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Geomorphology, Vegetation Succession, Soil Characteristics and Permafrost in Retrogressive Thaw Slumps near Mayo, Yukon Territory

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ABSTRACT. Three retrogressive thaw slumps of varying age have been initiated by erosion of ice-rich glaciolacustrine sediments on a bend of Stewart River, 3 km upstream from Mayo, Yukon Territory. Two of the slumps are presently active; the third stabilized before 1944. The rate of retreat of the active slump headwalls between 1949 and 1987, determined from aerial photographs and ground surveys, is up to 16 $m \cdot yr^{-1}$. Floors of the active thaw slumps contain well-defined vegetation successional communities that are distinct from the local, mature boreal forest. Although a few clumps of mature forest vegetation survive the fall into the slump, a birch/white spruce sere, similar to the original forest, is re-established after a period of 35-50 years. Changes in soil calcium carbonate and soil structure profiles on disturbed surfaces of varying age demonstrate the initiation of pedogenesis in the floor of the stabilized slump, but assays of pH, organic carbon and total nitrogen indicate that after about 40 years the new soils remain immature. Comparison of ground temperatures in the stabilized thaw slump and at undisturbed sites in the area indicates that the ground thermal regime may return to local conditions a century or more after disturbance.

Key words: permafrost, terrain disturbance, retrogressive thaw slump, vegetation succession, Yukon Territory

RÉSUMÉ. Trois décrochements de fonte régressifs, datant de différentes époques, ont été formés à l'origine par l'érosion de sédiments glaciolacustres riches en glace, à un tournant de la rivière Stewart, à 3 km en amont de Mayo dans le Yukon. Deux des décrochements sont actuellement en activité, le troisième s'étant stabilisé avant 1944. La vitesse de recul des parois des décrochements actifs entre 1949 et 1987, déterminée à partir de photographies aériennes et d'études au sol, est de jusqu'à 16 $m \cdot an^{-1}$. Le sol des décrochements de fonte actifs contient une végétation bien définie de communautés successives qui sont distinctes de la forêt boréale adulte environnante. Bien que quelques bouquets de la végétation de la forêt adulte survivent après leur chute dans le décrochement, une série de bouleaux et d'épinettes blanches, semblables à la forêt originale, se réinstalle après une période de 35 à 50 ans. Des changements dans les profils du carbonate de calcium et de la structure du sol sur les zones perturbées d'époques différentes, révèlent qu'une pédogénèse débute sur le sol du décrochement stabilisé, mais des analyses de pH, de carbone organique et d'azote total indiquent qu'après environ 40 ans, les nouveaux sols restent peu évolués. La comparaison des températures du sol dans le décrochement stabilisé et sur les sites non perturbés de la région montre que le régime thermal du sol peut retourner aux conditions locales un siècle ou plus après la perturbation.

Mots clés: pergélisol, perturbation du terrain, décrochement de fonte régressif, succession végétale, territoire du Yukon

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INTRODUCTION

The management of thaw-sensitive permafrost terrain is one of the challenges faced by industrial development in the North. Terrain disturbance may alter the ground thermal regime, melt ground ice, and lead to soil subsidence or accelerated erosion (e.g., Mackay, 1970; McRoberts and Morgenstern, 1974). Such conditions may also be created by natural events, for instance forest fires or coastal erosion (e.g., Johnson and Viereck, 1983; Mackay, 1986; Walker, 1983).

Retrogressive thaw slumps are among the most active geomorphological features in permafrost terrain. Also termed ground-ice slumps (Mackay, 1966), thermocirques (Czudek and Demek, 1970), tundra mudflows (Lamonthe and St-Onge, 1961), retrogressive flow slides (Hughes, 1972), bi-modal flows (McRoberts and Morgenstern, 1974), and so forth, they are initiated after ice-rich soil is exposed by disturbance. They consist of a steep, ice-rich headwall and a mudflow of gentler gradient downslope (see Lewkowicz, 1987a, and Mackay, 1978, for details). They are commonly found on the banks of northern rivers and lakes and along the arctic coast, especially where undercutting is active. Some have been initiated by terrain disturbance associated with the use of seismic lines and by road construction (Bliss and Wein, 1971; Lambert, 1972).

The slumps stabilize when ground ice exposed by the retreating headwall has been completely thawed or is covered by debris. Stabilized-slump floors therefore provide an environment where the recovery and re-establishment of natural conditions after disturbance may be studied. Although there is a general awareness of the need to minimize disturbance to ice-rich terrain, there is relatively little documentation of the recovery and re-establishment of equilibrium ground conditions, or of vegetation successional paths following disturbances such as in these slumps (Chapin and Shaver, 1981; Ebersole and Webber, 1983; Johnson and Viereck, 1983; Lambert, 1972; Viereck and Schandelmeier, 1980; Walker *et al.*, 1987).

In this paper we present results from field studies conducted since 1982 concerning the development of thaw slumps in the Mayo area, central Yukon Territory. We document: (1) the continuing development of two thaw slumps in the study area since 1949; (2) the vegetation succession in the floors of three thaw slumps; and (3) short-term soil development on surfaces of various ages in the slumps. We discuss the time required to re-establish the dominant vegetation on disturbed surfaces in the study area and to initiate pedogenic processes in fresh deposits, and note the nature of permafrost aggradation in a stabilized feature.

SITE CONDITIONS

Mayo (63°35'N, 135°35'W) has a mean annual air temperature of −4.0°C (Atmospheric Environment Service,

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1982) and is in the widespread permafrost zone (Brown, 1978; Fig. 1). The village of Mayo lies in boreal forest of the Stewart River Valley, about 20 km east of (within) the late-Wisconsinan, McConnell glacial limit (Bostock, 1966; Hughes, 1983).

