Soils of the Subarctic in the Lower Mackenzie Basin

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ABSTRACT. Nearly all of the medium- and fine-textured surficial materials are permanently frozen within one metre of the surface and have a hummocky microrelief. Indications of physical disturbance due to cryogenic processes are ubiquitous, and organic matter distribution ranges from incorporated, relatively undecomposed material to mobile organic acids. On the other hand, well-drained coarse-textured materials have no permafrost and are characterized by Brunisolic soil development.

Profile descriptions and characterizing analyses are discussed with respect to cryogenic soil-forming processes and soil classification. The suggestion is made that there is a need for re-evaluation of traditional concepts of soil development when dealing with permafrost soils of the Subarctic.

RÉSUMÉ. *Sols du Subarctique — bassin inférieur du Mackenzie.* Presque tous les matériaux de surface à texture moyenne ou fine sont gelés de façon permanente à moins d'un mètre de la surface et présentent un relief en buttes. Les exemples de cryoturbation se retrouvent partout et la distribution de la matière organique va du matériel relativement peu décomposé et incorporé aux acides organiques mobiles. D'autre part, les matériaux bien drainés à texture grossière n'ont pas de permagel et se caractérisent par le développement d'un sol brunilosique.

L'auteur discute des descriptions de profils et des analyses des caractères par rapport aux processus de cryopédogénèse et à la classification des sols. Il conclut au besoin d'une réévaluation des concepts traditionnels de pédogénèse lorsque l'on a affaire aux sols pergelés du Subarctique.

РЕЗЮМЕ. *Субарктические почвы нижнего бассейна Макензи.* Почти все находящиеся на поверхности материалы со средне — и мелкозернистой текстурой находятся в постоянно замороженном состоянии в поверхностном слое глубиной одного метра, а их поверхность имеет холмообразный микрорельеф. Повсеместны проявления физических дислокаций, связанных с криогенными процессами, а органические вещества распределяются от относительно неразложившихся включений до подвижных органических кислот. С другой стороны, хорошо просохшие материалы с грубой текстурой находятся в незамороженном состоянии и характеризуются брунисольным почвообразованием. Описания профилей и характеристические анализы обсуждаются с учетом криогенных процессов в почвообразовании и при классификации почв. Делается предложение о необходимости переоценки традиционных представлений о почвообразовании, когда рассматриваются вечномерзлые субарктические почвы.

INTRODUCTION

During a terrain and vegetation survey, conducted in 1971 and 1972 in the northwestern part of the District of Mackenzie, N.W.T., soils were encountered which were significantly different from any previously described or expected in the Canadian subarctic taiga. These were soils which had permafrost close to the surface and were strongly affected by attendant physical processes. In Canada it has been

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recognized that much of the area of organic soils in the subarctic region is permanently frozen (Nowosad and Leahey 1960; Brown 1969; Tarnocai 1972) but pedological information about mineral soils is extremely meagre (Leahey 1947; Day and Rice 1964).

There have been many studies over the past years concerned with permafrost soils in North America (Tedrow and Hill 1955; Hill and Tedrow 1961; Ugolini 1966; Holowaychuk *et al.* 1966; Everett 1968). These, however, have been

