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Permafrost Soils

Springer

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Preface

Most of the Earth's biosphere is characterized by low temperatures. Vast areas (>20%) of the soil ecosystem are permanently frozen or are unfrozen for only a few weeks in summer. Permafrost regions occur at high latitudes and also at high elevations; a significant part of the global permafrost area is represented by mountains.

Permafrost soils are of global interest, since a significant increase in temperature is predicted for polar regions. Global warming will have a great impact on these soils, especially in northern regions, since they contain large amounts of organic carbon and act as carbon sinks, and a temperature increase will result in a release of carbon into the atmosphere. Additionally, the intensified release of the climate-relevant tracer gas methane represents a potential environmental harzard.

Significant numbers of viable microorganisms, including bacteria, archaea, phototrophic cyanobacteria and green algae, fungi and protozoa, are present in permafrost, and the characteristics of these microorganisms reflect the unique and extreme conditions of the permafrost environment. Remarkably, these microorganisms have been reported to be metabolically active at subzero temperatures, even down to −20°C.

This book summarizes recent knowledge on various aspects of permafrost and permafrost-affected soils, including typical properties of these soils, distribution and biodiversity of permafrost microorganisms, examples for microbial activity in frozen soils, and genomic and proteomic insights into cold adaptation of permafrost bacteria. The impact of global warming on microbial communities, carbon dynamics, geomorphology, and frozen-ground engineering are further discussed. Other chapters describe the feasibility and limitations of methods for removing contaminants in frozen ground. Finally, terrestrial permafrost is considered as a model for extraterrestrial habitats.

I wish to thank all authors, who are authorities in their field, for their excellent contributions. I also thank Dr. Franz Schinner for many interesting discussions and Dr. Jutta Lindenborn and Dr. Dieter Czeschlik, Springer Life Sciences, for continuous support during the preparation of this volume.

Innsbruck, April 2008 Rosa Margesin

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Part I
Geological, Chemical and Physical Properties of Permafrost

Chapter 1
Arctic Permafrost Soils

Charles Tarnocai

1.1 Introduction

The Arctic region, the portion of the Northern Hemisphere lying north of the arctic tree line, covers a land area of approximately 7.2×10^6 km^2. Approximately equal extents of most of this area (66%) occur in Canada and Russia, with lesser extents occurring in the United States (Alaska), Greenland and Scandinavia. Glaciers cover approximately 1.9×10^6 km^2 (26%) of this land area, with most of the glaciers (92%) occurring in Greenland.

At the beginning of the twentieth century, German and Russian soil scientists carried out soil studies in the Eurasian Arctic region (Kvashnin-Samarin 1911; Sukachev 1911; Meinardus 1912; Blanck 1919). These scientists used primarily a geological approach to study Arctic soils. In the North American Arctic, Everett (1968), Leahey (1947), Tedrow and Douglas (1964) and Tedrow et al. (1968) carried out the early pedological studies in the Arctic. Although these North American scientists applied a pedological approach to their studies, they viewed these soils as merely frozen versions of temperate soils — formed by much weaker, but basically similar, processes to those taking place in unfrozen soils.

During the early 1970s, Canadian soil scientists carried out extensive pedological work in northern Canada. When they realized that the development of these soils was dominated by cryogenic processes, they developed the Cryosolic Order for the Canadian System of Soil Classification (Canada Soil Survey Committee 1978). This new approach was very quickly embraced by American soil scientists, and eventually led to the creation of the Gelisol soil order in the US Soil Taxonomy (Soil Survey Staff 1998). This concept enjoyed wide acceptance in Western Europe, and resulted in the establishment of the new Cryosolic major soil group for permafrost-affected soils in the World Reference Base for Soil Resources (Spaargaren 1994). The current state of knowledge about permafrost-affected soils was summarized by international experts in 37 papers in the book “Cryosols: Permafrost-Affected Soils” (Kimble 2004).

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In this chapter the geological, physical and chemical properties of permafrost-affected soils in the Arctic region will be discussed, along with the cryogenic processes that produce their unique characteristics. In addition, data for selected Arctic soils are presented in Tables 1.1 and 1.2.

Table 1.1 Location and source of data for selected pedons

Pedon no.	Field no.	Area	Latitude (N)	Longitude	Source of data
1	12–89–22	Ellesmere Is., Canada	81° 23′ 35″	76° 44′ 30″ W	Tarnocai (unpubl)
2	Isachsen 3	Ellef Ringnes Is., Canada	78° 47.098′	103° 33.125′.W	Ping (unpubl)
3	12–81–26	Prince Patrick Is., Canada	76° 14′	119° 20′ W	Tarnocai 2004
4	DB-4	Bathurst Is., Canada	75° 40′	97° 41′ W	Tarnocai 2004
5	SO1AK185006	Howe Is., USA	70° 18.986′	147° 59.647′ W	Ping (unpubl)
6	94FN825009	Chersky, Siberia, Russia	69° 27′ 49″	161° 45′ 57″ E	USDA Lab[a]
7	N5b	Tuktoyaktuk, Canada	69° 26′	133° 01′ W	Pettapiece et al. 1978
8	Y66	Yukon, Canada	68° 55′	137° 50′ W	Tarnocai (unpubl)

[a] US Department of Agriculture Soil Laboratory, Lincoln, NE, USA

Table 1.2 Site parameters for selected pedons

Pedon no.	1	2	3	4	5	6	7	8
Landform[a]	CB	DG	I	R	L	U	L	U
Drainage[b]	W	P	MW	W	I	MW	P	I
Parent material[c]	C	GM	C	C	A	L	P	C
Depth to permafrost (cm)	60	34	40	58	55	62	30	24
Patterned ground[d]	NC	TH	NC	SP	NC	IWP	IWP	EH
Vegetation[e]	D	ML	MS	ML	LT	GST	ST	ST
Soil class. (Canada)[f]	RTC	CTC	OETC	OETC	OETC	GTC	MOC	GTC
Soil class. (US)[g]	TP	GAT	TUT	TUT	MT	TAT	TH	TAT

