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Changes in the characteristics of the soil and vegatation during the primary succession in the marginal zone of the Werenskiold glacier, Spitsbergen

ABSTRACT: Changes taking place in weathered bedrock and vegetation of the ground moraine of Werenskiold glacier during about 50 years are presented. These results are based on phytosociological survey and analysis of the population structure of *Saxifraga oppositifolia* in 20 experimental fields and the analysis of physical and chemical features of the soils. In the process of succession, with chemical features not much changed and spongy structure just beginning, the number of vascular plants did not increase. In the process of succession the gradual increase in the density of *S. oppositifolia* population was observed. The size of its individuals and the share of flowering individuals also increased.

Key words: Arctic, Spitsbergen, soils, vegetation succession.

Introduction

The vegetation of Arctic semideserts is not very dense (Aleksandrova 1983). This results from climatic conditions and poorly advanced soil–forming processes (Jahn 1946, Szerszeń 1968, Linnel and Tedrov 1981). In Arctic semideserts pioneer species populate and survive in the areas left by retreating glaciers; this phenomenon is closely related to physical features of habitats (Svoboda and Henry 1987). In these areas, succession series are definitely shorter in comparison with lower latitude zones (Remmert 1985). Under these conditions, the process of succession of vegetation is almost entirely determined by biological features of pioneer species, mainly by their life strategies (Callaghan and Emanuelson 1985). In the studies carried out in the far Arctic the low influence of vegetation upon the habitat quality is stressed. This phenomenon results from the low growth rate and patchy distribution of plants.

In the relevant literature there are few data concerning the changes of soil features in relation to the time of plant succession in the marginal zone of retreating glaciers. This was the reason why the present studies on transformations of the surface soil layers during the primary succession in the marginal zone of Werenskiold glacier were undertaken.

Area and methods

Studies were carried out in 1988 in the marginal zone of Werenskiold glacier in the Hornsund Fiord region (Spitsbergen; 77°05'N, 15°20'W). From the front of this glacier to the Gull Lake in each of three sections crossing the areas with the richest vegetation (Fig. 1), 5–6 experimental fields (5x5 m) were set. Additional studies were carried out in the fields of similar dimensions on the groung moraine at the outcrops of fossil and subfossil soils. A total of 20 experimental fields were set out. For these fields the lists of vascular plants were prepared and their density was estimated. Additional observations of the population structure were carried out for *Saxifraga oppositifolia* – the plant of the greatest importance for plant succession in this area. Flowering and not–flowering individuals were counted separately; the length of their long–shoots was measured.

Samples of the soil from A_1 level in the reach of plants root system were taken from each experimental field. In the laboratory, in the air–dry material,

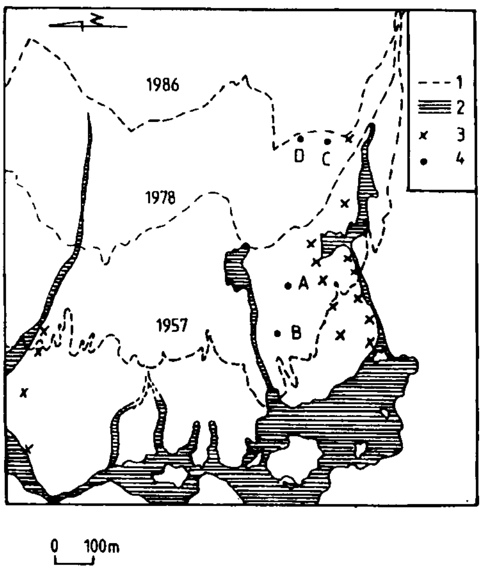

Fig. 1. Distribution of stations in the marginal zone of Werenskiold glacier: 1 – the forehead line of the glacier; 2 – surface waters, 3 – stations on autogenic soil, 4 – stations on fossil and sub-fossil soil

following features were determined; the share of the skeleton (ø < 1 mm), grain size distribution for the earth parts, pH in water and in KCl (electrometric method), C_{org} (Tiurin method), hydrolytic acidity (according to Kappen). Finally, after roasting in 560°C, in the extracts of concentrated HCl, the following analyses were carried out: SiO_2 content, Fe content (colorimetric method), the content of K, Na (photometric method), the content of Ca and Mg (titration with versenate). Observations of macroscopic soil pieces and aggregates were carried out as well.

Investigated surfaces were of different stages of weathering and succession, from 0 to 50 years. This time was estimated on the basis of the map of deglaciation of the investigated glacier prepared by Kolondra and Jania (*unpubl.*). Results are shown in tables where mean values for the investigated surfaces in 10-year period from the moment of the glacier retreat are presented.