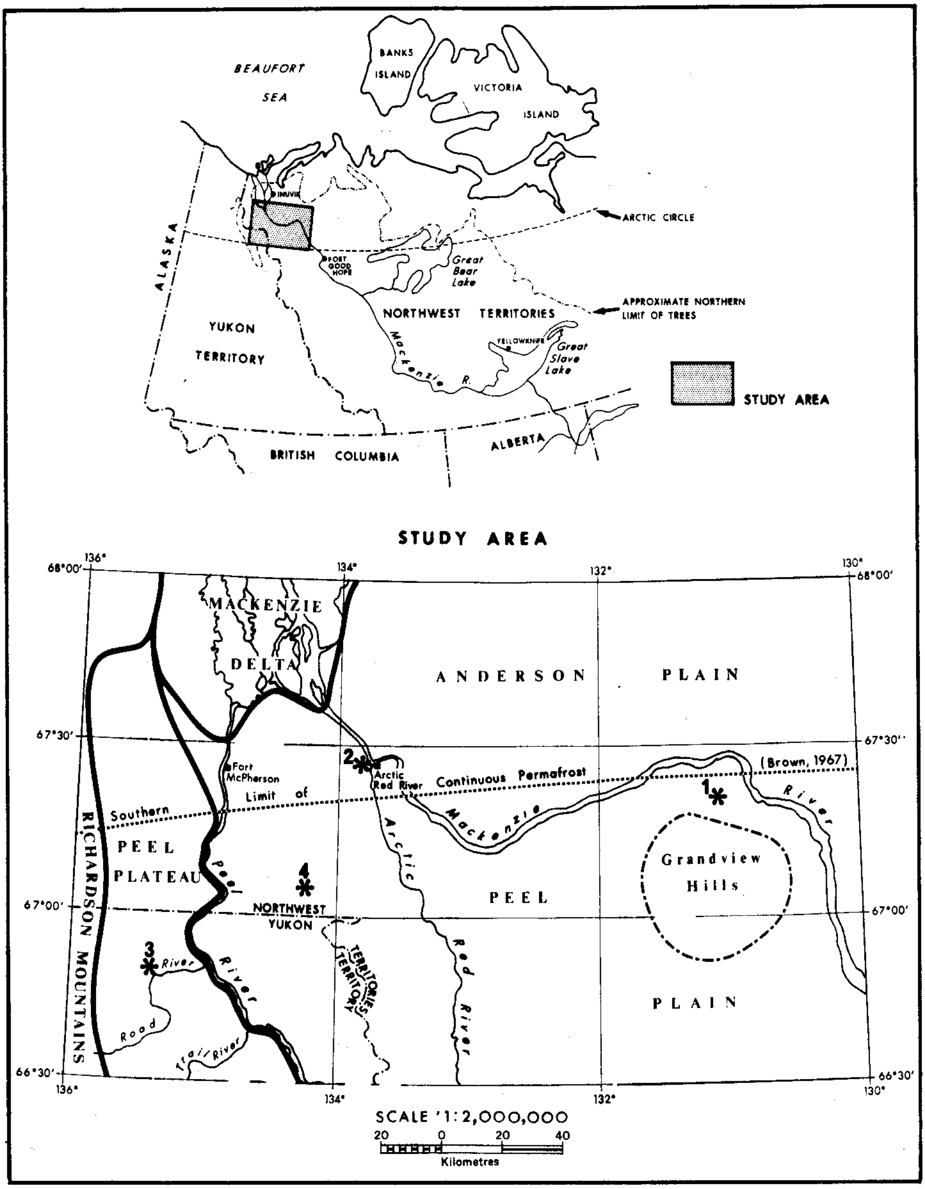

FIG. 1. Maps illustrating location and physiography of the study area.

centred almost entirely in the tundra environment. In eastern Russia there has been a longer history of permafrost-related investigations in the subarctic or frozen taiga (Nikiforoff 1928; Sokolov and Sokolova 1962; Ivanova 1963), but much of this work has become available only recently and there is a problem in correlation.

The purpose of this paper is to present field observations and analytical data for some selected soils from subarctic northwestern Canada. Also, an attempt is made to provide some basis for the classification of permafrost-affected soils — a group of soils which cover more than one quarter of Canada's land surface.

LOCATION, CLIMATE AND VEGETATION

The study area straddles the Mackenzie River from 66° to 68° N latitude and from 128° to 136° W longitude, the selected profile sites being located in the Arctic Red River—Fort McPherson vicinity (Fig. 1). The physiographic areas covered are the Anderson Plain, Peel Plain (extensions of the interior plains) and the Peel Plateau (Bostock 1965). All were glaciated during the Wisconsin time (Hughes 1972), and the surficial deposits are for the most part medium- to fine-textured till or lacustrine materials (Zoltai and Pettapiece 1973), though extensive areas of organic soils occur.

The climate of the study area is subarctic continental, with long, very cold winters and short, warm summers. Data (Tables 1 and 2) indicate a mean annual temperature of about −8 °C and a July mean of 15 °C. The mean annual precipitation is low, averaging about 285 mm, with summer (June, July, August) rainfall being about 115 mm. The continuous permafrost zone (Brown 1967) cuts across the northern part of the study area, but even in the discontinuous zone the only unfrozen areas are the waterlogged organic deposits and dry, gravel ridges. All medium- and fine-textured soils are underlain by permafrost at depths of 50-100 cm, and most organic soils are frozen at depths below 30-40 cm.

TABLE 1. Temperature, total precipitation and snowfall

	Monthly averages												Annual averages
	J	F	M	A	M	J	J	A	S	O	N	D	
Fort Good Hope													
Mean temperature (°C)	−30	−28	−20	−10	4	13	16	13	5	−6	−20	−28	−8
Mean total precipitation (mm)	13	10	10	9	13	27	46	46	33	25	23	15	270
Mean snowfall (cm)	13	10	10	9	13	3	—	—	15	25	23	15	135
Fort McPherson													
Mean temperature (°C)	−29	−27	−22	−11	1	11	14	12	4	−7	−20	−27	−8
Mean total precipitation (mm)	17	16	16	17	13	28	28	51	36	38	25	15	300
Mean snowfall (cm)	17	16	16	17	13	5	—	t	18	38	25	15	180

TABLE 2. Degree-days above selected temperatures

	Degree-days above			
	0°C	5°C	10°C	15°C
Fort Good Hope	1500	850	350	25
Fort McPherson	1225	625	180	0

The common vegetation on the permafrost soils is a black spruce (*Picea mariana* (Mill.) BSP), lichen (*Cladonia* spp.) association. Tamarack (*Larix laricina* (Du Roi) K. Koch) is a common component in poorly-drained sites, and white birch (*Betula papyrifera* Marsh.) often occurs after fire on better drained locations. The high shrubs usually present include dwarf birch (*Betula glandulosa* Michx.), willows (*Salix* spp.) and some alder (*Alnus crispa* (Ait.) Pursh), particularly after fire. Common low shrubs are Labrador tea (*Ledum groenlandicum* Oeder), northern Labrador tea (*L. palustre* L. var *decumbens* Ait.), blueberry (*Vaccinium uliginosum* L.), bog cranberry (*V. vitis-idaea* L.), crowberry (*Empetrum nigrum* L.), alpine bearberry (*Arctostaphylos rubra* (Rehder & Wils.) Fern.), small bog cranberry (*Oxycoccus microcarpus* Turcz), spirea (*Spiraea beauverdiana* Schneid.), and rose (*Rosa acicularis* Lindl.). Ground cover varies with micro-site. The drier sites are dominated by lichens (including species of *Cladina, Cladonia, Cetraria,* and others) with feather mosses (*Hylocomium* sp., *Pleurozium* sp., *Dicranum* sp.), and some sedges (*Carex* spp.) while the more poorly drained sites usually contain sphagnum mosses (*Sphagnum* spp.) with associated baked-apple berry (*Rubus chamaemorus* L.). Very poorly drained depressional areas or seepage runs have an increased abundance of sedge-like plants (*Carex* spp. and *Eriophorum* sp.) and shrubs such as leather leaf (*Chamaedaphne calyculata* (L.) Moench). Well-drained soils generally support a white spruce (*Picea glauca* (Moench) Voss) forest.

MATERIALS AND METHODS

Soils

Four soils were selected to represent the range in external and internal drainage and soil characteristics in the survey area. Classification and field descriptions follow the terminology suggested by the Canada Soil Survey Committee (1970, 1973). Explanatory notes are given in Appendix 1 to this paper. In the case of the permafrost soils the descriptions should be used in conjunction with the diagrams because of the variability in horizonation.

