POLISH POLAR RESEARCH
vol. 30, no. 2, pp. 161–178, 2009

Recent, relic and buried soils in the forefield of Werenskiold Glacier, SW Spitsbergen

Cezary KABALA and Justyna ZAPART

Instytut Nauk o Glebie i Ochrony Środowiska, Uniwersytet Przyrodniczy we Wrocławiu,
Grunwaldzka 53, 50-357 Wrocław, Poland
<cezary.kabala@up.wroc.pl> <justynazapart@gmail.com>

Abstract: Soils, having a well-developed sequence of A and Bw horizons, are widespread on the uplifted marine terrace 8–12 m a.s.l. in the proximity of Nottinghambukta Bay. The present-day origin of these soils is however questionable, while similarly developed soils, but buried under the cover of the youngest till were found on a forefield of the Werenskiold Glacier. To quantify an intensity of the soil-forming process under present climate conditions of SW Spitsbergen, the chronosequence of soils developed from the Recent, up to 70 year-old moraines, was studied on the forefield of Werenskiold Glacier. Significant dissolution of $CaCO_3$, decrease of pH, leaching of calcium and magnesium, increase of amorphous iron content, as well as an accumulation of organic matter and initial formation of aggregate soil structure were observed within the surface layer of recent till. The 70 year-long period of pedogenesis was, however, too short for a distinct morphological differentiation of the subsurface B horizon. It is concluded, that deep and structural Bw horizons of some surface and buried soils are relicts of a much longer period of relatively warm climate before the last transgression of glaciers.

Key words: Arctic, Svalbard, soil development, marine terrace, glacier forefield.

Introduction

Long-lasting, medieval period of climate warming on Spitsbergen was interrupted by the advance of glaciers during the so called Little Ice Age (LIA) in the 18th and 19th centuries, by the end of which glaciers reached their maximum size extent. Since the second decade of the 20th century, a rapid retreat of glaciers has been observed virtually all over Spitsbergen (Ziaja 2002; Bukowska-Jania 2003; Lonne and Lysa 2005). Presently observed relative climate warming combined with the deepening of active layer (Haugland 2004; Marsz and Styszyńska 2007) stimulate progress of soil-forming processes within the youngest glacigenic sediments on recently exposed forelands of retreating glaciers, or a renewal of these processes on older land surfaces, where pedogenesis was temporary retarded. Direction and intensity of these processes in polar conditions depend crucially on the local climate, geological, morphological and hydrological factors (Skiba *et al.* 2002; Bukowska-Jania 2003; Klimowicz and Uziak 2003; Melke and Chodorowski 2006), as well as on the intensity of biological succession (Pirożnikow and Górniak 1992; Alexander and Burt 1996; Anderson *et al.* 2000; He and Tang 2008).

Due to the unfavourable climate and scarce vegetation, only few soil types prevail in SW Spitsbergen, including Cryosols, Gleysols, Leptosols, Regosols, Fluvisols, and Histosols (Plichta 1977; Skiba *et al.* 2002). Most of these soils have little development of soil horizons due to an excessive frost-induced activity of surface layer and low intensity of mineral weathering (Szerszeń 1968; Chodak 1988; Skiba *et al.* 2002). However, well developed "arctic brown earths" are dominant soils on the flat (or gently sloping) and well drained marine terraces in the Bellsund and Kaffiøyra regions (Melke and Chodorowski 2006). Similar soils having a well-developed sequence of A and Bw horizons are widespread on the raised marine beach 8–12 m a.s.l. in the proximity of Nottinghambukta Bay and in the Hornsund region (Plichta 1977). The present-day origin of these soils is however questionable, while the time necessary for the development of such deep, structural and coloured horizons is significantly longer than the period of recent deglaciation. Furthermore, soils having similar morphology, but buried under the shallow cover of the youngest till were found on a forefield of the Werenskiold Glacier, that suggests their complete development before the last transgression of glaciers connected with LIA.

The aim of this paper is to quantify an intensity of the soil-forming process under present climate conditions of SW Spitsbergen, and to compare morphology and crucial physicochemical properties of surface and buried soils which prevail in the forefield of Werenskiold Glacier and in the surrounding of Nottinghambukta Bay.

Study area

The Werenskiold Glacier is a small, subpolar glacier of *ca* 27.4 km^2 of area and 9.5 km in length, located on the Wedel-Jarlsberg Land area in SW Spitsbergen (Bukowska-Jania 2003). The southern part of its proglacial zone is covered with a flutted moraine, changing towards the west into a flat moraine. The north part of the forefield is predominantly covered with glaciofluvial sedimets forming a mosaic of plains and fans. The proglacial zone of glacier is limited from the north and south by lateral moraines, and from the west by a terminal (frontal) moraine, formed probably during rapid glacial surge at the beginning of the 20th century. Both within the frontal and lateral moraines, there are well-preserved glacial cores, making the moraines' surface thermoactive and causing frequent landslides on their slopes (Bukowska-Jania 2003). West of the terminal moraine is located a widespread glaciofluvial (sandur) plain Elveflya, built of gravels and sands transported by the river Kvisla, draining the Werenskiold Glacier till the end of 1960s. Today, the transport of water and rock material within the Elveflya area occurs only occasionally in temporary existing channels.

The Werenskiold Glacier basin is located at the meeting point of three tectonic blocks of the Hecla Hoek formation. The southern neibourhood of the glacier is build of the metamorphic groups Isbjørnhamna and Eimfjellet, comprising Proterozoic amphibolites, migmatites, quartzites, chlorites and amphibolite-quartzite schists. The eastern surroundings of the accumulation field consist of the Deilegg formation, build predominantly of thick banks of phyllites, laminated schists and quartzite conglomerates with dolomite and marble precipitations. The Jens Erikfjellet formation, which limits the glacier basin from the north-west, is build predominantly of greenschists and mica-calcite-quartzite schists. The rock bed at the glacier terminus (glacier snout), in the area exposed from ice cover, consists of a Precambrian formation Vimsodden, including bands of chlorite-muscovite-quartzite schists, muscovite-calcite-quartzite schists, marbles and marble-quartzite conglomerates (Czerny *et al.* 1993).

The climate conditions in the forefield of Werenskiold Glacier are considered to be slightly milder than those in the direct proximity of the Hornsund station, where the average annual precipitation (in the period 1979–2006) amounts to 430 mm, and the average annual temperature is -4.4°C, with a distinct upward trend of +0.095°C/year (Marsz and Styczyńska 2007). The climate in the region of Hornsund is described as suboceanic or humid, characterized by the value of the Ivanov index (the ratio of precipitation to evapotranspiration) ranging between 2.1 and 2.3 (Marsz and Styczyńska 2007).

