Chapter 26
Levels of Biogenic-Abiogenic Interaction and Structural Organization of Soils and Soil-Like Bodies in Antarctica

Aleksei V. Lupachev, Stanislav V. Gubin and Evgeny V. Abakumov

Abstract Pedogenic processes of transformation and accumulation of organogenic matter and its interaction with the mineral matrix of the soils are very poor-expressed in Antarctica. Very often, these processes show up in a very special ways that can rarely be observed in the well-studied soils of moderate latitudes and even in the northern polar environments. The majority of the Antarctic soils do not develop well-expressed uppermost organomineral horizons. Mostly they are presented with the poorly aggregated mix of mosses' and lichens' detritus with the coarse-textured debris and rarely show macromorphological evidences of biogenic-abiogenic interaction. Using of state-of-the-art modern methods of soil science (scanning electron microscopy, micro- and mesomorphological analysis etc.) along with the regular methods of morphological analysis of soil profiles and spatial analysis of the soil cover allow distinguishing different levels of the structural organization of soils in the Antarctic region. The fine earth adhesion, forming of the organomineral coatings and films, deep alteration of primary minerals and ornithogenic impact on the soil material and profile structure is evident at all the studied levels of soil organization. Their manifestation degree rises from the continental Antarctica to the Subantarctic regions and from the soil-like bodies with no or very poor-expressed vegetation to the soils with relatively well-developed uppermost organo-horizons.

Keywords Antarctica · Soils · Cryosols · Leptosols · Scanning electron microscopy · Micromorphological analysis

A. V. Lupachev (✉) · S. V. Gubin
Institute of Physico-Chemical and Biological Problems in Soil Science RAS, Puschchino
Institutskaya st. 2/2, 142290 Moscow, Russian Federation
e-mail: a.lupachev@gmail.com

E. V. Abakumov
Department of Applied Ecology, Saint Petersburg State University, 16-line, 2, Vasilyevskiy Island, 199178 Saint Petersburg, Russian Federation

O. V. Frank-Kamenetskaya et al. (eds.), *Processes and Phenomena on the Boundary Between Biogenic and Abiogenic Nature*, Lecture Notes in Earth System Sciences,
https://doi.org/10.1007/978-3-030-21614-6_26

26.1 Introduction

The occurrence of pedogenic processes in soils of Antarctica still stays a very debatable scientific issue especially for the soils that develop in the high-latitudinal regions of the continental Antarctica due to their very poor expression in the majority of soils and soil-like bodies here. Soils here significantly differ from ones that are well studied in the moderate latitudes of the northern hemisphere and even from soils of the high Arctic (Bockheim et al. 2015). These two macroregions of the planet have passed through completely different geological history and palaeoenvironmental conditions of glaciation and deglaciation cycles. Vast territories in the high Arctic regions became nearly completely ice-free about 9–11 Kyrs before present. More of that, the significant part of the Arctic region (mainly in the North-East of Eurasia) has never been covered with continental glaciers and the soils here could continue developing even under the synlithogenic conditions through the whole Pleistocene period (Elias and Brigham-Grette 2013). The glaciation history of the Antarctic region is completely different. The relatively small and sporadically distributed oases (around 1–2% territory of the Antarctic continent) were partly covered by the continental glacier and revealed their modern relatively ice-free state only about 7–9 Kyrs before present and in some cases even later (Verkulitch 2009; Verkulitch et al. 2012). The absence of the uppermost organogenic and organo-mineral horizons, poor-expressed differentiation of the soil horizons and their lateral continuity, the lack of structure of soil material and rare evidences of clay minerals' forming are regular for the soils here. The main limiting factors for the plant cover distribution here are the lack of the liquid water, low temperatures, harsh winds and high level of the ultraviolet radiation.

The classification of the majority of the soils and soil-like bodies that form under the extremely harsh conditions of the Antarctic oases is very complicated due to the absence of the common approaches for their diagnostics. By now the most abridged approach to these natural biogenic-abiogenic bodies is given in the part of the USDA Soil Taxonomy (Soil Survey Staff 2010) which was developed specially for the Antarctic soils (Bockheim et al. 2006). Nevertheless, one should keep in mind that this approach was mainly based on the experience of studying of the soils and soil-like bodies of the extracontinental mountainous region of Dry Valleys (Central Victoria Land) that is situated roughly at the 75–77° S and significantly differs from other ice-free areas of continental Antarctica and surely from the maritime regions in terms of climatic and geological conditions.

Submicro-, micro- and mesomorphological methods are well known as useful tool for investigation of soil transformation under natural and human-impacted conditions. Methodology of the classical soil micromorphology provides the required information about the soil development at the micro level, such as changes in fine earth composition and soil plasma evolution (Kubiena 1938, 1970; Stoops 2009). These methods are widely used for analysis of soil palaeoprocesses (Rusakov et al. 2018), soil restoration on post-mining environments (Abakumov et al. 2005), soil elementary process in different environments (Lebedeva et al. 2010; Abakumov et al. 2013) and specification soil classification aspects (Kubiena 1970). However, the micromorphological methods have been applied to study Antarctic soils organization only in few studies (Abakumov et al. 2013; Meier et al. 2017).

Despite the relatively low thickness and spatial discontinuity of the superficial organo-mineral bodies in the Antarctic environments and the absence of the most of the features that are specific for the regular soils [even for the high latitudes of the northern hemisphere (Bockheim and Tarnocai 1998)] the number of diagnostic features that allow distinguishing soils and soil-like bodies which show evidences of biogenic-abiogenic interaction and have all of the levels of structural organization (e.g. the formation of the elementary soil particles and structural aggregates, organo-mineral interaction and stabilization of the soil organic matter, forming of the vertical paragenetic system of the soil horizons in the profile, the regularity of the spatial structure of the soil cover etc.). The main objective of the present study was to obtain the very essence of the pedogenesis in weakly developed soils and soil-like bodies—the interaction of the organogenic and mineral matter through the investigation of the Antarctic soil structural organization.

26.2 Objects and Methods

Different natural and human-affected soils were investigated while studying the surrounding environments of the maritime ("Bellingshausen"), coastal ("Molodeznaya", "Leningradskaya", "Russkaya") and interior ("Bunger Oasis", "Novolazarevskaya") scientific stations of the Russian Antarctic Expedition.

"Bellingshausen" station (62.197944° S, 58.960872° W) is situated at the Fildes Peninsula (King-George Island, South Shetland Islands). Gentle topography dominates here with a wide central plain at the elevation of around 40–50 m a.s.l., several other smaller plains at different altitudes (from 80 to 100 m a.s.l.) and three massive flat-topped volcanic remnants with numerous rocky outcrops and maximum heights from 120 to 150 m a.s.l. This area mainly consists of volcanic rocks (andesite basalts and their pyroclastics) with small outcrops of tuffs, volcanic sandstones and agglomerates (Smellie et al. 1984). Climate here is cold and relatively moist with mean annual air temperature of −2.2 °C and mean annual precipitation around 350–500 mm (Michel et al. 2014). Mean daily air temperatures above 0 °C last here for up to four months during the austral summer.

