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Lithosols of King George Island, Western Antarctica

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Abstract—Original data on soil formation in the coastal area of Antarctica in the vicinity of the Bellingshausen Antarctic Station are given. Soil morphology, micromorphology, and physicochemical properties are discussed. Specific features of humus formation under the severe climatic conditions of Antarctica are comprehensively studied. Data on the species composition and number of micromycetes in the studied soils are obtained.

INTRODUCTION

The soil cover of Antarctica is poorly studied. Investigations have only been performed in the areas of several experimental stations [3, 5, 15, 30, 31, 34]. The main regularities of the supergene processes in the coastal and inland areas of Antarctica have been studied by Markov [17, 18]; similar works are also known for the Arctic [9, 11]. Rock weathering and initial soil formation have been comprehensively studied by Glazovskaya [6], and ornithogenic soils in the areas of large bird colonies at Antarctica coasts have been described by Syroechkovskii [26]. Soil classification and an analysis of the soil cover zoning are given in [5]. It has been found that the reserves of organic matter in some soils of Antarctic coasts are considerable and comparable with those in soils of similar Arctic regions [3]. However, in general, the humus formation, biogenic accumulation of substances, biological turnover, and biological characteristics of Antarctic soils have yet to be studied. Some aspects of these problems are discussed in the works devoted to the soils of polar regions [3, 5, 6, 11, 19, 26], but comprehensive studies of the organic matter accumulation and transformation have only been performed for Arctic soils [7, 8].

In this context, data on the organic matter accumulation and transformation and the biological features of Antarctic coastal lithozems (Leptosols) in the area of the Bellingshausen Research Station are important for a better understanding of the soil functioning in specific Antarctic ecosystems.

OBJECTS AND METHODS

The main part of Antarctica is covered by ice. Only coastal areas of the continent and adjacent islands and small portions of inland territories become free from ice and snow in the summer. The Bellingshausen Research Station is situated on King George (Waterloo) Island, the largest island in the South Shetland Archipelago. The length of the island is 16 km from the northwest to the southeast and 50 km from the northeast to the southwest. The major part of the island is covered by a glacier with tongues falling into the ocean. The ice-free areas are represented a hilly surface with the hills composed of volcanic rocks (basalt and andesite–basalt). In some places, sea terraces composed of marine sediments and colluvium of volcanic bedrock are present. The Bellingshausen Research Station is located on a peninsula with continuous permafrost; the active layer thickness varies from 0.25 to 1.0 m.

Meteorological data obtained at the Bellingshausen Research Station show that the air temperature on the island crosses the zero point (0°C) 300 times a year. This favors intensive physical weathering of the massive crystalline rocks. The mean monthly air temperature varies from 1.3 to 2.8°C in January and from –11.1 to –13.1°C in July. The air temperature maximums are 4.9°C for January and –10°C for July, and the minimums are 0.9°C and –18.1°C, respectively. The annual precipitation within the last 36-year-long period varied from 471 to 852 mm with a predominance of snowfalls and hoarfrost.

Contrary to Arctic ecosystems, Antarctic ecosystems are characterized by the absence of dwarf shrubs and herbs. The plant communities of the South Shetland Archipelago are predominated by mosses and lichens. A grass species *Deschapmsia antarctica* is the only representative of higher plants. Huge colonies of birds and sea mammals exert a considerable effect on the formation of primitive Antarctic soils. In such places, the soils are enriched in nutrients and have an increased content of toxic substances from the animal's excrements. Areas around bird colonies are often occupied by ornithocoprophilous plant communities (the organic matter under them may be referred to as ornithogenic soil or soil-like substrate).

Data on the microorganisms dwelling in Antarctic soils are not numerous. In the soils of continental areas, *Alternaria alternata, Chrysosporium pannorum, Nectria peziza, Thelebolus microsporus, Phoma herbarum*, and *Mycelia sterile* are present [27]. The major part of microorganisms described in Antarctic soils are cosmopolites that inhabit soils of different continents. It should be mentioned that, in the Antarctic, microorganisms play a very important role in rock weathering in Antarctica. Along with mosses and lichens, lithobiont communities are represented by cyanobacteria, algae, and mycelial and yeastlike fungi [33]. The development of microbial communities results in the accumulation of organic matter on stony deposits and the initiation of soil formation.

