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Salinization of Permafrost Terrain Due to Natural Geomorphic Disturbance, Fosheim Peninsula, Ellesmere Island

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ABSTRACT. Efflorescences (surface salt accumulations) are common on the Fosheim Peninsula and elsewhere in the Canadian Arctic Archipelago, especially at elevations below the Holocene marine limit, and cover up to 9% of the terrain in the vicinity of lower Hot Weather Creek. They are most extensive on naturally disturbed slopes and in floodplain locations. More than 75% of efflorescences are related to geomorphic disturbances (active-layer detachment sliding, retrogressive thaw slumping, and gullying), which initiate the causal chain of (1) surface erosion; (2) local degradation of permafrost; (3) contact between supra-permafrost groundwater and soluble ions previously held within frozen sediments; (4) increase in total dissolved-solids concentrations in slope surface runoff; and (5) depending on the degree of channelization of drainage and the slope profile, transport of dissolved solids directly to the stream system or their redistribution and accumulation downslope. Concentrations of Na^+ in surface runoff reached almost 5 g l^{-1} during summer 1996 at a recent (1988) detachment slide scar in marine sediments. These concentrations are sufficiently high to negatively affect most terrestrial arctic plant species. Soluble Na^+ levels within the active layer suggest that concentrations in slope runoff will remain elevated for several decades. Climatic warming, if it causes an increase in annual thaw depths or in the frequency and extent of geomorphic disturbances, could also result in active layer salinization within areas of salt-rich permafrost, such as in marine surficial deposits.

Key words: arctic ecology, climatic warming, efflorescence, geomorphic disturbance, permafrost, salinization, transport of dissolved solids

RÉSUMÉ. On trouve couramment des efflorescences (accumulations de sel en surface) dans la presqu'île de Fosheim et à d'autres endroits dans l'archipel Arctique canadien, en particulier à des hauteurs situées sous la limite marine de l'holocène. Ces efflorescences couvrent jusqu'à 9 p. cent du terrain aux environs du cours inférieur de Hot Weather Creek. On les trouve en grande quantité sur des pentes ayant subi une perturbation naturelle et dans des zones où sont situées des plaines d'inondation. Plus de 75 p. cent des efflorescences sont reliées à des perturbations géomorphiques (glissement d'un décollement de la couche active, décrochement dû à la fonte régressive et ravinement), qui sont à l'origine de la chaîne causale suivante: 1) érosion de surface; 2) dégradation locale du pergélisol; 3) contact entre la nappe d'eau du suprapergélisol et les ions solubles contenus précédemment dans les sédiments gelés; 4) augmentation de la concentration totale de solides en suspension dans l'eau de ruissellement de surface sur les pentes; et 5), dépendant du degré de canalisation du drainage et du profil de la pente, transport direct des solides en suspension dans l'eau des ruisseaux ou leur redistribution et accumulation plus bas sur la pente. Les concentrations en Na^+ dans l'écoulement de surface atteignaient presque 5 $g \cdot l^{-1}$ durant l'été 1996 sur une niche de décollement récente (1988) dans des sédiments marins. Ces concentrations sont suffisamment élevées pour affecter de façon négative la plupart des espèces végétales terrestre de l'Arctique. Les niveaux de Na^+ en suspension au sein de la couche active suggèrent que les concentrations dans l'écoulement de la pente resteront élevées pendant encore plusieurs dizaines d'années. Le réchauffement climatique, s'il est responsable de l'augmentation de la profondeur du dégel annuel ou de la fréquence et de l'étendue des perturbations géomorphiques, pourrait aussi amener une salinisation de la couche active dans des régions où le pergélisol est riche en sel, comme c'est le cas pour les dépôts marins superficiels.

Mots clés: écologie arctique, réchauffement climatique, efflorescence, perturbation géomorphique, pergélisol, salinisation, transport de solides en suspension

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INTRODUCTION

Permafrost is a near-surface aquiclude. In areas with continuous permafrost, a small amount of water exchange occurs annually between the active layer and the uppermost layer of permafrost (Mackay, 1983), but chemical interaction between surface water and deeper earth materials is largely prevented (e.g., Michel and Fritz, 1982). Readily soluble salts, which could be leached if they were present in non-permafrost terrain, can be stored within permafrost for long periods of time. This characteristic has been used to contain chemical contaminants within frozen drilling muds at oil and gas well sites in permafrost terrain (French and Smith, 1980).

Lowering of the permafrost table has the potential to make soluble salts available for transport. In permafrost regions underlain by saline surficial deposits, the pore water salinity of permafrost is generally higher than in the active layer, which suggests that salts are leached from the seasonally thawed sediments (Hivon and Sego, 1993). Similarly, palaeoactive layers have been inferred from reduced electrical conductivities or lower Na^+ and Cl^- ions in soil water extracted from permafrost sequences (O'Sullivan, 1963; Péwé and Sellmann, 1973; Dubikov et al., 1988). It has also been hypothesized that higher dissolved loads in streams might result from increased active-layer depths associated with climate warming, as previously frozen regolith is exposed to weathering processes (English et al., 1991). Surface geomorphic disturbances that lead to permafrost degradation, such as active-layer detachment sliding, retrogressive thaw slumping, and gullying (Figs. 1 and 2), could cause comparable, but more intense, increases in dissolved loads at a local scale. Elevated amounts of soluble salts within the active layer could be significant biologically, because salinity affects plant growth and species diversity (Bliss and Svoboda, 1984; Iacobelli and Jefferies, 1991; Srivastava and Jefferies, 1995a, 1995b). This is especially true in arctic environments, which are already marginal for vascular plants (Svoboda and Henry, 1987).

The goal of this research was to examine the links between efflorescence (surface salt accumulation) formation and distribution, natural geomorphic disturbance, and solute transport on slopes. Furthermore, because the effects of geomorphic disturbances on permafrost degradation can be analogous to those of climatic warming, the results of the study can be used to infer the potential impacts of such a change. Although surface salt accumulations have been reported in the literature in the context of pedological (e.g., Tedrow, 1966), geological (e.g., Christie, 1967), and geophysical (e.g., Robinson, 1994) investigations in the Canadian Arctic, we are not aware of any previous study that has examined in detail their distribution or links to geomorphic processes.

STUDY AREA

Fieldwork was undertaken in the vicinity of lower Hot Weather Creek near its confluence with the Slidre River, Fosheim Peninsula, Ellesmere Island (Fig. 3). Aerial photo analysis was used to extend the possible application of our research to other parts of the Canadian Arctic Archipelago, including Banks Island, Cameron Island, and Ellef Ringnes Island.

The Hot Weather Creek area has been extensively described in the literature (e.g., Edlund et al., 1989; Woo et al., 1990; Robinson, 1993; Lewkowicz and Wolfe, 1994). It consists of rolling lowland with a maximum elevation of 300 m a.s.l. Both Hot Weather Creek and the Slidre River are characterized by a meandering morphology within valleys incised 25 to 50 m below the surrounding terrain. The watersheds are underlain by poorly consolidated sandstone and subordinate shale and coal of the Tertiary Eureka Sound Group (Hodgson et al., 1991). The area has not been glaciated since at least the late Wisconsinan (Bell, 1996). Since 9 ka B.P., the Fosheim Peninsula has undergone more than 140 m of emergence (Bell, 1996), and all of the study area and about one-third of the western part of the Peninsula (see Fig. 3B) fall below this marine limit. On a map of surficial deposits (scale 1:125 000) of the area (Hodgson et al., 1991), the terrain below the marine limit is described as "marine-washed bedrock" with limited exposures of "marine, estuarine and deltaic deposits"). In detail, the heterogeneous surficial materials in the main valleys and on the plateaux include variable thicknesses of colluvium derived from till and marine deposits, marine sands, silts and clays, alluvial deposits, till-like deposits, and poorly indurated bedrock.

The climate of the Fosheim Peninsula is cold and dry. Permafrost is about 500 m thick, and the active layer is typically between 0.5 and 0.9 m thick. Eureka, located on the north shore of Slidre Fiord, has a mean annual air temperature of -20˚C and annual precipitation of 64 mm (Atmospheric Environment Service, 1984). Redistribution of snow by prevailing southerly winds through the winter results in enhanced accumulations on north-facing slopes (Woo et al., 1990) and minimal cover on plateau areas. Several studies conducted at Hot Weather Creek (e.g., Edlund et al., 1989; Lewkowicz and Wolfe, 1994) show that summer temperatures and precipitation consistently exceed values recorded at Eureka.