Site 1: Grandview North (approximately 67°23'N, 131°5'W)

This Degraded Eutric Brunisol is an example of a well- to rapidly-drained profile. It is located in a channelled glaciofluvial plain on the flat top of a low knoll. Elevation is about 150 m. Vegetation consists of an open white spruce — white birch forest with scattered shrubs (alder, willow, rose) and discontinuous mats of bog cranberry. There are some lichens but very little moss present. There are no hummocks.

Horizon	*Depth (cm)*	*Description*
L-H	2-0	Very dark grey (10YR 3/1 d) loose organic material; discontinuous; abrupt, smooth boundary; 0-3 cm thick.
Ae	0-4	Pinkish grey (5YR 6/2 d) coarse sandy loam; single grain; loose, friable; plentiful fine random, plentiful medium horizontal roots; medium acid; abrupt, smooth boundary.
Bm1	4-20	Yellowish red (5YR 4/8 m) sandy loam to loamy sand; single grain; loose, friable; plentiful medium, few fine roots; medium acid; gradual, wavy boundary.
Bm2	20-35	Strong brown (10YR-7.5YR 5/6 m) loamy sand; single grain; loose; few fine vertical roots; neutral; clear, smooth boundary.
BCk	35-45	Dark brown (7.5YR 3/2 m) gravelly sand; single grain; friable; plentiful fine roots and root remains; moderately effervescent; clear, smooth boundary.
Ck	45-55 +	Greyish brown fine gravel; single grain; moderately to strongly effervescent.

Site 2: Arctic Red River 2 (67°27′N, 133°47′W)

This is a cryoturbated permafrost soil (Fig. 2) located in a moderately well drained, gently rolling hummocky upland. It is developed in a medium-textured till with internal drainage, in the rooting zone, varying from well to poor. There is marked earth hummock development, with mounds having 50 cm or more microrelief and diameters of about 1 m. The site is on the crown of a slope exposed to

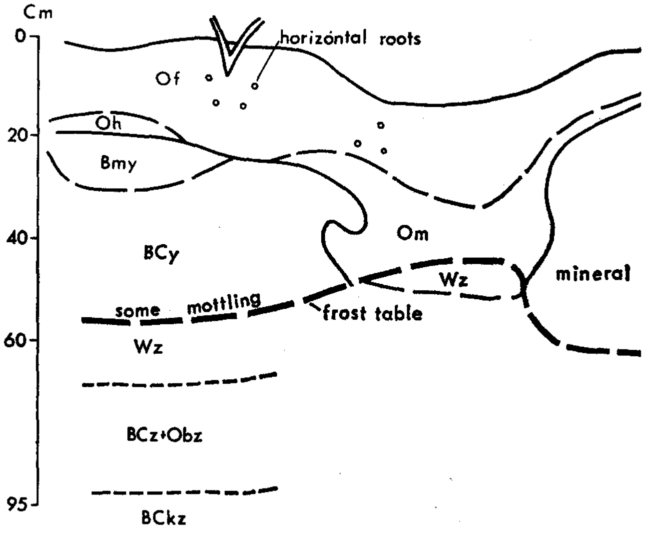

FIG. 2. Section through the edge of a hummock of the moderately-well-drained Arctic Red River soil (Site 2). Note location of the larger roots, the high ice content at the base of the active layer underlain by incorporated organic material and the relatively simple horizonation.

the south at an elevation of about 75 m. The mature white birch forest has some black spruce and a scattered high shrub layer composed mainly of alder and willow with minor cranberry (*Viburnum* sp.) and rose. The continuous low shrub layer consists mainly of Labrador tea (both species) and blueberry with bog cranberry and crowberry. There is a thick cover of feather mosses and lichens on the hummocks and sphagnum in the micro-depressions.

The horizontal descriptions for the cryoturbated soils are intended to cover the whole pedon and not simply a single vertical slice. Therefore, the associated diagrams must be referred to for a complete understanding of horizon distribution. Unless otherwise stated the depths given are for a representative vertical section through the hummock.

Horizon	*Depth (cm)*	*Description*
Of	10-2	Dark reddish brown (5YR 2/2 m) fibric organic material with a very high content of fine random roots, also abundant large horizontal roots near shoulders of hummocks, may include pieces of rotting stems and roots; extremely acid; clear, wavy boundary; 5-25 cm thick.
Oh	2-0	Black (5YR 2/1 m) humic organic material commonly containing charcoal; weak granular; abundant fine roots; very strongly acid; abrupt, wavy but discontinuous boundary; 0-2 cm thick.
Om	20-0 (trough)	Black (5YR 2/1-2/2 m) organic layer consisting of humic material and roots; abundant fine and medium roots; extremely acid; abrupt, irregular boundary; 0-20 cm thick.
Bmy	0-10	Brown to dark brown (7.5YR 4/4 m) clay loam; moderate to strong fine granular; friable; abundant fine roots; strongly acid; a few stones; clear, wavy but discontinuous boundary; 0-10 cm thick.
BCy	10-30	Very dark greyish brown (2.5Y 3/2 m) loam to clay loam; weak medium platy to amorphous; sticky; firm; few fine roots; 5 per cent gravel; neutral; abrupt, wavy boundary; 0-50 cm thick.
Wz	30-45	Very high ice horizon will scattered mineral and organic inclusions.
BCz + Obz	45-75	Frozen mineral and buried organic horizon.
BCkz	70-80+	Dark greyish brown loam; some organic material; 20 per cent gravel; weakly effervescent.

Temperature: 21 July 1971: Air, 18°C; 10 cm, 10°C; 20 cm, 6.5°C; 30 cm, 3°C.