Results

Soils

Investigated soils belonged to lithosols and regosols. The contribution of the skeleton varied from 35 to 70%. The moraine material with wathered autogenic rocks, up to 10 years after the retreat of the glacier, contained 60% of the skeleton in the soil mass, on the average (Tab. 1). In the soils with longer weathering–period (10–40 years) the contribution of the skeleton was rather stable; in the oldest soils (41–50 years) the contribution of the skeleton was the lowest. The contribution of different fractions in the earth parts of forming soils was typical of medium and heavy soils. The variability between the groups of fields is shown in Fig. 2. Coarse sand and colloidal clay were main fractions in the earth parts of the investigated surfaces but their contributions was rather variable. The contribution of other fractions was rather stable.

A rather variable morphology of soil aggregates was a characteristic feature of the investigated soils. Therefore, the structure of the weathered material was typical of the medium and heavy soils. In the soils up to 20 years old, typical soil aggregates were not observed; there were merely pieces of rocks. Sharp–edged, undurable aggregates, formed mainly by drying, were observed in the fields situated in the areas of longer weathering–time and more advanced succession of vegetation. Spongy, more durable aggregates with high contribution of free, bubble-like spaces were present in the soils older than 40 years.

Accumulation levels of fossil and sub-fossil soils had different physical features. Their grain size distribution was typical of heavy clays with variable contribution of skeleton (Tab. 1). In sub-fossil soils, aggregates were durable, hardly disintegrating under the influence of water.

In the described soils with poorly developed A_1 level, 10–15 cm thick, the mean pH reaction was alkaline and equal 7.0 in KCl (Tab. 1). These soils inherit this feature after their bed-rocks. As a consequence low and stable value of the

Table 1

Mean values of A_1 level characteristics, according to the age, on the ground moraine of Werenskiold glacier

Years	S	HA	pH		C_{org}	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	K_2O	Na_2O	P_2O_5
	%		H_2O	KCl	%	%	%	%	%	%	%	%	%
						Autogenic soils							
1–10	60	0.32	7.8	7.0	0.34	76.73	6.50	8.83	3.79	1.20	0.17	0.21	0.06
11–20	45	0.52	7.9	7.1	0.40	76.84	5.79	8.22	3.63	1.02	0.15	0.08	0.04
21–30	45	0.62	7.9	7.0	0.41	78.33	5.68	6.55	3.58	1.28	0.16	0.12	0.04
31–40	46	0.63	7.9	7.0	0.31	77.74	5.68	6.03	3.34	1.16	0.16	0.12	0.04
>40	39	1.35	7.8	7.0	0.44	78.54	4.52	5.66	3.04	1.11	0.16	0.16	0.03
						Fossil and sub–fossil soils							
						Station							
A	47	3.12	7.6	6.8	1.88	77.17	7.18	6.72	2.28	1.68	0.11	0.23	0.01
B	37	10.95	7.0	6.3	10.32	65.06	4.16	7.65	1.50	0.72	0.16	0.07	0.06
C	0	12.55	5.8	5.0	0.24	76.57	6.76	7.82	1.44	1.73	0.25	0.28	0.04
D	15	12.30	6.9	6.0	0.71	70.00	7.94	7.15	1.23	1.22	0.24	0.27	0.04

Explanations: S – Skeleton, HA – Hydrolytic acidity (meq/100 g)

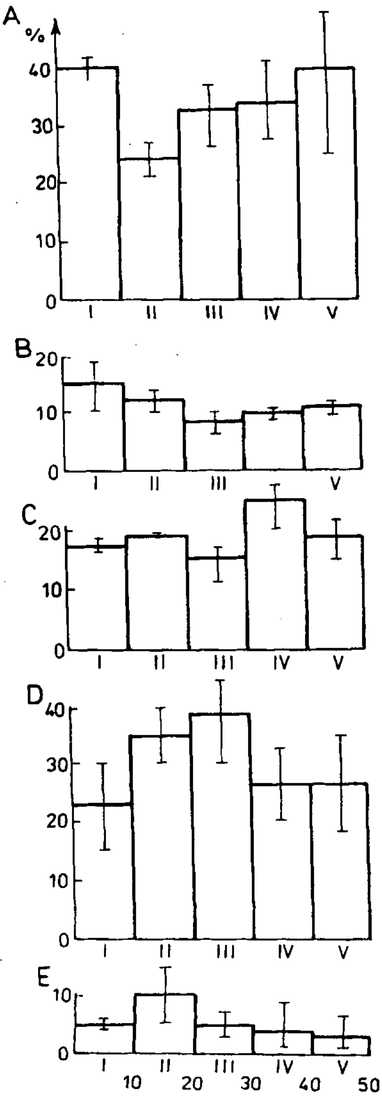

Fig. 2. Contribution of soil fractions in the ground parts of A_1 levels of the investigated soils, according to age: I – 0–10 years, II – 11–20; III – 21–30; IV – 31–40, V – 41 years; Fractions: A – 1–0.1 mm B – 0.1–0.05 mm, C – 0.05–0.02 mm, D – 0.02–0.002 mm; E – <0.002 mm