Our study is based on the samples obtained by D.Yu. Vlasov and V.A. Krylenkov on King George Island during the work of the 49th Russian Antarctic Expedition (January 2004). Thin soils developed from the residuum of volcanic rocks under the moss–lichen communities were sampled; in addition, samples of fine earth material from the cracks between large stones were taken.

In the soil samples, the organic carbon content was determined by the Tyurin method; the total nitrogen content, by the photometric method using a Nessler reagent; the pH values, by the potentiometric method; the general physicochemical and chemical characteristics, by routine methods [2]; and the fractional and group composition of the humus, by the Ponomareva procedure [24]. The micromorphological description of soil thin sections was performed according to the recommendations by Parfenova and Yarilova [21]. The available phosphorus content was determined by the method proposed by Kirsanov [2]. The lignin content in the surface organomineral horizons and lichen (*Usnea aurantiaco-atra* (Jacq.) Bory) plants was determined according to the method described in [13]. This lichen species predominates in plant communities and is one of the sources of organic matter in the studied soils. The biochemical composition of the lichens was determined by the method elaborated by the Department of Soil Science and Soil Ecology of St. Petersburg State University. The particle-size distribution analysis was performed by the method of screening for coarse fractions and by the pipette method of Kachinskii with pyrophosphate peptization of the aggregates for the fine fractions. The carbon content was determined by direct measurement of the amount of carbon dioxide released at wet combustion (the procedure elaborated by the Laboratory of Soil Biochemistry, Biological Research Institute of St. Petersburg State University [25]).

We used Czapek's medium, Saburo medium, and potato–glucose agar for the initial isolation, cultivation, and identification of the micromycetes [16]. This range of media permits one to distinguish between the species with different growth rates, nutrition sources, and development strategies under varying ecological conditions. For obtaining pure cultures of micromycetes, we added streptomycin sulfate (40–50 mg/l) to the nutrient medium in order to inhibit the development of bacteria.

The methods used for isolating fungi into pure cultures were as follows: (1) direct inoculation of soil particles and undecomposed plant remains onto the surface of the nutrient medium and (2) inoculation of soil suspensions (1 : 100) [16] into the nutrient medium. The numbers of colony-forming units (CFU) per 1 g of soil were determined.

Micromycetes were identified with respect to their phenotype characteristics using special guides [4, 14, 28, 29, 32, 35].

RESULTS AND DISCUSSION

A pit characterizing the profile of a lithozem (Leptosol) has been studied on a flat area between basaltic hills. Basalt and andesite–basalt bedrocks are covered by a thin layer of eluvium; cracks between coarse rock fragments are also filled with pebbly eluvium. The studied soil pit is found between two large blocks of bedrock and is characterized by a relatively thick layer of pebbly eluvium (the C horizon).

The total thickness of the soil profile does not exceed 10 cm. Only a thin layer of fine earth on the rock surface can be referred to as the soil body. Its upper horizons are enriched in partially decomposed plant remains. The soil surface is covered by living mosses and lichens that consolidate the fine earth material. The soil profile morphology is as follows.

O, 0–0.2 cm. Brownish dark gray, dry, loose, undecomposed or partially decomposed mosses and lichens.

OA, 0.2–1 cm. Dark gray, slightly dry, loose, structureless, partially decomposed organic material mixed with sandy fine earth; smooth boundary.

AT, 1–2 cm. Slightly dry; heterogeneously colored: brownish dark gray fragments are enriched in organic matter, whereas light-colored brownish gray fragments are composed of low-humus sandy material; loose, sandy; gradual transition, smooth boundary.

C, 2–10 cm. Brownish coarse-textured (pebbly) eluvium (products of physical weathering of the bedrock) between very coarse rock fragments.