Site 3: Road River (66°50'N, 135°23'W)

This cryoturbated permafrost soil (Fig. 3) is located in a similar landform to Site 2 but is developed in a finer textured material than that site and has more poorly expressed horizonation. Internal drainage, in the rooting zone, varies from imperfect to poor. Hummock development is strongly expressed and continuous, with a microrelief of 40-60 cm and diameters of 75-125 cm. The site is situated on a west-facing slope of 4 per cent gradient at an elevation of about 400 m. The forest consists of a rather open stand of black spruce, 3-4 m high, with sparse high shrubs of dwarf birch, alder, and willow; a moderately dense low shrub-layer of Labrador tea (both species), blueberry, bog cranberry and minor baked-apple berry and spirea; and a continuous ground cover of lichens and feather mosses on the hummocks, and sphagnum mosses with minor sedge in the depressions.

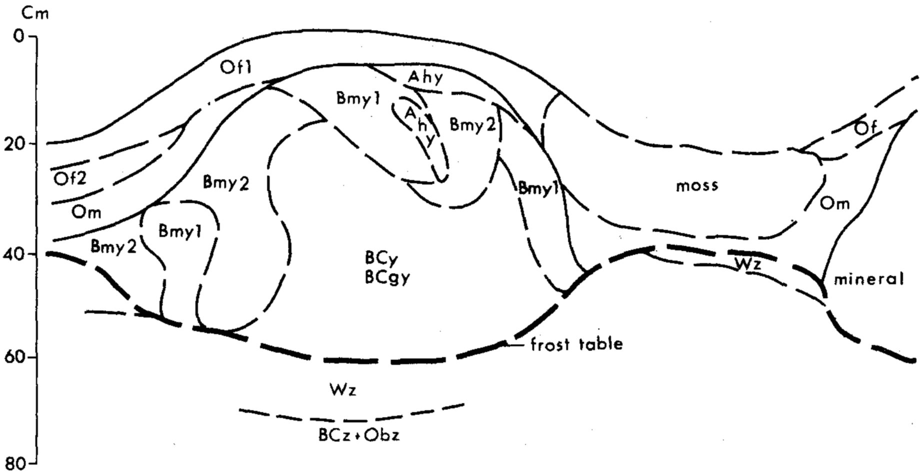

FIG. 3. Section through the centre of a hummock of the imperfectly-drained Road River soil (Site 3). Note the configuration of the permafrost table, the strongly cryoturbated internal horizonation and again buried organic material at depth.

Horizon	*Depth (cm)*	*Description*
Of1	8-0 20-13 (trough)	Reddish brown (5YR 5/4-4/6 m) fibric organic layer composed of fine roots, mosses, and lichen remains; abundant medium and coarse horizontal roots; extremely acid; clear, wavy boundary; 0-8 cm thick.
Of2	13-8 (trough)	Similar to Of1 except that the lichen remains are absent; 0-5 cm thick.
Om	8-0 (trough)	Dark reddish brown (5YR 2.5/2 m) mesic organic layer; abundant roots of all sizes, extremely acid; abrupt, wavy but discontinuous boundary; 0-10 cm thick.

Horizon	*Depth (cm)*	*Description*
Ahy	0-2	Very dark brown (10YR 2/2-3/2 m) silt loam; weak, fine granular; friable, nonsticky; abundant fine random roots; very strongly acid; clear, wavy but discontinuous boundary; 0-5 cm thick.
Bmy1	variable	Dark brown (10YR 3/3 w) clay loam; strong, fine granular to medium subangular blocky; friable; abundant fine random roots; strongly acid; clear, broken boundary; 0-20 cm thick.
Bmy2	variable	Very dark greyish brown (10YR 3/2 m) clay loam; some dark grey (10YR 4/1 m) and dark brown (7.5YR 4/4 m) areas; moderate, medium subangular blocky; firm to friable; few to plentiful fine black roots; strongly acid; clear, broken boundary; 0-40 cm thick.
BCgy	variable	Dark grey (10YR 4/1 m) clay loam; common fine to medium, prominent dark brown (7.5YR 4/4 m) mottles in upper portion grading to few near lower boundary; amorphous; firm; very few fine roots; a few stones; medium acid; abrupt, wavy boundary; 0-50 cm thick.
Wz	60-75	Greater than 90% ice with some streaks of organic and mineral material; 15 cm thick.
BCz + Obz	75-100+	Dark greyish brown (10YR 4/2 w) clay loam, about 60 per cent ice; some brownish streaks of organic matter and particulate organic remains; 5 per cent gravel.

Site 4: Satah River (67°07′N, 134°17′W)

This cryoturbated permafrost soil is located on a gently undulating plain with imperfect to poor drainage. It is developed in a moderately fine textured, calcareous till and has poor internal drainage. Microrelief is low on the organic surface

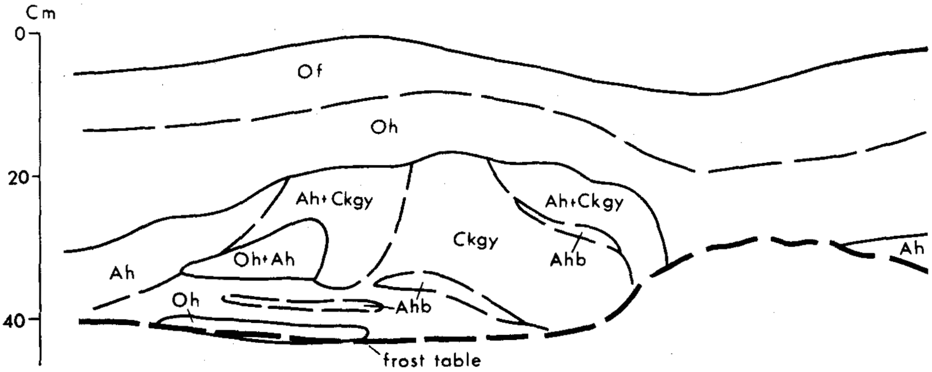

FIG. 4. Section through the poorly-drained Satah River soil (Site 4). Note the thick Oh horizon and the presence of irregular organic rich inclusions.

but up to 20 cm on the mineral surface (Fig. 4). The site is situated on a 1 per cent slope to the south at an elevation of about 100 m. The vegetation consists of an open stand of black spruce with some tamarack; dwarf birch with minor willow forms a continuous fairly dense high shrub layer; low shrubs include Labrador tea (two species), blueberry, bog cranberry, alpine bearberry and leather leaf; feather mosses form a continuous ground cover with minor amounts of lichens and patches of sphagnum mosses.