Material and methods

Field works were carried out during the XVII Polar Expedition of the University of Wrocław in July 2004. Soil profiles were situated (Fig. 1) in the southern part of forefield of the Werenskiold Glacier (soil profiles 1–3), on the frontal moraine (soil profile 4), on the glaciofluvial plain Elveflya (soil profile 5), and on the uplifted marine beach 8–12 m a.s.l., close the Glacier River mouth to Nottingham Bay (soil profile 6). Approximate age of moraine materials in the proglacial zone was assessed based on the previously published documentation of the glacier terminus (Baranowski 1977; Bukowska-Jania and Jania 1988; Pirożnikow and Górniak 1992). Age of fluvial sediments in particular zones of the Elveflya fan was not yet established. However, it is concluded that the sedimentation on Elveflya stopped between 1957 and 1970, after incision of the Glacier River into the southern part of the lateral moraine of the Werenskiold Glacier (Kosiba 1982). Radiocarbon dating of organic remains in sediments of the marine beach 8–12 m a.s.l. in the Notinghambukta area ascribe its age to about 8–7 ka (Chmal 1988). TL datings

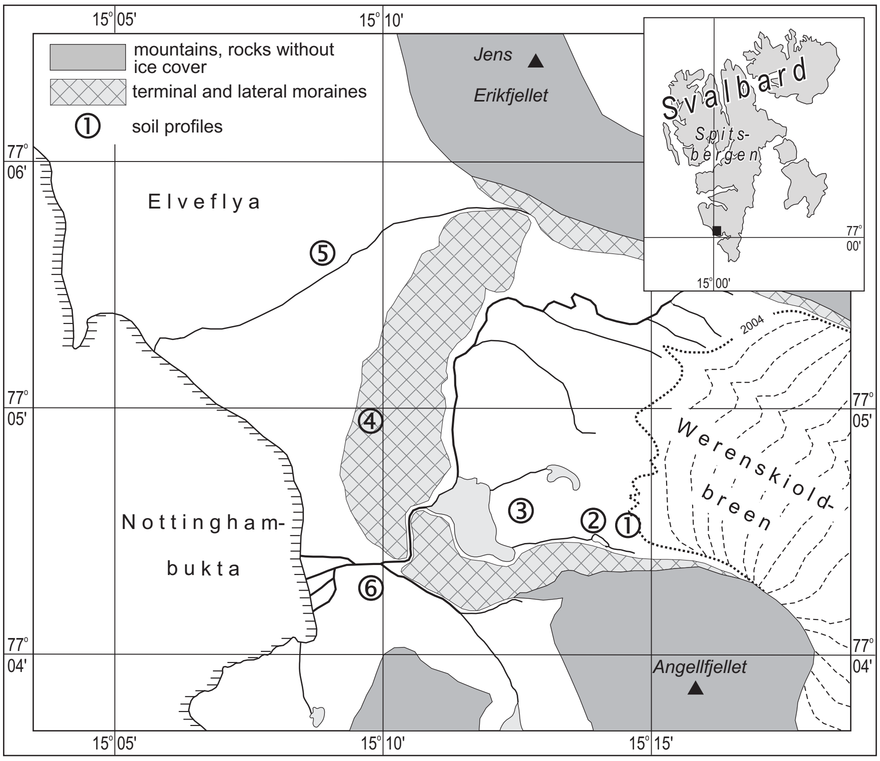

Fig. 1. Location of soil profiles in the forefield of the Werenskiold Glacier and in the proximity of the Nottinghambukta Bay (drawing based on S. Barna 1987. Spitsbergen, Werenskioldbreen. Topographic map 1:25 000. IG PAN, ST WP, IGiK).

of sediments of this beach, collected in the Russepynten and in the Nottinghambukta areas, suggest somewhat older age of 9±1.4 ka (Lindner *et al.* 1991).

Basic soil properties were determined using standard laboratory methods applied to soil classification purposes (Van Reeuwijk 2006). Particle size distribution, after removing the organic matter and sample dispersion with heksametaphosphate-bicarbonate solution, was made using sand separation on sieves and the hydrometer method to fine earth fractions (<0.1 mm). Soil pH in distilled water (soil to water ratio 1:2.5) was analyzed potentiometrically. Calcium carbonate content, using the gasometrical method of Scheibler, and determination of total organic carbon was performed by dry combustion using automatic apparatus (Ströhlein CS-mat 5500). Exchangeable base cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) were extracted with 1M ammonium acetate at pH = 7 (soil to solution ratio 1:10). Iron in non-silicate forms (“free” iron, Fe_d) was extracted with bicarbonate-dithionite-citrate buffer according to standard Mehra-Jackson method. Iron in amorphous or oxides and hydroxides (“active” iron, Fe_o) was extracted with acid ammonium oxalate according to Tamm’s method (Van Reeuwijk 2006). The concentration of metallic elements in all listed above extracts was measured by atomic absorption spectroscopy (Phillips-Unicam AAS).

Results

Morphology and classification of soils

The youngest moraine till in the forefield of Werenskiold Glacier is, in general, only 20–40 cm thick and rests on older glaciofluvial gravels and sands, or directly on bedrock schists. Only on the lateral and frontal moraines, the thickness of till is greater, reaching 100–130 cm to the contact with permafrost layer. Soils occurring on recent glacial deposits in the glacier's forefield and on the glaciofluvial plain Elveflya represent the initial development phases. Recent till in the proximity of glacier's snout is greenish grey, massive (structureless in pedological sense), and throughout gleyed due to prolonged saturation with melting water (soil profile 1). First morphological features of soil development on older moraines are accumulation of organic matter which changes the soil colour to dark greenish gray, and formation of subangular blocky soil structure. These transformations lead to the distinguishing of initial humic A horizon having a thickness up to 3 cm in soils 12–45 years old and 6–8 cm in soils older than 70 years. Initial subsurface B horizon may be distinguished only in better drained soils on frontal moraine (older than 70 years) and on sandur plain Elverflya (sediments probably older than 40 years). Initial B horizons are slightly more rusty coloured than subsoil (have Munsell colour hue 10Y instead of 5GY), have weak subangular blocky soil structure, and usually are interlaced with plant roots throughout. These layers, however, do not fulfil the requirements for diagnostic horizon *cambic* (IUSS 2006), due to insufficient thickness and too little differentiation of colour if compared to subsoil. Soils derived of shallow till on hard rocks in the forefield of glacier are therefore classified as Leptosols or Gleysols, and soils having permafrost in subsoil are classified as Cryosols, usually with Turbic properties (Bockheim *et al.* 2006; IUSS 2006).

In soil profile 3, below the very thin cover of young moraine, the unique, complete profile of buried soil was found. It involves well developed A and B horizons whose cumulative thickness exceeds 25 cm. Subsurface Bw layer meets all requirements of diagnostic horizon *cambic* (IUSS 006), and the buried soil represents typical "arctic brown earths" (Tedrow and Hill 1955), that correspond with Eutric Cambisols (IUSS 2006). The present soil (whole pedon 3) must be, however, classified as Cryosol due to the occurrence of permafrost in subsoil and cryoturbation features at soil surface (IUSS 2006).

Sandy or gravelly-sandy, well drained "arctic brown soils", as represented by profile 6, are widespread on flat and locally elevated parts of raised marine beaches 8–12 m a.s.l., covered with tundra vegetation with predominance of lichens. The vertical section of a such soil consists of a well developed (dark-coloured, structured and rich in humic matter) surface A horizon, whose thickness is in general not less than 6–8 cm, overlying brown Bw horizon and transitional yellowish brown BC horizon. Upper Bw layer extends to the depth 25 cm of the soil surface or more, has weak but easily recognizable subangular soil structure and is interlaced with plant roots. Despite of significant thickness and visible transformation of soil colour and structure, the horizon does not fulfil an official definition of *cambic* horizon, due to sandy grain size distribution, but meets the requirements of *brunic* qualifier (IUSS 2006). Permafrost is absent within profile, therefore a soil is classified as Brunic Regosol.