[a]Landform: *CB* colluvial blanket; *DG* dissected; *I* inclined; *L* level; *R* rolling; *U* undulating

[b]Drainage: *W* well; *MW* moderately well; *I* imperfect; *P* poor

[c]Parent material: *A* alluvium; *C* colluvium; *GM* glaciomarine; *L* loess; *P* peat

[d]Patterned ground: *EH* earth hummocks; *IWP* ice-wedge polygons; *NC* nonsorted circles; *SP* small (15–40 cm diam) polygons; *TH* turf hummocks

[e]Vegetation: *D* dryas–sedge tundra; *GST* grass–shrub tundra; *LT* lichen–shrub tundra; *ML* moss–lichen–saxifrage tundra; *MS* moss–sedge–lichen–willow tundra; *ST* shrub tundra

[f]Soil classification (Canada: Soil Classification Working Group 1998): *CTC* Glacic Turbic Cryosol; *GTC* Gleysolic Turbic Cryosol; *MOC* Mesic Organic Cryosol; *OETC* Orthic Eutric Turbic Cryosol; *RTC* Regosolic Turbic Cryosol

[g]Soil classification (US: Soil Survey Staff 1998): *GAT* Glacic Aquaturbel; *MT* Molliturbel; *TAT* Typic Aquaturbel; *TH* Typic Hemistel; *TP* Typic Psammoturbel; *TUT* Typic Umbriturbel

1.2 Arctic Environment

The Arctic climate is characterized by short, cold summers and long, extremely cold winters. It has 24 h of daylight during much of the summer, and darkness during much of the winter. Mean daily temperatures above 0°C occur only during the warmest part of the summer. The range of mean July temperatures is 7–10°C in the southern part of the Arctic and 3–5°C in the northern part. The coldest month is February, with temperatures of −20 to −40°C. Total annual precipitation is generally low (60–160 mm) and occurs mostly as snow.

The Arctic vegetation is a nearly continuous cover of shrub-tundra in the south, grading to a sparse cover of dwarf shrubs, herbs, mosses and lichens in the north. Permafrost is continuous, and reaches a thickness of 100–500 m in North America and >500 m in Siberia. The active layer (the surface layer which freezes and thaws annually) is about 30–60 cm thick. The soil surface is generally associated with patterned ground, which refers to a land surface that displays an ordered and repeated, more-or-less symmetrical, morphological pattern. A number of patterned ground classification systems occur in the literature, but the one most commonly used was developed for mineral terrain by Washburn (1980). This classification uses descriptive terminology based on geometric forms and the presence or absence of sorting of stones (coarse) and finer materials. The patterned ground forms for mineral terrain are circles, nets, steps, stripes, and polygons.

1.3 Geological Setting

The bedrock geology of the Arctic is dominated by large areas of sedimentary, igneous and metamorphic rocks. Repeated glaciations and erosional processes reshaped the landscapes and deposited various thicknesses of surficial materials. During the glacial periods, large parts of the Canadian and Scandinavian Arctic were covered by glacial ice, which deposited variable thicknesses of glacial materials. Remnants of this ice still remain in Greenland, and as ice caps in the northeastern part of the Canadian Arctic. Coastal areas usually are associated with marine deposits, because of sea-level changes and glacial rebound.

A large part of the Arctic in Eurasia and northwestern North America (Alaska and part of Yukon) was unglaciated, and is covered with thick surficial materials of eolian (loess), colluvial and lacustrine origin. Most of the Siberian Arctic is associated with deep yedoma sediments derived from windblown, reworked colluvial materials.

Peat deposits are common surficial deposits, especially in the southern part of the Arctic. These deposits, which are usually about 2–3 m thick, result from peat deposition during the last 5,000–8,000 years. They usually occur in lowlands, and are associated with ice-wedge polygons. These peat deposits play an important role in the carbon budget of the area.

1.4 Soil-Forming Processes

All soils are formed by the interaction of soil-forming factors, but because of the cold climate in the Arctic region, cryogenic processes, which lead to the formation of permafrost-affected soils, dominate the soil genesis. The presence and mobility of unfrozen soil water, as it migrates towards the frozen front along the thermal gradient in the frozen system, drives this process. The cryogenic processes that affect the genesis of Arctic soils are freeze–thaw, cryoturbation (frost churning), frost heave, cryogenic sorting, thermal cracking, and ice build-up. Other soil-forming processes that can leave an imprint on these soils include the gleying process, brunification, eluviation and salinization.

1.5 Properties of Arctic Soils

The presence of ice in permafrost-affected soils causes complex physico-chemical processes. Formation of ice in these soils creates stresses and pressures that result in deformation and rearrangement of the soil horizons, and translocation of materials and solutes. This leads to unique macromorphologies and micromorphologies, thermal characteristics, and physical and chemical properties.

1.5.1 Macromorphology

The morphologies of both the surface and subsurface of Arctic soils are shaped by cryogenic processes (Figs. 1.1 and 1.2). The soil surface is associated with various types of patterned ground caused by frost heave and sorting, while the subsurface is dominated by cryoturbation that results in irregular or broken soil horizons, involutions, organic intrusions, and organic matter accumulation, usually along the top of the permafrost table. Oriented rock fragments (Fig. 1.1), silt-enriched layers and silt caps are also common (Bockheim and Tarnocai 1998). The freeze–thaw process produces granular, platy and blocky structures (Table 1.3). The subsurface soil horizons often have massive structures and are associated with higher bulk densities, especially in fine-textured soils. This massive structure results from cryostatic desiccation (cryodesiccation), which develops when the two freezing fronts (one from the surface, the other from the permafrost) merge during freeze-back. Although these macromorphological properties occur primarily in the active layer, they also can be found in the near-surface permafrost because of the dynamic nature of the permafrost (Bockheim and Tarnocai 1998).