Horizon	*Depth (cm)*	*Description*
Of	25-15	Dark reddish brown (5YR 2/2 m) fibric forest peat; abundant, fine random and medium horizontal roots; strongly acid; lower 2-3 cm of this horizon are somewhat more humified; clear, wavy boundary; 5-15 cm thick.
Oh	15-0	Black (5YR 2/1 m) humic organic layer; few to plentiful fine vertical roots; often in felted masses; somewhat friable; neutral; abrupt, wavy boundary; 10-25 cm thick.
Ah	0-5	Black to very dark grey (10YR 2/1-3/1 m) clay loam; amorphous; firm, sticky; neutral; abrupt to gradual, irregular boundaries; 0-5 cm thick. This horizon may include streaks of pure organic material (Ob) and is often mixed with adjacent mineral horizons (Ckgy) due to cryoturbation processes.
Ckgy	5-15+	Dark grey (10YR 4/1 m) clay loam; often tending to olive grey (5Y 4/2 m); common, fine, prominent yellowish brown (10YR 5/6 m) mottles; amorphous to weak fine granular; firm, very sticky; often intermixed with lenses of Ah or Oh material; moderately effervescent; frozen at depths of 20-50 cm from the surface.

Temperature: 30 July 1971: 10 cm, 3.5°C; 20 cm, 2°C; 30 cm, 1°C; frozen at 42 cm.

Analytical methods

Samples from representative horizons were air-dried, and the less-than-2 mm portion was stored for analysis. Soil pH was measured using 1:2 soil, 0.01 M calcium chloride solution (Peech 1965). Total carbon was determined using induction furnace techniques, calcium carbonate equivalent by a calcimeter method (Bascomb 1961) and nitrogen by the Kjeldahl procedure (A.O.A.C. 1955). Cation exchange capacity was determined by the ammonium acetate pH 7 method and by a neutral salt method (Clark *et al.* 1966), and exchangeable cations from the ammonium acetate extract by atomic absorption spectrophotometry. Distribution of particle size was determined by a pipette method (Toogood and Peters 1953).

Iron and aluminium were extracted by pyrophosphate and oxalate procedures (McKeague 1967).

A subsurface organic sample from below the frost table at the Road River site was submitted to the Radiocarbon Laboratory of the Geological Survey of Canada for C^{14} dating.

RESULTS AND DISCUSSIONS

Soil features

The most obvious break in soil characteristics, reflected by the profile descriptions, comes between the coarse textured, freely drained soils not affected by permafrost (Site 1) and the medium- to fine-textured materials which have restricted internal drainage and irregular surface morphology directly related to the presence of permanently frozen ground (Sites 2, 3 and 4).

Well-drained sandy and gravelly soils typically have no permafrost, or else it is present at such a depth as not to be a factor in pedogenic soil development. The morphology, with its whitish eluviated Ae horizon and reddish, weakly-structured Bm horizon, indicates that podzolic processes are active. Substantiating evidence is provided by the chemical data (Table 3) which show acid reactions, low base saturation, and slight accumulation of amorphous iron and aluminium in the B horizon. An important variation, where there is little if any Ae development, tends to occur in slightly less well-drained landscape units and particularly near the tree line.

The vast majority of soils in the study area are those affected by permafrost. A striking feature of the finer textured soils is the development of a hummocky or undulating microrelief (Figs. 2, 3 and 4). Earth hummocks (Washburn 1956) are well documented in the tundra environment (Mackay, Mathews and MacNeish

TABLE 3. Chemical and physical data for the major soil horizons

			Particle-size distribution of <2 mm fraction (wt. %)							
	Horizon	Depth (cm)	sand 2.05	silt 0.5–0.002	clay 0.002	U.S. Dept. of Agriculture texture	Calcium carbonate equiv. %	pH 0.01M Calcium chloride	Organic carbon %	Carbon: nitrogen ratio
Site 1; Grandview North										
	Ae	0–4	68	30	2	SL	—	5.3	0.8	19
	Bm1	4–20	76	14	10	SL	—	5.3	0.4	22
	Ck	45–55+	89	8	3	S	15	7.2	—	—
Site 2; Arctic Red River 2										
	Of	10–2	—				—	4.0	39.8	28
	BMy	0–10	26	46	28	CL	—	4.7	2.3	15
	BCy	10–30	27	48	25	L	2	7.0	1.6	—
	BCkz	75–80+	34	46	20	L	5	7.2	—	—
Site 3; Road River										
	Of1	10–2					—	3.6	36.2	40
	Om	variable					—	3.3	40.2	29
	Ahy	variable					—	4.0	6.7	—
	Bmy1	variable	19	48	33	CL	—	4.5	4.2	21
	Bmy2	variable	21	47	32	CL	—	4.5	4.0	21
	BCy	variable	20	50	30	CL	—	4.7	3.2	20
	BCy	75–100+						6.2	12.2	—
Site 4; Satah River										
	Of	20–10					—	5.4	42.2	14
	Oh	10–0						6.5	38.0	21
	Ah	variable	29	39	32	CL	2	7.1	6.6	19
	Ckgy		30	40	30	CL	16	7.4	—	—

1961; Ivanova 1963; Day and Rice 1964) and in the forest tundra and frozen taiga soils of Siberia (Karavayeva *et al.* 1965). In the presence of adequate moisture, hummock development becomes more pronounced as silt and clay content increases (Zoltai and Pettapiece 1973). This suggests correlation with water holding capacity which is consistent with soil physics considerations (Williams 1967). It was noted that shape of the hummocks also varied with texture (Zoltai and Pettapiece 1973). For a medium texture, such as clay loam, maximum hummock development occurs under imperfect to poor drainage, that is, at moisture contents near saturation, with the drainage extremes generally exhibiting less microrelief (Zoltai and Pettapiece 1973). A comparison of Site 4 (poorly drained) to Sites 2 and 3 illustrates this effect.

