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GENESIS AND GEOGRAPHY OF SOILS

Endolithic Pedogenesis and Rock Varnish on Massive Crystalline Rocks in East Antarctica

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Abstract—Desert varnish and endolithic organisms are two widespread phenomena that have been studied in detail separately; their interaction and their genetic relationships have virtually escaped the attention of researchers. Both phenomena are of indubitable interest for pedology: endolithic organisms as an agent of soil formation and rock varnish as a probable product of pedogenesis. It is argued that the system of endolithic organisms, their functioning products, and the rock has all the features inherent to soils: the rock layer subjected to the influence of external abiogenic factors and living organisms dwelling in the rock and synthesizing and decomposing organic substances. The action of biogenic and abiogenic agents leads to the in situ transformation of the rock with the accumulation and removal of the products of this transformation and with the development of vertical heterogeneity in the form of microhorizons composing the soil microprofile. Instrumental measurements indicate that the carbon content in the endolithic horizons developed by biota in granitoid rocks of the Larsemann Hills oasis varies from 0.2 to 3.3%, the nitrogen content in these horizons varies from 0.02 to 0.47%, and the radiocarbon age of their organic matter reaches 480 ± 25 yrs. The products of the pedogenesis are represented by fine earth materials and by abundant and often multilayered films and coatings on the rock surface and on the lower sides of the desquamation (spalling) plates. Scanning electron microscopy with X-ray microprobe analysis indicates that the major elements composing these films are O, C, Si, Al, Fe, Ca, Mg, and S. It is shown that the films of the rock varnish and the organomineral films in the fissured zone of the rock under the plate with endolithic communities have certain similarity in their morphology and composition: the films of the rock varnish also contain biota (dead cells or cells in the dormant state), and their botryoidal structure is similar to the structure of the biofilms inside the endolithic system. In both types of films, amorphous aluminum and silicon compounds are present, and the accumulation of Fe, Ca, Mg, S, Cl, and some other elements takes place. It is argued that some varieties of rock varnish are the products of endolithic pedogenesis; in essence, they represent the horizons of micropaleosols exposed to the surface in the course of spalling and then transformed by the external environmental agents.

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INTRODUCTION

In the recent decades, pedologists have recognized that the range of the problems facing pedology is much wider than the study of loose subaerial bio–abiotic bodies on the Earth [17]. Thus, during the recent 19th World Soil Science Congress in Australia, a special symposium on astropedology was organized. Thus, the international soil science community is ready to include in the sphere of pedology new nontraditional bodies such as Lunar, Martian, and other regoliths and other surface formations [18, 51]. Earlier, soil-like bodies [10], or semisols [15], were examined by soil scientists under water [11, 13] and, later, in caves [14].

This paper is also devoted to nontraditional objects of pedology that, however, occur on the Earth surface and are influenced by the "usual" factors of pedogenesis but under highly specific extreme conditions. First and foremost, this concerns the soils of Antarctica, the interest in which among Russian [1–4, 8, 9, 36] and foreign [19, 21] soil scientists has greatly increased in the 21st century. To a large extent, this is explained by the radical improvement of the experimental methods that can be applied to the study of soils with microprofiles, which are widespread in Antarctica. For example, the application of electron microscopy and microprobes has made it possible to perform in-depth studies of the role of biota in mineral weathering [16]. Unfortunately, the lack of these technical possibilities in the past retarded the development of fruitful ideas on the essence of initial pedogenesis [12]. At present, we return to the same problem at a new technical level.

An important and omnipresent feature of the coastal parts of Antarctica devoid of the glacial shield—the Antarctic oases—is the red-brown color of the bedrock surface, which is observed even on the rocks that are not very rich in iron, such as granites, gneisses, enderbites, etc. Another characteristic feature of these surfaces is the dwelling of various organisms (algae, bacteria, micromycetes, and lichens) inside the rock close to its surface. Such endolithic communities in the rock are often invisible from the rock surface. Red, red-brown, and ocherous films, pendants, and crusts on the rock surface can be called desert varnish (this term is traditionally applied to similar formations in arid and semiarid regions). The term rock varnish is also applied to them in a somewhat wider sense (as this phenomenon may occur not only in deserts) [28, 29]. The organisms dwelling in the fissures inside hard rock are called endolithic organisms (endoliths) or, more specifically, cryptoendoliths, as these organisms are developed in the subsurface hollows (fissures) in the rock and are not seen from the surface [32]. Rock varnish and cryptoendoliths are widespread on the Earth. However, their manifestation in most of the regions is masked by the development of higher vegetation and the activity of pedogenetic and weathering processes of another character. Antarctica and, partly, the Arctic, as well as high-mountain and desert regions, are the areas where these masking factors are absent and where surface red-colored varnish films are clearly seen on rock faces and endolithic organisms serve as the initial producers on hard bedrock.

The polygenetic nature of the rock varnish has become better understood with the development of electron microscopy and microanalyses. Varnish films have been analyzed as specific features of arid pedogenesis. The study of endolithic organisms is of particular interest in the context of astrobiology; it can be supposed that life on the planets with unfavorable conditions may "hide" itself inside the rock, as well as in Antarctica and in desert regions of the Earth. However, both phenomena—rock varnish and endolithic organisms—are studied separately; their interaction has escaped the attention of researchers, including pedologists. In our study, we tried to apply the methodology of pedology to investigate the impact of endolithic organisms on the rock and their role in the formation of rock varnish on granite, gneiss, and enderbite rocks sampled in coastal oases of the Larsemann Hills and Molodezhnaya (Thalla Hills) in East Antarctica.

STATE OF THE PROBLEM

Rock varnish. Rock varnish was described by von Humboldt on rock outcrops near Santa Barbara as early as in 1852 (cited from [45]). Later, this phenomenon was described by Darwin [25]. In modern literature, the term rock varnish is applied as a more common term for desert varnish, because this phenomenon can be found far beyond arid regions, under different types of climate, and on different rock surfaces [6, 29]. There are several hypotheses concerning the origin of rock varnish. A predominant hypothesis suggests that the main mechanism of the development of rock varnish is accretion, i.e., the gradual upward growth of varnish films due to the "sticking" (accretion) of particles deposited from the air onto the rock surface [28, 29]. Within the framework of the accretion hypothesis, rock varnish represents an allochthonous formation with a thickness of up to 200 microns (usually, 1–10 μm) having a heterogeneous structure with microhorizons and with abundant inclusions of phyllosilicates [31, 41–43, 47]. In essence, these are sedimentary microlayers glued to the rock surface with Mn, Fe, and Si compounds. The main source of phyllosilicates in the rock varnish is aerial dust. The rate of the accretion in deserts is estimated at several microns per 1000 yrs [29]. The predominant elements in the films of rock varnish are Si and O; oxides of Fe, Mn, Al, Mg, Ti, and other elements also play an important role. The contents of Mn and Fe in the rock varnish may be several times higher than those in the rock [30]. It should be noted, however, that a content of these elements at the level of 0.5–2.0% is sufficient to ensure the ocherous, red brown, or black colors of the varnish. The fact that the Mn content in the films of the rock varnish in desert regions may exceed that in the rock by 50–70 times serves as an argument in favor of the allochthonous accretionary genesis of this phenomenon [28, 29]. According to Dorn [29], the development of rock varnish is described by four conceptual models: the abiotic, the biotic, the polygenetic, and the silica cementation. The abiotic model assumes that clay minerals deposited on the rock surface are bound with Mn and Fe oxides. The biotic model emphasizes the role of lithobiont communities and their residues in the concentration of Mn and Fe and the development of the phyllosilicate structure of the varnish. The polygenetic model includes (a) the initial concentration of Mn and Fe on the rock surface by bacteria, (b) the transformation of the nanoparticles of these elements into the labile form upon moistening, (c) the aerial deposition of phyllosilicate particles, and (d) the inclusion of Mn–Fe–bacterial fragments into the composition of the clay silicates with the cementation of clay particles (similar to the cementation of bricks with cement mortar) [40, 44]. The last model (SiO_2 cementation) emphasizes the role of amorphous silica as a substance that glues clay particles, mineral and organic detritus, and aerosols to the rock surface [45, 46].

In all these models, the autochthonous origin of the rock varnish is considered to be less important or is completely rejected. In foreign literature, the hypothesis of the in situ origin of rock varnish is rarely discussed. From our point of view, this hypothesis deserves more attention. In the pioneering work of Glazovskaya [7] devoted to desquamation (spalling) crusts (plates) in oases of East Antarctica, iron films and coatings are considered to be the result of the in situ rock weathering with the migration of Fe from the zone of active weathering to the rock surface at very small (up to several millimeters) distances. These formations were attributed by Glazovskaya [7] to desert varnish and, later, to rock varnish [6]. Similar ideas on the genesis of iron-rich films and crusts on rock faces in Antarctica were expressed by Campbell and Claridge [22]. However, these authors stressed that such formations differ from the classical desert varnish and that their development is best described by the term staining (including coloring, etching of the surface, and the development of spotty patterns). Friedmann and Weed [34] supported the accretionary hypothesis of the genesis of rock varnish in Antarctic oases and argued that the development of rock varnish is an important prerequisite for the stabilization of the rock surface with further colonization of the rock by endolithic organisms.

If we consider all these hypotheses about rock varnish, we can see that several types of surface films are very similar to varnish in their morphochromatic characteristics, though they cannot be attributed to rock varnish proper. These are (1) Fe films composed of iron (hydro)oxides without silicate admixtures, (2) Ca–Si–oxalate crusts developed directly under or near epilithic lichens, (3) organic films under/near lithobiont communities, and (4) films of amorphous silica with possible participation of Al or so-called silica glaze [28, 29 (with modification)]. This list can be complemented with morphologically different formations that are often found together with the considered films: (1) N-, S-, and Cl-containing salt sinters and crusts; (2) calcareous coatings and sinters; and (3) silty microsediments.

Thus, the questions to be answered can be formulated as follows: What is the origin of red-brown films, sinters, crusts, and other formations that are seen on the rock surfaces in Antarctica? Do they represent allochthonous material glued to the rock surface? Do they represent an autochthonous product of the rock weathering (and, probably, pedogenesis)? Should they be considered complex polygenetic accretionary–autochthonous formations? Can they be considered the results of quite different processes leading to similar morphological features? Can they all be attributed to the category of rock varnish?

