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A Comparison of some Upland and Valley Soils in the Ungava-Labrador Peninsula
Comparaison de quelques sols des montagnes et des vallées de la péninsule d'Ungava-Labrador
Ein Vergleich des Bodens einiger Berge und Täler der Halbinsel von Ungava-Labrador

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See table of contents

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Article abstract

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A COMPARISON OF SOME UPLAND AND VALLEY SOILS IN THE UNGAVA-LABRADOR PENINSULA

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ABSTRACT Thirteen soil profiles from northern Québec and Labrador, Canada, near the northern tree-line, were sampled and analysed. Five of these, located on poorly to imperfectly drained sites, are strongly cryoturbated soils with permafrost at a shallow depth. Below the surface horizon they have very uniform profile distributions of pH, carbon and extractable iron and aluminum due to the active mixing of the horizons. The eight soils from well-drained sites have profiles similar to those of soils in similar settings in more temperate climatic regions. One of these, developed in one of the most northerly valleys having a black spruce-larch forest vegetation, has the characteristics of a podzol (spodosol) except that the podzolic B (spodic) horizon is too thin. The other seven profiles all have color B horizons, although the coarse texture prevents their classification as cambic horizons; these soils all have carbon-rich A horizons varying in thickness from 1.5 to 20 cm. Soil temperature at 50 cm depth closely follows the elevational and latitudinal distribution of the soils; a range of 0 to 10° C was observed. Soil development, measured as depth of solum, organic carbon accumulation or degree of B horizon development, is closely related to soil temperature and site position. The presence of permanently frozen ice layers at shallow depth has a marked influence on soil genesis and the properties of the resultant soils.

RÉSUMÉ *Comparaison de quelques sols des montagnes et des vallées de la péninsule d'Ungava-Labrador.* Treize profils de sols provenant du Nouveau-Québec et du Labrador, près de la limite septentrionale des arbres, furent échantillonnés et analysés. Aux endroits mal drainés, cinq de ces profils sont fortement cryoturbés et se caractérisent par la présence du pergélisol à de faibles profondeurs. Sous la surface, le brassage des horizons associé à la cryoturbation tend à uniformiser la distribution verticale du pH, du carbone, et du fer et de l'aluminium extractibles. Les huit sols bien drainés possèdent des profils comparables à ceux qui se développent sur des sites bien drainés des régions plus tempérées. Un de ces sols sous couvert forestier, développé dans une des dernières vallées au nord a toutes les caractéristiques d'un podzol (spodosol) si ce n'est que l'horizon B podzolique (spodique) est trop mince. Les sept autres sols ont des horizons B identifiables par leur couleur; tous ces sols ont des horizons A riches en carbone dont l'épaisseur varie entre 1,5 et 20 cm. Il existe une étroite relation entre la température des sols à 50 cm de profondeur et la distribution altitudinale et latitudinale de ces sols; des températures variant entre 0° et 10°C ont été enregistrées. Il semble également exister une relation entre le développement pédogénétique et la température des sols ainsi que la position des sites. La présence de couches de glace, à faible profondeur, influence la pédogénèse et les différentes propriétés des sols qui en résultent.

ZUSAMMENFASSUNG *Ein Vergleich des Bodens einiger Berge und Täler der Halbinsel von Ungava-Labrador.* Von dreizehn Boden-Profilen von Nord-Quebec und Labrador, Kanada, nahe der nördlichen Baumgrenze wurden entnommene Proben analysiert. Davon sind fünf, die von schlecht dränierten Geländen stammen, stark kryoturbatisch und zeichnen sich durch das Vorkommen von Dauerfrost in geringen Tiefen aus. Unter der Oberfläche führt die Verknetung der Horizonte in Verbindung mit der Kryoturbation zu einer gleichmäßigen vertikalen Verteilung der Säure, des Kohlenstoffs und des gewinnbaren Eisens und Aluminiums. Die acht gut dränierten Böden besitzen Profile, die mit denen der gut dränierten Böden der mehr gemäßigten Gebiete vergleichbar sind. Einer dieser Böden, der sich in einem der letzten bewaldeten Täler im Norden entwickelt hat, besitzt alle Eigenschaften eines Podsol, außer daß der podsolige B-Horizont zu dünn ist. Die sieben anderen Böden haben alle B-Horizonte, identifiziert durch ihre Farben; all diese Böden besitzen an Kohlenstoff reiche A-Horizonte, deren Dicke zwischen 1,5 und 20 cm variiert. Es besteht eine enge Beziehung zwischen der Bodentemperatur in 50 cm Tiefe und der Höhen- und Breiten-Verteilung dieser Böden; Temperaturen zwischen 0°C und 10°C wurden registriert. Eine Beziehung scheint auch zu bestehen zwischen der bodengenetischen Entwicklung und der Temperatur der Böden sowie der Lage der Vorkommen. Das Vorhandensein von Eisschichten in mäßiger Tiefe beeinflußt die Bodenentwicklung und die verschiedenen Eigenschaften der Böden, die sich hieraus ergeben.

INTRODUCTION

In mid-July, 1982, a project was undertaken to study the distribution of pollen with depth in soils of northern Québec and Labrador. The movement of pollen was expected to be linked to the processes of soil profile formation; therefore the study was designed to include detailed pedological description and sampling. In part the study was intended to reveal whether there is a substantial age difference between the summits and valley positions, as would be the case if the former were exposed as nunataks during the last continental glaciation. To respond to this problem the sampling sites were chosen in two contrasting landscape positions: in blockfields or felsenmeer, located at high elevation, and in moraines and associated ice-contact deposits, located in the valleys.

The sites were therefore chosen for their value in the geomorphic-palynological study rather than for their importance as representative soil-landscape units. Despite the strong bias in the choice of the sampling sites, the study provides an interesting overview of the range of soil development caused by variations in latitude, elevation, climate and site position. The soils of the blockfields are all poorly drained, strongly cryoturbated profiles, in contrast to the relatively stable, well drained sites within the valleys.

The study was undertaken by helicopter; there were severe limitations imposed by the amount of helicopter time available and uncertain weather conditions. On average we had about 1 ½ hours per site, which is enough time to dig a good soil pit, fill in an abbreviated soil profile description form and collect samples. Unfortunately there was not enough time available to dig through frozen soil horizons, nor to describe and sample the complete variation in horizon sequence found in the cryoturbated profiles. In each situation a profile was chosen that best represented the site; when a choice had to be made between one that showed a non-cryoturbated horizon sequence or a strongly cryoturbated one, the former was selected as being more useful to the pollen profile study.

The area covered by the survey is located in the interior of the Ungava-Labrador Peninsula (Fig. 1); there are no published reports on the soils. The interior is almost completely uninhabited and therefore not exploited directly by man. Indirectly, however, the soils of the region play an important role in the subsistence economy of the Inuit; the region is both a feeding-ground for caribou and the headwaters of rivers where important fish species breed and pass the first part of their lives. The impact of man on the soils could have far-reaching implications for the people of the north. Although development is unlikely, some of the anthropogenic changes in the atmosphere may effect even this remote area. The soils are very acidic and, even though acid precipitation may not have an immediate effect on the soil pH or on the vegetation, it can be expected to result in an acidification of the very weakly buffered lakes and streams. In addition, increased aluminum leaching from the soils could have a detrimental effect on fish populations, as has been observed in Scandinavia and further south in Canada and the United States (OVERREIN *et al.*, 1980).