"Molodeznaya" scientific base (67.667646° S, 45.860785° E) is in the Thala Hills oasis that is located in the western part of Enderby Land. It consists of two parts—Molodezhny and Vecherny sites—with a total area of 20 km^2. The Molodezhny site extends for 8.3 km along the coast, its maximum width is 2.7 km, and it is bordered by ice sheet from the south. The maximum elevation is 109 m a.s.l., and the total area is 13 km^2. The Molodezhny site of the Thala Hills oasis is a hilly area with ridges. The ridges are 1 km long and up to 150 m wide. Depressions located between the ridges are mostly filled with snow patches, local glaciers, and lakes. The relative height of the ridges is about 10–40 m. The parent materials comprise drift and colluvium that provide a discontinuous and thin cover. Rock outcrops and patches of granulite-facies metamorphic and plutonic rocks dominate in the area (Dolgikh et al. 2015).

"Leningradskaya" base (69.501339° S, 159.392974° E) is situated in the North Victoria Land. It is a very mountainous region, with elevations ranging from sea level to about 3720 m (Mt. Hewson). The climate reflects these differences in elevation, with mean annual air temperatures ranging from −25 to −35 °C and mean annual precipitation ranging from 100 to 300 mm (Bockheim 2015). Vegetation is limited to isolated cryptogams. Upper Precambrian metasedimentary rocks are dominant here, with smaller areas of Cenozoic volcanic rocks, Beacon sandstone, Ferrar dolerite, and granite intrusives of varying ages (Bockheim 2015). The entire area is underlain by ice-cemented permafrost and the active-layer depths range from 8 to 70 cm in depth.

"Russkaya" station, the southernmost coastal Russian Antarctic station located on the Berks Cape of the Hobbs Coast (74.755212° S, 136.811186° W). One more study site in the relatively nearby was on the Lindsey Islands (73.603379° S, 103.032672° W). This territory consists of low (<150–200 m a.s.l.) rocky mountains composed of biotite–hornblende plagiogneiss (Lupachev and Abakumov 2013; Lupachev et al. 2015). Glacial processes often terrace relatively gentle slopes of the mounts. In some depressions of the relief, thin layers of loose sediments are accumulated. The mean annual air temperature here is −12.4 °C, the warmest month is January (−2.5 °C), and the coldest month is August (−19.8 °C). The absolute minimum of air temperatures is −46.4 °C, and the absolute maximum is +7.4 °C. Because of the coastal position of the station and the low temperatures in this area, the mean annual relative humidity of the air is high (78.7%).

"Bunger Oasis" scientific base (66.292569° S, 100.771091° E) is a coastal range on the Knox Coast in Wilkes Land in Antarctica, consisting of a group of moderately low, rounded coastal hills represented by schists, gneisses, and pegmatites, overlain by marine sediments and morainic drift and notably ice free throughout the year (Blume and Bolter 2015). Glaciers surround the Bunger Hills. On the southeast, the Bunger Hills is bordered by the steep slopes of the Antarctic ice sheet, on the south and west by outlet glaciers, and on the north by Shackleton Ice Shelf, which separates the area from the open sea. The ice-free area measures 450 km^2.

"Novolazarevskaya" station is located in the Schirrmacher Oasis (70.776506° S, 11.822197° E). It is presented with the Precambrian metamorphic rocks, including gneisses and crystalline shale. Ultramafic intrusive bodies and numerous pegmatite veins are found locally (Zazovskaya et al. 2015). The mean annual air temperature here is −10.3 °C; the temperature of the coldest month (August) is −17.9 °C, and the temperature of the warmest month (January) is −0.4 °C. The active layer of permafrost in the Schirrmacher oasis ranges from 30 to 120 cm in depth.

All the field procedures were carried out according to the "ANTPAS Guide" (Bockheim et al. 2006). Exact points of studying were chosen according to the structure of the soil cover at the study sites following the representativeness approach. Soil pits were excavated unless the large boulders, solid rock or ice-cemented permafrost prevented further digging. Soil material was sampled from every diagnostic horizon according to the structure of each soil profile. GPS location and elevation of each site was determined. Site features were described, including structure and density of vegetation cover; depth of active layer, ice texture of permafrost (if present); the degree of boulder and debris weathering; and structure and dimensions of cryogenic forms of relief (Bockheim and Tarnocai 1998; Beyer et al. 1999). The following soil properties were measured in the field: 10% hydrochloric acid test to distinguish carbonates in the soil profile; potassium ferricyanide test to detect redoximorphic features (Birkeland 1984).

Submicroscopic investigation of soils was carried out using the electronic scanning microscope Vega 3 Tescan (Tescan-Orsay Holding, Czech Republic). Thin sections were investigated with use of polarization microscope Leica DFC 320 (Leica Microsystems, Germany) under the transmitted and polarized light and using optical microscope Carl Zeiss Axiostar (Zeiss AG, Germany) at 10×–50× magnification under the transmitted and polarized light as well. The following soil micromorphological properties have been investigated: soil microfabric, spatial arrangements of fabric units, soil particles distribution, elements of microstructure and character of organic matter. Terminology used in this paper is published by Stoops (2009), also by Gagarina (2004) manuals and Gerasimova et al. (2011) review, where details of microorganization of soil were described in details. Normally, soil micromorphology was studied in the transmitted light, but in some cases with aim to clarify mineral weathering we used polarized light. Mesomorphological studies were carried out using the USB-microscope MiView M200UM (Cosview Technologies, China Republic) at 10×–200× magnification with the images taken under the reflected light.

26.3 Results

Samples that were taken from the horizons of the Antarctic soils of different genesis were analyzed using the submicro-, micro- and mesomorphological methods. The clear and abundant features of the pedogenic processes' occurrence were obtained in the studied soils. The fine earth adhesion, forming of the organomineral coatings and films, deep alteration of primary minerals and ornithogenic impact on the soil material and profile structure is evident at all the studied levels of soil organization. Their manifestation degree rises from the continental Antarctica to the Subantarctic regions and from the soil-like bodies with no or very poor-expressed vegetation to the soils with relatively well-developed uppermost organo-mineral horizons.

The most widespread features of the microaggregates' forming in the soils of Antarctica is the adhesion of the ultrafine earth particles on the surfaces of the stone gravel and smaller grains, belonging to the coarse fraction of the parent rock debris (Figs. 26.1, 26.8 and 26.10). Antarctic soils have shown various content of the fine earth—from 10 to 50%. This indicates the prevalence of the coarse fraction of weathered debris in the soil microfabric. The skeletal fraction/fine earth ratio strongly depends on the genesis of the parent rocks, the degree of their alteration and portion of sedimentary material. The human impact on soils that is realized in form of the