Cryic processes affect internal as well as external morphology. Sites 2, 3 and 4 all exhibit marked signs of cryoturbation with Site 3 (Fig. 3) having the most complicated horizon arrangement. It appears that internal drainage controls cryic processes within the soil body in a comparable manner to that of external drainage on hummock development. Again, moisture contents near saturation appear to result in maximal disturbance with the drainage extremes being less affected.

One of the more obvious features related to drainage is the range in development and distribution of the organic horizon. All the permafrost soils typically have a raw surface layer of reddish brown fibric "forest peat" (Of) which ranges up to 20 cm in thickness under mature forests. This horizon, associated with the relatively dry or raised surfaces (ombrotrophic), contains a high content of shrub roots and is usually extremely acidic (Table 3). The lower, blackish, mesic or humic (Om or Oh) layers are associated with more humid conditions and it is with these horizons that variations reflecting drainage are particularly apparent. Note, for example, the Arctic Red River site (Site 2) which has only a thin discontinuous Oh layer in the moderately well-drained portion of the soil body (Fig. 2) with an

TABLE 3. (continuation)

Exchangeable cations meq/100 g				Cation exch. capacity meq/100 g		pH dep. charge meq/100 g	% Base saturation		Extractable iron and aluminium (%)			
									Oxalate		Pyrophosphate	
Calcium	Manganese	Potassium	Sodium	pH7	neutral salt		pH7	neutral salt	iron	aluminium	iron	aluminium
Site 1												
0.9	0.05	0.05	0.03	4.9	2.5	2.4	21	100	0.10	0.06	0.03	0.04
0.8	0.10	0.05	0.03	7.0	4.4	2.6	14	100	0.25	0.19	0.06	0.13
—	—	—	—	2.2	—	—	100		0.13	0.04		
Site 2												
16.4	6.7	1.3	0.3	127			19					
8.3	4.8	0.3	0.1	25.2	13.4	11.8	65	100	0.78	0.23	0.30	0.17
17.0	4.5	0.2	0.1	19.7			100		0.43	0.13	0.08	0.09
—	—	—	—	9.2			100		0.44	0.11		
Site 3												
7.8	4.1	1.5	0.2	70.2			20					
9.4	4.1	0.6	0.4	102			14					
4.4	1.1	0.2	tr	29.5	24.8	4.7	19	88				
7.5	1.6	0.1	tr	23.0	16.1	6.9	40	99	1.69	0.23	0.81	0.26
8.8	2.0	0.1	tr	22.0	13.8	8.2	45	99	0.98	0.23	0.60	0.26
9.4	2.0	0.2	0.1	20.0	10.9	9.1	58	100	0.84	0.16	0.27	0.22
38.0	5.1	0.2	0.1	49.3			88					
Site 4												
51.6	1.0	1.0	0.3	128			42					
130	11.5	0.1	0.1	151			94					
35.9	8.0	0.1	0.1	41.1			100					
—	—	—	—	14.0			100					

Om layer confined to the poorly-drained portion of the profile. A similar kind of distribution may be noted for the Road River soil (Fig. 3) although imperfectly-drained soils characteristically have thin Om horizons over the entire mineral element. The poorly-drained Satah River soil (Fig. 4) on the other hand has a thick, continuous well-humified (Oh) organic layer beneath the fibric surface material. The thickness, colour and continuity are typical of poorly-drained sites. However, degree of humification, reaction, and structure and consistence may range widely among soils of the same drainage class. The presence of calcium carbonate is a major factor contributing to these variables. A near-neutral pH and the presence of calcium are favourable for the breakdown and mineralization of organic materials, with the more strongly acidic, organic layers being generally less humified.

Another very important feature of the permafrost soils is the presence of subsurface organic materials (Figs. 2, 3 and 4). This phenomenon is well documented in the Siberian taiga (Ivanova 1963; Dimo 1965), but in North America such observations have been confined until quite recently to the tundra setting (Washburn 1956; Mackay 1958; Tedrow 1965; Zoltai and Pettapiece 1973). There are three types of occurrence involved: (1) small isolated inclusions of organic material; (2) subsurface organic layers, usually continuous with material in the interhummock depressions; and (3) the presence of relatively large amounts of low-molecular-weight, mobile humic and fulvic acids.

The first type may be distributed throughout the active layer, associated with the base of the active layer, or both. The diagram of the poorly-drained Satah River soil (Fig. 4) illustrates this type. It is one of the first signs of cryoturbic activity and is commonly associated with soils at the southern reaches of the permafrost zone (Tarnocai, personal communication). Washburn (1968) reported the common occurrence of this type in the High Arctic in Greenland as well, and Brown (1969) has associated these features with ice-wedge activity on the Alaskan North Slope.

The second type appears to be consistently associated with the permafrost table. As a result of studies beyond tree line, various hypotheses have been put forward as to its origin. Tedrow (1965) associates this feature with poor drainage and frost action. Mackay (1958) and Mackay, Mathews and MacNeish (1961) suggest that the presence of a continuous subsurface organic layer is a result of progressive burial by frost-thrusting of organic material in the troughs, hummock-slumping during thaw and particularly by the downslope migration of earth hummocks. It seems probable that several interrelated factors are involved, with the dominance of any one dependent on local conditions such as soil texture, drainage or slope.

