PERMAFROST AND PERIGLACIAL PROCESSES
*Permafrost Periglac. Process.* **13**: 171–185 (2002)
Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/ppp.417

# Physical and Chemical Characteristics of the Active Layer and Permafrost, Herschel Island, Western Arctic Coast, Canada

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## ABSTRACT

Physical and geochemical characteristics of near-surface permafrost and the impact of permafrost degradation on soil and water chemistry were investigated at five sites on Herschel Island, Yukon Territory. The distribution of soluble cations, moisture and organic matter content in turbic cryosols from undisturbed terrain indicated a thaw unconformity 50 to 80 cm below the base of the present active layer. Palaeoactive-layer depth, estimated at between 90 and 100 cm, is less than at comparable sites in the Mackenzie Delta area. The difference may be due to the comparative proximity of Herschel Island to the Beaufort Sea coastline in the early Holocene. Soluble cations in permafrost and the active layer of static cryosols at recently disturbed sites were two orders of magnitude higher than in the active layer at undisturbed sites. $Na^+$ was the dominant cation in undisturbed permafrost, recently disturbed ground, and surface runoff derived from disturbed areas. Although degradation of permafrost following terrain disturbance has resulted in surface salinization, a condition detrimental to vegetation growth, leaching of soluble salts from disturbed areas has occurred over time. These processes have produced a range of soil conditions that contribute to the floristic diversity of Herschel Island. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS: aggradational ice; cryosols; Herschel Island; palaeoactive layer; permafrost; thaw unconformity; soil chemistry

## INTRODUCTION

Herschel Island is a glacier ice-thrust remnant, 100 km$^2$ in area, 5 km off the coast of Yukon Territory (Mackay, 1959; Figure 1). The island rises 180 m above sea level and is composed of shallow-water and marine sediments underlain by continuous permafrost (Bouchard, 1974; Rampton, 1982). The terrain is ice-rich, and massive segregated ice, ice-wedge ice, injection ice, and buried snowbank ice have all been identified in coastal exposures (Pollard, 1990). There are numerous active-layer detachment slides and retrogressive thaw slumps on the island, many due to coastal erosion (Rampton, 1982; de Krom, 1990; Pollard, 1990). Mackay (1959) noted that the basin underlying Ptarmigan Bay, southeast of Herschel Island, is of similar volume to the island, indicating the origin of the upthrust sediments. The ice thrusting occurred during Buckland Glaciation, the pre-Late Wisconsinan glacial period when a lobe of the Laurentide Ice Sheet reached its maximum northwestern extent along Yukon Coastal Plain (Rampton, 1982; Duk-Rodkin, 1999).

The geochemistry of near-surface permafrost terrain may be used to identify the extent of active-layer development, because the leaching of solutes may lead to distinct chemical characteristics in the

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Contract grant sponsor: Polar Continental Shelf Project; Contract grant number: 04201.


*Received 11 January 2002*
*Revised 8 April 2002*
*Accepted 8 April 2002*

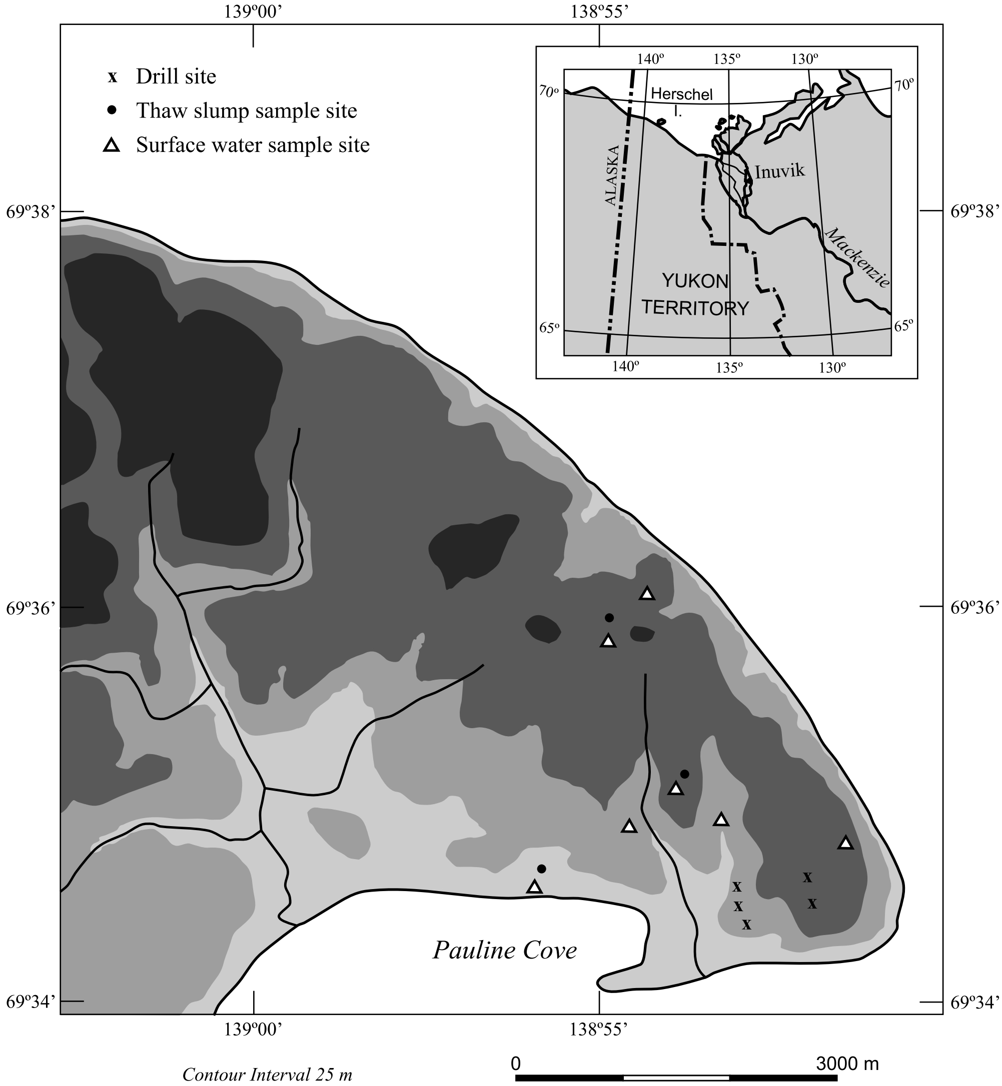


Figure 1 Location of the study area, northeastern Herschel Island, Yukon Territory. Crosses indicate locations where permafrost cores were obtained. Grey shading indicates elevation above sea level; contour interval 25 m.

active layer and underlying permafrost (Péwé and Sellmann, 1973; Kokelj and Lewkowicz, 1999). Permafrost in sediments that have been associated with a marine environment is commonly saline (Hivon and Sego, 1993), so assessment of near-surface pore-water geochemistry offers the prospect of determining the extent of the early Holocene thaw unconformity on Herschel Island. This unconformity is a widespread feature of the cryostratigraphy in Canada’s western Arctic coastlands, due to a warmer climate and maximum active-layer development in the region about 9000 years ago (Mackay, 1975, 1978, 1992; Murton and French, 1993, 1994; Burn, 1997). Near-surface geochemistry may also indicate the potential impact of climate warming and active layer deepening (e.g., Wolfe *et al.*, 2000) on the chemistry of soils and surface water. For instance, disturbance to marine sediments and degradation of near-surface saline permafrost on Fosheim Peninsula, Ellesmere Island, has resulted in surface salinization, and elevated total dissolved solid (TDS) concentrations in surface runoff (Kokelj and Lewkowicz, 1999).