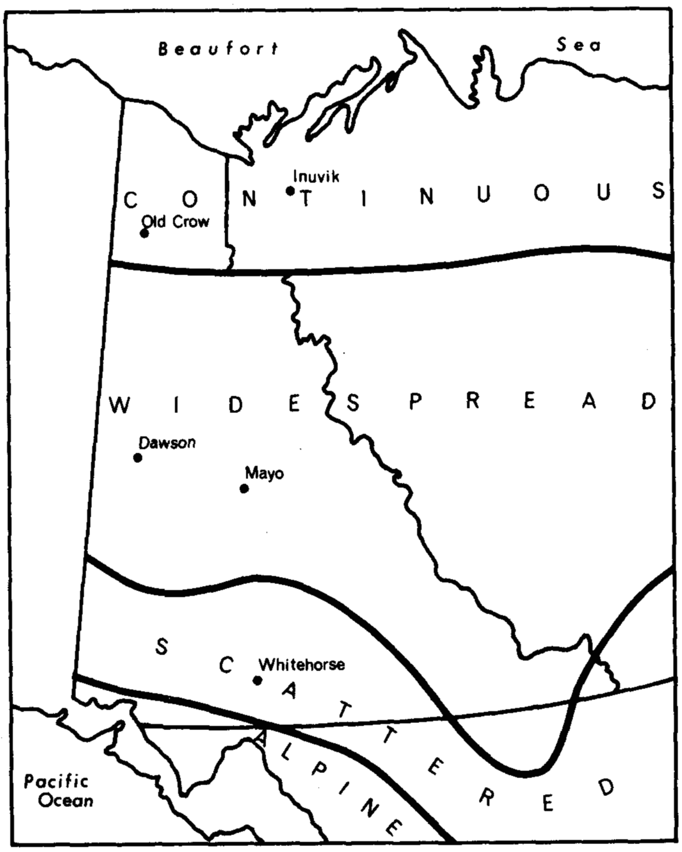

FIG. 1. Permafrost map of the Yukon Territory and western Northwest Territories (after Brown, 1978).

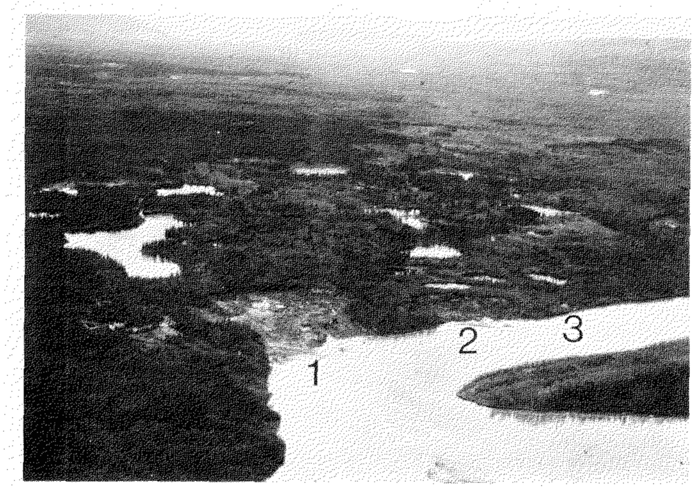

FIG. 2. Oblique aerial photograph of the study area, with the two active thaw slumps (1 and 2) in the foreground and the stabilized slump (3) on the right, 17 June 1982.

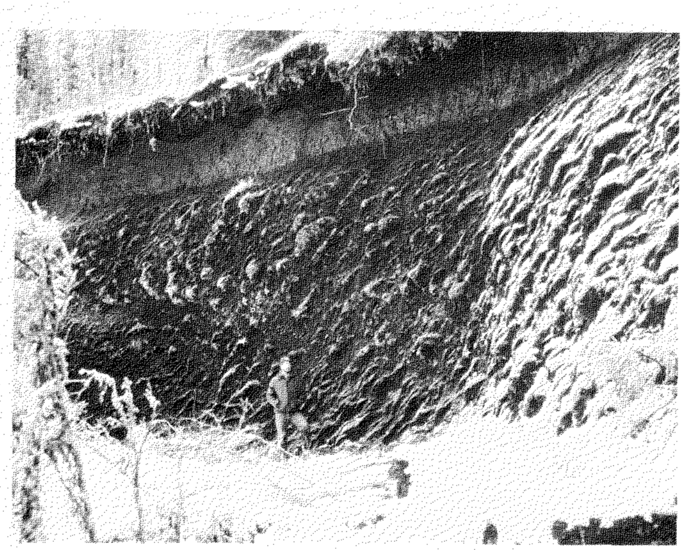

FIG. 3. Headwall of thaw slump 1, Mayo study area, 12 January 1986.

The thaw slumps are located in a body of ice-rich glaciolacustrine sediments 3 km southeast of Mayo, where there are several thermokarst lakes (Fig. 2). The ground-ice stratigraphy exposed in one thaw-slump headwall is discussed in detail by Burn *et al.* (1986). Records from over 30 holes drilled to 5 m depth at undisturbed sites in the study area indicate that the ground ice exposed in the headwall is representative of these ice-rich sediments. Apart from the active layer, over 60% by volume of the upper 8 m of the sediments consists of ice (Fig. 3).

There are three thaw slumps in the study area; all were initiated after riverbank erosion led to exposure of ice-rich sediment. Two of the slumps were initiated during the last 40 years and are still active. The third has been stable since at least 1949, throughout the period for which aerial photographs are available.

In the undisturbed forest, the glaciolacustrine silty clay (on average 1% sand, 57% silt, 42% clay) is covered by organic horizons up to 40 cm thick. The active-layer depth in September at forest sites varies from 35 cm to about 100 cm, depending on organic layer thickness, site wetness, and so on. The surface 10 cm of mineral soil is slightly acidic (pH = 6), indicating the mild leaching regime characteristic of central Yukon (cf. Rostad *et al.*, 1977), where mean June-September precipitation is 159 mm (Atmospheric Environment Service, 1982). The surface mineral horizons exhibit a distinct fine subangular blocky or granular structure as a result of ice segregation during the winter and wetting and drying in summer. The most common soil in Stewart Valley is the Orthic Eutric Brunisol (Rostad *et al.*, 1977).