The initially monolithic bedrock is rather intensively weathered, and its eluvium is mainly represented by coarse fraction (fragments of 0.10–1.00 cm in size). For this fraction, the smaller the particle size, the higher its content. The fine earth (<1 mm) content is only 26.8%, which is typical of many Arctic soils [11, 12, 19]. The main part of the fine earth is represented by fine sand (0.05–0.25 mm). The contents of silt and clay fractions are very low. These data attest to a high intensity of physical weathering, which is in agreement with published data [6, 17]. The chemical weathering in polar regions is relatively weak, which is explained by the short period of biological activity and soil formation and the low water-retention capacity of stony soils. The supergene transformation of bedrocks is related to their physical crushing, which is favored by the severe and unstable weather conditions of Antarctica. The high content of rock debris results in the low content of hygroscopic moisture even in the high-humus horizons.

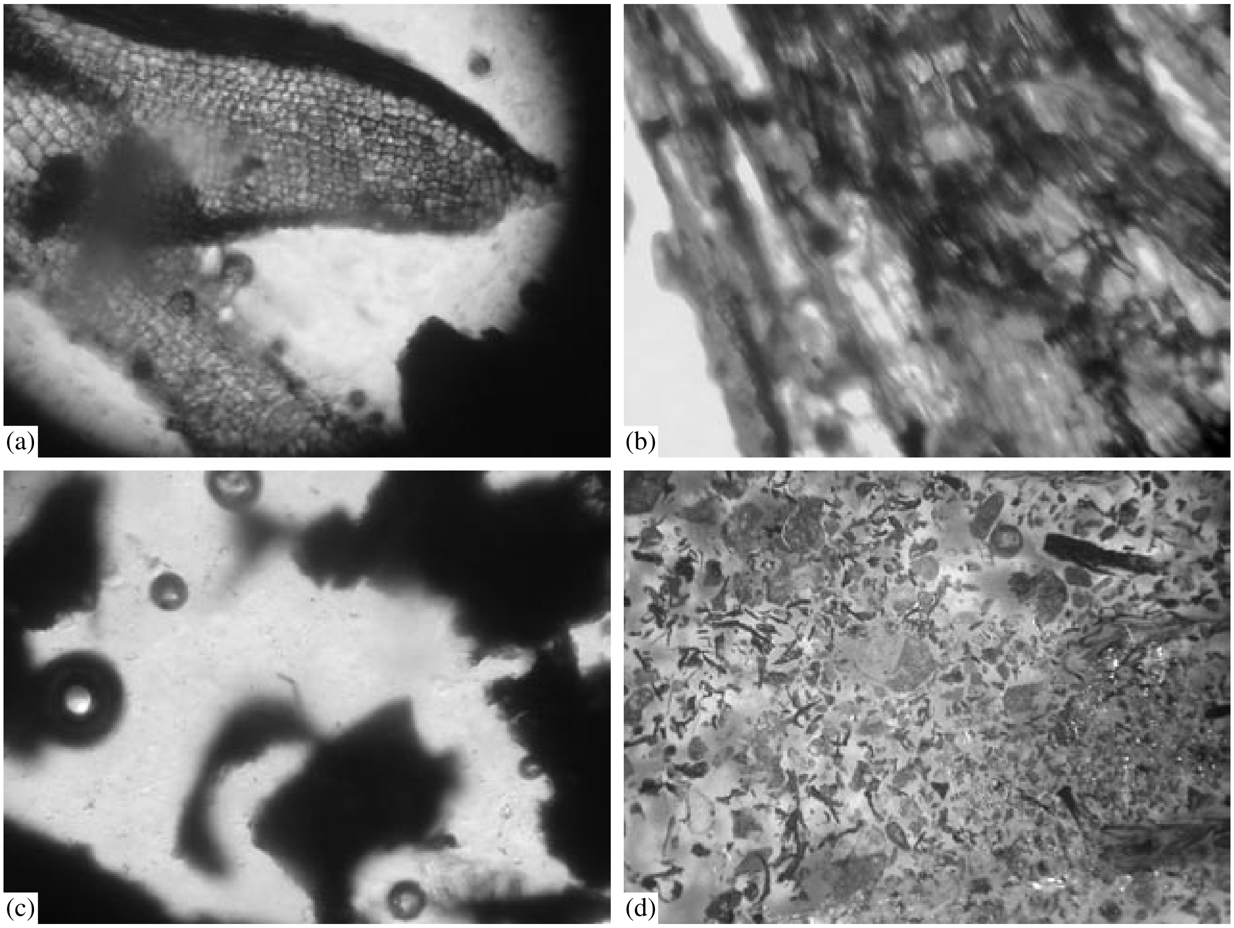

Fig. 1. Micromorphological features of the lithozem: (a) undecomposed organic material, L horizon, $N_{\cdot||}$, ×180; (b) moderately decomposed tissue of a lower plant with preserved cellular structure, $N_{\cdot||}$, ×180; (c) humified plant remains, $N_{\cdot||}$, ×180; and (d) microfabric of the A horizon, $N_{\cdot||}$, ×40.

The micromorphological study of the lithozem made it possible to characterize some specific features of the humus accumulation and weathering processes in this soil. The OA horizon is rich in undecomposed moss and lichen remains, which preserve the initial tissue and cellular structure and greenish brown color (Fig. 1a). The size of the undecomposed plant remains exceeds 0.05–0.10 mm. Plant remains of smaller sizes (0.03–0.05 mm) are partly decomposed, but the initial cellular structure is preserved in their central parts (Fig. 1b). The smaller the size of the plant remains, the higher the degree of their humification (Fig. 1c), which is related to the physical crushing of the dry and fragile thalli of primitive plants and may be enhanced by seasonal cryogenic processes in