Fieldwork was conducted in July 2000 on north-eastern Herschel Island to investigate the physical and chemical characteristics of the active layer and near-surface permafrost (Figure 1). Drill cores were obtained from three sites in undisturbed ground and two sites in terrain disturbed by active-layer detachment sliding. The undisturbed sites facilitated examination of palaeoactive-layer development, while the disturbed sites allowed investigation of the effect of disturbance on surface soil chemistry. In addition, the chemical characteristics of various ground-ice types were assessed by directly sampling three thaw-slump exposures near Pauline Cove, where the effect of permafrost degradation on surface-water chemistry was also examined (Figure 1). The purposes of this paper are (1) to discuss the geochemistry of the active layer and near-surface permafrost in cryosolic soils on northeastern Herschel Island, and (2) to determine the effect of permafrost degradation on soil and surface-water chemistry.

## EARLY-HOLOCENE THAW UNCONFORMITY

Palaeoclimatic investigations in western Arctic Canada indicate that the early Holocene climate was considerably warmer than it is today (Ritchie, 1984; Rampton, 1988). The warming was due in part to increased summer insolation attributed to Milankovitch cycles, but also to the palaeogeographic configuration of the coastline along the continental shelf of the Beaufort Sea (Ritchie *et al*., 1983; Ritchie, 1984; Mackay, 1992; Burn, 1997). Palynological investigations of peat obtained from Herschel Island and dated at 9380 ± 170 years BP (GSC-1483) indicate that shrub tundra covered the island at that time (Lowdon and Blake, 1976), in contrast with today's tussock tundra. *Betula* is a dominant species in the pollen spectrum from 9380 ± 170 years BP, but only a minor component today (Smith *et al*., 1989), indicating the recent climate is cooler than that of the early Holocene. In addition, *Populus* wood collected at Sabine Point on the Yukon coast has been dated at 9940 ± 90 years BP (GSC-2022) (Lowdon and Blake, 1976), yet Yukon Coastal Plain is north of the current range of this species (Cody, 1996).

The warmer climate led to an increase in active-layer depth and formation of a widespread thaw unconformity (Mackay, 1978, 1992; Burn *et al*., 1986; Murton and French, 1993, 1994; Burn, 1997). In the Mackenzie Delta area, a considerable proportion of the increase in summer thaw depth was likely due to northward extension of the taiga, leading to a deeper snow cover and warmer ground temperatures (Burn, 1997). Palaeoactive-layer depths of between 96 and 129 cm were estimated by Burn (1997, Table 2) for several sites in Tuktoyaktuk Coastlands, although the position of the unconformity was between 131 and 195 cm below the surface. The difference is attributable to aggradational ice, which accumulated above the unconformity as the active layer thinned (Mackay, 1972; Burn, 1988). In Tuktoyaktuk Coastlands, the thaw unconformity has been identified by truncation of ice wedges and variations in the cryostructure of ground ice (Mackay, 1975; Murton and French, 1993).

## STUDY SITES

Five soil cores were obtained from sites in varying settings on Herschel Island near Pauline Cove (Figure 1). These sites were selected because they represent a range of disturbed and undisturbed terrain and soil types encountered on the island (Smith *et al*., 1989). Sites 1 and 2 were on an undisturbed upland plateau, site 3 was on a stable slope in undisturbed ground, and sites 4 and 5 were in the scar zones of active-layer detachment slides. Site 1 was located on *Eriophorum* tussock tundra, a terrain that is characteristic of the oldest and most stable land surfaces on the island (Smith *et al*., 1989). The silty clay loam soil at the site was classified as gleysolic turbic cryosol (Soil Classification Working Group, 1998). Core samples were collected when the thaw depth was 20 cm, and the permafrost table was estimated to be at a depth of between 30 and 40 cm.

Sites 2 and 3 were located on an upland surface with earth hummocks. The dominant plants at the sites were *Salix, Dryas, Oxytropis*, and graminoid species, and the soil was silty clay loam classified as orthic eutric turbic cryosol. Site 2 was located on level ground, while site 3 was located on a slope of less than 4° between two active-layer detachment slides (Figure 2). Drilling was in the centre of hummocks. At the time of fieldwork, thaw depths at sites 2 and 3 were 40 and 45 cm respectively, while the permafrost was estimated at between 50 and 60 cm depth.

Sites 4 and 5 were located in the scars of active-layer detachment slides. Site 4 was in the older of the two disturbances, with the ground surface sparsely vegetated by grasses (Figure 3). At site 5 the ground was bare of vegetation, and salt efflorescence was apparent over several parts of the scar (Figure 4). The recently thawed sediments were classified as orthic eutric cryosols because they lacked evidence of cryoturbation. At both sites the thaw depth at the time of fieldwork was 60 cm and the permafrost table was estimated to be at between 90 and 100 cm depth.

Figure 2 Well-vegetated hummocky terrain on Herschel Island at site 3, July 2000.

Figure 4 A recent active-layer detachment slide scar (site 5). The scar surface is completely bare of vegetation. The photograph was taken during July 2000.

Figure 3 An old active-layer detachment slide scar on Herschel Island (site 4). The scar zone is sparsely vegetated by grasses while the surrounding undisturbed terrain is characterized by well-vegetated earth hummocks, July 2000.

## METHODS

Soil cores were extracted from depths to 170 cm using a 2-in diameter CRREL core barrel. Thaw depth at the time of sampling in early July was less than 60 cm. The location of the permafrost table was estimated by an increase in ground resistance to drilling and an increase in visible ground-ice content. The core samples were sectioned in 10-cm intervals, logged, double-bagged, and returned to a laboratory in Inuvik. Ground-ice samples were also obtained directly from exposures, after chipping surface materials away so that the samples would not be contaminated by meltwater. These samples were also double-bagged in polyethylene, sealed, and returned to the laboratory.

