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# The Structure and Dynamics of Earth Hummocks in the Subarctic Forest near Inuvik, Northwest Territories, Canada

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## Abstract

Surface microrelief, permafrost table configuration, ground-ice, and soil organic-matter contents are described for three sites near Inuvik, N.W.T., that are characterized by collapsed, poorly developed, and well-developed earth hummocks, respectively. The diameters of collapsed earth hummocks were significantly greater than those of well-developed vegetated hummocks. Hummock relief and inter-hummock distance increased along the continuum of forms, with the widest spacing and greatest relief measured at the site with well-developed vegetated hummocks. A bowl-shaped permafrost table mirrored the surface relief of most hummocks, but the collapsed hummocks were underlain by a planar or domed permafrost table. Segregated ice lenses parallel to the permafrost table, and small bodies of intrusive ice, were observed beneath the developing and well-developed hummocks. The configuration of the permafrost table and hummock relief, long-term observations of active-layer and hummock change, and hummock response to surface manipulation indicate that formation of a bowl-shaped permafrost table in association with organic accumulation and development of near-surface ground ice thrusts soils inward and upward causing hummock growth, whereas thaw subsidence may cause outward spreading and hummock collapse. Reaction-wood rings in black spruce trees growing on hummocky terrain indicate that tree tilting was associated with active-layer thinning and hummock growth. Cessation of reaction wood coincided with a period of active-layer deepening, degradation of ground ice, and outward spreading of the hummocks. In subarctic forests, hummock dynamics may be driven by ecological change associated with the fire cycle or climate change.

## Introduction

In the western Arctic and lower Mackenzie Valley, fine-grained, frost-susceptible sediments are commonly characterized by hummocky microrelief. Earth hummocks are circular to oval-shaped mounds, 100 to 200 cm in width and up to 60 cm in height (Fig. 1) (Tarnocai and Zoltai, 1978; Mackay, 1980). Unvegetated hummocks have been called mud hummocks (Mackay, 1980). The frost table beneath a hummock is bowl shaped and the near-surface permafrost is characteristically ice-rich (Tarnocai and Zoltai, 1978; Mackay, 1995; Kokelj and Burn, 2003).

The hummock form may persist for several thousand years (Zoltai et al., 1978), but torn roots and organic materials around the perimeter of hummocks, dilation cracks on their tops, and tilted trees growing on them indicate periods of heaving and soil movement (Zoltai, 1975a; Mackay, 1980, 1995). Involuted soil horizons, the grain-size distribution, and buried organic matter in the active-layer and near-surface permafrost indicate internal movements of hummock materials (Mackay, 1956, 1980; Zoltai et al., 1978; Swanson et al., 1999).

In this paper we investigate the role of permafrost aggradation or degradation as a mechanism driving changes in hummock form (Mackay, 1995; Shur et al., 2005a). We present detailed site investigations of earth hummocks from a location near Navy Road, 2 km north of Inuvik, N.W.T., where hummocks ranging from collapsed to well-developed forms occur close together. Long-term change of hummock form is discussed for a site near Caribou Creek, about 50 km south of Inuvik (Fig. 2). The hummocks, the active layer, and ground-ice development have been studied previously at these sites (Mackay, 1977, 1995; Pettapiece et al., 1978; Kokelj and Burn, 2003). Here we examine how changes in the upper layers of permafrost (the transient layer) affect active-layer processes and surface morphology. We describe the nature and origin of ground ice beneath poorly developed and well-developed hummocks, and investigate relations between hummock morphology and the configuration of the permafrost table. We present field experiments and observations of decadal-scale changes in hummock form associated with changes in the configuration of the permafrost table, and we reconstruct long-term dynamics of earth hummocks using reaction-wood rings in black spruce (*Picea mariana*) trees.

## Hummock Development

Freeze-thaw processes and frost action have been invoked to explain the vertical and horizontal movement of hummock soils and other patterned ground (Tarnocai and Zoltai, 1978; Mackay, 1980; Peterson and Krantz, 1998; Kessler et al., 2001). Mackay (1980) proposed that in winter, ice segregation and outward heave of hummocks followed by thaw settlement in spring would displace surface materials on hummock tops toward the surrounding depressions. Upfreezing and ice lens development above a bowl-shaped frost table would produce inward and upward heave in winter at the base of the active layer, whereas thawing


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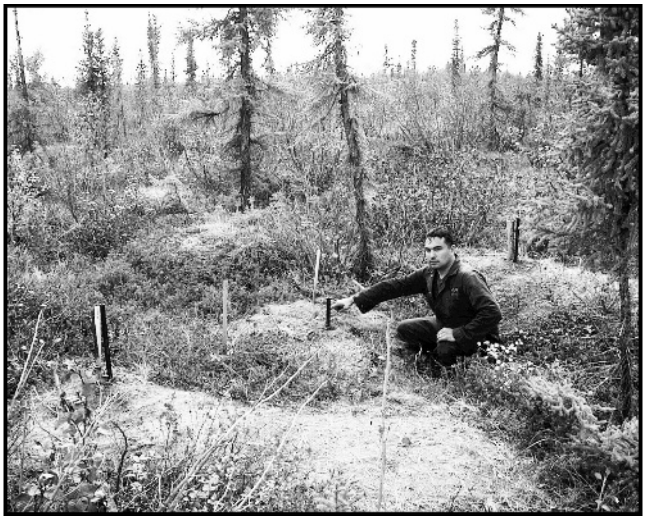

**FIGURE 1. Hummocky terrain, black spruce forest, Inuvik, N.W.T. The three black benchmarks are on sparsely vegetated hummock tops. Interhummock depressions are colonized by mosses and ericaceous shrubs.**

and gravity-induced settlement or viscous flow may transport the materials at depth towards the hummock center. Over decades to centuries, numerous seasonal freeze-thaw cycles might gradually redistribute soil within the hummock (Mackay, 1980; Peterson and Krantz, 1998).

Kessler et al. (2001) and Peterson et al. (2003) have developed models based on differential frost-heave processes to explain the self organization of patterned ground. Peterson et al. (2003) is applicable to non-sorted patterned ground in fine-grained sedi-

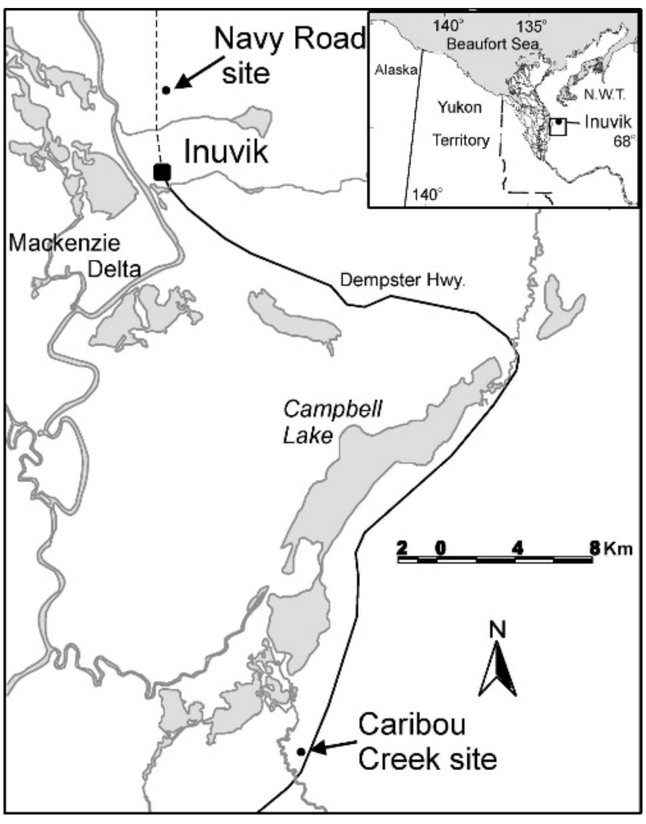


**FIGURE 2. Location map for hummock study sites in the subarctic boreal forest, Inuvik area, N.W.T.**

ments. The model predicts order of magnitude heave and spacing of non-sorted "frost boils" or hummocks, and describes the motion of soil within the hummock. The differential frost heave model (Peterson and Krantz, 1998; Peterson et al., 2003) and the equilibrium model (Mackay, 1979, 1980) assume that heave and settlement within the active layer principally drive soil movement within a hummock. These models do not consider how aggradation or degradation of underlying ice-rich permafrost may influence hummock form.