Arctic soils generally have high moisture content, especially near the permafrost table, which acts as a moisture barrier. As a result, gleying associated with grayish colours and redoximorphic features is a common occurrence, especially in loamy and fine-textured soils.

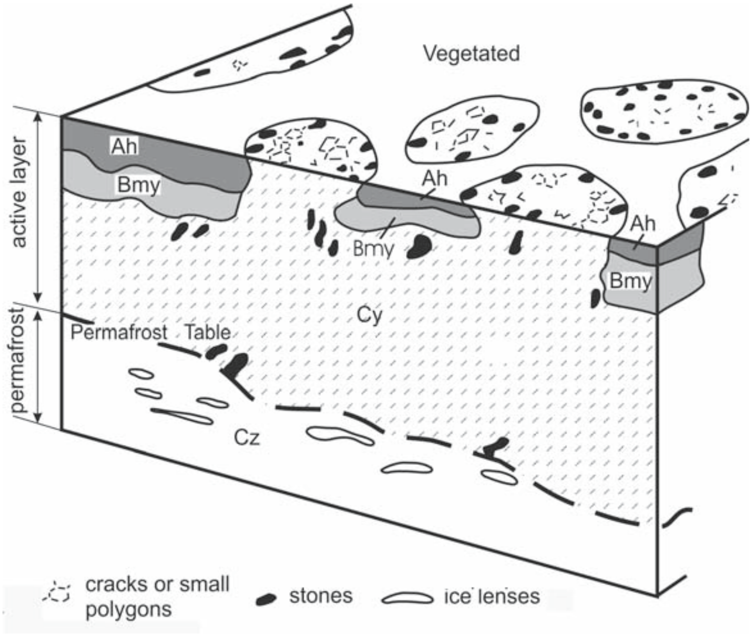

Fig. 1.1 Schematic diagram showing a nonsorted circle type of patterned ground with discontinuous and broken cryoturbated soil horizons (*y*) and oriented stones in the active layer, and ice lenses in the permafrost layer

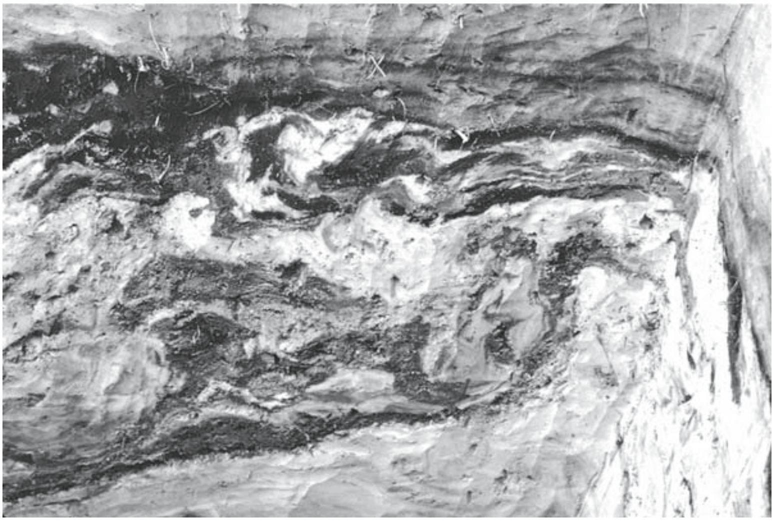

Fig. 1.2 Strongly cryoturbated soil with contorted and broken soil horizons

Table 1.3 Morphological characteristics of selected pedons

Pedon no.	Horizon	Depth (cm)	Colour	Texture[a]	Structure[b]	Ice content	Special features
1	Ck	0–15	10YR 4/1.5m	fSL	sbk	–	10% gravel
	Cky	15–60	10YR 3/2m	SiL	sbk	–	–
	Ckyz	60–100	10YR 3/2.5f	SiL	sbk	medium	ice crystals
2	Ajj1	0–10	10YR 3/2m	C	fgr	–	–
	Ajj2	10–18	10YR 4/3m	C	fgr	–	–
	Bw	18–34	10YR 4/3m	C	lenticular	–	–
	Wf/Bgf	34–40	10YR 4/2f	C	lenticular	high	–
	Wf	40–42	–	–	–	ice	pure ice
	Wf/Cf	42–57	10YR 4/2f	C	lenticular	high	–
	Wf	57–110	–	–	–	ice	pure ice
3	Ah	0–8[c]	10YR 2/1m	–	gr	–	–
	Bmy1	0–14	10YR 4/3m	SL	gr	–	–
	Bmy2	14–55	10YR 4/2m	SL	gr	–	–
	Cy	55–100	10YR 4/2m	SL	sg	–	oi[d]
	Ahyz	40–45[c]	10YR 2/1f	–	sl	high	–
	Cyz	45–80[c]	10YR 4/2f	SL	sl	high	oi[d]
4	Bmky	2–44[c]	10YR 3.5/2m	SL	gr	–	vesicular
	BCky	10–32[c]	10YR 3/3m	SL	gr	–	vesicular
	Ahky	1–15[c]	10YR 2/1m	SL	sg	–	vein ice
	Ckz	46–100	10YR 4/1m	SL	sl	–	ice crystals
5	A1	0–5[c]	10YR 3/2m	fSL	platy	–	–
	A2	5–40[c]	10YR 3/2m	fSL	platy	–	–
	Ajj	62–70[c]	7.5YR 3/2m	fSL	fgr	–	oi[d]
	C1	0–5[c]	2.2Y 4/2m	fSL	reticular	–	–
	C2	5–25[c]	10YR 3/2m	fSL	reticular	–	–
	Bwjj1	20–60[c]	10YR 4/2m	fSL	lenticular	–	–
	Bwjj2	20–65[c]	10YR 4/2m	fSL	reticular	–	–
	Bwjj3	55–68[c]	2.5Y 5/1f	fSL	massive	–	–
	Wfm/Cf	68–110[c]	7.5YR 4/1f	fSL	ataxitic	high	70% ice
	Cf	80–110[c]	2.5Y 4/1f	fSL	platy	–	–
6	Oi	0–11[c]	5YR 3/2m	Peat	–	–	–
	A	0–8[c]	2.5Y 3/2m	SiL	gr	–	–
	Bw	0–42[c]	2.5Y 3/2m	SiL	sbk	–	–
	Bwj	0–62[c]	2.5Y 5/3m	SiL	sbk	–	–
	Bgfm	12–15[c]	2.5Y 3/2f	SiL	sbk	–	–
	Ajfm	0–10[c]	10YR 2/1f	SiL	platy	–	–
	Oajfm	0–9[c]	10YR 2/2f	Organic	massive	–	–
	BCgfm	0–10[c]	2.5Y 3/2f	SiL	massive	–	–
7	Oh	0–30	2.5YR2.5/2m	Peat	–	–	–
	Ohz	30–40	5YR 2.5/2m	Peat	–	–	–
	Omz1	40–150	7.5YR 3/2f	Peat	–	medium	–
	Omz2	150–215	7.5YR 3/2f	Peat	–	medium	–
	Wz	215–268	–	–	–	ice	pure ice
	Cz	268–288	–	Si	–	high	–