Soil profile 1. — Location: proglacial zone, 20 m west of Werenskiold Glacier terminus, slope inclination *ca* 2°. Material: very gravelly (>40%) till covered with angular stones, age of sediment – 1 year. Surface: no marks of frost sorting, abundant tracks of water flow on soil surface. Vegetation: absent lichens and higher plants. Whole soil mass is wet and has gleyic (reductimorphic) properties.

Soil classification (IUSS 2006): Gleyic Leptosol (Calcaric, Skeletic)

Cg1	0–3 cm	greenish gray (10GY 6/1) loam, massive (structureless); 2.9% $CaCO_3$
Cg2	3–18	greenish gray (10GY 5/1) loam, massive or weak platy structure; 3.3–3.6% $CaCO_3$
R	18+	bedrock schists, mechanically cracked but unweathered chemically

Soil profile 2. — Location: proglacial zone, 280 m west of glacier. Material: very gravelly (33–47%) till covered with angular stones, age of sediment – *ca* 12 years. Surface: slope inclination *ca* 4°. Vegetation: surface covered in 20% with plants: lichens and mosses (50% of plant-covered surface), *S. oppositifolia* (40%) and *S. caespitosa* (10%). Gleyic (reductimorphic) properties occur below 6 cm from the soil surface.

Soil classification (IUSS 2006): Leptic Gleysols (Calcaric, Turbic, Skeletic)

Ag	0–3 cm	dark greenish gray (10Y 4/1) loam, weak subangular blocky structure; few roots of *Saxifraga*; 2.6% $CaCO_3$
AC	3–6	greenish gray (5GY 5/1) loam; weak subangular blocky structure; few roots; 5.6% $CaCO_3$
Cg1	6–15	greenish gray (10GY 5/1) loam; weak angular blocky structure; few roots; 4.5% $CaCO_3$
Cg2	15–30	greenish gray (10GY 5/1) loam; moderate angular-platy structure; plant roots absent; 4.6% $CaCO_3$
Cg3	30–45	greenish gray (10GY 5/1) loam; moderate angular blocky structure; 4.9% $CaCO_3$
R	45+	bedrock schists, mechanically cracked but unweathered chemically

Soil profile 3. — Location: proglacial zone, 750 m west of glacier, the site isolated among quartzite blocks on the margin of moraine plain. Material: very gravelly (50–55%) till covered with angular stones, age of sediment – *ca* 45 year, on older, stratified till and gravels. Surface: rock fragments in pavement locally sorted, some desiccation cracks. Vegetation: surface covered in 40% with plants: *S. oppositifolia* (60% of plant-covered surface), *S. caespitosa* (20%), lichens, mosses, single plants of *Poa alpigena* and *Cerastium alpinum*.

General soil profile description: cryoturbated soil developed from recent till on buried "brown earth" (Cambisol) with permafrost in subsoil.

Soil classification (IUSS 2006): Thaptocambic Cryosol (Calcaric, Reductaquic, Skeletic)

Ag	0–3 cm	dark greenish gray (10Y 4/1) loam, gravelly; subangular blocky structure; common roots of *Saxifraga*; 0.9% $CaCO_3$
AC	3–10	greenish gray (10Y 5/1) loam, gravelly; weak, thin platy structure; few roots; 2.8% $CaCO_3$, distinct boundary
Cg	10–14	light olive brown (2.5Y 5/3) silt loam, very few skeletal grains; very few roots; 3.6% $CaCO_3$, gleyic properties; abrupt, smooth boundary
2Ab	14–20	buried humic horizon; olive brown (2.5Y 4/3) sandy loam, gravelly, but not covered with pavement; strong, fine subangular blocky structure; many roots; 1.7% $CaCO_3$; gradual boundary
2ABb	20–26	dark olive brown (2.5Y 3/3) sandy loam, gravelly (37%); moderate subangular blocky structure; common roots; 1.6% $CaCO_3$
2Bwb	26–40	light olive brown (2.5Y 5/4) sandy loam, gravelly (36%); moderate, fine angular-platy structure; few roots; 0.8% $CaCO_3$; thin iron pan at the depth *ca* 35 cm
3C	40–70	olive yellow (2.5Y 6/6) loamy gravel covered with stony pavement; massive, or locally loose (sand lamellae); 0.6% $CaCO_3$; few roots
4Cx	70–90	light olive brown (2.5Y 5/5) sandy loam, very gravelly (50%); strong angular-platy structure; 1.8% $CaCO_3$
I	90+	permafrost layer

Soil profile 4. — Location: upper part of end moraine (W slope), 1600 m west of glacier, slope inclination *ca* 15°. Material: very gravelly (55–60%) till covered with stony pavement, age of sediment – more than 70 year. Surface: pavement locally frost-sorted, many regular cracks on soil surface. Vegetation: surface covered in 20% with plants: *S. oppositifolia* (70% of plant-covered surface), *S. caespitosa* (10%), mosses and single plants *P. alpigena* and *C. alpinum.* Gleyic (reductimorphic) properties occur below 10 cm from the soil surface.

Soil classification (IUSS 2006): Turbic Cryosol (Calcaric, Reductaquic, Skeletic)

A	0–6 cm	dark greenish gray (10Y 4/1) sandy loam; subangular blocky structure; common roots of *Saxifraga*; 2.5% $CaCO_3$
BCg	6–12	greenish gray (10Y 5/1) sandy loam; subangular blocky structure; common roots; 3.3% $CaCO_3$
Cg1	12–22	greenish gray (5GY 5/1) loam; moderate subangular blocky structure; few roots; 2.6% $CaCO_3$
Cg2	22–40	greenish gray (5GY 5/1) loam; moderate angular blocky structure; plant roots absent; 3.2% $CaCO_3$
Cg3	40–125	dark greenish gray (5GY 4/1) loam; coarse angular-platy structure; 4.1% $CaCO_3$
I	125+	ice nucleus involving little admixture of mineral grains

Soil profile 5. — Location: glaciofluvial (sandur) plain Elveflya, distance to the shoreline *ca* 1200 m, altitude *ca* 15 m a.s.l. Material: alluvial gravelly loam, covered with rounded gravel, on glaciofluvial gravels. Surface: pavement stones locally crushed and sorted, soil surface dissected with desiccation cracks. Vegetation: surface covered in 30% with plants: *S. oppositifolia*, *S. polaris*, *S. acaulis,* lichens and mosses. Gleyic properties occur in loam layer only.