Endolithic organisms. The existence of organisms in the subsurface layer of hard rocks was noted by the founder of micropaleontology C. Ehrenberg. Their possible role in the biochemical weathering and spalling processes in Antarctica was described by Glazovskaya [7]. The concept of endolithic organisms was suggested by Friedmann [32, 33], who also suggested the term endoliths and subdivided these organisms into crypto-, chasmo-, and euendoliths differing in the patterns of their colonization of the rock interior (through fissures, structural cavities, and drilled tunnels, respectively). As well as rock varnish, cryptoendoliths (microscopic algae) were first described in arid environments of the Sinai and Negev deserts [35]. Endoliths are very widespread organism; they are important primary produces in Antarctic oases, and they are pioneering organisms and agents of pedogenesis (to which little attention is paid beyond the areas with extreme environmental conditions). Penetrating into the rock along the initial fissures and channels, cryptoendoliths make these fissures wider and gradually form and colonize new hollows appearing due to the mechanisms of physical disintegration (in particular, the cryogenic disintegration under the impact of freezing–thawing of the water-containing biomass) and biochemical weathering. It is not quite clear whether endolithic organisms represent true lithotrophs, i.e., whether they utilize mineral components for biosynthesis and/or they only affect the rock via their exudates (predominantly, organic acids). It is probable that both mechanisms can take place. It is important that endolithic organisms (cyanobacteria, green algae, and photobiont components of lichens) play the crucial role in the rock destruction and serve as the only primary producers in the surface (subsurface) ecosystem developing in the hard rock. The organic matter synthesized by the endolithic producers is then decomposed by endolithic heterotrophs (micromycetes and bacteria); thus, it becomes an important biogenic component of the subsurface rock layer. The formation of the primary organic matter proceeds mainly at the expense of photosynthesis, because the rock (granitoid) contains translucent grains of quartz and some feldspars [32]. Light also penetrates inside the rock through microfissures [26]. However, it should be noted that the presence of green biofilms that clearly indicate the development of endolithic organisms in the rock is not necessarily associated with the ongoing photosynthesis. Chlorophyll can also be formed in shaded parts of the rock, because this pigment evolutionarily appeared even before cyanobacteria started using it for photosynthesis [48]. In such green-colored parts of the rock, the presence of chemolithotrophic endolithic organisms is also possible.

The vital activity of endolithic organisms often enhances the spalling processes, i.e., the exfoliation of the surface layers of hard rocks under the impact of abiotic (primarily, sharp temperature fluctuations) and biotic (including endolithic organisms) factors. Spalling is developed along the lines of weakened bonds between rock minerals or along the lines of the maximum shear stress. The platy or shell-like fragments separating from the major rock bodies are called spalling (desquamation) plates. Their thickness may vary from several millimeters to centimeters. Partial spalling describes the situation when such plates remain bound to the rock mass; complete spalling means that the plates are removed from the rock via gravitational mechanisms or via wind erosion. Spalling is a highly active process in Antarctica and other high-latitude regions, as well as in deserts and in high mountains.

OBJECTS AND METHODS

We studied multicomponent formations at the bedrock surfaces, including (1) the spalling plates with endolithic communities on the bottom sides and rock

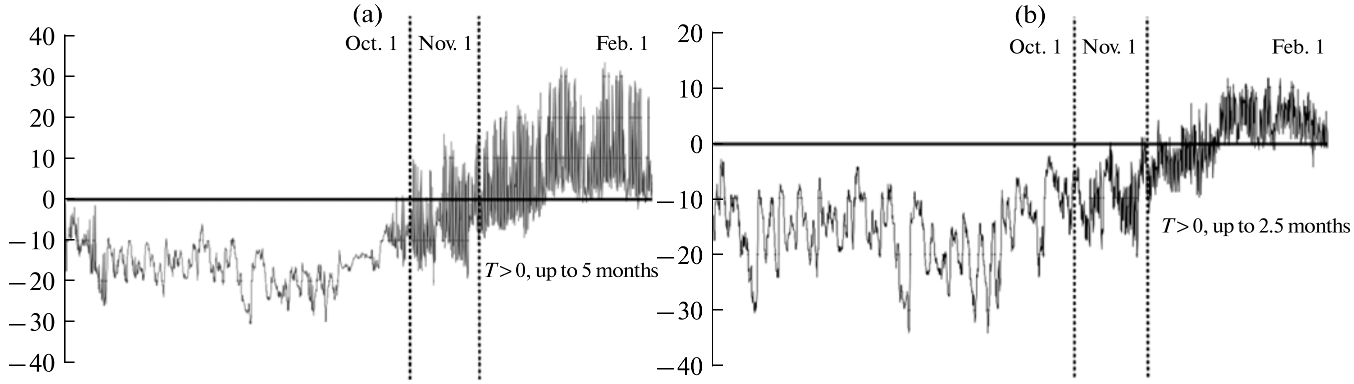

Fig. 1. Temperature (°C) of the granitoid rock surface at the depth of 0.5–1.0 cm in the Larsemann Hills: (a) the warm (northern) aspect and (b) the cold (southern) aspect.

varnish on the upper sides, (2) the mineral fine earth and biomass of the endolithic organisms from the system of fissures immediately under such plates, and (3) the rock surfaces under the plates and under the fine earth microlayer with endolithic organisms. As there are no definite terms for these objects, we suggest that these three components can be referred to as an endolithic system. The composition and morphology of this system resemble the soil system; therefore, a preliminary term—endolithic soils—was also suggested [8]. This suggestion was more thoroughly examined in the course of our study. The samples of endolithic systems were collected from the exposed bedrock surfaces in coastal oases of East Antarctica: the Larsemann Hills (69°20′ S, 76°20′ E) and the Molodezhnyi (67°40′ S, 45°20′ E). In both cases, the bedrock was represented by granitoid formations with granites and granite gneisses (consisting of feldspars, quartz, garnet, and biotite) in the Larsemann Hills and with enderbites (feldspars, quartz, hypersthene, diopside, amphiboles (hornblende), and biotite) in the Molodezhnyi oasis.

The morphology of the samples was studied under a Leica MZ6 microscope with a digital camera and under a scanning electron microscope (JSM-6610LV) with an X-ray microanalyzer (Oxford Instruments) making it possible to determine the elemental composition of the examined substrate. The carbon and nitrogen contents in the fine earth were determined by the dry combustion method using a Vario ELIII analyzer; the radiocarbon age of the organic matter, by accelerator mass spectrometry (AMS) using a 1.5SDH-1 Pelletron AMS device; and the temperature regime of the endolithic systems, with iButton Thermochron loggers.

RESULTS AND DISCUSSION

Environmental conditions. The climate of the oases is cold; the mean temperature of the warmest month (January) in the Larsemann Hills oasis is +0.6°C, and the mean temperature of the coldest month (August) is −15.9°C. In the Molodezhnyi oasis, the corresponding values are −0.7 and −18.8°C, respectively. According to their temperature parameters, the parts of hard bedrock with endolithic communities occur under relatively favorable (for Antarctica) conditions (Fig. 1). Their considerable warming under the insolation of dark surfaces with rusty to reddish brown color owing to the presence of rock varnish takes place. The most developed endolithic communities are usually found on the warm (in the Southern hemisphere) north-facing slopes. Under such conditions, the period of the rock temperatures above 0°C reaches 4.5 months, including two months with temperatures of about 20–30°C. On the rocky slopes of southern aspect, the temperature conditions are colder and are approximately the same as the temperature conditions in the gravelly fine earth soils developing in the bottoms and on the slopes of the local valleys: the period with $T > 0$°C lasts up to 2.5 months, and the surface soil (rock) temperature is about 10°C for 1.5 months.

Thus, the duration of the period with positive temperatures on the rock surfaces with well-developed endolithic communities is 1.8–2.0 times greater, and the absolute summer (day) temperatures are two—three times higher than those on other surfaces in the oases.

The availability of moisture for the endolithic communities on the rock faces is limited; in fact, this is also true for most of the inhabitants in the oases. This is related to the absence of liquid precipitation. The falling snow (200–300 mm in water equivalent) is rapidly redistributed by the wind to accumulate in snow patches; the larger part of the surface remains devoid of snow. On the rock surfaces, water appears due to melting of the snow accumulated in small cavities and fissures. Such potential sources of water are unstable. Snow may be blown out from them or it may disappear under the impact of sublimation without producing water. An additional source of water supply of the endolithic communities may be related to their own capacity to absorb water from the air and to store it "inside." The highly uneven moistening is one of the factors specifying the uneven distribution pattern of the endolithic biota in the rock.

Distribution of desert varnish. The uneven covering of the surface by the red brown and rusty pigment is a characteristic feature of barren rock faces. This unevenness does not display any regularities related to the slope aspect at the level of the mesorelief and at the level of separate rock boulders. On the rocks of similar composition, the varnish films have an uneven microblocky heterogeneous structure represented by alternating red brown, pale brown, or gray brown spots with characteristic sizes of $n \times 10^0$–$n \times 10^2$ cm^2. The analysis of the surface microtopography shows that the chromatic heterogeneity is usually related to the spalling process. In agreement with the accretionary hypothesis of the rock varnish (if we consider that it is represented by the dark red brown films), the microelevations on the rock surface should have thicker red films, whereas the films on the surfaces recently subjected to spalling should have lighter colors. However, this regularity is observed in about 60–70% of the cases, whereas the opposite regularity is observed in 30–40% of the cases studied on the granitoid rocks in the Larsemann Hills (the recent spalling exposes to the surface dark brown rock faces). The color of the rock varnish definitely depends on the lithogenic factor. Thus, the separate intrusions, the areas affected by the paleohydrothermal processes, and the areas with the outcrops of rocks enriched in weatherable iron-bearing silicates (e.g., biotite) usually have brighter red and, sometimes, even bluish black tints, and their surface films are usually thicker than those on iron-depleted rocks.

Macro- and mesomorphology of endolithic systems. The macrostructure of the endolithic system in its native state and its schematic representation are shown in Fig. 2. After the removal of the spalling plate with a thickness of 0.5–1.0 cm covered with rock varnish (Fig. 2a), a community of endolithic organisms with the active participation of green and blue-green algae, dead biomass, and fine earth of the coarse silty and fine sandy fractions is exposed to the surface (Fig. 2b). The fine earth material partly penetrates into the deeper rock zone along vertical fissures (Fig. 2c). Note that we only analyzed spalling plates having no fissures at the surface so that the aerial input of the fine earth into the rock interior could be excluded. The endolithic biota and the fine earth material compose a specific horizon of active weathering and, probably, pedogenesis (Fig. 2b). The thickness of such horizons may reach 0.2–1.2 cm. The living and inert biomass of endolithic organisms penetrates into the rock to a distance of several millimeters. In this zone, the mineral grains are covered by visible thin films. The components of living and inert organic matter may participate in the chemical weathering of the silicates and in the physical disintegration and biogenic/cryogenic structuring of the weathered mineral mass. These functions of the endolithic organomineral horizon make it similar to the "classical" surface organic horizons of soils.

The major elements of the endolithic system differ in their colors: the rock varnish on the surface of the spalling plates has colors within the range from YR 6(5)/4 to 7.5YR 6(5)/4, whereas the major mass of the rock and the rock surface devoid of varnish films are much lighter (7.5YR 7/2–10YR 7(8)/2(3)). The fine earth, rock fragments, and rock plates covered by the communities of endolithic organisms are differently colored. Their (yellow) green tint (5G 7/4–5Y 5(6)/2(4)) is observed in the loci enriched in chlorophyll-containing organisms, and their brown tints (5YR 5/6(8)) may be associated either with other pigments of autotrophic organisms or with newly formed Fe-(hydr)oxides. The color of the fine earth without organic substances is close to the color of the main mass of the rock or is somewhat darker because of the presence of the films of F-(hydr)oxides.