The third type, the low-molecular-weight organic acids, may be distributed throughout the active layer and are probably responsible for much of the soil colour. Common reference to this component is made in the Russian literature (Karavayeva and Targul'yan 1960; Ivanova 1963), where it is suggested that the mobility and distribution of the organic acids is governed to a significant extent by freezing phenomena, such as migration of moisture to a freezing front. This, combined with cryogenic activity, often results in a somewhat variegated soil appearance (note Fig. 3 and description of the Road River soil). Another controlling factor is the soil reaction. A strongly acid environment is conducive to both the persistence and mobility of these organic acids, while a neutral pH and the presence of excess calcium drastically curtails these attributes (Kononova 1966). A comparison of the BC horizons of the Arctic Red River and Road River soils (Table 3) illustrates this effect. As much as 3 per cent organic carbon may be present in this form in horizons where its presence is not at all obvious (BC horizons). Besides its apparent influence on colour, the soluble organic fraction is commonly associated with a high pH-dependent charge, a strongly acid reaction and high amounts of extractable iron and aluminium (Table 3). In fact, the aluminium is almost entirely bound up with the organic fraction (pyrophosphate extraction).

Root distribution is also an important pedogenic factor. Governed by temperature and moisture, roots are confined principally to the organic layers. This is particularly true for the larger (> 2 mm) roots, which in the better-drained sites show a definite preference for the hummock shoulders and sides. Cryoturbic activity may also be involved in restricting the distribution of large roots, and the combined effect of all factors has a controlling influence on tree distribution (Zoltai and Pettapiece 1974). The fine roots tend to be more evenly distributed over the hummock element. They may penetrate for 15 cm or more into the mineral material, and the best soil-structure development is associated with the highest concentration of roots. In the Road River and Arctic Red River profiles the imperfectly and moderately-well-drained elements have surface horizon structures which grade from strong fine granular to strong medium subangular blocky (Bm horizons). These grade to amorphous, firm, brownish or greyish horizons (BC horizons) with few roots. Because colour gradation may be weak, horizon separations are often made on these structural differences.

The Satah River soil does not have the marked microsite variations expressed in the other profiles, and the distribution of roots in this poorly drained, cold soil is more uniform and quite shallow. Bm horizons are typically absent in poorly-drained soils, although Bg horizons may occur and, in calcareous soils, granular Ah horizons may be present.

The lower portion of the active layer, the saturated zone immediately above the permafrost table, often has a plate-like structure due to ice lensing. This horizon, which is best expressed in the imperfectly-moderately-well-drained soils, is occasionally not encountered until the depth of thaw is approaching its maximum extent. Here mottling is most strongly expressed, although the upper BC horizons commonly have some mottling as well. In the cold northern environment the potential for oxidation and reduction is low, and it is only where large changes in moisture, and presumably in redox potential, occur that mottling from gleization processes is exhibited.

Soil formation and classification

Well-drained, coarse-textured soils exhibit podzolic features and support vegetation indicative of a soil climate comparable to the more southern boreal regions. It follows then that the pedogenic processes should also be similar. Podzolic features and processes have been reported even into the area beyond tree line (Tedrow and Cantlon 1958; Kuzmin and Sazonov 1965). However, they are only weakly expressed and have a restricted distribution. The brownish soils with no visible Ae would seem to correspond to the brown, non-differentiated, non-gleyed soils of the Russian literature (Karavayeva *et al.* 1965) and the Arctic Brown of Tedrow (Tedrow and Hill 1955).

In the case of the finer-textured soils with permafrost and impeded drainage, the soil features indicate not simply a weakening of classical processes but an abrupt change in the kinds of processes as well. The most obvious new phenomenon is cryoturbation which is intimately involved with soil formation and must be considered a pedological process. Two aspects are involved. First is the formation or establishment of earth hummocks and associated depressions, for it is with reference to this cyclic soil body that all other processes must be compared and judged. Mackay (1958) has suggested that these hummocks may maintain their identity for long periods of time. A radiocarbon date of 1960 ± 60 years (G.S.C. 1804) from the BC horizon of the Road River soil and other dates for subsurface organic materials ranging from 1500 to 3200 years BP (Pettapiece and Zoltai 1974) all imply some degree of morphological stability. This does not, however, preclude the second aspect of cryoturbation — the cryogenic mixing of soil materials, both mineral and organic, within such established microtopographical elements. In medium- and fine-textured soils with suitable moisture conditions, which are met in most permafrost situations, these processes dominate all others.

The cyclic nature of the cryoturbated soils associated with hummock development poses many special problems. A major concern is the question of what should be considered as the natural soil body. There is a wide variation in soil properties between the depressions and the hummock. Should such divergent characters be considered parts of a single body or are they separate soils? The answer to this is of paramount importance to soil classification and, although not as critical, it has a bearing on the approach used to study, describe and sample these soils as well.

It is apparent that the major external features of the microrelief formed contemporaneously. Certainly, subsequent pedological processes differed from one element to another and, particularly in the better-drained units, marked lateral variations were often developed. However, even in the extreme cases, it is difficult to consider one portion of the hummock-trough complex without reference to the other and there are features such as the subsurface organic horizon which serve to further bind all the parts together. These considerations along with that of soil as a three-dimensional body and the concept of the pedon (Johnson 1963; Knox 1965) suggest that it is valid to view the complete cycle as a single individual. This has also been concluded by Karavayeva *et al.* (1965) who indicate the need to examine the profile as a regular alternation of genetic horizons in the horizontal as well as vertical direction.