the pebbly soil. The remains of mosses and lichens of less than 0.03 mm in size are well humified and have a brownish gray or dark gray color. Their content does not exceed 15–20% of the total content of organic remains in the soil. Thus, the transformation of plant remains in the studied soil is very slow and gradual. Decomposition stages that normally last for one–two years in the humid taiga or natural steppe zones may continue for decades in the Antarctic soils. A general tendency for the preservation and accumulation of undecomposed or half-decomposed plant remains in the soils of polar regions has been noted by Gubin [10] and Beyer *et al.* [3]. These authors demonstrated that Arctic and Antarctic soils are characterized by the accumulation of dry-peat (folic) fine plant detritus in the topsoil, which is favored by the low temperatures and low soil moistening, which inhibit the organic matter mineralization.

The microfabric of the soil studied is of the monic type with the predominance of sand-size particles and considerable pore space (30–40%). This is related to the low content of the clay and fine silt fractions that usually fill the spaces between coarse particles and glue the particles together into soil aggregates. The angular shape of the coarse particles and their mechanical corrosion point to the autochthonous physical weathering of the mineral soil part. The interaction between the organic and mineral matter is only seen in the silt fraction, in which colloidal humic substances glue together separate soil particles. Local accumulations of finely dispersed humified organic material are seen in the cav-

Table 1. Physicochemical characteristics of the lithozem

Horizon	pH		Ac	$Ca^{2+} + Mg^{2+}$	CEC	V
	H_2O	KCl	meq/100 g of soil			
OA	6.0	5.4	Not det.			
AT	6.4	6.1	8.45	4.67	13.12	35.6
C	7.0	6.6	2.35	7.52	9.87	76.2

Note: Ac is the total (hydrolytic) acidity, CEC is the cation exchange capacity, and V is the degree of base saturation (%).

Table 2. The contents of organic carbon as determined by the Tyurin method (C_{ox}) and direct method (C_{CO_2}), nitrogen, phosphorus, potassium, and hygroscopic moisture and the loss on ignition in the lithozems