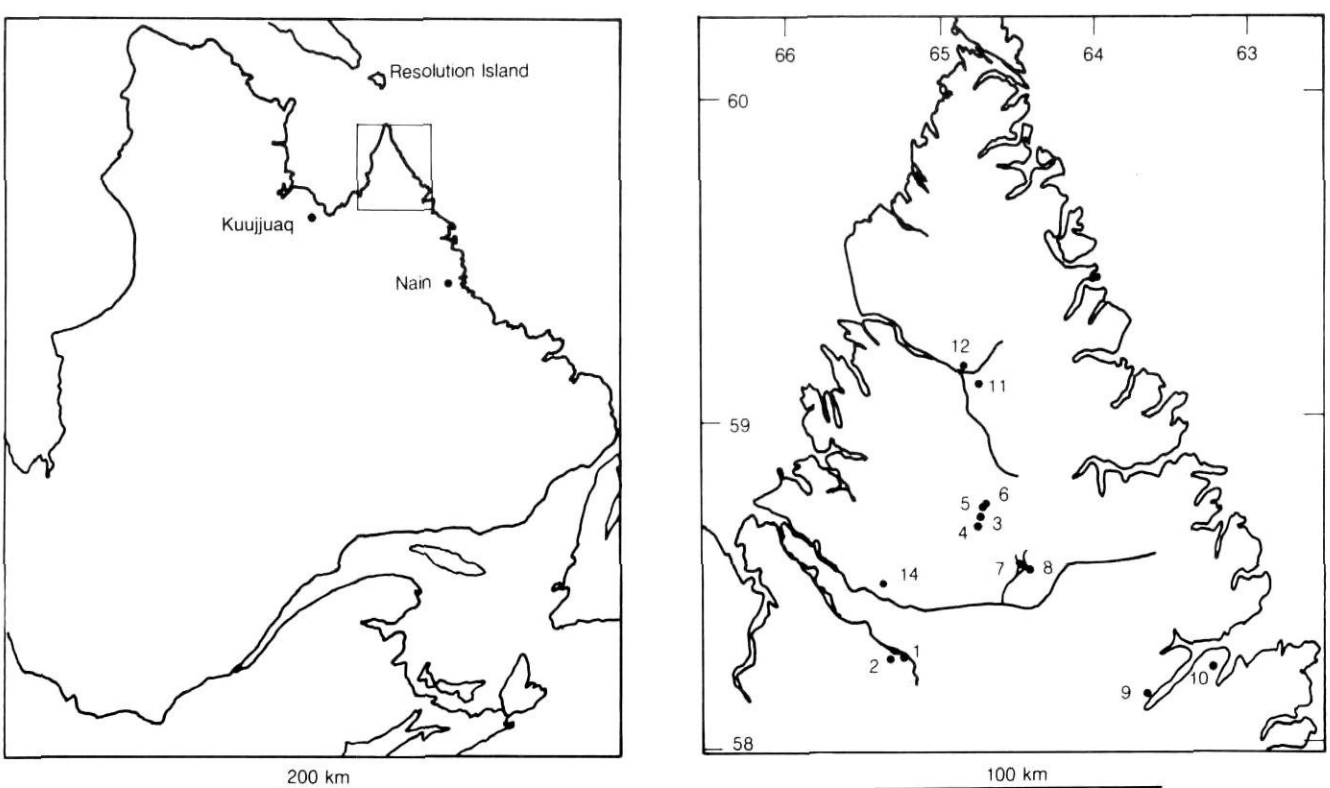

FIGURE 1. Location of the study sites.

Localisation des sites étudiés.

MATERIALS AND METHODS

Soil profile descriptions were made using the CanSIS manual as a reference (CANADA SOIL SURVEY COMMITTEE, 1978a). Only a limited number of observations were recorded in the field: soil horizons, depth, moist color of the matrix and mottles of mottled soils, structure, roots, percentage of gravel, boundary , plus any remarkable features. In addition, soil temperature was measured with a dial-type thermometer at 50 cm below the soil surface or at the bottom of the soil pit when it was shallower than 50 cm. Site information includes altitude, parent material, landform, slope and aspect, and both internal and external drainage.

Immediately on arrival in the laboratory, moist soil color was measured on crushed peds; the soils were then dried and dry-color determined. All samples were passed through a 2 mm sieve and the fine-earth fraction was used in all subsequent analyses. Particle size analysis was performed using the pipette method of FOLK (1980) after the removal of organic matter with sodium hypochlorite bleach (LAVKULICH and WIENS, 1970). Total organic carbon was measured by the Walkley-Black wet-oxidation method (ALLISON, 1965). Total nitrogen was determined by acid digestion and colorimetry (HENDERSHOT, 1984). Exchangeable bases and aluminum were measured after displacement with 0.1 *M* $BaCl_2$; CEC was taken as the total of Na^+, K^+, Ca^{2+}, Mg^{2+}, and Al^{3+}, and base saturation was calculated as the sum of the bases divided by the CEC times 100 (HENDERSHOT, 1984). Soil pH was determined in 0,01 *M* $CaCl_2$ with soil-to-solution ratio of 1:2 for mineral and 1:4 for organic horizons (McKEAGUE, 1978). Extractable iron, aluminum and manganese were determined on samples ground to < 0.15 mm by three methods: 1) sodium pyrophosphate, to extract organically complexed forms; 2) acid ammonium oxalate, to extract amorphous inorganic and organic forms; and 3) sodium citrate, bicarbonate, dithionite, to extract crystalline iron oxides in addition to amorphous iron and aluminum (McKEAGUE, 1978).

CLIMATE AND VEGETATION

The closest weather stations to the study area are at Kuujjuaq, Nain and Resolution Island (Fig. 1). Climatic data are presented on Table I. The average annual temperature is below zero for all three; in the study area, the mean monthly temperature is probably above freezing for the months of June through September. About half the precipitation received falls as snow; the maximum precipitation falls as rain during the months of July, August, and September. The study area is situated at a higher elevation and farther from the coast than the weather stations; therefore the climate is probably significantly colder than at either Kuujjuaq or Nain and, due to the adiabatic effect, wetter than at either Kuujjuaq or Resolution Island.

According to TARNOCAI (1978), the region is described as having a Low Arctic Climate; it has an extremely cold soil temperature regime with a mean annual soil temperature below −7°C and a mean summer soil temperature between 0 and 3°C, measured at a depth of 50 cm. The soil moisture regime is given as varying between humid (never dry 90 consecutive days) to aquic (saturated for moderately long periods). The observations made in the field generally confirm Tarnocai's statements, although the exposed mountain summit positions are colder and the more protected valley positions

TABLE I

*Climatic data**

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year	Code‡
Mean Daily temperature (°C):														
Kuujjuaq A	−23.3	−22.4	−17.7	−9.2	0.2	6.9	11.4	10.4	5.4	−0.9	−8.3	−18.4	−5.5	1
Nain	−17.0	−16.4	−11.3	−4.9	1.1	6.0	9.8	9.7	5.9	0.4	−5.3	−12.4	−2.9	8
Resolution Island†	−18.4	−19.6	−16.7	−10.8	−3.6	0.2	3.6	3.6	0.8	−3.2	−7.4	−14.2	−7.4	8
Mean Rainfall (mm):														
Kuujjuaq A	0.3	0.1	0.5	1.8	15.5	47.0	57.7	63.4	48.5	22.4	5.7	0.6	263.5	1
Nain	0.5	1.0	1.0	5.5	28.1	50.6	78.7	68.7	61.8	24.8	8.0	2.4	331.1	8
Resolution Island†	0.3	0.4	0.0	0.2	3.0	17.5	61.6	67.2	54.0	13.7	2.6	0.1	220.5	8
Mean snowfall (cm):														
Kuujjuaq A	32.8	33.8	26.8	21.7	15.3	3.6	T	0.4	8.5	27.2	35.8	39.3	245.2	1
Nain	86.9	46.9	69.5	39.6	17.8	4.5	0.0	0.0	6.2	22.3	50.7	80.0	424.4	8
Resolution Island	15.9	12.3	14.4	10.0	11.5	4.9	1.0	1.7	5.1	23.4	22.6	20.6	143.2	8
Total precipitation (cm):														
Kuujjuaq A	33.1	33.3	26.0	23.2	31.7	50.8	57.7	63.8	57.7	48.6	40.1	38.2	504.2	1
Nain	87.4	55.7	72.4	38.1	42.5	56.1	79.2	68.7	65.7	45.5	50.3	78.2	739.8	8
Resolution Island†	15.9	12.5	14.2	10.4	15.0	21.6	62.6	68.1	56.8	37.4	24.1	20.3	358.9	8

* Source: Environment Canada — *Canadian Climate Normals* 1951-1980

‡ Code 1: Complete 30 years

Code 8: Adjusted normals based on 5 to 19 years

† Average of two stations

warmer than predicted (Table II). From air temperature measurements and observations made by local pilots, the soils probably thaw out late in June (at about the same time as the lakes become ice-free) and freeze up again in late September-early October.