Mesomorphological studies (Fig. 3) indicate that the outer surface of the spalling plates with rock varnish (Fig. 3a) bears clear indications of weathering processes in the form of separate caverns, etched faces, and fissures; it is often covered by virtually transparent films with greasy luster.

Despite the visibly homogenous character of the reddish brown varnish film, it is clearly seen at the mesomorphological level that Fe pigments are concentrated in loci of 0.1–1.0 mm in size. The rock surface inside the endolithic system (Fig. 3c) also contains clear features of weathering; the bonds between the mineral grains are relatively loose, and they can be easily separated from one another. The mineral grains are covered by thin light green biofilms of autotrophic organisms. The fine earth in the fissure zone (Fig. 3b) consists of the fine sand fraction with a considerable admixture of coarse silt and a small admixture of clay particles. Sand and silt particles are also often covered by light green biofilms and, sporadically, by reddish brown iron-bearing films.

Submicromorphology of the endolithic system with elements of the X-ray spectral microprobe analysis. The films of rock varnish on the outer faces of spalling plates (Figs. 4a, 4c, 5a, and 5b) represent Fe–Al–Si–C-containing amorphous formations 1–20 μm in thickness that are subjected to disintegration under the impact of an electron beam. They also contain other elements such as K, Na, Mg, Ca, S, and Cl. The Fe content may be less than 1%, though this amount is sufficient to ensure the red brown color of the varnish film. Varnish films covering spalling plates mask the grains of feldspars, quartz, garnet, biotite, and hornblende in the rock upon their observation under the scanning electron microscope, though some parts of such films are semitransparent or even invisible upon the macro- and mesomorphological study. Figure 5b displays a varnish film 10–15 μm in thickness and

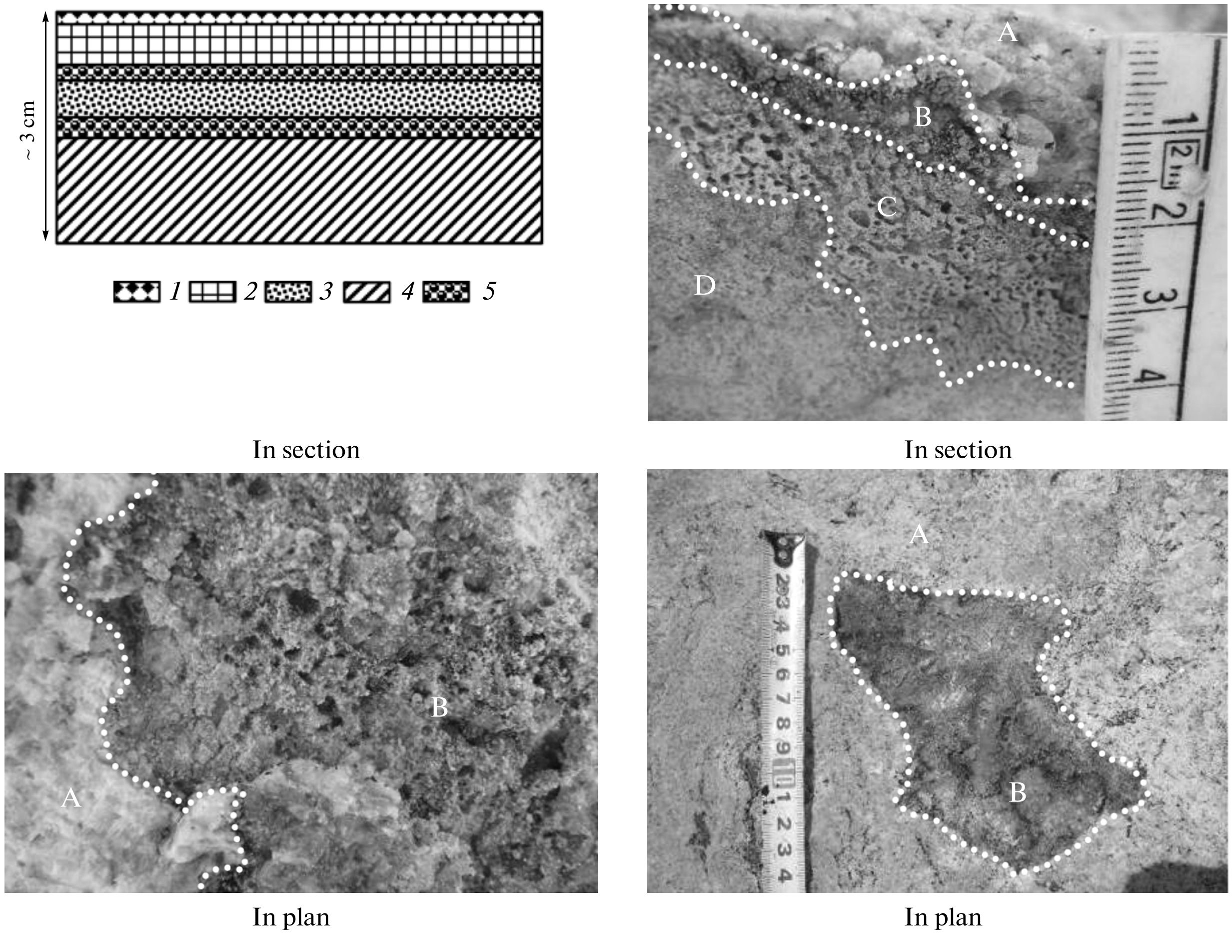

Fig. 2. Endolithic system on the north-facing surface of granite rock in the Larsemann Hills oasis: (A) the granite surface with the rock varnish; (B) the endolithic organisms and mineral fine earth under the spalling plate (the plate 0.5 cm in thickness was removed); (C) the coarse silty fine earth in a vertical fissure; and (D) the major rock mass under the endolithic community: (*1*) varnish film, (*2*) spalling plate, (*3*) mineral fine earth and endolithic organisms (organomineral horizon), (*4*) massive rock, and (*5*) endolithic organisms and organomineral films.

enriched in organic compounds (up to 60% C). Numerous cells are incorporated into the amorphous Fe–Al–Si–C-containing mass creating a botryoidal structure. These particular amorphous compounds (presumably, amorphous silica (opal)) are responsible for the greasy luster of the surface of the spalling plates clearly seen upon macro- and mesomorphological investigations.

The appearance of fissures in the films under the impact of an electron beam (Figs. 4c and 5a) is a common phenomenon for the studied samples attesting to the relatively weak bonds between the film proper and the underlying rock. This circumstance can be considered an argument in favor of the sedimentary hypothesis of the genesis of varnish films rather than the hypothesis of their appearance during in situ weathering. However, the sedimentation in this case does not necessarily mean the allochthonous or accretionary nature of the sediments. Varnish films may be the result of local redistribution (illuviation) of the products of weathering in the endolithic system before the spalling event. To test this hypothesis, we should answer two questions: (1) Are there sources of the components of the Fe–Al–Si–C films inside the endolithic system? (2) Are there films analogous to those described as rock varnish on the surface of spalling plates under the endolithic community?

Figure 4b shows the lower part of a spalling plate immediately under an endolithic community. We can see a clear surface of potassium feldspar with large cells of yeasts (as can be judged from their morphology) attached to it and elongated streaks composed of the amorphous Fe–Al–Si–C-containing weathering products. The elongated shape of such streaks may be related to the gravitational outflow of weathering products of the feldspars from their surfaces (analogous to a stalactite structure). Figures 5c and 5d show the lower side of the spalling plate (or the "ceiling" of the endolithic community hidden under it) with a continuous cover of the colonies of microorganisms and amorphous mineral formations. This biofilm masks mineral grains, and it has a typical botryoidal

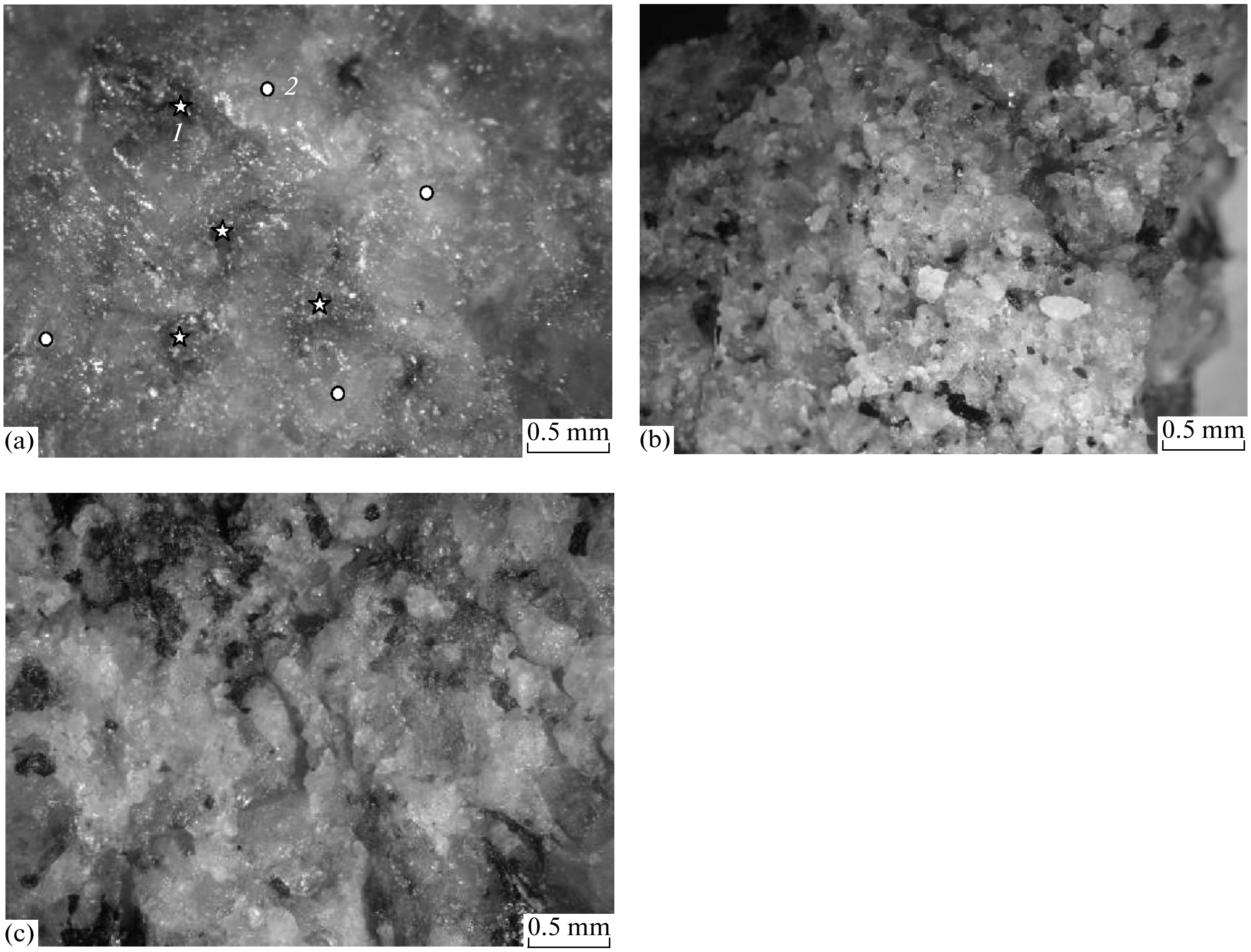

Fig. 3. Mesomorphology of the endolithic system on the north-facing surface of granite rock in the Larsemann Hills oasis: (a) granite surface with rock varnish (*1*—ferrugination loci and *2*—SiO_2 films with greasy luster), (b) fine earth and endolithic organisms under a spalling plate, and (c) weathered rock surface under the endolithic community.

structure. At the level of mesomorphological observations, such films correspond to light green coatings composed of colonies of unicellular algae.