hydrolytic acidity of soils under 40 years old was observed. Only in the oldest soils it rises to over 1 meq/100g of the soil. The contribution of organic carbon in these soils was also low: from 0.2 to 0.55%.

In all investigated experimental fields over 75% of the soil mass consisted of SiO_2. The contribution of Fe and Al compounds decreased with the time of weathering (Tab. 1). The contribution of Ca and Mg compounds was variable and did not show any regularities. The K and P compounds were the least variable in the investigated soils. The contribution of P compounds was very low: from 0.03% to 0.06%.

Fossil and sub-fossil soils occurring as small patches in the marginal zone of Werenskiold glacier differed from autogenic soils in their lower pH values in KCl (below 7). Hydrolytic acidity of these soils was equally high as in the case of autogenic soils. The remnants of old soils coming from interstadial periods contained higher values of C_{org} (even over 10% dry weight). Such soils may contain slightly more K and Na than contemporarily formed soils but they are poorer in Ca. Fossil and sub-fossil soils form a definitely different habitat than autogenic soils.

Vegetation

The plant cover is poorly developed on the major part of the ground moraine of Werenskiold glacier. It is relatively richer in the river valleys and at the outcrops of solid rocks. In the fields most recently uncovered (up to 10 years) single plants occurred and the cover of the soil is lower than 1% (Tab. 2). As the succession proceeded the cover developed; vascular plants covered about 12% of the soil surface in the oldest fields from where the glacier retreated the earliest.

Table 2

Characteristics of the plant cover and of *Saxifraga oppositifolia* population during primary succession on the ground moraine of Werenskiold glacier

Age of moraine (years)	PLANT COVER: Coverage %	PLANT COVER: Average number of species per 25 m^2	POPULATION OF *SAXIFRAGA OPPOSITIFOLIA*: Density of population per 1 m^2	POPULATION OF *SAXIFRAGA OPPOSITIFOLIA*: Flowering individuals %	POPULATION OF *SAXIFRAGA OPPOSITIFOLIA*: Average length of long-shoots (cm)
Autogenic soils					
1–10	0.5	6.5	2.80	0.0	4.9
11–20	0.5	1.5	1.40	19.0	11.6
21–30	3.4	4.8	2.86	28.2	11.0
31–40	5.3	6.5	6.51	22.7	10.4
>40	11.7	6.3	8.21	28.0	14.4
Sub–fossil soil (B)					
33	30.0	9.0	28.50	35.6	19.8

The number of species of vascular plants was low. In 16 experimental fields with autogenic soil, each of the surface of 25 m^2, the total of 14 species occurred; 4 of them were found only occasionally (Tab. 3). The number of vascular plants inhabiting the ground moraine in particular 25 m^2 fields varied from 1 to 8. Ten species took part in the first stage of the succession (up to 10 years). During next 10 years the number of species rapidly dropped to 2. Afterwards the number of species slowly increased (Tab. 3).

Table 3

The occurrence of vascular plants on autogenic and sub-fossil soils on the ground moraine of Werenskiold glacier in different succession stages

No.	Species	Autogenic soils Years					Sub-fossil soils
		1–10	11–20	21–30	31–40	>41	
1.	*Saxifraga oppositifolia* L.	+	+	+	+	+	+
2.	*Saxifraga caespitosa* L.	+	+	+	+	+	+
3.	*Phippsia algida* (Solander) R. Br.	+		+	+	+	+
4.	*Cerastium alpinum* L.	+		+	+	+	+
5.	*Poa alpigena* (Fries) Lindman	+		+	+	+	
6.	*Cerastium regelii* Ostenf.	+		+	+	+	+
7.	*Draba* sp.	+			+	+	+
8.	*Cochlearia fenestrata* R.Br.	+					
9.	*Papaver dahlianum* Nordh.	+					
10.	*Saxifraga cernua* L.	+					
11.	*Sagina intermedia* Fenzl			+	+	+	+
12.	*Braya purpurascens* (R.Br.) Bunge			+		+	+
13.	*Salix polaris* Wahlenb.			+			
14.	*Oxyria digyna* (L.) Hill					+	+
15.	*Deschampsia alpina* (L.) R.S.						+

Saxifraga oppositifolia was one of the pioneer species appearing in the ground moraine after the retreat of the glacier and was always present in plant assemblages during the vegetation succession in the investigated area. The density of *Saxifraga oppositifolia* population varied from 1 to 8 ind.m^{-2} and gradually increased during the succession. Only in the fields from 10 to 20 years old the density of the population was lower (Tab. 2).