The extreme variation in climate, from the low lying valley at site 1 (elevation 215 m) to the mountain summit position at site 11 (1230 m), is matched by a variation in vegetation. The warmest site is in a region of black spruce-larch forest vegetation. Most of the sites located in the more northerly valley positions have a typical tundra vegetation of moss, lichen, grass and heath. The coldest sites on the mountain summit positions have only sparse vegetation composed primarily of lichen and moss; these sites in the blockfields at first appear to be devoid of both vegetation and soils. Closer inspection reveals that on perhaps 15% of the surface there are reasonably well developed soils and a thin vegetation cover.

RESULTS AND DISCUSSION

The thirteen sampling sites are shown on Figure 1 and site information is presented on Table II. A fourteenth site (site 13) is that of an organic palsen located in the valley of the Koroc River and described in MATHIEU (1984). In most cases the parent material was what would be expected for the landform; till makes up the moraines, for example. At site 12, on the other hand, the lateral moraine appeared to be covered by fluvial or glacio-fluvial material and it is in this material that the soil is developed. In order to minimize the variability between sites, level ground was chosen for the soil pit whenever possible.

SOIL MORPHOLOGY

On the basis of profile morphology the soils can be clearly divided into two distinct groups (Table III). One group is comprised of the five poorly to imperfectly drained soils of the mountain summit locations, which show signs of strong, active cryoturbation. The horizons are irregular in thickness and order with darker, more organic rich horizons located below paler material in some cases. The pedons examined are all located in what appear to be active sorted or non-sorted circles. They are considered active because in each case the centre of the circle is barren or appears to be upwelling. Strongly cryoturbated soils are very widely distributed in arctic and alpine environments where sufficient water is available (TARNOCAI, 1978; TARNOCAI and ZOLTAI, 1978; WALMSLEY and LAVKULICH, 1975a).

The second group is comprised of eight relatively well-drained soils located on till or ice-contact stratified drift located within the valleys; some of the sites are valley bottom deposits while others are located higher on the valley sides in proglacial deltas or lateral moraines. They all exhibit a degree of "normal" upland soil development, with organic matter accumulations at the surface and color B horizons due to weathering *in situ* or to weakly expressed translocation of sesquioxides. In this context a color B horizon is a horizon that is distinguished from the C horizon by a change in color, rather than the other

TABLEAU II

Site information for the soils of Ungava-Labrador

Site	Location	Lat. & Long.	Landform	Parent Material	Geliform	Elevation m	Slope & Aspect	Soil Temp. at 50 cm	Drainage	Vegetation‡
1	Lac des Moraines	58°27'N 65° 3'W	valley end moraine	till	none	215	0-0	10	well	grass, moss, sedge, dwarf birch, black spruce
2	Lac des Moraines	58°26'N 65° 8'W	summit-blockfield	diamicton†	sorted circle	915	0-0	2	imperfectly	lichen, moss
3	Grenier	58°53'N 64°36'W	summit-blockfield	diamicton	sorted circle	855	2-E	0	imperfectly	moss, lichen, grass, willow
4	Grenier	58°51'N 64°38'W	moraine-delta	glacio-fluvial	non-sorted circle	395	0-0	$4\frac{1}{2}$	well	lichen, willow, grass
5	Grenier	58°55'N 64°35'W	proglacial delta	glacio-fluvial	none	590	5-E	$5\frac{1}{2}$	well	moss, willow, lichen, heath
6	Grenier	58°56'N 64°35'W	proglacial delta	glacio-fluvial	none	545	0-0	6	well	lichen, willow, moss, grass
7	Naksarulak	58°46'N 64°18'W	lateral moraine	till	none	800	0-0	4	well	lichen, moss, heath, grass
8	Naksarulak	58°46'N 64°17'W	valley end moraine	till	none	715	5-S	5	well	moss, lichen, willow, heath
9	Saglek	58°20'N 63°35'W	lateral moraine	till	none	565	0-0	7	well	willow, lichen
10	Pinguksoak	58°25'N 63°12'W	summit-blockfield	diamicton	sorted circle	1230	2-N	1	poorly	moss, lichen, grass
11	Alluviaq	59°18'N 64°39'W	summit-blockfield	diamicton	sorted circle	1005	5-E	0 at 15 cm	poorly	moss, lichen
12	Alluviaq	59°21'N 64°45'W	lateral moraine	glacio-fluvial	none	195	0-0	4	well	lichen, grass, willow
14	Korok	58°40'N 65° 9'W	summit-blockfield	diamicton	sorted circle	620	2-NW	5 at 40 cm	poorly	moss, grass, lichen, willow

† Diamicton is used since there is a debate as to whether the matrix is derived from till or *in situ* weathering.
‡ Listed in decreasing order of abundance.

TABLEAU III

Soil classification and morphological properties

Horizon Can.	Am.	Depth cm	Color	Texture	Gravel %	Structure	Roots	Boundary
Site 1. Eluviated Dystric Brunisol (Pergelic Cryopsamment)								
LFH	0	2.5-0	N 2/0	S	0	single grain	com fine	ab sm
Ae	A2	0-6	10YR4.5/1	GS	30	single grain	—	ab sm
Bf	B21ir	6-9	5YR2.5/2	S	10	single grain	—	ab sm
Bm1	B22	9-16	10YR4/4	S	10	single grain	few fine	cl sm
Bm2	B23	16-27	10YR5/4	GS	30	massive	—	di sm
Bm3	B24	27-41	10YR5/4	GS	30	massive	—	cl sm
C1	C1	41-61	10YR6/4	GS	20	massive	—	cl sm
C2	C2	61-81	10YR6/4	GS	20	massive	—	di sm
C3	C3	81-97	10YR5/3	GS	20	massive	—	—
Site 2. Regosolic Turbic Cryosol (Pergelic Cryorthent)								
Cy1	C1	0-10	10YR3/3	SL	10	wk co prism	few fine	cl sm
Cy2	C2	10-20	10YR3/3	SL	10	wk col prism	few fine	di sm
Cy3	C3	20-40	10YR3/3	GSL	20	massive	—	gr sm
Cy4	C4	40-60	10YR3/3	GSL	40	massive	—	—
Site 3. Regosolic Turbic Cryosol (Pergelic Cryopsamment)								
Ah	A1	0-2.5	10YR2/1	S	0	single grain	com fine	ab sm
Cy1	C1	2.5-12	10YR3/3	LS	10	single grain	few fine	di sm
Cy2	C2	12-33	10YR3/2	GS	30	massive	—	di sm
Cy3	C3	33-55	10YR4/2	S	5	massive	—	di sm
Site 4. Orthic Sombric Brunisol (Pergelic Cryopsamment)								
LFH	0	5-0	10YR2/2				com fine	ab sm
Ah	A1	0-10	10YR2/2	S	5	wk med gran	com fine	cl br
Bm1	B21	10-20	10YR3/2	S	5	wk med gran	com fine	cl br
Bm2	B22	20-35	10YR3/3	S	5	massive	few fine	cl sm
C1	C1	35-55	10YR3/2	S	10	massive	—	di sm
C2	C2	55-75	10YR4/3	S	10	massive	—	cl sm
C3	C3	75-95	10YR4/2	S	5	massive	—	—
Site 5. Orthic Sombric Brunisol (Pergelic Cryumbrept)								
Ah1	A11	0-5	10YR2/1	LS	0	wk fine gran	com fine	ab sm
Ah2	A12	5-12	10YR2/2	LS	5	wk fine gran	few fine	ab sm
Ah3	A13	12-20	10YR2/1	GLS	30	wk med gran	few fine	ab sm
Bm	B2	20-40	10YR2/2	VGS	70	single grain	few fine	di sm
C1	C1	40-60	10YR2/2	VGS	80	single grain	—	di sm
C2	C2	60-70	10YR2/2	VGS	80	single grain	—	—
Site 6. Orthic Sombric Brunisol (Pergelic Cryorthent)								
LFH	0	1.5-0	10YR2/1					
Ah1	A11	0-10	10YR2.5/1	GS	30	wk fine sbk	ab fine & med	ab sm
Ah2	A12	10-20	5YR2.5/1	GS	30	wk fine sbk	ab fine & med	gr sm
Bm1	B21	20-30	7.5YR3/3	VGS	50	single grain	ab fine	cl sm
Bm2	B22	30-40	10YR3/3	VGS	60	single grain	com fine	gr sm
C1	C1	40-60	10YR3/3	VGS	60	single grain	—	di sm
C2	C2	60-80	10YR4/3	VGS	60	single grain	—	—
Site 7. Orthic Dystric Brunisol (Pergelic Cryopsamment)								
Ah1	A11	0-1	10YR2/1	S	15	wk med gran	ab fine	ab sm
Ah2	A12	1-4	10YR2/1	GS	25	wk med gran	ab fine	ab sm
Bm	B2	4-15	5YR2.5/2	S	10	massive	com fine	ab sm
BC	B3	15-26	2.5Y4/3	GS	20	massive	few fine	di sm
C1	C1	26-46	2.5Y4/2	GLS	30	massive	few fine	di sm
C2	C2	46-66	2.5Y4/2	GLS	30	massive	—	di sm
C3	C3	66-81	2.5Y4/3	GLS	30	massive	—	—

