Relict and contemporary soils on uplifted marine terraces of Kvartsittsletta, SW Spitsbergen

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Abstract: The soils of Arctic regions are of great interest due to their high sensitivity to climate change. Kvartsittsletta coast in the vicinity of the Baranowski Research Station of the University of Wrocław constitutes a sequence of differently aged sea terraces covered with different fractions of beach material. It is a parent material for several developing soil types. Despite the low intensity of the modern soil-forming processes, the soil cover is characterized by high diversity. Soil properties are formed mainly by geological and geomorphological factors, which are superimposed by the influence of climate and living organisms. The degree of development of soil is usually an indicator of its relative age. This article highlights the dominant influence of lithology and microrelief over other soil-forming factors, including the duration for which the parent material was exposed to external factors. The soils on the highest (oldest) terrace steps of the Kvartsittsletta rarely showed deep signs of soil-forming processes other than cryoturbations. On the youngest terraces, deep-reaching effects of soil processes associated with a relatively warm climate, including the occurrence of *cambic* horizons, were observed. Their presence in Arctic regions carries important environmental information and may be relevant to studies of climate change.

Keywords: Arctic, Svalbard, arctic soil, Cryosols, Cambisols, soil processes, permafrost.

Introduction

The Arctic has been of great interest to researchers for several decades due to a high sensitivity of its environments to climate change. The Svalbard archipelago is characterized by climate conditions that are non-typical for high latitudes. The relatively high precipitation, as well as high air humidity and temperature affect the rate and the direction of soil-forming processes. In the Holocene alone, the climatic fluctuations that spread over the Arctic left clear traces in the environment (IPCC 2022). The last warming of the Medieval Warm Period that lasted from *ca.* 800 to 1300 AD, led to the development of "brown soils" in this area (Tedrow and Hill 1955; Baranowski and Karlen 1976). The following Little Ice Age (LIA) (Matthews and Briffa 2005) was the period with the largest Holocene glacier extent on Spitsbergen (Salvigsen 2008). The subsequent climate warming observed from the beginning of the 20th century has dynamically accelerated in recent decades. This in turn heavily impacted the glacier recession processes (Rachlewicz *et al.* 2007), exposing fresh glacial and fluvioglacial deposits. Moreover, less visible changes occurred below the ground surface. Systematic lowering of the top of permafrost (Rachlewicz and Szczuciński 2008; Marsz *et al.* 2011) resulted in an increase in the thickness of the active layer, activating a number of processes. Signs of these changes can be found in soils.

Studies focusing on the soils of Spitsbergen were initiated already at the beginning of the 20th century by Norwegian researchers (Plichta 1993). Polish geomorphological-pedological research was initiated in the Hornsund area in 1957 as a part of the 3rd International Geophysical Year. It was carried out by scientists from several academic centers in Wrocław (Kowaliński and Szerszeń 1962; Szerszeń 1968). Over the course of consecutive expeditions, the research was conducted in the coastal area between Hans Glacier (Hansbreen) in Hornsund and Werenskiold Glacier (Werenskioldbreen) in Nottinghambukta region, as well as in the forefield of Werenskiold Glacier itself (Szerszeń 1965; Baranowski 1977; Plichta 1977; Chodak 1988; Pirożnikow and Górniak 1992).

The previous pedological studies were mainly conducted near a few permanent settlements and scientific stations (Zwoliński *et al*. 2013; Iavid *et al*. 2018; Szymański *et al.* 2019a). Since the beginning of the 21st century, an increased interest in the study of Arctic soil cover is observed, which results from the great sensitivity and rapid response of this ecosystem to climate change in recent decades (Skiba and Ziaja 2002; Zwoliński *et al.* 2008; Van der Meij *et al.* 2016). Moreover, the awareness of the importance of polar research in understanding the mechanisms of historical climate change has been on the rise (Zwoliński *et al.* 2008), and new data have appeared on the environmental impact of contemporary processes taking place in the polar zone, such as the phenomenon of "tundra greening" (Doetterl *et al.* 2021). As permafrost disappears, CO_2 is released into the atmosphere, thereby intensifying the

greenhouse effect. This, in turn, activates a positive feedback phenomenon and accelerates global warming (Biskaborn *et al.* 2019; Wieder *et al.* 2019; Szymański *et al.* 2022).

The extraordinarily rapid recession of Arctic glaciers has caused much of the research interest to shift towards the fairly recently exposed glacier forefield areas. The results of the research conducted there also provided indirect indications of the development of soil covers in non-glaciated areas (Stachnik *et al.* 2022). The soils that have been developing for hundreds of years on elevated marine terraces are of particular interest (Skiba *et al.* 2002; Kabala and Zapart 2009, 2012; Kabała and Korabiewski 2013; Skiba 2013a, 2013b; Wietrzyk *et al.* 2018; Szymański *et al.* 2019b). The raised sea terraces associated with glacio-isostatic uplift are of completely different nature with beach sediments being the parent material for various soil types (Szymański *et al.* 2013, 2016a, 2016b).

The glacial sediments released from the ice or lifted glacio-isostatic marine deposits are exposed to the influence of external soil-forming factors. The lithology of parent material and presence of an active layer constitutes an internal factor that determines the development of these processes. The depth of seasonal permafrost thawing and lithology determine the water circulation in the soil profile and the intensity of cryogenic phenomena, *i.e.*, solifluction, frost swelling, *etc*. Identification of soil-forming processes and the degree of their advancement may be an indicator of the duration of optimal climatic conditions. The presence of endopedons, especially *cambic* horizons, may indicate that non-cryogenic, soil-forming processes have already begun to occur in the active layer, and their thickness may be an indirect indicator of the rate and extent of permafrost decay. The study of permafrost in the vicinity of the Polish Polar Station in Hornsund and other places showed a systematic increase in the thickness of the active layer (Rachlewicz and Szczuciński 2008; Dobiński and Leszkiewicz 2010). Relation between the depth of permafrost presence and the distance from the sea was also observed (Kasprzak *et al.* 2016, 2018). The aim of this study was to determine the advancement of soil formation processes taking place on relatively old surfaces of sea terraces, beyond the reach of glaciations, where the decisive factor should be the exposure time, substrate lithology, and the depth of permafrost presence.

