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Properties, Formation, Classification and Ecology of Arctic Soils: Results from the Tundra Northwest Expedition 1999 (Nunavut and Northwest Territories, Canada)

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Abstract: Soils of Arctic Canada were sampled during the Tundra Northwest Expedition 1999 (TNW-99) at 17 sites that cover the ecological regions of the High, Mid and Low Arctic zones. Almost all locations consisted of a mesic and a dry habitat and are described with respect to their ecological function. Analyses on soil characteristics were performed for soil morphology, texture and chemistry. The data showed a wide variability due to local aspects. Statistical evidence did not indicate that larger-than-local ecological regions could be defined in most cases by either soil chemical characteristics or vegetation patterns. Soil classification according to the World Reference Base of Soils (WRB) showed the dominance of different Cryosols, but also Gelic Cambisols and Gelic Regosols were found; according to US Soil Taxonomy, they could be classified as different *Orthels, Turbels* and *Histels.* Low temperature, high stone content and low nutrient availability were noted as factors hampering plant growth and soil activity.

Zusammenfassung: Böden der kanadischen Arktis wurden während der Expedition "Tundra Northwest 1999" (TNW-99) an 17 Standorten untersucht. Sie stellen Profile aus den Regionen der Hohen, Mittleren und Niederen Arktis dar. Es wurden an den Standorten jeweils trockene und feuchte Habitate vergleichend beprobt. Die Böden wurden im Gelände nach den Richtlinien der FAO beschrieben. Im Labor wurden Eigenschaften ermittelt, die eine Klassifikation der Böden nach der US Soil Taxonomy und der World Reference Base of Soils (WRB) ermöglichen und zugleich Aussagen als Pflanzenstandorte und Lebensräume von Mikroorganismen erlaubten. Nach der US Soil Taxonomy handelt es sich um *Orthels, Turbels* und *Histels,* nach WRB um Cryosole sowie Gelic Cambisols, Regosols und Histosols. In der Hohen und Mittleren Arktis waren die Böden stark durch Permafrost geprägt. Wachstum begrenzende und die Bodenaktivität einschränkende Faktoren sind niedrige Temperaturen und hohe Steingehalte sowie niedrige Nährstoffgehalte.

INTRODUCTION

Arctic soils have received much attention in Global Change discussions for many years now. A tundra environment covers about 5.5 % of the world's land surface, (BROWN et al. 1980). This area with one of the lowest temperatures and shortest growing seasons is one of the main carbon resources on earth, accounting for about 14 % of terrestrial C (POST et al. 1982, GILMANOV & OECHEL 1995). Their role in the process of global C budgets, however, is still not fully understood. This is not because of a lack of knowledge of individual processes, but because these soils contain a great heterogeneity in both organisms and stocks of nutrients. This varied state of affairs does not allow a simple upscaling of local measurements to large areas. Special attention must be given to distribution and variability caused by small-scale patchiness, (e.g., polygons) and by varying landscapes. Great difference exists between the vast continental mass of Siberia and the archipelago of northern Canada.

The most important feature of the soils in our study is permafrost. About 40 % of the Canadian landmass is influenced by it, 30 % located in the arctic region (BLISS 1997). Many permafrost soils contain a relatively high content of organic matter. This results from harsh weather conditions, short growing seasons, strong light and continuous freeze-thaw and dry-wet cycles, which lead to a decoupling of production and decomposition that results in high residual carbon content (BATJES 1996, BLUME et al. 1996, MICHAELSON et al. 1996). Most recent reviews on these soils have been compiled in KIMBLE (2004).

Soil development and soil biology are closely related to each other because of environmental constraints. Harsh climate conditions impose various stress factors on the living world in the arctic region; the frequent freeze-thaw cycles and dry-wet situations influence physical and chemical processes of weathering. The islands of northern Canada receive minimal precipitation, making them polar (biological) deserts or semi-deserts. Such landscapes are typical for the high-arctic Queen Elizabeth Islands (BLISS 1981), which show mainly poor soil development (EVERETT et al. 1981). Elevated landscapes are all but barren with no significant plant biomass. Other places, like the oases of more southern regions, are filled with a rich plant life and have animal populations.

The tundra, which covers nearly 20 % of both northern continents, was the focus of two expeditions of the Swedish Arctic Council. The first cruise visited the Siberian realm in 1996 (GRÖNLUND & MELANDER 1994), the second in 1999 went to the Canadian territories Nunavut and the Northwest Territories (TNW-99). General aspects of the region, the locations and sampling sites are given by ERIKSEN et al. (2006). This paper describes the localities and the dry to mesic sites in more detail with emphasis on soil characteristics after FAO / ISRIC (1990), and the two major soil taxonomies: the US Soil Taxonomy (SOIL SURVEY STAFF 1999) and that of the World Reference Base for Soil Resources (WRB) (ISSS-FAO-ISRIC 1998). TARNOCAI (2004) published a set of data from stations close to those of TNW-99, which he visited on earlier expeditions. The sites located closest are referred to in more detail below in chapters Results / Discussion. Further, we apply a soil ecological rating according to SCHLICHTING et al. (1995) and adapted to polar soils (BÖLTER & BLUME 2002, BLUME & BÖLTER 2004).

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MATERIAL AND METHODS

Site Descriptions and Sampling

Sampling was carried out during two legs of Tundra Northwest Expedition (Tab. 1, Fig. 1) from late June to the end of Au-gust 1999 and had two aspects of local variability, which followed East-West and North-South orientations. A detailed list of the environmental patterns found during this study is given in ERIKSEN et al. (2006); further, that contributions provides photos of sampling sites and some pits.

During Leg 2 sampling was performed by Dr. Anders Dahlberg, Uppsala. As his primary interest was the analysis of mycorrhiza, the data considered were only from the topsoil (in general: depth 0-10 cm), and the characterization and classification could be based only on the main rooting depth.

Samples were taken from two pits per site: one soil with a dense vegetation cover (mesic) and a second in the neighbourhood but with a low vegetation cover (dry). Soils of the nine sites of Leg 1 were sampled down to the permafrost or one meter, sometimes more. Characteristics of soil horizons were described in the field as well in the laboratory: soil colour under moist conditions (Munsell charts), soil structure, texture, gravel and stone content after FAO/ISRIC (1990).

Sampling was performed by mass samples as well as volume samples whenever possible (using metal cylinders: d = 4 cm, h = 4 cm). Special care was taken for surface layers and plant cover samples. All samples were inspected directly after sampling onboard the ship for micro-arthropods and other soil-dwelling organisms. Samples were stored deep-frozen pending further analysis in the laboratory.

Analytical Methods

The methods generally follow the instructions given by SCHLICHTING et al. (1995) if not stated otherwise.
- Gravel (2-63 mm) and stones (>63 mm) (= soil skeleton) were separated by sieving. All of the following analyses were performed with fine soil (<2 mm).
- Particle size: sieve method for sand (0.063-2 mm) and pipette method for silt (2-63 μm) and clay (<2 µm) fractions after H_2O_2 oxidation of organic carbon, HCl extraction of carbonates, and $(NaPO_3)_6$ dispersion.
- Total organic carbon (TOC): dry oxidation at 1200 °C, coulometric. CO_2 measurements and subtraction of carbonatic C (measured as loss of C after acidification).
- Carbonates: H_3PO_4 treatment at 80 °C and CO_2 measurement as for TOC, transformation into $CaCO_3$.
- Total nitrogen (N_t): Kjeldahl digestion, colorimetric measurement of NH_4.
- Total phosphorus (P_t): colorimetric measurement.
- Pedogenic oxides: dithionite-citrate-bicarbonate extraction of Fe_d (= sum of pedogenic oxides and Mn_d), oxalate extr. of Fe_o (= only organically bound and poorly crystallised oxides).
- Cation exchange capacity (CEC) and exchangeable cations (exchange of Ca_a, Mg_a, K_a, Na_a, and Al_a with $BaCl_2$, measurement by AAS).
- Exchangeable H_a (and Al) (pH (Ca-acetate at pH 7.2) measurement); CEC = $H_a + Ca_a + Mg_a + K_a + Na_a$, and calculation of the base saturation intensity (= b.s.).
- Soil reaction: potentiometric measurement of pH ($CaCl_2$) at 1:2.5 (soil: water).
- Electrical conductivity: measurement at 1:2.5 (soil: water) and transformation to the water content of the saturation extract after determining the content of clay and organic matter.
- C/N: using C_{tot} (from TOC) and N_t; also thermogravimetry after KRISTENSEN (1990).
- Available water capacity (awc in vol. %) was calculated in