(continued)

Table 1.3 (continued)

Pedon no.	Horizon	Depth (cm)	Colour	Texture[a]	Structure[b]	Ice content	Special features
8	L,H	0–6[c]	10YR 3/2m	–	litter	–	–
	Bmgy1	0–12	10YR 5/3m	SiL	gr	–	oi[d]
	BCgy1	12–24	10YR 4/4m	SiL	sbk	–	oi[d]
	BCgyz1	24–47	10YR 4/4m	SiL	sbk	–	oi[d]
	Cz1	47–60	5Y 3/1m	SiL	massive	–	–
	Cz2	60–100	5Y 3/1m	SiL	massive	–	–
	Bmgy2	0–24	10YR 4/2m	SiL	gr	–	oi[d]
	BCgy2	24–34	5Y 3/1m	SiL	sbk	–	oi[d]
	BCgyz2	34–56	5Y 3/1m	SiL	sbk	–	oi[d]

[a] Texture: *SiL* silt loam; *SL* sandy loam; *fSL* fine sandy loam; *Si* silt; *C* clay

[b] Structure: *gr* granular; *fgr* fine granular; *sg* single grain; *sl* structureless; *sbk* subangular blocky

[c] Range of thicknesses-given for discontinuous, cryoturbated horizons

[d] *oi* organic intrusions

Thin eluvial or leached layers resulting from the brunification process occur primarily in sandy soils in the southern part of the Arctic. Salt crusts on the soil surface are also characteristic. These salt crusts develop during dry periods in the summer because of higher evapotranspiration from the soil surface.

Thixotropy, which results in an unstable soil surface, is frequently present in the thawed portion of permafrost-affected soils, and is often associated with soils having high silt content. When a thixotropic soil dries out, a characteristic vesicular structure develops.

1.5.2 Micromorphology

The fabric of Arctic soils varies from granular-like (granic and granoidic) in the surface horizons to mainly porphyroskelic in subsurface horizons (Fox 1985). The terminology for microfabrics associated with permafrost-affected soils, which was developed and described by Fox and Protz (1981), is summarized as follows. Orbicular fabric, which is common in cryoturbated soils, has skeletal grains organized into circular patterns, probably as a result of sorting. Suscitic fabric has skeleton grains oriented in a vertical fashion, often with an underlying accumulation of finer matrix material (Fig. 1.3). Conglomeric fabric has individual structural units enclosed by finer matrix. Ice lensing and vein ice lead to the development of lenticular or platy structure (Fig. 1.4). Cryodesiccation and cryoturbation can lead to granic (granular) or blocky fabrics.

1.5.3 Thermal Characteristics

Probably the most striking thermal characteristics of Arctic soils are the low soil temperatures, the steep vertical temperature gradient, and the perennially frozen nature of a portion of the subsoil. Although soil temperatures are directly related to