Soil classification (IUSS 2006): Fluvic Turbic Cryosols (Calcaric, Reductaquic, Skeletic)

Ag	0–3 cm	olive gray (5Y 4/1) sandy loam; moderate subangular blocky structure; many roots; 2.4% $CaCO_3$
BCg	3–10	grayish gray (10Y 4/2) sandy loam; moderate subangular blocky structure; many roots; 4.3% $CaCO_3$
Cg	10–21	greenish gray (5GY 5/1) sandy loam; moderate angular blocky structure; few roots; 6.1% $CaCO_3$
2C1	21–40	grayish brown sandy gravel; structureless (loose); plant roots absent; 6.2% $CaCO_3$
2C2	40–90	grayish brown coarse gravel (sandy); structureless; 6.5% $CaCO_3$; groundwater below 70 cm
I	95+	permafrost

Soil profile 6. — Location: raised marine terrace 8–12 m a.s.l., slope inclination 2–4°. Material: fine sand stratified with medium-grain sand. Surface: covered with rounded gravel, locally weathered (crushed) and sorted. Soil surface dissected with cracks into polygons 6–12 m in diameter. Profile situated on the contact of three filled cracks. Wedge depth >125 cm, diameter – 40 cm at soil surface, and 10–20 cm at 100–120 cm below soil surface, wedge fillings: vertically layered gravelly-sandy-organic material, coarser than the texture of adjacent sandy sediments. Vegetation: surface covered in >90% with lichens, *S. polaris*, *S. oppositifolia*, *S. caespitosa, S. acaulis,* and grasses.

Soil classification (IUSS 2006): Brunic Regosol (Eutric, Turbic, Arenic)

Ah	0–2 cm	humic horizon containing many plant roots fills interstices between gravel of pavement
A	2–4	very dark grayish brown (10YR 3/2) humic horizon, fine sand, very gravelly (55%); medium subangular blocky structure; many roots; $CaCO_3$ absent
ABw	4–8	dark grayish brown (10YR 4/2) fine sand, gravelly (35%, fine gravel); weak, medium subangular blocky structure; common roots; $CaCO_3$ absent
Bw	8–25	brown (10YR 4/3) fine sand, gravelly (30%); weak, medium subangular blocky structure; few roots; $CaCO_3$ absent
BC	25–45	dark yellowish brown (10YR 4/4) fine sand, gravelly (25%); very weak subangular structure or structureless; few roots; $CaCO_3$ absent
C	45–150	yellowish brown (10YR 5/4) fine sand, gravelly (8–11%), stratified with sand almost gravel-free (1.5–5%); structureless; plant roots absent; traces of $CaCO_3$; groundwater at *ca* 105 cm
R	150+	bedrock schists

Grain size distribution and chemical properties of soils

The share of individual grain-size fractions within the soil profile varies in space and with depth only insignificantly. Skeletal fraction (fine and medium gravel) forms usually 40–60% of the overall soil mass. The content of silt fraction

(0.002–0.05 mm) is in the range of 40–45% of the fine-earth fractions and clay fraction (<0.002 mm) is usually in the range of 9–15% (Table 1). However, the decrease of clay fraction in the surface soil layer (0–3 cm) is distinctly visible (Fig. 2) as compared in the chronosequence from the glacier snout (15% of clay in soil profile 1) to the terminal moraine (5–7% of clay in soil profile 4). This could be interpreted as a result of natural variability of glacial sediments, however, the possibility of clay translocation in Arctic soils due to cryoturbation or formation of internal aggregate soil structure has been often mentioned (Jacobson and Birks 1980; Alexander and Burt 1996; He and Tang 2008). Subsequent layers of materials which presently form soils on the sandur plain Elveflya sedimented under various conditions, and their texture classes change with the depth (as in soil profile 5) from gravelly sandy loam to coarse gravel. In contrast, the soil on the marine beach 8–12 m a.s.l. has uniform texture of gravelly sand throughout the profile with higher contribution of coarse gravel at the surface only.

All soils developed on the recent glacial sediments (soil profiles 1–5) contain considerable amounts of $CaCO_3$ (up to 6.6%). The dissolution of carbonates is detect-

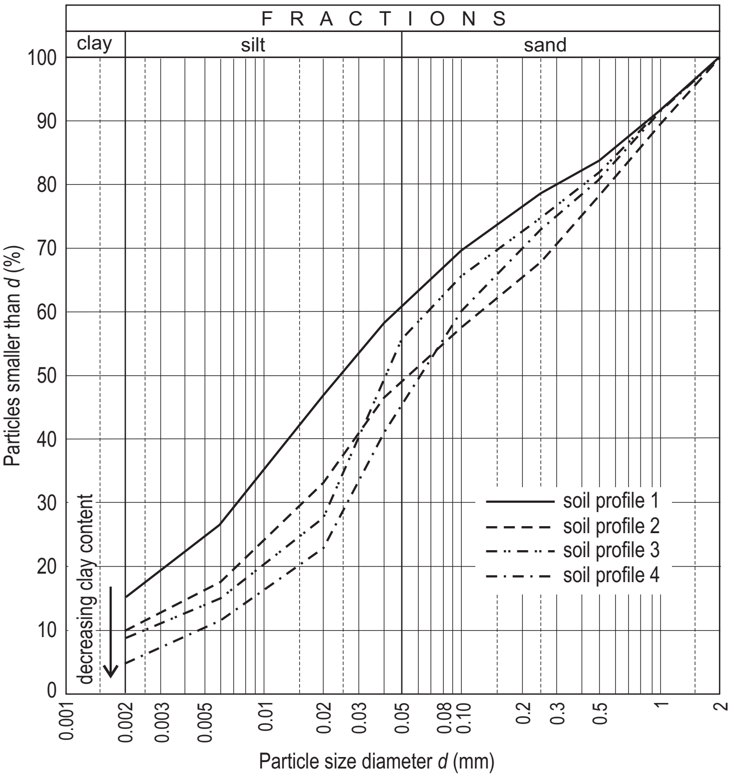

Fig. 2. Cumulated curves of particle-size distribution in thin surface layers (0–3 cm) of soils derived from till in the forefield of Werenskiold Glacier. Decrease of clay content is apparently visible in developing soils.

Table 1

Particle size distribution and basic chemical characteristics of soils in the forefield of Werenskiold Glacier and on the raised marine beach