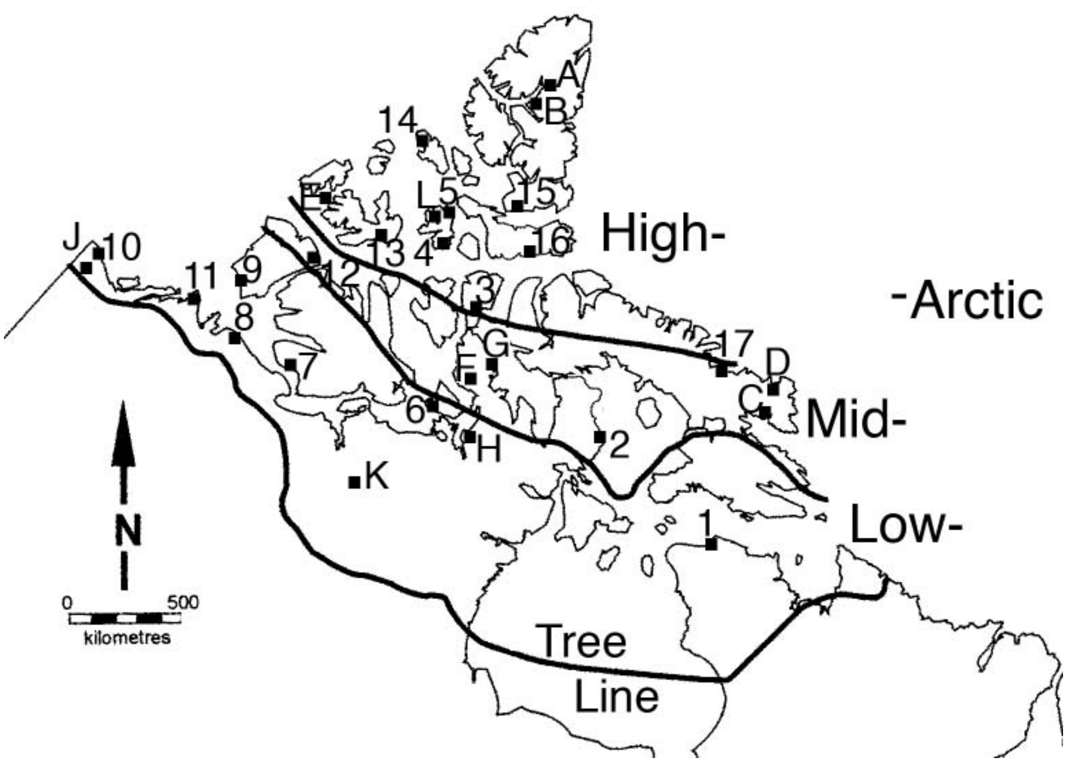

Fig. 1: Location and sampling sites 1 through 17 of the expedition Tundra Northwest 1999 (TNW-99) as well sites A to L of TARNOCAI (2004).

Abb. 1: Stationen 1 bis 17 der Expedition Tundra Northwest (TNW-99) sowie der Standorte A bis J von TARNOCAI (2004).

Site / Location		Date	Latitude Longitude	Moist.	Altitude (m)
1	Ungava	02.07.99	62°22.25 73° 47.76	Mesic	60
2	Melville Peninsula	05.07.99	67°35.02 81° 42.20	Dry	140
		05.07.99	67°53.11 81 ° 43.02	Mesic	90
3	Somerset Island	10.07.99	72°55.38 93° 27.02	Dry	85
		10.07.99	72°55.31 93° 26.73	Mesic	70
R	Resolute	12.07.99	74°41.99' 94° 49.78	Dry	30
4	Bathurst Island South	13.07.99	75°04.42 98° 30.98	Dry	150
		13.07.99	75°04.34 98° 31.01	Mesic	110
5	Bathurst Island East	16.07.99	76°26.22 97° 56.64	Mesic	20
6	King William Island	20.07.99	69°06.66 98° 55.09	Dry	10
		20.07.99	69°06.06 98° 55.90	Mesic	5
7	Wollaston Peninsula	23.07.99	69°26.46 114° 43.50	Dry	200
		23.07.99	69°26.40 114° 43.51	Mesic	180
8	Paulatuk	26.07.99	69°45.84 122° 02.84	Dry	110
		26.07.99	69°45.85 122° 03.02	Mesic	80
9	Banks Island South	28.07.99	71°43.01 123° 44.14	Dry	290
		28.07.99	71°42.96 123° 44.36	Mesic	250
10	Ivvavik	04.08.99	69 25.10' 139° 38.40'	Dry	290
11	Cape Bathurst	08.08.99	70°29' 127° 50'	Dry	n.d.
		08.08.99	70°29' 127° 50'	Mesic	n.d.
12	Banks Island North	10.08.99	73°37.32' 115° 52.02'	Dry	30
		10.08.99	73°37.33' 115° 51.43'	Mesic	20
13	Melville Island	13.08.99	75°06.35' 107° 38.11'	Dry	30
		13.08.99	75°06.37' 107° 38.35'	Mesic	30
14	Ellef Rignes Island	18.08.99	78°55.59 104° 38.21'	Dry	100
		18.08.99	78°55.54' 104° 38.34'	Mesic	100
15	Ellesmere Island South	22.08.99	76°31.00' 86° 46.08'	Dry	180
		22.08.99	76°31.07' 86° 46.01'	Mesic	180
16	Devon Island South	25.08.99	74°32.49' 82° 47.19'	Dry	60
		25.08.99	74°32.49' 82° 47.10'	Mesic	60
17	Baffin Island East	30.08.99	68 26.21' 66° 49.24'	Dry	50
		30.08.99	68 26.22' 66° 49.24'	Mesic	50

Tab 1: Geographical items of the locations sampled for soil analyses during TNW99. Sites 1-9 refer to Leg 1, sites 10-17 refer to Leg 2, altitudes are given in meter (m).

Tab. 1 Geografische Angaben zu den Standorten der Probennahmen während der Expedition TNW99. Die Standorte 1-9 beziehen sich auf den Abschnitt 1, die Standorte 10-17 auf den Abschnitt 2 der Reise. Höhenangaben in Meter (m).

relation to texture and contents of organic matter, stones and gravel (SCHLICHTING et al. 1995).

Micro-organisms were estimated by epifluorescent microscopy after acridine orange staining and filtering on membrane filters. For bacteria and fungi a pore size of 0.2 μm was used, for algae and cyanobacteria 3.0 µm. Conversion to biovolume was performed by using the organism's geometry for cocci and rods (BÖLTER et al. 1993). Further conversions to biomass and C content followed the assumption that 20 % of the wet biovolume relates to dry mass and 50 % of this to carbon (SCHLEGEL 1992).

As no climatic data of the individual sampling points were available, data from climatic stations in the neighbourhood (Canadian weather stations) were taken and corrected according to differences in elevation (1 °C per 100 m altitude). Such data are only rough estimates but have been applied as a basic approach to this study.

RESULTS

In the following we describe characteristics of 15 soil pits of sites 1-9 and of a further 14 topsoils from sites 10-17 (Tab. 1) as described by ERIKSEN et al. (2006). For comparison and a broader view, we include the characteristics of an additional eleven soil pits from the same area (locations A-L in Fig. 1), as published by TARNOCAI (2004).

During Leg. 1, air temperatures between 2 and 16 °C were monitored. Soil temperatures at -1 cm reflected this range by and large (4-18 °C), at 10 cm: 4-12 °C. The depths of the active layer varied between 35 cm (Site 2, mesic) and >100 cm (Site 7, dry and mesic; Site 8, dry; and Site 9, dry). Generally, the permafrost was found in deeper layers at the dry sites than at the wet sites.

The parent material of the soils was acid in the east and became more basic to the west (sites 4-9), the latter ones being basically carbonatic sandstone. Root depths were found between 10 cm (Site 4, dry) and 40 cm, mean 25 cm. Frost patterns were not an important feature at the local sampling points. Sampling and soil description were often difficult due to high stone content, which frequently exceeded 70 %. Animal disturbances, e.g., trampling, were not evident. Faeces of caribou were monitored at sites 1, 2, 7, 10, 11, 14, (of fox: 1; lemming: 1, 5; hare: 2, 12, 13, 15, 16, 17; musk ox: 3, 7, 9, 10, 11, 12, 13, 15, 16; grizzly: 8; goose: 11, 12, 14, 15, 16, 17; ptarmigan: 10, 11, 12, 13, 15, 16, 17. Soil inspections by low magnification showed that nearly all soils showed an abundance of various nematodes. Soils from mesic sites also often showed rotators and collembolans. Soils of sites 1, 2 and 3 were strongly overgrown by fungi.

Results of the soil analyses (Tab. 2)

Soil Structure

Most topsoils have a fine granular structure due to frost activity and physical weathering. The subsoil of sandy soils (sites 2m and 6; as well as pedon C of TARNOCAI 2004) were single grained; loamy B horizons, partly sub-angular to angular blocky, C were horizons sometimes coherent.