Vegetation in the study area is strongly influenced by moisture supply. Two sources of soil moisture (precipitation and melting of ground ice) enable a tundra and wet meadow vegetation to grow in this region, where sparse polar desert vegetation would otherwise be expected (Edlund et al., 1989). Vascular plant species total 140, compared with fewer than 35 on similar materials in the western and central Queen Elizabeth Islands (Edlund et al., 1990). Typical vegetation cover is up to 50% on hummocky *Salix-Dryas* tundra and less than 20% on drier, more exposed slopes (also dominated by a *Salix-Dryas* community), and recently disturbed areas are largely vegetation-free. Poorly drained floodplains may exhibit sedge-wet meadow and sedge-willow communities (Edlund et al., 1989).

Active-layer detachment slides are common in the lowlands of the Fosheim Peninsula (Lewkowicz, 1990, 1992;

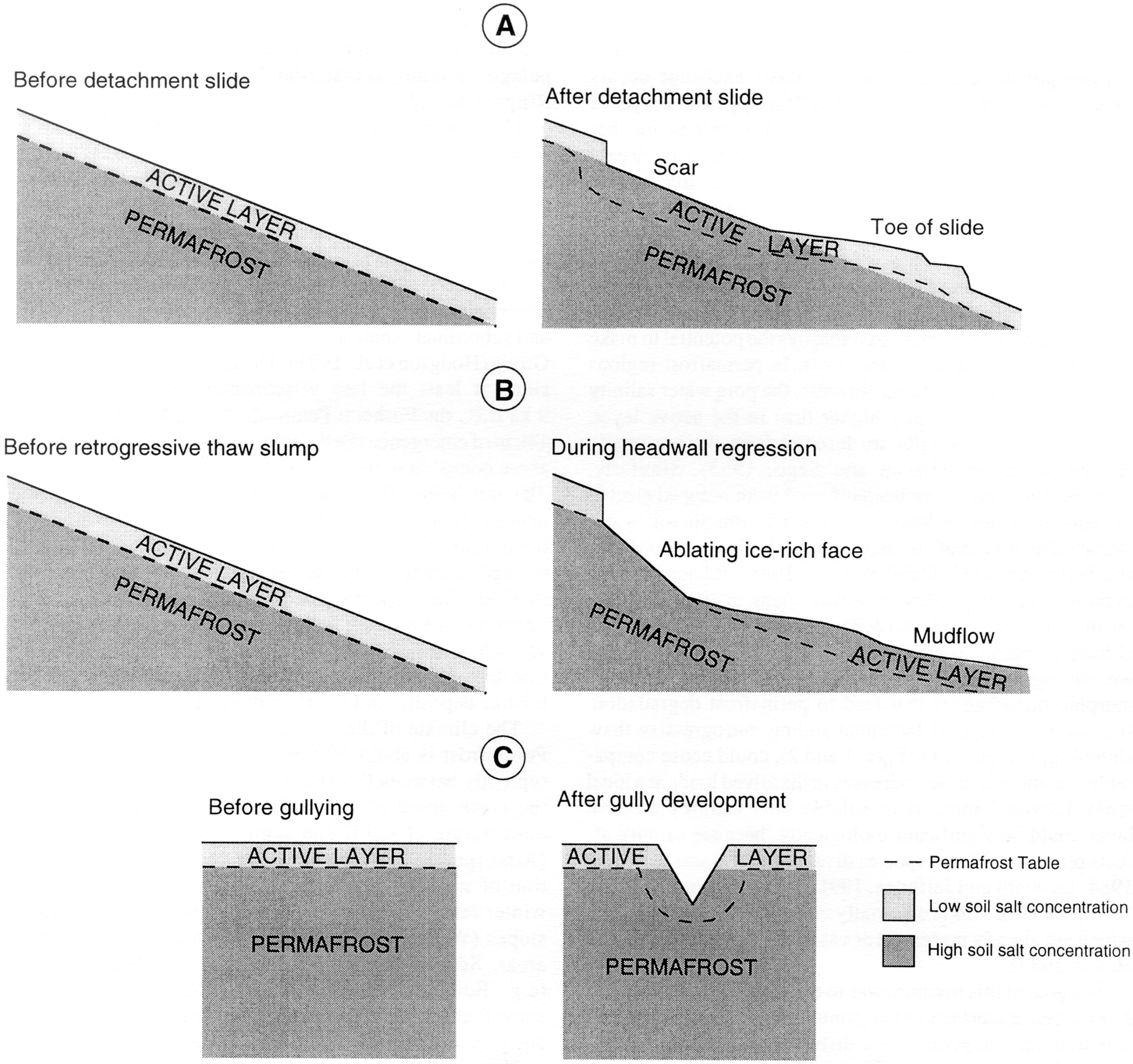

FIG. 1. Conceptual model of the effect of selected geomorphic disturbances on permafrost degradation and availability of salts. It is assumed that before the disturbance shown, the slope has been stable and subject to a lengthy period of annual removal of dissolved solids. A: Active-layer detachment sliding (downslope profile); B: Retrogressive thaw slumping (downslope profile); C: Gullying (cross-slope profile).

Harris and Lewkowicz, 1993). A particularly warm period during July and August 1988 initiated more than 40 detachment slides (representing a 32% increase in the total number of slides) in the 2 km of Hot Weather Creek valley immediately downstream from site A (Fig. 3C) (Lewkowicz, 1992). These shallow landslides, which involve the rapid translation downslope of the thawed layer, leave an unvegetated scar zone (see Fig. 1A). A new active layer begins to develop within the scar immediately following failure. Scar floors and areas downslope from detachment slides frequently develop efflorescences as the soil dries out following snowmelt (see Fig. 2A). The frequency of detachment sliding may increase during climatic warming (Lewkowicz, 1990; Fitzharris, 1996).

Retrogressive thaw slumps (Burn and Lewkowicz, 1990) also are widespread on the Fosheim Peninsula, primarily below marine limit (Pollard, 1991; Robinson, 1994; Pollard and Bell, 1998; Robinson and Pollard, 1998). They are generally initiated by fluvial erosion at the toe of a slope or by detachment sliding that exposes ground ice. The ice-rich permafrost thaws and the mudflow deposits that develop within the slump (see Figs. 1B and 2B) often exhibit efflorescences (Robinson, 1994). The presence of