The surface of the main rock mass under the spalling plate and endolithic community (Figs. 4d and 5f) is the zone of accumulation of the products of weathering and pedogenesis illuviated from the upper layer and retained on the mechanical barrier. This zone also contains biofilms of living organisms, though their major amount is attached to the "ceiling" of the endolithic system, which is better lighted because of the absence of shading by the fine earth. The thick film seen in the upper left corner of Fig. 5f is bordered by the vertical chip across quartz and feldspar grains along the fissure in the upper right corner. The contrast between the clear mineral surface devoid of the film and the "laminated" mineral surface is clearly seen, though these elements are found in different planes. The film is a polycomponent formation; it contains little iron and is represented by the Al–Si–C-containing amorphous mass binding biogenic cells and silt- and clay-sized silicate particles. In the bottom right segment, we can see the film covering the quartz–feldspar mineral support; this is the part of the natural fissure that appeared before the preparation of the sample. In the bottom left segment, we see a large feldspar grain and silty silicate particles. The latter have an in situ rather than an eolian genesis because the spalling fissure was closed from the surface in the native state. The fine earth accumulating in the fissure under the spalling plate (Fig. 5e) has a silt size. Some part of the silt fraction is bound with Al–Si–C-containing amorphous products of weathering and is included in the composition of the organomineral films.

Thus, the submicroscopic investigation demonstrated that the organomineral films and the silty fraction of the fine earth are the major products of weathering and pedogenesis in the endolithic system. The endolithic films and varnish films on the surface have similar morphologies and compositions, which makes it possible to suppose a tight genetic relationship

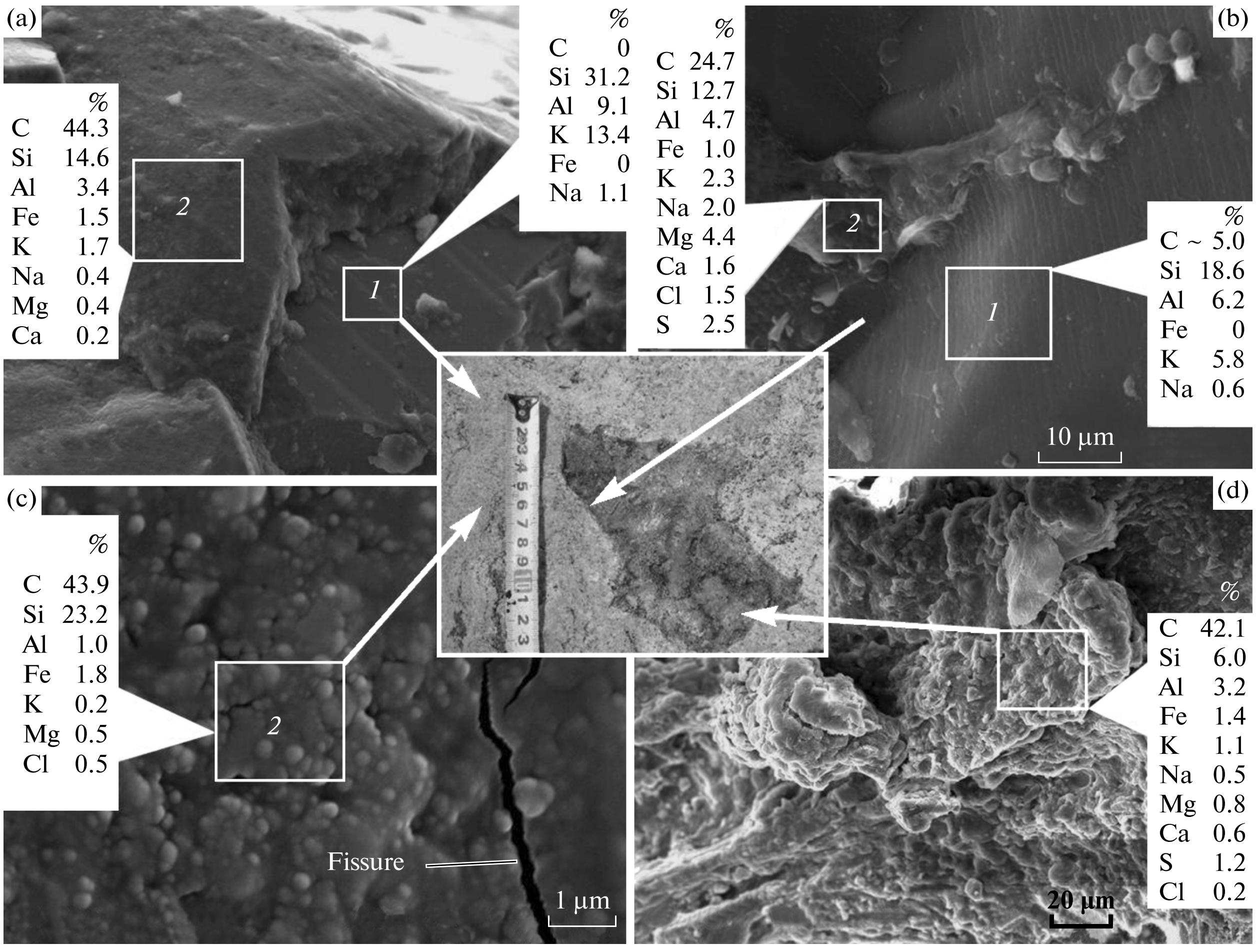

Fig. 4. Morphology and elemental composition of rock varnish films and endolithic biofilms: (a, c) surface of the spalling plate (*1*—clean surface of the K–Na feldspar and *2*—organomineral varnish film), (b) lower internal face of the spalling plate with endolithic biota (*1*—clean surface of the K feldspar and *2*—organomineral sinter (product of pedogenesis in the locus of biota attached to the feldspar)), and (d) surface of the main rock covered by the organomineral film under the spalling plate and the endolithic community.

between them. Besides the films and the fine earth, there are also other features of mineral alteration attesting to the ongoing weathering and pedogenetic processes. Thus, in Fig. 6, we can see the features of the transformation of feldspar grains via their complete dissolution (the cavern shown in Fig. 6a) and etching (Fig. 6b). The etching of the surface is also typical of quartz grains (Fig. 5c). Biotite is locally transformed into hydromica as indicated by the light-colored uneven edges of the biotite flakes (Fig. 6d).

We can conclude that the functioning of the endolithic communities leads to the transformation of the initial lithomatrix, and the products of this transformation are arranged in the form of separate microhorizons (films or etching surfaces). This points to the soil-like arrangement of the endolithic system. In order to identify the qualitative changes in the composition of the rock and the differences between the separate microhorizons, it is insufficient to perform point measurements of the elemental composition of separate loci. Numerous measurements, including measurements within certain larger areas with further systematization of the factual data, are necessary to characterize the filmlike microhorizons.

Elemental composition of the microhorizons in the endolithic system. The microprobe X-ray spectral analysis of the particular elements of endolithic systems makes it possible to distinguish between clean and laminated (covered by films) loci, because they have different morphologies as seen from the obtained photos. Thus, we can determine the differences in the elemental compositions of the clean surfaces of the rock-composing minerals (feldspars, quartz, biotite, hornblende, and garnet) and the laminated mineral surfaces. The latter can be subdivided into two morphological groups: varnish films and biofilms in the interior of the endolithic system. The microprobe was also applied to study the elemental composition of the surface of the fine earth particles in the samples, where we were sure of the autochthonous genesis of the material.

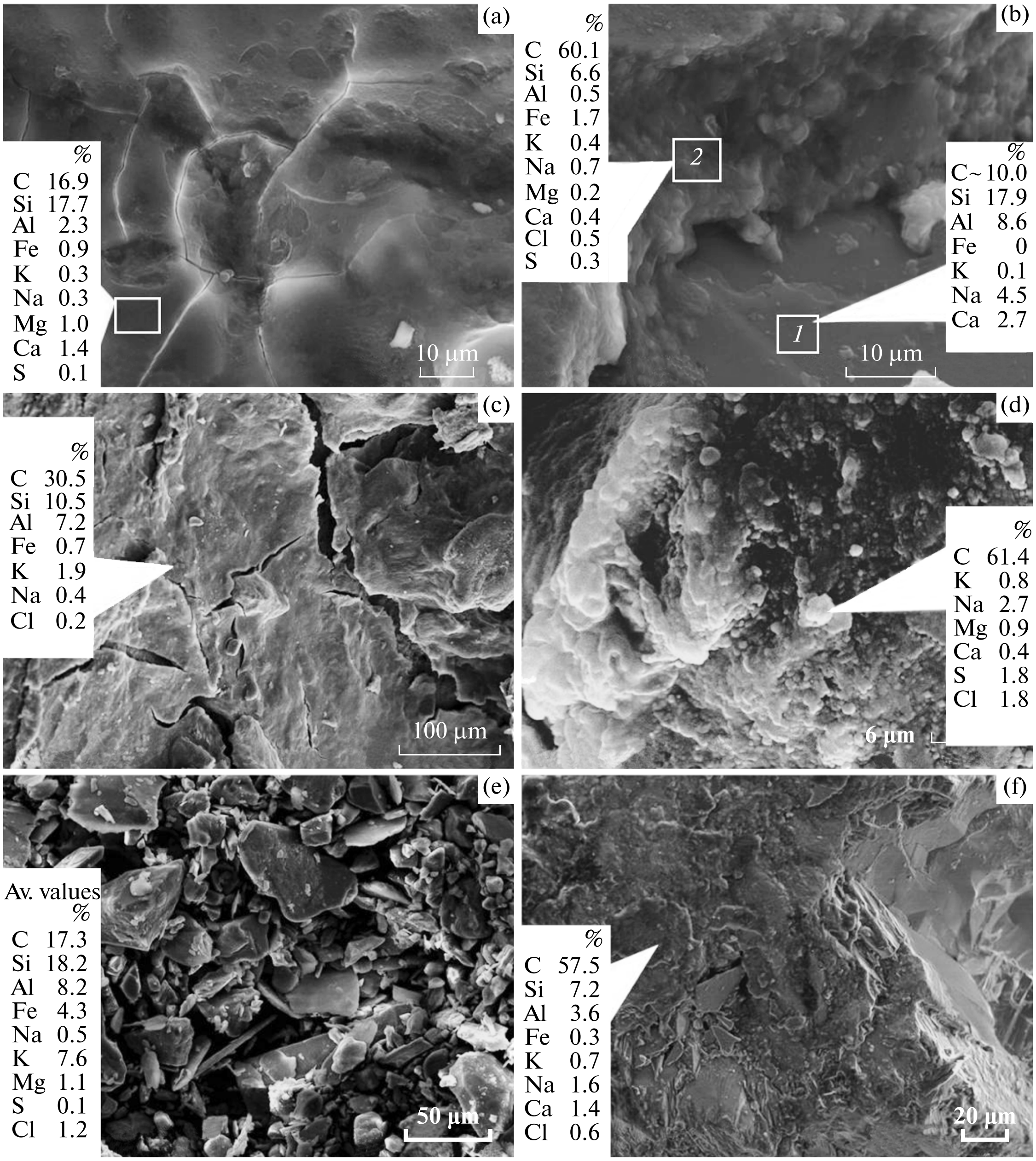

Fig. 5. Morphology and elemental composition of the rock varnish films, endolithic biofilms, fine earth, and the rock: (a, b) surface of the spalling plate (*1*—clean surface of the K–Na feldspar and *2*—organomineral varnish film), (c, d) lower internal side of the spalling plate with endolithic biota, (e) fine earth from the fissure under the spalling plate, and (f) surface of the main rock covered with an organomineral film under the spalling plate.