Horizon Can.	Am.	Depth cm	Color	Texture	Gravel %	Structure	Roots	Boundary
	Site 8. Orthic Dystric Brunisol (Pergelic Cryopsamment)							
Ah	A1	0-1.5	10YR2/1	LS	0	massive	few fine	ab sm
Bm1	B21	1.5-10	7.5YR2/2	LS	5	massive	com fine	cl wa
Bm2	B22	10-20	10YR3/2	LS	5	wk med sbk	—	ab sm
C1	C1	20-38	10YR3/3	LS	5	wk fine sbk	—	di sm
C2	C2	38-55	10YR4/2	LS	5	single grain	—	—
	Site 9. Orthic Sombric Brunisol (Pergelic Cryorthent)							
Ah1	A11	0-10	10YR3/2	GS	20	single grain	few fine	cl sm
Ah2	A12	10-20	10YR2/1	GS	40	wk med gran	few fine	cl sm
Bm	B2	20-30	10YR3/4	GS	40	wk med gran	few fine	gr sm
C1	C1	30-50	10YR5/4	GLS	20	massive	few fine	di sm
C2	C2	50-70	10YR4/3	GLS	20	massive	—	—
	Site 10. Regosolic Turbic Cryosol (Pergelic Cryorthent)							
Ah	A1	0-1.5	10YR2/2	LS	0	massive	com fine	ab sm
Cy1	C1	1.5-10	10YR3/3	SL	0	mod med sbk	few fine	di sm
Cy2	C2	10-20	10YR3/3	SiL	5	mod med sbk	—	di sm
Cy3	C3	20-40	10YR3/3	GSiL	20	wk fine sbk	—	—
	Site 11. Regosolic Turbic Cryosol (Pergelic Cryorthent)							
Cy1	C1	0-5		G	100	single grain	—	cl sm
Cy2	C2	5-15	10YR3/3	SL	15	massive	—	—
	Site 12. Orthic Sombric Brunisol (Pergelic Cryumbrept)							
Ah1	A11	0-5	10YR2/2	S	2	single grain	ab fine & med	gr sm
Ah2	A12	5-10	10YR3/2	S	2	massive	ab fine & med	gr sm
Bm1	B21	10-20	10YR3/3	S	2	massive	ab fine & med	gr sm
Bm2	B22	20-40	10YR3/3	S	2	massive	com fine	ab sm
C1	C1	40-58	10YR3/4	S	2	massive	com fine	ab br
C2	C2	58-65	10YR3/3	S	2	massive	few fine	ab br
IIAhb1	IIA13b	65-82	7.5YR2/2	GS	45	wk med gran	com fine	ab wa
IIIC3	IIIC3	82-90	7.5YR4/4	GS	45	single grain	few fine	ab wa
IVAhb2	IVA14b	90-105	10YR3/3	GS	25	single grain	few fine	—
	Site 14. Brunisolic Turbic Cryosol (Pergelic Cryumbrept)							
Ahy1	A11	0-4	10YR3/2	GSL	25	wk med gran	ab fine	gr wa
Ahy2	A12	4-10	10YR3/2	GSL	25	wk med gran	ab fine	gr wa
Bmy1	B21	10-21	10YR3/2	GLS	25	massive	com fine	cl wa
Bmy2	B22	21-35	10YR3/2	GSL	25	massive	com fine	ab wa
Bmy3	B23	0-26	10YR3/2	GSL	25	massive	few fine	ab br
C	C	35-42	2.5Y4/2	GSL	25	massive	few fine	ab wa

Abreviations used: Texture: G-gravelly; VG-very gravelly; S-sand; Si-silt; L-loam.
Structure: wk-weak; mod-moderate; co-coarse; gran-granular; prism-prismatic; sbk-subangular blocky.
Roots: ab-abundant; com-common; med-medium. Boundary: ab-abrupt; cl-clear; gr-gradual; di-diffuse; sm-smooth; wa-wavy; br-broken.

properties, such as texture or structure, that permit the identification of a B horizon. This type of soil is quite common in tundra environments and has been labeled by TEDROW (1977) as the Arctic Brown Soil. Numerous other authors have described similar soils in arctic and alpine regions (MOORE, 1974; PAWLUK and BREWER, 1975; WALMSLEY and LAVKULICH, 1975a & b; TARNOCAI and ZOLTAI, 1978; BOCKHEIM, 1979; VAN RYSWYK and OKAZAKI, 1979).

The poorly to imperfectly drained soils are all underlain by ice-rich permafrost at a shallow depth (15 cm at site 11 and 55 cm at site 3); at sites 2, 10, and 14, the frozen horizons were not actually reached because of the presence of large blocks or bedrock. In these cases the soil temperature can be used to estimate the depth to the 0°C isotherm; at site 2 and 10, frozen horizons would be reached within the first metre, and at site 14 within two metres. Subsequent research in the area has indicated that in mid-summer, the temperature in well drained soils decreases at approximately 1°C per 25 cm; more poorly drained soils cool off even more rapidly with depth. Although these soils are saturated with water most of the thaw period, they are not considered to be aquic by Soil Taxonomy (SOIL SURVEY STAFF, 1975) nor gleyed by the

Canadian classification system (CANADA SOIL SURVEY COMMITTEE, 1978b); the cold temperatures inhibit microbial activity that causes reduction and mottling (MOORE, 1974). Except for the soil at site 14, the most striking characteristic of the strongly cryoturbated profiles is the lack of contrast in the sub-surface horizons. Although in certain cases faint differences in color were visible, they proved to be one unit of chroma or value, or less, on the Munsell scale. Site 14 had a more strongly developed soil horizonation, with a clearly visible Bm (B2) horizon.

The well drained soils have morphological characteristics similar to soils found in the same setting in more temperate climatic regions. Each has a color B horizon due to one or both of two pedogenic processes: 1) accumulation of translocated iron and aluminum organometallic complexes, and 2) *in situ* weathering that has resulted in liberation, but not migration, of sesquioxides. From morphological evidence, this latter process is dominant in all except the soil at site 1. All of the sites are developed in either sand or loamy sand, the dominant texture of the tills of this region.