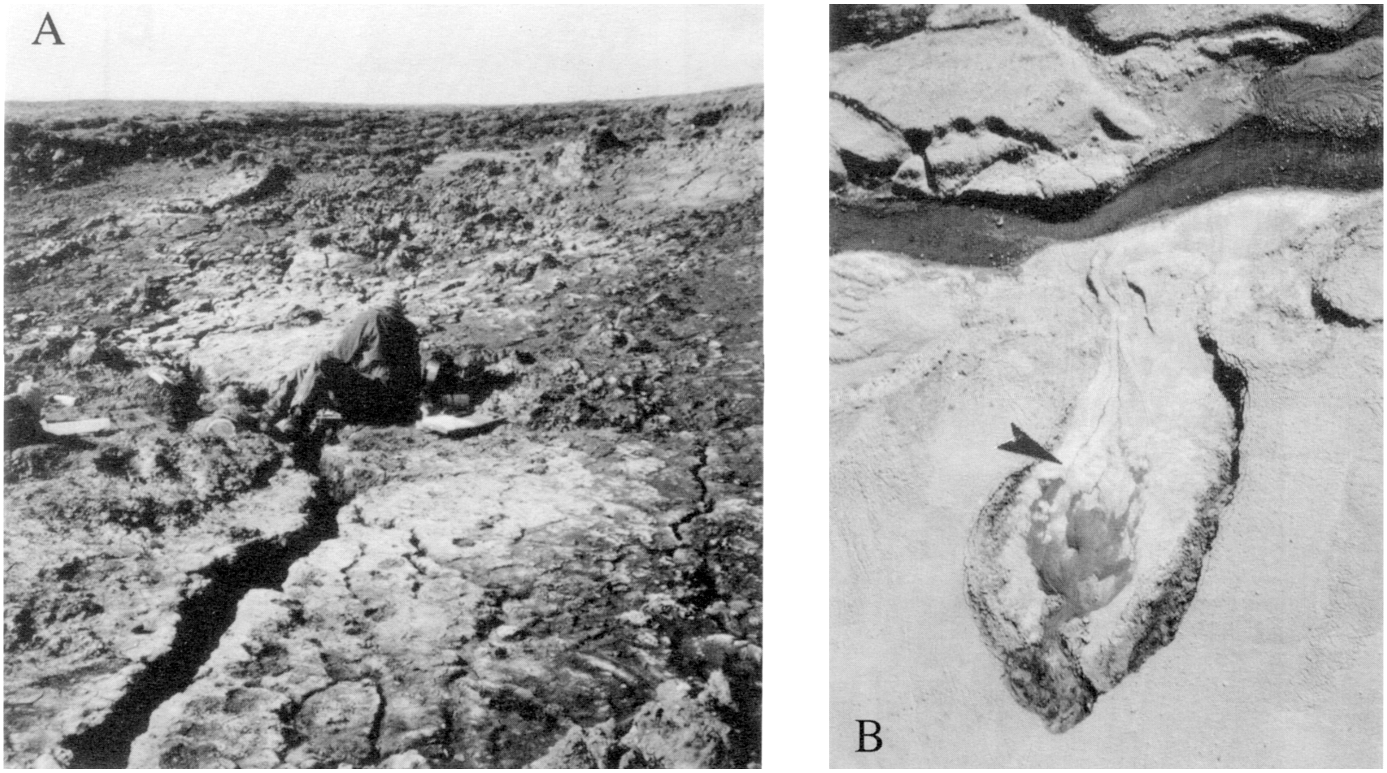

FIG. 2. A: Photograph of salt efflorescences that form alongside a large rill on an unvegetated active layer detachment slide scar as the slope dries following snowmelt, Plot A1, Hot Weather Creek. The detachment slide occurred in 1988. B: Vertical aerial photograph of retrogressive thaw slump 30 km south of Eureka. The ice in the thaw slump headwall is actively melting and efflorescences (arrowed) are present on the surface of the dried mudflow. The slump is approximately 30 m wide.

saline, ice-rich permafrost on the Fosheim Peninsula below marine limit is shown by electrical conductivity values of 500 – 2300 μS cm^{-1} in ground ice (Pollard and Bell, 1998). These values are much higher than those reported in the literature for massive ice bodies elsewhere (Pollard and Bell, 1998), and since salt is excluded during freezing (Hallet, 1978), concentrations in the sediments are likely to be still higher than those in the ground ice.

The potential for rill and gully development on slopes is great wherever runoff develops on highly erodible, fine-grained material with an incomplete plant cover. However, on the Fosheim Peninsula, a protective vegetation cover is often present on slopes where there is significant snow accumulation. Thus erosion by surface wash is low at such sites. Gullying can occur in detachment slide scars because snow accumulates preferentially within the scar depression, surface runoff is enhanced (Kokelj and Lewkowicz, 1998), and the vegetation cover has previously been stripped.

METHODS

Efflorescence Distribution

The distribution of efflorescences in Hot Weather Creek was examined using colour aerial photographs at a scale of 1:2000 taken on 5 August 1990. Efflorescences were easy to distinguish because their white colour contrasted with the surrounding tan-coloured terrain. Evaluation of the area of efflorescences visible on aerial photos normally provides only a minimum estimate of salinized terrain. But because summer 1990 was exceptionally dry (16 mm of precipitation from June to August), the efflorescences were well developed at the time of the aerial photography and likely near their maximum extent. The method used was to (1) select three 5 km transects running north-south along parallel flight lines (Fig. 3C); (2) establish 400 m lines at 100 m intervals, perpendicular to the main north-south transects; and (3) measure the percentage of each 400 m line that is underlain by efflorescences. Five 0.2 km^2 sites (see Fig. 3C, sites I-V), represented in five individual aerial photos, were analyzed in greater detail to examine the relationships between efflorescences, terrain units, and geomorphic disturbance. We chose these sites as examples of typical terrain and to cover changes in efflorescence cover that occur from north to south. Three of the sites were located along the transects, and two were on intermediate flight lines.

Solute Transport

To assess the effect of geomorphic disturbance on the transport of dissolved solids, nine runoff plots, ranging in size from 95 m^2 to 15 860 m^2, were established on slopes adjacent to transect 2 in summer 1996. The plots were located both on slopes with active layer detachment slide scars of various ages and on undisturbed slopes (Figs. 3D and 3E). Runoff was

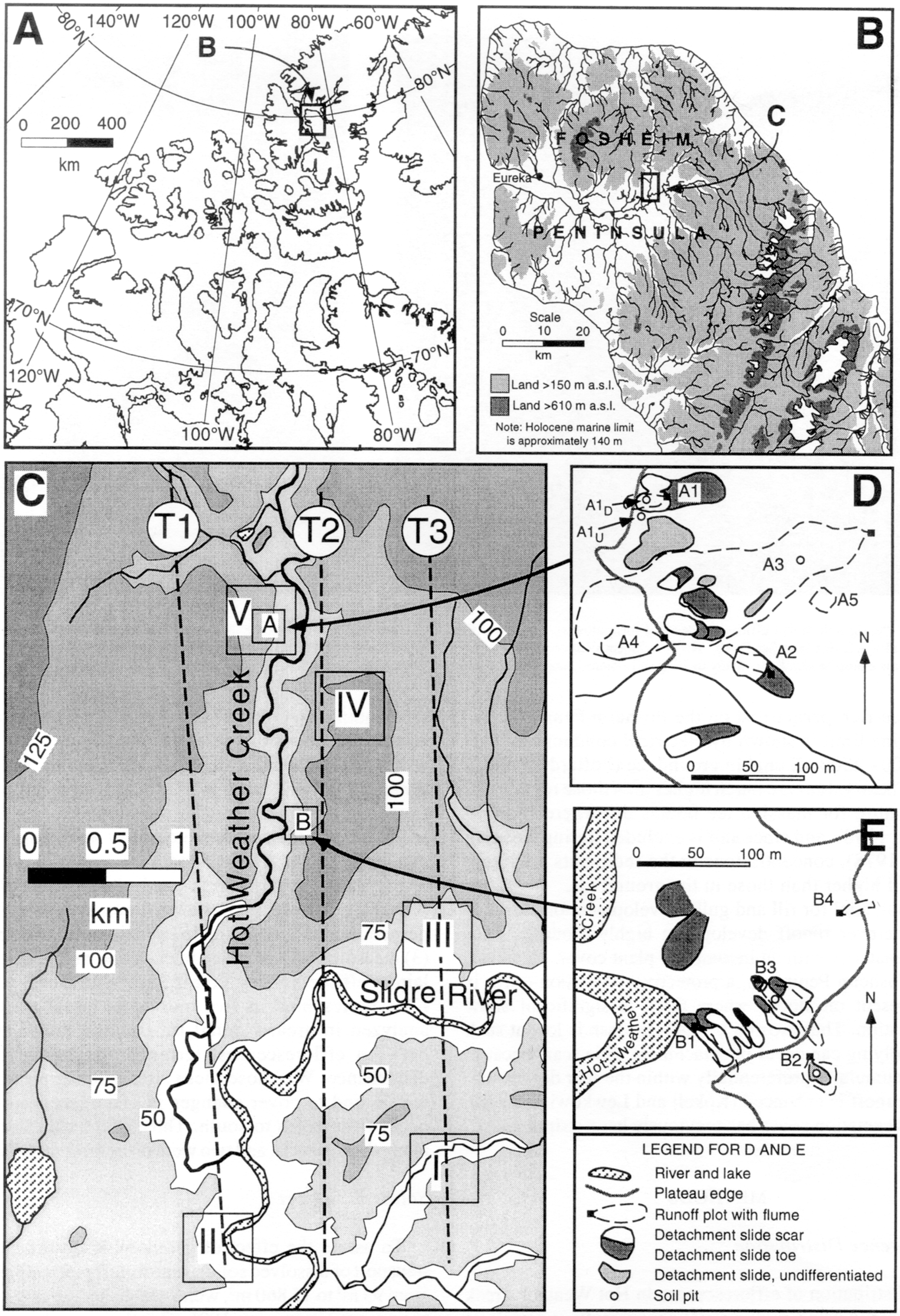

FIG. 3. Study area map. A: Queen Elizabeth Islands; B: Fosheim Peninsula; C: Topographic map of lower Hot Weather Creek and Slidre River showing transects (T1–T3) and study sites (I–V) used to evaluate efflorescence distribution. Contours are at 25 m intervals. Source: 1:50 000 NTS map; D: Study Runoff Plots A; E: Study Runoff Plots B.