Hummocky terrain is commonly underlain by ice-rich ground (Tarnocai and Zoltai, 1978; Mackay, 1980; Kokelj and Burn, 2003; Shur et al., 2005b). The ground ice develops when a rising permafrost table traps ice lenses formed by upfreezing at the base of the active layer and also following an imbalance of summer downward and winter upward movement of pore water between the active layer and subjacent permafrost (Mackay, 1972, 1983; Cheng, 1983). The growth of aggradational ice results in surface heave, whereas its thawing can cause high pore-water pressures, soil instability, and subsidence of the terrain surface (Mackay, 1970). Modifications to hummock form, associated with changes in active-layer thickness, were observed during long-term field studies near Inuvik (Mackay, 1995), suggesting that hummock dynamics may be influenced by the aggradation or degradation of the ice-rich zone at the top of permafrost (Shur et al., 2005a).

## Study Sites

The main study area (Navy Road site) is located on a colluvial bench between Mackenzie Delta and the southern extension of Caribou Hills in an area underlain by continuous permafrost (Heginbottom et al., 1995). The surface materials are till and clayey silts derived from hills and gullies to the east (Rampton, 1988). The silt-clay soils are frost susceptible, and the underlying permafrost is ice-rich (Smith, 1985; Kokelj and Burn, 2003, Table 1 and Fig. 3).

The three individual study sites are located within 200 m of each other on gently sloping, well-drained hummocky terrain at the Navy Road site near Inuvik (68°23′N, 133°44′W) (Fig. 2). Flat, large diameter, mud hummocks, which we refer to as collapsed hummocks, occur in an area burned by fire in 1968 (Mackay, 1995). Fire charred vegetation and, since then, sedges and low shrubs have grown in the interhummock depressions (Mackay, 1995). Sedges have also encroached onto the hummocks, but most tops remain bare. At present, alders up to 2 m high, rooted primarily on hummock sides and in troughs, form the overstory.

A site with poorly developed hummocks is situated 50 to 100 m south of a fire-break that protected it from burning during the 1968 wildfire (Mackay, 1995). A previous fire burned the Inuvik area about 120 years ago (Black and Bliss, 1978; Landhäusser and Wein, 1993). In the late 1960s scattered black spruce trees composed a sparse overstory with sedge tussocks growing between the mud hummocks (Mackay, 1995). The moisture and nutrients from the thaw of ice-rich permafrost during the early 1970s may have promoted the growth of alder (Mackay, 1995, Fig. 12; Kokelj and Burn, 2005). Since the 1970s, alder, ground birch, ericaceous shrubs, sedge tussocks, and grasses have colonized the tops of mud hummocks so that most are transitional between mud hummocks and vegetated hummocks (Fig. 1).

The poorly developed hummocks grade over a few tens of meters eastward into a small area of well-developed vegetated hummocks. The overstory is composed of randomly leaning black spruce and some alders with an understory of ericaceous shrubs.

TABLE 1

**Mean minimum and maximum diameters, interhummock distances, hummock reliefs, hummock top active-layer depths, interhummock trough active-layer depths, and permafrost table reliefs of 15 collapsed, poorly developed, and well-developed hummocks, respectively, Navy Road, Inuvik. Sample standard deviations are indicated in brackets. Means were compared between the three hummock types. Significant differences (identified by Fisher's LSD test) are indicated by different subscript letters. Group means that are not significantly different share a common subscript letter.**

| | Hummock diameters (cm) | | Interhummock distances (cm) | | Hummock relief (cm) | | Hummock top active layer (cm) | Interhummock trough active layer (cm) | | Permafrost table relief (cm) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Hummock type | ($Hd_{min}$) | ($Hd_{max}$)* | ($IHw_{min}$)* | ($IHw_{max}$)* | ($Hr_{min}$)* | ($Hr_{max}$) | ($HTt$) | ($IHt_{min}$) | ($IHt_{max}$) | ($PTr_{min}$) | ($PTr_{max}$) |
| Collapsed | 181.7 [19.4]$^a$ | 215.3 [38.1]$^a$ | 27.6 [11.1]$^a$ | 79.3 [20.9]$^a$ | 11.5 [11.1]$^a$ | 22.9 [3.5]$^a$ | 100.0 [8.3]$^a$ | 68.1 [8.5]$^a$ | 89.5 [10.6]$^a$ | −5.0 [11.0]$^a$ | 13.4 [11.1]$^a$ |
| Developing | 178.7 [21.4]$^a$ | 214.3 [27.3]$^a$ | 46.3 [14.1]$^b$ | 101.3 [24.2]$^a$ | 15.5 [5.7]$^a$ | 33.7 [5.2]$^b$ | 88.9 [6.1]$^b$ | 31.5 [8.4]$^b$ | 62.2 [12.3]$^b$ | 6.0 [8.7]$^b$ | 29.7 [9.1]$^b$ |
| Well-developed | 141.0 [19.0]$^b$ | 189.0 [40.7]$^b$ | 67.3 [36.9]$^b$ | 200.0 [93.3]$^b$ | 26.9 [11.7]$^b$ | 48.1 [7.2]$^c$ | 92.8 [5.3]$^b$ | 25.9 [6.7]$^b$ | 55.0 [16.1]$^b$ | 2.2 [9.8]$^{ab}$ | 26.6 [9.0]$^b$ |

* ANOVA was performed on logarithmically transformed data.

Sedge tussocks occur on the hummock perimeters. Thick mosses are found in the interhummock depressions, while hummock tops are completely covered by a thin layer of mosses or lichens.

Mackay (1995) monitored active-layer development and hummock area at the burned site with collapsed hummocks and, in the adjacent unburned area, with poorly developed hummocks, from 1968 to 1993. At the burned site, the active layer deepened and caused surface subsidence, collapse, and sometimes coalescence of earth hummocks. In the decade following burning, mean thaw depth increased from 68 to 102 cm beneath interhummock depressions, and from 116 to 132 cm beneath hummock tops. The mean area of five hummocks staked by Mackay (1995) increased from 1.9 to 4.5 $m^2$ between 1968 and 1978. Active-layer deepening of a similar magnitude was recorded at the adjacent unburned site, but the mean area of five staked hummocks increased only slightly from 2.4 to 2.8 $m^2$.