Study area

The study area is located in the SW part of the Wedel-Jarlsberg Land on the Spitsbergen island, near the Werenskiold Glacier and the Baranowski Research Station of the University of Wrocław (Fig. 1). The geological structure of Kvartsittsletta coast is not very diversified. It is dominated by quartzites that form the core of the Gulliksenfjellet massif (Birkenmajer 2013) and the main part of the bedrock of the Kvartsittsletta coastal platform. From the side of Nottinghambukta, on the edge of the lowest terrace, metamorphic mica schists
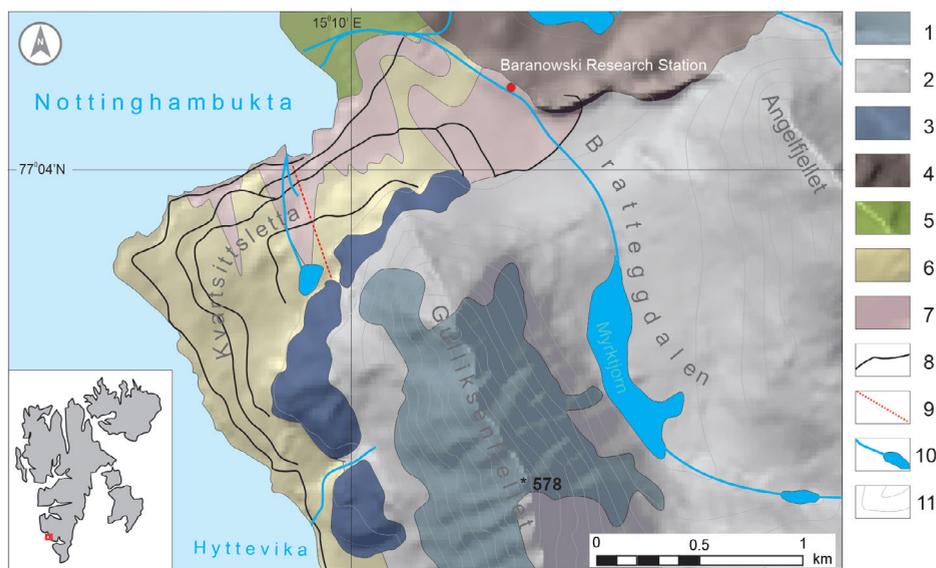
Fig. 1. Location of the transect shown in Fig. 2 on the geological-geomorphological sketch of the Kvartsittsletta area, based on Karczewski *et al. (1984)*, Birkenmajer (2013), Latocha and Parzóch (2013) and www.geokart.npolar.no: 1 - rocky slopes, 2 - debris mantled slopes, 3 - rock glaciers, 4 - moraine ridges, 5 - outwash fan complex of Elveflya, 6 - raised marine terraces on quartzite bedrock, 7 - raised marine terraces on mica schist bedrock, 8 - terrace edge/cliffs, 9 - transect location, 10 - streams and lakes, 11 - contour lines.

(Czerny *et al*. 1993), *i.e.*, green phyllites of the Eimfjellet Formation (geokart. npolar.no), are exposed, constituting the bedrock of several lower sea terraces, mainly in the NW part (Fig. 1). The Brattegg Valley (Bratteggdalen) is built up of different varieties of amphibolites. It is mostly covered by debris (Fig. 1). Three major types of relief present in this area are: (*i*) a mountainous terrain with sharply pointed crests, a widespread superficial debris mantle, and valleys partially covered with glaciers and rock glaciers, (*ii*) an extensive foreland zone of the Werenskiold Glacier (Werenskioldbreen) with glacial and fluvioglacial landforms, modified by melt-out processes, and (*iii*) a bedrock-cut coastal platform 1–4 km wide with a system of raised marine terraces and relict cliffs (Migoń and Kasprzak 2013).

The seaside platform of Kvartsittsletta is a part of the coastal zone in the Nottinghambukta area, which is inclined towards the sea (Fig. 1) and elevated isostatically to *ca.* 46 m a.s.l. It consists of a most complete in the area 6-stage system of abrasive terraces, that reach the elevations of 4–6, 8–12, 16–18, 22–25, 32–35 and 40–46 m a.s.l. and are covered by marine deposits (Migoń and Kasprzak 2013). The sediments are composed of coarse gravels, sandy-gravels and loamy-sandy-gravels of variable thickness, from several up to >150 cm. The fine rounded gravels and pebbles forming this gravelly layer are the remains of former beach material. The boundaries of the terraces inclined towards the sea are

often emphasized by the relicts of rocky marine cliffs. In their vicinity, the thickness of sediment decreases and the proportion of sharp-edged material increases. Both the cliffs and the bedrock of the terraces are composed mainly of white and green quartzite of the Gulliksenfjellet Formation (Czerny *et al.* 1993). The lithology of the bedrock influences the degree of weathering of the material and the amount of fine fraction, most of which is provided by mica schists. The terrace surfaces are uneven, especially in the central and eastern parts, where denudation-resistant quartzites form bedrock ridges and denudation outliers are up to several meters high.

The northern coast of Kvartsittsletta is composed of mica schists of the Bratteggdalen Formation. The rocks form the denuded edges of sea terraces and cliffs. The highest terrace, at the foothill of the Gulliksenflejet, is built up with the skeletal and sandy loam material of rock-glacier (Fig. 1). Northeastern part of the Kvartsittsletta is limited by Bratteggleva, as well as glacial and fluvioglacial accumulation forms of Werenskiold Glacier. The width of the Kvartsittslettas terrace system varies in the studied from *ca.* 600 m transect to *ca.* 900 m, and the length of the coast from Bratteggelva estuary to Hyttevika Bay reaches 3500 m.

The estimated ages of the terraces vary, depending on the method used. For the terrace 4.5–6 a.s.l., its age ranges from *ca.* 1–4 ka BP (Lindner *et al.* 1991) to 4.5–7.5 ka BP (Salvigsen and Elgersma 1993). The age of the terrace 8–12 m a.s.l. is 7–16 ka BP (Lindner *et al.* 1991; Salvigsen and Elgersma 1993). The age of the terrace 16–18 m a.s.l. was determined to be *ca.* 24 ka BP (Lindner *et al.* 1991). The higher the terraces, their ages are older.

The climate of the SW coast of Spitsbergen is characterized by low average annual air temperature reaching −3.7°C, with an increasing tendency of >1.0°C per decade in the last 40 years, and relatively high precipitation for the Arctic. Average annual precipitation in the Hornsund area amounts to 477 mm (Wawrzyniak and Osuch 2020). This has several consequences: the deep occurrence of permafrost, the top of which can go down below 150 cm during the Arctic summer (Dobinski and Leszkiewicz 2010), the occurrence of cryogenic processes, the predominance of physical weathering processes and mineralization of organic matter, as well as the eluviation process. The presence of permafrost implies that even changes at the microrelief scale cause large variability in soil moisture (Plichta 1993). The most frequently observed phenomenon is stagnation of water at the surface, which can lead to the intensification of erosion, flushing and solifluction processes.