Soil horizon	Depth (cm)	Particle size distribution (%; grain diameters in mm)				pH_{H2O}	$CaCO_3$	Organic carbon	Base exchangeable cations				Fe_o	Fe_d	Fe_o/Fe_d
		>2[a]	2.0–0.05[b]	0.05–0.002[b]	<0.002[b]				Ca^{2+}	Mg^{2+}	K^+	Na^+			
							%		cmol(+) kg^{-1}				%		
Soil profile 1. Proglacial zone, 20 m west of Werenskiold Glacier terminus															
Cg1	0–3	50	40	45	15	8.35	2.9	0.50	30.0	3.83	0.70	0.20	0.47	1.04	0.46
Cg2	3–10	42	40	44	16	8.36	3.3	0.47	34.4	4.05	0.81	0.31	0.46	1.03	0.45
Cg2	10–18	38	40	45	15	8.38	3.6	0.38	30.4	4.02	0.73	0.30	0.46	1.03	0.45
Soil profile 2. Proglacial zone, 280 m west of Werenskiold Glacier terminus															
Ag	0–3	47	55	35	10	7.78	2.6	1.04	12.9	5.62	0.46	0.10	0.56	1.08	0.52
AC	3–6	38	49	40	11	8.13	4.6	0.46	18.7	2.78	0.55	0.13	0.53	1.07	0.50
Cg1	6–15	39	43	46	11	8.29	4.5	0.43	26.8	3.96	0.62	0.18	0.50	0.95	0.52
Cg2	15–30	33	42	46	12	8.34	4.6	0.51	25.2	3.83	0.57	0.17	0.42	0.89	0.47
Cg3	30–45	47	41	45	14	8.29	4.9	0.48	25.6	3.26	0.82	0.26	0.46	0.97	0.47
Soil profile 3. Proglacial zone, 750 m west of Werenskiold Glacier terminus															
Ag	0–3	55	44	47	9	7.73	0.9	1.33	18.7	1.58	0.46	0.04	0.81	1.31	0.62
AC	3–10	50	40	48	12	8.02	2.8	0.45	21.2	2.68	0.68	0.21	0.80	1.32	0.61
Cg	10–14	6	33	62	5	8.05	3.6	0.57	29.2	5.10	0.67	0.06	0.63	1.35	0.47
2Ab	14–20	37	69	27	4	7.31	1.7	1.46	36.8	6.97	0.82	0.04	0.87	1.48	0.59
2ABb	20–26	37	62	24	4	7.22	1.6	1.31	32.4	5.10	0.75	0.09	0.73	1.43	0.51
2Bwb	26–40	36	68	29	3	7.08	0.8	0.43	37.6	6.05	1.02	0.13	0.39	1.55	0.25
3C	40–70	80	67	31	2	7.09	0.6	0.33	39.6	4.71	0.92	0.11	0.25	1.40	0.18
3C	70–80	81	68	30	2	7.21	1.8	0.16	37.6	10.10	0.98	0.23	0.23	1.10	0.21

Explanation: [a] percentage of bulk soil sample; [b] percentage of fine earth fractions (<2 mm).

Table 1 (continued)

Particle size distribution and basic chemical characteristics of soils in the forefield of Werenskiold Glacier and on the raised marine beach

Soil horizon	Depth (cm)	Particle size distribution (%; grain diameters in mm)				pH_{H2O}	$CaCO_3$	Organic carbon	Base exchangeable cations				Fe_o	Fe_d	Fe_o/Fe_d
		>2[a]	2.0–0.05[b]	0.05–0.002[b]	<0.002[b]				Ca^{2+}	Mg^{2+}	K^+	Na^+			
							%		cmol(+) kg^{-1}				%		
Soil profile 4. Terminal moraine, 1600 m west of Werenskiold Glacier terminus															
A	0–3	55	59	36	5	7.74	2.3	2.52	27.2	0.55	0.52	0.26	0.81	1.23	0.66
A	3–6	58	58	36	6	7.92	2.6	0.87	31.2	0.75	0.59	0.06	0.63	1.01	0.62
BCg	6–12	60	68	25	7	8.16	3.3	0.44	33.2	0.82	0.44	0.08	0.47	0.92	0.51
Cg1	12–22	55	51	40	9	8.23	3.3	0.40	34.3	0.56	0.38	0.07	0.47	1.02	0.46
Cg2	22–40	60	49	41	10	8.23	3.2	0.44	38.6	0.50	0.27	0.08	0.43	0.95	0.45
Cg3	40–125	60	48	41	11	8.24	4.1	0.49	37.8	0.42	0.15	0.06	0.14	1.09	0.40
Soil profile 5. Sandur (glacio-fluvial) plain Elveflya															
Ag	0–3	56	59	39	2	7.91	2.4	0.88	29.6	0.67	0.19	0.07	0.55	0.87	0.63
BCg	3–10	58	62	35	3	8.24	4.3	0.53	26.0	0.76	0.17	0.05	0.54	0.90	0.60
Cg	10–21	74	81	15	4	8.40	6.1	0.62	27.6	0.72	0.23	0.07	0.42	0.86	0.49
2C1	21–40	82	93	5	2	8.39	6.2	0.41	23.6	0.62	0.17	0.04	0.21	0.61	0.34
Soil profile 6. Marine beach 8–12 m a.s.l., near Glacier River estuary															
Ah	0–2	68	89	10	1	4.88	0	4.96	0.5	0.31	0.07	0.03	0.35	0.51	0.69
A	2–4	55	88	11	1	4.95	0	1.15	0.6	0.32	0.11	0.02	0.25	0.43	0.59
ABw	4–8	35	94	5	1	5.01	0	0.58	1.4	0.54	0.19	0.04	0.26	0.46	0.57
Bw	8–15	30	98	1	1	5.34	0	0.46	1.2	0.32	0.12	0.03	0.25	0.46	0.55
Bw	15–25	30	98	1	1	5.26	0	0.32	1.5	0.33	0.10	0.02	0.28	0.53	0.52
BC	25–35	25	96	3	1	5.19	0	0.31	5.0	0.35	0.32	0.23	0.30	0.53	0.56
BC	35–45	25	96	3	1	5.38	0	0.31	8.2	0.34	0.51	0.08	0.33	0.62	0.52
C	45–60	11	96	2	2	6.80	<0.5	0.12	8.8	0.26	0.59	0.03	0.20	0.47	0.42
C	60–80	2	97	2	1	6.86	<0.5	0.26	15.1	4.43	1.05	0.03	0.22	0.44	0.50
C	80–120	8	97	2	1	6.93	<0.5	0.17	21.6	0.85	0.08	0.03	0.23	0.43	0.55

Explanation: [a] percentage of bulk soil sample; [b] percentage of fine earth fractions (<2 mm).

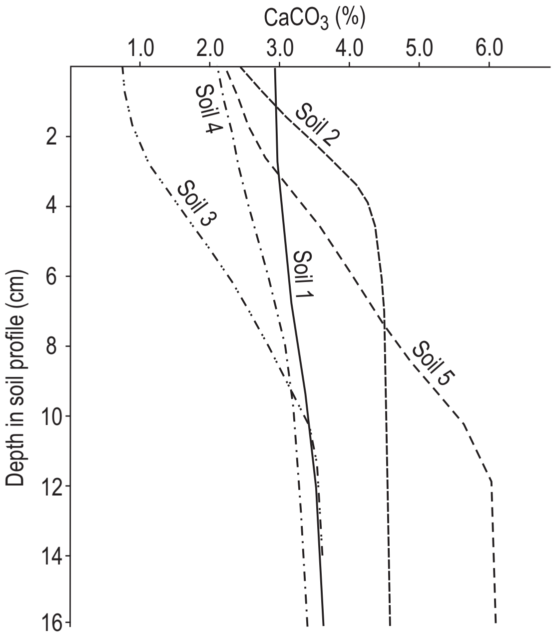

Fig. 3. Calcium carbonate content in surface layers of soils in the forefield of glacier.

able in sediments which are 10–12 year old (profile 2) but only in the upper 0–3 cm layer, while in the 45–70 year old formations the leaching of $CaCO_3$ reaches the depth 12–14 cm of soil surface (Fig. 3). Glaciofluvial deposits on the Elveflya plain are also rich in carbonates (up to 6.2%), the content of which distinctly decreases towards the soil surface. Buried older glaciofluvial gravels in the proglacial zone of Werenskiøld glacier (found in the lower part of soil profile 3), as well as sands on the raised marine beach (soil profile 6) contain much less $CaCO_3$, namely 0.6–1.8% and <0.5% in profiles 3 and 6, respectively. With the dissolution of $CaCO_3$, also the pH of soil decreases. Initial pH of the youngest moraine tills is about 8.3–8.4 throughout till layer. Value of pH in the 0–3 cm soil layer falls below 8.0 already in 12 year old sediments, nevertheless, the acidification of a deeper layer (3–6 cm) can be observed only in soils more than 70 year old (Fig. 4). The decrease of pH results directly from the dissolution of $CaCO_3$ and the subsequent colonisation of glacial forefield by plants, followed by the accumulation of humic substances. The most recent glacial deposits contain no more than 0.5% of organic carbon, but already in 12 year old soils this amount rises above 1%, and up to 2.5% in soils more than 70 years old (in the 0–3 cm layer). The content of organic carbon in the buried humic horizon (soil profile 3) is relatively high, in the range 1.6–1.7%, in whole 12 cm deep layer. Similarly, the mean content of organic carbon within the upper 0–6 cm of soil on the marine beach (profile 6) is about 2.2% and reaches almost 5% in the top layer 0–2 cm (Fig. 5).