Horizon	C_{ox}	C_{CO_2}	RIO, % of C_{CO_2}	N,%	C_{ox}/N	C_{CO_2}/N	P_2O_5	K_2O	P_2O_5	HW	LI
	%						total, % of abs. dry soil		according to Kirsanov, mg/100 g	%	
Lichen *Usnea aurantiaco-atra*											
O	41.20	32.40	–27.2	0.83	49.6	39.0	0.15	1.15	34	6.6	98.2
Pit 1											
OA	11.96	9.37	–27.6	0.93	12.9	10.1	0.17	1.15	39	2.9	38.2
AT	5.30	4.50	–17.8	0.57	9.3	7.9	0.07	0.64	30	1.5	Not det.
Pit 2											
OA	18.48	13.84	–33.5	0.80	23.1	17.3	0.11	1.44	45	2.9	31.4
AT	4.14	3.50	–18.3	0.49	8.4	7.1	0.07	0.64	30	1.6	Not det.
Fraction of eluvium between rock blocks, mm											
1–0.5	0.48	0.36	–33.3	0.07	6.9	5.1	0.13	0.29	39	Not det.	
0.5–0.25	0.46	0.36	–27.8	0.07	6.6	5.1	0.07	0.26	44	″	
<0.25	0.50	0.70	+28.6	0.14	3.6	5.0	0.05	0.23	49	″	

Note: RIO is the rate of intramolecular oxidation of organic matter; HW is hygroscopic water, and LI is the loss on ignition.

ities on the surface of large quartz grains. The mineral soil matrix is mainly composed of clastic quartz and feldspar grains. In general, the study of thin sections proved that the organic matter in the studied soil is weakly bound with the mineral matrix (Fig. 1d).

The physicochemical data on the studied soil (Table 1) show that the bedrock eluvium (C horizon) has a neutral reaction; in the upper horizons, the reaction becomes slightly acid due to acidification and leaching processes. This is accompanied by a rise in the cation exchange capacity, higher total acidity, and a drop in the absolute and relative content of exchangeable bases in the soil adsorption complex. A rise in the CEC and total hydrolytic acidity is indirect evidence of the formation of finely dispersed soil matter under the impact of organic acids on soil minerals, i.e., chemical weathering. This conclusion is also confirmed by the fact that the fine earth content in the AT horizon rises up to 40–50%, in contrast to 26% in the eluvium between the stone blocks in the C horizon.

The initial parent material (C horizon) contains very low amounts of total potassium (Table 2). Its content is high only in the sand-size fraction, which is obviously related to its specific mineral composition. Both potassium and phosphorus are involved in the biological turnover in the course of soil formation. Their notable accumulation is seen in the OA horizon, while, in the AT horizon, the potassium content increases only two times as compared with the initial rock. The total phosphorus content in the studied soil is not high. In the eluvium between the rock blocks, its highest content is in the sand fraction, and notable accumulation is seen in the OA horizon, where it is obviously related to the organic matter.

The organic carbon content in the fine earth (particularly in the OA horizon) is very high (Table 2). This is explained by the high content of slightly decomposed microscopic lichen detritus. Under these conditions, the degree of intramolecular reduction of the organic matter is high. We have analyzed the organic matter distribution between different particle-size fractions. The

Table 3. Biochemical composition of the mixed remains of lower plants (the O horizon), the organic OA horizon, and the organomineral AT horizon (% of absolutely dry soil)

Horizon	N	Ash	Lignin	Wax resin	Raw protein	Hemicelluloses	Cellulose	Water-soluble substances	
								sugars	total carbon
O	0.81	7.2	9.37	6.17	5.08	47.72	9.28	1.79	20.63
OA	0.93	61.6	4.65	Not det.*					
AT	0.57	90.0	1.05	″					

* For the OA and AT horizons, the fractional composition of humus has been determined.

particle-size distribution (% of the total weight of the sample) in the eluvium between the rock blocks is as follows: >10 mm, 18.8%; 7–10 mm, 6–9%; 5–7 mm, 12.5%; 3–5 mm, 15.4%; 1–3 mm, 16.9%; and <1 mm, 26.8%. The fine earth fractions are distributed as follows: 0.25–1.0 mm, 23.5%; 0.05–0.25 mm, 58.1%; 0.01–0.05 mm, 8.7%; 0.005–0.01 mm, 0%; 0.001–0.005 mm, 3.0%; <0.001 mm, 6.7%; and <0.01 mm, 9.7%.