Horizon	depth cm	structure	skelet %	colour moist	pH	e.c mS	sa %	si %	cl %	TOC %	C/N	Carb %	CEC	b.s. %	Fe_o ‰	Fe_o : Fe_d	P ‰	Mn_d ppm	Nt ‰

1m: Ungava Peninsula, Haplorthel with very weak frost pattern of moraine deposits on granite; pm: 65 cm; surface 100 % plant cover

Ah	0-10	GR	30-50	10YR2/1	5.0	0.4	89	8	2.6	3.9	14	0	16.8	49	0.44	0.36	0.51	180	2.8
E	20-30	SG	30-50	10YR7/3	5.6	0.4	96	3	0.6	0.2	23	0	2.6	68	0.11	0.06	0.22	91	0.1
Bsw	30-50	SG	30-50	10YR4/4				S											

2m: Melville Peninsula, Aquiturbel with polygon structure of moraine deposits; pm: 35 cm; surface 90-95 % plant cover beside stones

Ah	0-5	GR	< 5	2.5Y2/2	5.1	0.8	84	8	8.3	4.5	15	0	10.8	57	0.26	0.36	0.47	39	2.9
Bw	5-10	SG	< 5	2.5Y6.2	5.2	0.3	82	27	0.8	0.3		0	1.7	69	0.07	0.11		119	
Bg	30-35	SG	< 5	2.5Y6.2				LS											

2d: Melville Peninsula, Haploturbel with frost boils on moraine deposits, pm 65 cm; surface 80-90 % plant cover beside stones

Ah	0-10	GR	10-30	5Y3/2	5.7	0.4	81	16	3.2	0.6	21	0	2.4	45	0.09	0.43	0.39	60	0.27
AB	10-20	GR	10-30	5Y4/2	5.9	1.1	50	37	1.3	0.4	38	0	2.1	46	0.08	0.14	0.48	50	0.11
Bw	60-65	SB	10-30	5Y4/1				SL											

3m: Somerset Island, Haploturbel with polygons on moraine till; pm: 40 cm; surface: 95 % plant cover beside stones

O	0-5	GR	30-50	5YR2.5/1						>15									
Ah1	5-15	GR	30-50	7YR3/3	7.4	1.0	50	31	19	3.3	12	34	18.5	100	0.12	0.11	0.35	90	1.8
Ah2	20-30	SB	30-50	7YR3/3	7.4	0.9	46	30	24	2.1	10	32	13.6	100	0.10	0.15	0.19	69	2.1

3d: Somerset Island, Haploturbel with polygons to stripes on moraine till; pm 55 cm; surface: 10 % plant cover beside 2/3 gravel + stones and 1/3 fine soil

Ah1	0-4	GR	30-50	7YR3/3	7.2	1.5	53	33	14	1.9	8.8	42	11.9	100	0.08	0.18	0.38	26	2.1
Ah2	10-20	SB	30-50	7YR3/3	7.4	1.0	47	38	15	2.4	10	37	13.5	100	0.09	0.16	0.39	19	2.3
Bw	50-60	SG	30-50	6YR4/3.5				LS											

4m: Buthurst Island S., Aquiturbel with polygons on moraine till; pm: 50 cm;surface: 100 % plant cover

Ah1	0-10	SB	5-10	10YR2.5/1	7.4	0.8	19	49	32	1.9	13	50	7.6	100	0.39	0.13	0.57	67	1.5
Ah2	10-20	SB	5-10	10YR2.5/1	7.5	0.5	25	50	25	1.7	13	51	7.3	100	0.37	0.12	0.57	50	1.3
AC	40-50	CO	5-10	10YR3/1				SL											

4d: Bathurst Island S., Haploturbel with polygons on moraine till; pm: 45 cm; surface: 5 % plant cover beside 1/2 stones + gravels and 1/2 fine soil

Ah1	0-10	SB	50-70	10YR3/1.5	7.7	1.2	26	45	29	1.8	14	58	7.7	100	0.32	0.16	0.64	107	1.2
Ah2	10-20	GR	50-70	10YR3/1	7.7	1.3	37	60	2.7	1.8	17	57	7.7	100	0.35	0.19	0.60	154	1.1
AC	40-50	CO	50-70	10YR3/2				SL											

6m: King Williams Land, Haplororthel with weak polygons of moraine sands on limestone; surface: 95 % plant cover beside stones

Ah	0-10	GR	>70	7YR2.5/1	7.4	1.8				6.9	34	35	84.6	100	0.15	0.16	0.93	121	2.0
AC	15-25	GR	>70	10YR3/2	7.4	03	98	1	1.3	4.4		57	1.1	100	0.03	0.02		26	
C	40-50	SG	>70	10YR6.5/3				S											

6d: King Williams Land; Haplororthel with weak polygons of fluvio glacial sands on limestone; pm 80 cm; surface: 5 % plant cover beside gravel + stones

Ah	0-10	GR	>70	2.5Y4/4	7.6	1.2	67	24	8.9	0.6	26	88	1.2	100	0.02	0.06	0.07	218	0.25
Cw	10-20	SG	>70	2.5Y6/2	7.6	1.2	95	4	0.9	0.5	19	97	1.4	100	0.04	0.13	0.11	114	0.27
C	70-80	SG	>70	2.5Y7/2.5				S											

7m: Victoria Island. Mollorthel with hummocks on moraine till; pm: >100 cm; surface: 90 % plant cover beside gravel + stones

Ah1	0-10	GR	10-20	10YR3/2	7.6	1.4	56	43	1.0	3.1	14	38	10.4	100	0.28	0.27	0.28	79	2.2
Ah2	10-20	GR	20-30	7.5YR3/3	7.5	1.2	45	54	1.0	2.5	11	35	12.3	100	0.36	0.27	0.08	158	2.2
C	100-110	SG	50-70	9YR5/5	7.5	1.2	77	22	1.0	0.2	10	52	2.2	100	0.10	0.06	0.11	224	0.19

7d: Victoria Island, Haplorthel with weak stone stripes on moraine till; pm: >100 cm; surface: 10 % plant cover beside 3/4 stones + gr. and 1/4 f. soil

Ah	0-10	GR	10-30	8YR5/4	7.8	2.4	39	41	20	0.4	12	63	3.3	100	0.31	0.13	0.19	62	0.34
Cw	10-20	AB	10-30	5YR3.5/3	7.8	1.6	35	44	21	0.2	10	64	3.3	100	0.19	0.08	0.20	111	0.22
C	80-90	CO	30-50	7.5YR4/3				L											

8m: Paulatuk, Haplorthel on moraine till; pm: 105 cm; surface: 90 % plant cover beside 1/2 gravel + stones and 1/2 fine soil

Ah1	0-10	GR	10-30	10YR3/2	7.7	2.0		LS		2.8	13	30	13.7	100	0.27	0.18	0.24	226	2.2
Ah2	15-25	GR	10-30	10YR3.5/4	7.7	2.0	51	48	1.0	0.9	7.6	30	8.9	100	0.29	0.22	0.22	34	1.2
C1	30-40	CO	10-30	10YR5/4	7.7	1.7	70	22	7.5	0.2	25	32	2.7	100	0.15	0.13	0.17	26	0.09
C2	>100	CO	>30	9YR5/4				CL											

8d: Paulatuk, Haplorthel on moraine till; pm: >100 cm; surface: 2 % plant cover beside 3/4 gravel + stones and 1/4 fine soil

Ah	3-13	GR	10-30	8YR4/4	7.7	1.3	45	38	17	0.6	10	76	4.1	100	0.45	0.23	0.13	207	0.60
C1	30-40	CO	30-50	8YR5/4	7.7	1.1	49	33	16	0.1	10	43	3.1	100	0.89	0.14	0.17	205	0.13
C2	90-100	CO	>70	8YR5/3				CL											