Twelve water samples were collected from first-order tundra ponds and creeks in disturbed and undisturbed ground. These samples were collected in polyethylene bottles and, with the ground-ice samples, kept cool and dark before processing in Inuvik.

Laboratory analyses were conducted on the samples to determine soil moisture and excess-ice content, pore-water electrical conductivity, and dissolved solids. Permafrost and active-layer samples were thawed and homogenized, poured into beakers, weighed, and allowed to settle. The volumes of sediment and supernatant water were recorded to estimate the excess ice content of the samples. Supernatant water was extracted from these samples with a syringe and filtered through a 0.45 μm millipore cellulose filter. If the sample was not supersaturated, an equal weight of distilled, deionized water was added. The sample was then mixed thoroughly, re-weighed, and the sediment was allowed to settle for 12 h. The supernatant water was then extracted and filtered. The remainder of the sample was dried for 24 h at 105 °C so that field moisture content and the moisture content at extraction could be determined. A semi-quantitative estimate of soil organic matter content of the oven-dried samples was obtained by the loss on ignition method and particle-size distributions were determined by the pipette method (Sheldrick, 1984).

The electrical conductivity and TDS of soil and surface waters were measured, immediately after filtering, using a Yellow Springs Instruments model 30 conductivity/salinity probe calibrated against a NaCl reference solution. Analysis for water soluble $Ca^{++}$, $Mg^{++}$, $Na^{+}$, and $K^{+}$ extracted from soil samples was by atomic adsorption spectrophotometer at Simon Fraser University. Since the moisture content of samples was determined, soluble ion concentrations in soil-water extractions were converted to milliequivalents per unit weight of dry soil (meq/100 g) to facilitate comparison of solute concentration between core samples of varying moisture contents.

## RESULTS

### Moisture Content

Gravimetric water-content profiles from the five sites are presented in Figure 5. An ice-rich zone was recorded directly below the base of the contemporary active layer at undisturbed sites, and the moisture content up to 60 cm below the base of the active layer was over 100% (Figures 5a, b, c). Characteristically, the moisture content was greatest 20 to 40 cm below the base of the active layer. Ice lenses were abundant in near-surface permafrost at all three undisturbed sites. Lower moisture contents were observed below this upper ice-rich zone, but another increase in moisture content was observed at depth (Figures 5a, b). The deeper zones of increased moisture content were 20 to 30 cm thick and contained ice lenses up to 2 cm thick. Moisture content profiles from the disturbed sites did not indicate an ice-rich zone in near-surface permafrost (Figures 5d, e). Thin ice lenses were observed in the top of permafrost at site 5, but the water content was less than at saturation.

### Organic Matter Content

At undisturbed sites the soil organic matter content in the active layer was greater than in the underlying permafrost. Within the undisturbed active layer (sites 1, 2 and 3), organic matter content was between 3 and 25% by weight (Figure 6a, b, c). In permafrost, organic-matter content declined with depth and was less than 3% below 120 cm and 90 cm at sites 1 and 2 respectively (Figure 6a, b). The organic matter contents in the active layer at disturbed sites were similar to values observed at depth in undisturbed terrain (Figure 6).

### Soluble Cations

At undisturbed sites, the total soluble cations in samples obtained from permafrost were greater than in mineral soil at the base of the active layer (Figures 7a, b, c). Variation in cation concentration of over an order of magnitude was recorded between the active layer and permafrost at depth. An increase in total soluble cations of more than an order of magnitude was observed at site 1 between depths of 120 and 130 cm, over 80 cm below the base of the active layer (Figure 7a). At site 2, a similar increase in cation concentration was observed at depth (Figure 7b). Samples from the present active layer in detachment slide scars had concentrations about an order of magnitude greater than from the active layer at undisturbed sites (Figures 7d, e). The total cation concentrations near the base of the active layer at the disturbed sites were similar to the values measured at depth in undisturbed terrain, on the order of 10 meq/100 g.

$Na^{+}$ was a dominant cation in all samples obtained from Herschel Island. At site 1, soluble $Na^{+}$ concentrations ranged from 0.08 meq/100 g to 0.42 meq/100 g in the ice-rich zone just below the base of the active layer, but increased by over an order of magnitude between 120 and 130 cm depth, as did the total soluble cations (Figures 8a). The maximum concentration of $Na^{+}$, 8.0 meq/100 g, was measured at depths of 150 to 160 cm. The relative proportion of $Na^{+}$ with respect to other cations also increased with depth, from 25% at the base of the active layer to over 70% at 110 to 120 cm. Similar trends in relative and absolute concentration of soluble $Na^{+}$ were observed at sites 2 and 3 (Figures 8b, c). At sites 4 and 5, $Na^{+}$ comprised more than 90% of the total cations, and the peak in concentration occurred near the base of the active layer (Figures 8d, e). The maximum values at sites 4 and 5 were on the same order as at undisturbed sites. Within the active layer at site 5 the concentration was in the same range as the values measured at depth at the other sites.

Concentrations of soluble $Ca^{++}$, $Mg^{++}$, and $K^{+}$ were higher in permafrost than in the active layer at all sites, with an increase in concentration of an order of magnitude or more recorded at some sites, as with $Na^{+}$. Figure 9a presents the variation in concentration of $Ca^{++}$ with depth at site 1 to illustrate these data from undisturbed terrain. Soluble $Mg^{++}$ was recorded in very low concentrations in the active layer and near-surface permafrost at all sites, with a maximum concentration of 0.04 meq/100 g, but an increase in the concentration was detected at depth in permafrost (Figure 9b). A similar trend in concentration of $K^{+}$ with depth was obtained at site 1, but the absolute concentrations of this cation were low, not more than 0.45 meq/100 g (Figure 9c).