The organic matter in the coarse sand fraction is characterized by a high degree of intramolecular reduction. Slightly decomposed plant detritus is accumulated in this fraction, which correlates well with the content of total nitrogen [23]. Oxidized organic matter represented by colloidal humus compounds accumulates in the finer fractions (<0.25 mm).

The biochemical composition of the organic residues of lower plants—the main source of humic substances—is of particular interest (Table 3). The biochemical composition of mosses and lichens is characterized by a low content of lignin and raw protein and a high content of hemicelluloses. As a result of the organic matter transformation, the lignin content in the OA horizon decreases considerably and the nitrogen content somewhat increases. The low nitrogen content in the plant remains hampers the humification of organic matter. In addition, it is hampered by the high content of hemicelluloses in the plant detritus. In general, the biochemical characteristics of lichen *Usnea aurantiaco-atra* are similar to those of other lower plants [1]. The high content of water-soluble carbon attests to the considerable potential of the plant remains for mineralization, which is not realized due to the severe climatic conditions and low nitrogen content. The slowing down of the biochemical processes in the studied soils may also be related to the small number of microorganisms. For example, the mycological analysis of the soil samples taken under mosses and lichens has shown relatively small numbers of micromycetes (no more than 400 CFU per 1 g of soil). We have identified eight fungus species: *Aspergillus terreus, Penicillium canescens, P. caseicola, P. lanosoviride, P. striatum, Phytium ultimum, Trichoderma viride*, and *T. koningii.* The genus *Penicillium* predominates with respect to the species abundance. Relatively abundant species are represented by *Penicillium lanosoviride* and *Trichoderma koningii.* The low population density of micromycetes in the studied soil is obviously caused by the inhibiting effect of the mosses and lichens on the soil mycobiota.

The fractional and group composition of the humus composition in the investigated lithozems is generally typical of polar soils (Table 4). The soil humus is very rich in the nonhydrolyzable residue (humin) fraction (74–94%). This attests to the low intensity of the mineralization and humification processes in the soil. The humin fraction is almost completely represented by undecomposed or partially decomposed remains of mosses and lichens. Its content gradually decreases downward through the soil profile, while the humification rate (the percentage of humic and fulvic acids in the soil humus) somewhat increases. The lowest humin content is typical of the fine earth fraction of the eluvium between rock blocks, where it is obviously represented by the forms firmly bonded to the mineral soil part.

The fractional composition of the humus in the OA horizon is characterized by a predominance of the first (free) fraction of humic and fulvic acids. Down the profile, the content of humic and fulvic acids bound to calcium (second fraction) and stable sesquioxides (third fraction) increases.

The degree of humification as estimated by the C_{ha}-to-C_{total} ratio [20] is higher in the AT horizon than in the slightly decomposed litter (OA horizon). At the same time, the C_{ha}-to-C_{fa} ratio in the OA horizon is higher than in the AT horizon. This is probably explained by the following specific features of the humification. In the taiga, tundra, and Arctic zones, humification results in the formation of practically insoluble brown humic acids that are accumulated in the place of their origin and do not migrate down the soil profile [22, 23]. At the same time, fulvic acids migrating with solutions in the soil profile are one of the products of organic matter transformation in a severe cold climate. They are accumulated in the AT horizon and are bonded to calcium and iron at geochemical microbarriers. Thus, the maximum degree of humification in the AT horizon is accompanied by the lowest C_{ha}-to-C_{fa} ratio.

The optical properties of humic acids as characterized by the extinction coefficient ($E_{465}^{0.001\%}$ = 0.015–

Table 4. Fractional and group composition of the organic matter of lithozems (above the line, % of the soil; under the line, % of C_{total} as determined by Tyurin's method)