The dominant tree species in the study area is white spruce (*Picea glauca*), but black spruce (*P. mariana*) and paper birch (*Betula papyrifera*) are sparsely distributed throughout the forest. Tree-ring counts from numerous increment borings indicate that trees in the undisturbed forest range from saplings up to 150 years in age. *Salix glauca* forms clumps in the understorey and, with *S. arbusculoides*, is a common shrub. *Shepherdia canadensis*, *Vaccinium vitis-idaea*, *Ledum decumbens*, *Arctostaphylos rubra*, *Linnaea borealis* and *Geocaulon lividum* are common sub-shrubs. Herbs are dominated by *Hedysarum boreale*. Several species of orchid and *Moneses uniflora* can be found in closed parts of the forest. The ground cover is dominated by feathermosses, notably *Hylocomium splendens*. The white spruce/feathermoss forest type is typical of the warmer soils in valley-bottom locations in the northern boreal forest (Bliss, 1978; Viereck and Schandelmeier, 1980).

According to the native population of Mayo, there have been no fires in the study area during the past 80 years. However, Burn and Smith (1988) suggest that the thermokarst lakes near the thaw slumps formed approximately 130 years ago as a result of forest fire. Charred wood from the forest floor with a radiocarbon age of 150 ±80 years BP (BGS-846) also suggests that the area was burned early in the last century. In addition, the transitional replacement of feathermosses by *Sphagnum* spp. throughout the boreal forest zone is thought to take 100-200 years after disturbance (Foster, 1984; Van Cleeve and Viereck, 1981). Since feathermosses still dominate the ground cover of the study area, it is likely the most recent fire occurred before 1850.

FIELD AND LABORATORY METHODS

The development of thaw slumps in the study area has been traced for the period 1949-76 from aerial photographs taken in 1949, '50, '61, '65, '70 and '76. In addition, plane-table surveys were made in the summers of '82, '83, '84, '85 and '87. More detailed investigations of the rate of headwall retreat were made on a daily and weekly basis during the summer of 1982, when twice-daily measurements of ablation were made with white dowel rods placed in holes 30 cm deep drilled into frozen soil or ice. The dowels were frozen in the holes less than three hours after installation (Burn, 1982).

Field studies of vegetation distribution and characteristics of the soil in the slumps were conducted during July 1987. Vegetation unit boundaries in the largest active thaw slump were mapped by plane table, with five vegetation units defined in the slump floor, each being differentiated by its visual homogeneity. Two further units were defined as the communities in the floor of the stabilized slump and in the undisturbed forest respectively. In addition, two final units were identified but are not considered in detail: (1) the uncolonized soil slurry, which had only recently slumped; and (2) an *Equisetum* marshland, fed by headwall meltwater. The marshland unit was assumed to be in equilibrium with present moisture conditions and may continue succession after the slump has stabilized.

Plant specimens were collected during field mapping, and initial species lists were constructed for each unit. Seed plants and trees were identified in the field using Welsh (1974) and Viereck and Little (1972) respectively. Cryptogams were identified using Hale (1979), Lawton (1971) and Thomson (1984) at the University of British Columbia herbarium. Full scientific names of the species are presented in the Appendix. The vegetation characteristics of each unit were determined in four randomly selected sample plots. The sample plot size used in each unit was defined by the Nested-plot technique, and complete species lists and cover-abundance estimates were generated using the Braun-Blanquet cover-abundance scale (Mueller-Dombois and Ellenberg, 1974:48, 59).

Vegetation remnants from the original surface in the youngest colonized unit were ignored, and samples were confined to the disturbed surface between remnant islands in order to represent clearly the nature of initial colonization. The sample plot size in this unit was 1 m^2 (see Table 1). In the older units, where the vegetation islands were less distinct, the species on the islands were included in the sampling. As a result, these vegetation units required larger sample plots (up to 256 m^2). Raw cover abundance data from the four sample plots in each unit were averaged qualitatively to produce a single value for each species. Species were placed in partial tables and sorted to emphasize the change in species composition with time.

TABLE 1. Age[a] of vegetation units and area of sample plots, Mayo thaw slumps

Unit	Sample-plot size (m^2)	# of trees sampled	Age range from trees (yrs)	Age range from aerial photographs and ground surveys (yrs)
1. Active	0.25	–	–	0-1
2. *Funaria*	1	–	–	1-2
3. *Senecio*	128	5	2-5	3-8
4. *Equisetum/Salix*	256	4	6-9	4-10
5. *Equisetum*	64	–	–	6-15
6. *Salix/Betula*	16	3	12-15	10-21
7. *Picea/Betula*	256	3	43	>37
8. *Picea*	256	35	90-150	–

[a]Years before 1986.

The ages of vegetation units were determined from aerial photographs, from field observations made since 1982 and by examination of the growth rings of small trees that survived the fall into the slump. (The mean age and diameter of the 15 trees sampled were 37 years and 32 mm respectively.) Specimens were cut, and discs were taken from the bent portion near the base. The number of rings from the bark to the beginning of most recent reaction wood was counted with the aid of a hand lens. This was assumed to approximate the period from disturbance to the 1986 growing season. Dates of disturbance in each unit were established on the basis of at least three trees sampled per unit. The ages of the units were checked with reference to the aerial photograph record of slump development (Table 1).

In order to examine soil development in the slumps, a pit 1 m deep or to the frost table, if the unfrozen layer was less than 1 m, was dug at each sample plot. Soil profiles were examined to determine: (1) depth of litter; (2) depth to frost; (3) depth to lime ($CaCO_3$); and (4) depth of aggregate development in the soil. The depth of the litter horizon and the depth of aggregate development were determined by eye; the depth to the frost table was measured by probing with a steel rod; and the depth to lime was determined by dropping weak HCl on the soil. Samples were collected from the uppermost 10 cm for laboratory analyses to determine pH (in 0.01M $CaCl_2$) and calcium carbonate (by gravimetric method for loss of CO_2), organic carbon (by wet oxidation) and total nitrogen contents. Laboratory analyses were conducted according to McKeague (1978).