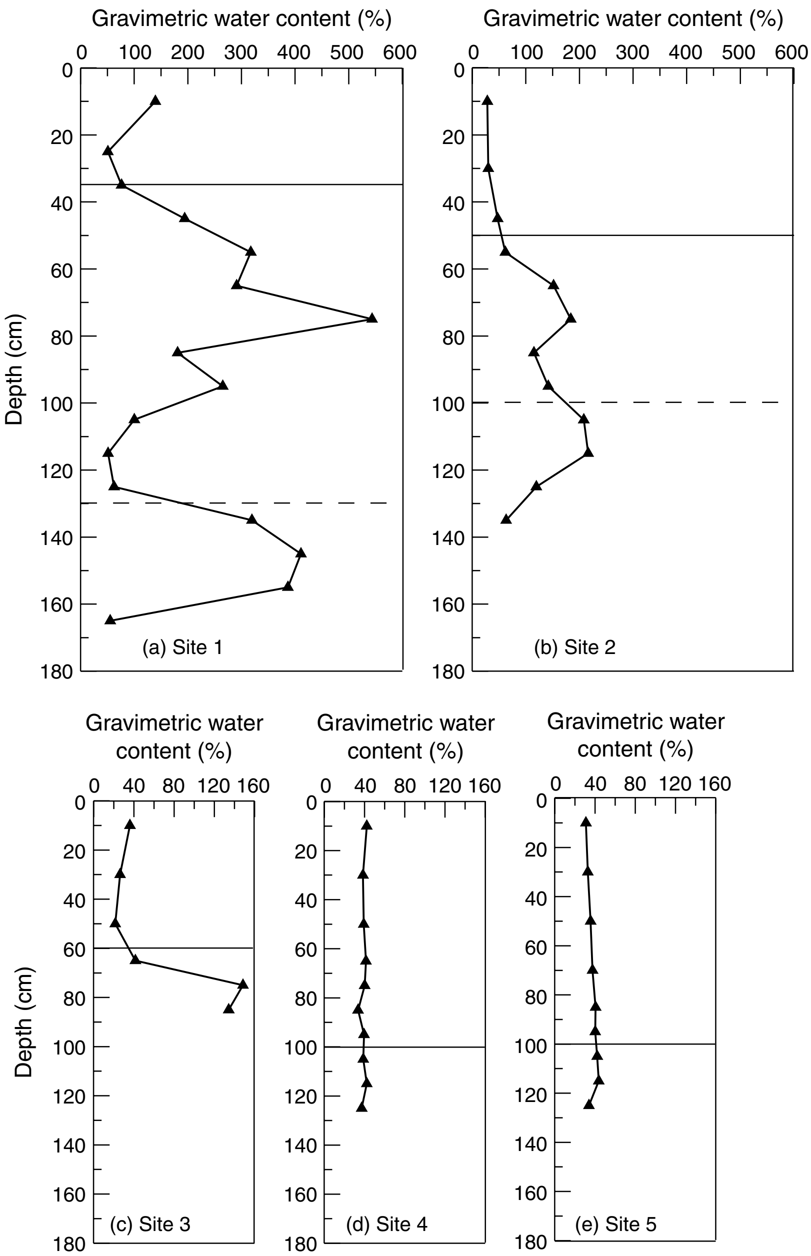


Figure 5 Profiles of gravimetric moisture content in the active layer and near-surface permafrost, Herschel Island, Yukon Territory. (a) site 1; (b) site 2; (c) site 3; (d) site 4; (e) site 5. The solid line marks the permafrost table and the dashed line marks the depth of the inferred thaw unconformity.

## Massive Ice

Five samples were collected from ground-ice exposures, to compare their chemical characteristics with those of the core samples obtained from near-surface permafrost (Figure 1). The geochemical data for samples of ice-wedge ice were determined directly as concentrations (meq/l), because the ice contained almost no sediment. The measured soluble cation concentrations in the other samples were expressed per unit weight of dry soil (meq/100 g dry soil).

 

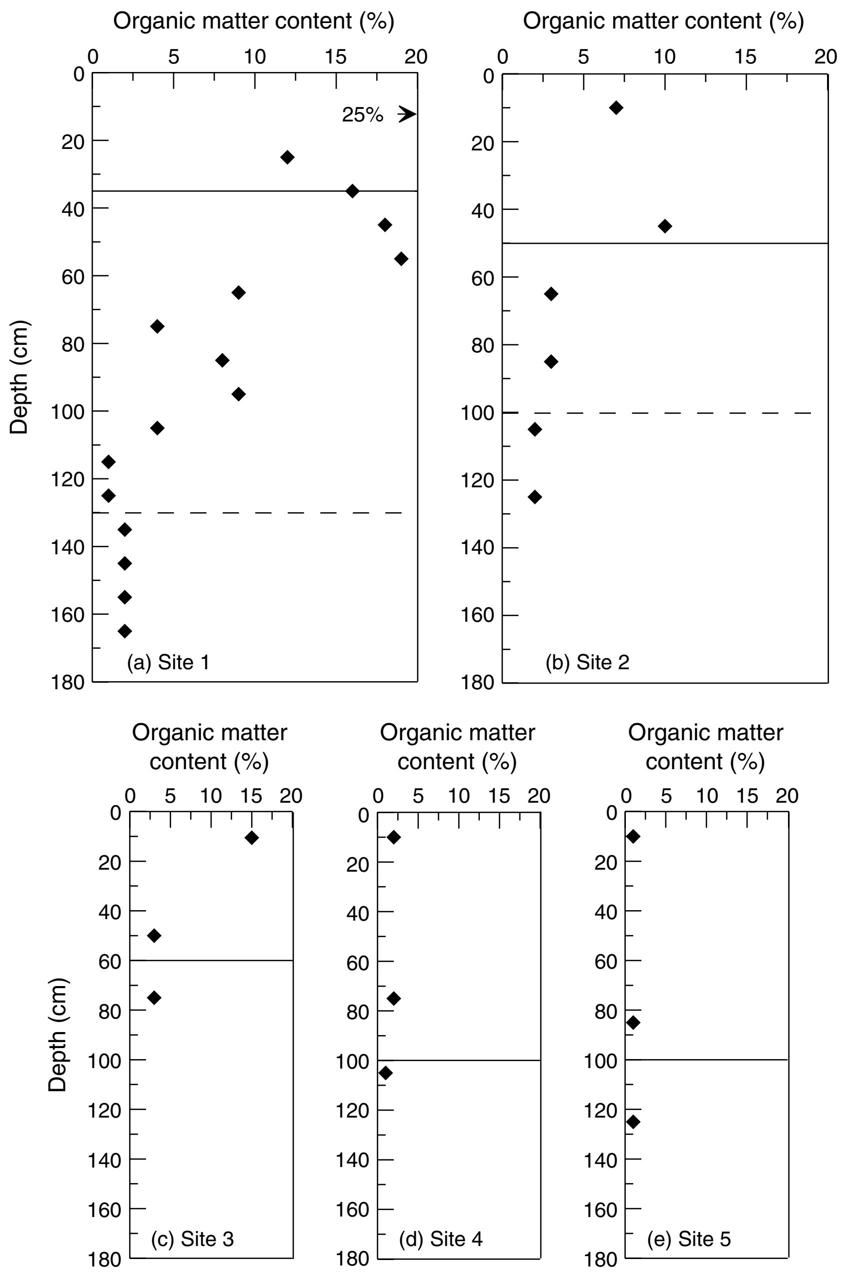


Figure 6 Profiles of soil organic matter content in the active layer and near-surface permafrost, Herschel Island, Yukon Territory. (a) site 1; (b) site 2; (c) site 3; (d) site 4; (e) site 5. The solid line marks the permafrost table and the dashed line marks the depth of the inferred thaw unconformity.