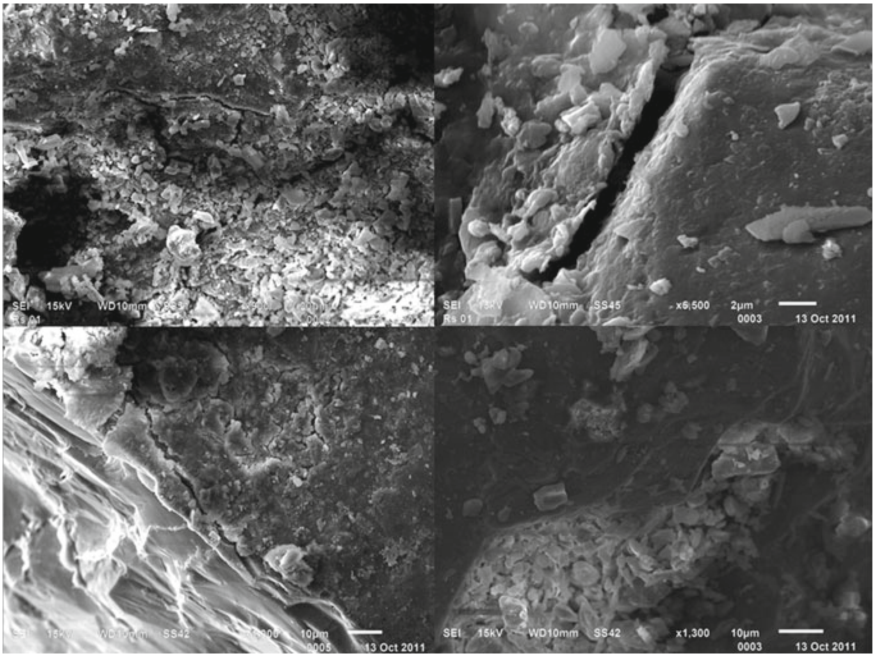


Fig. 26.1 "Russkaya" station. The fine earth particles aggregated on the parent rock grains

sporadic gasoline spills result in the formation of organic pseudoplasma on the surfaces and inside the soil aggregates and these gasoline and motor oil leaks provide chemical agents that highly increase the fine earth's adhesive properties (Fig. 26.2). This micromorphological feature appears to be typical for the soils of Antarctica in the surroundings of the diesel stations and fuel storages located close to permanent and seasonal scientific stations.

Micromorphological investigation has shown that despite the coarse texture of the soil material the microzones of the relatively stable soil mineral matrix can be formed. The most often observed types of the microstructure of the matrix are granular and sandy-plasmic along with the microareas of the clay plasma. These microareas have features of fluidity and optically oriented clay accumulation and can show features of ferrugination (Fig. 26.3). Some mineral grains of the parent rocks are covered with thin clayish films and even cutans and this feature additionally strengthens the fact of clay mobilization in the given stable microzones of these soils.

In the soil material of the interior oases (e.g. Schirrmacher Oasis, Bunger Oasis) where sedimentary and sedimentary-metamorphic rocks occur, the features of the calcium carbonates neogenesis and redistribution can often be obtained. In some cases, the microcrystallic calcareous aggregation and cementation of the skeletal particles can be obtained (Fig. 26.4). Rare clay-carbonate cutans in the soil pores and cavities can be obtained here as well (Fig. 26.5).

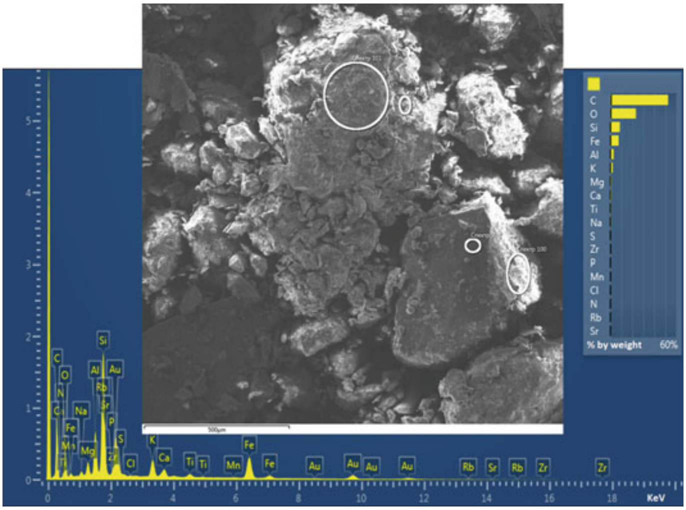


Fig. 26.2 "Russkaya" station. The fine earth particles aggregated on the parent rock grains in the soils under the diesel gasoline spill

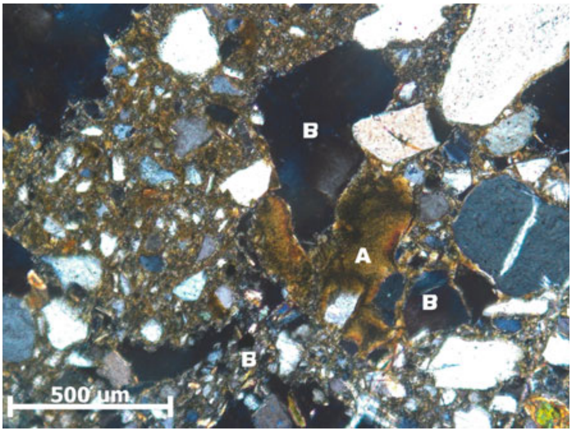


Fig. 26.3 "Novolazarevskaya" station. The clots of the optically oriented clay (**a**) in the relatively stable microzones of the skeletal fraction (**b**). X N

Another result of biogenic-abiogenic interaction is the formation of stable organo-mineral coatings on the surface of mineral particles, even the quartz grains (Fig. 26.6). The initial mechanism of this interaction was obtained at the mesomorphological level in the mixture material of the coarse fraction, fine earth, plant detritus and remnants of the ornithogenic origin. This type of organo-mineral interaction plays an important role in stabilization of the soil surface which is important for stable existing of soil cover in conditions of extremely high wind velocity.

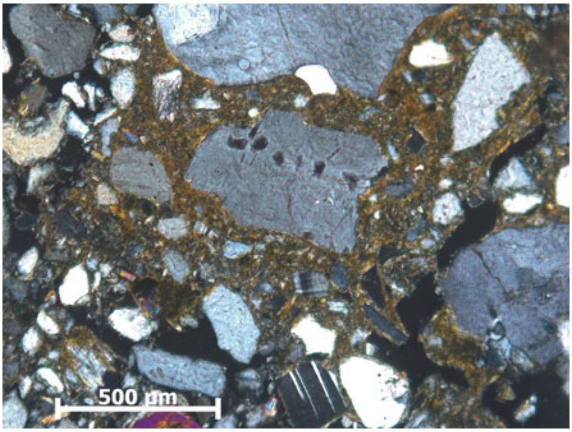


Fig. 26.4 "Novolazarevskaya" station. Calcareous cementation of the skeletal fraction by the clay-carbonate plasma. X N

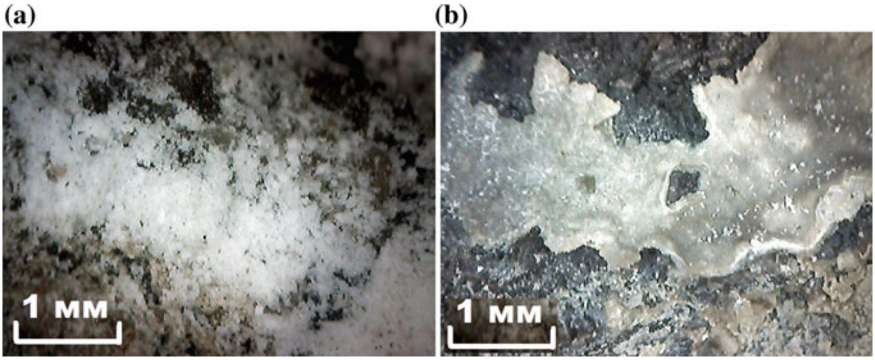


Fig. 26.5 "Bunger Oasis" station. Carbonate neogenesis on the uppermost (**a**) and lowermost (**b**) surfaces of the gravel and boulders

Plasma structure in the ornithogenic soils has well-expressed mobile-laminar structure with inclusions of shaggy zones in the guano material. It covers the grain surfaces very densely and forms thick films and wide microzones of compacted skeletal structure. In some microzones, the clots and concretions are forming and in the peripheral parts of the plasma and the microscopic crystals of biogenic phosphates and sulphates are forming (Fig. 26.7). Plasma includes the abundant fungi hyphae and sporangia as well as the colonies of the unicellular algae (Fig. 26.8).