Thus, we determined the elemental composition in all the major components of the endolithic system. Overall, 135 point and area measurements were made. The Data on each of the studied endolithic systems were averaged for their particular components (Table 1). Because of certain limitations of the method, these data reflect qualitative rather than quantitative differences. The major elements (in their mass portion) in the rock and in the films are oxygen, silicon, and aluminum. The mass portion of oxygen in the rock is about 50–65%; in the films, it decreases to 15–60%. This is explained by the appearance of new elements and, hence, a decrease in the relative content of oxygen, as well as by changes in the composition of the oxygen-containing substances with a decrease in the portion of oxides. We suppose that the representation of the experimental data in the mass percent of the elements (and not their oxides) is more adequate in this case.

In all the films, the major role is played by Si and Al compounds and by C. As follows from the morpholog-

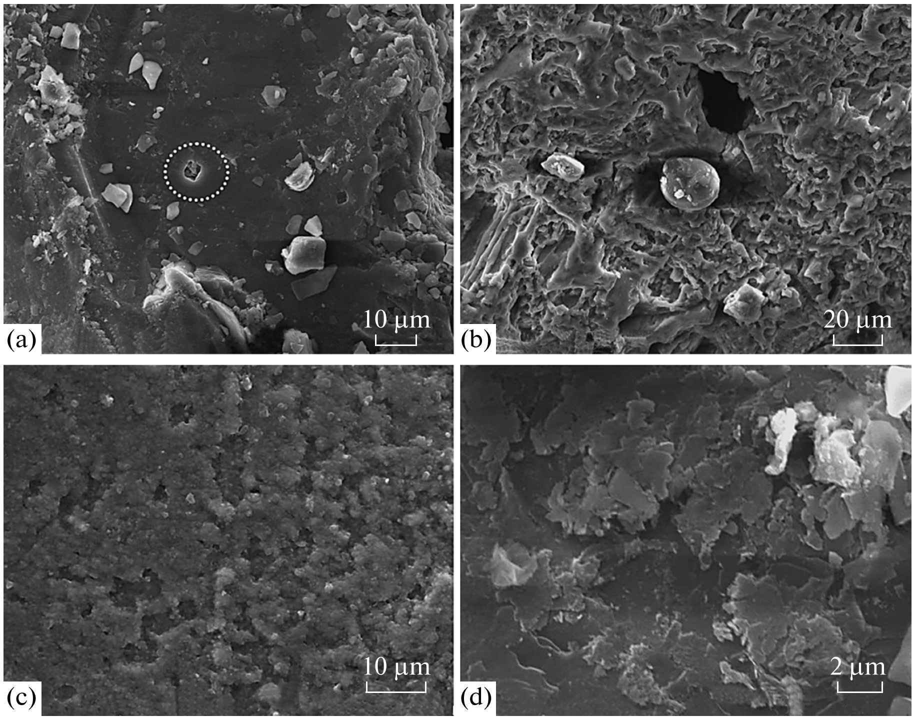

Fig. 6. Weathering of (a, b) feldspars, (c) quartz, and (d) biotite in the endolithic system.

ical analysis of the films, Si and Al compounds are present in them in the predominantly amorphous forms, including silica. The elemental composition of the films differs from the elemental composition of the rock (Fig. 7) in the following way: (1) the films are depleted of Si, Al, Na, and K; (2) the films are enriched in Mg, Ca, S, Cl, and Fe; and (3) the films have a high content of C and, sometimes, N.

Note that Mn is absent in the studied rock varnish films, though this element is considered to be typical of them. In fact, Mn-free rock varnish is a widespread phenomenon in Antarctica, though some exceptions are known [30]. The absence of Mn is an additional argument in favor of the autochthonous hypothesis of the genesis of the studied rock varnish. The high concentrations of Mn in the varnish films (by many times exceeding the Mn concentration in the rock) point to the allochthonous genesis of the varnish via the accretion of mineral particles deposited from the air. Magnesium has been detected in most of the studied films. Its content in the endolithic biofilms is often higher than that in the rock, whereas its content in the surface varnish film is lower than that in the rock (Fig. 7). It is probable that the Mg in the endolithic biofilm is included in the composition of relatively unstable chlorophyll. The averaged data attest to the accumulation of Fe in the endolithic biofilms and rock varnish films, though there is no definite regularity in the distribution of this element in each particular case (Table 1). This is related to the uneven distribution of Fe with its concentration in separate loci. The comparison of the data on the morphology of the films and on their elemental composition confirms that the Fe content reaching the first decimals of a percent in the upper micron of the film is sufficient to ensure the reddish brown color of the surface. Some loci of rock varnish and endolithic biofilms may be completely devoid of Fe and, at the same time, preserve their reddish brown color owing to the light reflected from the Fe-containing loci and spreading in the translucent amorphous silicate mass. The contents of Fe in the rock varnish and in the endolithic biofilms are notably different. This may be partly explained by the relative increase in the Fe concentration in the rock varnish owing to the decomposition of organic components of the biofilms after their exposure to the surface. Another factor favoring the accumulation of Fe in the surface rock varnish films is the continuing weathering of the primary minerals in the rock with the migration of Fe along the network of microfissures toward the oxidation barrier on the rock surface.

The presence of S and Cl in the rock varnish may be related to the phenomenon of salt impulverization (the eolian transport of sea drops) in the coastal oases. In the open endolithic systems, direct aerial deposition of these elements in the form of salts is possible; in the "sealed" endolithic systems (which were the main object of our study), these elements may migrate with solutions infiltrating through microfissures during rare events of moistening of the rock surface. Some part of the Na, K, Ca, and Mg in the films may also be of marine origin.

Table 1. Distribution of elements by different components of the endolithic system (average values; the number of analyzed samples is given for every component)

Object	Si	Ti	Al	Fe	Mg	Ca	Na	K	S	Cl	C	N	O	Al/Si	Fe/Si
	Profile 1. The Larsemann Hills, granite														
Varnish film ($n = 12$)	13.38	0.00	2.98	1.08	0.84	0.29	0.75	1.96	1.73	0.41	40.62	20.24	15.72	0.22	0.08
Clean mineral surface ($n = 9$)	22.09	2.16	8.34	2.93	0.92	1.03	2.19	6.44	0.00	0.26	0.00	0.00	53.64	0.38	0.13
Silt fine earth particle ($n = 11$)	18.22	1.48	8.24	4.31	1.06	0.00	0.50	7.59	0.10	1.17	17.26	0.00	40.07	0.45	0.24
Endolithic biofilm ($n = 8$)	2.27	0.00	0.68	2.31	0.33	2.24	0.59	3.65	3.17	6.19	33.58	27.92	17.09	0.30	1.02
	Profile 2. The Larsemann Hills, granite														
Varnish film ($n = 15$)	8.95	0.01	2.94	2.90	0.09	1.02	1.52	0.46	0.11	0.51	51.99	0.00	29.50	0.33	0.32
Clean mineral surface ($n = 12$)	16.28	0.23	6.97	1.74	0.37	1.52	2.72	2.81	0.00	0.03	9.07	0.00	58.27	0.43	0.11
Endolithic biofilm ($n = 14$)	6.45	0.00	3.47	1.57	0.60	1.01	1.73	2.02	1.44	2.28	41.27	0.00	38.18	0.54	0.24
	Profile 3. The Larsemann Hills, granite														
Varnish film ($n = 8$)	8.3	0.00	2.7	16.6	0.0	1.1	1.1	2.7	0.3	0.6	33.5	0.00	33.10	0.33	2.01
Clean mineral surface ($n = 8$)	28.2	0.00	8.9	2.9	0.1	1.4	2.2	4.6	0.0	0.0	0.0	0.00	51.67	0.32	0.10
Endolithic biofilm ($n = 10$)	5.9	0.00	3.2	1.2	0.8	0.4	0.5	1.2	0.9	0.2	41.0	0.00	44.76	0.54	0.20
	Profile 4. The Molodezhnyi oasis, enderbite														
Varnish film ($n = 11$)	20.69	0.00	2.54	0.63	0.78	0.37	0.93	0.61	0.15	0.24	11.15	0.00	61.92	0.12	0.03
Clean mineral surface ($n = 7$)	18.92	0.00	6.22	0.25	0.00	0.27	2.99	5.88	0.19	0.00	2.17	0.00	63.10	0.33	0.01
Endolithic biofilm ($n = 10$)	7.52	0.00	3.09	0.44	1.87	0.87	1.94	1.27	1.95	0.61	35.54	0.00	44.88	0.41	0.06

The results of the submicromorphological investigations and X-ray microprobe analyses point to three important circumstances: (1) the films of rock varnish on the surface of the rocks may contain dead or dormant biota; (2) the morphology of these films, including their botryoidal structure, is similar to the morphology and composition of the biofilms inside the endolithic system; and (3) both types of films contain considerable amounts of amorphous Al and Si. Therefore, we may suppose that the biofilms in the rock interior and on the rock surface are genetically interrelated. The botryoidal structure of the surface films may be created by epilithic microorganisms, including lichens [23], or microcolonial fungi (MCF) [49], though the structural patterns created by them are somewhat different from the patterns observed by us, in which the cells of microorganisms are plunged into the Al–Si amorphous mass. A question arises: How can the cells be "built into" the in situ forming or accretionary rock varnish? Such an integration of organic and mineral components can hardly be achieved on the rock surface subjected to the action of strong katabatic winds; it is much more probable in the closed or partly closed volume of the endolithic system. In other words, the films of modern rock varnish may be the products of weathering and pedogenesis inside the endolithic system that were later exposed to the surface and partly transformed by the external agents. From the pedological point of view, such type of rock varnish is an in situ endolithic formation exposed to the surface, or the horizon of a surface micropaleosol. Indeed, such a horizon could hardly be formed on the surface under the severe conditions of the Antarctic climate, though it could be formed under the more favorable conditions of the endolithic system inside a rock. A soil horizon developing in a desert oasis may be considered an analogy. After the disappearance of the oasis (e.g., upon the lowering of the groundwater level), such a horizon appears on the surface in the arid desert, though its morphology preserves the "memory" about the former oasis conditions. It should be noted that amorphous compounds of Si and, probably, Al are the main components of both the endolithic organomineral films and the sur-