The lowest soluble ion concentration was measured in ice-wedge ice, and the highest concentration was determined for a sample of massive tabular ice (Table 1). Despite the low concentrations in the melt, the levels of soluble cations expressed on a per unit weight of dry soil basis were comparable to that from near-surface ground ice (sites 1–3), due to the high moisture contents of the massive ice samples. $Na^+$ was a dominant cation in all of the massive ice samples (Table 1).

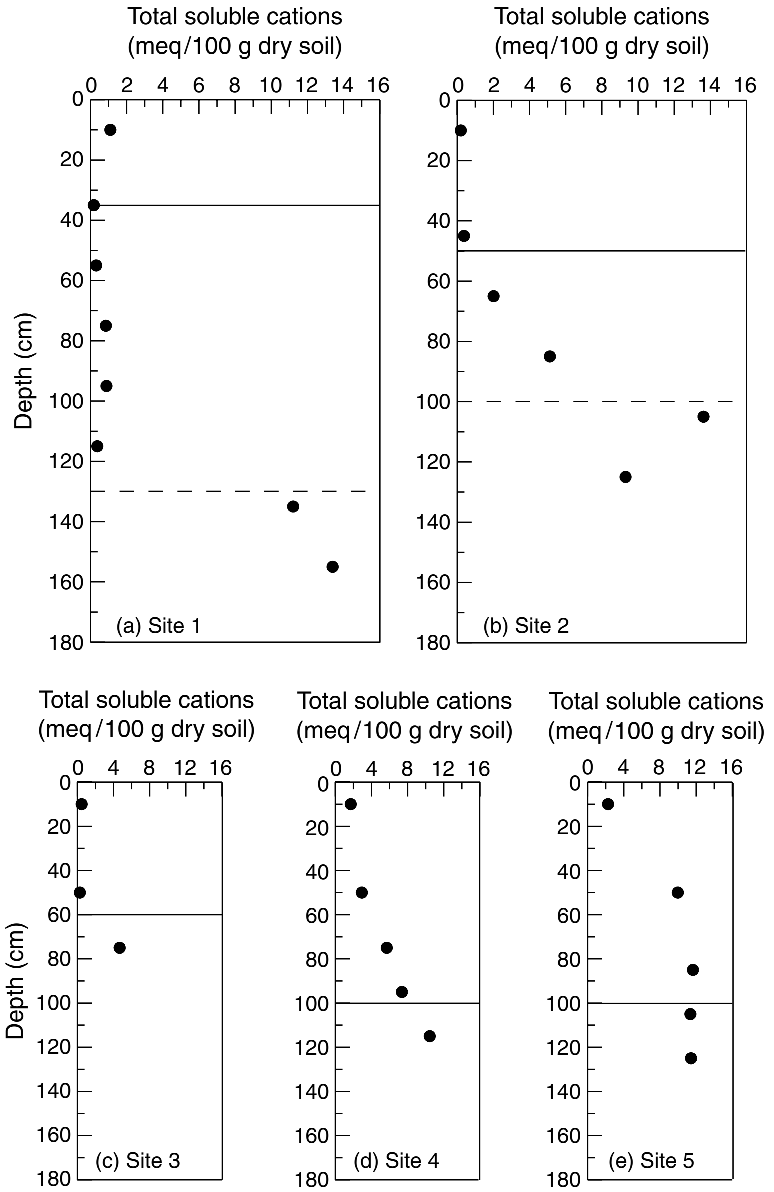


Figure 7 Profiles of total soluble cations in the active layer and near-surface permafrost, Herschel Island, Yukon Territory. (a) site 1; (b) site 2; (c) site 3; (d) site 4; (e) site 5. The solid line marks the permafrost table and the dashed line marks the depth of the inferred thaw unconformity.

## Surface Water

Twelve water samples were collected from disturbed and undisturbed ponds and small creeks on northeast Herschel Island (Figure 1). Some of these samples were obtained from sites close to the sampling points for massive ice. Of the five surface water samples obtained from undisturbed localities, three were from ponds and two from small creeks. The mean TDS of these samples was 153 mg/l, with a range of 95 mg/l to 262 mg/l (Table 2). $Na^+$ and $Mg^{++}$ were dominant cations in these samples, with the mean relative proportion of $Na^+$ 32%.

Three water samples were collected from tundra ponds directly affected by permafrost degradation, and four others from disturbed terrain (Table 2).

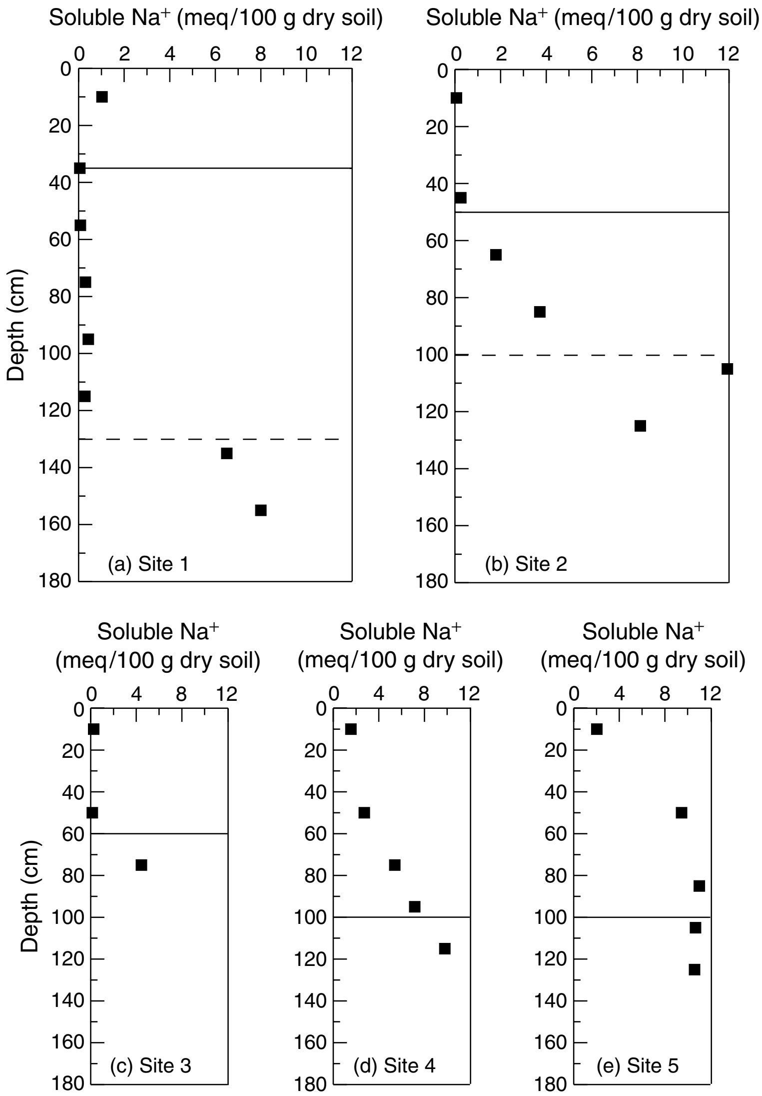


Figure 8 Profiles of soluble $Na^+$ in the active layer and near-surface permafrost, Herschel Island, Yukon Territory. (a) site 1; (b) site 2; (c) site 3; (d) site 4; (e) site 5. The solid line marks the permafrost table and the dashed line marks the depth of the inferred thaw unconformity.