Materials and methods

The fieldwork was carried out during the polar expeditions of the University of Wrocław in the years 2004–2011. In order to characterize the soils in the area, a transect was delineated through all terraces from the rock glacier on the SE to

the edge of the lowest terrace on the NW (Fig. 2). Along or near the transect line, seven soil pits were excavated to the depth of 70–100 cm. The classification of soil profiles followed the international soil classification of WRB (IUSS Working Group WRB 2022). From each of the distinguished horizons, samples were taken for laboratory analyses. Basic soil properties were determined using standard laboratory methods (Van Reeuwijk 2006). The content of soil particles was determined with the use of a combined method: fraction >1 mm, including sand 1–2 mm (Soil Science Division Staff 2017) was determined by sieving, while the content of particles <1 mm, including 1–0.05 mm sand, was determined by laser diffraction method, using Malvern Mastersizer 2000 diffractometer. The average grain size (Mz) was calculated by Folk and Word graphic method, using Gradistat software (Blott and Pye 2001). Soil organic carbon (SOC) content was measured with the use of the Tiurin method. Soil pH in distilled water and in 1M KCl (soil to water and soil to KCl ratio 1:2.5) was measured potentiometrically. The total iron content was determined by the atomic absorption spectrometry (AAS) flame method, using the GBC Avanta apparatus, after prior mineralization of 1 g of the sample <1 mm in HNO_3. The color determination was performed twice. The basic field determination was performed using the Munsell Soil Color Charts (2000). Additional assessment was performed in the laboratory on dry samples using a Konica Minolta CM 600d spectrophotometer (Sprafke *et al*. 2020). The results obtained in the CIE-L*a*b color space were then converted to RGB and Munsell scales.
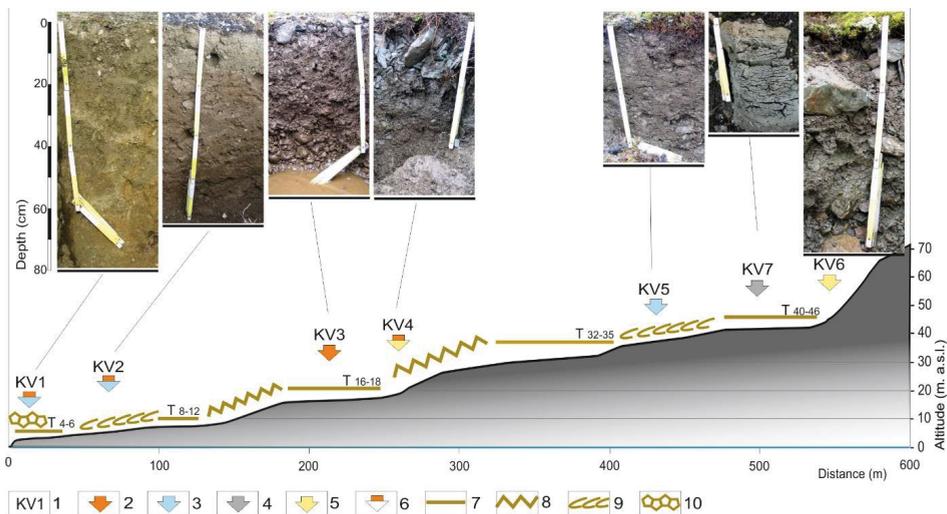

Fig. 2. Schematic transect through marine terraces in the Kvartsittsletta area: 1 - soil profile names, 2 - Cambisols, 3 - Cryosols, 4 - Gleysols and Histosols, 5 - Leptosols, 6 - Cambic horizon in other soil types, 7 - pronounced flattening, 8 - pronounced terrace edges/cliffs, 9 - solifluction lobes, 10 - patterned ground. The photographs show soil profiles all in one scale.

Results

Soil morphology. — The flat, dry parts of the three lowest terraces in the study area are dominated by soils morphologically similar to "arctic brown soils" (Tedrow and Hill 1955), characterized by a thin A horizon and clear visible brown *cambic* horizon. The maximum thickness of the gravel cover in the marginal zones reaches 3 m on the marine terrace 4–5 m a.s.l., lying on the solid bedrock. Locally, the terrace is overbuilt by storm beach gravels and cobbles. The surface shows signs of patterned ground such as polygons 50–80 cm in diameter. Below the 3 cm thick Ah horizon (profile KV1 on Fig. 2), there is ABw@ horizon (Munsell color 2.5Y 5/3) reaching the depth of 10–15 cm, with signs of ice-wedge pseudomorphs and fissures filled with organic matter. Below, to the depth of 35–45 cm, there is the *cambic* horizon Bwg@ (Munsell color 10YR 6/3) with signs of gley processes and probably presently inactive cryogenic processes. Underneath, at the depth of 35–45 cm, fossil, discontinuous Ab horizon and a stony fossil pavement are present. Below, reaching 80 cm depth, there is BCg horizon in direct contact with the weathered sericite schist of the CR bedrock. Bwg@ horizon meets all the requirements of diagnostic *cambic* horizon (IUSS Working Group WRB 2022), and the fossil soil represents typical "arctic brown earths" (Tedrow and Hill 1955) that correspond with Dystric Cambisols (IUSS Working Group WRB 2022). However, the present soil, *i.e.*, the entire pedon, must be classified as Cambic Cryosols (Dystric) due to the cryoturbation features at the soil surface (IUSS Working Group WRB 2022).

The second, slightly higher marine terrace is located at 8–10 m a.s.l. On its surface, inclined at an angle up to 5° towards the NE, distinct solifluction structures are visible. The forms are 80–120 cm wide, and up to 150 cm long. The fronts of lobes are 10 cm high and are preserved by lichens and moss. The cross-section (profile KV2 on Fig. 2) through these forms shows a 2 cm thick Ah horizon. Below, the light olive-grey ABg horizon lies, reaching 15–20 cm deep and showing signs of gleyic processes and silt loam texture. This allochthonous solifluction material, covering the lower horizon, is texturally different. Below, as far as 65 cm deep, lies the brown (Munsell color 7.5YR 6/4) *cambic* horizon 2Bw with a much coarser granulometric composition of sandy loam. From 65 cm onwards, a more skeletic 3Bw horizon begins. Throughout the profile, the predominance of rounded material over the sharp coarse debris material type is noticeable. This is an example of gley cambisol formed from slightly coarse solifluction loam layered over strongly coarse loam with a thin layer of rounded marine terrace material at its base. Despite the large thickness of the *cambic* horizon, this soil must also be classified as Cryosol due to the presence of signs of cryoturbation and soliflucation tongues on the surface (IUSS Working Group WRB 2022). This soil is classified as Skeletic Cambic Cryosol (Dystric).