At site 1 the soil has the morphological characteristics of a weakly developed Podzol (Spodosol) with a distinct eluviated albic horizon, followed by a dark illuvial B horizon 3 cm thick. The subsequent B horizons are too pale in color to be mistaken for Podzolic B (Spodic) horizons. Soils, in which iron and aluminum migration is an important process, have been identified in the Forest-Tundra transition zone and also in parts of the tundra zone under arctic heath vegetation (LARSEN, 1972; MOORE, 1974; UGOLINI *et al.*, 1981).

Of the other seven well drained profiles, five have thick dark Ah (A1) horizons (sites 4, 5, 6, 9 and 12); those of the other two profiles (sites 7 and 8) are much thinner. In the case of site 8 only a very thin A horizon was identified; however, the B horizon was rich in carbon.

Generally soil temperatures at 50 cm (measured in July) show a trend that correlates well with the degree of soil development. The warm sites have deeper soils (A plus B horizons), higher organic matter contents and more strongly expressed B horizons than the colder sites. This relationship is not perfect; there are variations that are probably due to site disturbance by cryoturbation, and variations in other factors such as depth of snow pack, texture, mineralogy of the parent material, and precipitation.

TEXTURE AND EXCHANGEABLE CATIONS

Selected horizons from the thirteen profiles were subjected to more detailed study in order to characterize the soil material (Table IV). Particle size analysis confirms the field determination of texture; the soils are all very sandy. The summit soils (sites 2, 3, 10, 11, and 14) tended to have higher silt content than those in valley positions, with a maximum of 40% and a minimum of 10%; these same soils have between 88% and 50% sand and less than 7% clay. Various researchers (*e.g.* TEDROW, 1977) have hypothesized that the prevalence of silt, as compared to clay, is due to the physical weathering of rocks or to the influx of windblown silt-sized particles. The valley soils, as has been stated, are located on well drained till or glacio-fluvial deposits; mechanical analysis reveals that they contain more than 75% sand and in some cases as much as 99%; silt contents are less than 23% and clay less than 3%.

Given the low content of clay, the very low cation exchange capacities are not surprising. The highest values are found in organic matter rich horizons where exchange sites on organic colloids, rather than on clay minerals, provide the exchange capacity. The highest value of 157 mmol (p^+) kg^{-1} is still low (this translates into the more familiar 15.7 meq/100 g in non-SI units). With low clay contents the main sources of CEC will be the organic matter and amorphous sesquioxide coating material, both of which carry dominantly pH-dependent charge; therefore at the low pH of these soils the CEC is very low. Higher values of CEC would probably have been recorded using a method which employs solutions buffered at neutral pH. The unbuffered $BaCl_2$ solution employed here gives exchange capacities at near the soil pH; thus the values are more nearly representative of the exchange capacity in the field.

The low pH of these soils also explains the high exchangeable Al values, which in some instances account for more than 90% of the total exchange capacity. Generally the CEC was highest in the surface horizons and decreased as organic matter content decreased with depth. The presence of amorphous material in the B horizons adds to their CEC, although it is difficult to separate the contribution of sesquioxides from that of organic matter. The C horizons tend to have relatively low CEC and high base saturation compared to the surface horizons, owing to their higher pH and lower organic matter and sesquioxide content. In general Al is the dominant exchangeable cation in these soils, followed by Ca. The quantities of exchangeable Mg, K, and Na are very low.

PROFILE DISTRIBUTION OF pH, CARBON, NITROGEN AND IRON AND ALUMINUM OXIDES

Examination of the distribution of certain elements can yield valuable insights into the processes of soil formation. In the following discussion, iron and aluminum extractable by sodium pyrophosphate (Fe_p and Al_p) and acid ammonium oxalate (Fe_o and Al_o) will be considered along with pH, total organic carbon (C) and total nitrogen (N). Sodium pyrophosphate extracts iron and aluminum contained in organo-metallic complexes, while ammonium oxalate extracts amorphous organic and inorganic forms (McKEAGUE *et al.*, 1971). The former is used to identify podzolic B horizons in Canada. For relatively young Canadian soils, it provides results comparable to those obtained by the pyrophosphate-dithionite method used in the United States for identifying spodic horizons (SHELDRICK and McKEAGUE, 1975). Crystalline iron oxides are extracted by the citrate-bicarbonate-dithionite (CBD) method of McKEAGUE and DAY (1966), but the results are difficult to interpret for soils such as those studied, which contain appreciable quantities of mafic minerals (data not presented).

TABLEAU IV

Partical size analysis, exchangeable Al and bases, cation exchange capacity

Sample		Sand	Silt	Clay	Al	Ca	Mg	K	Na	CEC	B.S.	Exch.
						Exchangeable Cations						
			%			mmol (p⁺)kg⁻¹					%	pH
Site 1	LFH	91.8	5.5	2.7	16.2	114.5	23.4	2.0	0.9	157.0	90	3.08
	Bf	96.4	3.6	0.0	5.9	0.0	0.0	0.2	0.2	6.3	6	4.68
	C1	96.2	2.6	1.2	0.4	0.0	0.3	0.1	0.1	1.2	67	5.33
Site 2	Cy1	57.9	37.1	5.0	3.0	0.6	0.0	0.1	0.1	3.8	21	4.85
	Cy3	63.3	31.1	5.6	3.0	0.3	0.0	0.0	0.1	3.4	12	4.83
Site 3	Ah	88.1	10.4	1.5	20.0	8.6	3.3	1.5	0.2	33.6	28	4.04
	Cy2	87.5	10.5	2.0	0.0	31.5	3.2	0.5	0.1	35.3	100	5.36
Site 4	Ah1	91.3	8.1	0.6	5.7	5.2	1.1	0.5	0.2	12.7	55	4.69
	Bm2	92.4	6.8	0.8	1.9	1.0	0.3	0.1	0.2	5.7	67	4.76
	C2	99.2	0.3	0.5	0.2	2.7	0.7	0.3	0.1	4.0	95	5.61
Site 5	Ah2	76.6	21.9	1.5	21.3	2.4	0.3	0.2	0.2	24.4	13	5.36
	Bm	98.0	2.0	0.0	3.9	1.1	0.4	0.2	0.2	5.8	33	5.42
Site 6	LFH	94.0	5.1	0.9	16.0	2.8	0.5	0.5	0.1	19.9	20	5.20
	Bm1	99.0	1.0	0.0	2.4	0.8	0.1	0.1	0.1	3.5	31	5.19
	C2	98.4	1.6	1.0	1.4	0.7	0.1	0.1	0.1	2.4	42	4.77
Site 7	Ah1	89.1	8.9	2.0	47.8	13.2	3.1	1.9	0.2	66.2	28	4.40
	Bm	87.7	11.5	0.8	7.2	1.2	0.1	0.2	0.1	8.8	18	4.65
	C1	81.3	16.1	2.6	1.2	0.0	0.0	0.2	0.1	1.5	20	4.97
Site 8	Ah	75.4	22.2	2.4	41.1	26.2	4.7	2.0	0.2	74.2	45	4.17
	Bm1	83.1	15.6	1.3	12.0	2.4	0.2	0.1	0.2	14.9	19	4.55
	C1	72.9	24.8	2.4	2.0	0.0	0.0	0.1	0.1	2.2	9	4.86
Site 9	Ah1	97.2	2.2	0.6	1.2	0.6	0.0	0.1	0.0	1.9	37	4.90
	Bm	86.7	12.5	0.8	0.5	2.4	0.4	0.2	0.1	3.6	86	5.01
	C2	83.0	14.6	2.4	0.2	3.0	0.8	0.3	0.1	1.7	95	5.16
Site 10	Ah	73.1	22.5	4.4	38.9	21.2	10.2	1.6	0.6	72.5	46	4.24
	Cy2	55.7	40.7	3.6	0.8	9.2	3.2	0.6	0.2	14.0	94	4.88
Site 11	Cy2	49.7	49.4	0.9	0.5	15.5	2.4	0.3	0.1	18.8	97	4.99
Site 12	Ah1	95.8	3.1	1.1	3.0	21.8	3.6	0.8	0.1	29.3	90	4.45
	Bm1	95.8	3.2	1.0	7.1	2.5	0.9	0.5	0.1	11.1	36	4.48
	C1	97.1	2.9	0.0	2.5	1.6	0.4	0.3	0.0	4.8	48	4.84
Site 14	Ahy1	72.5	23.6	3.9	27.1	2.5	2.2	2.6	0.2	34.6	22	4.22
	Bmy1	81.3	15.8	2.9	6.0	0.3	0.2	0.0	0.0	6.5	8	4.66
	C	54.2	38.6	7.2	1.5	0.0	0.1	0.0	0.1	1.7	12	4.82

10 mmol $(p^+)kg^{-1}$ = 1 meg/100 g.