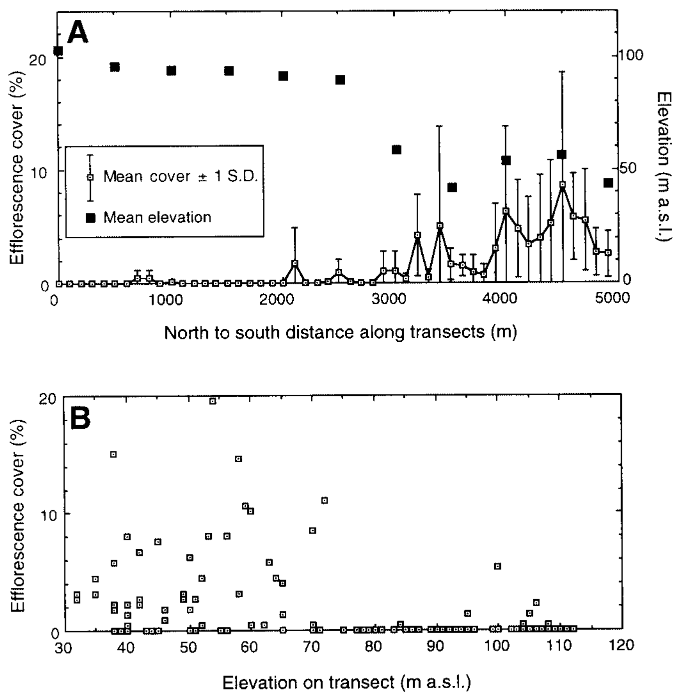

FIG. 4. Efflorescence cover along transects T1, T2 and T3, Lower Hot Weather Creek and Slidre River area. A: Mean and standard deviation of efflorescence cover (%) and mean transect elevation; B: Scattergram of salt efflorescence cover and elevation along the transects. For transect locations, see Figure 3C.

measured at places where drainage naturally converged: (1) two fresh (1988) detachment slide scars (A1 and B1); (2) two pre-1950 detachment slide scars that are now moderately vegetated (A2 and B2); (3) two undisturbed, well-vegetated slopes (A4 and B4); (4) two mixed plots that included undisturbed areas as well as young and old detachment slide scars (A3 and B3); and (5) an undisturbed, unvegetated slope (A5). Runoff data for summer 1993 are also available for two of the plots (A1 and A3).

Discharge from each runoff plot was measured using a trapezoidal flume (Bos et al., 1984) equipped with a stilling well and an electronic water-level recorder connected to a Campbell 21X data logger. Electrical conductivity probes (Stone et al., 1993), immersed in runoff immediately upslope of the flumes, were connected to the data loggers. Calibration of the flumes was undertaken by regular collection and volumetric measurement of discharge over short periods, and the probes were calibrated using frequent spot measurements with a YSI Model 30 conductivity meter. At least three filtered water samples were kept from each site: one from the early melt period, one from the peak melt period, and one from the late melt. Half of each sample was evaporated so that total dissolved solids (TDS) concentrations could be determined and a relationship could be established between TDS and conductivity. The other half of the sample was analyzed with a Diorex DX 100 ion chromatograph for anions and an Atomscan 25 ICP atomic emission spectrometer for cations. The discussion below focuses on the dominant anions (Cl^-, NO_3^-, SO_4^{--}) and cations (Ca^{++}, Mg^{++}, K^+, Na^+)

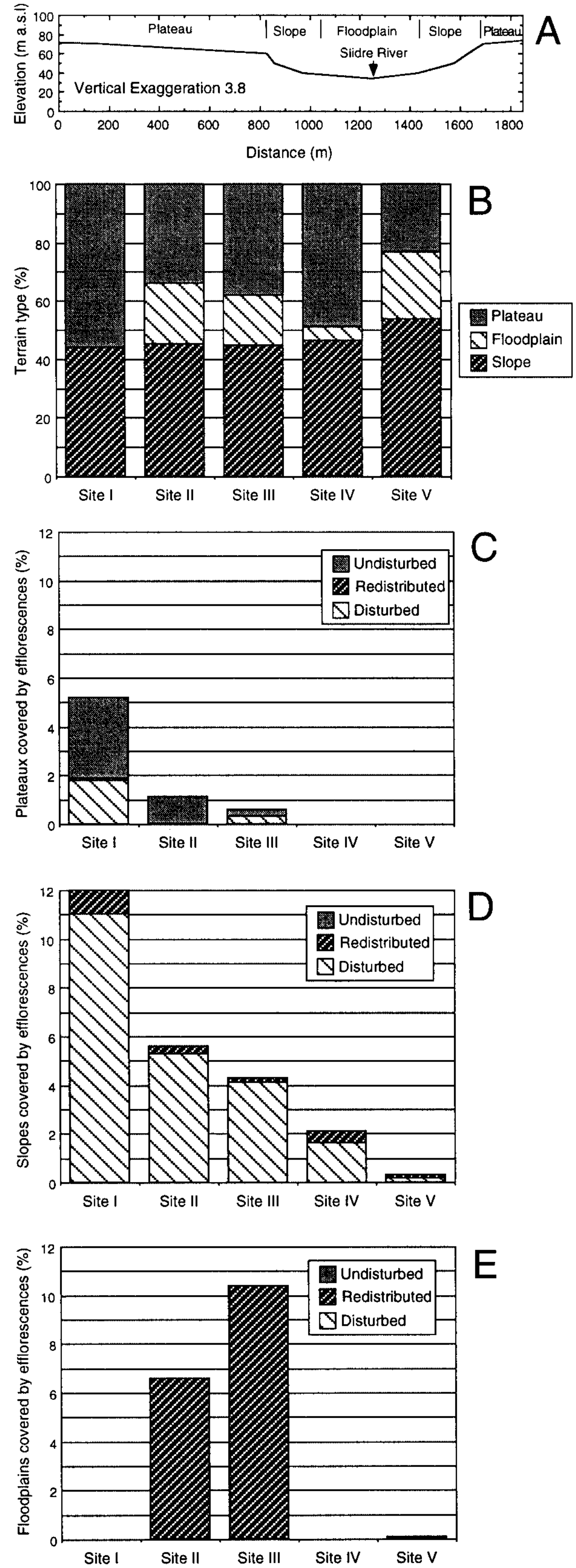

FIG. 5. Association of terrain units and efflorescences at study sites I–V. A: West-east topographic cross-section of Slidre River valley in the vicinity of site II showing examples of terrain units; B: Distribution of terrain units; C: Percentage of plateaux covered by efflorescences; D: Percentage of slopes covered by efflorescences; E: Percentage of floodplains covered by efflorescences.

TABLE 1. Size (m^2) and number of salt efflorescences in relation to surface characteristics at study sites in Lower Hot Weather Creek and Slidre River basins.

Surface	Site I[a]			Site II[a]			Site III[a]			Site IV[a]			Site V[a]		
	Av	Max.	N[b]	Av.	Max.	N	Av.	Max.	N	Av.	Max.	N	Av.	Max.	N
Disturbed	87	1116	137	60	1724	77	80	1041	51	25	187	55	8	26	21
Downslope of disturbed area	16	161	65	56	1162	52	286	3547	14	27	103	13	10	44	28
Undisturbed	42	504	93	20	137	50	15	152	19			0			0
All types	57	1116	295	48	1724	179	100	3547	84	25	187	68	9	44	49

[a] All sites are 0.2 km^2 in area; locations are shown on Figure 3C.
[b] Av. = sample mean; Max. = sample maximum; N = sample size.

analyzed. In 1993, conductivity was not measured continuously, but sample values were recorded.