Horizon	depth cm	structure	skelet %	colour moist	pH	e.c mS	sa %	si %	cl %	TOC %	C/N	Carb %	CEC	b.s. %	Fe_o ‰	Fe_o: Fe_d	P ‰	Mn_d ppm	Nt ‰
9m: Banks Island S., Molliturbel with weak polygons and hummocks on moraine till; pm: >100 cm; surface: 98 % plant cover beside stones																			
Ah1	3-13	GR	5-10	9YR3/2	7.6	1.8	45	33	22	4.3	13	3.3	27.6	100	0.88	0.21	0.44	200	3.4
Ah2	15-25	GR	5-10	10YR2.5/1	7.5	1.2	47	31	22	3.8	13	3.6	24.9	100	0.97	0.23	0.43	216	2.9
AC	50-55	AB	5-10	10YR2.5/1				CL											
9d: Banks Island S., Haploturbel with weak polygons on moraine till; pm: >100 cm; surface: 30 % plant cover beside 3/4 gravel + stones and 1/4 fine soil																			
Ah	0-10	GR	50-70	10YR2.5/2	7.3	07	57	21	22	1.7	12	13	12	100	0.67	0.17	0.33	119	0.14
AC	30-40	SB	50-70		7.7	1.1	58	32	10	0.7		16	3.6	100	0.36	0.12	0.27	144	0.10
C	80-90	CO	>70	10YR2.5/1				CL											
10d: Ivvavik, Psammoturbel on schist with thin moraine cover; surface with patterned ground of stones and 5 % vegetation cover																			
Ah	0-10	GR	>50	10YR4.5/3	5.3		87	8.5	4.3	1.0	12	0	6.8	80	0.38	0.11	0.28	67	0.77
10m: Ivvavik, Haploturbel on schist with thin moraine cover: surface patterned ground of hummocks with dense vegetation cover																			
OAh	0-10	SB	10-30	10YR4/2	4.6	0.5	56	26	18	13	27	0	19.0	62					4.7
12d: Banks Island N, Haploturbel on moraine till: surface with patterned ground of gravel and stones with some lichens																			
Ah	0-10	GR	30-50	10YR3/3	7.3		57	29	14	2.0	10	1	11.9	100					2.0
12m: Banks Island N, Haploturbel on moraine till: surface patterned ground with hummocks and dense vegetation cover																			
Ah	0-10	GR - SB	<5	9YR2.5/2 4/2.5	7.2	1.1	37	40	23	5.6	12	2.2	31.4	100	0.58	0.08	0.58	190	4.7
13d: Melville Island, (Lithic) Haploturbel on stony moraine: patterned ground w. 1/3 vegetation cover, 1/6 fine soil and 1/2 stones																			
Ah	0-10	GR	50-70	10YR3.5/2	6.7		50	36	14	1.1	15	0	6.7	96	0.38	0.36		81	0.71
13m: Melville Island, Haploturbel on stony moraine: pattered ground with hummocks and dense vegetation cover																			
O/Ah	0-10	GR	10-30	10YR2/2 - 3/3	6.3	0.7	73	19	7.7	3.0	14	0	11.4	78	0.86	0.68	0.19	46	2.2
14d: Ellef Ringnes Isld., Haploturbel on glaciofluvial clay: surface bleached polygons with deep cracks without vegetation cover																			
Ah/ Bw	0-10	SB- AB	<5	3Y4/3- 5/3	6.5		1	32	67	0.6	6.3	0	14.9	97			0.39		0.90
14m: Ellef Ringnes Isld., Haploturbel on glaciofluvial clay: surface hummocks with vegetation cover beside polygons with deep cracks																			
Ah/ Bw	0-10	GR- SB	0	2Y3/3-_4/3	6.4	0.4	3	36	61	2.7	13	0	17.9	82	0.58	0.31	2.05	2.6	2.1
15d: Ellesmere Island S, Haploturbel on moraine till; surface with stony patterned ground and 1/3 vegetation cover																			
Ah	0-10	GR	5-10	10YR4/2	7.4		13	84	2.7	0.9	8.4	72	6.5	100	0.15	0.35	0.18	11	1.1
15m: Ellesmere Island S, Haploturbel on moraine till: (no picture available)																			
Ah	0-10	GR	<5	1.5Y4/2	7.6	2.0	12	61	27	0.8	8.7	73	6.0	100	0.35	0.84	0.17	4.5	0.93
16d: Devon Island S. Psammoturbel on stony moraine sands: surface stony patterned ground with1/10 vegetation cover																			
Ah	0-10	GR- SG	10-30	7YR2.5/2- 3/2	7.0		88	7.3	4.2	1.6	3.0	0	10.7	55	ß.36	0.17	1.17	22	5.3
16m: Devon Island S, Folistel on moraine sands: surface patterned ground with hummocks and dense vegetation cover																			
H	0-10	SS- GR	0	6YR2.5/1	5.9	0.6	74	16	10	9.7	87	1.5	26.8	70	0.82	0.31	0.28	61	1.1
17d: Baffin Island E, Haploturbel on stony moraine sands: surface with stony patterned ground and 1/2 vegetation cover																			
Ah/ Bw	0-10	GR	10-30	9YR3/1.5- 3.5/2.5	4.8		74	17	8.6	1.5		0	17.8	30	0.29	0.29	0.28	7.2	0.74
17m: Baffin Island E, Haploturbel on stony moraine sands: surface with stony patterned ground and dense vegetation cover																			
Ah/ Bw	0-10	GR	10-30	9YR2/2- 4/2.5	5.1	0.6		LS		2.1	17	0	10.7	16	0.70	0.33	0.27	5.1	1.2

Tab. 2: Soil properties. Structure: AB = angular blocky, CO = coherent, GR = granular, SB= subangular blocky, SG = single grained, SS = stratified (by litter), skel = stones + gravel, sa = sand; si = silt; cl = clay (or texture: C = clay, L = loam, S = sand, Si = silt), H = clay; pH in $CaCl_2$; CEC in $cmol_c/kg$; h = humification intensity after von Post; pm = permafrost depth. Descriptions of soil surfaces are based on notes performed during the landings and by photos taken from the individual spots.

Tab. 2: Bodeneigenschaften. Struktur: AB = polyedrisch, CO = kohärent, GR = feinkrümelig, SB = subpolyedrisch, SG = Einzelkorn, SS = stratifiziert (durch Streu), skel = Steine + Kies, sa = Sand, si = Silt, cl = Ton, (oder Textur: C = Ton, L = Lehm, S = Sand, Si = Silt), H = Ton; pH in $CaCl_2$; CEC in $cmol_c/kg$; h = Humifikation nach Post; pm = Permafrosttiefe. Beschreibungen der Bodenoberflächen erfolgten aufgrund der Feldprotokolle und Photos.

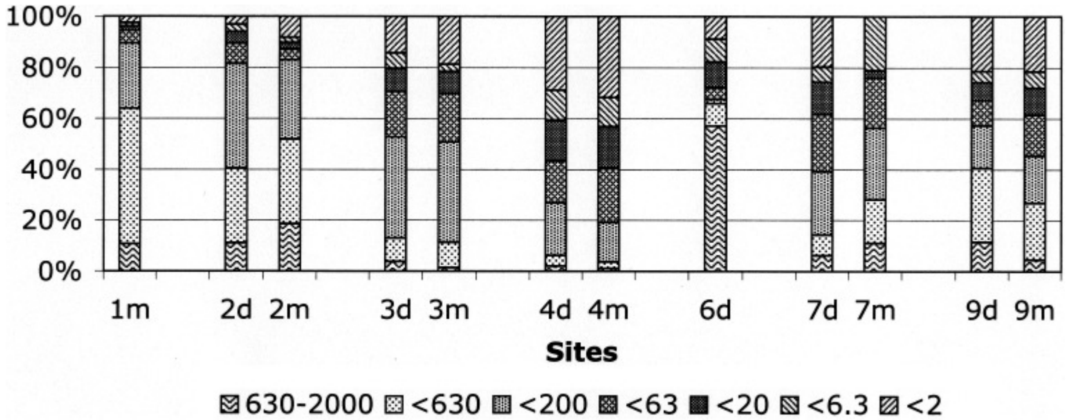

Fig. 2: Shares (wt.%) of grain sizes (μm) of soil samples (Leg 1, TNW-99).

Abb. 2: Anteile (Gew.%) von Korngrößenfraktionen (μm) von Bodenproben (Abschnitt 1, TNW-99).

Texture

A strong variation in the content of gravel and stones as well as the texture of fine soil was found (Tab. 2, Fig. 2). The dominant grain sizes were mS (median: 13.1 %), fS (24.8 %), and gU (14.9 %). Comparing the samples of dry (n = 21) and mesic (n = 23) sites, important shifts could be seen for the medians of gS (dry: 8.0 %; mesic: 4.7 %), mS (9.9 %; 17.0 %) and T (13.5 %; 8.3 %). A much higher content of gS were found in the surface layers of the dry *versus* mesic sites (median: 10.8 % and 2.9 %) indicating erosion due to lacking shelter of plant cover. Samples 1m (20-30 cm), 6d (0-10, 10-20 cm), 6m (15-25 cm) and 10d (0-10 cm) show extreme high values for gS (>50 %). Pedon 2m contained nearly no gravel and stones (like pedons C, J and K of Tarnocai 2004), sites 6m and 6d more than 70 %. In many cases no changes with depth were found (e.g., sites 2 and 3). In others, content of gravel and stones did rise with depth, partly combined with high content on the soil surface (e.g., Site 8d). Most soils were loamy: loam (e.g., 7d, 8d, 9m), clay loam (4m), and silt loam (4d, 7m), but also sands (1m, 6m) and loamy sands (e.g., 2m) did occur. But the analysed clay content was normally higher than the field test values (due to high content of fine silt calcite, destroyed before texture analysis). Tarnocai (2004) also described sandy pedons (C), sandy loams (E-G, K), and silt loams (A, B, J).

Organic matter and nitrogen (Tab. 2)

Soil organic matter was highly variable in content (>2 % TOC) and vertical distribution. Surface layers, especially at mesic sites, had a high TOC content, which decreased with depth at sites 1m, 2m, 6m, and 8m. There were no pronounced differences with depth in some cases (e.g., 4d, 9m, where low Munsell values and chroma in the subsoil indicated high TOC content in the subsoil, too). It also becomes evident that organic matter acts as the main buffer for moisture in relation to soil minerals.

C/N ratios show that this stock of organic matter was somewhat poor in nitrogen (e.g., 2d, 6, 10, 16), but still had mostly unremarkable values (C/N 10-20). Values of C/N >14 correspond with a dominance of annual plant species, whereas soils covered mainly perennials (like site 1m with heath) showed a wider range of values. Tarnocai (2004) found many soils with a strong difference in TOC content with depth (pedons E-G, J, K), due to intensive cryoturbation. The estimations of C/N ratios of Kristensen (1990), however, were found to be reasonably close in only a few instances. The procedure this earlier investigator used for determining TOC was based on volatile nitrogen-containing material as indicated by the $LOI_{(280)}$. But this method fails to include a significant portion of the soil organic matter.

Nitrogen and phosphorous are intensively involved in the processes of carbon cycling, biomass stock and microbial activity. Total nitrogen ranged between 0.09 and 5.3 mg g^{-1}, i.e., it varied over nearly a 60-fold span, with a median at 1.24 mg g^{-1}. A clear trend was apparent of decreasing content with increaseing depth, strongest at sites 1m, 3m, 7m, 8m and 9m.