Strongly Cryoturbated Soils

Of the five upland, poorly to imperfectly drained soils, four are represented on Figure 2. The fifth, site 11, was frozen at a depth of 15 cm; it is not depicted since only one horizon was sampled and analyzed. The chemical characteristics of this horizon are similar to the C horizons of the other four sites. These soils were sampled in blockfields where the surface is largely rock-covered; the vegetation is very sparse and is composed mainly of moss and lichen.

Certain properties are common to all of these soils. The C and N contents remain relatively high throughout the profiles and either the pH remains uniform or increases gradually with depth. Reversals in these trends occur where horizons contain material incorporated from either lower down or higher up in the profiles. Two conflicting forces of pedogenesis are apparent: 1) Cryoturbation mixes and homogenizes the profile; and 2) the accumulation of organic matter at the surface and its incorporation into the profile, combined with leaching and hydrolysis, work to differentiate the horizons.

The soil profile at site 2 is very weakly differentiated; nearly all of the soil properties remain constant with depth. The exceptions are C, mirrored by N, which records a slight increase, and Fe_p, which decreases with depth. The homogeneity of the profile distributions is attributed to very active cryoturbation that mixes the horizons faster than the processes of soil genesis can differentiate them.

At site 3 the regular decrease with depth of Fe_p, Al_p, C, and N, and the increase in pH, reverse abruptly in the lowest horizon, Cy3 (C3). The properties of the horizon indicate that it has been incorporated, by cryoturbation, from a position closer to the surface. The results of chemical analysis show that horizon Cy1 (C1) and Cy3 (C3) are virtually identical, while Cy2 (C2) is less well developed.

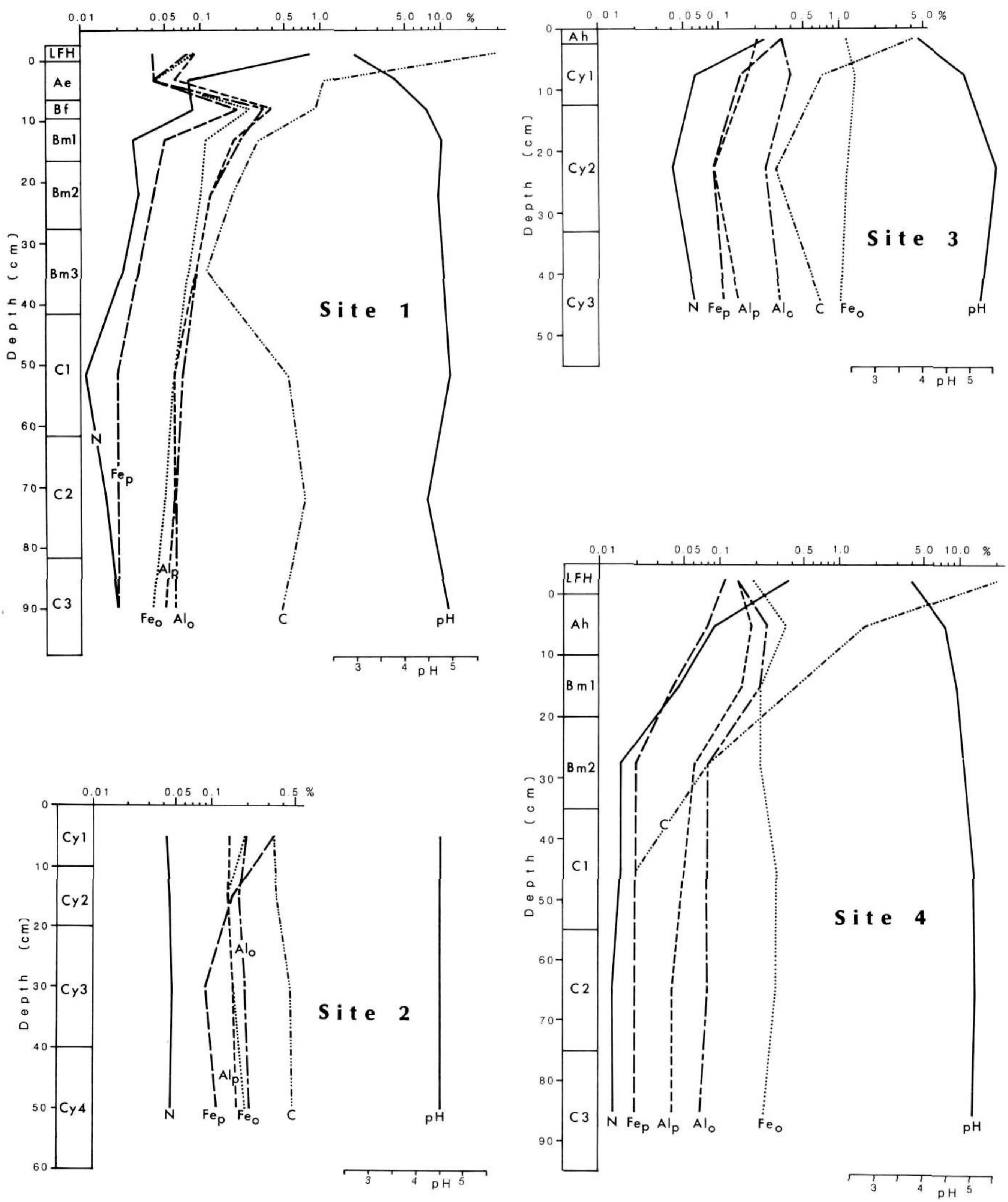

FIGURE 2. Profile distribution of organic carbon, nitrogen, pH, and Fe and Al extractable in pyrophosphate and oxalate.

Profils de distribution du carbone organique, de l'azote, du pH, et de Fe et Al extractibles en pyrophosphate et en oxalate.

At site 10 there is no evidence of buried horizons; the low content of C, N, and extractable Fe and Al in the lower horizons is indicative of the less active pedogenesis. This is the highest elevation site studied; sparse vegetation cover and low biomass production must also be considered in explaining the relatively weak soil profile development. Compared to the underlying C horizons, the surface horizon is significantly richer in C and N and more highly weathered, as indicated by the higher values of extractable Fe and Al. The relatively uniform profile below the surface horizon is due to active mixing by cryoturbation.

At site 14 the first Ah (A1) horizon contains considerably more C and N than the underlying horizons. The amounts of extractable Fe and Al are very constant with depth down to the lowest Bmy horizon. The further decrease in the C horizon confirms that it does not contain an admixture of material from other horizons. In the C horizon, the decrease in C and N is accompanied by a decrease in Fe_p and Al_p. In contrast, Fe_o and Al_o remain constant through almost the entire profile, indicating a constant degree of weathering. The high C content ($>$ 1%) in the first four horizons supports the contention that this profile is undergoing active cryoturbation, while the C horizon is not affected.