Overall sum of exchangeable base cations (Ca, Mg, K, Na) in soils under investigation is influenced primarily by the large amounts of calcium ions (Table 1) re-

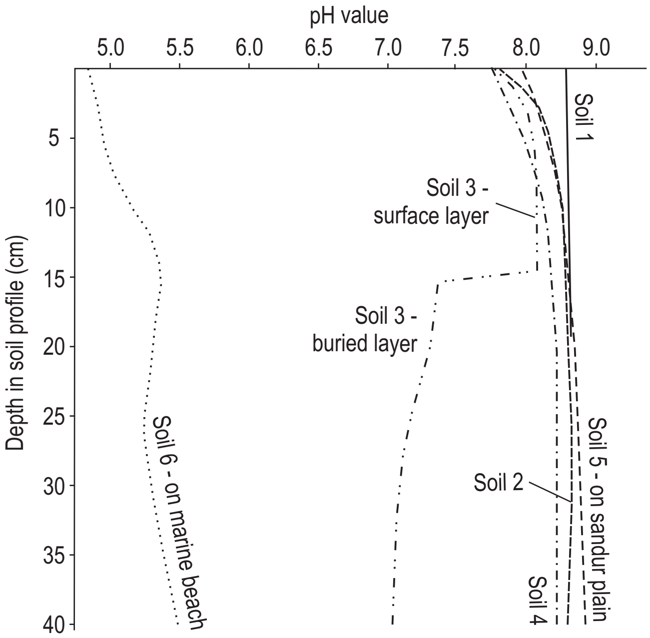

Fig. 4. Changes in pH value in vertical sections of soils in the forefield of glacier.

leased from $CaCO_3$, that explains differences between the amount of base cations in soils derived from glacial and marine sediments. Relative share of exchangeable magnesium and potassium is low, despite the high content of these elements in rocks surrounding the glacier. The decrease of the total sum of base cations, observed in top layer of soil chronosequence in the glacier's forefield, is therefore correlated with the loss of calcium carbonate. However, also magnesium is a subject of leaching from the surface soil layers, which is in contrast to potassium and sodium, the content of which remains stable (within particular soil profiles). The content of base cations in soil developed from marine sands is several times smaller than that of soil formed of glacial till. It clearly increases with the depth, from *ca* 0.6 cmol(+) kg^{-1} in the 0–2 cm layer to over 20 cmol(+) kg^{-1} at the depth of 80 cm, indicating advanced leaching of base cations, long-lasting under conducive climatic conditions.

The ratio of amorphous iron to free iron (Fe_o:Fe_d) is regarded one of most important indicators describing the intensity of the weathering of primary minerals and the advance of pedogenesis (Blume and Schwertmann 1969; Melke and Chodorowski 2006). In fresh glacial till this ratio amounts to <0.5 (soil profile 1). In the soil chronosequence in the glacier forefield, the value of Fe_o:Fe_d indicator in the 0–3 cm layer rises from 0.46 to 0.66. This change is primarily due to the increase in the "amorphous" iron content. For soils developed from loam and sand, the values of the Fe_o:Fe_d indicator are in fact incomparable, but in profile 6 (on the marine beach) the indicator value rises towards the soil surface, up to the value of 0.6–0.7, indicating advanced transformation of iron-bearing minerals.

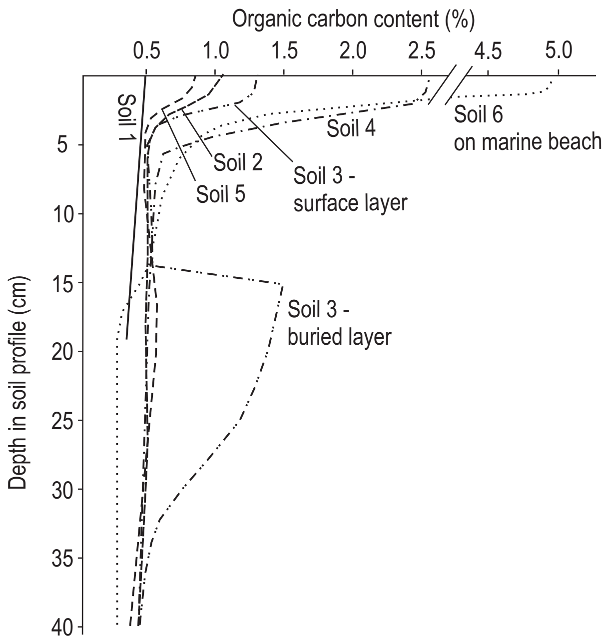

Fig. 5. Accumulation of organic carbon in surface horizons of soils in the forefield of glacier. Sub-fossil A horizon of buried soil (profile No 3) contains more organic carbon than surface layer of recent soil.

Discussion

Svalbard archipelago is situated in the High Arctic zone, characterized by very low advance of soil development and the dominance of Cryosols and Leptosols in soil cover (Goryachkin *et al.* 2004). Present-day climate warming is conducive to pedogenic transformation of recently sedimented moraines, including those located in the forefield of Werenskiold Glacier. However, in soils younger than 45 years the pedogenic transformations reach the depth not more than 3 cm of the soil surface, and in soils 45–70 years old bear soil layer to the depth of 6–10 cm. The changes being observed are caused by the percolation of water from rain precipitation and snow melting, as well as by the pioneering vegetation, which enters the moraine as soon as 5–6 years after deglaciation. The chemical transformation is accompanied by the morphological changes only to a very limited extent. The first morphological symptoms of the pedogenesis are: development of weak angular and subangular soil structure and accumulation of organic matter followed by darkening of top soil layers. First changes in the colour of subsurface horizons cannot be seen earlier than in soils which are over 40–70 years old.

It is therefore concluded, that the development of complete soil profile as in soil pit 6 on raised marine beach proceeded under favourable climate during much longer time than the 70–80 year-lasting period of present relative climate warming. Describing buried soils derived during warmer periods of late Pleistocene on dunes in Poland and Germany, Borówka *et al.* (1986), Manikowska (1991), and Kaiser *et al.* (2006) indicated, that 200–300 years during the Bølling period was suitable for the development of very thin humic horizon or single gleyed layer only, whereas the formation of initial two-layered soil required at least 600–1000 years of milder climate as indicated during Allerod period. Development of complete profiles of sandy "rusty soils", involving A and B horizons, took place under favourable climate and vegetation and lasted at least 1000 years (Manikowska 1991). By analogy we suggest therefore, that the formation of well developed "arctic brown soils" on raised marine beaches of south-eastern Spitsbergen lasted similarly long period and started several centuries before the LIA.