Ground temperatures at depths of up to 5 m have been monitored on a monthly basis since August 1985 at several sites in the study area. The temperatures are read from thermistor cables installed in one-inch PVC pipes filled with diesel oil. The thermistors (YSI 44004) were calibrated to $\pm 0.05°C$ in a controlled temperature bath before installation. The thermistors are "aged" by the manufacturer, and therefore should not drift from the calibration if installed in this way. The sites were drilled and instrumented in July 1985. The soil materials and moisture contents at each site were determined from continuous-core samples obtained during drilling.

GEOMORPHOLOGY OF MAYO THAW SLUMPS

Thaw slumps are initiated when ice-rich sediment is exposed and begins to melt. Aerial photographs indicate that one (slump 1) of the two active slumps in the study area was initiated shortly before 1949, and the other (slump 2) between 1961 and 1965. Each slump consists of a near-vertical 8 m headwall, an overhanging active layer and a footslope of approximately 2°.

The headwalls of the thaw slumps face northeast and do not receive direct insulation between mid-October and mid-April, when normal air temperatures are continually below 0°C. Headwall retreat occurs only when maximum air temperatures are above 0°C, generally from mid-April to September. Detailed studies of the energetics of slump headwalls have been presented by Pufahl and Morgenstern (1980) and Lewkowicz (1986, 1987a); the latter has developed an effective technique for predicting short-term ablation from meteorological data. The following discussion is limited to a description of the gross characteristics of the development of thaw slumps near Mayo.

Short-term Ablation

Between 30 June and 9 July 1982, mean retreat rates determined with dowel rods at two sites on the slump headwall were 7.4 $cm \cdot day^{-1}$ and 11.1 $cm \cdot day^{-1}$. However, on 11 July, 29 cm of retreat was observed at one site during a rainstorm lasting 12 hours. The increase in retreat rate resulted primarily from rapid removal of debris that fell or accumulated on the thawing face. Acceleration of retreat during rainfall has also been noted by Lambert (1972:100).

Long-term Development

The development of the two active thaw slumps, as traced from aerial photographs and ground surveys, is presented in Figures 4 and 5. Mean headwall retreat rates of approximately 14 $m \cdot yr^{-1}$ and 12 $m \cdot yr^{-1}$ have been measured, since initiation, for slumps 1 and 2 respectively. At times an annual retreat of up to 16 m has been measured for slump 1 (e.g., 1985). These retreat rates are among the highest recorded in the literature for the development of such features (Table 2) and are partly due to the warm summer temperatures at Mayo (mean July air temperature is 15.2°C) and the long thaw season. Comparable retreat rates have been measured for *south-facing* headwalls on Banks Island, N.W.T. (Lewkowicz, 1987b). Higher values are reported from sites where both thawing and headwall undercutting are accompanied by rapid removal of slumped debris (cf. Are, 1978; Jahn, 1975:117).

Retreat rate depends not only upon atmospheric conditions, but also upon the rate availability of ice-rich material. Field measurements have indicated that the relationship be-

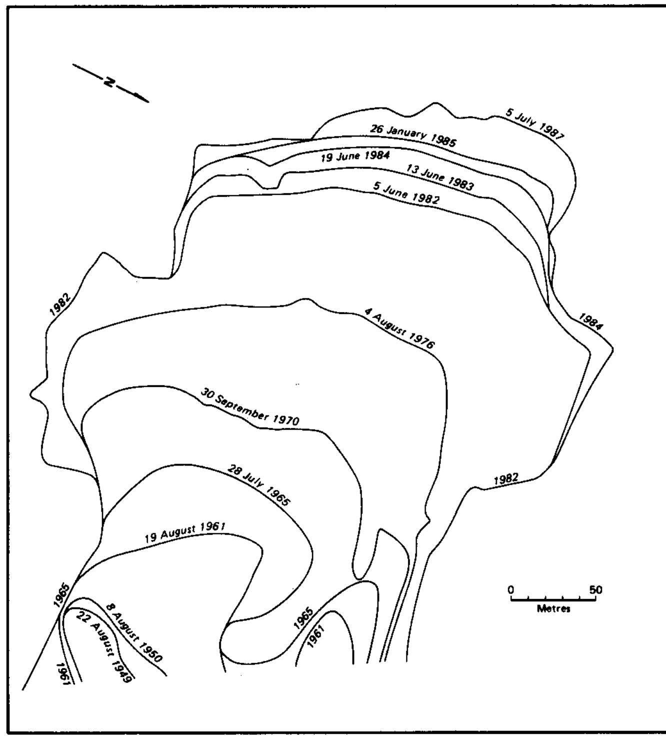

FIG. 4. Development of thaw slump 1, Mayo study area, 1949-87.

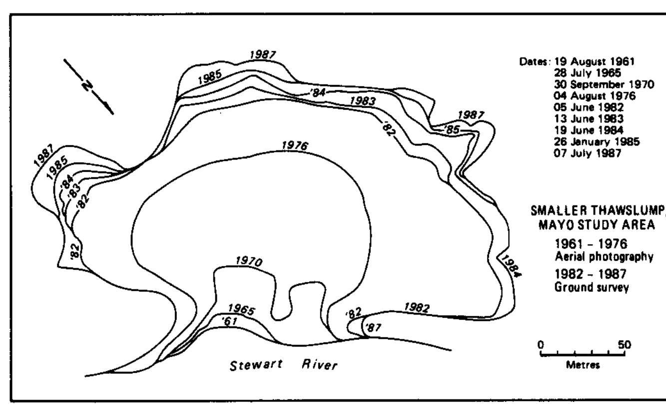

FIG. 5. Development of thaw slump 2, Mayo study area, 1961-87.

tween retreat rate and headwall ground-ice content is not linear, although short-term observations indicate that it is positive and monotonic (Burn, 1982:65). Portions of the headwalls of the Mayo features that have stabilized recently are associated with a dry substratum. Kerfoot (1969) notes that the critical factor influencing the longevity of thaw slumps is the maintenance of fresh exposures of substrata that have a high ice content.