Much less variability was noted with total phosphorous. The range of the data, 0.07-1.17 mg g^{-1}, was mainly due to two extremes (6m, 0-10 mg g^{-1} and 16d, 0-10 mg g^{-1}). The median value is 0.28 mg g^{-1}. The variability within individual profiles was also much lower than for nitrogen, only three sites showing a pronounced decrease with depth (1m, 3m, 7m).

pH and CEC (Tab. 2)

Most soils are alkaline due to their content of carbonates. Only Site 1 and Site 2 in the east (plus some pedons of Tarnocai 2004) were characterised by pH ($CaCl_2$) values <6, corresponding with base saturation values of <60. Strong differences in CEC values between 1 and 28 cmolc kg^{-1} were found, corresponding with differences in clay and TOC contents. Ca^{2+} clearly dominated the exchangeable bases. The cation-exchange capacity of all soil samples showed a median of 7.6 cmolc kg^{-1}. An exceptionally high value was found at site 6m (0-10 cm: 84.6 cmolc kg^{-1}). This was related to the high amount of Ca and due to the alkalinity of the parent material, a basic carbonatic rock. Other elevated values of elevated level (>21.0 cmolc kg^{-1}) were found in samples of sites 9m (3-13 cm: 27.6; 15-25 cm: 24.8 cmolc kg^{-1}), 12m (0-10 cm: 31.4 cmolc kg^{-1}), and 16m (0-10 cm: 26.8 cmolc kg^{-1}). Generally, CEC decreases with increasing depth.

The influence of the carbonate on pH($CaCl_2$) becomes evident. A threshold for pH($CaCl_2$) >7 becomes evident when there is more than 4-5 mg g^{-1} carbonate.

Carbonates and exchangeable cations (Tab. 2)

The great amount of exchangeable earth alkali cations Ca and Mg of some soils is due to the abundance of carbonatic parent material in this region. The distribution of $CaCO_3$ separates the region into two areas: On one hand, sites 1, 2, 10, 13, 14, 17 showed concentrations below 10 mg g^{-1}; on the other, sites 3-8 and 15 revealed amounts between 138 and 972 mg g^{-1}. At Site 9 the dry site contained 125 (0-10 cm) and 165 mg g^{-1} (30-40 cm), while the corresponding mesic site contained 33 and 36 mg g^{-1} at 3-13 cm and 15-25 cm, respectively. At Site 12d we found 260 mg g^{-1} (0-10 cm) and at 12m 22 mg g^{-1}. There is no evidence for a regular pattern within the depth profiles. A direct correlation between the parameters exchangeable Ca (mmolc kg^{-1}) and $CaCO_3$ (mg g^{-1}) could not be established.

Except for sites 1 and 2 (as well as pedons C, D and H of Tarnocai 2004) all soils in the east were enriched with carbonates between 3 % (9m) and >80 % (6d). Most of these revealed little difference between topsoil and subsoil, whereas Tarnocai found decarbonisation down to 57 cm at his Site J.

Exchangeable Mg contribution is mostly below 5 %, except for samples 7d (0-10 cm, 10-20 cm) 8 %; 9d (0-10 cm) 7 %; 14m (0-10 cm) 6 %. Higher content was found in samples 6m (0-10 cm) 3.5 cmolc kg^{-1}; 9d (0-10 cm) 0.84 cmolc kg^{-1}; 9m (3-13 cm) 1.13 cmolc kg^{-1}; 9m (15-25 cm) 1.05 cmolc kg^{-1}; and 16m (0-10 cm) 0.88 cmolc kg^{-1}.

The two exchangeable earth-alkali elements are highly correlated. The Pearson correlation coefficient showed a high agreement ($r = 0.956$, $n = 47$). Similarly, the correlations between CEC and Ca and Mg were very high (0.999 and 0.961, respectively). Linear relationships to K and Na could not be established, reflecting their low influence on CEC. Exchangeable potassium was elevated in samples 2m (0-5 cm) 0.27 cmolc kg^{-1}; 6m (0-10 cm) 0.37 cmolc kg^{-1}; 14d (0-10 cm) 1.27 cmolc kg^{-1}; and 14m (0-10 cm) 0.84 cmolc kg^{-1}. The values of sodium were very evenly distributed, only samples 6d (10-20 cm) 0.79 cmolc kg^{-1}; 6m (0-10 cm) 0.54 cmolc kg^{-1}; and 17d (0-10 cm) 3.09 cmolc kg^{-1} were exceptions. Potassium and sodium contributed, as is normal, to only a small degree to the CEC (mostly below 10 %) and exceptions can be seen in samples with low CEC values.

Salt (Tab. 2)

Most soils had low salt content, e.g., values between 0.75 and 2.4 mS cm^{-1} in the saturation extract (Tab. 2), especially in the topsoil, which could be an influence of ocean water spray. Many data of Tarnocai (2004) show the same effect when transforming his data to the water content of the saturation extract.

The conductivity (median 126 μS cm^{-1}) showed a clear decreasing tendency with increasing depth. Direct relationship to one of the cations could not be established; but the Pearson correlation coefficient between CEC and conductivity had a value of 0.613. Total salt concentrations, derived from the conductivity data, thus showed values between 14 and 327 mg L^{-1} (median 140 mg L^{-1}).

Pedogenic oxides (Tab. 2)

Strong differences in the contents of oxalate extractable iron (Fe_o mainly ferrihydrite and organic Fe compounds; Schlichting et al. 1995) were found. Higher values corresponded with higher TOC content in some cases (e.g., 1m, 2m, 4m), but not in all (e.g., 8d). In most cases the Fe_o/Fe_d quotients were low so that most of the dithionite-extractable iron (Fe_d) was likely to be lithogenetic and thus part of the parent material. Both soils of Site 3 were red in colour (Munsell 6 to 7 YR), but had low Fe_o content: they were therefore probably formed from haematitic parent rock (formation of haematite occurs only in warm climates).

The depth distribution of iron shows no homogeneous pattern. Slight increases could be monitored for dithionite extractable iron at sites 1m, 2d, 3d, 3m, 6m, 7d, 7m, and 9m.

Manganese showed a stronger differentiation among depth layers. Increasing content with depth was shown for 2m, 4d, 7d, 7m, 9d, 9m, two fewer than at sites of decreasing content with depth, namely 1m, 2d, 3d, 3m, 4m, 6d, 6m, 8m. A decrease in the content of Fe_o and Mn_d with depth is typically accompanied by a decreasing rate of silicate weathering and browning reaction. If there had been a maximum of them in the subsoil this would have indicated enrichment by podzolisation or gley formation.

Local plant, soil and mineral variability.

Strong differences existed in the intensity of plant cover (Tab. 3a) and the amount of bacterial biomass (Tab. 3b), especially between mesic and dry soil of the same site. This indicated strong variability in ecological conditions. The indicators for specific site conditions have been taken from Walter & Breckle (1991) and Dierssen (1996). The main plant species (Tab. 3a) reflected the site conditions. As examples, *Vaccinium vitis idaea* and *V. uliginosum* shared the drier and meso- to dystrophic conditions of Site 1; *Carex bigelowii* was present in the wet and mesotrophic conditions of Site 2; *Carex aquatilis* and *C. misandra* were noted to be growing together with *Eriopherum angustifolium* and *Salix arctica* in the wet and eutrophic to calcitrophic site conditions of Site 4.

Statistically we cannot separate the dry from mesic sites. The ranges of the individual parameters invariably had such wide overlaps that discrimination among them was not possible. This held true for both inorganic and organic matter. Nevertheless, individual sites demonstrated some marked patterns that are worthy to be mentioned.

The highest contents of coarse sand (gS) were found at Site 6 (King William Island), over 90 % being found in the deep layers of the dry and the mesic site (for details cf. Tab. 2 and Fig. 2). The site at Ivvavik (10d, m) showed nearly 40 % (dry) and more than 60 % (mesic) of this sandy material. Combining the next size classes (mS + fS), sites on Ungava (1m), Melville Peninsula (2m), Devon Island (16d) and Baffin Island (17d) were noted to have dominant proportions of this material. Sites on Melville Island (13m), Ellef Ringnes Island (14m), Ellesmere Island (15d), Devon Island (16d) and Baffin Island (17d) were found to contain high amounts of silt (mU, fU). Only site

site	a.s.l.[1] (m)	direc-tion	months snow[2]	temp. °C [3]	frost[4] (cm)	main plant species
1m	60	W	3-4	3	65	*Vaccinium vit.-idaea + uliginosum, Salix herbacea, Cassiope tetragona*
2m	90	W	2	2	35	*Cassiope tetragona, Dryas integrifolia, Salix arctica, Carex bigelowii*
2d	140	-	1-2	1.5	65	*Cassiope tetragona, Dryas integrifolia, Saxifraga opp., Salix arctica*
3m	40	S	2	2	40	*Carex misandra, + stans, Arctagrostis lat., Erioph. ang., Dryas integrifolia, Salix arctica*
3d	85	S	1-2	1.5	55	*Dryas integrifolia, Salix arctica, Saxifraga opp., Carex rup.*
4m	110	SW	0-1	0.2	50	*Hierochoe alp., Carex aquat., - misan., Erioph. ang., - scheuchz., Arctagr. latif., Draba corymbosa, - lactea, Saxifraga spp., Salix arctica*
4d	150	SW	0-1	0.1	45	*Dryas integrifolia, Salix arctica, Papava radi., Draba corymbosa, Saxifraga oppositifolia*
6m	5	-	3	1.5	>50	*Poa arct., -abbrev., Car. misan., - scirp., Dryas integrifolia, Saxifr. tri., Draba corymbosa*
6d	10	-	3	1.5	80	*Dryas integrifolia, Sax. Tri., - opp., Draba corymbosa, Papava radi., Salix arctica*
7m	180	S	1-2	2.5	40	*Salix arct., - reticulata, Dryas integrifolia,*
7d	200	S	1-2	2.5	>100	*Dryas integrifolia, Saxifraga oppositifolia*
8m	80	-	4	5	105	*Carex spp., Dryas integrifolia, Saxifraga oppositif., Silene acaulis, Hedysarum mackenzei*
8d	110	W	3-4	4.5	>100	*Carex spp., Dryas integrifolia, Saxifraga oppositifolia*
9m	250	W	2	3	55	*Carex spp., Dryas integrifolia, Salix arctica*
9d	290	-	1-2	2.5	>100	*Dryas integrifolia, Draba cinerea, Artemisia borealis, Salix arctica*