The mean TDS of these samples was 671 mg/l, with a range of 126 to 1370 mg/l. Maximum solute concentrations were measured in surface runoff derived from a retrogressive thaw slump. Again, $Na^+$ was a dominant cation in all samples, on average contributing 52% of total soluble cations.

## DISCUSSION

The data presented in Figure 7 indicate that the active layer and underlying permafrost are geochemically distinct at undisturbed sites on Herschel Island. These data show an increase with depth in soluble cation concentration of about one order of magnitude, from 0.18 meq/100 g to 1.10 meq/100g, in the active layer, to 13.62 meq/100g at depths over 100 cm. At disturbed sites, soluble cation concentrations in the active layer were greater than in the undisturbed active layer (Figures 7 and 8), but the concentration declined with age of disturbance. The latter observation indicates that cations were leached from the active layer over time. Indeed, surface runoff

 

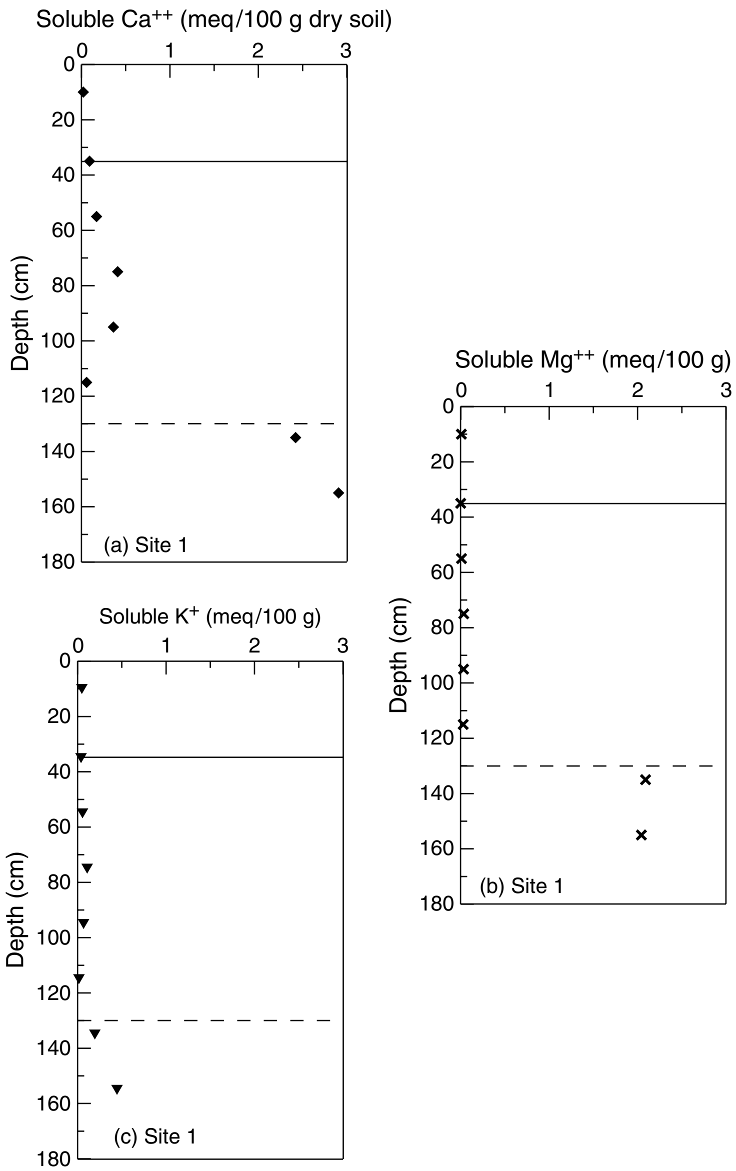


Figure 9 Profiles of soluble $Ca^{++}$, $Mg^{++}$, and $K^{+}$ in active layer and near-surface permafrost, Site 1, Herschel Island, Yukon Territory. (a) Soluble $Ca^{++}$; (b) soluble $Mg^{++}$; (c) soluble $K^{+}$. The solid line marks the permafrost table and the dashed line marks the inferred thaw unconformity.

derived from thaw slumps and ponds influenced by thermokarst processes had a mean TDS of 670 mg/l, more than four times greater than the concentrations in surface water in undisturbed terrain (Table 2). In addition, during soil freezing, water and soluble ions move together along thermal gradients (Cary and Mayland, 1972; Qui *et al*., 1988), therefore some base cations may have also been drawn downward along with water, from the active layer into near-surface permafrost.

$Na^{+}$ constituted between 60 and 95% of the soluble cations measured at depth in permafrost at undisturbed sites and in the active layer at disturbed locations. The relative abundance of $Na^{+}$ in surface water samples associated with terrain disturbance ranged from 40 to 63%, with a mean

Table 1 Physical and chemical characteristics of massive ground ice and ice wedges sampled on Herschel Island, Yukon Territory. Sample numbers correspond with associated disturbed surface water samples in Table 2.

| | Conductivity (μS/cm) | Moisture content (%) | Soluble cations (meq/100 g dry soil) | | | | | Soluble cation concentrations (meq/l) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $Na^+$ | $K^+$ | $Ca^{++}$ | $Mg^{++}$ | Total | $Na^+$ | $K^+$ | $Ca^{++}$ | $Mg^{++}$ | Total |
| Ice wedge 1 | 217 | | | | | | | 0.12 | 0.09 | 0.19 | 0.10 | 0.50 |
| Ice wedge 4 | 263 | | | | | | | 1.06 | 0.10 | 0.26 | 0.18 | 1.60 |
| Massive ice 4 | 1120 | 680 | 1.90 | 0.24 | 0.57 | 2.16 | 4.87 | 2.80 | 0.35 | 0.84 | 3.17 | 7.16 |
| Massive ice 6a | 249 | 1500 | 1.36 | 0.10 | 0.41 | 0.25 | 2.12 | 0.91 | 0.07 | 0.27 | 0.17 | 1.42 |
| Massive ice 6b | 222 | 1800 | 1.48 | 0.15 | 0.43 | 0.27 | 2.33 | 0.82 | 0.08 | 0.24 | 0.15 | 1.29 |