Soils that are formed on the coarse rock debris in the surroundings of stations "Russkaya" and "Leningradskaya" are characterized by the relatively high content of several minerals of the mica group (muscovite, biotite and phlogopite) in the soil matrix. The presence of these minerals often indicates the low degree of the initial parent materials' transformation under the influence of biogenic and abiogenic

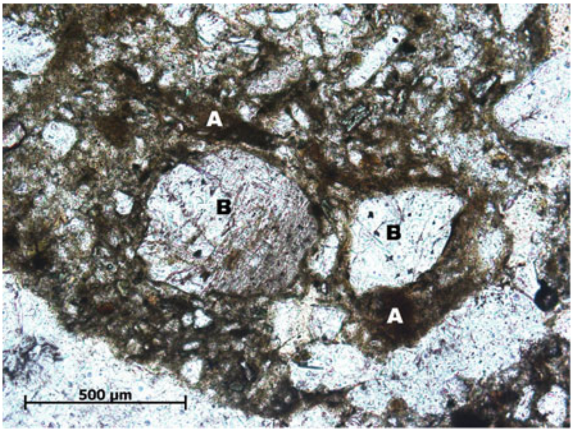


Fig. 26.6 “Novolazarevskaya” station. Organo-mineral coatings and films (**a**) on the surfaces of the mineral grains (**b**). II N

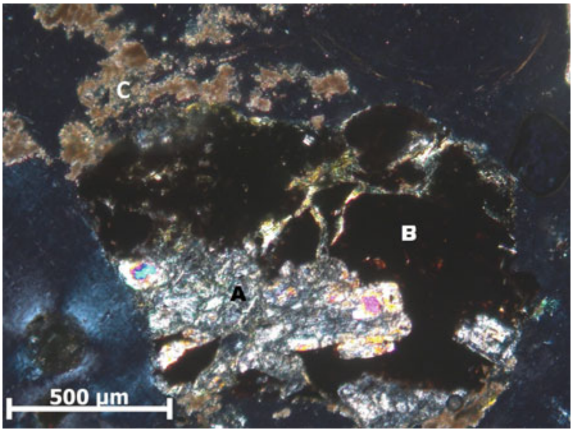


Fig. 26.7 “Bellingshausen” station. Weathered mineral particles (**a**), mobile-laminar structure of the organogenic plasma (**b**) and the microcrystals of the biogenic salts (**c**). X N

weathering processes (Gagarina 2004; Abakumov et al. 2013). Unaltered grains of mica (muscovite and biotite) are presented in various projections in the Fig. 26.9a, b, c and d. The most evident presence of these minerals is seen under the polarized light. The initial stage of biotite weathering is presented on the Fig. 26.9e and f, here one can see the destruction of this mineral on the periphery and the accumulation of the iron oxides at some spots. Uppermost soil horizons demonstrate alteration and weathering of minerals. Here the alteration of the mica is evident in a porous media of soil in surroundings of “Leningradskaya” station (Fig. 26.9l). Another important feature of the Antarctic soils is the sericitization of plagioclases, which can be considered as the alteration of the primary minerals of the soil-forming rocks (Fig. 26.10).

The highest level of the biogenic-abiogenic interaction in a pedological sense was revealed in the structure of the soil cover in the Antarctic oases. It is realized in forms of combination and can be complicated by the complexes of the soil cover