Soil Chemistry

In summer 1997, five pits were dug to obtain information on total (ammonium acetate–extractable) and soluble cations in the active layer. Samples of about 200 g were collected at 10 cm intervals, bagged, shipped to Ottawa, and placed in a freezer until they were analyzed. Total cations (exchangeable and soluble combined) were extracted from 20 g of dried soil using 100 ml of a neutral 1N ammonium acetate solution, which was agitated with the sample for 30 minutes. After the sediment had settled, the supernatant solution was poured off and passed through a 1.2 µm filter. This solution was then analyzed in the same way as the runoff samples (see above). Using separate 100 g sub-samples, we extracted soluble cations by saturating the dried soil sample with an equal weight of deionized water. The sample was mixed briefly, and the sediment was allowed to settle for 12 hours. The same procedure was then followed for filtering the supernatant water, and the filtrate was analyzed.

RESULTS

Spatial Distribution of Salt Efflorescences

Salt efflorescences are numerous and cover a significant percentage of the landscape in the study area. More than 650 individual efflorescences ranging in size from 1 to 3550 m^2 were mapped in the 1 km^2 area comprising sites I-V. Along the three transects, a maximum average cover of 9% was measured (Fig. 4A).

A strong spatial trend in the distribution of efflorescences is influenced by altitude, with maxima in the south and low percentage cover in the north of the transects. Efflorescences are found mainly at elevations below 80 m a.s.l. (Fig. 4B).

The high standard deviation in percentage cover among the transects (Fig. 4A) is linked to the varying proportions of terrain types. The terrain units within the five sites (I-V) were classified as plateaux (relatively flat terrain adjoining the incised river valleys), valley-side slopes, or floodplains (Fig. 5A). In terms of terrain units, the sites have similar percentages of slopes, but varying percentages of floodplains and plateaux (Fig. 5B). Efflorescences on plateaux cover significant parts of the terrain only at Site I (Fig. 5C) and are absent entirely at Sites IV and V. Efflorescences occupy 12% of the slopes at Site I, about 5% of slopes at Sites II and III, and 2% or less of slopes at Sites IV and V (Fig. 5D). Floodplain efflorescences are significant at Sites II and III and cover more than 10% of the terrain unit at the latter (Fig. 5E). In contrast, Site I does not have a floodplain (see Figure 5B), and well-developed drainage between the slopes and the stream largely prevents accumulation of salts.

Efflorescences at the five study sites also were identified as formed (1) on disturbed terrain; (2) on terrain downslope of, and linked by drainage to, disturbed terrain; or (3) on undisturbed terrain. Efflorescences are largest and most numerous when associated with natural geomorphic disturbance (Table 1). Overall, more than 75% of the total area covered by visible salt accumulations at each of the five sites is within geomorphically disturbed areas or immediately downslope of them (Table 2). Wash processes can double the areal effect of the original disturbance (Table 2, site III) and the most extensive efflorescence mapped, located on the surface of a former oxbow lake basin in the Slidre River Valley, formed as a result of salt redistribution from surrounding slope disturbances (Fig. 6). Efflorescences not associated with disturbance were mapped only on plateau areas; they develop in poorly drained terrain with little topographic relief and, with a few exceptions, are small in size.

It can be concluded that the high concentration of efflorescences below 80 m in the south of the transects and at the more southerly study sites is linked to (1) the distribution of marine silts and clays which are mostly present well below the Holocene marine limit of 140 m and (2) the susceptibility of these materials to geomorphic disturbance.

Soil Chemistry

Total extractable (by ammonium acetate) and soluble cations within the active layer were examined. Samples were collected (1) at a 1988 detachment slide scar ($A1_D$); (2) adjacent to $A1_D$ on an unvegetated undisturbed slope

TABLE 2. Proportions of area covered by efflorescences (%) in relation to surface characteristics at study sites in Lower Hot Weather Creek and Slidre River basins.

Surface	Site I	Site II	Site III	Site IV	Site V	All Sites
Disturbed	70.7	54.1	48.8	79.7	37.5	61.7
Downslope of disturbed area	6.2	34.1	47.8	20.3	62.5	23.9
Undisturbed	23.2	11.7	3.4	0	0	14.4

($A1_U$); (3) at a pre-1950 detachment slide scar (B2); and (4) on vegetated, undisturbed slopes (A3, B3) (see Figs. 3D and 3E). Of these sites, $A1_D$ was in marine clayey silts, B2 had a thin veneer of marine deposits over bedrock, and the remaining sites were in colluvial materials derived from till, marine deposits, aeolian deposits, and poorly indurated bedrock. Sampling at the A sites was undertaken two days after a rainfall of more than 20 mm (exceptional for this region), while a further two days elapsed before sampling at the B sites. The results for major cations (single samples) are shown in Table 3.

The pattern displayed for each of the four major soluble cations is that levels are relatively similar among four of the sites, but elevated at $A1_D$. For example, the values for soluble K^+ are 0.22–0.23 meq 100 g^{-1} of soil at $A1_D$, while the range at the other sites is 0.01–0.05 meq 100 g^{-1}. Similarly, soluble Mg^{++} is 0.23–0.36 meq 100 g^{-1} at $A1_D$ and 0.01–0.07 meq 100 g^{-1} at the remaining sites. The differences are somewhat less for Ca^{++}, but greater for Na^+: the Na^+ values for $A1_D$ are 3.23–4.21 meq 100 g^{-1}, compared to 0.03–0.37 meq 100 g^{-1} for the remaining sites. This pattern is repeated for total extractable K^+, Mg^{++}, and Na^+, except that the relative differences in levels are smaller. In addition, the values for Mg^{++} and Na^+ at the surface of B2 are equal to or greater than those at $A1_D$. The values of total extractable Ca^{++} are not regarded as valid, because carbonates are plentiful in the study area, and the extraction method used can result in their dissolution (Thomas, 1982). Consequently, these values are not discussed further.

Several points arise from Table 3. First, examining the total extractable and soluble cation values at $A1_D$, it is reasonable to assume that soluble Na^+ ranges between 3 and 4 meq 100 g^{-1} throughout the profile. These high soluble values result from active layer development in marine sediments that were part of permafrost until 1988. Second, comparing $A1_D$ and $A1_U$, the data confirm field observations that the pit section at the latter consisted of colluvium rather than marine sediment. However, marine sediments likely underlie the active layer at $A1_U$, so that a detachment slide here would result in the exposure of saline sediments as at the adjacent plot. Third, the high total extractable values of Mg^{++} and Na^+ at the surface of B2 (an old detachment slide scar in marine deposits) are likely due to high soluble values: evaporative processes were starting to produce faint efflorescences on the