Table 2 Geochemistry of surface water samples derived from undisturbed and disturbed tundra, Herschel Island, Yukon Territory. Adjacent sampling sites are indicated by corresponding numbers.

| Sample | Electrical conductivity (μS/cm) | Total dissolved solids (mg/l) | Soluble cations (meq/l) | | | | |
|---|---|---|---|---|---|---|---|
| | | | $Na^+$ | $K^+$ | $Ca^{++}$ | $Mg^{++}$ | Total |
| *Undisturbed* | | | | | | | |
| Pond 1a | 200 | 95 | 0.45 | 0.04 | 0.29 | 0.35 | 1.14 |
| Pond 2a | 548 | 262 | 0.50 | 0.08 | 0.56 | 1.71 | 2.85 |
| Pond 3a | 228 | 108 | 0.35 | 0.07 | 0.41 | 0.62 | 1.44 |
| Stream 7a | 426 | 204 | 1.21 | 0.05 | 0.74 | 1.83 | 3.83 |
| Stream 8 | 207 | 98 | 0.48 | 0.03 | 0.35 | 0.13 | 0.99 |
| *Mean* | *322* | *153* | *0.60* | *0.05* | *0.47* | *0.93* | *2.05* |
| *Disturbed* | | | | | | | |
| Pond 1b | 266 | 126 | 0.88 | 0.05 | 0.48 | 0.55 | 1.97 |
| Pond 2b | 456 | 217 | 1.64 | 0.07 | 0.56 | 1.01 | 3.29 |
| Pond 3b | 1640 | 809 | 6.83 | 0.24 | 1.90 | 4.04 | 13.01 |
| Slump runoff 3b | 1932 | 954 | 8.50 | 0.44 | 1.07 | 3.57 | 13.58 |
| Slump runoff 4b | 1150 | 558 | 3.30 | 0.23 | 1.32 | 3.65 | 8.50 |
| Slump runoff 5b | 1406 | 665 | 5.22 | 0.44 | 0.83 | 2.66 | 9.14 |
| Slump runoff 6b | 2740 | 1370 | 10.00 | 0.20 | 2.44 | 4.80 | 17.43 |
| *Mean* | *1370* | *671* | *5.20* | *0.24* | *1.23* | *2.90* | *9.56* |

of 52% (Table 2). At undisturbed sites, the relative proportion of $Na^+$ in the soluble cations of the active layer ranged from 25 to 92%, with a mean of 48%, while in runoff from undisturbed sites $Na^+$ constituted 32% of the total cations. The dominance of $Na^+$ in the ionic composition of permafrost is likely associated with the marine origin of the sediments. The decline in $Na^+$ representation in the undisturbed active layer, and its abundance in surface runoff from disturbances, demonstrates the high solubility of $Na^+$ with respect to other cations. The contribution of $Na^+$ to the terrestrial system from ocean salt spray was not evaluated, but it is unlikely that marine aerosols would account for all the observed differences in geochemistry of soil and surface water between disturbed and undisturbed terrain.

The high soluble cation concentrations and the dominance of $Na^+$ within permafrost and in the static cryosolic soils of recently-disturbed active layers indicate that degradation of permafrost on Herschel Island may lead to the release of $Na^+$ into the soil system producing locally salinized or sodic soil. High levels of $Na^+$ can be toxic to plants or lead to the development of adapted plant communities distinct from those on adjacent undisturbed sites. Soil erosion by surface runoff was indicated on the island by rills and gullies on slopes with a history of geomorphic disturbance (Figure 10). High suspended sediment concentrations were observed in

 

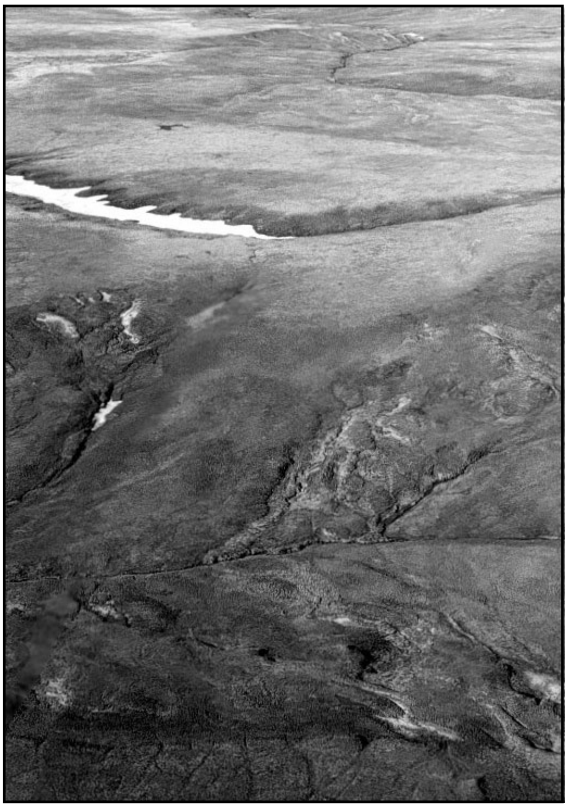

Figure 10 Rill and gully development in the scar zones of old slope disturbances in rolling tundra, Herschel Island, Yukon Territory.

runoff derived from thaw slumps, and ponds affected by permafrost degradation were more turbid than pools in undisturbed terrain. Several thaw slump scars and active-layer detachment slides on Herschel Island were made conspicuous by their reduced vegetation cover, compared with the surrounding tundra. Soluble $Na^+$ concentrations in the active layer at recently disturbed sites were in the range of soil-water concentrations associated with low biomass and reduced plant growth in coastal lowlands near La Pérouse Bay, Manitoba (Srivastava and Jefferies, 1996). The cycle of permafrost degradation, resultant soil salinization, and eventual salt leaching from the active layer has produced a continuum of soil conditions responsible in part for the floristic diversity of Herschel Island.

## Thaw Unconformity

Péwé and Sellmann (1973) used pore-water conductivity to interpret palaeoactive-layer extents in sedimentary sequences from central Alaska. On Herschel Island, an order of magnitude increase in soluble ion concentrations was observed between the active layer and near-surface permafrost at depths below 130 cm at site 1 and 100 cm at site 2. The high cation concentration at depth indicates that these sediments have not been subject to leaching, and implies they have remained in permafrost. The lower cation concentrations above 130 cm and 100 cm at the sites imply that these horizons have been leached of solutes. While the present active-layer thickness is estimated as approximately 35 and 50 cm, these data suggest past thawing to the 130 and 100 cm levels at sites 1 and 2 respectively.