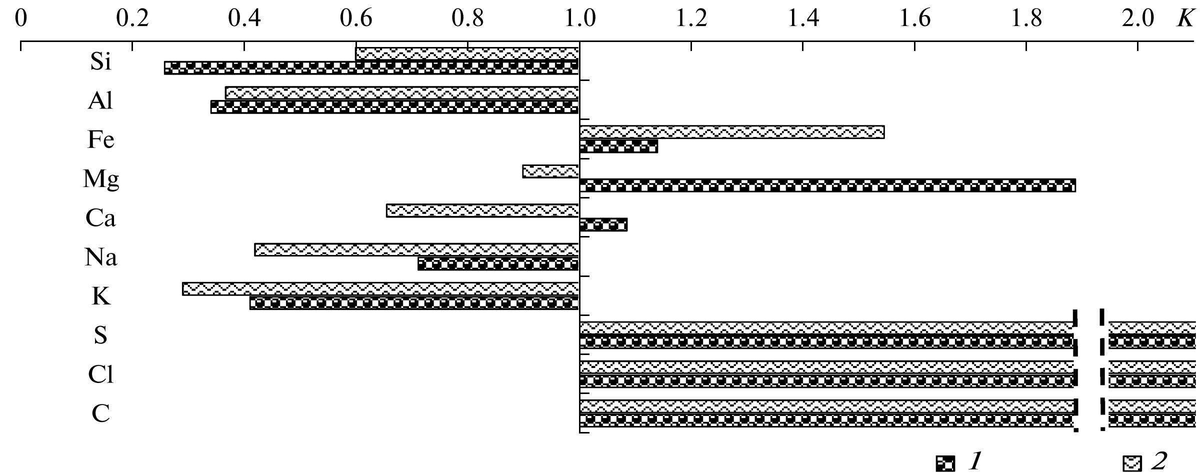

Fig. 7. Relative depletion ($K < 1$) and accumulation ($K > 1$) of elements in the (*1*) endolithic biofilms and (*2*) rock varnish films in comparison with the rock (according to microprobe analyses of the entire set of samples and data on the bulk composition of the rock). Note that the coefficient for S, Cl, and C tends to infinity because these elements are absent in the rock.

face films of rock varnish. In most cases, the films are depleted of silicon and aluminum in comparison with the parent rock, but these elements still predominate in the films. The amorphous Al and Si compounds represent transformation products of the Si- and Al-containing rock that have been transformed from the crystalline state into the amorphous state. In foreign literature, such films are referred to as silica glazes [24, 29, 46 et al.]. These particular formations are responsible for the greasy luster of the rock varnish seen during the mesomorphological investigations. One of the hypotheses of their origin considers them as solidified gels of silicic acid. The latter represents a transient product of the biochemical dissolution of silicate minerals in the presence of water or water vapor [27, 52]. We suppose that this process takes place inside the endolithic system. Indeed, the periods of moistening of the endolithic systems in Antarctic oases are short. Upon their drying, the concentrations of dissolved substances increase, and the condensation of silicic acid takes place. In the course of the formation of the gel, it naturally includes living cells, organic and mineral detritus, and other weathering products. Upon the further dehydration of the gel, these components become incorporated in the body of the solidified amorphous film [45, 46]. Thus, the elemental composition of the film is an integral index specified by the condensed amorphous compounds together with the weathering products mechanically incorporated into the film. At present, we cannot definitely say about the form of the Al compounds in the films. Partly, these are amorphous compounds, which is indicated by the morphology of the points from which the signal of Al is obtained. However, it is probable that at least some part of this signal comes from the particles of silicate crystals incorporated into the film. The mass portion of Si may also depend on the admixture of mineral detritus in the films. Iron compounds are unevenly distributed in the amorphous silica mass forming separate concentrations. The dissolution of silicate minerals of granitoid rocks may be affected by the exudates and decomposition products of endolithic organisms. For example, endolithic lichens synthesize oxalic acid and its derivatives. It is known that the availability of Si, Al, Fe, and K increases in the presence of oxalates. It can be supposed that some part of these elements is present in the endolithic horizon in the form of oxalate complexes. The formation of oxalate complexes is a widespread process of rock alteration with the participation of endolithic lichens in Antarctica [20, 38]. The decomposition of oxalates, including their photooxidation to CO_2, leads to the release of Si, Fe, and Al from the complexes with their further precipitation in the form of amorphous silicates or oxides [38].

Endolithic organomineral horizon. The properties of the endolithic organomineral horizon depend on the ratio between the organic and mineral components. A specific feature of this horizon is that its organic components are mainly represented by the biofilms of endolithic organisms covering mineral grains. This results in the high variability of the measured parameters, because the presence of just several mineral grains without the biofilms affects the results of the elemental analysis. The reaction of the medium is close to neutral (Table 2). It is probable that the acidifying effect of the biota is neutralized by the alkalization effect from the salts deposited from the air.

The carbon content determined in the bulk samples of the endolithic horizon (i.e., not with the microprobe) varies within 0.2–3.3%, and the nitrogen content varies within 0.02–0.47%. These values are usually higher on stable horizontal surfaces than on the vertical surfaces, where the spalling effect is enhanced by the gravitational force. Also, these values are expectedly higher in the endolithic horizons formed in the rocks on warmer slopes of northern aspect in comparison with the rocks on cold slopes of southern aspect. Under these stable and thermally favorable conditions, the C/N ratio decreases to 7.1, which points to the fact that the endolithic systems in such environments are more "mature." The meso- and micromorphological observations indicate that a larger part of the organic matter in the endolithic horizon is represented by the biomass of unicellular algae. The contribution of more conservative components of the organic matter, including the organic substances bound with the mineral phase, is roughly estimated at 10–30%.

The radiocarbon age of the organic matter of the endolithic horizons was determined in two samples: (a) from the vertical rock cliff of the warm northern aspect (10-45 B) and (b) from the horizontal surface of the same rock (10-47 2B1) (Table 3).

Though the volumes of the analyzed biomasses and fine earth were approximately equal, in the first sample, the radiocarbon age of the organic matter was very young (less than 60–80 yrs), whereas, in the second sample, the mean residence time of the organic matter in the endolithic horizon reached 480 ± 25 yrs. This result is quite explainable, because, in the case of the north-facing vertical cliff, the lifetime of the endolithic system is reduced due to the more active gravitational processes enhancing spalling. This system is characterized by the intensified weathering and renewal of the organic matter because of the more favorable temperature conditions. The ^{14}C age of the organic matter from the endolithic system on the horizontal rock surface indicates that the endolithic "organic" horizons are not ephemeral formations. The average value of the radiocarbon age of the organic matter in this endolithic system means that some part of the organic matter is older than the obtained value, because the young components of the system (e.g., the biomass of the living organisms) rejuvenate the measured age. Therefore, we may conclude that the absolute age of the endolithic systems under stable conditions, i.e., the time that has passed since the settling of the endolithic organisms in the rock, is more than 500 yrs. Surely, this assumption needs additional verification. Literature data indicate that some endolithic systems forming on stable surfaces (without active spalling) in Antarctic oases may be very old; their age is estimated at several thousand years [39, 50]. In this case, we operate with an almost geological timescale, and this allowed the authors to suppose that the endolithic communities might be the slowest growing communities on earth [39]. However, taking into account the observed intensity of the spalling processes and the dates obtained by us, including the date attesting to the modern radiocarbon age of the organic matter, such old endolithic systems may represent an exception rather than the rule. Under the conditions of Antarctica, they may only be developed in relatively rare "shelters."

Table 2. Some properties of the autochthonous fine earth (oragnomineral horizon) under the spalling plate with the endolithic community (the Larsemann Hills oasis)

Sample	pH_{H_2O}	C	N	C/N
		%		
10-45 B	6.4	3.33	0.47	7.1
10-47 2B1	6.8	1.54	0.21	7.3
10-45 B1	6.5	0.21	0.02	10.5
10-47 B2	6.7	1.71	0.09	19.0
10-54 B1	7.8	1.04	0.12	8.7
10-58 B1	6.8	2.76	0.25	11.0
10-64 B1	7.8	3.01	0.39	7.7
10-64 B2	7.6	0.86	0.08	10.8
10-61 B1	6.3	2.48	0.27	9.2
10-65 B2	6.8	1.69	0.14	12.1
μ	6.9	1.86	0.20	10.3

The values of $\delta^{13}C$ obtained for the dated samples attest to a somewhat heavier isotopic composition of the organic matter in comparison with the values typical of C3 plants (usually, –24 to –30‰), as well as with the values obtained for the endolithic material from the Dry Valleys of Antarctica [37]. The heavier isotopic composition of the samples studied by us may be specified by the significant contribution of cyanobacteria and green algae to the organic matter at the expense of heterotrophic organisms (micromycetes and bacteria). For a more reliable interpretation of the "isotopic memory" of the system, a larger number of measurements are required. It is also necessary to obtain data on the isotopic composition of nitrogen in the studied samples.