The warming of the European climate between A.D. 800 and 1200 has been well-documented (Lindner *et al.* 1986; Stuiver *et al.* 1995; Dahl-Jensen *et al.* 1998). This period, often called the Holocene secondary climatic optimum, was characterized by development of vineyards in England and expansion of the Vikings to Iceland and Greenland. Several investigations of fossil (or sub-fossil) plant residues made in northern Scandinavia and on Spitsbergen indicate that during the Viking Age all the region experienced a warm period with distinct retraction of glaciers and well-developed tundra in the glacier forefields (Baranowski and Karlén 1976). Datings of fossil tundra remnants from the forefield of Werenskiold Glacier made by Baranowski (Baranowski and Karlén 1976; Baranowski 1977) play crucial role in reconstruction of soil development on this area. The average age of the whole stratum was dated to 1080±105 years B.P. The age of the upper part of the layer was dated to 760±145 years B.P., and the lower part to 1565±235 years B.P. These results confirm a long-lasting and continuous period of tundra vegetation occurrence that certainly favoured soil development. The soil profile 3, analysed in present study, is located exactly in the same area where Baranowski (1977) revealed fossil tundra, and we suppose that the buried soil found in this profile represents tundra soils developed already during the Viking Age. The period was sufficiently long (*ca* 800 years) and warm for developing of two-layered "arctic brown earths" within well-drained gravelly-sandy loam. Formation of this soil was stopped by an advance of Werenskiold Glacier during the LIA.

Goryachkin *et al.* (2004) indicated that present climatic conditions in the High Arctic zone are not favourable for the formation of "arctic brown earths" which occur rather in the Low Tundra and Subarctic Tundra zones (as in southern Greenland, northern Scandinavia and Canada). Well developed soils found in some localities in the High Arctic and Antarctic zones may be relics of a former warmer climate (Campbell and Claridge 1987). In our opinion, "arctic brown earths" occurring on raised marine beaches between Hornsund and Nottinghambukta are such surface relic soil (Ruellan 1971) in such sense, that the soil formation started and achieved an advance stage during sufficiently long warm period before the LIA. Present milder climate favour the renevation of pedogenesis, which was stopped in these soils during the LIA. From the analysis of soil chronosequence in the glacier's forefield we concluded that present pedogenic processes are of the same nature that before the LIA and probably will result in similar final soil profiles. However, they are still at initial stage and could not be responsible for advanced development of deep A and Bw horizons (as occurring in soil profile 6), which are in fact analogues of horizons in buried soil (within profile 3) on the forefield of Werenskiold Glacier, developed during the Viking Age.

It must be stressed, that well preserved, relic surface „arctic brown soils" occur extensively on the raised terrace 8–12 m a.s.l. in specific locations only. There are nearly flat and locally elevated surfaces, built of on marine sands and gravelly sands, well drained and relatively dry, and covered with rather scarce vegetation dominated by lichens. The soil surface is dissected with cracks into large polygons 8–10 m in diameter. The thickness of cracks is 20–40 cm at soil surface and their depth generally exceeds 120–140 cm. Cracks are filled with sandy-humic material, laterally stratified. Cracks, large polygons and gravelly pavement on soil surface are cryogenic features developed during last cold period of LIA. However, the nearly levelled interior of large polygons has no visible marks of cryoturbation, probably due to sandy texture of soil and insufficiency of interstitial water (Van Vliet-Lanoe 1998). Due to weak frost action in such sandy and dry material, preservation of existing soil horizonation was possible, even at soil surface (Vanderberghe 1988). On most other areas of the raised beaches, *e.g.* in local depressions, along streams *etc.* where soils are saturated with water during thawing period, we observed significant (cryo-) turbation within upper soil layers. These soils have mostly loamy or silty grain size distribution, and are characterized by relatively high water retention, which makes the soil more susceptible to cryoturbation. In most of such soils, we found remains of older humic or cambic horizons, but strongly fragmented and displaced within soil profile, which is in apparent contradiction to well preserved vertical sequence of horizons in soils located on elevated sandy parts of raised terraces.

Conclusions

In the surface layer of the youngest moraine in the forefield of Werenskiold Glacier the soil-forming processes occur, which include the dissolution of $CaCO_3$, decrease of pH, leaching of calcium and magnesium cations, transformations of mineral forms of iron, organic matter accumulation, and the formation of aggregate (subangular blocky) soil structure. The 70 year-long period of pedogenesis is, however, too short for a clear, morphological differentiation of soil horizons other than surface humic A horizon. Initial B horizons have too weak expression of newly formed pedogenic features to meet criteria of diagnostic soil horizons.

Therefore, soils occurring on the marine beach 8–12 m a.s.l., having deep and well-developed A and Bw horizons are *in fact* relic surface soils whose formation started and achieved an advanced stage before the Little Ice Age. Buried "arctic brown earths" occurring locally in the forefield of the Werenskiold Glacier under thin cover of the youngest moraine are sub-fossil analogues of "arctic brown earths" occurring on raised beach, developed under the same climatic conditions during of so-called Viking Age. This period was sufficiently warm and long-lasting for the formation of A-Bw sequence of soil (diagnostic) horizons.

References

ALEXANDER E.B. and BURT R. 1996. Soil development on moraines of Mendenhall Glacier, southeast Alaska. 1. The moraines and soil morphology. *Geoderma* 72: 1–17.

ANDERSON S.P., DREVER J.I., FROST C.D. and HOLDEN P. 2000. Chemical weathering in the foreland of a retreating glacier. *Geochimica et Cosmochimica Acta* 64: 1173–1189.

BARANOWSKI S. 1977. Results of dating of the fossil tundra in the forefield of Werenskioldbreen. *Acta Universitatis Wratislaviensis* 387: 31–37.

BARANOWSKI S. and KARLEN W. 1976. Remnants of Viking Age tundra in Spitsbergen and Northern Scandinavia. *Geografiska Annaler, Series A, Physical Geography* 58: 35–40.

BLUME H.P. and SCHWERTMANN U. 1969. Genetic evaluation of profile distribution of aluminium, iron, and manganese oxides. *Soil Science Society of America Preceedings* 33: 438–444.

BOCKHEIM J.G., MAZHITOVA G., KIMBLE J.M. and TARNOCAI C. 2006. Controversis on the genesis and classification of permafrost-affected soils. *Geoderma* 137: 33–39.

BORÓWKA R.K., GONERA P., KOSTRZEWSKI A., NOWACZYK B. and ZWOLIŃSKI Z. 1986. Stratigraphy of eolian deposits in Wolin Island and the surrounding area, North-West Poland. *Boreas* 15: 301–309.