Weakly Developed Soils

The profiles at sites 9 and 12 are only weakly developed; the vegetation cover is relatively sparse and dominated by grasses, lichens, and willow. Owing to their coarse texture and slightly raised topographic position, these are the driest sites studied. At site 9 there is a slight increase in C and N from the Ah1 (A11) to Ah2 (A12) horizon, and then a gradual decrease down the profile. At both sites 9 and 12, the extractable Fe_p and Al_p also increase in the second Ah horizon and then stay relatively constant with depth. Although both are well drained soils with a color B horizon, there is very little evidence of this genesis in the results of the chemical analyses.

At site 9 there is an unexplained decrease in Fe_o in the Ah2 (A12) horizon that corresponds to a maximum for Fe_p, Al_p, and Al_o. Although in most cases an increase in extractable Fe and Al just below the surface is caused by eluviation from the overlying horizon and subsequent deposition, another possibility must be considered. At site 12 there is a large wind eroded surface adjacent to the soil pit. The low values of extractable Fe and Al in the Ah1 (A11) may be due to the recent entrapment of windblown material in the vegetation mat. At site 9 there was no apparent source of aeolian sand and the high gravel content (20%) rules out this explanation.

From geomorphic evidence, the well sorted sands at site 12 are attributed to fluvial deposition on top of a lateral moraine. It is difficult to determine from soil morphology alone whether this deposition was synchronous with valley glaciation or has occurred much more recently. The first buried IIAhb1 horizon has higher C, N, and extractable Fe and Al than the surface Ah horizons, indicating that the buried material has undergone more intense pedogenesis than the surface soil. The possibility that this buried material is from a well developed Ah horizon that was eroded from further upslope is strongly suggested by the very weakly developed IIIC3 horizon situated immediately below it. If the IIAhb1 (IIA13b) had developed *in situ*, the IIIC3 should reveal stronger pedogenesis. The last horizon sampled, IVAhb2 (IVA14b), has properties similar to those of IIAhb1 (IIA13b), and may represent another cycle of erosion and deposition.

Moderately Developed Soils

Five soils, at sites 4, 5, 6, 7, and 8, show reasonably well developed profiles having an Ah (A1) horizon over Bm (B2) horizon. These sites are all relatively humid (rarely dry), with a fairly dense tundra vegetation cover of moss, lichen, grass, willow and heath. At these sites there is a gradual pH increase and C and N decrease with depth. Generally the maximum for Fe_p and Al_p is just below the surface in the Ah1 (A11) or Ah2 (A12) horizon, and it decreases with depth below that point. The maximum for Al_p or Al_o are usually lower in the profile than the corresponding maxima for Fe. This same trend is evident in podzol profiles and is interpreted as indicating that Al is translocated farther down the profile than Fe (BLUME and SCHWERTMAN, 1969).

The profile distribution of the soil at site 4 does not show the effects of cryoturbation; however the other side of the soil pit was extensively perturbated by frost action. Although the profile sampled is classified as an Orthic Sombric Brunisol, the soil mapping unit would be a complex made up of the Brunisol and a Brunisolic Turbic Cryosol. The values in the C2 and C3 horizons of C, N, and Fe_p of 0.02, 0.13, and 0.02, respectively, are the lowest for any of the sites studied.

At site 5 the maximum accumulation of Fe and Al occurs in the Ah3 horizon. The profile distribution of C and N is a little irregular; higher quantities are found in the C than the Bm horizons. This may be due to translocation, as is sometimes seen in soils with frozen layers; however, there is no ice in this profile. It is probably more reasonable to interpret the distribution as being related to the organic matter content of the sediment at the time of deposition or to a period of cryoturbation sometime in the past. There is no morphological evidence of active cryoturbation.

At site 6 the Fe_p and Fe_o maxima are in the Ah1 horizon while the Al_p and Al_o maxima are in the Ah2. Otherwise the profile distribution decreases very smoothly with depth.

The profile at site 7 is notable for the shallowness of soil development. The Bm horizon ends at 15 cm depth and the chemical characteristics of the BC horizon are very similar to those of the C. Nonetheless, the Bm is fairly well developed compared to the underlying C horizons.

The soil at site 8 is characteristic of the other moderately developed soils with an even increase in pH with depth and a steady decrease in C, N, and extractable Fe and Al.

Strongly Developed Soil

At site 1 the soil has the morphological properties of a weakly developed Podzol (Spodosol). This site is covered by a black spruce-larch forest vegetation and has the warmest temperature of any of the soils examined. The Ae (A2) horizon, in agreement with the morphological properties, is strongly

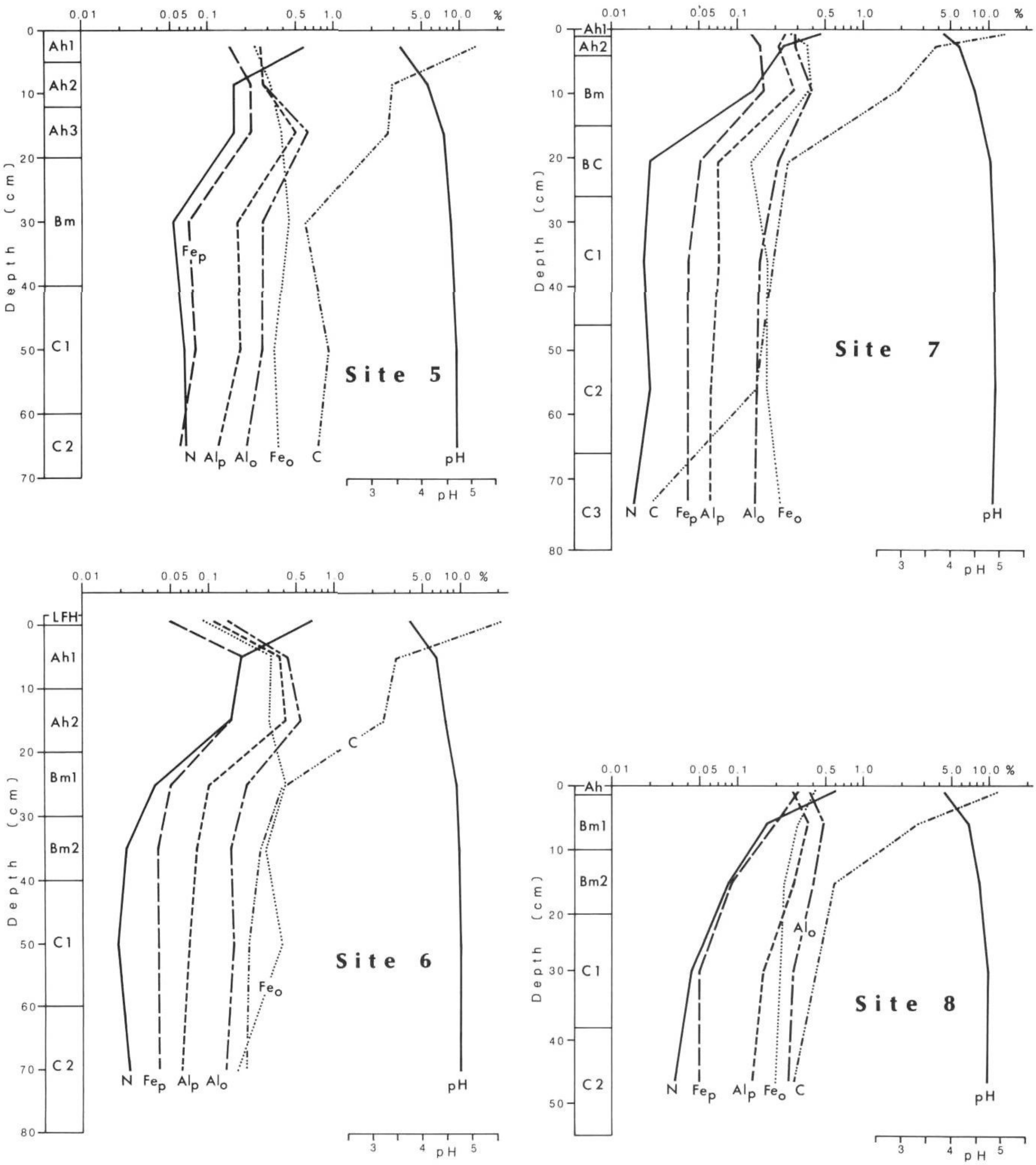

FIGURE 2. Profile distribution of organic carbon, nitrogen, pH, and Fe and Al extractable in pyrophosphate and oxalate.