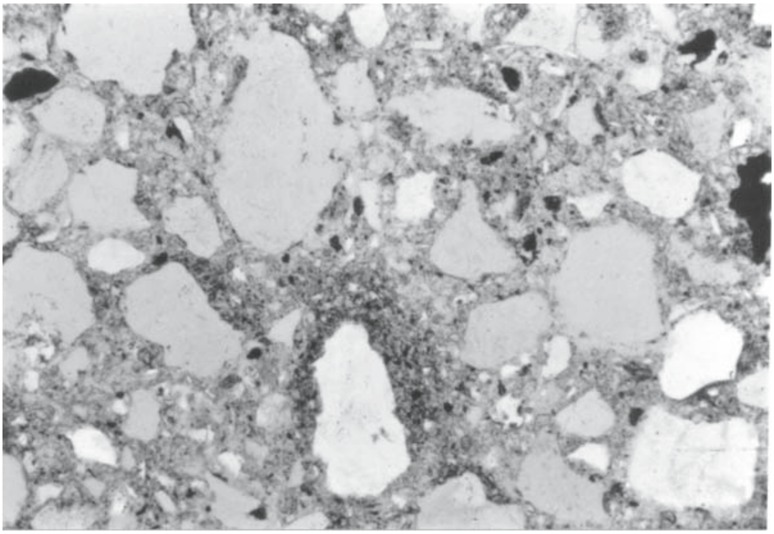

Fig. 1.3 Cryoturbated microfabric showing oriented sand grains

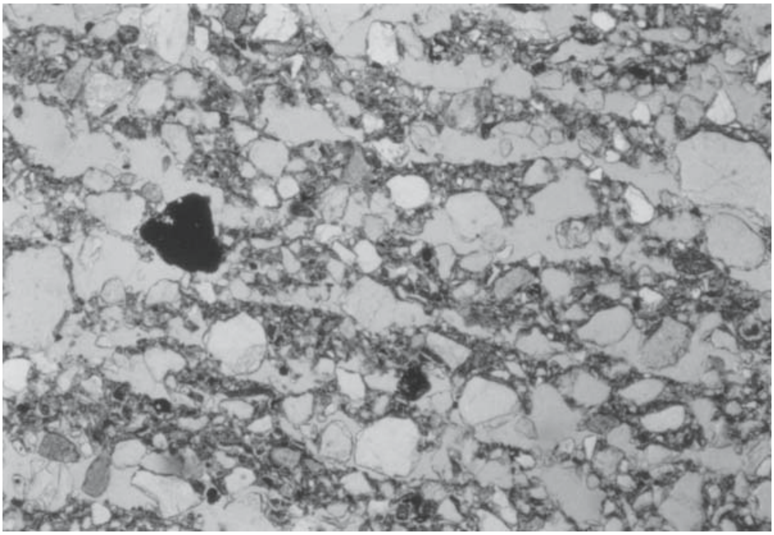

Fig. 1.4 Cryoturbated microfabric showing lenticular or platy structure

air temperature (Fig. 1.5), factors such as vegetation cover, soil moisture, thickness of snow cover, and underlying permafrost have a modifying effect. Since the active layer has very little buffering capacity, however, soil temperatures rapidly reflect fluctuating air temperatures, especially when they are cooling (Tarnocai 1980).

Relationships between air temperature and soil temperatures at depths of 50 and 100 cm at two latitudes are shown in the graphs in Fig. 1.5. The Overlord site (Fig. 1.5a)

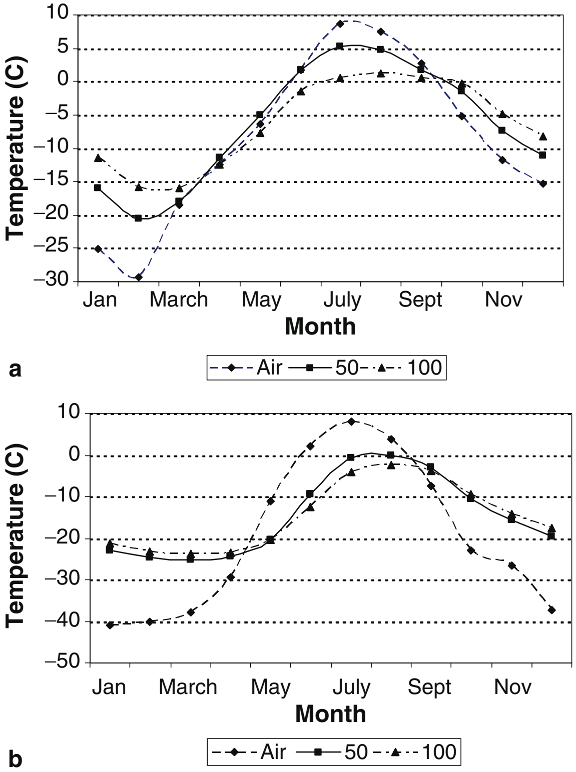

Fig. 1.5 Mean monthly soil (50 and 100 cm depths) and air temperatures measured in 1999 on southern Baffin Island **(a)** and northern Ellesmere Island **(b)** in the Canadian Arctic

on Baffin Island in the southern part of the Arctic (Lat. 66° 23′ 30″ N; Long. 65° 29′ 20″ W) has temperatures above zero at the 0–100 cm depth during the summer months. At the Lake Hazen site (Fig. 1.5b) on Ellesmere Island in the High Arctic (Lat. 81° 49′ 15″ N; Long. 71° 33′ 17″ W), however, only the surface 0–45 cm of the soil thaws during the summer months; below this depth, the soil remains frozen throughout the year.

As a result of the very thin and compacted snow cover in much of the Arctic region, the subsoil cools rapidly as the air temperatures drops, leading to a very small, or negligible, thermal gradient in the soil, especially in the High Arctic (Tarnocai 1980).

1.5.4 Physical Properties

Arctic soils have a wide range of textures, including clay, silty clay, loam, sandy loam and coarse gravelly sand (Table 1.3), with the texture depending mainly on the mode of deposition of the parent material.

Fig. 1.6 Vein ice formation in the subsoil, resulting in a lenticular or platy structure

The structure of the soil, as has already been mentioned in the macromorphology section (see Sect. 1.5.1), is the result of cryogenic processes. The granular structure (Table 1.3) is the result of freeze–thaw processes, which induce desiccation and rolling by frost action. The common platy structure (Table 1.3) is the result of vein ice formation, as is shown in Fig. 1.6. The massive structure is the result of cryo-desiccation during freeze-back.

One of the unique features of Arctic soils is that not all of the water in the permafrost layer is in the form of ice throughout the year. The ice in the subsoil is very dynamic, and increases in thickness and volume over time because of the migration of this liquid water along the thermal gradient from warm to cold.