Horizon	Humic acids				Fulvic acids					C_{ha}/C_{fa}	NR
	1	2	3	Σ	1-a	1	2	3	Σ		
Pit 1											
OA	$\frac{0.10^*}{0.9}$	$\frac{0.07}{0.6}$	$\frac{0.05}{0.4}$	$\frac{0.22}{1.9}$	$\frac{0.28}{2.3}$	$\frac{0.04}{0.3}$	$\frac{0.08}{0.07}$	$\frac{0.10}{0.9}$	$\frac{0.49}{4.2}$	0.45	$\frac{11.2}{94.0}$
AT	$\frac{0.14}{2.6}$	$\frac{0.15}{2.9}$	$\frac{0.10}{1.9}$	$\frac{0.39}{7.4}$	$\frac{0.08}{1.4}$	$\frac{0.14}{2.6}$	$\frac{0.49}{9.2}$	$\frac{0.20}{3.8}$	$\frac{0.91}{17.2}$	0.42	$\frac{4.00}{75.4}$
Pit 2											
OA	$\frac{0.60}{3.3}$	$\frac{0.20}{1.1}$	$\frac{0.10}{0.5}$	$\frac{0.90}{4.9}$	$\frac{0.45}{2.5}$	$\frac{0.30}{1.6}$	$\frac{0.25}{1.4}$	$\frac{0.15}{0.9}$	$\frac{1.16}{6.3}$	0.78	$\frac{16.42}{88.8}$
AT	$\frac{0.13}{3.1}$	$\frac{0.07}{1.2}$	$\frac{0.13}{3.2}$	$\frac{0.33}{8.0}$	$\frac{0.11}{2.7}$	$\frac{0.13}{3.1}$	$\frac{0.35}{8.5}$	$\frac{0.14}{3.4}$	$\frac{0.73}{17.7}$	0.45	$\frac{3.08}{74.4}$
Eluvium between rock blocks											
C	$\frac{0.02}{4.0}$	$\frac{0.04}{8.0}$	$\frac{0.04}{8.0}$	$\frac{0.10}{20.0}$	$\frac{0.02}{4.0}$	$\frac{0.02}{4.0}$	$\frac{0.08}{16.0}$	$\frac{0.04}{8.0}$	$\frac{0.16}{32.0}$	0.63	$\frac{0.24}{48.0}$

Note: NR is the nonhydrolyzable residue (humin) fraction.

0.025) are closer to fulvic acids than to humic acids [20]. The prevalence of slightly condensed humus acids in Arctic soils has been shown by Dobrovol'skii [11]. The extinction coefficients of the humic acids in the AT horizon of the studied soils are considerably higher than those in the OA horizon, which attests to the more active humification in the AT horizon. These data are also confirmed by the chromaticity coefficient. Coefficients E4/E6 decrease with the depth (from 7–10 to 5–6), which points to the greater humification of organic matter with the formation of optically active molecule centers responsible for light absorption in the visible spectrum. It should be mentioned that there is a clear tendency for a rise in the "maturity" of molecules from the first to the third fraction of humic acids (the E4/E6 values in the first, second, and third fractions are 10, 6, and 4, respectively), whereas the chromaticity coefficients in this sequence decrease by two times and more.

Thus, the humus formation under the unfavorable climatic conditions of Antarctica is accompanied by the conservation of plant remains and accumulation of slightly decomposed components in the fraction of nonhydrolyzable residue. Brown humic acids and fulvic acids represent the typical humification products. With respect to optical properties, the former occupy an intermediate position between fulvic and humic acids. Acid raw fulvate humus is typical of the studied soils, and the considerable portion of humic substances bonded to calcium (the second fraction) is explained by the very low intensity of the leaching processes.

CONCLUSIONS

The investigated soils, together with the soils of Antarctic polar deserts [15], are the main components of the soil cover in the areas of supergene weathering beyond the ice sheets of Antarctica. Physical weathering plays the leading role in the transformation of the initial bedrock and mineral soil mass. The studied soils are formed under the moss–lichen cover and are characterized by their high content of slightly transformed organic matter and low degree of humification. Slightly condensed brown humus acids and fulvic acids are the main products of the humification processes. The content of micromycetes in the soil samples is rather low, which is obviously explained by the inhibiting effect of mosses and lichens on the soil mycobiota. In general, the lithozems of King George Island are characterized by a low population density and activity of fungi and a low intensity of organic matter transformation and humification. These features are related to the severity of the climatic conditions and the specificity of the biochemical composition of the lower plants.

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