Temporal changes in the endolithic systems. On the basis of our data and the literature analysis, we can refine the initial simplified notion of the endolithic system (Fig. 2) and suggest the following hypothesis of its development (Fig. 8). In this scheme, the major phases of the development of endolithic systems are illustrated by factual material. **Phase I** represents an exposed surface of granitoid rock partly or completely covered by the amorphous organomineral Fe–Al–Si–C films of rock varnish. Theoretically, we may also assume the existence of phase 0 represented by the exposed granitoid without rock varnish films and without indications of weathering processes. However, we have no factual data on this phase. During phase I, the rock and the varnish film are subjected to the action of external agents resulting in the physical disintegration of the rock with the development of a network of microfissures, including those subparallel to the surface. Endolithic organisms colonize these fissures. **Phase II** is the phase of functioning of the endolithic community accompanied by the physical and biogeochemical weathering, so that the bonds between

Table 3. Radiocarbon age and isotopic composition of the carbon in the organic matter of the endolithic horizon (the Larsemann Hills oasis)

Sample	Material	$\delta^{13}C$, ‰	Portion of modern C, %	^{14}C age, BP
10-45 B	Organic matter in the fine earth from the fissure	−23.7	102.86 ± 0.28	Modern
10-47 2B1		−21.0	94.19 ± 0.26	480 ± 25

the rock minerals become very loose, and some rearrangement of the mineral material takes place. A part of the mineral grains is separated in the form of the coarse fractions of the fine earth; larger fissures appear in the rock. Colonies of endolithic organisms cover the larger part of the walls of fissures and partly cover the grains of the fine earth material. Under their impact, the zones of the biogeochemical transformation of the rock appear in the system. **Phase III** is the phase of the development of organomineral films as the products of weathering. These films cover fissure walls inside the rock, particularly under the endolithic community. The biomass of endolithic organisms in the system increases, as well as the volume of the fine earth material; the network of fissures becomes more pronounced. **Phase IV** corresponds to considerable weakening of the bonds between the upper rock plate and the major rock mass under the endolithic community; the spalling of the upper plate takes place under the impact of gravitational forces or wind erosion. The plate with the remains of endolithic organisms and biofilms is subjected to partial destruction. It is transported to the nearest accumulative positions in the landscape. The fine earth material is removed by wind and transported to considerable distances. After the spalling, the organomineral film created inside the endolithic system on the main rock surface becomes exposed to the action of exogenous factors. It can be

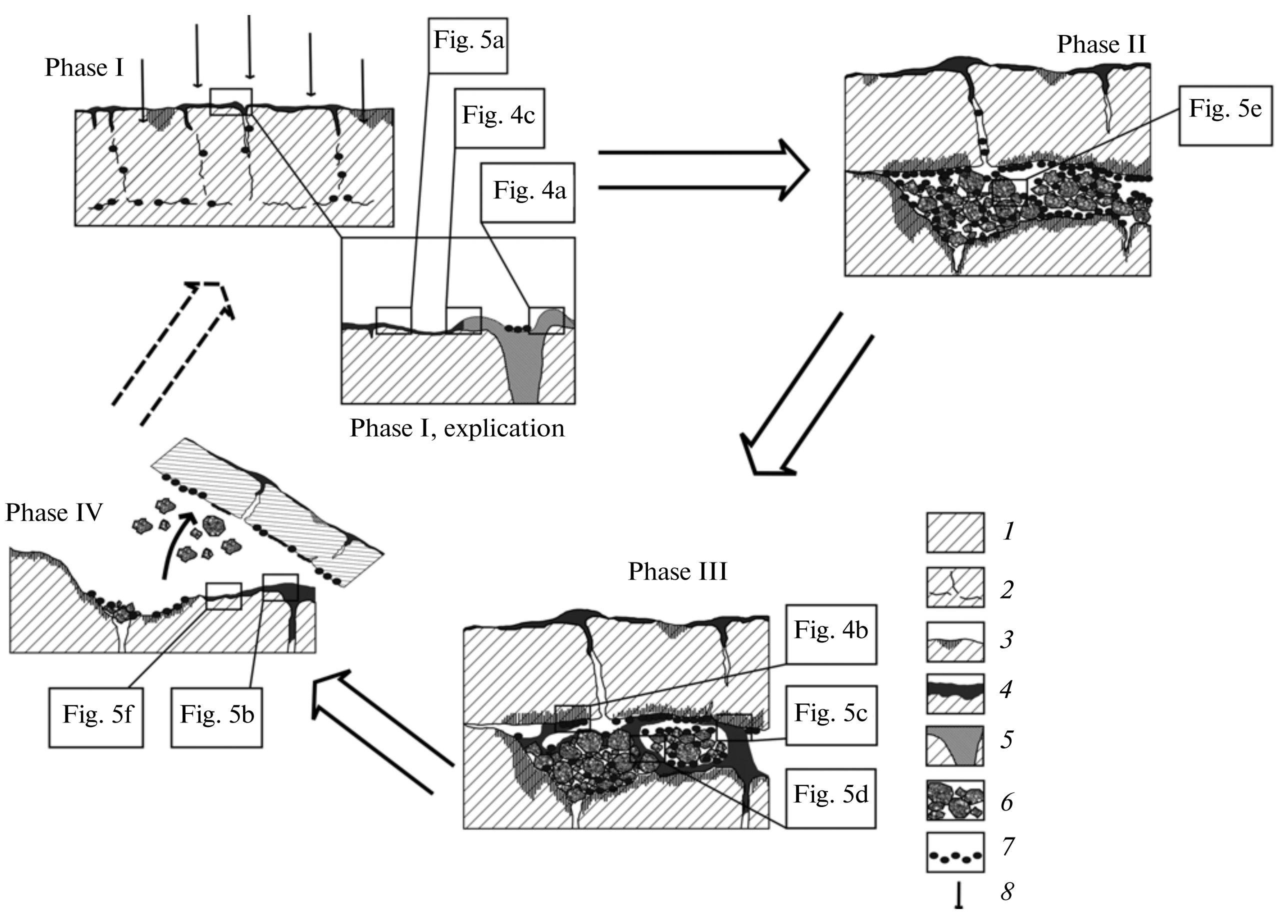

Fig. 8. Hypothetic scheme of the morphology and transformation of an endolithic system (references to previous figures are given in the frames): (*1*) massive crystalline rock, (*2*) fissures in the rock, (*3*) zones of biogeochemical weathering, (*4*) amorphous organomineral films without visible cells, (*5*) amorphous organomineral films with incorporated cells, (*6*) loci with sand and silt fractions, (*7*) endolithic organisms, and (*8*) external environmental impacts.

supposed that some mechanisms of the ageing (maturing) of the film take place: the film is polished by the wind, its organic components are transformed, and its active oxidation takes place. During this stage, the accretionary–eolian mechanism of the growth of the film may also take place. Thus, the exposed biofilm of the initially endolithic origin is transformed into the typical red-brown rock varnish film on the rock surface in Antarctica (**Phase I**). According to our hypothesis, such a film represents a polygenetic formation. The exposure of the initially endolithic film to the surface may also lead to it complete destruction owing to abrasion by the wind.

CONCLUSIONS

An endolithic system is a soil. The results of this study allow us to recognize than endolithic systems have all the characteristic features of soils: (1) the rock (parent material) layer subjected to the action of external abiogenic factors, (2) the living organisms functioning in this rock and synthesizing and decomposing the organic matter, (3) the in situ transformation of the initial rock under the impact of abiogenic and biogenic factors with the accumulation and removal of the products of this transformation and with the development of the vertical heterogeneity in the form of microhorizons composing the microprofile.

Thus, we suggest that endolithic systems can be called endolithic soils, and the totality of the processes taking place in them can be referred to as endolithic pedogenesis. Several specific features of endolithic soils can be distinguished: (1) the main focus of biomineral interactions—the endolithic organomineral horizon—is found not on the rock surface but inside the rock; (2) the soil microprofiles are developed on both sides of the "organic" horizon containing the endolithic community, i.e., in the spalling plate above it and in the main rock volume under it; (3) the major products of the endolithic pedogenesis are the silty–sandy fine earth and abundant amorphous Fe–Al–Si–C-containing films with admixtures of K, Na, Mg, Ca, S, and Cl that are formed on the walls of the fissures inside the rocks and on the lower face of the spalling plate; the precipitation of these film is specified by the mechanical and oxidation geochemical barriers at the air/rock interface; (4) the development of macrohorizons is impossible because of the periodic rejuvenation of the rock surface under the impact of spalling; and (5) after the spalling, the fine earth is removed by the wind, and the exposed rock surface is only covered by the Fe–Al–Si–C-containing films, which are partly abraded and transformed by the external agents.

Spalling as the result of endolithic pedogenesis. The action of endolithic pedogenesis results in loosening of the hard rock and the appearance of holes and fissures, in which water and ice actively destroy the rock. Thus, the more developed the endolithic pedogenesis, the more chances for the destruction of the endolithic soil. The probability of the gradual transformation of the endolithic soil into the normal in situ soil decreases with an increase in the degree of development of the endolithic soil. Such a pedogenesis can be called self-destroying pedogenesis.

Indeed, the living activity of organisms in the internal volume of the surface rock layers often leads to spalling (exfoliation, desquamation) of these layers. This is the decisive factor in the fate of the endolithic soil, and it affects the entire landscape. At the same time, we should admit that the presence of the network of fissures created in the rock by physical weathering is necessary for the rock colonization by endolithic organisms. The physical weathering precedes the biochemical weathering. However, afterwards, both processes act together enhancing one another by many times. As noted by Glazovskaya [7], spalling plates (crusts, scales) represent the most widespread type of weathering in Antarctica. The spalling of mineral plates is the final stage of the endolithic–disintegration cycle. After it, the newly exposed surface is again subjected to the physical and biochemical weathering, and endolithic organisms occupy their niche in the rock fissures. When the bonds inside the rock get loose under the action of these organisms so that the rock cannot resist the gravitational and wind erosion forces, new spalling takes place. This cycle is not closed; it involves the removal of the products of the weathering and the involvement of new portions of fresh rock. The removed parts of the rock (spalling plates) at the first stages are subjected to the more rapid set of processes transforming the mineral substrate in the landscape: they become the part of the loose sediments that are subjected to intense actions of wind, water, and vegetation. Thus, they participate in weathering and "normal" pedogenesis. It is important that the spalling plates bear the memory of the former functioning of the endolithic community and often contain its organic residues or dormant forms of organisms that also enter the loose sediments thus bringing the organic components to them. Thus, some part of the fine earth sediments in the bottoms of Antarctic valleys and in the large cut-in basins in the rock are the derivatives of spalling plates. Sometimes, this can be judged from their morphology, though it often impossible to determine the former history of the fragments of spalling plates destroyed to the gravel or coarse sand size. These substrates bearing the "endolithic" memory are colonized by mosses upon their sufficient moistening with snowmelt from snow patches, and normal full-profile (for Antarctica) soils are developed from them [9].

Rock varnish as a horizon of the surface micropaleosols. The memory of the endolithic soil may also remain in the place of its origin. Important products of the endolithic pedogenesis are represented by the Fe–Al–Si–C-containing films on the rock face. Being exposed to the surface, they are either destroyed completely or are partly transformed and preserved. These formations are often described as rock varnish. We agree with this term. However, we should bear in mind that this term denotes quite different genetic formations, including the films of the accretionary, in situ epilithic, and in situ endolithic geneses.

The rock varnish film of the in situ endolithic genesis examined by us represents a horizon of the endolithic soil that existed in the surface layer of the rock in the past. From the viewpoint of pedology, such a varnish film is a horizon of the surface micropaleosol. From the viewpoint of paleontology, it is a fossil or chemofossil formation. Indeed, it is a fossilized body, because the amorphous silica contains the remains of the endolithic community of organisms and the products of its interaction with the rock. In this context, the radiocarbon dating of the rock varnishes of the endolithic genesis seems to be promising. Though this procedure involves numerous technical difficulties, it is possible because the varnish contains biota. We suppose that the inclusion of such bodies into the category of surface paleosols is quite reasonable.

In conclusion, we should stress that the hypothesis of rock varnish as the product of endolithic pedogenesis does not claim to explain the genesis of the diverse forms of rock varnish that may have different origins, including an allochthonous origin.