The marine terraces are often emphasized by the relics of rocky cliffs. In their vicinity, the soils present completely different features. Soil profile KV3

(Fig. 2) is located on a slightly inclined marine terrace of 17–18 m a.s.l., at *ca.* 10 m from a low, strongly eroded cliff and *ca.* 15 m from the edge of the terrace. The 5-centimeter-thick A horizon consists of humus, plant root system and cobble-gravel pavement. Below, to a depth of 10 cm, there is a transitional horizon with signs of gley processes ABg. At the depth of 10–20 cm, the *cambic* horizon (Munsell color 10YR 3/3) Bwg1 lies with signs of gley processes, which covers *ca.* 15 cm thick second *cambic* horizon (Munsell color 7.5Y 3/3) Bwg2. At the depth of 35–50 cm, transitional horizon BC lies. At the depth of 50 cm, the groundwater level is present. This soil belongs to Gleyic Skeletc Cambisol (Gelistagnic) (IUSS Working Group WRB 2022).

The edges of the sea terraces are often emphasized by relics of rock cliffs. This causes a lot of sharp-edged, coarse rock material to accumulate near this edge. In such material, there are no signs of soil-forming processes, or they are in the initial stage due to the lack of fine material. The coarse material allows for the development of highly permeable, weakly transformed initial soils with considerably lower fertility, characterized by thin plant cover or its lack. Soil profile KV4 (Fig. 2) is located at the elevation of *ca.* 30 m a.s.l., in the lower part of a degraded, multi-stepped sea cliff. The cliff is composed of quartzite with schist interbedding, in the axes of which numerous depressions are formed. A large number of sharp-edged quartzite fragments are visible on the surface, covered by a thick blanket of lichens and mosses in the depressions. The described profile is relatively shallow. Transitional horizon ABwg of slightly darker brown color lies below the 2 cm thick A horizon formed by lichens and moss, heavily overgrown with stems and roots of dwarf willow *Salix reticulata*. This horizon reaches up to 25 cm from the surface. Below, to the depth of 50 cm, *cambic* horizon Bw is present. The bedrock has an uneven surface and appears at the depth of *ca.* 30 cm. Despite the presence of *cambic* horizon, this soil should be classified as Leptosols, due to its low thickness, and highly skeletal material. The qualifier *umbric* indicates a significant organic matter content in the surface horizon, while the term *gleyic* indicates the presence of gleyic features. The features described indicate Cambic Umbric Leptosol (Gleyic).

The highest terrace on the Kvartsittsletta platform (40–46 m a.s.l.) does not have a distinct edge and gradually turns into a lower step. On this relatively gentle inclined surface slope, numerous cobbles with diameters of more than several dozen centimeters are present, along with numerous solifluction structures and convex thufur-type forms covered with moss (profile KV5 on Fig. 2). On the top of this form, bipartite organic horizon O is present. Its thickness reaches up to 20 cm. It is made of moss fragments, with the upper part showing rusty-brown color and the lower transformed part showing grey-black color. Underneath, a Ag horizon with signs of gley processes is located. At the depth of 6–50 cm, a highly skeletal horizon is present, showing silt loam texture in the fine earth material, with the signs of cryoturbation forming the BCg@ horizon with a distinct platy structure and signs of gleyic processes. Below, to the depth of 65 cm, parent material is

present, showing some evidence of gleyic processes (Cg, 2Cg). The presence of the forms such as thufurs on the surface and the internal structure of the profile with the signs of frost heaving could indicate the *cryic* horizon, but other distinctive features, *e.g.*, massive ice, are missing. Evidence of cryoturbation, however, indicates *turbic* qualifier. Such features allow to classify this soil as Cryosols. All of these factors define this soil as Skeletic Turbic Cryosol (Dystric).

The lowered trough or depression surfaces with permanent water excess are dominated by loamy and silt loamy-textured relatively fertile gley soils (Eutric Gleysols). They have an increased content of organic matter and can sometimes occur adjacent to shallow peatlands (Histic Gleysols). In these soils, the effects of cryogenic processes are generally poorly visible. Typical organic soils with the thickness of organic layer exceeding 40 cm occur only in small, isolated areas in the Brateggelva valley, in the northern part of Kvartsittsletta. In the profile of such soils, sometimes, an ice lenses (Cryic Histosols) can be found, which gives the bog the shape of a small pingo. The highest (*ca.* 44 m a.s.l.) flat marine terrace of Kvartsittsletta is in direct contact with the rock glacier at the foothill of Gulliksenfjellet. Its surface is wet and peaty, partially covered by a small lake. Due to reducing conditions related to the occurrence of shallow groundwater, soils in this area are characterized by strong gley processes (soil profile KV7 on Fig. 2). In slightly drier areas, under a thin cover of lichens and decomposed mosses, there is an oxidized horizon Cgo showing light yellowish brown color (Munsell 10YR 6/4) and silt loam texture (Mz=0.17) with the thickness of 1–5 cm. Beneath, there is redox Cgr (Mz=0.45) and color light bluish gray (Munsell color – GLEY 2 7/10B), which is almost entirely gleyed. The ground water level was very high and stabilized very quickly at about 15 cm. This soil can be classified as Reductic Gleysol.

On the lower and considerably wetter part of this terrace, the peat is often located. Its thickness, depending on micro-relief, can reach up to 10 cm and create soils that can be classified as Histic Gleysols (Gelic). The typical Histosols with an organic layer as thick as 40 cm and more are found only at small, isolated sites.

The rock-glacier occurring at the footslope of Gulliksenfjellet entered this highest terrace and partially covered it. Similarly to the soil profile KV4, debris and silty-debris material at the footslope and rock glaciers also show weak transformation. Hyperskeletic Leptosols, *i.e.*, initial soils filling the gaps between debris material, occur in such locations. The soil described in the soil profile KV6 (Fig. 2) also belongs to the Leptosols. Its vertical section presents the bottom part of a rock glacier, *ca.* 2 m above the level of the highest terrace. The inclination of slope in this position reaches 40–45° with lichens and mosses covering the surface of cobbles and gravels. The content of the rock fragments in this profile exceeds 75% (Mz=−2.3 to −3.2). The texture of fine earth material (< 2 mm) is indicative of sandy loam (SL), and the SOC content in the surface horizon A does not exceed 4.5% (Table 1), all of which makes it possible to classify this soil as Hyperskeletic Leptosol.

Table 1.

