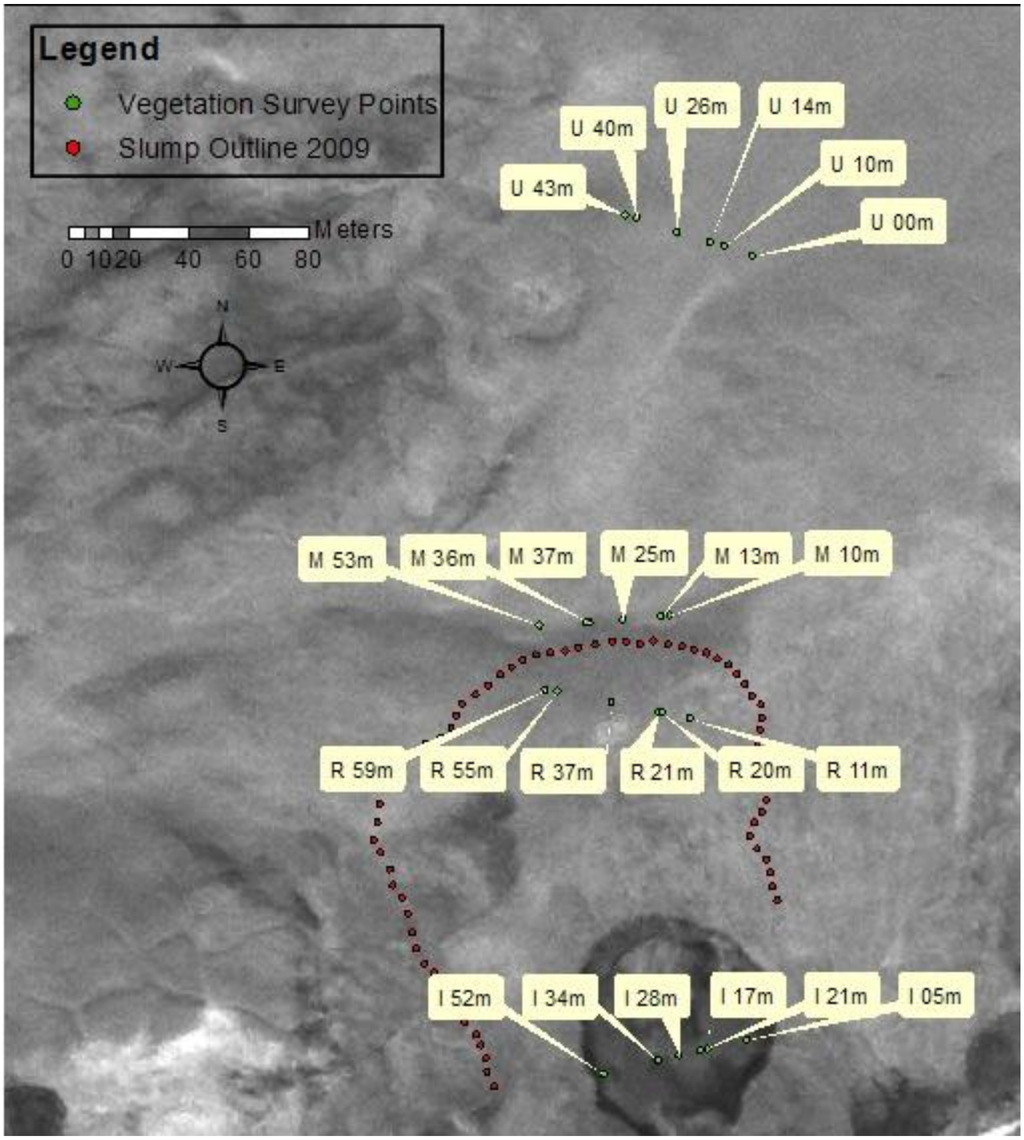
Family	Genus	Species
	Moss B	
	Immature grass 1	
	Forb sp.	
	Immature forb 1	