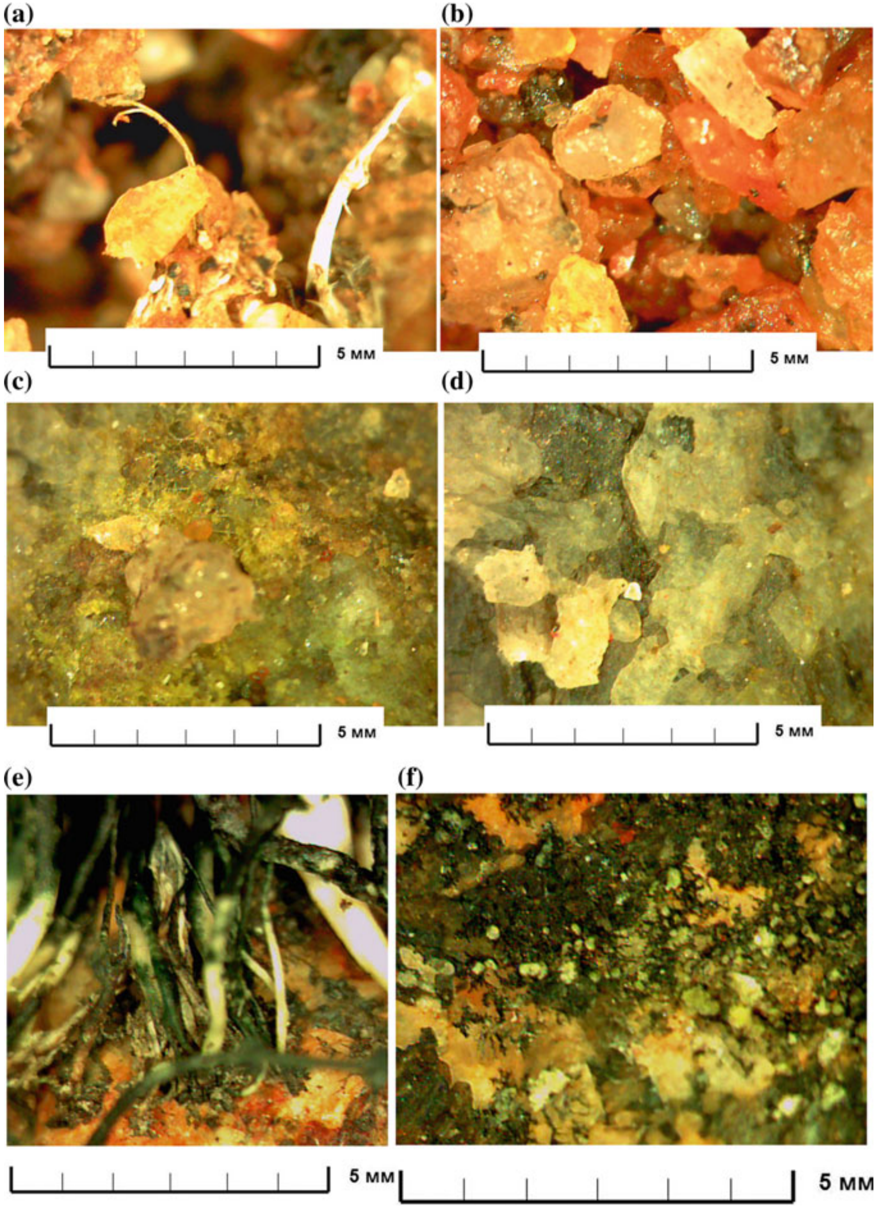


Fig. 26.8 "Russkaya" station. Mesomorphological features of regular Cryosols and Cryosols with the ornithogenic impact. **a** ornithogenic matter remnants; **b** fine earth of Cryosols; **c** association of mineral particles with organic remnants of *Prasiola crispa*, green nitrophilous algae; **d** parent material; **e** ingrowth of the lichen into the parent rock; **f** accumulation of organo-mineral fine earth on the mineral surface; **g** lichen material on the surface of parent rock boulder; **h** accumulation of organic particles of the surface of quartz

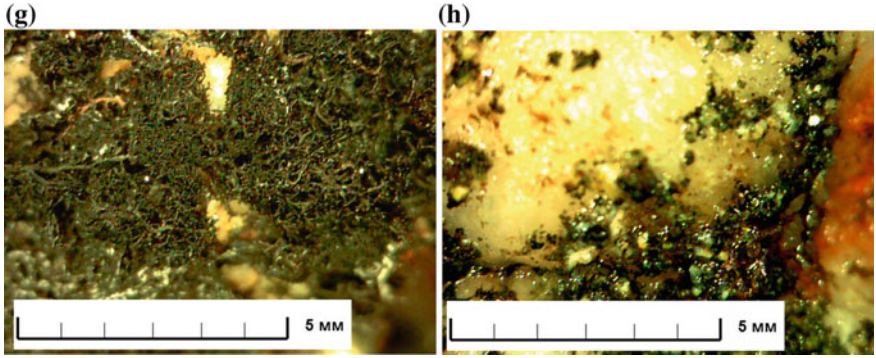


Fig. 26.8 (continued)

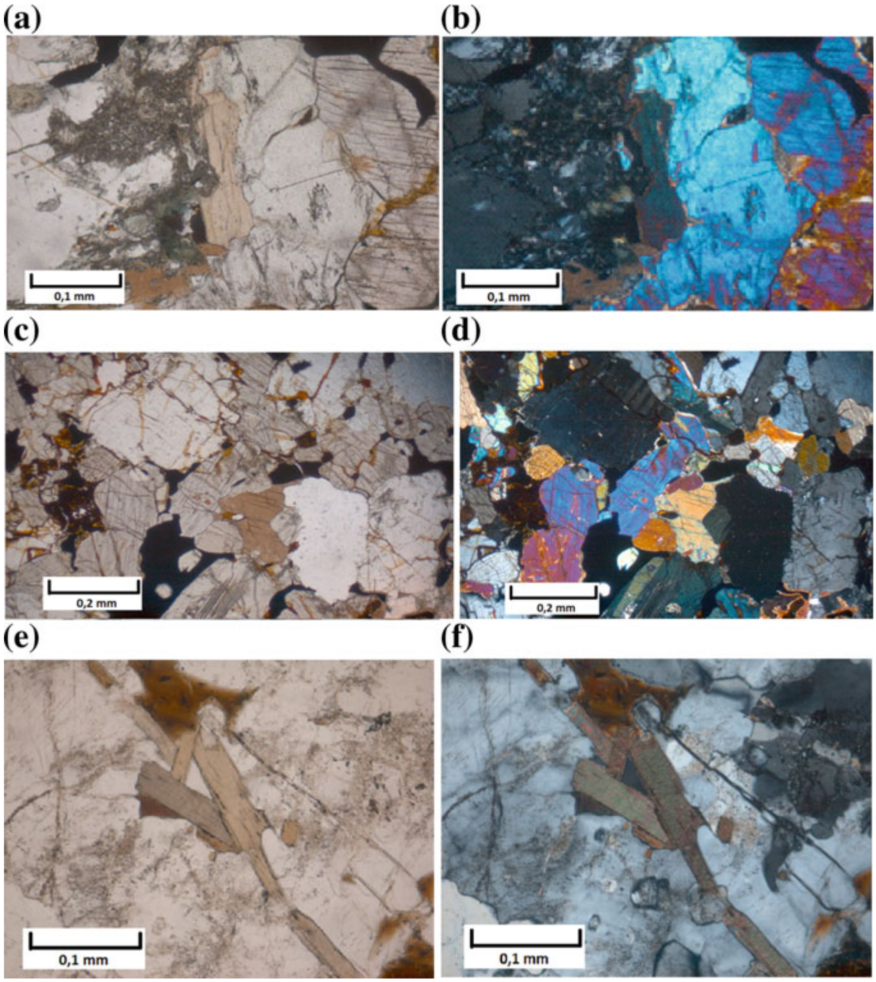
on the each element of the mesorelief. Such complexes are mostly formed in the environments rich with accumulated or transited liquid water and underlied by the permafrost or the rock bed and are clearly distinguished by the very specific surface microrelief—stone pavements, rock circles and polygons, rock stripes etc. In these cases, the central parts of the circles and polygons as well as the intrastripe linear areas that are enriched with fine earth are most often poor with plant cover. In opposite, the peripheral areas that are super-enriched with gravel and boulders serve as the micro wind shelters and additional water supply for the moss pads, lichen thallomes and vascular plants (Fig. 26.11).

26.4 Discussion

Authors intentionally do not consider below the issues of the pedogenic processes at the atomic, ion-molecular and elementary soils particles' levels because these processes are more or less the same in the most of the soils and mainly do not show direct dependence from the environmental conditions such as climate and vegetation cover but depend on the parent rock genesis (Birkeland 1984). Thus, the first and the very lowest level of soil structure organization that is considered and discussed further is the level of the soil micro- and macroaggregates and pedogenic neoformations.