Particle size distribution and basic chemical characteristics of soils in the raised marine terraces in Kvartsittsletta: Mz - average grain size calculated by Folk and Word graphic method using Gradistat software (diameter expressed in *phi* units); particle size distribution: >2 mm - percent of bulk soil sample; (2–0.05 mm; 0.05–0.002 mm; <0.002 mm) - percent of fine earth fractions <2 mm; textural classes: SiL - Silt Loam, SL - Sandy Loam, S - Sand, LS - Loamy Sand; types of soil structure: MA - massive, AB - angular blocky, AS - angular and subangular blocky, SB - subangular blocky, PL - platy; Munsell color - field method using color charts, moisture material; laboratory method (spectrophotometer Konica Minolta CM 600d; dry material). For the names of fractions and soil texture groups, the standard USDA (Soil Science Division Staff 2017) division was used. The colors in the pH column indicate the degree of soil acidity from extremely acidic (red) to neutral (green). The shades of brown in the Munsell color 2 column correspond to the colors of the soil in the dry state.

| Soil profile | Sample | Horizon | Depths (cm) | Particle size distribution (%; grain diameter in mm) | | | | Soil texture | Mz | Soil structure | Munsell color 1 (field determination) | | Munsell color 2 (spectrophotometer) | | | | pH | | | Fe total | SOC |
				>2	2–0.05	0.05–0.002	<0.002				Symbol	Name	Hue	Value	Chroma		H₂O	KCl	differ.	(%)	(%)
KV 1	1	Ah	0–3	n.d.	n.d.	n.d.	n.d.	n.d.	*n.d.*	SB	10YR 5/2	grayish brown	n.d	n.d	n.d		n.d.	n.d.	n.d.	3.57	5.77
	2	ABw@	3–12	19	39	59	2	SiL	1.13	AS	2.5Y 5/3	light olive brown	1.8 Y	5.9	2.5		5.77	3.99	1.78	3.48	0.38
	3	Bwg@	12–35	33	43	55	2	SiL	0.45	AB	10YR 6/3	pale brown	2 Y	5.9	3.2		6.13	4.07	2.06	3.53	0.28
	4	Ab	35–45	47	47	51	2	SiL	-0.65	SB	10YR 5/2	grayish brown	1.2 Y	5.2	2.6		6.25	4.58	1.67	2.83	0.44
	5	BCg	45–80	32	52	47	1	SL	0.30	AS	5YR 6/4	light reddish brown	1.0 Y	4.9	3.0		6.58	4.72	1.86	2.93	0.28
	6	CR	<80	34	80	20	0	LS	-0.63	bedrock	bedrock	bedrock	0.3 Y	3.9	2.0		5.62	5.18	0.44	n.d.	0.01
KV 2	7	Ah	0–2	75	78	21	1	LS		SB	2.5Y 4/1	dark gray	1.9 Y	3.7	1.7		5.85	5.59	0.26	3.23	3.12
	8	ABg	2–15	28	48	51	1	SiL	0.57	PL/AB	5Y 6/2	light olive gray	1.7 Y	5.8	2.7		5.58	4.20	1.38	3.26	0.40
	9	2Bw	15–65	50	55	43	2	SL	-0.80	AB	7.5YR 6/4	light brown	0.4 Y	5.3	3.3		6.47	4.75	1.72	3.22	0.45
	10	3Bw	65–100…	45	67	32	1	SL	-0.83	AB	7.5YR 5/4	light brownish gray	9.6 YR	4.9	3.5		6.68	4.90	1.78	2.64	0.38
KV 3	11	A	0–5	80	99	1	0	S	-2.82	SB	7.5YR 3/3	dark redish brown	9.3 YR	3.2	1.7		n.d.	n.d.	n.d.	2.26	12.53
	12	ABg	5–10	85	76	24	0	LS	-2.99	AS	7.5YR 4/3	brown	0.0 Y	4.1	1.9		4.78	4.50	0.28	3.66	4.32
	13	Bwg1	10–20	71	59	40	1	SL	-2.25	AB	10YR 3/3	dark brown	9.2 YR	3.9	2.1		5.15	4.44	0.71	3.32	2.60
	14	Bwg2	20–35	91	67	32	1	SL	-3.39	AB	7.5YR 3/3	dark brown	9.4 YR	3.6	2.3		5.35	4.59	0.76	2.80	1.75
	15	BC	35–60	99	100	0	0	S	-4.21	SB	7.5 YR 4/2	brown	7.9 YR	3.8	1.8		5.90	5.20	0.70	3.09	1.65

| Soil profile | Sample | Horizon | Depths (cm) | Particle size distribution (%; grain diameter in mm) | | | | Soil texture | Mz | Soil structure | Munsell color 1 (field determination) | | Munsell color 2 (spectrophotometer) | | | pH | | | Fe total | SOC |
				>2	2–0.05	0.05–0.002	<0.002				Symbol	Name	Hue	Value	Chroma	H_2O	KCl	differ.	(%)	(%)
KV 4	16	A	0–2	56	99	1	0	S	−1.21	SB	5YR 3/1	very dark grey	9.4 YR	2.4	1.2	4.44	4.07	0.37	0.94	17.19
	17	ABwg	2–10	77	76	24	0	LS	−2.36	SB	7.5YR 5/2	brown	0.7 Y	4.3	1.7	4.31	3.55	0.76	3.73	2.79
	18	ABwg	10–25	78	63	36	1	SL	−2.53	SB	7.5YR 5/2	brown – pinkish gray	1.5 Y	4.3	1.8	4.41	3.59	0.82	5.13	2.35
	19	Bw	25–50	72	64	35	1	SL	−1.77	AB	10YR 6/2	light brownish gray	10.0 YR	4.7	2.4	4.81	3.81	1.00	4.94	1.33
	20	R	<30	72	58	42	1	SL	−2.29	bedrock	bedrock	bedrock	0.4 Y	5.2	2.8	5.07	3.85	1.22	3.21	0.95
KV 5	40	A/O	0–2	86	100	0	0	S	−3.26	SB	10YR 4/2	dark greyish brown	9.2 YR	3.0	1.8	4.66	4.28	0.38	2.22	8.26
	39	Ag	2–6	62	62	37	1	SL	−1.21	SB	5Y 6/2	light olive gray	1.4 Y	5.3	2.5	4.84	4.02	0.82	2.76	1.22
	38	BCg1@	6–30	34	37	61	2	SiL	0.31	PL	2.5Y 6/2	light brownish gray	1.0 Y	5.5	2.7	5.00	4.00	1.00	3.46	1.09
	37	BCg2@	30–50	65	45	54	1	SiL	−1.29	PL	2.5Y 6/2	light brownish gray	0.7 Y	5.7	2.8	5.15	4.04	1.11	3.47	1.16
	36	Cg	50–60	75	74	25	1	LS	−1.98	MA	2.5Y 6/3	light yellowish brown	1.2 Y	5.7	2.7	5.60	4.17	1.43	2.65	0.69
	35	2Cg	60–80	62	65	34	1	SL	−1.58	MA	2.5Y 6/3	light yellowish brown	0.2 Y	5.7	2.6	5.29	4.06	1.23	2.46	0.73
KV 7	41	A	0–1	88	100	0	0	S	−2.93	SB	10YR 2/2	very dark brown	1.6 Y	2.5	1.2	5.40	5.08	0.32	0.81	17.91
	42	Cgo	1–5	34	42	57	1	SiL	0.17	PL/AB	10YR 6/4	light yellowish brown	0.5 Y	5.8	2.7	4.69	3.46	1.23	3.71	0.85
	43	Cgr	5–20	26	43	56	1	SiL	0.45	PL	GLEY 2 7/ 10B	light bluish gray	1.5 Y	5.9	2.4	4.27	3.21	1.06	3.51	0.71
	45	2Cgr	20–40	37	43	56	1	SiL	−0.13	PL	GLEY 2 7/ 10B	light bluish gray	2.1 Y	5.9	2.1	4.11	3.29	0.82	4.02	1.09
	44	3Cgr		55	43	56	1	SiL	−0.72	PL/MA	GLEY 2 8/ 10B	light bluish gray	0.7 Y	5.8	2.4	4.18	3.36	0.82	4.28	1.52
KV 6	31	A/R	8–20	32	45	54	1	SiL	0.46	SA	10YR 3/3	dark brown	1.4 Y	5.4	2.0	3.97	3.51	0.46	3.74	4.48
	32	BCg	20–30	84	65	34	1	SL	−3.16	AB	2.5Y 5/2	grayish brown	2.3 Y	5.7	2.1	5.11	4.27	0.84	3.13	1.95
	33	R/Cg1	30–55	74	56	43	1	SL	−2.51	AB	2.5Y 5/3	olive brown	3.6 Y	5.8	1.8	5.82	5.01	0.81	2.64	0.84
	34	R/Cg2	<55	76	64	39	1	SL	−2.31	AB	2.5Y 5/3	olive brown	2.1 Y	6.2	1.9	5.06	4.42	0.64	3.01	1.42