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REFERENCES

1. E. V. Abakumov, “Particle-Size Distribution in Soils of West Antarctica,” Eur. Soil Sci. **43** (3), 297–304 (2010).
2. E. V. Abakumov, “The Sources and Composition of Humus in Some Soils of West Antarctica,” Eur. Soil Sci. **43** (5), 499–508 (2010).
3. E. V. Abakumov, *Soils of West Antarctica* (Izd. SPbGU, St. Petersburg, 2011) [in Russian].
4. A. A. Abramov, R. S. Sletten, E. M. Rivkina, V. A. Mironov, and D. A. Gilichinskii, “Geocryological Conditions of Antarctica,” Kriosfera Zemli, No. 3, 3–19 (2011).
5. D. Yu. Vlasov, E. V. Abakumov, M. A. Nadporozhskaya, et al., “Lithosols of King George Island, Western Antarctica,” Eur. Soil Sci. **38** (7), 681–687 (2005).
6. M. A. Glazovskaya, “Biogeochemical Weathering of Volcanic Rocks of Andesitic Composition under Subantarctic Periglacial Conditions,” Izv. Akad. Nauk, Ser. Geogr., No. 3, 39–48 (2002).
7. M. A. Glazovskaya, “Weathering and Initial Soil Formation in Antarctica,” Nauch. Dokl. Vyssh. Shkoly, Geol.-Geogr. Nauki, No. 1, 63–76 (1958).
8. S. V. Goryachkin, D. A. Gilichinskii, E. V. Abakumov, E. P. Zazovskaya, N. S. Mergelov, and D. G. Fedorov-Davydov, “Soils of Antarctic: Diversity, Geography, Genesis (Case Study of Russian Antarctic Stations), in *Diversity of Frost-Affected Soils and Their Role in Ecosystems*, Materials of the 5th Int. Conf. on Cryopedology (Moscow–Ulan-Ude, 2009), p. 32.
9. S. V. Goryachkin, D. A. Gilichinskii, N. S. Mergelov, D. E. Konyushkov, A. V. Lupachev, A. A. Abramov, and E. P. Zazovskaya, “Soils of Antarctica: First Results, Problems, and Prospects of the Study,” in *Geochemistry of Landscapes and Soil Geography (on the 100th Jubilee of M.A. Glazovskaya)*, (Moscow, 2012) [in Russian].
10. E. A. Dmitriev, “Soils and Soil-like Bodies,” Eur. Soil Sci. **29** (3), 275–282 (1996).
11. A. M. Ivlev and O. V. Nesterova, “On the Study of Aquasols,” Vestn. DVO RAN, No. 4, 47–52 (2004).
12. B. B. Polynov, “First Stages of Soil Formation on Massive Crystalline Rocks,” Pochvovedenie, No. 7, 327–339 (1945).
13. V. A. Roslikova, “Modern Notions on the Subaqual Pedogenesis,” Tikhookean. Geol. **25** (4), 97–103 (2006).
14. A. A. Semikolennykh and V. O. Targulian, “Soil-Like Bodies of Autochemolithotrophic Ecosystems in the Caves of the Kugitangtau Ridge, Eastern Turkmenistan,” Eur. Soi Sci. **43** (6), 614–627 (2010).
15. I. A. Sokolov, “The Paradigm of Pedology from Dokuchaev to the Present Day,” Eur. Soil Sci. **29** (3), 222–232 (1996).
16. T. A. Sokolova, “The Role of Soil Biota in the Weathering of Minerals: A Review of Literature,” Eur. Soil Sci. **44** (1), 56–72 (2011).
17. V. O. Targulian, “Exogenesis and Pedogenesis: Development of the Conceptual Basis of Pedology,” Vestn. Mosk. Univ., Ser. 17: Pochvoved., No. 1, 33–43 (1983).
18. V. O. Targulian and S. V. Goryachkin, “The 19th World Congress of Soil Science,” Eur. Soil Sci. **44** (9), 1041–1047 (2011).
19. L. Beyer and M. Boelter (Eds.), *Geoecology of Antarctic Ice-Free Coastal Landscapes* (Springer-Verlag, Berlin Heidelberg, 2002).
20. R. L. Blackhurst, M. J. Genge, A. T. Kearsley, and M. M. Grady, “Cryptoendolithic Alteration of Antarctic Sandstones: Pioneers or Opportunists?,” J. Geophys. Res. **110**, 12–24 (2005).
21. J. G. Bockheim and M. Balks (Eds.), “Antarctic Soils and Soil Forming Processes in a Changing Environment,” Geoderma **144**, 1–414 (2008).
22. I. B. Campbell and G. G. C. Claridge, *Antarctica: Soils, Weathering Processes and Environment* (Elsevier Sci. Publ., Amsterdam & New York, 1987).

23. J. Chen, H.-P. Blume, and L. Beyer, "Weathering of Rocks Induced by Lichen Colonization—A Review," Catena **39**, 121–146 (2000).

24. B. Curtis, J. B. Adams, and M. S. Ghiorso, "Origin, Development and Chemistry of Silica-Alumina Rock Coatings from the Semi-Arid Regions of the Island of Hawaii," Geochim. Cosmochim. Acta **49**, 49–56 (1985).

25. C. Darwin, "Bahaia-Brazil. Habits of a Diodon," *Journal of Researches into the Natural History and Geology of the Countries Visited during the Voyage of H.M.S. Beagle round the World*, pp. 12–13 (1887).

26. A. De Los Rios, J. Wierzchos, L. G. Sancho, A. Green, and C. Ascaso, "Ecology of Endolithic Lichens Colonizing Granite in Continental Antarctica," The Lichenologist **37** (5), 383–395 (2005).

27. R. I. Dorn, "Formation of Silica Glaze Rock Coatings through Water Vapor Interactions," Submitted to Physical Geography (2011) (published electronically).

28. R. I. Dorn, *Rock Coatings* (Elsevier, Amsterdam, 1998).

29. R. I. Dorn, "Rock Varnish," in *Geochemical Sediments and Landscapes* Ed. by D. J. Nash and S. J.. McLaren (Blackwell, London, 2007), pp. 246–297.

30. R. I. Dorn, D. H. Krinsley, T. Liu, S. Anderson, J. Clark, T. A. Cahill, T. E. Gill, "Manganese-Rich Rock Varnish Does Occur in Antarctica," Chem. Geol. **99**, 289–298 (1992).

31. R. I. Dorn and T. M. Oberlander, "Rock Varnish," Progr. Phys. Geogr. **6**, 317–367 (1982).

32. E. I. Friedmann, "Endolithic Microorganisms in the Antarctic Cold Desert," Science **215**, 1045–1053 (1982).

33. E. I. Friedmann and R. Ocampo, "Endolithic Blue-Green Algae in the Dry Valleys: Primary Producers in the Antarctic Desert Ecosystem," Science **193**, 1247–1249 (1976).

34. E. I. Friedmann and R. Weed, "Microbial Trace-Fossil Formation, Biogenous, and Abiotic Weathering in the Antarctic Cold Desert," Science, 703–705 (1987).

35. I. Friedmann, Y. Lipkin, and R. Ocampo-Paus, "Desert Algae of the Negev (Israel)," Phycologia **6**, 185–196 (1967).

36. D. Gilichinsky, E. Abakumov, A. Abramov, D. Fyodorov-Davydov, S. Goryachkin, A. Lupachev, N. Mergelov, and E. Zazovskaya, "Soils of Mid and Low Antarctic: Diversity, Geography, Temperature Regime," Symp. WG 1.4 "Cold Soils in a Changing World," *Proc. 19th World Congr. Soil Sci.* (DVD), (Brisbane, Australia, 2010), pp. 32–35.

37. D. W. Hopkins, A. D. Sparrow, E. G. Gregorich, B. Elberling, P. Novis, F. Fraser, C. Scrimgeour, P. G. Dennis, W. Meier-Augenstein, and L. G. Greenfield, "Isotopic Evidence for the Provenance and Turnover of Organic Carbon by Soil Microorganisms in the Antarctic Dry Valleys," Environ. Microbiol. **11**, 597–608 (2009).

38. C. G. Johnson and J. R. Vestal, "Biogeochemistry of Oxalate in the Antarctic Cryptoendolithic Lichen-Dominated Community," Microbial Ecol. **25**, 305–319 (1993).

39. C. G. Johnson and J. R. Vestal, "Photosynthetic Carbon Incorporation and Turnover in Antarctic Cryptoendolithic Microbial Communities: Are They the Slowest Growing Communities on Earth?" Appl. Environ. Microbiol. **57**, 2308–2311 (1991).

40. D. Krinsley, "Models of Rock Varnish Formation Constrained by High Resolution Transmission Electron Microscopy," Sedimentology **45**, 711–725 (1998).

41. D. H. Krinsley, R. I. Dorn, and N. K. Tovey, "Nanometer-Scale Layering in Rock Varnish: Implications for Genesis and Paleoenvironmental Interpretation," J. Geol. **103**, 106–113 (1995).

42. T. Liu and W. S. Broecker, "How Fast Does Rock Varnish Grow?" Geology **28**, 183–186 (2000).

43. T. Liu and W. S. Broecker, "Rock Varnish Microlamination Dating of Late Quaternary Geomorphic Features in the Drylands of the Western USA," Geomophology **93**, 501–523 (2008).

44. D. A. McKeown and J. E. Post, "Characterization of Manganese Oxide Mineralogy in Rock Varnish and Dendrites Using X-Ray Absorption Spectroscopy," Am. Mineralogist **86**, 701–713 (2001).

45. R. S. Perry and V. M. Kolb, "Biological and Organic Constituents of Desert Varnish: Review and New Hypotheses," in *Instruments, Methods, and Missions for Astrobiology VII* Ed. by R. Hoover and A. Rozanov, pp. 202–217.

46. R. S. Perry, B. Y. Lynne, M. Sephton, V. M. Kolb, C. C. Perry, J. T. Staley, "Baking Black Opal in the Desert Sun: The Importance of Silica in Desert Varnish," Geology **34**, 537–540 (2006).

47. R. M. Potter and G. R. Rossman, "Desert Varnish: The Importance of Clay Minerals," Science **196**, 1446–1448 (1977).

48. J. A. Raven, S. J. Douglas, and A. W. D. Larkum, *Photosynthesis in Algae* (Kluwer Academic, 2003).

49. J. T. Staley, F. Palmer, and J. B. Adams, "Microcolonial Fungi: Common Inhabitants on Desert Rocks?," Science **215** (Iss. 4536), 1093–1095 (1982).

50. H. J. Sun and E. I. Friedmann, "Growth on Geological Time Scales in the Antarctic Cryptoendolithic Microbial Community," Geomicrobiology J. **16** (Iss. 2), 193–202 (1999).

51. V. Targulian, N. Mergelov, D. Gilichinsky, S. Sedov, N. Demidov, S. Goryachkin, and A. Ivanov, "Dokuchaev's Soil Paradigm and Extraterrestrial Soils," Symp. 1.1, *Proc. 19th World Soil Sci. Congr.* (DVD) (Brisbane, Australia, 2010), pp. 1–4.

52. G. Zubay, *Origins of Life on the Earth and in the Cosmos* (Academic Press, San Diego, 2000).