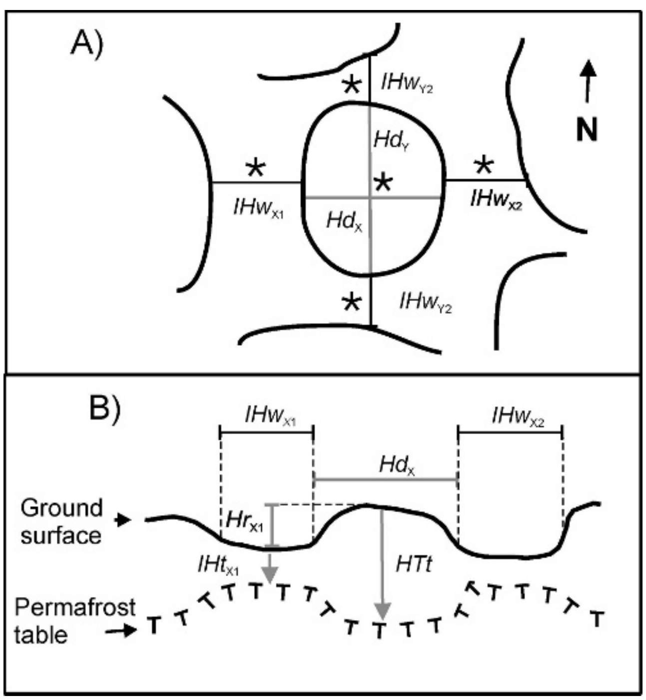


**FIGURE 3. Parameters measured at each hummock along survey transects. (A) Plan view, and (B) cross-sectional view. *IHw*—hummock to hummock distance; *Hd*—hummock diameter; *Hr*—hummock relief; *IHt*—interhummock depression active-layer depth; *HTt*—hummock top active-layer depth. Active-layer depth was probed at locations indicated by (*).**

Proliferation of alder in the late 1970s and 1980s increased ground shading, causing active layers beneath hummocks and interhummock depressions to thin by an average of 21 and 57 cm in the burned area (collapsed hummocks), and by 17 and 32 cm in the unburned area (poorly developed hummocks) (Mackay, 1995). The recently aggraded permafrost beneath poorly developed hummocks is characterized by permafrost with low ice contents (<15% excess ice) underlain by older ice-rich permafrost with ice contents ranging from 20 to 40% (Kokelj and Burn, 2003). By 1993, mean hummock areas had decreased from 4.5 to 4.1 $m^2$ in the burned and 2.8 to 1.9 $m^2$ in the unburned areas, respectively.

At Caribou Creek the surficial material is a fine-grained till. Well-defined earth hummocks characterize the surface microtopography. The vegetation is a mature black spruce forest with a thick organic ground cover.

## Field and Laboratory Methods

Surface and permafrost table morphology were described along transects through the three study sites at Navy Road (Fig. 2). In August 2003, 15 hummocks were surveyed along each of the transects. Hummock diameter was measured along an east-west ($Hd_x$) and north-south ($Hd_y$) axis (Fig. 3). Interhummock distance ($IHw$) was determined for each hummock in four directions by extending the x and y axes from the hummock edge to the perimeter of the adjacent hummocks (Fig. 3). Trough-to-top relief (hummock center) was measured along extensions of the x and y axes at the deepest point of the respective interhummock troughs ($Hr_{x1,\ x2,\ y1,\ y2}$) (Fig. 3). Thaw depths for hummock centers ($HTt$) and troughs ($IHt$) were determined by probing in late August (Fig. 3).

Permafrost table relief ($PTr$) beneath each hummock was determined for four sides of each feature using:

$$PTr = [HTt - (Hr + IHt)], \qquad (1)$$

where $HTt$ is active-layer thickness beneath the hummock top, $Hr$ is hummock relief, and $IHt$ is interhummock depression active-layer depth between hummocks (Fig. 3B).

For each parameter quantified, the mean and standard deviation of minimum and maximum hummock measurements were determined for the collapsed, poorly developed, and well-developed hummock sites. Variation in minimum and maximum values among the three groups was investigated using analysis of variance (Sokal and Rohlf, 1995). Fisher's least significant difference (LSD) procedure was used to determine which groups differed from one another (Sokal and Rohlf 1995). Non-normally distributed data were logarithmically transformed to meet the assumptions of the ANOVA (Sokal and Rohlf, 1995).

In 2002, cores were obtained from beneath the top and interhummock depression of a well-developed hummock using a 5-cm-diameter CRREL core barrel. The core samples were sectioned in the field, logged, and double-bagged. The samples collected were analyzed at a laboratory in Inuvik to determine soil moisture and excess ice content following Kokelj and Burn (2003).

Organic-matter contents were determined on active-layer samples from the troughs and tops of collapsed, poorly developed, and well-developed hummocks. A semi-quantitative estimate of soil organic-matter content in the oven-dried samples was obtained by the loss on ignition method (Sheldrick, 1984).

## Hummock Characteristics—Navy Road

At the Navy Road site, collapsed, poorly developed, and well-developed hummocks occur within a few hundred meters of each other (Fig. 2). Hummock morphology, surface organic-matter contents, and ground-ice characteristics are described for these features to show changes that are associated with hummock development.

### *MORPHOLOGY*

Figure 4 presents cross sections showing typical surface and permafrost-table configurations for the hummocks. The east-west and north-south diameters ($Hd_x$, $Hd_y$,) of the 45 hummocks that were surveyed ranged from 120 to 320 cm. Hummocks were roughly circular, but some were elongated as indicated by minimum and maximum diameters in Table 1. No preferred orientation of elongation was evident. Mean minimum and maximum diameters of hummocks were greatest for collapsed hummocks and smallest for well-developed hummocks (Table 1). The diameters of well-developed hummocks were significantly less than those of collapsed and poorly developed mud hummocks (Table 1).

Differences in the space between hummocks were reflected in measures of interhummock distance (*IHw*), which ranged from 10 cm between collapsed mud hummocks to more than 300 cm between some well-developed hummocks. Table 1 indicates an increase in mean minimum and maximum interhummock distance between the collapsed, poorly developed, and well-developed forms. Comparisons among the minimum and maximum populations indicate statistically significant differences in separation between the hummock forms, with two exceptions. Mean maximum interhummock distance for collapsed and poorly developed hummocks and mean minimum distance for poorly developed and well-developed hummocks are both similar.

Hummock relief ranged from 5 cm for a collapsed feature to almost 60 cm for a well-developed hummock. Table 1 shows that mean minimum and maximum trough-to-hummock top relief (*Hr*) increased from the collapsed to the well-developed forms.

Active-layer depths below hummock tops (*HTt*) ranged from 80 cm at a poorly developed mud hummock to 114 cm for a collapsed feature. Mean thaw depths beneath interhummock depressions were less than beneath the hummock tops for all hummock types (Table 1). Top and trough active-layer depths were similar between poorly developed and well-developed hummocks, but active-layer depths were significantly greater for collapsed hummocks (Table 1).

The relative magnitudes of $HTt - (Hr + IHt)$ show that the permafrost table beneath collapsed hummocks is generally planar

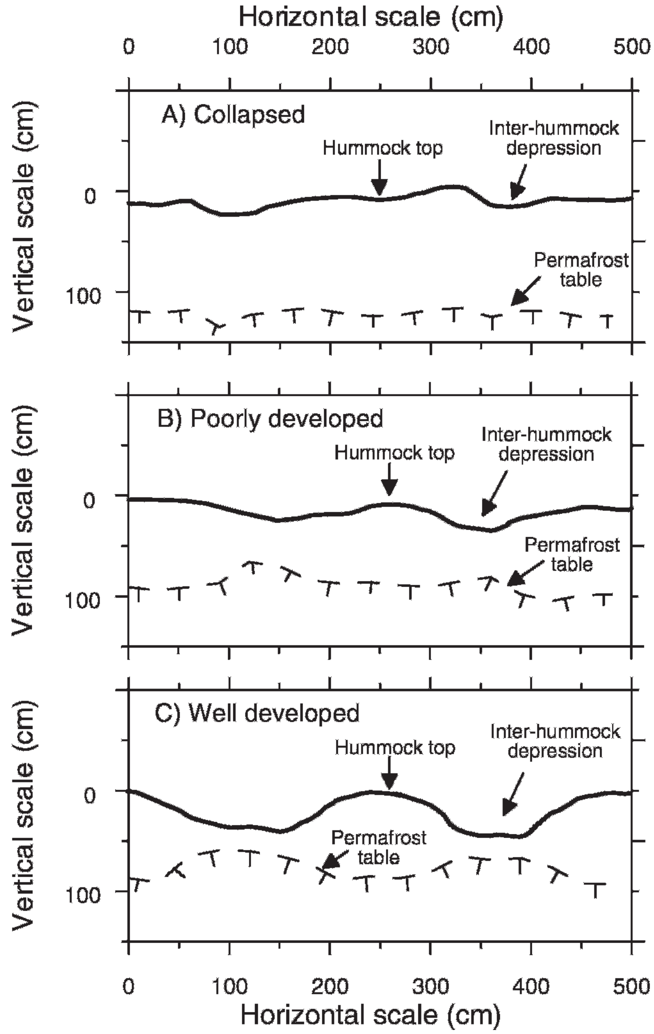


**FIGURE 4. Cross sections of earth hummocks showing surface and permafrost table relief, Navy Road site, Inuvik. (A) Collapsed hummock in burned area; (B) poorly developed hummock in unburned area; and (C) well-developed hummock in unburned area.**