VEGETATION SUCCESSION

While the distribution of permafrost is broadly correlated with climatic conditions, the ground thermal regime at any site is governed by the surface temperature regime (e.g., Smith, 1975). This is a function of the energy balance and thermal properties of the ground surface, which depend on the vegeta-

TABLE 2. Measured rates of retreat of thaw-slump headwalls from various locations

Location	Rate ($m \cdot yr^{-1}$)	Source
Arctic coast, U.S.S.R.	10	Are (1983)
Central Yakutia, U.S.S.R.	7- 9.5	Are (1978)
Ellef Rignes Island, N.W.T.	7-10	Lamonthe and St-Onge (1961)
E. Melville Island, N.W.T.	7- 8	Heginbottom (1984)
E. Banks Island, N.W.T.	7-10	French and Egginton (1973)
E. Banks Island, N.W.T.	6- 8	French (1974)
S. Banks Island, N.W.T.	14	Lewkowicz (1987b)
Tuk. Peninsula, N.W.T.	7	Mackay (1986)
Garry Island, N.W.T.	7.2	Kerfoot and Mackay (1972)
Mackenzie Delta, N.W.T.	1.5- 4.5	Mackay (1966)
Mayo, Yukon Territory	14-16	This paper
Colville Delta, Alaska	1- 3	Walker (1983)
Macleod Point, Alaska	10-18	Black (1983)

tion cover in summer and snow conditions in winter. Therefore, the sequence of vegetation communities after disturbance moderates the return of the ground thermal regime to equilibrium conditions (Benninghoff, 1952; Brown, 1963). The following discussion describes the re-establishment of the forest community on disturbed surfaces.

The vegetation units mapped in the larger thaw slump are indicated in Figure 6. Ring counts of *Picea glauca* specimens defined the age limits for units dominated by *Senecio*, *Equisetum/Salix*, *Salix/Betula* and *Picea/Betula* spp., which have been dated from 1984 to 1943. The ages of the fresh unit and the unit dominated by *Funaria* could be determined from plane-table surveys of the headwall position made since 1982 (Fig. 4). The age of the *Equisetum* unit was estimated from aerial photographs. Comparison of Figures 4 and 6 indicates that the dates determined by tree-ring counting are consistent with the ages of the units as determined from aerial photographs (cf. Table 1).

The vegetation succession in the thaw-slump floors is documented in Table 3, which provides a visual impression of the change in species composition with time for the various units. During the six years following disturbance, the proximity of the ablating headwall ensures that the soils remain close to saturation. Subsequently, as distance from the headwall increases, two distinct community types develop: (1) a *Salix/Equisetum* or *Equisetum* community in areas supplied by headwall meltwater; and (2) in dry areas, a successional sequence re-establishing the original forest community. The latter sequence originates with fast-growing, wind-dispersed herbs and shrubs, followed by tree saplings after 10-15 years. Thirty-five to 50 years after disturbance, a well-stocked *Betula papyrifera/Picea glauca* stand, with a patchy feathermoss ground cover, is established. Notes on the vegetation characteristics of the units are provided below.

Unit 1. Active Thaw Front

Material at the slump face collapses, destroying and burying most of the original vegetation mat. However, small islands of the vegetation mat, up to 2 m in diameter, remain to cover 5-10% of the surface. The species composition of these islands is similar to that of the forest, but many of the annual herbs do not reappear after disturbance. Some islands harbor small spruce saplings, which may be used in older units for reaction-wood dating. No vegetation covers the surface between the islands in the year of disturbance.

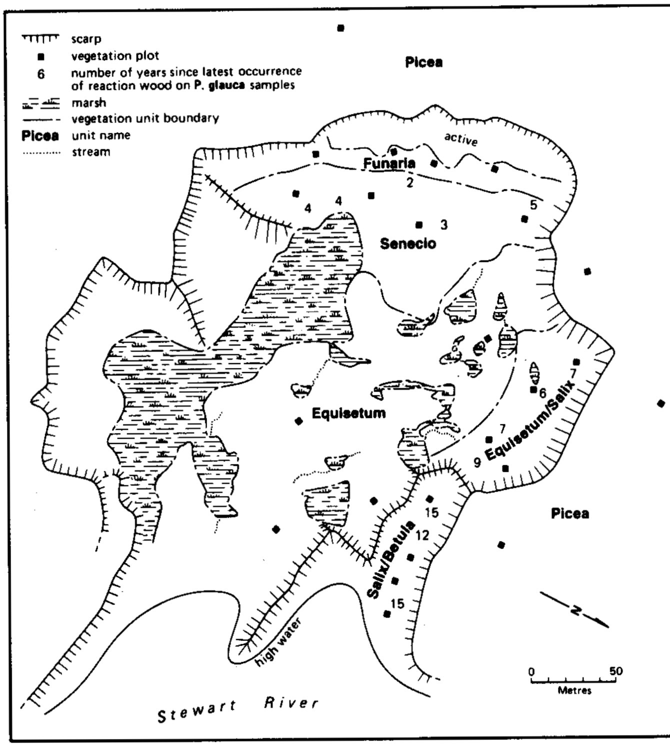

FIG. 6. Vegetation units mapped in thaw slump 1, Mayo study area, July 1987. Unit ages as in July 1986. *Picea/Betula*-dominated unit constitutes the stabilized slump (slump 3).

Unit 2. Funaria *(1-2 years after disturbance, saturated)*

In this unit, the vascular plants *Senecio congestus* and *Epilobium palustre* and the moss *Funaria hygrometrica* colonize the exposed surface, although the first two species do not reach the stage of fluorescence by July. *S. congestus* is dominant and locally may cover the entire surface.

Unit 3. Senecio *(2-5 years after disturbance, saturated)*

In this unit, more weedy colonizers including *Equisetum arvense* and willow seedlings appear. *Senecio congestus* is well established, but faces some competition, as weed species are more diverse and *Rubus ideaus, Rosa acicularis, Ribes hudsonianum* and *Hedysarum boreale* appear between the surviving islands of forest vegetation. *Leptobryum pyriforme* is the dominant moss.