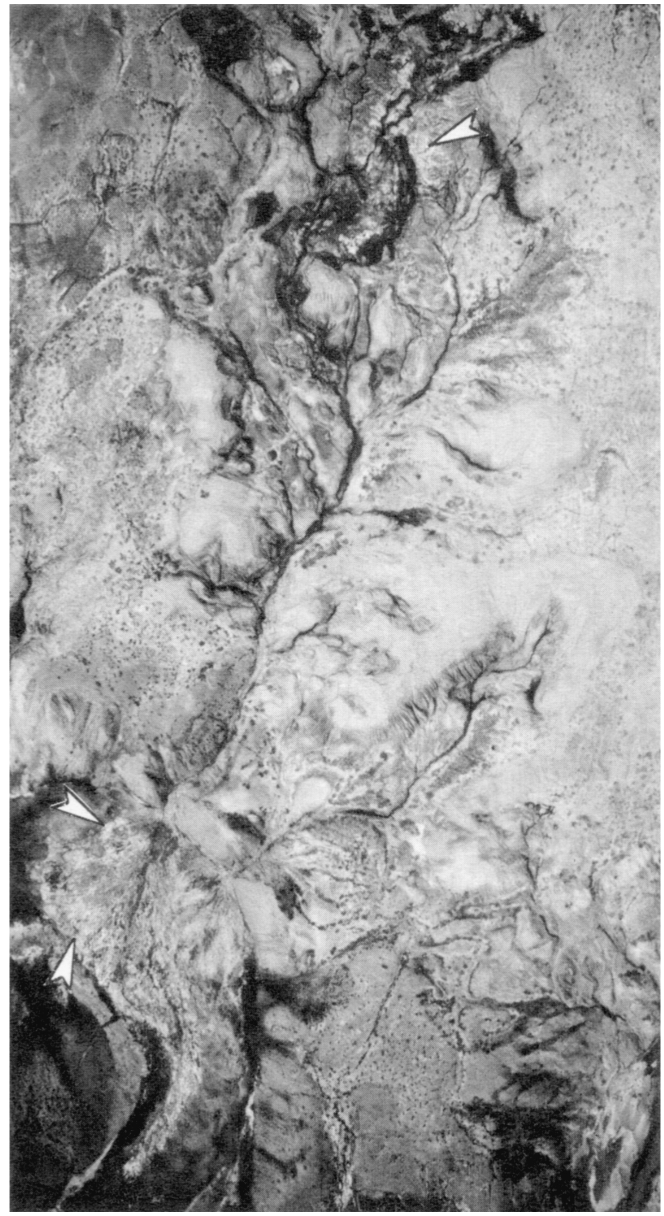

FIG. 6. Aerial photograph of a small basin eroded into fine-grained, unconsolidated marine sediments, and affected by thaw slumping and detachment sliding, Site III. Small dark dots represent vegetation. Efflorescences are present on the disturbed terrain in the upper part of the catchment (single arrow). The drainage network empties into a former oxbow lake basin where salts have accumulated over most of the old lake bed and cover more than 3500 m^2 (pair of arrows). Scale 1:2000.

surface at the time of sampling. Because the sampling at $A1_D$ was undertaken so soon after a heavy rainfall, a pronounced near-surface peak in soluble cations was not present; but such a peak would be expected after several days of evaporation (see Srivastava and Jefferies, 1995b), since efflorescences do develop at this site (see Fig. 2A).

Dissolved Solids in Slope Surface Runoff

Significant amounts of soluble salts in the soils at certain of the runoff plots resulted in high dissolved

TABLE 3. Soluble and total extractable cations[a] in Hot Weather Creek soil samples (meq 100 g^{-1}).

Site and sample depth (cm)	Ca^{++}		Mg^{++}		K^{+}		Na^{+}	
	Soluble	Total Extractable[b]	Soluble	Total Extractable	Soluble	Total Extractable	Soluble	Total Extractable
$A1_D$-5	0.27	9.98	0.23	7.12	0.22	1.23	3.23	8.42
$A1_D$-15		10.1		7.86		1.2		7.92
$A1_D$-25		9.63		7.91		1.28		8.85
$A1_D$-35		9.32		7.15		1.21		7.63
$A1_D$-45		9.65		7.24		1.24		8.90
$A1_D$-55		9.79		8.07		1.30		11.22
$A1_D$-65	0.31	9.35	0.36	8.10	0.23	1.31	4.21	11.72
$A1_U$-5	0.18	13.67	0.07	3.29	0.04	0.26	0.13	0.36
$A1_U$-15		13.72		3.18		0.27		0.42
$A1_U$-25		13.01		3.22		0.19		0.50
$A1_U$-35		12.13		3.38		0.39		0.74
$A1_U$-45		11.96		5.63		0.76		1.46
$A1_U$-55		11.19		4.65		0.66		1.28
$A1_U$-65	0.03	10.31	0.02	4.04	0.05	0.65	0.37	2.02
$A1_U$-75		8.53		3.45		0.68		2.82
A3-5		12.6		2.69		0.19		0.76
A3-15		13.15		2.35		0.07		0.16
A3-25		13.48		2.65		0.09		0.15
A3-35		12.76		2.38		0.16		0.15
A3-45	0.08	13.67	0.01	2.60	0.01	0.14	0.03	0.14
B2-5		9.87		7.22		0.38		22.96
B2-15		12.57		6.36		0.36		4.93
B2-25		13.45		4.74		0.35		1.80
B2-35	0.06	14.74	0.02	6.37	0.03	0.41	0.33	1.99
B2-45		11.88		4.09		0.33		1.27
B2-55		11.08		3.34		0.28		1.54
B3-5		17.02		5.15		0.23		0.42
B3-15		14.91		3.99		0.21		0.46
B3-25	0.14	14.99	0.04	3.93	0.02	0.20	0.04	0.29
B3-35		15.08		3.59		0.19		0.26
B3-45		16.20		3.90		0.20		0.27
B3-55		14.71		3.67		0.18		0.61

[a] Exchangeable cations can be calculated by subtracting soluble values from total extractable values.

[b] Using ammonium acetate (see methods).

solids concentrations in slope surface runoff. TDS concentrations in overland flow during the 1996 runoff season ranged from a low of 40 mg l^{-1} to a maximum of 12 800 mg l^{-1} (Table 4). Average values for the entire runoff season were lowest at undisturbed plot B4 (160 mg l^{-1}) and highest at plot A1 (1620 mg l^{-1}), the 1988 detachment slide in marine sediments. Average TDS concentrations decreased as the age of the active layer increased from A1 to A2, and from B1 to B2 to B4. The mixed plot (A3) had low average concentrations, indicating that its water chemistry was influenced primarily by discharges from its vegetated undisturbed lower sections, while B3 had relatively high concentrations, suggesting that it was affected more by the 1988 detachment slides that constitute the central part of the plot. Surface runoff was not produced at one of the vegetated undisturbed plots (A4) or at the unvegetated undisturbed plot (A5).

TDS concentrations during snowmelt varied inversely with diurnal discharge (Fig. 7). Exceptions to this pattern occurred after minor spring snowfall events, which resulted in the maximum concentrations of the snowmelt period at all the plots except B4. For example, peak TDS concentrations at A1 followed snowfall on 9–10 June (Fig. 7). These higher concentrations were due to the fresh snow melting over efflorescences that had quickly formed through evaporation from the thin thawed layer on the previously snow-free sections of the plots. The flush of salts ended when the new snow had completely ablated.

Maximum TDS concentrations during rainfall-induced runoff were greater than during snowmelt at A1, A2, A3 and B2 (Table 4). These higher concentrations are due to antecedent accumulation of salts and longer flow paths taken by the rainfall-induced runoff. The highest TDS concentrations at any plot, 12 800 mg l^{-1}, occurred at A1 on 25 June (Fig. 7). Maximum TDS concentrations during rainfall increased from A3 to A2 to A1. At the B site (see Table 4), however, the maximum value of 3560 mg l^{-1} occurred at B2 (pre-1950 detachment slide), probably because part of this scar is underlain by marine sediments.

Average TDS concentrations measured during snowmelt in 1993 at A1 and A3 were slightly lower than those in 1996 (Table 4). In particular, the very high values measured in 1996 were not present in 1993, when there was no

TABLE 4. TDS concentrations in slope surface runoff.

Runoff plot	Disturbance characteristics	Average and range of TDS concentrations for runoff season[a] (mg l^{-1})		Average and range of TDS concentrations for snowmelt[a] (mg l^{-1})	
A1	1988 scar	1620	(135–12800)	917	(135–4140)
A2	pre-1950 scar	590	(49– 3600)	463	(49–2730)
A3	Mixed plot	317	(70– 1890)	173	(70– 346)
B1	1988 scar	720	(300– 2010)	630	(308–2010)
B2	pre-1950 scar	650	(141– 3560)	352	(141–2340)
B3	Mixed plot	605	(169– 1250)	526	(169–1250)
B4	Undisturbed	160[b]	(40– 241)	160[b]	(40– 241)
A1 1993[c]	1988 scar	813[b]	(290– 1550)	813[b]	(290–1550)
A3 1993[c]	Mixed plot	158[b]	(108– 330)	158[b]	(108– 330)

[a] Calculated from conductivity measurements (see methods).

[b] No rainfall-induced runoff was recorded; hence, values are the same in both columns.

[c] Values in 1993 were obtained from statistical analyses based on intermittent sampling (A1, n = 28; A3, n = 39).