or domed (Fig. 4; Table 1). In contrast, poorly developed and well-developed vegetated hummocks are underlain by a permafrost table that is bowl-shaped. Mean minimum permafrost table relief indicates that a complete bowl-shaped profile does not underlie all poorly developed and well-developed forms (Table 1). The greatest permafrost table relief was on average associated with the poorly developed features, suggesting that factors other than establishment of a bowl-shaped permafrost table contribute to the modification of hummock form.

### *ACTIVE-LAYER ORGANIC-MATTER CONTENTS*

Near-surface organic-matter content in the depression between two collapsed hummocks was 30% by weight, but was as high as 80% in the trough between the well-developed hummocks (Fig. 5A). Organic-matter content declined with depth to less than 10% near the permafrost table, except in well-developed hummocks, where the trough active layer between the hummocks was dominated by organic materials (Fig. 5A). All hummock centers consisted of mineral soil, except at the surface of the well-developed hummocks (Fig. 5B).

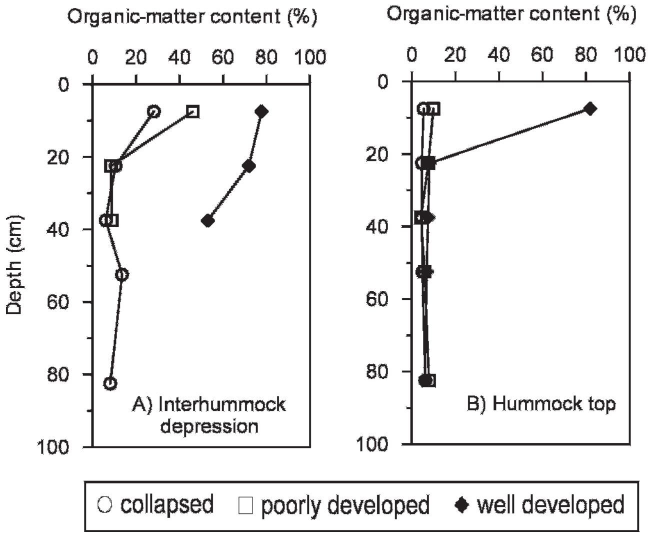


**FIGURE 5. Active-layer organic-matter contents by weight for (A) interhummock depressions and (B) hummock tops (collapsed, poorly developed, and well-developed hummocks).**

*NEAR-SURFACE GROUND ICE CHARACTERISTICS*

The recently aggraded permafrost beneath interhummock depressions and hummock tops of collapsed and poorly developed features had low excess ice content (<15% by volume) (Kokelj and Burn, 2003). In contrast, well-developed vegetated hummocks were underlain by ice-rich permafrost with excess ice contents of between 20 and 40%. The ground ice consisted of thick segregated ice lenses oriented parallel to the bowl-shaped permafrost table (Fig. 6). These ice lenses form perpendicular to the direction of heat flow. Individual lenses 0.5 to 3 cm thickness dipped with the bowl-shaped permafrost table and in some cases were near vertical (Fig. 6). Development of these ice lenses would have heaved the soil in and up toward the hummock center. Ice lenses extended from beneath the interhummock trough to the center of the bowl-shaped permafrost table where their angle decreased to near horizontal. Small bodies of intrusive ice were also encountered, typically at the interface of organic and mineral soil beneath the interhummock depressions and around hummock perimeters. These ice bodies ranged from 2 to 10 cm in thickness and 10 to 20 cm in length and width. Rootlets hanging from overlying organic soil were suspended in the ice, which contained elongated vertical bubbles. The upper and lower ice contacts were typically abrupt. Ice-rich clayey silts occurred beneath the intrusive ice.

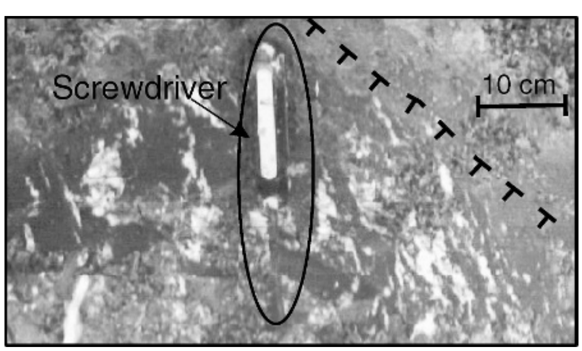


**FIGURE 6. Cross section of near-surface permafrost underlying a well-developed earth hummock showing segregated ice lenses beneath the sides of a bowl-shaped permafrost table. Ice lenses 0.5 to 3 cm in thickness were tilted at 60 to 90° from horizontal. The hatched line shows the permafrost table.**

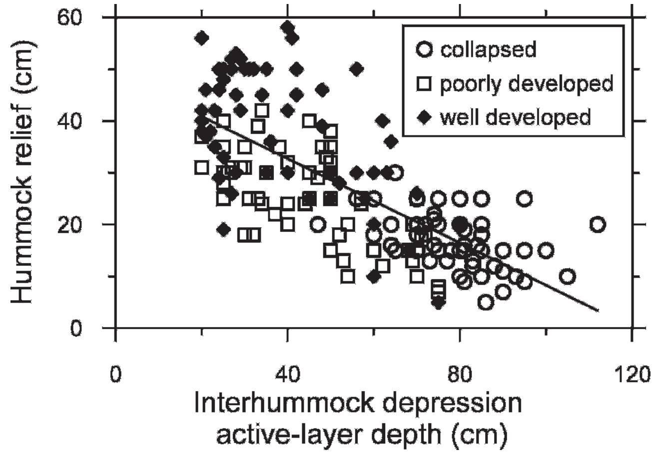


**FIGURE 7. Interhummock depression active-layer depth (*IHt*) and hummock relief (*Hr*), Navy Road site, Inuvik. The respective measurements were made on the four sides of each hummock (collapsed, poorly developed, and well-developed hummocks). The relation between the two variables is described by: $(Hr) = -0.407*(IHt) + 48.98$; $r = 0.73$; $N = 180$.**

*RELATIONS BETWEEN PERMAFROST TABLE AND HUMMOCK MORPHOLOGY*

The relations between permafrost table and hummock morphology have been investigated using all data collected in the hummock surveys (Fig. 3; Table 1). An inverse relation between interhummock depression active-layer thickness and hummock relief is indicated in Figure 7, suggesting that aggradation of permafrost beneath the troughs and development of a bowl-shaped permafrost table contribute to hummock growth (Mackay, 1980). However, only a weak positive correlation (Spearman's rank-order) exists between permafrost table and hummock relief (Fig. 8) ($r = 0.24$; $N = 180$; $P < 0.01$) (Sokal and Rohlf, 1995). Hummock growth and establishment of vegetation cover on the hummock top may cause the base of the bowl-shaped permafrost table to rise, on average reducing the relief of the permafrost table between poorly developed and well-developed features (Table 1; Fig. 8).