1.5.5 Chemical Properties

The pH of Arctic soils varies greatly (Table 1.4), and depends on the chemistry of the parent materials. The similarity of the pH to that of the parent material results, in part, because of cryoturbation, which not only mixes and translocates fresh parent material to the near surface, but also mixes soil material among the soil horizons.

The nitrogen, potassium and phosphorus contents of Arctic soils are generally low (Table 1.4), since most of these nutrients are locked into the surface organic matter (Broll et al. 1999). The movement of moisture along the thermal gradient from warm to cold results in the transfer of nutrients carried by solutes, enriching the perennially frozen layer of the soils. The movement of nutrients by this process occurs in both organic and mineral soils (Tarnocai 1972; Kokelj and Burn 2005).

Table 1.4 Selected chemical and physical characteristics of selected pedons

Pedon no.	Horizons	pH	$CaCO_3$ equiv. (%)	C (%)	N (%)	CEC (meq)	Total sand (%)	Silt (%)	Clay (%)
1	Ck	7.3	10.2	2.3	0.10	–	61.0	36.8	2.2
	Cky	7.4	13.3	3.1	0.24	–	18.7	58.7	2.6
	Ckyz	7.1	7.4	2.8	0.20	–	40.2	54.7	5.1
2	Ajj1	5.0	–	3.2	0.2	21.4	18.0	36.8	45.2
	Ajj2	4.9	–	2.7	0.3	21.3	16.0	36.8	47.2
	Bw	5.0	–	2.7	0.2	20.0	14.0	38.8	47.2
	Wf/Bgf	4.9	–	2.7	0.2	26.4	16.0	38.8	45.2
	Wf/Cf	4.9	–	2.8	0.2	23.3	20.0	36.8	43.2
3	Ah	6.2	–	10.3	0.9	37.0	–	–	–
	Bmy1	7.2	1.85	1.4	0.1	11.3	62.8	23.3	13.8
	Bmy2	7.3	1.76	1.1	0.1	10.3	63.2	23.3	14.5
	Cy	7.0	1.10	2.2	0.2	16.0	64.4	23.9	11.8
	Ahyz	6.6	–	13.4	0.8	51.8	–	–	–
	Cyz	6.9	–	2.4	0.2	19.8	59.0	29.3	11.7
4	Bmky	7.4	7.5	1.7	0.1	–	72.3	16.0	11.7
	BCky	7.2	4.6	0.2	0.1	–	75.3	14.0	10.7
	Ahky	7.4	<1	5.5	0.3	–	76.9	14.2	8.9
	Ckz	7.5	13.8	0.4	<1	–	82.5	11.7	5.8
5	A1	7.9	27	2.2	0.2	11.9	54.9	38.5	6.6
	A2	7.9	25	2.4	0.2	9.7	49.2	42.2	8.6
	Ajj	8.0	–	4.2	0.2	16.0	–	–	–
	C1	8.6	22	1.5	0.1	7.9	33.2	43.4	23.4
	C2	8.3	22	0.8	0.1	7.5	36.2	42.9	20.5
	Bwjj1	8.1	23	0.8	0.1	7.2	38.1	43.3	18.6
	Bwjj2	8.0	23	4.4	0.1	7.2	38.9	44.9	16.2
	Bwjj3	8.0	33	1.8	0.1	9.1	31.3	59.4	9.3
	Wfm/Cf	7.9	22	2.8	0.1	8.5	41.0	43.6	15.5
	Cf	7.4	36	2.8	0.1	6.4	54.2	35.6	10.2
6	Oi	4.1	–	17.2	0.6	2.2	20	60	20
	A	4.1	–	2.4	0.2	0.9	20	62	18
	Bw	4.6	–	1.4	0.1	0.7	18	62	20
	Bwj	4.7	–	1.1	0.1	0.7	19	62	20
	Bgfm	4.7	–	1.6	0.1	0.7	15	66	19
	Ajfm	5.2	–	3.0	0.2	0.9	18	63	20
	Oajfm	5.3	–	14.1	0.8	1.5	14	48	38
	BCgfm	6.3	–	3.3	0.2	1.2	19	64	18
7	Oh	3.4	–	36.9	1.4	–	–	–	–
	Ohz	3.5	–	47.3	1.5	–	–	–	–
	Omz1	3.9	–	37.8	1.7	–	–	–	–
	Omz2	4.0	–	45.1	1.8	–	–	–	–
	Wz	7.0	–	–	–	–	–	–	–
8	L,H	4.2	–	43.3	1.1	70.7	–	–	–
	Bmgy1	3.9	–	1.7	0.1	11.8	22.3	54.7	23.0
	BCgyz1	3.9	–	1.5	0.1	11.5	22.8	56.0	21.2
	Cz1	4.0	–	2.3	0.1	11.7	20.4	56.2	23.4
	Cz2	4.3	–			17.0	22.3	52.6	25.1
	Bmgy2	4.1	–	3.8	0.1	15.3	18.3	52.3	29.4
	BCgyz2	4.0	–	4.3	0.2	14.0	19.9	53.2	26.9

The electrical conductivity of arctic soils is generally low, except for those soils developed on marine clays or marine shale. For example, soils developed on marine clay in the Tanquary Fiord area of Ellesmere Island have an electrical conductivity of 1.64–2.73 mmhos cm^{-1}, while soils developed on marine shale on Ellef Ringnes Island have a conductivity of 0.350–0.500 mmhos cm^{-1}. Salt crusts usually develop on the surfaces of both of these types of soils during dry periods in the summer.

One of the most striking features of Arctic soils is the large amount of organic carbon in both the active layer and the perennially frozen portion of the soils (Table 1.4). Although permafrost-affected ecosystems produce much less biomass than do temperate ecosystems, permafrost-affected soils that are subject to cryoturbation have the unique ability to sequester a portion of this organic matter and store it for thousands of years.