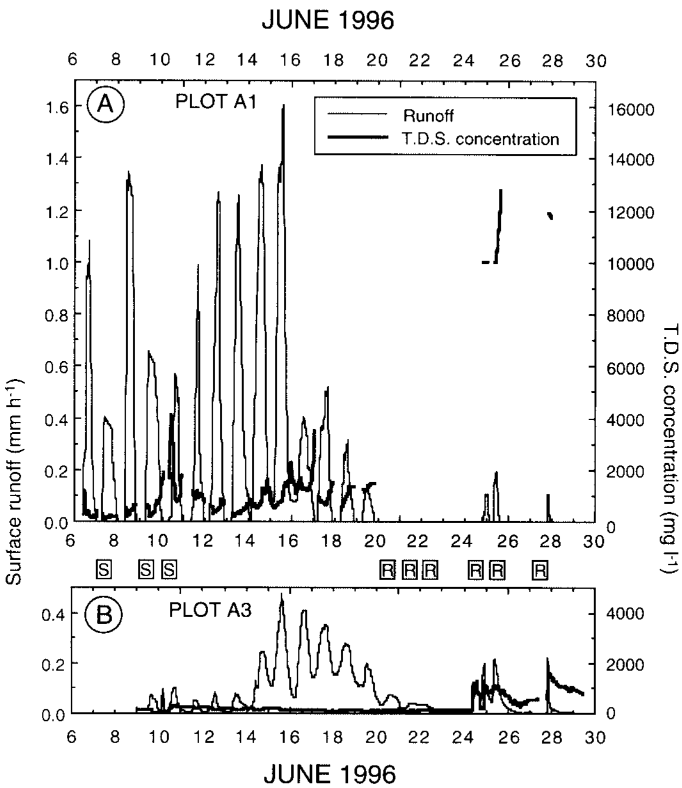

FIG. 7. Slope surface runoff and TDS (total dissolved solids) concentrations, June 1996. A: runoff plot A1; B: runoff plot A3. TDS concentrations calculated from electrical conductivity measurements (see text). Snowmelt runoff took place at A1 from 6 to 20 June and at A3 occurred from 9 to 23 June. Precipitation events are shown as S (snow) and R (rain).

spring snowfall or early summer rainfall-induced runoff. However, this earlier season of measurements confirms the spatial and temporal trends observed in 1996.

Na^+ was the dominant cation by weight in samples with widely varying TDS concentrations at the site A runoff plots (Fig. 8A). Cl^- was the most important anion at plot A1 in marine sediments, but SO_4^{--} was generally of equal or greater importance at the other site A plots. At the B site, Na^+ dominated the cation load at plots B2 and generally at B4, while Ca^{++} was more important at B1 and B3. Among the anions, SO_4^{--} was dominant at all the B sites, but Cl^- was also significant at B2 and B4 where Na^+ was dominant.

The concentrations of individual ions in solution at the plots varied through time. This variation is attributed to changes in the runoff-generating area and the pathways taken by the runoff between the melting snow and the flume. At A3, for example, the sample on 20 June was dominated by SO_4^{--} because it was collected in the early morning, when virtually all flow was derived from snowbanks on vegetated sands in the lower part of the plot. SO_4^{--} concentrations were similar, but relatively less important, in the afternoon on 10 June, when higher discharges came in part from recent detachment slide scars in marine deposits in the upper part of the plot. These runoff-generating areas contributed additional Na^+ and Cl^-. Similarly, the variability in the water chemistry among plots noted above reflects the substrate present. The runoff at plots B1 and B3 (which have poorly lithified bedrock exposed in scar floors) is dominated by Ca^{++} and SO_4^{--}. In contrast, the other plots are at least partly in marine sediments and are dominated by Na^+, and in the case of A1, also by Cl^- (Fig. 8B). The biggest variation in relative composition of the runoff, at A3, is due to that plot's mixed nature and its varying contributory areas.

Cation Liberation and Flushing of Na^+ Following Detachment Slides

High amounts of salt in the fresh active layer and in runoff at detachment slides may inhibit revegetation of the scar. For example, grasses and *Stellaria* sp. had colonized parts of the 1988 detachment slide scar at B1 (poorly lithified bedrock) by 1996, while the scar of the same age at A1 (marine sediments) remained completely unvegetated. The inability of plants to grow on a fresh scar prolongs the period of modified drainage and enhanced erosion. A temporal perspective on the geomorphic and ecological impacts of detachment sliding can be given by estimating the time required for soluble Na^+ to be removed.

It is possible to use measured electrical conductivity to predict the concentration of Na^+ in the surface runoff at A1,

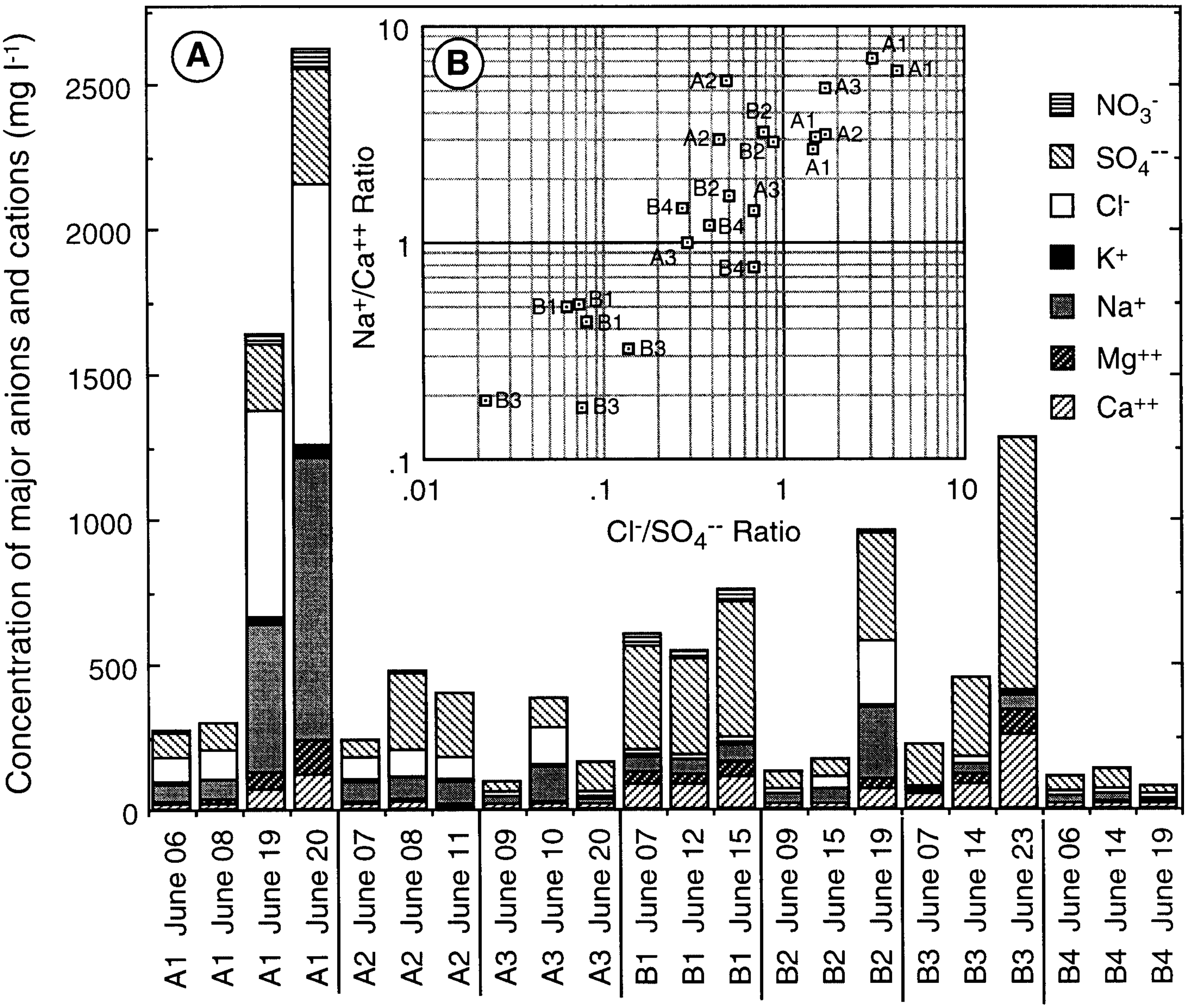

FIG. 8. A: Concentrations of major anions and cations by weight in snowmelt-induced slope surface runoff at sites A and B; B: Ratios calculated as meq of Na^+/Ca^{++} vs. Cl^-/SO_4^{--} for the samples shown in part A of the figure.

even though only four samples were obtained, because the relationship is linear: $Na^+ = 0.21 \cdot$Conductivity; where Na is in mg l^{-1} and Conductivity in µS cm^{-1}; $r^2 = 0.99$. Since the maximum conductivity measured during early summer rainfall events was more than 21 000 µS cm^{-1}, this relationship indicates that concentrations of Na^+ in the surface wash at that time were 4600 mg l^{-1}. The best-fit relationship was employed with the continuous conductivity record and resulted in an estimate of 14 kg for the total amount of Na^+ removed from plot A1 during the 1996 runoff season. Assuming that the entire amount is derived from the scar area of the detachment slide within the plot, 37 g m^{-2} of Na^+ was removed from the scar by surface wash.