Table 1 suggests that the greatest changes in hummock form occur between poorly developed and well-developed features,

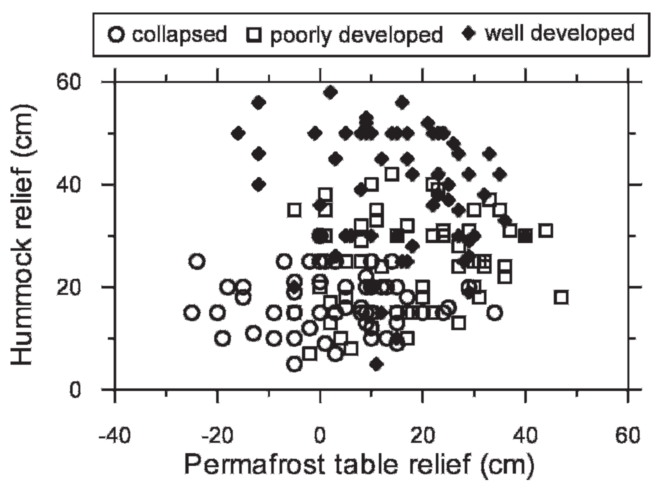


**FIGURE 8. Permafrost table and hummock relief, Navy Road site, Inuvik. Respective measurements ($N = 180$) were made on the four sides of each hummock (collapsed, poorly developed, and well-developed hummocks).**

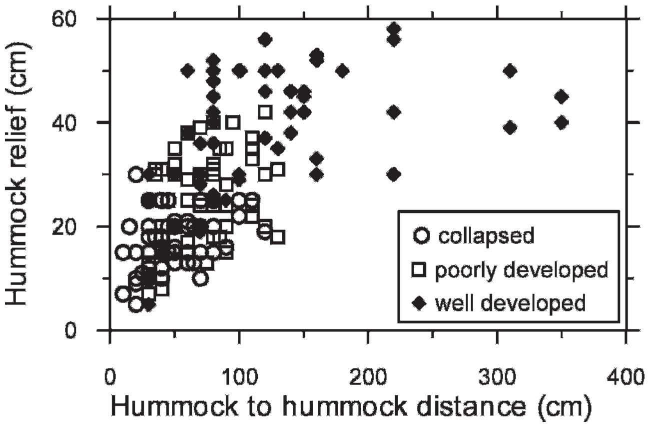


**FIGURE 9. Hummock-to-hummock distance and hummock relief, Navy Road site, Inuvik. Respective measurements ($N$ = 180) were made on the four sides of each hummock (collapsed, poorly developed, and well-developed hummocks).**

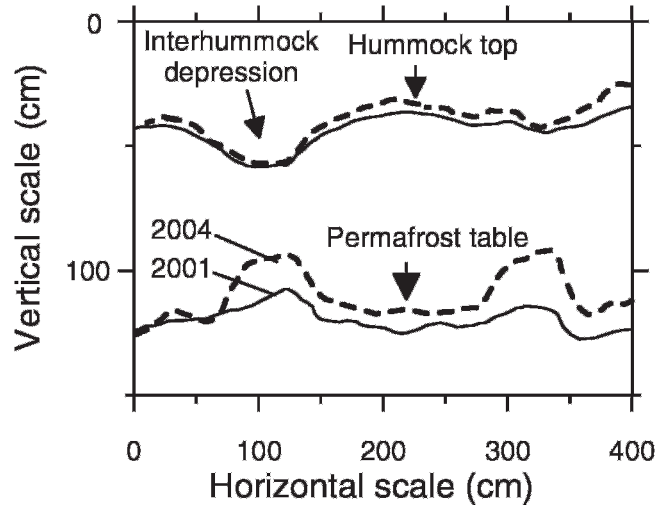


**FIGURE 10. Cross section of surface and permafrost table relief of a hummock where the permafrost table was artificially aggraded, Navy Road, Inuvik. Surface and permafrost table profiles in 2001 are indicated by solid thin lines, and the respective profiles from 2004 are indicated by thick dashed lines. Note 2× vertical exaggeration.**

following the initial establishment of a bowl-shaped permafrost table. Modifications in form include an increase in maximum hummock-to-hummock distances, a decrease in diameter, and an increase in hummock relief (Fig. 9; Table 1). Spearman's rank-order correlation of data in Figure 9 indicates the strong positive relation between hummock-to-hummock distance and surface relief ($r$ = 0.68; $N$ = 180; $P < 0.0001$) (Sokal and Rohlf, 1995). This observation suggests that trough widening, or radially inward aggradation of the bowl-shaped permafrost table beneath a hummock contributes to progressive development of hummock form (Fig. 9). The force driving the modification of hummock form is the heave derived from the development of segregated ice lenses beneath an aggrading permafrost table (Fig. 6) (Kokelj and Burn, 2003).

## Experimental Results: Hummock Modifications Associated with Active-layer Change

The permafrost table beneath a poorly developed and a well-developed earth hummock has been manipulated at the Navy Road site to examine the response to permafrost aggradation and degradation (Fig. 2). The experiments were initiated in August 2001 and results are presented for three years after initial manipulation.

Styrofoam insulation was placed around the perimeter of a poorly developed mud hummock to enhance development of a bowl-shaped permafrost table. At a nearby site, an organic layer approximately 10 to 20 cm thick was removed from the interhummock depression surrounding a well-developed hummock. Steel benchmarks 2.5 cm in diameter were anchored with steel plates 7.5 cm in diameter in permafrost in the middle of each hummock to determine seasonal heave and settlement by taking late winter and summer measurements of protrusion. At the end of each summer, topographic profiles and thaw depths were determined across the respective hummocks.

Upward aggradation of the permafrost table beneath the interhummock depressions by up to 35 cm was associated with a slight increase in hummocky relief (Fig. 10). Seasonal changes in benchmark protrusion indicate active-layer heave and settlement on the order of 1 to 3 cm, but the net change in protrusion between August 2001 and August 2004 shows that the hummock top heaved by 7.5 cm.

Near-surface permafrost was thawed at a nearby well-developed hummock by removing organic materials from the surrounding interhummock depression. Active-layer deepening by as much as 30 cm beneath the hummock top and 60 cm beneath the interhummock depression destroyed the bowl-shaped permafrost table and caused ponding of water in the interhummock depressions (Fig. 11). In the three years following perturbation, hummock top elevation decreased by as much as 36 cm. Comparison of the profiles indicates subsidence and outward spreading of the hummock. The total subsidence with respect to active-layer deepening indicates a mean volumetric ice content of degrading permafrost of about 45%, which is comparable with the ice volume estimated beneath an adjacent well-developed hummock.

The removal of organic materials around the well-developed hummock resulted in active-layer deepening comparable to the thawing that occurred in the nearby hummock field following the 1968 forest fire (Mackay, 1977, 1995). This experiment demonstrates that degradation of near-surface ground-ice and hummock collapse may be a rapid process (Fig. 11) (Mackay, 1977, 1995). Organic accumulation in inter-hummock trough areas and a bowl-shaped permafrost table may establish in less than a decade, but hummock growth is gradual, because near-surface ice enrichment, necessary to thrust the hummock inward and upward, progresses over decadal time scales (Fig. 10) (Mackay, 1995; Kokelj and Burn, 2003). In both cases, the net heave or settlement of the hummock surface associated with aggradation and degradation of near-surface permafrost greatly exceeded seasonal active-layer heave and settlement.