Organic, or peatland, soils, which occur mainly in southern areas of the Arctic, contain large amounts of organic carbon that have accumulated as a result of the gradual build-up process. Although this process may be interrupted periodically by wildfires or other environmental changes, the build-up process has continued for thousands of years. The organic carbon content of these organic soils ranges from 43 to 144 kg m^{-2} (Tarnocai et al. 2007). The organic carbon content of cryoturbated, permafrost-affected, mineral soils, which occur throughout the Arctic, is also large, ranging from 49 to 61 kg m^{-2} (Tarnocai et al. 2007).

1.6 Conclusion

The development of Arctic soils is dominated by cryogenic processes, which are driven by the formation of ice in the soils. A number of models have been developed to explain the mechanisms involved in cryoturbation, which is one of the most common cryogenic processes in these soils. The most recent model involves the process of differential frost heave (heave–subsidence), which produces downward and lateral movement of materials (Walker et al. 2002; Peterson and Krantz 2003). Other processes, such as brunification and, especially, podzolization, are not common, probably because of the lack of leaching resulting from the shallowness of the active layer. Gleyic processes are common, and can occur in soils developed on various parent materials.

Soil properties such as soil texture, pH, salinity and the presence of carbonates depend on the parent materials. The nitrogen content of Arctic soils is generally very low, and has been regarded as a more limiting factor for plant growth than phosphorus and potassium contents (Broll et al. 1999). Other limiting factors for plant growth are low soil temperatures, high stone content and, in some cases, high carbonate content and the occurrence of salts (Bölter et al. 2006).

The high amounts of organic carbon stored in Arctic soils, and the relatively rapid warming of this region as a result of climate change, are probably the main reasons so much attention has been focused on these soils in recent times. These soils (both mineral and organic) have operated as carbon sinks for thousands of years. In general, small amounts of organic matter are produced annually by the vegetation. This organic matter is then deposited as litter on the soil surface, with some decomposing as a result of biological activity. A large portion of this litter, however, builds up on the soil surface, forming an organic soil horizon. Cryoturbation causes some of this organic material to move down into the deeper soil layers (Bockheim and Tarnocai 1998). In addition, roots contribute organic carbon that is also translocated by cryoturbation. Soluble organic materials move downward because of the effect of gravity and the movement of water along the thermal gradient toward the freezing front (Kokelj and Burn 2005). Once the organic material has moved down to the cold (0 to –15°C), deeper soil layers, where very little or no biological decomposition takes place, it may be preserved for many thousands of years. As a result, the average carbon content of cryoturbated, permafrost-affected mineral soils is approximately 49–61 kg m^{-2}, while that of organic (or peatland) soils is 43–144 kg m^{-2} (Tarnocai et al. 2007).

Little is known about soils in much of the Arctic, because the harsh climatic conditions and the relative inaccessibility of most of this vast region have made such studies very difficult. We know even less about how the climate-warming that is already affecting this region will transform these northern soils and their properties.

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Chapter 2
Antarctic Permafrost Soils

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2.1 Introduction

Antarctica, with an area of 14 million km^2, is the worlds largest continent, yet exposed ground on which permafrost soils occur covers a mere 49,000 km^2, or about 0.35% of the entire continent (Fox and Cooper 1994). The continent is roughly circular in outline, and its topography is dominated by two massive ice sheets (Fig. 2.1); the East Antarctic Ice Sheet with an average elevation of around 3,000 m, and the West Antarctic Ice Sheet with an average elevation of around 1,500 m. A major physiographic feature is the Transantarctic Mountains, which extend over 3,500 km and separate the two ice sheets. Bare ground areas are found scattered around the margin of the continent where the ice sheets have thinned or receded, in the Antarctic Peninsula and along the Transantarctic Mountains (Fig. 2.1). The largest ice-free area is in the Transantarctic Mountains (23,000 km^2 estimate), which includes approximately 7,000 km^2 in the Dry Valley region, the largest contiguous area of bare ground.

The climate for formation of soils and permafrost throughout Antarctica is severe. With very low mean annual temperatures, negligible effective precipitation and rare occurrences of mosses and lichens, except for the Antarctic Peninsula where plant life including some grasses are more abundant, the soils have aptly been described as Cold Desert Soils (Tedrow and Ugolini 1966; Campbell and Claridge 1969). The exposed landscapes are dominated by glacial valleys with land surfaces and deposits that show the influence of glacial activity, which has extended from the Late Pleistocene to earlier than Miocene times (Denton et al. 1993; Marchant et al. 1993). Notwithstanding the tiny proportion of the continent that is ice-free and exposed to weathering processes, a large degree of diversity is found in both the soils and permafrost, owing to the wide variations in the environmental and geomorphic forces.