Tab. 3a: Ecological conditions of representative Canadian soils with permafrost to a depth of 30 cm. Climatic and vegetational characteristics of sites 1-9. [1] meter above sea level; [2] months without snow; [3] mean temperature of summer months; [4] depth of permafrost in cm.

Tab. 3a: Ökologische Eigenschaften repräsentativer Böden Kanadas mit Permafrost bis zur Tiefe von 30 cm. Klimatische und vegetationskundliche Charakteristika der Stationen 1-9. [1] Meter über NN; [2] Monate ohne Schnee; [3] mittlere Temperatur der Sommermonate; [4] Permafrosttiefe in cm.

site	oxyg. defic.	sali-nity[1]	Skelet. %	awc[2] $l\ m^{-2}$	K_a $g\ m^{-2}$	Ca_a $g\ m^{-2}$	Mg_a $g\ m^{-2}$	P_t $g\ m^{-2}$	org.m. $kg\ m^{-2}$	C/N	roots[3] cm	bac-C $mg\ m^{-2}$
1m	-	not	40	21	4.1	150	1.4	69	2.8	13	30	170
2m	+	not	<5	62	20	120	1.9	89	7.0	15	20	108
2d	-	v. l. - l.	20	53	9.4	41	0.94	72	2.7	32	20	149
3m	-	v. l.	40	59	11	540	6.1	85	24	11	25	397
3d	-	v. l.	40	49	13	600	15	71	7.3	10	15	150
4m	+	not	8	57	12	380	5.9	175	9.2	13	25	172
4d	-	v. l.	60	34	4.9	170	6.3	74	3.8	16	10	42
6m	-	v. l.	85	9	3.2	290	7.9	43	4.0	34	30	66
6d	-	v. l.	85	9	0.5	11	0.4	5	0.5	22	15	27
7m	-	v. l.	20	75	10	530	14	44	13	12	40	137
7d	-	l. - v. l.	20	60	17	134	7.7	48	1.4	11	35	158
8m	-	l. - v. l.	20	60	15	510	10	56	9.2	9	25	97
8d	-	l.	30	54	7.3	134	3.3	32	1.7	10	15	64
9m	-	l.	8	80	21	1340	37	122	23	13	35	319
9d	-	l.	60	27	8.0	166	8.2	36	3.1	12	40	18

Tab. 3b: Ecological conditions of representative Canadian soils with permafrost to a depth of 30 cm. Summarized data for bacterial C (bac-C), available water capacity (awc), nutrients and humus (TOC x 2) were done for total soil (incl. skeleton) and a postulated bulk density of 1 kg l^{-1} for loamy and/or humus (>2 % TOC), and 1.2 kg l^{-1} for other soil horizons; for methodical details see BÖLTER et al. (2002) and SCHLICHTING et al. (1996). [1] salinity calculated from electrical conductivity of the saturation extract in mS; (not) = <0.75 mS, very low (v.l.) = 0.75-2 mS, low (l) = 2-4 mS); [2] awc = available water capacity; [3] deph of plant roots in cm; skeleton = volume of stones + gravel; available water capacity = sum of pores with a diameter between 0.2 and 50 μm; K_a, Ca_a, Mg_a = exchangeable cations; P_t = total P; org. m = organic matter (= TOC x 2).

Tab. 3b: Ökologische Eigenschaften repräsentativer Böden Kanadas mit Permafrost bis zur Tiefe von 30 cm. Zusammenfassungen für bakteriellen Kohlenstoff (bac-C), verfügbares Wasser (awc), Nährstoffe und Humus (TOC x 2) wurden berechnet für den Gesamtboden (inkl. Skelettanteil) und eine angenommene Dichte von 1 kg l^{-1} für lehmige und/oder humose Böden (>2 % TOC), und 1.2 kg l^{-1} für andere Bödenhorizonte; methodische Details bei BÖLTER et al. (2002) sowie SCHLICHTING et al. (1996). [1] Salzgehalt erechnet aus der elektrischen Leitfähigkeit des Sättigungsextraktes in mS; kein (not) = <0,75 mS; sehr gering (v.l.) = 0,75-2 mS; gering (l) = 2-4 mS); [2] awc = verfügbares Wasser; [3] Tiefe der Durchwurzelung in cm; Skelett = Volumina von Steinen + Kies; awc = Summe der Poren mit Durchmessern 0,2 bis 50 μm; K_a, Ca_a, Mg_a = austauschbare Kationen; P_t = gesamt P; org. m = organic Material (= TOC x 2).

14d at Ellef Ringnes Island was recorded with an extraordinary amount of clay (67 %).

Site 6d was strongly layered, being formed from fluvio-glacial sands and gravel (whereas TARNOCAI (2004) studied two sites – C and D – of eolian sand). The other soils were formed from glacial sediments (and solifluction deposits) as indicated by their irregularly deposited gravel and stones. Most of the mesic sites were situated on ground moraines, whereas most of the dry sites were on stony end moraines. The moraines of Site 1 (Ungava Peninsula) and Site 2 (Melville Peninsula), as well as the sandy pedons on Baffin Island of TARNOCAI (2004) in the east, were found to be poor in or free of carbonates, reflecting the granite petrography of the landscape. The parent material of the other soils is influenced by limestone as well as calcareous schist, sands and clays.

It has been mentioned that sample 6m (King William Island, 0-10 cm) showed the outstanding value for CEC (84.0 cmolc kg^{-1}). Exceptional values for this parameter could nearly always be found in samples from mesic sites (Sommerset Island, Banks Island and Devon Island).

High amounts for sodium and potassium were only observed on Melville Peninsula (2d, m) and King William Island (6d, m). No other sites had a noteworthy content of these nutrients. The content of calcium was very high for all samples in terms of its contribution to all cations, generally more than 80 %. This value is also true for the extreme on King William Island. For this element, it is worthwhile to mention that the sites on Melville Peninsula and Baffin Island had a much lower content than the other sites. Magnesium showed high variability with regard to its share of the total cations (Wollaston Peninsula, Banks Island south, Ellef Ringnes Island), but extreme levels could only be monitored for King William Island (6m, 0-10 cm).

The pH seems to be a parameter more appropriate than any of the others for grouping sites into regions. A dividing line appears to fall at $pH(CaCl_2) = 7$. Below this level were found to be the sites on Ungava, Melville Peninsula, Ivvavik, Ellef Ringnes Island, Baffin Island and the mesic sites on Melville Island and Devon Island. This coincides widely with the carbonatic parent material of the other sites where the soils have a more alkaline reaction.

Values for conductivity were noted to be widely scattered; dry and wet sites, as well as samples from individual horizons, yielded great differences, e.g., on Melville Peninsula (2m), King William Island (6m), Paulatuk (8m) Banks Island South (9m), Ivvavik (10), Melville Island (13), Ellesmere Island (15) and Devon Island (16).

Almost all samples had a content of nitrogen (N_t) between 0.1 and 3 mg g^{-1}. Exceptions were valid only for Ivvavik (10m: 4.7 mg g^{-1}), Banks Island north (12m: 4.7 mg g^{-1}) and Devon Island (16d: 5.3 mg g^{-1}). Similarly, the content of phosphorous (P_t) for nearly all samples was between 0.01 and 0.6 mg g^{-1}. Only the sites on King William Island (6m) and Devon Island (16d) were exceptions with 0.9 and 1.2 mg g^{-1}, respectively. For King William Island this coincided with the high level of calcium. On Devon Island this cation is not that dominant; its content is just 5.3 cmolc kg^{-1}.

Organic matter content (C_{org} % d.wt.) also cannot be used to discriminate sets of stations from others, i.e., to elucidate regional aspects. Generally, the mesic sites have higher values when comparing individual locations, and, further, the top soil level showed highest content of C_{org} in a profile. This became especially evident for the mesic plots at sites Ungava (1), Melville Peninsula (2), King William Island (6), and Paulatuk (9). Sites exceeding all others by far were the mesic sites at Ivvavik (10) and on Devon Island (16). This description is also true for absolute C content and generally for the data from loss on ignition. Differences among these data sets probably are due to variabilities among individual samples.