Unit 4. Equisetum/Salix *(6-9 years after disturbance, moist)*

Senecio congestus relinquishes dominance to *Equisetum arvense* and *Cinna latifolia*, and some forest herbs return. Vegetation from the remnant islands spreads successfully onto the disturbed surface. Willows 1-2 m tall dominate the shrub layer, although spruce and birch seedlings are common. *Bryum caespiticum* is the dominant moss.

Unit 5. Equisetum *(6-15 years after disturbance, saturated)*

When compared to units 4 and 6, the vegetation in unit 5 illustrates the influence of saturated soil conditions on succession. Water drains from the active slump face into the unit,

TABLE 3. Species composition of thaw-slump vegetation units[a,b]

Unit[c]	2	3	4	5	6	7	8
Age of surface (yr)	1-2	2-5	6-9	6-15	12-15	43	mature
Species							
i. Cryptogams							
Funaria hygrometrica	2	3			+		
Leptobryum pyriforme		3	+	1			
Marchantia polymorpha		+	1		r		
Bryum caespiticum			4	2	1		
Peltigera aphthosa			+		r	+	1
Aulacomnium palustre			+		1	3	2
Hylocomium splendens			+	+	1	2	4
Cladonia uncialis			r			+	1
Polytrichum juniperinum				r			+
Tomenthypnum nitens					2	3	2
Cladonia major						+	+
Cladonia cyanipes						+	+
Sphagnum girgensonii							1
Dicranum acutifolium							+
Ditrichum heteromallum							r
Stereocaulon grande							r
Total species:	1	3	7	4	7	7	12
ii. Herb cover							
Senecio congestus	4	3	r	r			
Chenopodium capitatum		r					
Descurainia richardsonii		+					
Senecio lugens		r					
Epilobium palustre	1	1	1	+			
Polygonum alaskanum		r	r	r			
Stellaria longifolia		r	r		r		
Equisetum arvense		3	4	4	2	1	+
Cinna latifolia		1	3	1	+	+	+
Epilobium angustifolium		+	2	1	+	1	+
Hedysarum boreale		+	+	1	1	2	2
Arnica alpina			r	+	+	+	+
Equisetum scirpoides			r			1	+
Hordeum jubatum			r	+			
Habenaria hyperborea				+	r		
Gentianella propinqua				r	+	+	r
Parnassia palustris				+	1	+	r
Astragalus agrestis				r	r	+	r
Erigeron acris				r	+		
Corallorhiza trifida					r		
Aster commutatus					r		
Ranunculus orthorhynchus					+		
Achillea millefolium				r	r	r	r
Rubus arcticus					r	+	+
Carex concinna						2	1
Habenaria obtusata						+	r
Listera borealis							r
Moneses uniflora							r
Goodyera repens							r
Carex aurea							r
Total species:	2	11	11	16	16	13	17
iii. Sub-shrubs							
Ribes glandulosum			r				
Rubus idaeus		+	2	r	r		
Ribes hudsonianum		+	2	+	+	+	+
Shepherdia canadensis		r	+	+	+	3	2
Vaccinium vitis-idaea		+	+	+	+	2	2
Rosa acicularis		+	1	1	1	1	+
Ledum decumbens		+	1	+	r	1	2
Linaea borealis		+	+	+	+	1	1
Arctostaphylos rubra		r	r	+	r	1	1
Pyrola asarifolia		r	r	+	r	1	1
Viburnum edule			r	r		+	+
Potentilla fruticosa					+		
Geocaulon lividum			+			1	1
Empetrum nigrum						+	+
Pyrola secunda						+	+
Total species:	0	9	11	10	10	12	12
iv. Tree seedlings and shrubs							
Salix lasiandra		+	r	r			
Salix interior		+	r	r	r		
Salix alaxensis		r	+	+	+		
Salix novae-angliae		r	2	1	1	2	+
Salix arbusculoides		+	3	2	1	1	2
Salix glauca	r	+	2	2	1	2	2
Populus balsamifera			r	1	+		
Betula papyrifera		r	2	+	1	+	+
Picea glauca		r	1	r	2	2	+
Total species:	1	8	9	9	8	5	5
v. Trees							
Picea glauca					r	2	3
Betula papyrifera					+	2	+

[a] Species ordered to illustrate successional sequence toward mature cover.
[b] Braun-Blanquet cover abundance scale: r = solitary, small cover; + = few, small cover; 1 = numerous, but <5% cover; 2 = 5-25%; 3 = 25-50%; 4 = 50-75%; 5 = >75% cover.
[c] Units: 2. *Funaria*; 3. *Senecio*; 4. *Equisetum/Salix*; 5. *Equisetum*; 6. *Salix/Betula*; 7. *Picea/Betula*; 8. *Picea*.

maintaining saturated soil conditions. The species diversity is similar to that of adjacent units, but *Equisetum arvense* dominates, with 50-75% ground cover. The cover provided by the remaining species is patchy.

Unit 6. Salix/Betula *(12-15 years after disturbance, moist)*

The islands that survived disturbance cannot be distinguished in this unit. Forest species are more diverse, and the original weedy colonizers are less diverse. White spruce and paper birch seedlings and saplings are common among the willows. The shrub layer is 2-2.5 m tall.

Unit 7. Betula/Picea *(approximately 43 years after disturbance, moist)*

The species composition in this unit is similar to the undisturbed forest: all important constituents are established, although the diversity is somewhat reduced, and the moss cover is discontinuous. White spruce dominates both the canopy and shrub layers in the unit. However, while paper birch is common in the canopy, birch seedlings are scarce. This is a significant change from the *Salix/Betula*-dominated unit, where birch seedlings are common, and indicates that spruce should increasingly dominate the canopy, until the forest is primarily composed of this species. The canopy reaches a height of 10 m.