In order to estimate the time required for soluble Na^+ to be removed following a detachment slide, the calculated rate of removal must be compared with total soluble Na^+ within the active layer. On the basis of (1) a dry bulk density of 1.3 g cm^{-3}; (2) an active layer depth of 0.7 m; (3) an average amount of soluble Na^+ of 3.7 meq 100 g^{-1} at A1 (the average of measurements in the eight-year-old active layer); and (4) the measured rate of loss, we calculate that it would take approximately 20 years for the Na^+ to decline from the 1996 levels to the low levels found at the other sites, or almost 30 years from the date of the detachment sliding. This estimate would be somewhat shortened if significant amounts of Na^+ were removed in subsurface wash, although runoff coefficients show subsurface flow to be much less important volumetrically than overland flow (Kokelj and Lewkowicz, 1998). On the other hand, the estimate of 30 years could be too short; 1996 was a wetter year than average, and further release of Na^+ from the permafrost will occur as surface erosion of the unvegetated slope continues and the permafrost table falls. Given the uncertainties in the solute system for the active layer and permafrost, the best use of this calculation is to indicate that the perturbation of the system caused by the detachment sliding will affect the local ecology for at least several decades.

DISCUSSION

The ecological impact of surface salinization can be indicated qualitatively by comparing the surface runoff TDS concentrations and soil salts with observations made by Srivastava and Jefferies (1995a) regarding the coastal lowlands of southwestern Hudson Bay. They studied the effect of salinity on the growth of salt-tolerant graminoids (*Puccinellia phryganodes* and *Carex subspathacea*). Both species can be found on the coast of Ellesmere Island (Porsild, 1957), but they have not been observed in Hot Weather Creek (Woo et al., 1990). They are relevant here as examples of plants that would be expected to be most tolerant of salinization.

Srivastava and Jefferies (1995a) showed that increases in soil salinity result in decreased plant growth and increased plant mortality, with extremes occurring under hypersaline conditions. They also found that applications of a saline solution had negative effects on the growth of the two graminoids. At runoff plot A1, the high amounts of soluble Na^+ measured within the active layer, as well as the extensive efflorescence formation observed after the slopes become snow-free, indicate that hypersaline conditions can develop in the near-surface of the fresh scar. Moreover, because the vast majority of efflorescences in lower Hot Weather Creek and the Slidre River area are associated with fine-grained marine sediments, it can be inferred that the results from A1 are applicable to these sites. Maximum TDS measured in the rainfall runoff exceeded 12 g l^{-1} (see Fig. 7), a concentration sufficient to reduce vegetative growth in *Puccinellia phryganodes* (Srivastava and Jefferies, 1995a). Therefore, it can be inferred that if runoff from fresh detachment slide scars in marine sediments were to saturate vegetated areas immediately downslope, or ponds at the base of slopes, the active layer would become progressively more saline. The vegetation in those areas (most of which is certainly less salt-tolerant than *Puccinellia phryganodes* and *Carex subspathacea*) would be adversely affected.

The majority of salt efflorescences in lower Hot Weather Creek and the Slidre River are related to geomorphic disturbance. When drainage networks from terrain disturbances are traced, extensive areas of salt accumulation are often found where the channel gradient decreases. Valley bottoms with broad floodplains and abandoned river channels are favoured locations for the accumulation of salts. Despite the high moisture availability in these areas, they remain almost completely unvegetated. Similar effects can be observed elsewhere on the Fosheim Peninsula below marine limit (e.g., lower Black Top Creek and lower Station Creek) and on other islands of the Canadian Arctic Archipelago. For example, retrogressive thaw slumps in the Sand Hills Moraine on southern Banks Island (Lewkowicz, 1987) and on Prince of Wales Island (Dyke at al., 1992) develop efflorescences on their floors. Anthropogenic disturbances on Ellef Ringnes Island frequently show efflorescences, and they are also widespread on Melville Island (D. Hodgson, pers. comm. 1998). The common characteristics of these locations are low precipitation, fairly shallow active layers, and geomorphic disturbance to allow salt release from permafrost.

Another way that salts could be released as a result of permafrost degradation is through the effects of climatic warming: warming causes a general lowering of the permafrost table, allowing transport of soluble material from the newly thawed soil and ground ice by wash processes. If permafrost sodium concentrations are assumed to be the same as in the active layer at site A1 (or slightly higher, since the active layer had been exposed to salt removal for eight years at the time of the study), the annual amount of Na^+ removed by surface wash is equivalent to the amount of soluble Na^+ present in a newly thawed layer of sediment 5–10 mm thick. Modelling of climate change for the Mackenzie Delta shows that it is unlikely that permafrost would degrade faster than this over 50 years during an effective doubling of atmospheric CO_2 (Burgess et al., in press), and rates would be even slower in the colder Canadian Arctic Archipelago. Thus it should be possible for removal of salts to keep pace with permafrost degradation rates, at least in areas where runoff amounts are similar to or greater than at plot A1 (i.e., = 100 mm yr^{-1}). The ecological impact of such high rates of solute transport from the entire landscape would be considerable, since all areas of drainage concentration would have the potential to develop efflorescences. In areas of warmer permafrost with marine deposits, such as in the Tyrrell Sea sediments surrounding Hudson Bay and James Bay, the effects could also be pronounced. While precipitation is more abundant, permafrost degradation could be more rapid.

Climatic warming may result in a higher frequency of geomorphic disturbance (e.g., Woo et al., 1992; Fitzharris, 1996), as well as general thickening of the active layer, so that both localized and widespread release of salts from permafrost could occur contemporaneously. Clearly, in these circumstances, the individual effects would be compounded.

CONCLUSIONS

We conclude the following:

1. Salt efflorescences in the lower Hot Weather Creek area on Ellesmere Island cover significant parts of the terrain below marine limit. The great majority form on surfaces disturbed by detachment sliding, retrogressive thaw slumping or gullying and downslope from the disturbed areas, where the gradient decreases and channelized surface runoff disperses.
2. Efflorescences are common on disturbed terrain because surface erosion lowers the permafrost table, allowing the

release of soluble materials previously held in saline permafrost. Levels of soluble cations in recently exposed marine sediments can be high enough to restrict growth and inhibit colonization by arctic plants.
3. Total dissolved solids (TDS) concentrations in runoff at a detachment slide plot in marine sediments were more than an order of magnitude greater than those at an undisturbed plot in nonmarine sediments. Runoff from fresh detachment slide scars in marine deposits (particularly during rainfall events) contains solutes at concentrations that could be detrimental to the growth of most terrestrial arctic plants.
4. Despite the greater quantities of snowmelt runoff generated from disturbed slopes and the very high TDS concentrations in runoff, it is estimated that it will take several decades for the sodium in a fresh active layer developed in marine sediments to be removed.
5. Because of the redistribution of salts by wash processes, the ecological effects of detachment sliding, retrogressive thaw slumping, and gullying in marine sediments extend beyond the area directly affected by the geomorphic disturbance.
6. Climatic warming could affect salt release by raising the frequency of geomorphic disturbance and, by gradually increasing the thickness of the active layer, could also lead to the widespread release of salts from degrading saline permafrost.

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