DISCUSSION

The expedition TNW-99 has provided further insights into soil ecological properties in the arctic realm of Canada. Earlier studies in the region by soil scientists and botanists have described several sub-regions for this area, as summarized and presented recently by Goryachkin et al. (2004), Smith & Veldhuis (2004) and Tarnocai (2004). Detailed analyses of site-related soils, however, reveal wide variability and point to several local aspects overlying general zonations. Such effects can also be seen in the data of Tarnocai et al. (2004). In any case, they all show the dominant features of Cryosols.

The tundra soils of this transect reflect a wide range of soil-forming factors and processes. Soil formation is strongly affected by local topographic, geologic, hydrologic and climatic features; cryoturbation leads to an unstable environment which hampers the settlement of rooting and non-rooting plants (Tedrow 1968, 1977). The dominant soil-forming processes in this area are cryoturbation, physical and partly chemical weathering together with acidification, humus accumulation, and sometimes braunification, podzolisation, gleying, and mottling due to water stagnation, calcification is common in areas with lime stone and dolomite under dry conditions (see also Bliss 1997).

Soil thaw depths were mostly found within 20-100 cm they are comparable to other locations of this area (e.g., Everett et al. 1981, Muc et al. 1994, Nams & Freedman 1994). Permafrost starts in our and in Tarnocai's soils at a depth between 35 and 85 cm in the High Arctic, 35 and 85 cm in the Mid Arctic, and 57 and >100 cm in the Low Arctic. It starts at a lower depth under dense vegetation cover due to strong insolation, and in loamy soils due to higher water capacity in relation to soils with a low vegetation cover or with a sandy to stony texture.

Most soils show cryoturbation phenomena such as stone circles (e.g., Site 2), earthy hummocks (e.g., site 6m) and stripes on slopes (e.g., site 3d). In some soils almost no difference in content of stones, clay, TOC and/or carbonates occur (e.g., 2d, 4m, 9m) because of a strong early or recent mixing by cryoturbation above the permafrost. Other soils have discontinuous depth functions of humus, like pedons 5-7, 9 and 10 of Tarnocai (2004), due to an incomplete mixing by cryo-turbation. In other soils an enrichment of stones and gravel on the soil surface had taken place (e.g., Site 3d) and stone plates are standing vertically due to an upward movement of coarser particles (see also Blume et al. 2002a). The stones of other soils had silt cups on their upper surface, but clear surfaces elsewhere (e.g., 2d), which is typical for solifluction deposits on slopes.

Practically all studied soils of the High Arctic are strongly influenced by cryoturbation, whereas in the Mid and in the Low Arctic some soils without an active cryoturbation were observed, especially sandy ones like 1m, 6m and 6d, together with pedons C and D of Tarnocai (2004) and stony ones like 8d. Coarser and well-drained soils covered with lichens show fewer cryoturbation patterns; they occur mainly at mesic sites, where earth hummocks or other typical frost patterns are seen. Cryoturbation is often an important factor for the distribution of soil organic matter. Frost action has also been described as an important cause of the breakdown of organic particles (Rieger 1974).

A strong humus accumulation took place in most soils, especially on mesic sites with a complete vegetation cover (e.g., sites

3m, 7m, 9m in Tab. 4), due to an absolutely low but relatively high biomass production corresponding to extremely low litter decomposition by soil organisms together with a translocation of TOC by cryoturbation into the subsoil (which is typical for similar soils in the Antarctic as well; BLUME et al. 2002b).

Due to a parent substrate free of carbonates, the soils of Site 1 in the Low Arctic and Site 2 in the Mid Arctic were acidified and had lost part of their bases, as at sites C and D of Tarnocai in the Mid Arctic. This was also found under similar conditions in the Antarctic (BLUME et al. 2002a,b). Soils H to K of Tarnocai in the Low Arctic were acidified in the topsoil, due to low contents of carbonates in the parent material. Our studied top soils 10d, m in the Low Arctic, 17d,m in the Mid Arctic and 16m in the High Arctic also had this property.

Sites on the Queen Elizabeth Islands (Bathurst, Ellesmere, Melville, Devon, Cornwallis, Axel Heiberg and Ellef Ringnes), where base-rich dolomitic deposits were found, showed slightly alkaline reactions (EVERETT et al. 1981; BLISS et al. 1984). Soils at shores of Devon Island (Truelove Lowland) were noted to have pH ($CaCl_2$) values between 5.5 and 6.1 (BLISS & GOLD 1994). Calcareous soils were also found in northern Alaska (DOUGLAS & TEDROW 1960) and the Prudhoe Bay region (EVERETT & PARKINSON 1977), where they might have been derived from loess and lacustrine materials.

We think that at least in soil 1 (and in C of Tarnocai) a chemical weathering also took place and a Bw horizon was formed by braunification (after ARNOLD 1983) at low temperature, due to strong physical weathering and cryoturbation. By this process, chemical weathering becomes possible despite low temperature. This soil also showed a bleached albic E due to podzolisation, but a pronounced spodic B was not found, i.e., enrichment with relocated Fe compounds. The other soils were probably partly decalcified, but this cannot be observed in soils of other climate zones due to a mixing of soil material above the permafrost. Other soils did not show braunification patterns despite low acidification and weak silicate weathering.

In the area of the Canadian Arctic Archipelago, larger outcrops of limestone, gypsum and dolomite as dominant features for soil chemistry are found only south of Lancaster Strait – Barrow Strait – Viscount Melville Sound, i.e., northwestern parts of Baffin Island, Somerset Island, Prince of Wales Island, western Boothia Peninsula, King William Island, and Victoria Island (FORD 1993); our study did not include such observations.

Sites 2m and 4m as well as the soils D and J of TARNOCAI (2004) had a stagnic colour pattern (ISSS/ISRIC/FAO 1998) due to water stagnation – and therefore oxygen deficiency – above the permafrost. This meets descriptions of reports from the CANADIAN SOIL SURVEY COMMITTEE (1978), who also describe several soils of the High Arctic as Pergelic Cryaquepts. A similar, more detailed, study was undertaken by BLEICH & STAHR (1978) on Banks Island (Low Arctic). They found the formation of a thin iron pan in addition, which is typical for mountains of Central Europe under perhumid climate conditions.

Soil Classification

According to the US Soil Taxonomy all soils are Gelisols due to permafrost, at least in the second meter, together with gelic materials above the permafrost (Tab. 4). Except for one Folistel (16m) all studied soils of the Low Arctic were Turbels. This is in agreement with TARNOCAI (2004), who also described one Hemistel (L) in addition to Turbels in the High Arctic. In the Mid and in the Low Arctic Orthels exist beside Turbels. Orthels also showed some weak cryoturbation phenomena, but they are much more pronounced in the Turbels: Very weak polygons or stripes seem to be relictic in the Orthels. TARNOCAI (2004) described the same phenomena.

No.	Soil Taxonomy (Soil Survey Staff 1999)	WRB (ISSS/ISRIC/FAO 1998)
1m	Typic Haplorthel (sandy-skeletal, non acid, pergelic)	Skeleti-gelic Cambisol (albic)
2m	Psammentic Aquiturbel (non acid, hypergelic)	Stagni-turbic Cryosol (eutric, Arenic)
2d	Typic Haploturbel (loamy, non acid, hypergelic)	Hapli-turbic Cryosol (dystric)
3m	Typic Haploturbel (loamy-skeletal, calcareous, hyp.gelic)	Calcari-turbic Cryosol (chromic, skeletic)
3d	Typic Haploturbel (loamy-skeletal, calcareous, hyp.gelic)	Calcari-turbic Cryosol (skeletic, chromic)
4m	Typic Aquiturbel (loamy, calcareous, hypergelic)	Stagni-turbic Cryosol (mollic, calcaric)
4d	Typic Haploturbel (loamy-skeletal, calcareous, hyp.gelic)	Skeleti-turbic Cryosol (calcaric)
6m	Lithic Haplorthel (sandy-skeletal, calcareous, pergelic)	Skeleti-leptic Cryosol (calcaric)
6d	Typic Haplorthel (sandy-skeletal, calcareous, pergelic)	Skeleti-haplic Cryosol (calcaric)
7m	Cumulic Molorthel (loamy, calcareous, pergelic)	Humi-mollic Cryosol (calcaric)
7d	Typic Haplorthel (loamy, calcareous, pergelic)	Haplic Cryosol (calcaric)
8m	Typic Haplorthel (loamy, calcareous, pergelic)	Molli-gelic Cambisol (calcaric)
8d	Typic Haplorthel (loamy-skeletal, calcareous, pergelic)	Calcari-gelic Regosol (skeletic)
9m	Cumulic Molliturbel (loamy, calcareous, pergelic)	Molli-turbic Cryosol (humic, calcaric)
9d	Typic Haploturbel (loamy-skeletal, calcareous, pergelic)	Skeleti-haplic Cryosol (calcaric)

Tab. 4: Classification of representative soils in northern Canada.

Tab. 4: Klassifikation repräsentativer Böden in Nordkanada.