Moisture content profiles at sites 1 and 2 also indicate development of a palaeoactive layer (Figures 5a, b), as two principal zones of ice enrichment were observed in the samples obtained from undisturbed permafrost. The first was immediately below the base of the present active layer, extending for approximately 50 cm. The second coincided with the depths at which soluble cations increased by an order of magnitude, 130–160 cm at site 1 and 100–120 cm at site 2. Segregated ice lenses in these sections appeared in similar form to the cryostructures observed immediately below the base of the contemporary permafrost table.

Permafrost at the base of the active layer is characteristically ice-rich due to downward moisture migration from the active layer into frozen ground at the end of summer (Mackay, 1983; Burn and Michel, 1988). Cheng (1983) suggests that the annual downward flux may be greater than water movement out of this zone in winter, when the temperature gradient is reversed, leading to a small annual enrichment in ice of the permafrost. Over time, this annual accumulation leads to development of an ice-rich zone. The ice-rich zone below 130 cm at site 1 and 100 cm at site 2 is therefore consistent with the interpretation, based upon solute concentration, of a palaeoactive layer extending to these depths with a thaw unconformity at its base.

Finally, the organic matter content of samples from sites 1 and 2 also provides evidence of palaeoactive-layer development (Figure 6a, b). The soil organic-matter content is usually highest in the active layer and the uppermost portions of the permafrost because of roots and the movement of organic material from the soil surface by cryoturbation (Mackay, 1980; Smith *et al*., 1991; Bockheim *et al*., 1999). For example, at site 1, the organic matter content of permafrost samples above 110 cm ranged between 4 and 20%, while below 130 cm the organic contents were less than 3%. These data are also consistent with the interpretation of a thaw unconformity at the 130 cm level.

The present depth of the thaw unconformity does not imply the thickness of the palaeoactive layer, because there is a considerable amount of near-surface aggradational ice above the interpreted unconformity (Figures 5a, b) (Mackay, 1972; Burn, 1997). Subtracting the ice content from the interval between the base of the active layer and the unconformity provides estimates of palaeoactive-layer thickness of 98 and 93 cm at sites 1 and 2 respectively, approximately double the present active-layer thickness.

Burn (1997, Table 2) reports a palaeoactive-layer thickness from elevated terrain in the Mackenzie Delta area of approximately 125 cm for the early Holocene. This value is greater than the thickness estimated for the same feature on Herschel Island. If the two points from undisturbed terrain on the northeast part of Herschel are, indeed, representative of conditions on the island, then these data suggest that the summer climate of Herschel Island was cooler than at the sites studied by Burn (1997) on Richards, Garry, and Pelly Islands.

At present, there is a steep environmental gradient in growing-season conditions between sites near the Beaufort Sea and warmer locations inland (Burn, 1997). The palaeoactive layers identified in the Mackenzie Delta area developed at sites that were about 100 km inland during the early Holocene. Since that time, relative sea level north of the present Mackenzie Delta has risen about 70 m (Hill *et al.*, 1993). The substantial coastal recession that has occurred north of the delta is partly due to the low gradient of the continental shelf in this area. In turn, coastal retreat may account for one to two thirds of the climatic cooling experienced at points within 100 km of the coast since then (Burn, 1997).

Near Herschel Island, however, bathymetric charts indicate a smaller continental shelf, so that the shoreline was only 4 to 15 km north of the island in the early Holocene (Matthews, 1975). The pollen spectrum from Herschel Island described earlier contains no indication of spruce forest in the early Holocene near the site, unlike evidence from Richards Island and Tuktoyaktuk Peninsula (Ritchie, 1984). This suggests that arctic maritime effects influenced the growing-season climate of Herschel Island in the early Holocene. The contrasting palaeogeography and palaeoecology of Herschel and Richards Islands may account for the thinner palaeoactive-layer depths observed on Herschel Island.

## CONCLUSIONS

From the data and interpretations presented, we conclude:

1. Soil soluble-cation concentrations, moisture contents and the pattern of soil organic-matter distribution in samples collected by drilling near the surface of undisturbed terrain on northeastern Herschel Island indicate a thaw unconformity 50 to 80 cm below the base of the present active layer. Maximum palaeoactive-layer thickness is estimated at approximately 1 m. If these estimates are representative of conditions on the island, the proximity of Herschel Island to the Beaufort Sea coastline during the early Holocene may account for the thinner palaeoactive layer interpreted at these sites in comparison with sites in the Mackenzie Delta area.
2. Soluble cation concentrations in permafrost were one to two orders of magnitude higher than in the active layer at undisturbed sites. $Na^+$ was a dominant soluble cation in undisturbed permafrost and in the active layer at recently disturbed sites.
3. High soil soluble cation concentrations within the active layer are associated with recent geomorphic activity that has resulted in lowering of the surface and the permafrost table. Evaporation from the surface of recently exposed sediments produces salt concentrations high enough to be detrimental to revegetation. Leaching of salts from disturbed areas appears to proceed with time, allowing a succession of vegetation types to establish on these surfaces, contributing to the floristic diversity of Herschel Island.

## ACKNOWLEDGEMENTS

This work was supported by the Natural Sciences and Engineering Research Council of Canada, the Northern Science Training Program of Indian Affairs and Northern Development Canada, the Yukon Territorial Government, the Aurora Research Institute, and the Polar Continental Shelf Project, Natural Resources Canada. Field assistance by Dorothy Cooley, Catherine Kennedy, Martin Kienzler, and Rob Savard is gratefully acknowledged. Logistical support was provided by the Yukon Department of Renewable Resources, Yukon Territorial Parks and the Ranger staff of Qikiqtaruk (Herschel Island) Territorial Park. Facilities at the Taiga Environmental Laboratory, Yellowknife, were provided through the good offices of Bill Coedy, Indian Affairs and Northern Development Canada, Anne Wilson, Environment Canada, and Brett Elkin, Government of the Northwest Territories. Office logistical support in Yellowknife was provided to the senior author through the generosity of Hal Mills, Geonorth Ltd. Lance Lesack, Simon Fraser University, provided use of the atomic adsorption spectrophotometer, and Maggie Squires contributed valuable guidance in analytical procedure. The authors thank Christine Earl and Phillip Wilson for cartography and Jamey Coughlin for the digital photo imagery. S. A. Kokelj, W. H. Pollard, C. Spence, and two anonymous reviewers provided helpful comments on the manuscript. PCSP Contribution No 04201.

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