APPENDIX D

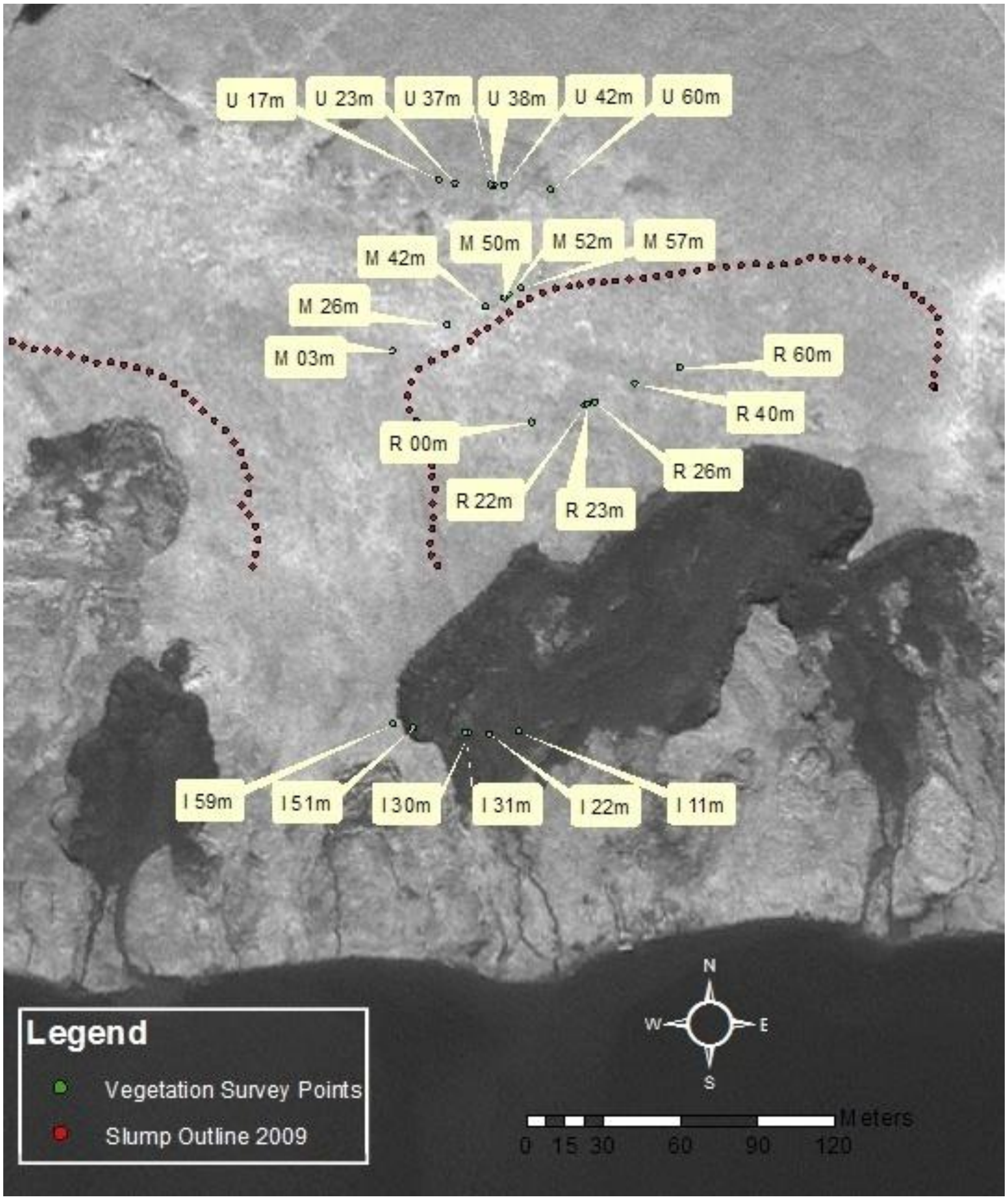
Location of each vegetation sample plot. Figures show the 2009 slump outline and use a 2001 IKONOS image as the background.



1. The vegetation sample plots located at the Ranger's Slump, Herschel Island, YT.



2. The vegetation sample plots located at the Collinson Head Slump, Herschel Island, YT.



3. The vegetation sample plots located at Slump A, in Thetis Bay, Herschel Island, YT.