These observations suggest that the original forest community, although immature, may be re-established 35-50 years after disturbance. Hettinger *et al.* (1973:96) note that the re-establishment of the forest community following fire in the Peel-Porcupine plateau requires a similar period. It is important to recognize that soil moisture conditions may alter vegetation succession locally. The *Equisetum* communities, which appear at sites fed by slump meltwater, persist briefly in the area and occupy a significant portion of the floor in the active thaw slump. At such sites, a longer period subsequent to disturbance may be required for re-establishment of the forest community. It should also be noted that a mossy litter layer, characteristic of the undisturbed forest and a critical element in the ground thermal regime, is not continuous in the *Betula/Picea*-dominated unit at least 43 years after disturbance.

SOIL CHARACTERISTICS

Distinct landform-soil associations have been used in central Yukon to demarcate at least three separate advances of the Cordilleran ice sheet into Beringia during the Pleistocene (e.g., Bostock, 1966; Tarnocai *et al.*, 1985). Soils of the unglaciated area of central Yukon west of the Pleistocene glacial maximum are among the deepest and most intensely weathered in Canada, while those within the limits of McConnell glaciation are relatively undeveloped (Foscoulos *et al.*, 1977).

The various soils have been used successfully as correlative features by Tarnocai *et al.* (1985) to determine the relative age of glacial landforms in the region. Attempts have also been made to deduce palaeoclimatic information from the intensity of chemical alteration and the physical characteristics of the soils. However, present rates of soil development in the region are unknown, and therefore it is difficult to isolate the relative contributions of time and changing environmental conditions to pedogenesis.

To this end, changes in the physical and chemical composition of soils in the thaw slumps may be used to investigate initial soil development in these deposits, for as the headwall retreats, the footslope mudlobes provide fresh parent material in which pedogenesis is initiated. The results presented form a preliminary examination of pedogenic processes in fresh deposits. With the field evidence available, it is not possible to provide a detailed account of the rate of profile development in the slump sediments.

Field observations and laboratory results of soil analyses are presented in Table 4. Physical indications of profile development appear 6 years after disturbance, in the form of soil aggregates and a sparse litter cover in unit 4. Both of these elements develop with increasing age of surface. In addition, the leaching of lime from the surface of the soil in unit 7 demonstrates the start of chemical weathering after, at most, 40 years.

The assays of pH, organic C, total N and percent $CaCO_3$ content of samples from the surface 10 cm at all sites fall into two groups. Results from all disturbed sites (units 1-7) form one batch. Some variation within this batch is inherited from the heterogeneous sediment that forms the parent material. The values obtained with the mature forest samples (unit 8) are distinct from the disturbed-site samples. This indicates that soil development at the disturbed sites is still at an early stage. Chemical changes are dependent on the presence of a surface litter horizon in which fulvic and humic acids may be generated. After about 40 years, this horizon is, at most, thin (i.e., less than 5 cm thick), and often absent.

PERMAFROST CONDITIONS

Drilling at several recently disturbed sites in the floors of the active thaw slumps has indicated that the surficial 3 m of slump floors are not perennially frozen during the first 10 years after disturbance (cf. depth to frost, Table 4). However, a comparison of the ground thermal regime at an undisturbed forest site and in the floor of the stabilized slump indicates the re-establishment of permafrost in the slump floor (Fig. 7). The disturbed site was first drilled to 5 m depth in 1982, when all ground below 0.8 m was frozen. Therefore, permafrost was re-established by approximately 38 years after disturbance.

TABLE 4. Soil physical and chemical characteristics

1. Physical characteristics

Unit	Age (yr)	Depth of aggregates (cm)	Thickness of litter (cm)	Depth to frost (cm)
1. Active	0	0	0	75
2. *Funaria*	1-2	0	0	>110
3. *Senecio*	2-5	0	0	>110
4. *Equisetum/Salix*	6-9	0.5	0.2*	>110
5. *Equisetum*	6-15	–	–	>110
6. *Salix/Betula*	12-15	3.8	0.3*	135
7. *Picea/Betula*	43	7.2	3.9*	95
8. *Picea*	mature	11.6	7.1	49

2. Chemical characteristics

Unit	Depth to $CaCO_3$ (cm)	$CaCO_3$ equivalent (%)	pH	Organic carbon (%)	Total nitrogen (%)
1	0	–	–	–	–
2	0	3.8	7.3	1.7	0.15
3	0	5.1	7.2	1.5	0.15
4	0	3.7	7.4	2.0	0.14
5	–	3.6	7.4	1.5	0.14
6	0	4.3	7.4	1.9	0.17
7	9.3	3.6	7.3	1.9	0.17
8	37.3	1.8	6.2	5.5	0.32

*Discontinuous; in places non-existent.
Note: Results are mean values of four samples from each unit.

Ground temperature envelopes from both sites for the calendar years 1986 and 1987 are presented in Figure 7. Warmer temperatures were recorded at the disturbed site, where the ground thermal regime is recovering from the disturbance effected by the thaw slump.

However, we should note: (1) that loss of ground ice during thaw-slump development has altered soil thermal properties, and therefore the ground thermal regime at the two sites will differ even if surface temperatures are similar; and (2) that the ground surface temperatures, which drive the ground thermal regime at the sites, are unlikely to be similar before comparable surface conditions are established. In particular, over time a thicker moss layer should cover the disturbed site.

Nevertheless, given present ground temperatures in the slump, the estimate of time since disturbance of about 43 years, and in anticipation of further changes in ground surface conditions, it is unlikely that the ground thermal regime at the disturbed site will reach equilibrium in less than a century after disturbance. In particular, further development of organic horizons, which are discontinuous in the stabilized slump, may be expected to affect ground temperatures.