Most soils were classified as Cryosols after WRB (ISSS-ISRIC-FAO 1998), the Turbels as turbic subunits. But sites 8m and 8d were classified as gelic subunits of Cambisol and Regosol due to low influence of cryoturbation, and permafrost in the second meter only. But these Cambisols show only acidified and physically weathered B horizons and in relation to the C horizons no braunification. Site 1m was also classified as a gelic subunit, because the existence of pronounced albic E without any cryoturbation phenomena clearly shows the relictic character of the very weak frost pattern on the soil surface, which is most probably relictic.

Arctic soils as habitats for plants and soil organisms

Organic matter contents are low in the dry sites, seldom higher than 1 %, if there is no spot of dense plant cover. Although the nature of this material was not characterized in detail, its quantity does not allow more non-plant life than microbes or few collembolans and nematodes close to roots (ERIKSEN et al. 2006). Storages of organic matter in arctic tundra environments have become a focus point, since the hypothesis has been introduced that the tundra changes from a CO_2 sink to a CO_2 source because of global warming (OECHEL et al. 1993, 1995, WAELBROECK et al. 1997).

The strong differences in the intensity of plant cover as indicated by soil organic matter content and the amount of bacterial biomass (Tab. 3b and BÖLTER 2006) were evident among the studied soils. Even mesic and dry soil of the same site showed strong differences in the ecological conditions. Table 5 shows ratings for these factors.

These ratings were taken from SCHLICHTING et al. (1995), but were adapted to arctic climatic conditions after BÖLTER & BLUME (2002). We restricted the rating of soil conditions to a depth of 30 cm, because most roots were found above this depth. The highest amount of bacterial biomass was found in sites 3m and 9m. These were sites with extremely high amounts of organic matter with a low C/N value (because of the low inorganic N in relation to microbes = organic N), with a medium to slightly high available water capacity and medium (K, Mg) to extremely high (Ca) amounts of inorganic nutrients. But the vegetation period of these sites is relatively short and is combined with a low mean temperature. So the bacterial biomass is absolutely low. But the biomass of all of the other sites is also low, under conditions of a longer vegetation period together with a higher mean temperature. We think the main restrictions came from low amounts of organic matter (e.g., 6d), relatively low amounts of nutrients, especially Mg (e.g., 1m, 2m, 6d, 8d), a low available water capacity (e.g., 6m, 6d) and/or oxygen deficiency at sites 2m and 4m.

Our data on soil organic matter (Tab. 5) range from 0.5-7.3 kg m^{-2} (mean: 2.9) for the dry sites and from 2.8-24 kg m^{-2} (mean: 11.5) for the wet sites. In other studies between 4 and 94 kg C m^{-2} were reported for dry to wet tundra (POST et al. 1982; OECHEL & BILLINGS 1992; TARNOCAI et al. 1993). A high content has been found in coastal plain tundra (94 kg), a low content in alpine slope soils (MICHAELSON et al. 1996). The upper layers were found to contain 20-30 kg C m^{-2}, where the horizons A and O are the most important places of C storage (CHAPIN et al. 1980, OECHEL & BILLINGS 1992). Thus, the bulk of organic matter can be assumed to be located above the permafrost table (and thus comparable to ours), but permafrost soils are also known to have C accumulations in deeper layers (ZIMOV et al. 1993) These stores may serve as a pool to maintain microbial populations (i.e., sustain basic metabolism) during the cold season as long as available water is present (OECHEL et al 1997).

Much of the soil organic matter belongs to the below-ground standing crop as graminoid roots or rhizomes. These plant parts are shown to contribute between 59 % (sandy stream bank) and 99 % (wet meadow) of this stock at Alexandra Fjord; the majority of this, however, could be defined as dead organic matter, and ratios between above-ground and below-ground plant standing crop of wet to mesic meadows range between 0.01 and 0.25 (HENRY & SVOBODA 1994). A comparable share of dead roots (80 %) was found by DENNIS et al. (1978) in meadows at Barrow.

As previously stated, Table 4a shows the main plant species. WALTER & BRECKLE (1991) and DIERSSEN (1996) give indicators for specific site conditions. However, during this study, plant species with very different optimal site conditions were found with each other: e.g., *Dryas integrifolia* (likes dry eutrophic sites) was observed in close proximity to *Eriopherum angustifolium* (likes wet mesotrophic sites) at site 3m. This is probably the result of large differences in site conditions, which sometimes change from decimeters to decimeters: e.g., the seemingly incongruous combination results from stony dry rings and loamy moist centres of polygons.

On the other hand, the main plant species do reflect special site conditions, e.g., *Vaccinium vitis idaea* and *V. uliginosum* share the drier and meso- to dystrophic conditions of Site 1; *Carex bigelowii* is present in the wet and mesotrophic conditions of Site 2; *C. aquatilis* and *C. misandra* are growing together with *E. angustifolium,* and *Salix arctica* is present in wet and eutrophic to calcitrophic site conditions of Site 4.

step	1 very low	2 low	3 medium	4 slightly high	5 high	6 very high	7 extr. high
snow free period in months	0-1	1.5	3	6	9	12	
penetrability by roots[1] (%)	100	85	60	40	15	0	
available water capacity [2] (l m^{-2})	< 15	30	60	90	140	200	>
K_a (g m^{-2})	< 2	8	24	48	80	200	>
Ca_a (g m^{-2})	< 4	15	50	100	200	500	>
Mg_a (g m^{-2})	< 2	5	15	30	60	150	>
P_t (g m^{-2})	< 5	25	125	175	250	400	>
organic matter (kg m^{-2})	< 0.2	0.5	1.0	2	4	8	>
bacterial biomass[3] (g C m^{-2})	< 0.3	0.6	1.2	3	6	>	

Tab. 5: Assessments of ecological site conditions (BÖLTER et al. 2002, after SCHLICHTING et al. 1996) in polar regions for 3 dm soil depth of soils with permafrost in Canada. [1] penetrability by roots = mass % of stones + gravel, rock = 100 %; mean of 3 dm. [2] available water capacity (+ groundwater if high groundwater table). [3] bacterial biomass in g C m^{-2} {rating of 1/2 microbial biomass after MACHULLA (1997), with adaption due to mean temperature of the vegetation period after BLUME et al. (1991)}.

Tab. 5: Einschätzung der ökologischen Bedingungen für Böden in den Polarregionen Kanadas mit Permafrost, geltend für 3 dm Bodentiefe (BÖLTER et al. 2002, nach SCHLICHTING et al. 1996). [1] Durchwurzelung (% = Masse Steine + Kies, 100% = Fels); [2] Verfügbare Wasserkapazität (+ Grundwasser bei anstehendem Wasser); [3] Bakterienbiomasse in g C m^{-2} {Schätzung nach MACHULLA 1997), unter Einbeziehung von mittlerer Temperatur während der Vegetationsperiode nach BLUME et al. 1991)}.

The amounts of N and P entering the system via precipitation are low in relation to the total pools. Freeze – thaw cycles can replace some loss of phosphorous via mineral weathering. At Devon Island as well as at Barrow (Alaska) N comes mainly from precipitation, the amount at Barrow being 23 mg N m^{-2} in 120 mm precipitation (ALEXANDER 1974). Thus snowfall contributes to about 30 % of the total N input, while phosphorous from precipitation amounts to only 6 % of the labile inorganic phosphor pool (GERSPER et al. 1980). Horizontal snowmelt runoff leads to a net loss of nutrients, a main cause of nutrient depletion of arctic soils (GERSPER et al. 1980, RYDEN 1981), and the remaining nutrients are only marginally available for plants.

Nitrogen has been regarded to be more limiting than phosphorous or potassium (HAAG 1974). The N limitation, however, may be the cause of elevated C/N ratios of microbial biomass (CHENG & VIRGINIA 1993). This effect may further be a result of decoupling of N mineralization from C mineralization (GIBLIN et al. 1991, NADELHOFFER et al. 1991), thus affecting the N availability for plants. Denitrification is of minor importance and probably not a significant factor in N loss (GERSPER et al. 1980). This is probably due to the well-aerated soil properties of the mesic tundra sites; denitrifiers do not exceed 5 % of the culturable bacteria at Barrow (BUNNELL et al. 1980).

CONCLUSIONS

The soils of the Mid and High Arctic are mixed by cryoturbation; thus there are mainly Turbels and Histels. The Low Arctic soils are less dominated by this process and so we find primarily Orthels. Soil texture is determined by the parent material. Soils from carbonatic parent material show only low acidification and content of available Ca and Mg is high. Carbonate-poor or carbonate-free soils have stronger acidification, but podzolisation is rare (only at Site 1). Significant braunification was not observed. Humic topsoils reveal a fine coagulate structure, with no crumbles observed such as could be produced by small arthropods. Subsoils of sandy substrates have a single-grained structure, those from loamy to silty substrates a subangular to prismatic structure, possibly results from swell – shrink processes.

Growth conditions for higher plants and living conditions for microbes are dominated by low temperatures and a short vegetation period. Further limiting conditions are a high stone content and a scarcity of available nutrients, consequences of sandy soil structure and acidic conditions. Cryoturbation seems to be of minor importance for plant growth and soil activity. Soils in the vicinity of coasts showed elevated contents of salts, but not to an extent that could limit plant growth significantly. Most soils showed good aeration.

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