## Conceptual Model of Earth Hummock Growth and Degradation

Hummock models presented by Mackay (1979, 1980) and Peterson et al. (2003) suggest that seasonal freeze-thaw above a bowl-shaped permafrost table drives soil movements within a hummock. The approach here considers the effects of heave and thaw settlement due to the aggradation and/or degradation of ice-rich materials in the transient layer (Shur et al., 2005b), which can

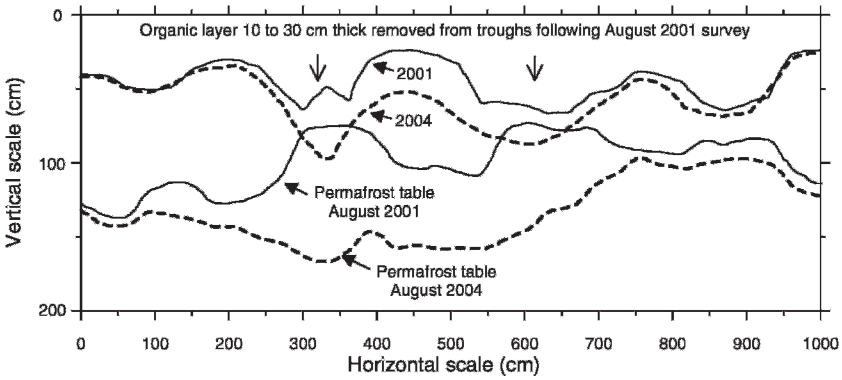


**FIGURE 11. Cross section of surface and permafrost table relief of a hummock where the permafrost table was artificially degraded, Navy Road, Inuvik. Surface and permafrost table profiles in 2001 are indicated by solid thin lines, and the respective profiles from 2004 are indicated by thick dashed lines. Note 2× vertical exaggeration.**

occur over decadal time scales due to ecological or climate change (Mackay, 1995; Mackay and Burn, 2002). The preexistence of a hummock pattern was assumed with initial features being large diameter, collapsed forms underlain by a planar permafrost table (Fig. 12A) (Mackay, 1977, 1995).

Figure 12B shows a poorly developed mud hummock underlain by a bowl-shaped permafrost table. There is a tendency for vegetation to first colonize interhummock depressions, promoting gradual, upward aggradation of the underlying permafrost table (Fig. 5; Table 1) (Mackay, 1980, 1995; Walker et al., 2004). However, the comparable morphology of collapsed and poorly developed hummocks suggests that the establishment of a bowl-shaped permafrost table is not the principal driver of hummock growth (Table 1; Figs. 12A, B).

Development of near-surface ground ice, which occurs in association with an aggrading permafrost table, is the main cause of hummock growth. Figure 12C is a cross section of a typical well-developed vegetated hummock (Tarnocai and Zoltai, 1978). In contrast with the poorly developed hummock, it is smaller in diameter, greater in relief, and the top is vegetated (Table 1). Organic accumulation in the interhummock depression modifies ground-thermal conditions (Tarnocai and Zoltai, 1978) resulting in the inward and upward aggradation of the bowl-shaped permafrost table. Modification of the permafrost table is accompanied by gradual ice enrichment, causing the hummock contents to be thrust radially inward and upward (Figs. 6, 12C) (Kokelj and Burn, 2003). Differential uplifting is indicated by dilation cracks across the tops of some growing and well-developed hummocks and by torn organic materials and cracks around the perimeter of some well-vegetated features (Figs. 12B, 13). Gradual aggradation of permafrost into the organic material beneath interhummock depressions yields frozen ground with low bulk density, resulting in only minor heave of the interhummock areas (Walker et al., 2004). Collection of water in the troughs may also promote development of pool ice around hummock perimeters (Fig. 12C).

The permafrost-table configuration and ground-ice conditions beneath well-developed hummocks (Fig. 12C) indicate their sensitivity to active-layer deepening. Degradation of the bowl-shaped permafrost table beneath a well-developed earth hummock (Fig. 12D) can result in (1) thaw subsidence beneath the interhummock depression and saturation of the active layer; (2) outward spreading and subsidence of the hummock tops; and (3) gradual infilling of interhummock depressions. This sequence of earth movements will result in hummock collapse and can explain how organic materials become rapidly redistributed within a soil profile in hummocky terrain (Fig. 12D). If the permafrost were to degrade entirely, the hummock cycle would cease to operate and features could become fossilized, maintaining the collapsed hummock morphology (Tarnocai and Valentine, 1989).

## Long-term Observations of Hummock Morphology

Figure 14A is the cross section of a hummock at the Caribou Creek site in 1975 (Tarnocai et al., 1993). Thick organic accumulation in the interhummock depressions separated the adjacent well-developed hummocks. The permafrost table was

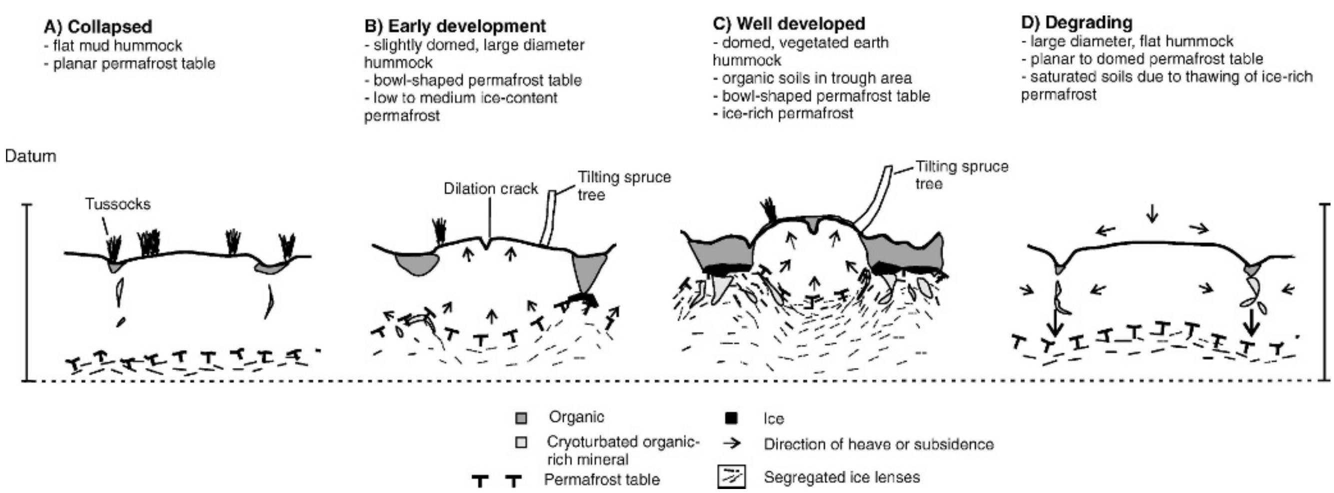


**FIGURE 12. Schematic of hummock dynamics as a function of change in the configuration of the permafrost table and aggradation or degradation of ground ice.**

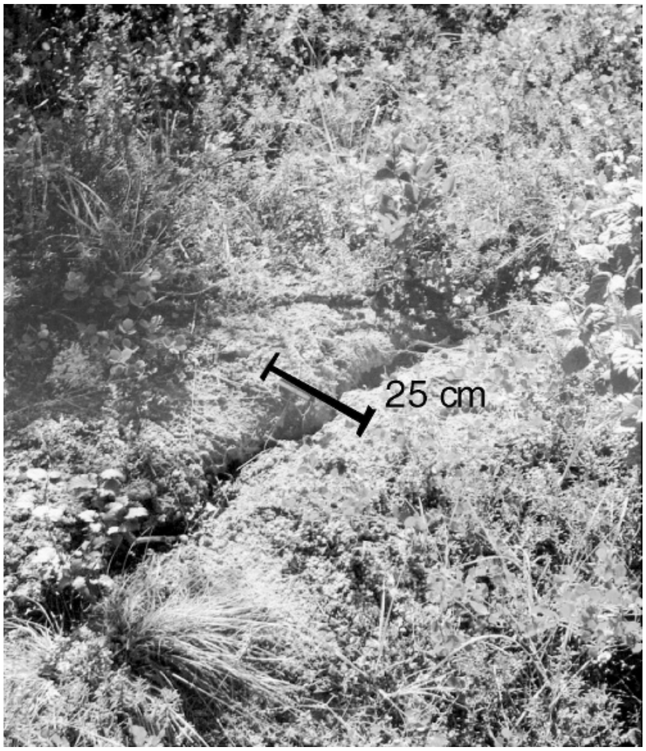


**FIGURE 13. Dilation crack across the top of a developing mud hummock, August 2004, Navy Road site, Inuvik. The crack was observed during an initial site visit in summer 1999. Note the vegetation encroaching onto the hummock top.**