Profils de distribution du carbone organique, de l'azote, du pH, et de Fe et Al extractibles en pyrophosphate et en oxalate.

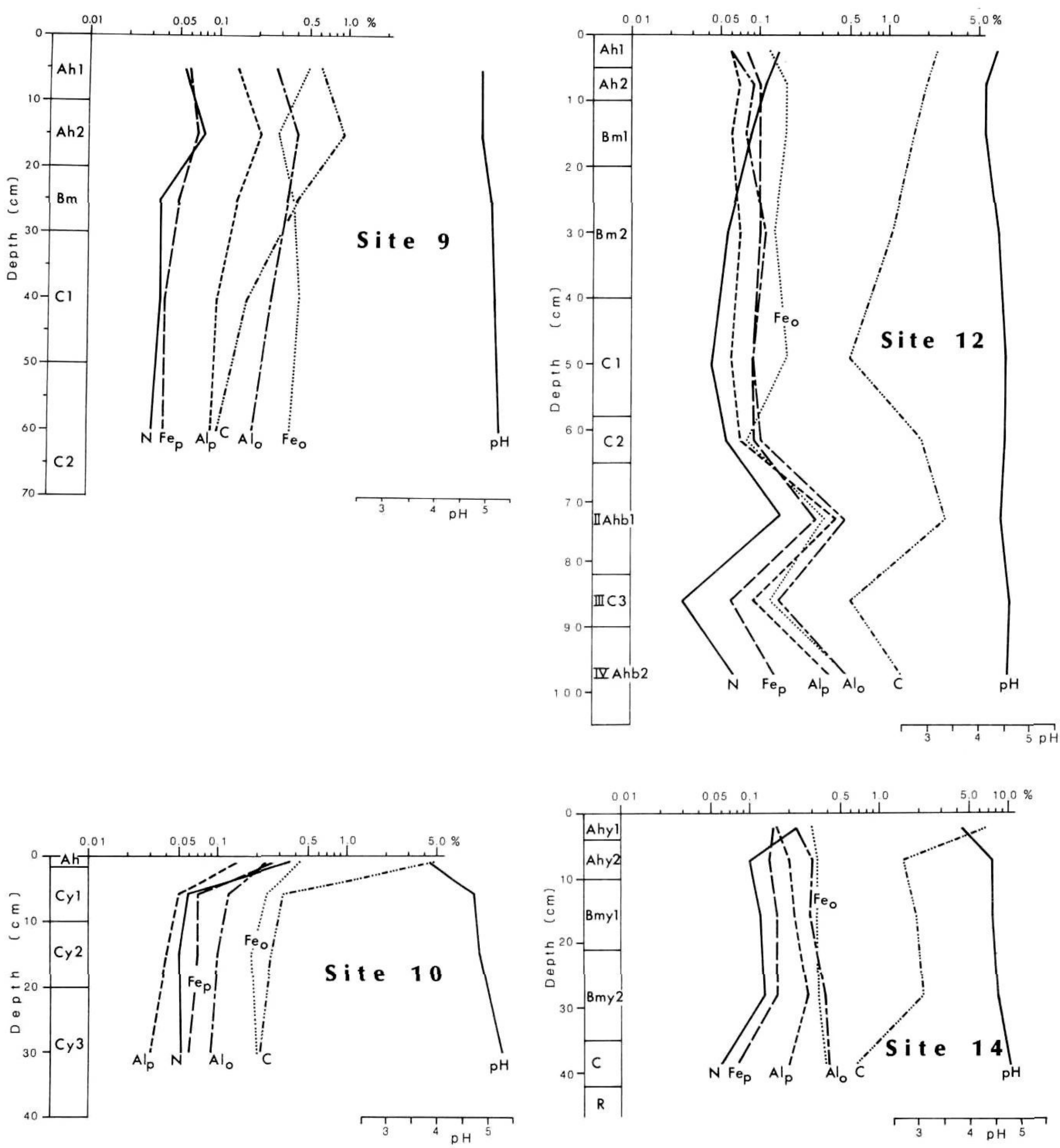

FIGURE 2. Profile distribution of organic carbon, nitrogen, pH, and Fe and Al extractable in pyrophosphate and oxalate.

Profils de distribution du carbone organique, de l'azote, du pH, et de Fe et Al extractibles en pyrophosphate et en oxalate.

leached with low values of extractable Fe and Al. This is followed by the Bf (B21ir) horizon in which there is a significant accumulation of Fe, Al, and C. There is enough organically complexed Fe and Al to meet the requirements of a podzolic B horizon, but it is too thin to be so classified. Extractable Fe and Al decrease regularly with depth below the Bf; the organic C content increases in the C horizon. Although not clearly expressed at this site, many of the soils on this moraine complex have been cryoturbated in the past. This may explain the anomalously high C values; the slight acidification of the C2 horizon supports this theory. Soils with the morphological properties of podzols are well known in arctic and sub-arctic environments that have either a forest or tundra vegetation cover (MOORE, 1974; LARSEN, 1972; UGOLINI *et al.*, 1981).

CONCLUSION

As expected, these soils, developed in a cold environment with only a short period of thaw, display signs of relatively weak pedogenesis. For example, the poorly drained soils are not reduced strongly enough to be considered to have an aquic moisture regime (SOIL SURVEY STAFF, 1975) nor to be given the suffix "g" indicative of strong gleying (CANADA SOIL SURVEY COMMITTEE, 1978b). Another example of the weak pedogenesis is that the texture in the B horizons has not been changed by weathering; the horizons are too sandy to be called cambic. The soils encountered vary markedly in terms of their degree of soil genesis; most noticeable are the variations in the thickness of the solum, the thickness and carbon content of the Ah (A1) horizons, and the degree of development of the B horizons.

Within the region studied there are differences in soil development due to several site factors. Soils at lower elevation and latitude tend to be more strongly developed than those that are higher or farther north. To a certain extent the distribution of the soil temperature measured at 50 cm follows the degree of soil genesis (Table II). Obviously other factors such as mineralogy and texture of the parent material and the amount of precipitation have modified these trends.

Topography of the site also plays a major role by controlling soil drainage. The five strongly cryoturbated soils on the mountain summit locations all had their drainage limited by either shallow permafrost or bedrock. The soils on the relatively flat summit positions drain slowly, since there is very low relief and the water is forced fo flow horizontally for a considerable distance. In comparison, the soils from the valley locations had either high local relief or very coarse, freely drained parent material; the water could either flow rapidly down hill or percolate through the soil matrix.

The high elevation of the summit sites contributes to the development of impermeable ice layers at shallow depths; the subsequent poor to imperfect drainage helps to maintain the permafrost by keeping the soil temperatures low. In addition, the summit sites probably have very little snow cover in winter because of their exposure to wind. This would result in lower winter soil temperatures and reduce the depth of the thaw layer. In considering the distribution of soils, it is interesting to note that site position can be more important than elevation. For example, the strongly cryoturbated profile at site 14 is situated at a lower elevation than the soils at sites 7 and 8. The first is on a relatively flat mountain summit in an exposed position, while the last two are on well drained glacial moraines.

Four pedogenic processes dominate in the soils studied: 1) cheluviation, the migration of iron and aluminum as organometallic complexes; 2) *in situ* weathering, mainly hydrolysis and oxidation; 3) the formation of organic rich Ah (A1) horizons and the reactions of the organic matter with sesquioxides in the A and B horizons; and 4) cryoturbation, which mixes soil horizons on the poorly to imperfectly drained sites.

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