Particle-size distribution. — The soils formed from sediments in raised marine terraces are predominantly characterized by a coarse grain size composition and a variable thickness. The grain size composition and the degree of grain roundness vary depending on the width of the terrace and the distance from the rocky cliff. The two lowest and youngest terraces (4–6 and 8–12 m a.s.l.) are characterized by relatively fine-grained material (sites KV1 and KV2). Only in one soil horizon (Ah in KV2), the skeleton material (>2 mm) is clearly dominant. Particle size analysis in fine earth material shows that the dominant texture on the lowest terrace steps is silt loam and sandy loam (Table 1). On the lowest terrace, silt (0.05–0.002 mm) is the dominant fraction, and on the upper terrace (8–12 m a.s.l.), sand prevails (2.0–0.05 mm).

The sediments on the highest terrace (44 m a.s.l.) present by far the finest texture (Table 1). The fine-grained material is conducive to maintaining high soil moisture and stagnating water on the surface. Silt was the dominant component in the fine earth material, soil texture is silt loam. The sediments on the other terrace steps have a much coarser texture. In most cases, the skeletal fraction (>2 mm) exceeds 70% (sites KV3, KV4, KV5 and KV6) and the soil is sandy loam, sand and loamy sand. It should be noted that the relatively low content of skeleton of Hyperskeletic Leptosols (site KV6) results from difficulties in collecting and measuring the coarse fractions with a diameter of more than several dozen cm, present in the pit.