The size of individuals of *Saxifraga oppositifolia* on the ground moraine was very variable. The mean value of the longest long—shoots in the first stage of the succession (up to 10 years) amounted to 5 cm; in next stages it was from 10.4 to 14.4 cm, respectively. The contribution of flowering individuals in *Saxifrage oppositifolia* population on the ground moraine changed also during the succession. In the first period no flowering individuals were found (Tab. 2). In the fields from 10 to 20 years old flowering individuals constituted 19% of the population. In still older fields the contribution of flowering individuals was rather constant amounting to about 28%.

The richest vegetation was observed in the field of sub-fossil soil (field B, Fig. 1) where plants covered 30% of the soil surface. The succession lasted there about 30 years. On the surface of 25 m^2 9 species of vascular plants occurred. Most of them, except of *Deschampsia alpina* were also common in other parts of the moraine. Similarly to autogenic soils, *Saxifraga oppositifolia* played the most important role in the succession. However, the density of *S. oppositifolia* population was here 3 times higher than in the fields of autogenic soil most advenced in succession. The contribution of flowering individuals was also the highest there. Specimens of this species had the length of the longest long shoots equal to 20 cm. In another field of sub-fossil soil of similar time after glacier retreat (field A, Fig. 1) the vegetation cover was similar to that for the field B. *Deschampsia alpina* played here the most important role.

On the outcrops of fossil soils (fields C. D; Fig. 1) no vegetation was observed. These surfaces were uncovered the same year as our observations were made.

Discussion

The development of the vegetation during the primary succession depends not only on the time of duration but also on the habitat conditions. Air and soil temperatures during vegetation period are of major importance for the plant development in the Arctic (Aleksandrova 1983). In summer, near the front of the glacier, air and soil temperatures are considerably lower than in the moraine itself (Pereyma and Sobik 1987). Low temperatures in the neighbourhood of the glacier limit the development of vegetation but they do not limit the settlement process.

Few plant species found favourable conditions for growth and development in the ground moraine with high contribution of skeleton and sharp-edged pieces of rock. In the investigated surfaces of autogenic soils a total of 14 vascular plant species was found, whereas Fabiszewski (1975) has found earlier 17 species of plants on the surface of the whole investigated moraine. A rather characteristic pattern was observed: during first 10 years of succession relatively large number of vascular plant species appeared, then, during next 10 years, they partially retreated, and re-appeared on the moraine after next 10 – 20 years. This phenomenon may be related to unfavorable changes in physical features of the soil. These changes were caused by intense processes of swellling of argillaceous slates and frost weathering of the bed rocks. As a result sharp-edged solid aggregates and pieces are formed which destroy the existing plant root system, slowing the succession. During next stages of soil weathering and plant succession, spongy aggregates began to appear. Their presence in Arctic soils is commonly known (FitzPatrick 1956, Van Vilet-Lanoe 1985). The presence of the bubble-like free interaggregate spaces can change the conditions of water accessibility for vascular plants. This is an important factor favouring the development of vegetation during next stages of the succession.

In contrast to the improving physical conditions of the soils the content of biogenic elements in the soils was rather stable. A strong hydration can also occur causing gleization and oxygen shortages (Melke and Uziak 1989). In Arctic semi-deserts, in many well hydrated habitats the amount of water available for plants may be not high (Aleksandrova 1983).

With the climate becoming more and more severe in Arctic and in the habitats not favourable for plant settlement, the vegetative rather than generative reproduction is of major importance for settlement of populations (Johanson 1969, after Callaghan and Emanuelson 1985). Our studies on *Saxifraga oppositifolia* confirmed this conclusion. This plant in the Hornsund region has the biggest ecological amplitude (Godzik 1987). Its morphological plasticity (Ronning 1964), ability for vegetative reproduction (Silova 1988) and resistance to low temperature in summer (Aleksandrova 1983) make this plant a pioneer in the primary succession on the moraines. Single rooted individuals of this plant can be found already 2 years after the retreat of the glacier. Pieces of sprouts are brought from lateral moraines and sea terraces by wind and water. Due to the high soil humidity during the vegetation period and high content of biogenic kations (Ca and Mg) the process of plant rooting is fast. This type of reproduction is impossible in more dry habitats (Pirożnikow, *unpubl.*). According to Fabiszewski (1975) the development of vegetation on the ground moraine of Werenskiold glacier is limited by soil solifluction movements. The richest development of vegetation could be observed near solid rock outcrops, where solifluction movements are relatively the weakest. In our opinion, the amount of soil water available for plants is also an important factor limiting the development of vegetation. In 1988 in the investigated area the richest flora occurred in always moistened river valley in the southern part of the ground moraine. The presence of the outcrops of fossil soils in source region is favourable for development of vegetation in the valley. Baranowski and Szerszeń (1968) and Fabiszewski (1975) observed this phenomenon in their earlier papers. These vegetation patches are not big and cannot play the deciding role in the plant succession all over the marginal zone of the glacier however they can be a plant expansion centre for this region.