SUMMARY AND CONCLUSIONS

The observations presented here describe the regeneration of forest vegetation after its obliteration during thaw-slump

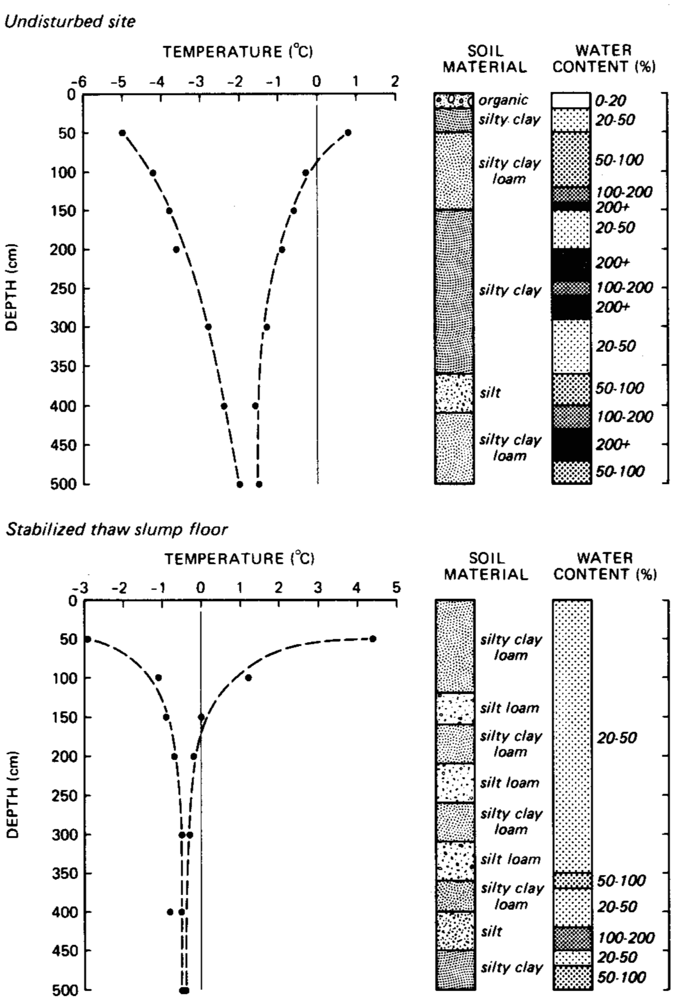

FIG. 7. Temperature envelopes (10 October 1985 to 10 October 1987), soil material and gravimetric water contents at a mature forest site and in the stabilized slump.

development at sites near Mayo, Yukon Territory. The re-establishment of plant communities is associated with the initiation of soil development in fresh soil substrata. Ground temperature measurements indicate permafrost aggradation in a regenerating slump floor. From the various observations presented, we conclude:

(1) Succession toward a closed-canopy spruce forest is well under way about 40 years after disturbance. The community differs from the mature forest in that the bryophyte cover is poorly developed and birch trees constitute a large portion of the canopy. The absence of birch saplings from the shrub layer implies that *Picea glauca* will inevitably become established as the principal tree species. It is possible that the absence of birch saplings is due to chance, and that such saplings may appear in a few years' time. However, we consider this unlikely, since birch is virtually absent from the mature forest.

(2) Soil development on fresh surfaces is initiated in the first decade following disturbance, but chemical changes may only be detectable after a longer period, once an organic horizon has developed. After 40-50 years, the soils still appear quite immature.

(3) Near-surface permafrost is eradicated during and in the years immediately following thaw slumping. However, it is re-established in the 40 years after disturbance, but is still not in equilibrium with surface conditions and may be expected to continue aggrading.

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APPENDIX

Full scientific names of plants in Mayo study area

i. Cryptogams

Funaria hygrometrica Hedw.
Leptobryum pyriforme (Hedw.) Wils.
Marchantia polymorpha L.
Bryum caespiticum Hedw.
Peltigera aphthosa (L.) Willd.
Aulacomnium palustre (Hedw.) Shwaegr.
Hylocomium splendens (Hedw.) B.S.G.
Cladonia uncialis (L.) Wigg
Polytrichum juniperinum Hedw.
Tomenthypnum nitens (Hedw.) Loekse
Cladonia major (Hag.) Sandst.
Cladonia cyanipes (Sommerf.) Nyl.
Sphagnum girgensonii Russ.
Dicranum acutifolium (Lindb. and Arn.) C.Jens.
Ditrichum heteromallum (Hedw.) Britt.
Stereocaulon grande (H. Magn.) H.Magn.

ii. Herbs

Senecio congestus (R.Br.) DC. var. *palustris* (L.) Fern.
Chenopodium capitatum (L.) Achers.
Descurainia richardsonii (Sweet) Schulz
Senecio lugens Rich.
Epilobium palustre L.

Polygonum alaskanum (Small) Wight
Stellaria longifolia Muhl.
Equisetum arvense L.
Cinna latifolia (Trev.) Griseb.
Epilobium angustifolium L.
Hedysarum boreale Nutt.
Arnica alpina (L.) Olin.
Equisetum scirpoides Michx.
Hordeum jubatum L.
Habenaria hyperborea (L.) R.Br.
Gentianella propinqua Rich.
Parnassia palustris L.
Astragalus agrestis Dougl.
Erigeron acris L.
Corallorhiza trifida Chatelin
Aster commutatus
Ranunculus orthorhynchus Hook. ssp. *alachensis* (Benson) Hult.
Achillea millefolium L.
Rubus arcticus L.
Carex concinna R.Br.
Habenaria obtusata (Pursh.) Rich.
Listera borealis Morong
Moneses uniflora (L.) Gray.
Goodyera repens (L.) R.Br.
Carex aurea Nutt.

iii. Sub-shrubs
Ribes glandulosum Grauer
Rubus idaeus L. var. *canadensis*
Ribes hudsonianum Rich.
Shepherdia canadensis (L.) Nutt.
Vaccinium vitis-idaea L.
Rosa acicularis Lindl.
Ledum decumbens (Ait.) Lodd.
Linnaea borealis L.
Arctostaphylos rubra (Fern.) Rhed. and Wils.
Pyrola asarifolia Michx.
Viburnum edule (Michx.) Raf.
Potentilla fruticosa L.
Geocaulon lividum (Rich.) Fern.
Empetrum nigrum L.
Pyrola secunda L.

iv. Trees and shrubs
Salix lasiandra Benth.
Salix interior Rowlee
Salix alaxensis (Anderss.) Cov.
Salix novae-angliae Anderss.
Salix arbusculoides Anderss.
Salix glauca L.
Populus balsamifera L.
Betula papyrifera Marsh.
Picea glauca (Moench) Voss