Chemical properties. — Most of the described soil profiles show a constant decrease in SOC content with depth (Figs. 3 and 4). In some cases however, in the deeper parts of soil, a slight increase in the SOC content is observed (KV1, KV6 and KV7). In the surface horizons of some soil profiles (KV3, KV4 and KV7), very high content of SOC is observed. Nevertheless, the presence of SOC is found even at a depth of several dozen cm, in the amount of *ca.* 1% (Table 1). For some soils (KV4 and KV7), the SOC content in the thin surface level exceeds 17% and then decreases sharply (Fig. 4, Table 1). The youngest terrace levels show the lowest SOC content. Soil pH does not exceed the value of 6.7 in most of the horizons. Moreover, in this comparison, the soils of the two lowest terraced steps differ greatly from the other soils. The pH_{H_2O} in the KV1 and KV2 profiles range from 5.58–6.68 (Table 1), *i.e.*, from moderately acidic to neutral reaction (Soil Science Division Staff 2017). The horizons in the remaining profiles are characterized by a much lower pH_{H_2O} in the range of 3.97 (extremely acidic) to the maximum of 5.82 (moderately acidic). Interestingly, the soils of the lowest terrace also differ from the soil occurring on the higher terraces. In both soils (KV1 and KV2), the difference between the pH_{H_2O} and the pH_{KCl} is the greatest and often exceeds the value of 1.0 (maximum 2.0). In the remaining soil profiles, it only exceeds 1.0 a few times, reaching the maximum value of 1.43. Any attempts to determine the $CaCO_3$ content in the soils were unsuccessful. In general, all surface horizons are characterized by a lower Fe concentration that recorded in the deeper horizons. Fe content fluctuates in the range of 2.2–5.2%.
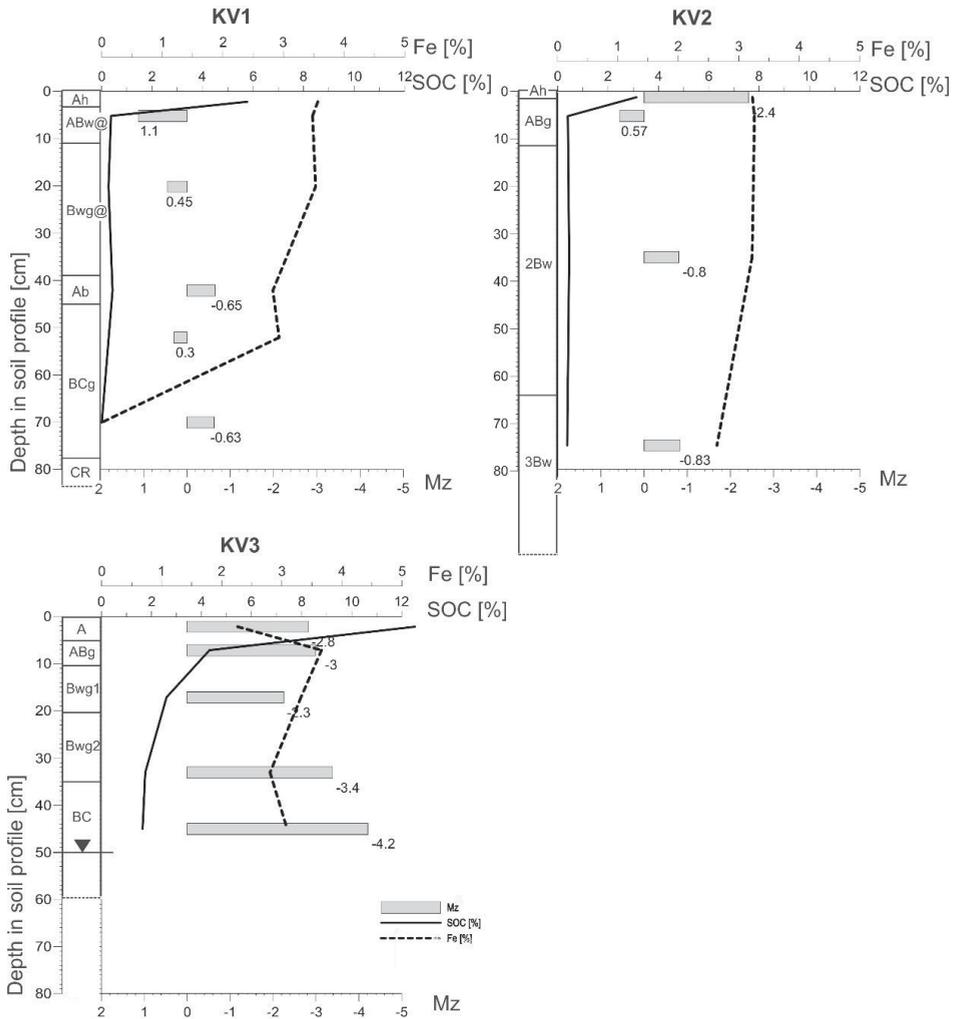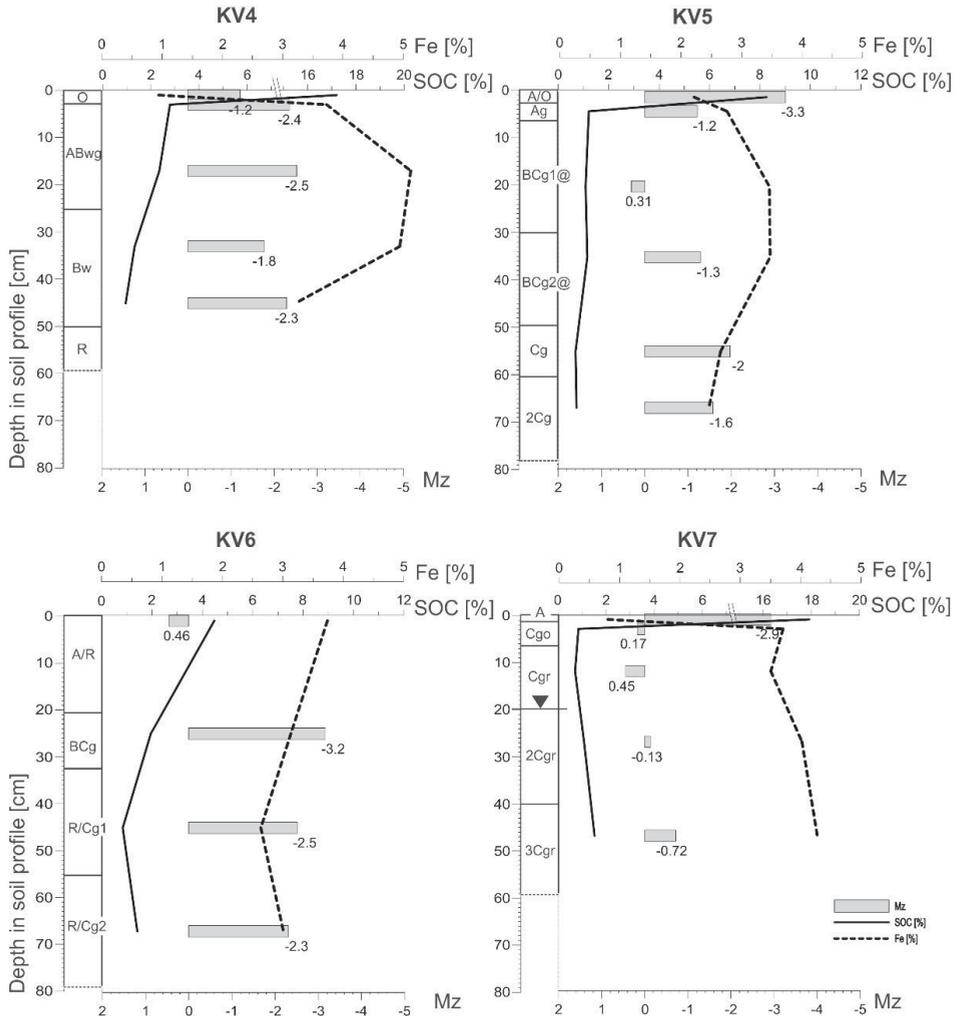
Fig. 3. Schematic drawing of soil profiles KV1 to KV3 against the results of selected laboratory analyses: Mz – average grain diameter according to the graphical method of Folk and Word (in phi units), SOC - soil organic carbon, Fe – total iron content. Soil structure and texture as in Table 1.

Discussion

Of the various soil types found in the Arctic region, Cambisols or soils having a *cambic* horizon seem to be the most remarkable, as they do not typically occur on these latitudes. Their presence can therefore be an indicator of past and present environmental conditions. Modern climate warming and glacier recession contribute to the development of soils on the exposed moraine surfaces and marine terraces (Kabala and Zapart 2009, 2012; Wietrzyk *et al.* 2018; Szymański *et al.* 2019b). The beginning of deglaciation ending the LIA dates back to the end of the 19th century. The proglacial zone of Werenskiold Glacier is covered with

Fig. 4. Schematic drawing of soil profiles KV4 to KV7 against the results of selected laboratory analyses: Mz – average grain diameter according to the graphical method of Folk and Word (in phi units), SOC - soil organic carbon, Fe – total iron content. Soil structure and texture as in Table 1.

recent moraine till that was exposed in the mid-20th century and the pedogenic transformations of the moraine till have only reached 10 cm (Kabala and Zapart 2009). More pronounced changes in color, indicating the onset of "browning processes", are only observed in soils that are older than 70–80 years (Kabala and Zapart 2009). The discovered signs of fossil tundra under this youngest moraine till, aged 1080±105 to 760±145 years BP (Baranowski 1977), indicate that the buried soil is a relic of warm climatic conditions that preceded the LIA period. Most likely this was the Medieval Warm Period, which lasted continuously for about 800 years and led to the development of "Arctic brown soils" (Kabala and Zapart 2009).

The soils on the marine terraces were formed under different conditions and from different parent material. Marine terraces of Kvartsittsletta were formed as a result of rapid post-glacial isostatic uplift of this part of Spitsbergen. The age of the lowest terrace (4–6 m a.s.l.) is estimated at 1 ka BP to 4.5–7.5 ka BP, and higher (8–12 m a.s.l.) at 7–14 ka BP (Lindner *et al.* 1991; Migoń and Kasprzak 2013). Thus, during the Medieval Warm Period, these areas were already elevated and exposed to external factors, allowing soil-forming processes to operate. During this period, the deep *cambic* horizon might have formed. The results of the present study confirm the presence of such horizons on the Kvartsittsletta marine terraces. They correspond directly with the horizon of fossil "Arctic brown soils" in the Werenskiold Glacier foreland.