26.4.1 Soil Aggregates and Neoformations

The process of the soil aggregates' formation and the adhesion of the fine earth material is most clearly expressed in the soils that are developed on the sedimentary (or in some case on the sedimentary-metamorphic) rocks that are less stable to the physical and biogenic weathering and provide fine-textured debris. However, even in



◀**Fig. 26.9** Elements of the micromorphological structure of the Antarctic soils: "Russkaya" station. Unweathered mica on the skeletal particle surface (**a** transmitted light and **b** polarized light); "Russkaya" station. Unaltered parent soil material (**c** transmitted light and **d** polarized light); "Leningradskaya" station. Weathering of mica on the surface of quartz (**e** transmitted light and **f** polarized light); Lindsay islands. Guano on the surface of plagioclase (**g** transmitted light and **h** polarized light); Lindsay islands. Guano aggregation of mineral particles, transported by wind (**i** transmitted light and **j** polarized light); "Leningradskaya" station. Sericitization of the feldspars—formation of mica mineral on the surface (**k** polarized light); "Leningradskaya" station. Mica weathering in a porous media of soil (**l** polarized light)

a.lupachev@gmail.com

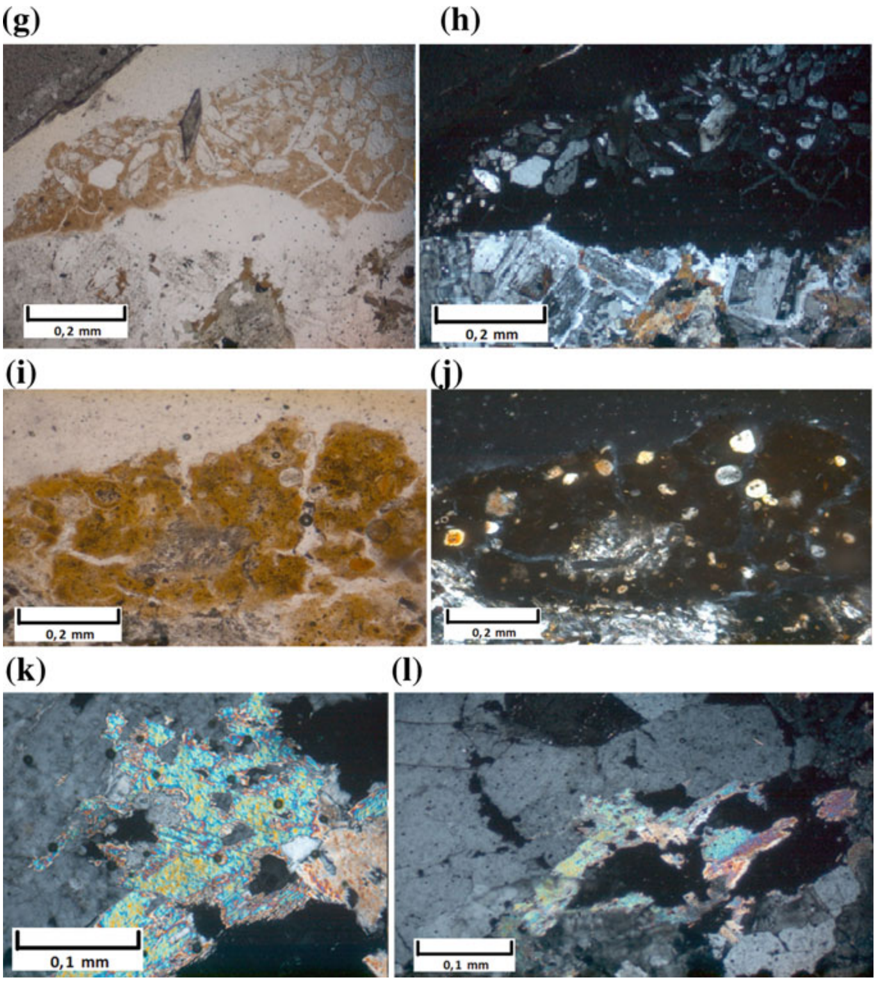


Fig. 26.9 (continued)

the debris material of the coarse-grained parent rocks such as granites and gneisses this process can be obtained (Fig. 26.1). The fine earth accumulation and its further aggregation take place more intensively depending on the degree of the superficial vegetation cover development. Relatively thick organogenic material prevents fine earth material from aeolian redistribution in the environment and additionally helps to accumulate the allochthonous material derived from the surrounding areas that are not covered with vegetation. The process of the fine earth particles' aggregation can also be triggered by the anthropogenic impact in the human-affected soils and soil-like bodies (Fig. 26.2). The intense use of the tracked vehicles physically grind the parent rock debris and provide sufficient amount of the fine earth that could hardly been derived by the regular processes of the physical and biogenic weathering in the

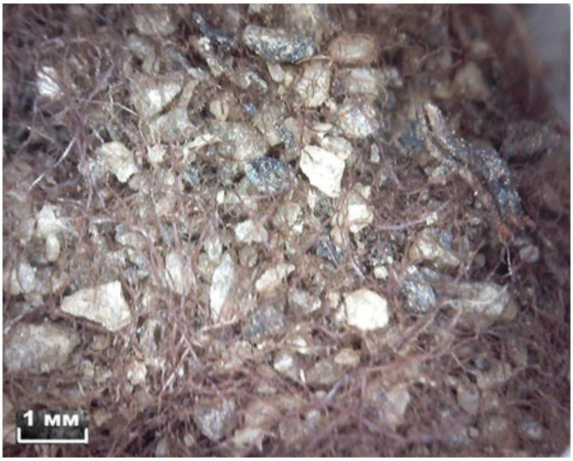


Fig. 26.10 "Molodeznaya" station. Fine earth accumulation in the rhizoidal sphere of the moss pads

Fig. 26.11 "Russkaya" station. Rock-sorted polygons with the vegetation-free central part and moss-lichen cover in the peripheral part

very same environmental conditions. It is well known that the fine earth content in the uppermost horizons of the human-affected soils can reach 30–50% and in the very same soils that are not affected by tracked vehicles its content rarely exceeds 10–15% (Abakumov 2010, O'Neill et al. 2015).

The micromorphological analysis have shown that the basic elements of Antarctic soils' microstructure are coarse-textured debris particles and intrasoil cavities; the most often observed form of the clay distribution in the fine earth material is the diffusive form (Kubiena 1970; Abakumov et al. 2013). This feature is determined by the very low degree of the biochemical weathering of parent rock material due to the relatively low rate of the vegetation colonization of the soil surface. The harsh climatic conditions of the continental Antarctica strongly limit the rock weathering by the nearly only physical factors. The formation of the optically oriented clay, clay-carbonate plasma and features of the carbonate cementation were only obtained in the soils of the interior oases where sedimentary and sedimentary-metamorphic calcareous rocks are distributed (e.g. Schirrmacher and Bunger oases; Figs. 26.3 and 26.5). The neoformations of the relatively thick carbonate films were regular in the uppermost horizons, covering the boulders and gravel. This fact also points at the relatively stable microstructure of the soil material. The evidence of the seasonal dynamics of the hydrothermal regime and thus the carbonates' aggregation can be partly proven by the occurrence of their different morphological forms on the uppermost and lowermost surfaces of the coarse debris' fragments and boulders (Fig. 26.5a and b).

The features of the biogenic-abiogenic interaction of the organogenic and mineral material of soils here (except for the widely expressed and well-described accumulation of the plant detritus within the coarse-textured soil material) is expressed in the forming of the humus plasma coatings and films on the surfaces of the grains of the skeletal fraction which are in the direct interaction with the rhizoidal sphere of the moss pads or with the talloms of lichens or algae-bacterial mats (Fig. 26.6). The relatively low thickness of these coatings can be determined by the environmental factor: the lack of the liquid water during the most of the warm season along with the intense percolation in the coarse-textured material during the snow melting in the early austral summer. On the other hand, the harsh climatic conditions prevent the active accumulation and interaction of the biogenic humus compounds within the material of the parent rock debris.