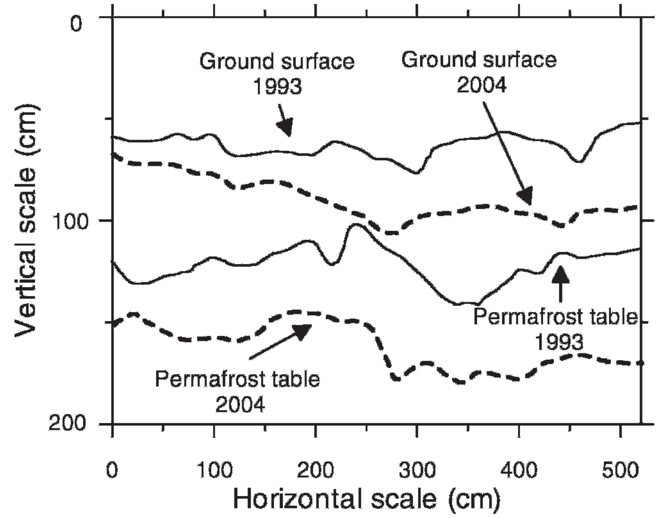


**FIGURE 15. Cross section of surface and permafrost table relief of hummocky terrain at Caribou Creek, N.W.T. Surface and permafrost profiles in 1993 are indicated by solid thin lines, and the respective profiles from 2004 are indicated by thick dashed lines. Surveys were tied into two benchmarks anchored in permafrost at the two ends of the transect. Note 2× vertical exaggeration.**

bowl-shaped, and high ice contents were encountered in near-surface permafrost (Fig. 14A). In 2004, the hummocks at this site were much flatter than in 1975 (Fig. 14B). Although the 2004 permafrost table was bowl-shaped, visible ice in excavations of near-surface permafrost was very low, and the zones of pure ice observed in the interhummock depressions in 1975 were absent (Fig. 14). The degradation of ground ice likely caused outward spreading and collapse of the previously well-developed, domed-shaped hummocks (Fig. 14). In 2004, the excavation revealed a tin can, believed to have been discarded in 1993, buried approximately 25 cm beneath the ground surface in the interhummock depression.

Approximately 30 m from the excavation at Caribou Creek, thaw depths measured at 20 cm intervals along a 5.2 m transect in late August 2004 were compared with data collected in late summer 1993. Steel benchmarks anchored with small metal plates were drilled approximately 2 m into the permafrost and marked the two ends of the transect. Active-layer and surface topography was measured with respect to these benchmarks. In 2004, mean thaw depths were 13 cm greater than in 1993 (STD = 8 cm) (Fig. 15). Mean surface subsidence along this transect from 1993 to 2004 is estimated to be 31 cm (STD = 11 cm) (Fig. 15). There has been a proliferation of alder at this site, similar in nature to that reported by Mackay (1995) at Navy Road, but it remains unclear whether vegetation change was the cause of active-layer deepening or a response to moisture and nutrient contributions from the thawing of ice and nutrient-rich permafrost (Kokelj and Burn, 2005).

The cross section of a hummock in the 1968 burned area at Navy Road was described in 1975 by Pettapiece et al. (1978). At that time, the permafrost table was approximately planar and well-defined interhummock troughs, free of organic materials, separated the large, flat, closely spaced earth hummocks (Fig. 16A). The 2004 cross section revealed tongues of poorly decomposed organic material extending from trough areas into mineral soils beneath the poorly defined interhummock depressions (Fig. 16B). These organics were redistributed within the soil profile during outward spreading and collapse of the hummock (Fig. 12D). The interhummock troughs have filled with mosses and sedges leading to development of the bowl-shaped permafrost table (Fig. 16B; Table 1) (Mackay, 1995). Some organic materials

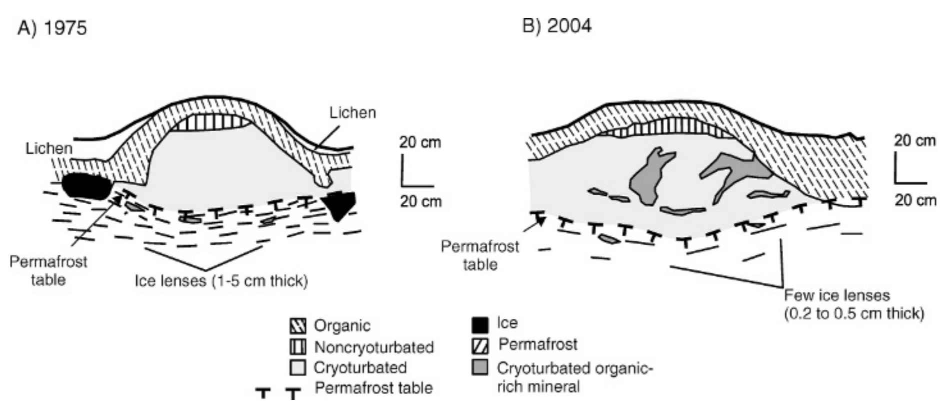


**FIGURE 14. Soil descriptions for two hummocks at Caribou Creek, N.W.T. Hummock A was excavated in 1975, and hummock B was excavated in 2004.**

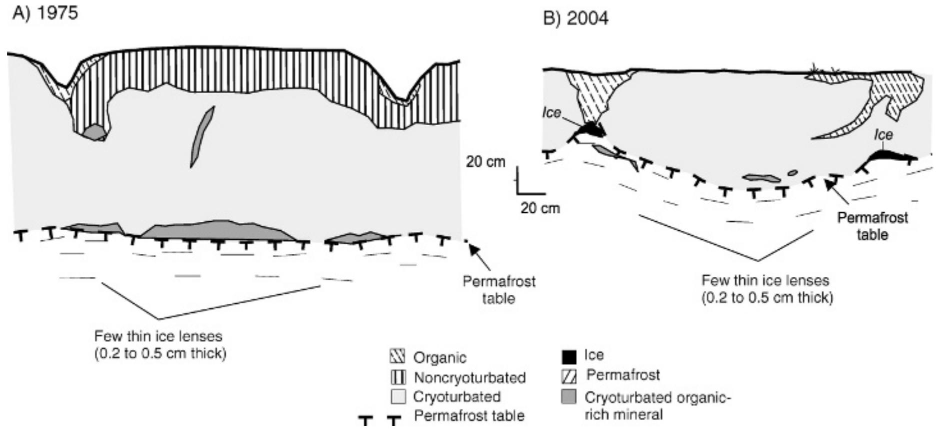


**FIGURE 16. Soil descriptions for two hummocks in an area burned by wildfire in 1968, Navy Road, Inuvik. Hummock A was excavated in 1975, and hummock B was excavated in 2004.**

have become trapped in near-surface permafrost. At present, the hummock is flat because the near-surface permafrost remains ice-poor (Fig. 16B).

The observations at Caribou Creek indicate that even in the absence of major terrain disturbance, an increase in thaw depth, possibly due to climate warming as reported for Inuvik (Burn et al., 2004), can alter the form of well-developed hummocks underlain by ice-rich permafrost (Figs. 14 and 15). In the burned area at Navy Road, destruction of surface organic materials, permafrost degradation, and hummock collapse was followed by gradual reestablishment of mosses in the troughs and shrub growth, leading to active-layer thinning and in some cases the development of a bowl-shaped permafrost table (Fig. 16) (Mackay, 1995). We suggest that the slow rate of near-surface ice enrichment (Kokelj and Burn, 2003) provides an explanation for the gradual development of hummock relief (Figs. 14 and 16).