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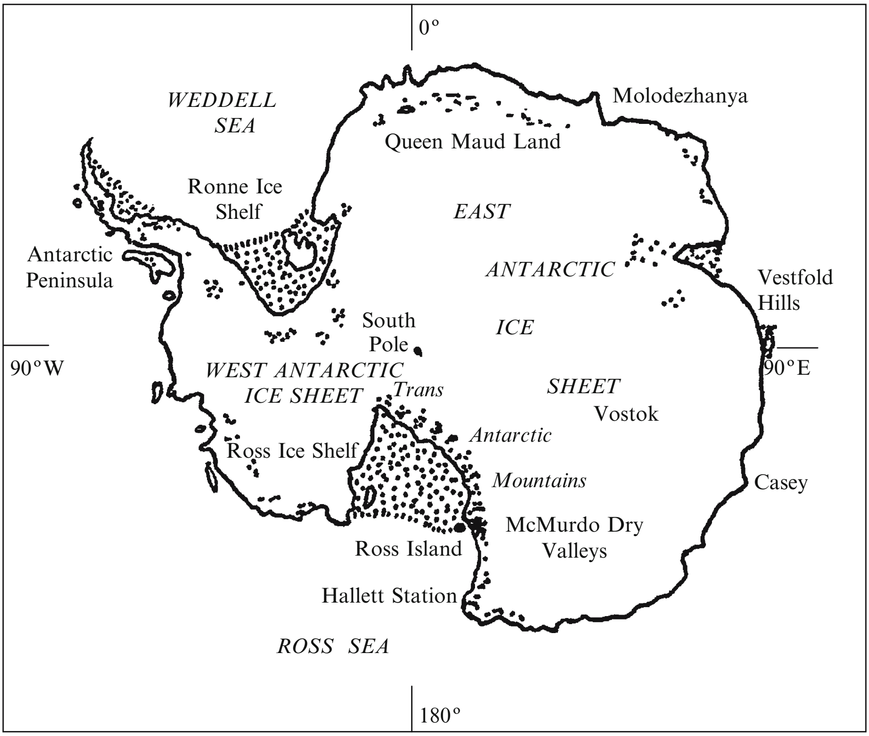

Fig. 2.1 Location map with areas of ice-free ground (not exact or to scale)

2.2 The Climatic Environment

The climate of Antarctica embraces the most extreme cold conditions found on Earth. Antarctica is cold because the solar radiation is only 16% of that at equatorial regions, and also because of the high average surface elevation of the ice sheet, which in places exceeds 4,000 m. Temperatures as low as −89°C have been recorded at Vostok (Fig. 2.1), and −49°C at the South Pole. However, mean annual air temperatures increase nearer the coast where land is exposed, and in the northernmost areas (−25°C at Mt. Fleming at the head of Wright Dry Valley near the edge of the Polar Plateau, −20°C at Vanda Station in the Dry Valleys, −18°C at McMurdo Station on Ross Island, −15°C at Hallett Station). Further north, in coastal areas of East Antarctica, warmer climates are found (MacNamara 1973; Burton and Campbell 1980). At Davis Station in the Vestfold Hills, mean annual temperature is −10.2°C, while at Molodezhnaya and Casey (Fig. 2.1) similar temperatures to those at Davis Station are experienced.

Air temperatures directly influence permafrost properties, with the active layer thickness decreasing from around 80 to 100 cm in the warmer coastal and northern regions to 2 cm or less in the cold inland high-elevation sites (Fig. 2.2) following the

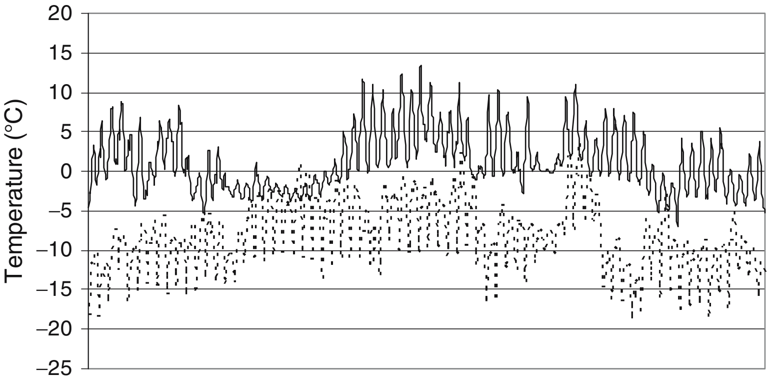

Fig. 2.2 Hourly temperature records from Marble Point (*solid line*; 70 m above sea level (asl), measurement at 7.5 cm) and Mount Fleming (*dashed line*; 2,000 m asl, measurement at 2 cm) from December 4 2002 to February 12 2003. The records illustrate the large difference that site climate has on soil thermal properties

adiabatic lapse rate (Campbell and Claridge 2006). Other soil thermal properties related to geographic differences in climate include the length of the thaw period, the number of thaw days during summer, the number of freeze/thaw cycles that occur and the length of time that the soil may be continuously above freezing. At Marble Point, for example [approximately 70 m above sea level (asl) and permafrost table at 60 cm], the thaw period (measured at 7.5 cm depth) extended over 70 days, there were 34 freeze–thaw cycles and 16 days when the soil temperature was continuously above 0°C (Fig. 2.2). By contrast, at Mt. Fleming (2,000 m asl, permafrost table approximately 2 cm) the thaw period, measured at 2 cm depth, extended over 31 days, but with only 6 days in which soil temperature was briefly above 0°C.

The mean annual precipitation over Antarctica averages around 50 mm per year, with least falling inland and most in coastal locations. In the McMurdo Dry Valleys, one of the driest areas of Antarctica, precipitation averaged 13 mm per year on the valley floor near Lake Vanda and 100 mm per year in nearby upland mountains. Around the periphery of East Antarctica, precipitation is much higher, with 650 mm per year at Molodezhnaya in Enderby Land (MacNamara 1973). The precipitation normally falls as snow, and little is available for direct soil moistening because of ablation and evaporation. Despite the minimal amounts of soil moistening, distinct soil climate zones, based on moisture availability, have been recognized (ultraxerous, xerous, xerous to subxerous, oceanic subxerous and moist zones; Campbell and Claridge 1969). Soils of the ultraxerous zone are found in arid inland areas, rarely if ever have liquid water present, and have ground temperatures that are seldom above freezing point. At the other extreme, moist soils in coastal environments may be moistened at the soil surface, and ground temperatures remain above freezing point for periods throughout the year.

In Antarctica, the soil climate and permafrost properties are strongly influenced by the surface radiation balance, since the soil thermal regime is consequent upon