The very specific type of the organogenic plasma that is formed in the ornithogenic and postornithogenic soils under the modern and abandoned penguin rookeries is the humus-like plasma and it represents another wide-distributed example of organo-mineral interaction in the different environments of Antarctica. It can be accumulated on the surface of the coarse grains in form of the guano and poorly decomposed ornithogenic material (fragments of feathers, eggshells, tissues and bones) as well as in form of organic colloidal plasma (Fig. 26.7). The formation of the biocrusts is also determined here by living and dead remnants of the nitrophilous algae colonies (mainly from *Prasiola crispa*) on the soil surface and stone boulders and gravel. The colonization of the surface by these algae seems not to be lithologically specific. In conditions of nitrogen-enriched substrate, the colonization is quite aggressive and very intensive, which is typical for the initial stages of ecogenetic succession, caused by the high content of easily available nutrients. Fresh organic material is light brown and after desiccation it forms a rubber-like mantle, which covers debris and shields it from removal of fine-earth material by strong winds. The abundance of coarse angular debris fragments increases downward. If the rookery becomes inactive, cryogenic sorting of mineral material begins to move coarse fragments upward to the soil surface burying the organic matter with time. Later, these environments become more appropriate for the colonization by lichens and mosses and the degree of the biogenic-abiogenic interaction intensively grows.

Features of the mesomorphological structure of the soils, sampled in the surroundings of the "Russkaya" station such as accumulation of the fine-earth, organomineral interaction with mosses and lichens, organic films and coatings on the mineral surfaces are presented on the Fig. 26.8. Accumulation of fresh ornithogenic material that is mixed with the mineral particles triggers the formation of primitive aggregates, which is not evident in case if parent rocks' material is not affected by birds. Interaction of lichen thallomes with mineral particles in non-ornithogenic soil is expressed at the mesomorphological level in adhering of the lichens on the skeletal particles, accumulation of organic microlayer on the stone surface, accumulation of organic lichen remnants and their further decomposition on the stone surfaces and organomineral aggregation. Organic horizons of soils that are formed in the vicinity of the "Leningradskaya" station show evident formation of the porous media and free space in topsoil in comparison with almost monolith massive crystallic rock, composed by quartz, mica and feldspars.

26.4.2 Soil Horizons and Profile Organization

Antarctic soil profiles rarely exceed a half-meter depth. They are extremely lithogenic—the percent of gravel and boulders can reach 90–95% in the uppermost horizons and 50–70% in the central and lowermost parts of the soil profile. The coarse fraction/fine earth ratio can be 95–98%/2–5% and insignificantly drops downwards down to 70–80%/20–30% (Abakumov 2010; Lupachev and Abakumov 2013). The soil material under the lichen associations most often lacks aggregation at meso- and microlevel. In the rare cases, the densely mixed lichen thallomes can consolidate the mineral material of the uppermost soil horizons and prevent it from the wind erosion. The soil morphology diagnostics in the pedons under the lichen associations can often be only possible basing on the change of the particle size and the abundance of the ferruginous films and thin fine-earth coatings ("silt cappings") on the coarse mineral particles.

In case of the moss pads growing on the surface of the soils the rhizoidal sphere encases the coarse gravel and boulders and the smaller skeletal particles (< 1 cm) are densely intermixed with the thin rhizoids (Fig. 26.10) and the very specific aggregates ("strings of beads") are forming and may serve as the analogue of the similar structure on the roots of the flowering plants in the circumpolar soils of northern hemisphere. The relatively poor-expressed stripes and microtongues of humus impregnation in the fine earth material can also characterize such soils. The soils under algae-bacterial mats are very often have features of gleyic and stagnic processes. Dark-gray horizons rich with sulphates, bluish gleyic and reddish ferruginous zones and morphones are typical for these soils so the organization of pedon can be obtained relatively clearly. In some cases when soils have significant supply of liquid water and in presence of the ice-cemented permafrost or impermeable rock bed the structure of the genetic horizon can be disturbed by the processes of cryoturbation.

The very special type of the uppermost organogenic soil horizons is the birds' guano that serves as the substrate for the very special type of the plant cover even for Antarctica. The dominance of the nitrophilous algae and bacterial mats and the sporadic occurrence of the vascular plats are regular for the environments of the modern and abandoned penguin rookeries. The well-expressed succession of the plant cover is clearly observed while studying these soils. The degree of the guano toxicity drops with the processes of water leaching and freezing/thawing cycles. During the time the guano deposits become dark-colored and dense thus preventing the uppermost soil horizons from the wind erosion and drying out. The mix of the biogenic and abiogenic material contains plant and animal tissues, feathers, bones, eggshells etc. Contrarily to the majority of the Antarctic soil these ones have maximum fine earth content in the uppermost horizons due to the adhesive properties of the guano material that prevents as well from the intense wind-snow corrasion. Is case of the abandoned rookeries the cryoturbation and rock sorting processes may move the gravel and boulders upwards thus burying the fragments of the former uppermost guano cover. The role of the accumulation and adhesive "consumption" of different size mineral particles is important for soil formation especially in conditions of strong wind and aeolian processes in Antarctica.

The occurrence of the relatively wide distributed spatial continuity of the plant cover (widespread moss pads or lichens) or zoogenic organic material (guano coats) is quite rare in the continental and even in the maritime Antarctica and occur most often in subantarctic environments. Thus the distinguishing of the pedon vertical organization is often complicated due to the highly differing microclimatic and geomorphological conditions even in the scale of micro- and mesorelief here.

26.4.3 Elements of the Soil Cover Structure

Spatial soil cover structure is one of the highest levels of biogenic-abiogenic interaction in the environment in terms of the pedogenic processes development rate. Long-term geological history of glaciation and deglaciation cycles; relatively mild climatic conditions; abundant and diverse fauna and flora; and the dominance of the sedimentary rocks (e.g. in the High Arctic) allowed soils of the northern hemisphere to develop a continuous, dense and thick cover with strong hierarchy of the elements. In opposite, the harsh bioclimatic conditions of Antarctica, rare and specific plant and animal species as well as the unique geological and geomorphological conditions the relatively wide in terms of area soil cover is very rare and poor-expressed here.

The most widespread group of the soil cover elements that is presented in the Antarctic environments is the combination of the highly lithogenic insufficient with liquid water soils under the lichens [including endolithic soil-like bodies (Mergelov et al. 2012)] on the rocky watersheds and relatively steep slopes in the mesorelief structure and the fine earth rich soils well-supplied with liquid water under the moss-lichen associations and algae-bacterial mats on the shallow slopes, local depressions and wind shelters. Soil complexes of the environments are rich with disintegrated debris and form stone pavements, rock circles and polygons, rock stripes etc. Depending on the availability of the liquid water and shelter from harsh winds and snow corrasion, the regular redistribution of the flora species takes place. One of the soil cover structure phenomena here that have to be further investigated in details is the forming of the soil mosaics, which presumably depends on the parent rock genesis (Fig. 26.11).

At the moment, authors develop the approach for the distinguishing of the soil mosaics in the soil cover of the Antarctic oases. This mosaic can possibly be determined by the weathering susceptibility of the parent rocks and its debris, the structure of the vegetation cover, moisture-holding capacity of the fine earth material and other significant soil properties that make pedogenesis possible in the harsh environmental conditions of Antarctic oases.