From a classification standpoint the problem is analogous to that of grumic soils or Vertisols (Soil Survey Staff 1960), another instance where soil development is greatly influenced by a disrupting physical process. These soils are recognized at the Order level in all major classification schemes (FAO/UNESCO 1968); however, only the Russian pedologists (Rozov and Ivanova 1968) separate permafrost soils and those affected by cryoturbation at the highest level of abstraction. The Canadian system (C.S.S.C. 1970) can only be applied to segments of the cyclic natural soil body, which makes its applications awkward and its meanings obscure. Drew and Tedrow (1962) suggest that concepts developed in temperate regions are often difficult to apply in the Arctic, and that it may be necessary to integrate microrelief into any classification scheme.

Another concept commonly used in regard to soils is that of zonation or zonality. Tedrow and Cantlon (1958) suggested that only well-drained soils should be considered in the application of the term, and warned against confusing it with regional dominance. According to this concept, zonal soils in the Arctic would be confined to coarse-textured materials, and all soils having impeded drainage due to fine texture, topographical location or permafrost would be classed as Azonal, similar to the gley soils of more temperate regions. However, Karavayeva *et al.* (1965) suggest that the earth hummock soils (called suprapermafrost glei) since they are developed in medium-textured materials and cover all the landscape elements, should be considered Zonal (Ugolini, 1966). The fact that the poor drainage is induced by permafrost (a zonal characteristic) and that the elevated elements of the microrelief are not excessively wet for extended periods supports the latter argument, as does the fact that the "Zonal" vegetation is associated with these soils and not the excessively-drained types. This line of reasoning can be applied with equal facility in the subarctic region where the disparities with texture and drainage are even more obvious and suggest that permafrost-affected soils should be considered at a high level in any classification system.

CONCLUSIONS

The results and discussion suggest the following conclusions about subarctic soils:

1. Well-drained, coarse-textured soils have features similar to those of more southerly areas.
2. Nearly all the medium- and fine-textured soils in this region are affected by permafrost and cryoturbation — a much larger extent than was previously thought.
3. There is an abrupt break in soil character associated with earth hummock development. This includes:
   (a) hummocky microrelief,
   (b) cryoturbation which is most pronounced in imperfectly-poorly-drained situations, and
   (c) organic material present as turned-under or buried layers and as mobile organic acids.
4. There is need for re-evaluation of traditional concepts of soil development and classification when dealing with cryoturbated ("tundra") soils with permafrost.
5. The pedon concept, which can recognize a cyclic soil body, is basic to the classification and interpretation of these soils.
6. Classification of cryoturbated permafrost soils should be considered at the Order level (see Appendix 2).

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APPENDIX 1: Notes on horizon nomenclature

The horizon descriptions for the cryoturbated soils are intended to cover the whole pedon and not simply a single vertical slice, so the associated diagrams (Figs. 2-4) need to be used as reference for a complete understanding of horizon distribution.

L-H: an organic layer formed mainly from leaves, twigs and woody materials under generally well-drained conditions.

O: an organic layer formed largely from mosses or sedges under generally wet conditions. They may be fibric (f), mesic (m) or humic (h), depending upon the amount of fibre present.

A: a surface mineral horizon characterized by the accumulation of organic material (Ah) or the eluviation of mobile constituents (Ae).

Bm: a mineral horizon slightly altered by hydrolysis, oxidation, solution or accumulation to give a change in colour or structure.

C: a mineral horizon deemed to be the unaltered parent material.

BC: a transition horizon in the lower part of the solum.

g: a horizon characterized by dull colours or prominent mottling indicative of permanent or periodic reduction. Associated with wetness.

k: denotes the presence of carbonates as indicated by effervescence when treated with dilute hydrochloric acid.

z: a frozen layer. When used with W (Wz) it means ice.

y: a horizon affected by cryoturbation as manifested by disrupted and broken horizons, incorporation of materials from other horizons, and mechanical sorting.

Colours are indicated in accordance with the Munsell system.

APPENDIX 2: Classification of Cryosols

Since submission of the paper, the Canada Soil Survey Committee has issued a tentative classification proposal to accommodate all soils having permafrost within 1 m of the surface (Cryosols). Great Group subdivisions are based on amount of cryoturbation (Turbic vs Static) or kind of material (Organo). Subgroup separations recognize internal features such as horizon development, wetness and character of organic material.

Tentative classification system:

Order	*Great Group*	*Subgroup*
Cryosolic	Turbic Cryosol	Brunisolic
		Regosolic
		Gleysolic
	Static Cryosol	Brunisolic
		Regosolic
		Gleysolic
	Organo Cryosol	Fibric
		Mesic
		Humic

For correlative purposes a comparison of Canadian, American, Russian and world classifications is set out in Table 4.

TABLE 4. A comparison of various classification systems

Classification*	Grandview North (Site 1)	Arctic Red River 2 (Site 2)	Road River (Site 3)	Satah River (Site 4)
Canadian 1	Degraded Eutric Brunisol	Cryic Eutric Brunisol	Cryic Orthic Regosol	Cryic Peaty Gleysol
Canadian 2	Degraded Eutric Brunisol	Brunisolic Turbic Cryosol	Regosolic Turbic Cryosol	Gleysolic Turbic Cryosol
American	Boralfic Cryochrept	Ruptic-Histic Pergelic Cryaquept	Ruptic-Histic Pergelic Cryaquept	Histic Pergelic Cryaquent
Russian	Podzolic Illuvial-Ferruginous	Cryogenic Taiga-glei	Cryogenic Taiga-glei	Cryogenic Taiga peaty-glei
World	Eutric Cambisol	Tundric Eutric Cambisol	Tundric Eutric Cambisol	Tundric Eutric Gleysol

*Classifications are from the following sources:
Canadian 1: C.S.S.C. 1970
Canadian 2: the proposed system (C.S.S.C. 1973)
American: 7th approximation (Soil Survey Staff 1960 and supplements)
Russian: Ivanova 1963
World: Reported in C.S.S.C. 1970