Conclusions

1. In the marginal zone of Werenskiold glacier lithosols and regosols are contemporarily formed; with the time passing the contribution of skeleton decreases and sharp-edged aggregates are changed into spongy ones.

2. Pedogenesis leads to slight decrease in Fe and Al content in the weathered material. During the soils evolution the content of C_{org} and biogenic elements did not change significantly.

3. During the primary succession gradual increase in the number of vascular plant species was not observed. *Saxifraga oppositifolia* was the pioneer species, always present during the succession. The density of the *Saxifraga oppositifolia* population, the size of individuals and the contribution of flowering individuals increased gradually.

4. The process of the vegetation succession on the ground moraine was influenced by changes of physical features of the accumulation levels of the soils formed as well as their thermic conditions; chemical features were practically constant.

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Streszczenie

Zbadano fizyczne i chemiczne właściwości gleb w czasie sukcesji pierwotnej roślinności, trwającej ok. 50 lat na przedpolu lodowca Werenskiold na Spitsbergenie. W poziomach A_1 zbadano udział szkieletu, uziarnienie, odczyn w wodzie i w KCl, kwasowość hydrolityczną, zawartość C_{org}, SiO_2, Fe, P, Ca, K, Na i Mg oraz wykonano obserwacje makroskopowe okruchów i agregatów glebowych. Sukcesję roślinności opisano na podstawie składu gatunkowego, pokrycia pokrywy roślinnej oraz niektórych cech struktury populacji *Saxifraga oppositifolia* — gatunku uczestniczącego od początku sukcesji na morenie dennej Werenskiold. Badania prowadzono na 16

poletkach o powierzchni 25 m^2 każde, usytuowanych w różnej odległości od czoła lodowca na glebach autogenicznych oraz na 2 poletkach na wychodniach gleb fosylnych i 2 — na glebach subfosylnych (Rys. 1).

Badane gleby zaliczono do regosoli i litosoli. Z upływem czasu w glebach zmniejsza się nieco szkieletowość oraz struktura agregatów (z ostrokrawędzistych na gąbczaste). Pedogeneza prowadzi do nieznacznego zubożenia zwietrzeliny w żelazo i glin (Tab. 1). W czasie ewolucji gleb trwającej do 50 lat nie obserwuje się istotnego zwiększenia zawartości węgla organicznego oraz zmian chemicznych poziomów A_1.

W toku sukcesji pierwotnej na glebach autogenicznych na morenie dennej pokrycie powierzchni roślinami naczyniowymi w okresie pierwszych 20 lat jest bardzo małe, a potem stopniowo zwiększa się. W toku sukcesji nie obserwuje się stopniowego zwiększenia liczby gatunków roślin naczyniowych (Tab. 2). Na 16 poletkach na glebach autogenicznych występowało 14 gatunków roślin naczyniowych (Tab. 3). Gatunkiem pionierskim, stale utrzymującym się w sukcesji na badanym terenie jest *Saxifraga oppositifolia*. Obserwowano stopniowy wzrost zagęszczenia osobników, zwiększenie przeciętnej długości długopędów oraz wzrost udziału osobników kwitnących (Tab. 3). Ze względu na korzystniejsze warunki siedliskowe na glebach subfosylnych niż autogenicznych (Tab. 1) pokrywa roślinna była bujniejsza, a wskaźniki struktury populacji *S. oppositifolia* wyższe (Tab. 2). Jakkolwiek płaty gleb subfosylnych na badanej morenie były niewielkie, mogły jednak stanowić centrum ekspansji roślin naczyniowych na tym terenie. Na przebieg sukcesji roślinności na morenie dennej znaczący wpływ mają zmiany właściwości fizycznych tworzących się gleb, gdyż ich właściwości chemiczne w badanym okresie rozwoju są niemal jednakowe.