The difference between the soils on the marine terraces and the proglacial zone of Werenskiold Glacier emerged at a later stage of their development. The soils in the proglacial zone were covered and preserved by fresh moraine materials of the advanced glacier during the LIA period. Soils on marine terraces during the LIA period remained exposed and underwent further transformation under the influence of periglacial climate (Stachnik *et al.* 2022), and are now relict soils (Ruellan 1971; Kabala and Zapart 2009).

The claim that the described *cambic* horizons on the Kvartsittsletta marine terraces are a relic of pre-LIA soils is supported by the results of the studies of soils formed on the youngest moraine material in the foreland of nearby Werenskiold Glacier (Kabala and Zapart 2009). The low rate of "browning processes" there indicates that such high thickness (35–100 cm and more) *cambic* horizons, occurring on the Kvartsittsletta marine terraces (KV1, KV2, KV3 and KV4), could not have formed during the short, modern post-LIA climate warming. They must, therefore, be a relic of an older, perhaps a single, prolonged period of a climatic optimum. According to many studies (Marsz and Styszyńska 2007; Wawrzyniak and Osuch 2020), despite the ongoing warming of the climate, the contemporary climatic conditions prevailing in the High Arctic are not yet favorable for the formation of "Arctic brown earths" (Goryachkin *et al.* 2004; Kabala and Zapart 2009).

Although permafrost occurs in these soils in the summer at the depths generally >150 cm (Marsz *et al.* 2011), certain signs of cryogenic processes associated with ground ice or slope processes, including solifluction, are common in their profile. The presence of this disturbance at the top of the contemporary soil profile, above the *cambic* horizon or buried A horizon, should be associated with the last cool period, *i.e.*, the LIA. This is a second evidence that indicates the fossil/relict character of "brown soils".

As a result of the periglacial conditions, the patterned ground is present on the surface of the lower, flat, relatively dry and weakly inclined terraces of Kvartsittsletta (KV1), as it is the case, for instance, in nearby Hornsund (Szymański *et al.* 2015). These conditions in the soil profile lead to changes in the form of cryoturbation, cracks and ice wedges, as well as frost sorting. Thus,

vertical movement of soil material occurs. The presence of these structures classifies these soils as modern Cryosols. Older soils with *cambic* horizons were also transformed during the LIA period due to cryogenic processes.

Periglacial processes on the higher, wetter and inclined surfaces of the terraces were marked by solifluction lobes. These soils should also be classified as modern Cryosols (KV2 and KV5). An additional record of cryoturbation processes occurring in Cryosols may be the slight increase of SOC content observed in the deeper parts of the profile of some soils (KV1 and KV6). The presence of the signs of cryogenic transformation, both on the surface and in the soil profile, is the reason for which many of the soils, despite the presence of distinct and thicker old Bw horizon, fall into the category of Cryosols rather than Cambisols.

The second important group of modern soils are the Gleysols. Although signs of gleyic processes associated with a high-moisture environment were observed in all of the soils studied, Gleysols include those found on the highest terraces of the Kvartsittsletta (KV7). This is due to the lithological nature of the parent, relatively fine-grained material, the gently inclined, nearly flat surface of the terrain, and the high moisture content, likely due to the close proximity of the rock-glaciers. On the rocky sea cliffs, which form the edges of the higher terraces, as well as on the slopes and foothills, there are soils of an early stage of development, which are called Leptosols. In this case, lithology is also the main factor that determines their systematic classification.

It is commonly accepted that the spatial soil heterogeneity is mainly caused by soil age, morphological position within a terrace and parent material (Van der Meij *et al*. 2016). Sparse vegetation cover, except for the soils covered by mossy tundra, has a very small effect on soil variability, and the most important factor is the site wetness (Szymański *et al*. 2019a). Studies on the Kvartsittsletta coastal plain have shown that if one takes the presence and degree of development of the *cambic* horizon as an indicator of the age of the soil and terraces on which they are formed, it cannot be a decisive indicator in the case of the studied soil catena. The *cambic* horizon occurs regardless of the age of the terraces, mainly on the lowest, *i.e.*, the youngest terraces; in the other ones, the morphology and lithology of the parent material play the main role.

Conclusions

Among the many soil-forming processes marked for the soils in the Kvartsittsletta area, the most intriguing and informative, regarding the changing climate of the Arctic, are the processes that lead to the formation of *cambic* horizon, which can occur in both buried and relict soils. Other processes, such as cryoturbation, solifluction, ice segregation and gleyic processes lead to formation of the more typical Arctic soils, such as Cryosols and Gleysols.

The results of this study indicate that almost all soils, with the exception of highly skeletal soils, show the effects of frost processes such as cryoturbation, ice-wedge pseudomorphs, solifluction lobes and patterned ground on the surface, making Cryosols the predominant type of contemporary soils. Towards the lower terraces, there is an increase in the thickness of soil profile. Occurring on the lowest/youngest, flat and weakly inclined marine terraces, the horizons with brownish features, usually of high thickness, bear signs of cryogenic transformation. It is likely that the permeable parent material of gravels and sands with high thickness did not promote water retention and gleyic processes. On the gently inclined terraces, *cambic* horizons were transformed by solifluction lobes. Such conditions, favoring the preservation of old *cambic* horizons, indicate relic Cambisols.

The higher and older terraces are dominated by Cryosols and Gleysols, while in areas neighboring relict sea cliffs and rock-glacier Leptosols are present. There is a strong relationship between the intensity of the brown soil processes in the micro-relief, *i.e.*, flat terrain with a slight slope and distance from the cliff's edge, and the local lithological conditions, such as sediment thickness and granulo-metric composition. Apparent gley processes occur in all profiles, and their intensity strongly depends on the granulometric composition and surface micro-relief enabling stagnation of water. Regardless of the position of the terraces and their age, initial soils (Leptosols) occur on the slopes and nearby cliffs.

The chemical properties of the soils in the Kvartsittsletta area are strongly influenced by the lithology of the bedrock. Non-carbonate rocks (quartzites and mica schists) contribute to the low or very low pH of all the studied soils. The results of this study indicate that on the catena scale, it is not the age of the terrace nor its position that pre-determines the scale of modern soil processes, but rather its lithological structure, sediment thickness and granulometric composition.

With the current set of climatic factors, one should expect a slow acceleration of the weathering processes, further transformation of mineral and organic components and progressive browning of arctic soils. While modern soil processes associated with contemporary climate warming are too short-lasting to have developed a distinct *cambic* horizon seen mainly in young sediments, Cambisols and other soils with high thickness *cambic* horizons can be associated with long periods of Holocene climatic optima, including the Medival Warm Period *ca.* 800–1300 AD. At that time, all of the described marine terraces were elevated and were subject to pedogenic processes.

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