## Hummock Development and the Drunken Forest

### *TILTING OF BLACK SPRUCE TREES ON HUMMOCKY TERRAIN*

Black spruce growing on the sides of earth hummocks may respond to earth movements (Zoltai and Pettapiece, 1974; Zoltai, 1975a) associated with hummock development and collapse. In the unburned area at the Navy Road site, a total of 30 trunk cross sections were obtained from tilted black spruce trees growing on hummock sides to examine the tree rings for reaction wood (Fig. 1). The data are presented and discussed in the context of historical data on active-layer variation, ground-ice conditions, and hummock form (Mackay, 1995; Kokelj and Burn, 2003).

In cross section, reaction-wood rings are characterized by an eccentric crescent of dark, dense wood (Fig. 17). In coniferous species, reaction wood is produced on the side of the tree in the direction of tilt (Zoltai, 1975a; Kokelj and Burn, 2004). Annual growth rings provide the age of the tree, while reaction-wood rings indicate the time of perturbation, and the duration and orientation of leaning (Zoltai, 1975a).

The black spruce trees sampled at the Navy Road site were characteristically less than 3 m height and ranged from 52 to 93 years in age, with a mean age of 70 years. The stand probably developed following a fire that burned through the Inuvik region more than 120 years ago (Black and Bliss, 1978; Landhäusser and Wein, 1993). The presence of only a few seedlings in the adjacent 1968 burn area indicates that several decades may pass following fire before spruce trees reestablish in this region.

Some of the sectioned trees had as many as five distinct sequences of reaction-wood growth punctuated by stability as indicated by normal growth rings (Fig. 17). On average, the trees experienced two periods of movement. The average duration of a reaction-wood sequence was approximately 10 years; however, two of the trees have grown reaction wood continuously since the 1950s.

The percentage of the trees that produced reaction wood in a given year indicates periods of greater tree movement or quiescence (Fig. 18A). Prior to 1950, reaction-wood rings were observed in less than 20% of the sampled trees. Percentages increased in the 1950s and peaked in 1966 when 80% of trees produced reaction wood (Figs. 17 and 18). The prevalence of reaction wood in annual growth rings declined throughout the late 1960s and early 1970s (Fig. 18). By 1976 only 22% of annual tree rings were characterized by reaction wood. From 1982 to 1988, the percentage of trees with reaction wood increased from 27% to 97% indicating that virtually all of the trees were tilting (Fig. 18). The percentage of trees that produced reaction wood remained above 80% per annum for the rest of the record.

**FIGURE 17. Trunk cross section of a tilted black spruce tree growing on a hummock side, Navy Road, Inuvik. The tree was 73 years old, and there were two distinct periods of tilting. The first period of tilting was initiated in 1966 and the second in 1986. The arrows indicate the orientations of tilting, and the lengths of the arrows indicate duration of tilting.**

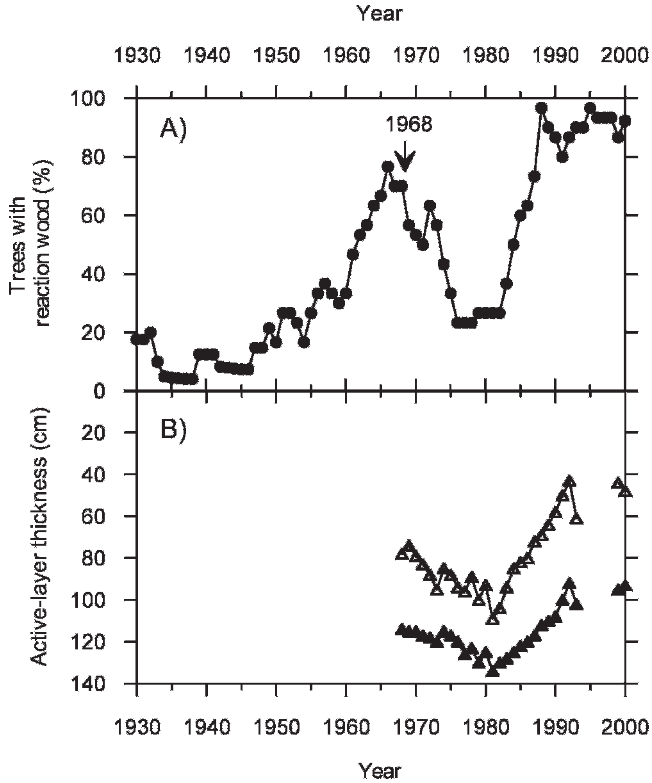


**FIGURE 18. (A) The percentage of black spruce trees ($N = 30$) producing reaction wood in a given year, 1930–2000, Navy Road, Inuvik. (B) Depth of thaw for hummocks (▲) and interhummock depressions (Δ), 1968–1993 and 1999–2000, black spruce forest, Navy Road, Inuvik. Active-layer data for 1968–1993 are from Mackay (1995, Fig. 2).**

### *TREE MOVEMENTS AND HUMMOCK DYNAMICS*

The tilting of trees in the 1950s and 1960s is consistent with a period of post-fire vegetation succession and associated active-layer thinning, aggradational-ice development, and hummock growth (Fig. 12) (Zoltai, 1975b). By 1968, hummock forms and a bowl-shaped permafrost table were well established (Mackay, 1995). Active-layer deepening, destruction of the bowl-shaped permafrost table, and degradation of ice-rich permafrost in the late 1960s and early 1970s caused hummocks to spread outward and their relief to decrease (Figs. 12D and 18B) (Mackay, 1995; Kokelj and Burn, 2003). The abrupt decline in reaction-wood production between 1966 and 1976 suggests that the decrease in hummock relief caused the tilt of most trees growing on hummock sides to decrease (Fig. 18A).

In the 1980s, the proliferation of alder increased ground shading, and establishment of mosses in interhummock troughs modified ground-thermal conditions, promoting upward aggradation of the permafrost table (Mackay, 1995). Reestablishment of the bowl-shaped permafrost table and ground-ice development heaved hummock soils inward and upward, decreasing hummock diameter, increasing hummock relief, and causing trees to tilt (Figs. 12C and 18) (Mackay, 1995; Kokelj and Burn, 2003).

## Summary and Conclusions

From the results and discussion, the following conclusions can be drawn:

(1) Aggradational-ice development is the principal mechanism driving the modification of hummock form. Establishment of a bowl-shaped permafrost table is associated with colonization of mosses and shrubs in the interhummock depressions. Gradual ice-enrichment beneath the aggrading bowl-shaped permafrost table can thrust soils radially inward and upward, decreasing hummock diameter while increasing hummock spacing and relief.

(2) Active-layer deepening that leads to destruction of the bowl-shaped permafrost table and degradation of near-surface ground ice is the primary cause of subsidence and outward spreading of well-developed hummocks. Climate change, fire, or anthropogenic disturbance may lead to degradation of the bowl-shaped active layer.

(3) Following degradation of the bowl-shaped permafrost table and subsidence of the interhummock depressions, materials in the trough areas can be buried by the outward spreading of the adjacent hummocks.

(4) Black spruce trees growing on the sides of earth hummocks have tilted in response to active-layer thinning, aggradational-ice development, and hummock growth. The trees have righted during periods of gradual active-layer deepening, degradation of the bowl-shaped permafrost table, and outward spreading of the hummocks.

(5) In the boreal forest, hummock dynamics are strongly influenced by fire, which may incinerate ground vegetation and lead to thawing of near-surface ground ice and hummock collapse. Post-fire vegetation succession leads to reestablishment of a bowl-shaped permafrost table followed by gradual ice-enrichment of near-surface permafrost and hummock growth. Well-developed hummocks in mature forests with thick organic ground cover and high ice-content permafrost are susceptible to modification as the result of active-layer deepening due to fire disturbance or climate change.

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