26.5 Conclusions

Pedogenic processes of transformation and accumulation of organogenic matter and its interaction with the mineral matrix are poor-expressed in the soils in Antarctica and take place most intensively in the soils that are supplied with the liquid water and are sheltered from the harsh winds that allow vegetation to actively colonize the soil surface.

Studied soils and soil-like bodies in Antarctica show the number of diagnostic features (the fine earth adhesion, forming of the organomineral coatings and films, deep alteration of primary minerals, ornithogenic impact of guano etc.) that allow distinguishing biogenic-abiogenic interaction at all the levels of structural organization from elementary soil particles and aggregates up to the spatial structure of the soil cover.

The distinguishing of the pedon vertical organization and spatial structure of the soil cover is often complicated due to the highly differing microclimatic and geomorphological conditions in Antarctica. The degree of macromorphological pedon structure manifestation rises from the continental Antarctica to the Subantarctic regions.

The most widespread groups of the soil cover elements that are presented in the Antarctic environments are the combinations, complexes and mosaics of the water-insufficient and highly lithogenic soils under the poorly expressed vegetation cover and biogenic water-sufficient soils under the relatively well-developed vegetation cover or guano coats occupying different elements of the meso- and microrelief.

Acknowledgements Studies were carried out according to the Russian Federation governmental task 0238-2016-0013 and partly supported by Russian Fund for Basic Researches (18-04-00900a).

References

Abakumov EV (2010) Particle-size distribution in soils of West Antarctica. Eur Soil Sci 43(3):297–304

Abakumov EV, Gagarina EI, Lisitsyna O (2005) Land reclamation in the Kingisepp area of phosphorite mining. Eur Soil Sci 38(6):648–655

Abakumov EV, Gagarina EI, Vlasov DY, Sapega VF (2013) Micromorphological features of the fine earth and skeletal fractions of soils of West Antarctica in the areas of Russian Antarctic stations. Eur Soil Sci 46(12):1219–1229

Beyer L, Bockheim JG, Campbell IB, Claridge GGC (1999) Genesis, properties and sensitivity of Antarctic Gelisols. Antarctic Sci 11:387–398

Birkeland PW (1984) Soils and geomorphology. Oxford University Press, New York

Blume HP, Bolter M (2015) Soils of Wilkes land. In: Bockheim J. (ed) The soils of Antarctica

Bockheim JG (2015) Soils of Victoria Land. In: Bockheim J. (ed) The soils of Antarctica

Bockheim JG, Balks MR, McLeod M (2006) ANTPAS guide for describing, sampling analyzing and classifying soils of the Antarctic region Earth. ANTPAS, UK

Bockheim JG, Tarnocai C (1998) Recognition of cryoturbation for classifying permafrost-affected soils. Geoderma 81:281–293

Bockheim JG, Lupachev AV, Blume HP, Bölter M, Simas FNB, McLeod M (2015) Distribution of soil taxa in Antarctica: a preliminary analysis. Geoderma 245–246:104–111. https://doi.org/10.1016/j.geoderma.2015.01.017

Dolgikh AV, Mergelov NS, Abramov AA, Lupachev AV, Goryachkin SV (2015) Soils of Enderby Land. In: Bockheim J. (ed) The soils of Antarctica

Elias SA, Brigham-Grette J (2013) Late Pleistocene glacial events in Beringia. In: Elias SA, Mock CJ (eds) Encyclopedia of quaternary science, 2nd edn. Elsevier, 2:191–201

Gagarina EI. (2004). Micromorphological method of soil investigation. S-Petersburg. (in Russian)

Gerasimova MI, Kovda IV, Lebedeva MP, Tursina TV (2011) Micromorphological terms: the state of the art in soil microfabric research. Eur. Soil Sci. 44(7):804–817

Kubiena WL (1938) Micropedology. Collegiate press, Ames, Iowa

Kubiena WL (1970) Micromorphological investigations of Antarctic soils. Antarctic J 5(4):105–106

Lebedeva M, Gerasimova M, Golovanov D (2010) Systematization of the topsoil fabrics in soils of the arid lands in northwest of central Asia. World Congress of Soil Science, Soil Solutions for a Changing World (1–6 August 2010). Brisbane, Australia. Published on DVD. 96

Lupachev AV, Abakumov EV (2013) Soils of Marie Byrd Land (West Antarctica). Eur Soil Sci 46(10):994–1006

Lupachev AV, Abakumov EV, Abramov AA, Goryachkin SV (2015) Soils of Marie Byrd Land. In: Bockheim J. (ed) The Soils of Antarctica

Mergelov NS, Goryachkin SV, Shorkunov IG, Zazovskaya EP, Cherkinsky AE (2012) Endolithic pedogenesis and rock varnish on massive crystalline rocks in East Antarctica. Eur Soil Sci 45(10):901–917

Meier L, Krauze P, Prater I, Scholten T, Wagner D, Kühn P, Mueller C (2017) Soil micromorphology, geochemistry and microbiology at two sites on James Ross Island, Maritime Antarctica. In: Geophysical Research Abstracts. vol. 19. EGU 2017-12618-3

Michel RFM, Schaefer CEGR, López-Martínez J, Simas FNB, Haus NW, Serrano E, Bockheim JG (2014) Soils and landforms from Fildes Peninsula and Ardley Island, Maritime Antarctica. Geomorphology 225:76–86. https://doi.org/10.1016/j.geomorph.2014.03.041

O'Neill TA, Aislabie J, Balks MR (2015) Human impacts on soils. In: Bockheim J. (ed) The soils of Antarctica

Rusakov A et al (2018) Late pleistocene paleosols in the extra-glacial regions of Northwestern Eurasia: pedogenesis, post-pedogenic transformation, paleoenvironmental inferences. Quat Int 501(A):174–192.https://doi.org/10.1016/j.quaint.2018.03.020

Soil Survey Staff (2010) Keys to soil taxonomy (11th edit.). U.S. Dep. Agric., Natural Resources Conserv. Serv. Washington, D.C

Smellie JL, Pankhurst RJ, Thomson MRA, Davies RES (1984) The Geology of the South Shetland Islands: VI. Stratigraphy, Geochemistry and Evolution. British Antarctic Survey Scientific Reports 87 (85)

Stoops G (2009) Evaluation of Kubiena's contribution to micropedology. At the Occasion of the Seventieth Anniversary of his book "Micropedology". Eur Soil Sci 42(6):693–698

Verkulitch SR (2009) Conditions and regime of the last deglaciation in the edge zone of Antarctica. Earth Cryosphere 2:73–81 (in Russian)

Verkulitch S, Pushina Z, Tatur A, Dorozhkina M, Sukhomlinov D, Kurbatova L, Mavludov B, Savatyugin L (2012) Holocene changes of environments on the Fildes Peninsula, King-George Island (Western Antarctica). Probl Arctic Antarctic 3(93):17–27 (in Russian)
Zazovskaya EP, Fedorov-Davydov DG, Alekseeva TV, and Dergacheva MI (2015) Soils of Queen Maud Land. In: Bockheim J. (ed) The soils of Antarctica