BUKOWSKA-JANIA E. 2003. *The role of glacier systems in the migration of calcium carbonate in the natural environment*. Wydawnictwo Uniwersytetu Śląskiego, Katowice: 247 pp. (in Polish)

BUKOWSKA-JANIA E. and JANIA J. 1998. Changes of the geometry of Werenskiold Glacier terminus (Spitsbergen) in years 1957, 1973, 1982, 1983. *In*: *Wyprawy Polarne Uniwersytetu Śląskiego*. Wydawnictwo Uniwersytetu Śląskiego, Katowice: 64–91. (in Polish)

CAMPBELL I.B. and CLARIDGE G.G.C. 1987. *Antarctica: Soils, Weathering Processes and Environment*. Developments in Soil Science 16, Elsevier, Amsterdam: 328 pp.

CHMAL H. 1988. Late Quaternary sea level changes and glacial history of the Hornsund area, Spitsbergen. *15th Polar Symposium, Wrocław, May 19–22*: 109–114.

CHODAK T. 1988. Iron and clay minerals in periglacial environment. *Proceedings of the Fifth International Conference on Permafrost, Trondheim, Norway, August 2–5, 1988*, Vol. 1: 316–319.

CZERNY J., KIERES A., MANECKI M. and RAJCHEL J. 1993. Geological Map of the SW part of Wedel-Jarlsberg Land, Spitsbergen, 1:25000. Institute of Geology and Mineral Deposits, University of Mining and Metalurgy, Kraków: 61 pp.

DAHL-JENSEN D., MOSEGAARD K., GUNDESTRUP N., CLOW G.D., JOHNSEN S.J. and BALLING N. 1998. Past temperatures directly from the Greenland ice sheet. *Science* 282: 268–271.

GORYACHKIN S.V., BLUME H.P., BEYER L., CAMPBELL I., CLARIDGE G., BOCKHEIM J.G., KARAVAEVA N.A., TARGULIAN V. and TARNOCAI C. 2004. Similarities and differences in Arctic and Antarctic soil zones. *In*: J.M. Kimble (ed.) *Cryosols. Permafrost-affected soils*. Springer, Berlin-Heidelberg: 49–70.

HAUGLAND J.E. 2004. Formation of patterned ground and fine scale soil development within two late Holocene glacial chronosequences: Jotunheimen, Norway. *Geomorphology* 61: 287–301.

HE L. and TANG Y. 2008. Soil development along primary succession sequences on moraines of Hailuogou Glacier, Gongga Mountain, Sichuan, China. *Catena* 72: 259–269.

IUSS 2006. World Reference Base for Soil Resources 2006. 2nd edition. *World Soil Resources Reports* 103, FAO, Rome: 122 pp.

JACOBSON G.L. and BIRKS H.J.B. 1980. Soil development on recent end moraines of the Klutlan Glacier, Yukon Territory, Canada. *Quternary Research* 14: 87–100.

KAISER K., BARTHELMES A., CZAKO PAP S., HILGERS A., JANKE W., KUHN P. and THEUERKAUF M. 2006. A Lateglacial paleosol cover in the Altdarss area, southern Baltic Sea coast (northeast Germany): investigations on pedology, geochronology and botany. *Netherlands Journal of Geosciences* 85: 197–220.

KLIMOWICZ Z. and UZIAK S. 2003. Spatial differentiation of soil properties along southern coast of Bellsund, Spitsbergen. *Polish Journal of Soil Sciences* 36: 31–39.

KOSIBA A. 1982. Glacio-hydrodynamic processes and changes on the Werenskiold Glacier and Hans Glacier, SW Spitsbergen. *Acta Universitatis Wratislawiensis* 525: 133–152.

LINDNER L., MARKS L. and PĘKALA K. 1986. Outline of Quaternary chronostratography of the northern Hornsund area, southern Spitsbergen. *Bulletin of the Polish Academy of Sciences, Earth Sciences* 34: 427–436

LINDNER L., MARKS L., ROSZCZYNKO W. and SEMIL J. 1991. Age of raised marine beaches of northern Hornsund Region, South Spitsbergen. *Polish Polar Research* 12: 161–182.

LONNE I. and LYSA A. 2005. Deglaciation dynamics following the Little Ice Age on Svalbard: Implication for shaping of landscapes at high latitudes. *Geomorphology* 72: 300–319.

MANIKOWSKA B. 1991. Vistulian and Holocene aeolian activity, pedostratigraphy and relief evolution in Central Poland. *Zeitschrift für Geomorfologie, Supplement* 90: 131–141.

MARSZ A.A. and STYSZYŃSKA A. 2007. *The climate in the vicinity of Polish Polar Station in Hornsund*. Akademia Morska, Gdynia, 376 pp. (in Polish)

MELKE J. and CHODOROWSKI J. 2006. Formation of arctic soils in Chamberlindalen, Bellsund, Spitsbergen. *Polish Polar Research* 27: 119–132.

PIROŻNIKOW E. and GÓRNIAK A. 1992. Changes in the characteristics of the soil and vegetation during the primary succession in the marginal zone of the Werenskiold Glacier, Spitsbergen. *Polish Polar Research* 13: 19–30.

PLICHTA W. 1977. Systematics of soils of the Hornsund region, West Spitsbergen. *Acta Universitatis Nicolai Copernici, Geografia* 13: 175–180.

RUELLAN A. 1971. The history of soils: some problems of definition and interpretation. *In*: D.H. Yaalon (ed.) *Paleopedology – Origin, Nature and Dating of Paleosols*. International Society of Soil Sciences: 3–13.

SKIBA S., DREWNIK M. and KACPRZAK A. 2002. Soil of the western coast of Sørkappland. *In*: W. Ziaja and S. Skiba (eds) *Sörkappland landscape structure and functioning (Spitsbergen, Svalbard).* Wydawnictwo Uniwersytetu Jagiellońskiego, Kraków: 51–86.

STUIVER M., GROOTES P.M. and BRAZIUNAS T.F. 1995. The GISP2 δ^{18}O climate record of the past 16,500 years and the role of the sun, ocean, and volcanoes. *Quaternary Research* 44: 341–354.

SZERSZEŃ L. 1968. Preliminary investigations of soil cover in the region of Hornsund, Vestspitsbergen. *In*: K. Birkenmajer (ed.) *Polish Spitsbergen Expeditions*. Polish Academy of Sciences, Warszawa: 217–227.

TEDROW J.C.F. and HILL D.E. 1955. Arctic brown soil. *Soil Science* 80: 265–275.

VANDENBERGHE J. 1988. Cryoturbations. *In*: M.J. Clarks (ed.) *Advances in Periglacial Geomorphology*. Wiley: 179–198.

VAN VLIET-LANOE B. 1998. Frost and soils: implications for paleosols, paleoclimates and stratigraphy. *Catena* 34: 157–183.

VAN REEUWIJK L.P. 2006. Procedures for soil analysis. 7th edition. ISRIC – World Soil Information Centre, *Technical Reports* 9, Wageningen, Netherlands, 150 pp.

ZIAJA W. 2002. Changes in the landscape structure of Sørkappland. *In*: W. Ziaja and S. Skiba (eds) *Sørkappland landscape structure and functioning (Spitsbergen, Svalbard)*. Wydawnictwo Uniwersytetu Jagiellońskiego, Kraków: 18–50.

Received 10 December 2008
Accepted 20 March 2009