Soil-like Patterns Inside the Rocks: Structure, Genesis, and Research Techniques

Chapter · January 2016

DOI: 10.1007/978-3-319-24987-2_17

Soil-like Patterns Inside the Rocks: Structure, Genesis, and Research Techniques

Nikita S. Mergelov, Ilya G. Shorkunov, Victor O. Targulian, Andrey V. Dolgikh, Konstantin N. Abrosimov, Elya P. Zazovskaya and Sergey V. Goryachkin

Abstract Microprofiles established due to the activity of endolithic communities inside the solid rocks of East Antarctica were studied with the approaches of soil science. Major products of endolithic rock transformation in situ are the silty-sandy fine earth and abundant organo-mineral films that are formed within the porous space of endolithic system. Such films are the result of interaction between biofilms and mineral surfaces and reflect elemental composition of both components, mainly comprising C, O, Si, Al, Fe, K, Ca, Na, and Mg. Morphology observed on different hierarchical levels and microtomography data indicated that different layers of endolithic system are connected with the fracture network serving for the elements transfer in the subsurface part of solid rocks. Examined profiles in granites with high quartz content had clear eluvial–illuvial differentiation patterns similar to macroprofile of a common Podzol (Spodsol) on loose substrates. It is shown, that subaerial segment of hard rocks is not sealed and is potentially permeable for dissolved products of endolithic weathering and pedogenesis. As a unique result—the soil-like pattern is established inside the massive, crystalline rock. Understanding modern processes in endolithic systems is of fundamental importance to decrypt paleosol record, as such systems may be the closest modern analogues of protosoils that existed on our planet before the higher vascular plants with root systems established.

Keywords Extreme environment · Endoliths · Soil-like bodies · Exfoliation · Eluvial–illuvial differentiation · Podzols

N.S. Mergelov (✉) · I.G. Shorkunov · V.O. Targulian · A.V. Dolgikh · E.P. Zazovskaya
S.V. Goryachkin
Institute of Geography, Russian Academy of Sciences, Moscow, Russia
e-mail: nikvox@yandex.ru

K.N. Abrosimov
V.V. Dokuchaev Soil Science Institute, Russian Academy of Sciences, Moscow, Russia

O.V. Frank-Kamenetskaya et al. (eds.), *Biogenic—Abiogenic Interactions in Natural and Anthropogenic Systems*, Lecture Notes in Earth System Sciences,
DOI 10.1007/978-3-319-24987-2_17

1 Introduction

Communities of endolithic organisms and the microenvironment they create inside the rocks are among the least-explored terrestrial ecosystems with pronounced photoautotrophic component. Their potential ranges are enormous: rock outcrops occupy up to 20 % of the Earth's land surface. However, actual habitats are largely attributed to various areas of external stress where development of biota at the surface is inhibited by the lack of moisture, UV radiation, wind corrasion, etc. Under such conditions, organisms find their ecological niche inside the rocks which interact with minerals and establish specific endolithic systems. These biotic–abiotic bodies possess many of soil attributes. However, they are never perceived as soils or at least soil-like bodies. Dominant autotrophic components of endolithic systems are cyanobacteria and green algae existing primarily in the form of biofilms. The most suitable rocks for colonization by endolithic photoautotrophs are sandstones, various granitoids, marbles and any others with a significant content of translucent and/or transparent mineral grains, which make primary production of organic matter possible inside the rock even under limited levels of available light.

Organisms inhabiting subsurface layer inside solid rocks captured attention of K. Ehrenberg, the founder of micropaleontology. Their possible role in biochemical weathering and exfoliation was indicated by Glazovskaya (1958) in her pioneering study of initial pedogenesis in Antarctica, but conceptually this phenomenon was described by geobiologist Friedmann et al. (1967), Friedmann and Ocampo (1976), Friedmann (1982), etc. who applied the term "endoliths" to such organisms. Later, they were divided into crypto-, chasmo-, and euendoliths according to the differences in mode of development and penetration into cracks and structural cavities of rocks (Golubic et al. 1981). Since 1967, when microscopic endolithic algae and cyanobacteria were discovered by I. Friedmann in Sinai and Negev deserts they continue to be systematically studied in various extreme environments of the world by geo(micro)biologists and ecologists focusing on diversity and growth conditions. In recent years, the emphasis has shifted to their metagenome decoding (Sigler et al. 2003; De los Rios et al. 2007; Walker and Pace 2007; Horath and Bachofen 2009 and many others). Studies on biochemical weathering and biomineralization in endolithic systems (De los Rios et al. 2003, 2014; Wierzchos et al. 2005 and others) are not so numerous and we still experience a lack of comprehensive understanding of their (bio)geochemistry.

Except for trace fossils and biosignature issues (Golubic and Schneider 2003) endolithic bio–abiotic systems are not fully recognized as paleo protosoils and modern soil-like bodies and are not investigated using the methods and techniques of pedology. However, they are actual precursors to more advanced soil formations, and often the only equilibrium soil-like bodies with external factors in many areas of cold and hot deserts and high mountains of the planet. Endolithic bio–abiotic systems are relatively simple formations and are among best suitable objects to study organo-mineral interactions at a detailed level. This is extremely important for the modern soil science, where so called "organo-mineral complexes" are considered to be one of the major mechanisms of organic matter stabilization (Kögel-Knabner et al. 2008; Schmidt et al. 2011). There is also a knowledge gap in biogeography concerning diversity and spatial patterns of endolithic biotic complexes. Understanding modern processes in endolithic systems is of fundamental importance to decrypt paleosol record, as such systems may be the closest modern analogues of protosoils that existed on our planet before the higher vascular plants with root systems established.

In recent decades, soil scientists realized that the challenges they face are more than just the study of loose subaerial bio-abiotic formations on the surface of Earth (Targulian and Goryachkin 2011). Previously, soil-like bodies (Dmitriev 1996) or semi-soils (Sokolov 1996) soil scientists began to study under water (Ivlev and Nesterova 2004; Roslikova 2006), and later in caves (Semikolennykh and Targulian 2010). This work is also devoted to nontraditional objects of soil science that, however, occur on the Earth surface and are influenced by the "usual" factors of pedogenesis but under highly specific extreme conditions.

It was suggested earlier (Gilichinsky et al. 2010; Mergelov et al. 2012) that endolithic systems could represent the most widely spread soil-like bodies or even soils in Antarctica. However, it is still disputable whether superficial rock layers biochemically transformed by endoliths could be qualified as soils. The main objective of this study was to evaluate properties and processes occurring under the influence of organisms living inside the rocks in East Antarctica from the perspective of soil science.

2 Materials and Methods

The samples of endolithic systems were collected from the exposed bedrock surfaces in coastal oases of East Antarctica: the Larsemann Hills (S69° 20′, E76° 20′) and the Thala Hills (S67° 40′, E45° 20′). The bedrock in both cases was represented by granitoid and gneiss formations with granites and granite gneisses (consisting of feldspars, quartz, garnet, and biotite) in the Larsemann Hills and with orthogneiss and enderbites (feldspars, quartz, hypersthene, diopside, amphiboles (hornblende), and biotite in various combinations) in Thala Hills. According to temperature parameters that we measured in situ (Mergelov et al. 2012), the parts of hard bedrock with endolithic communities occur under relatively favorable (for Antarctica) conditions due to insolation of dark surfaces with rusty to reddish varnish/silica glaze. The most developed endolithic communities are usually found on the warm (in the Southern hemisphere) north-facing slopes where duration of positive temperatures period reaches 4.5 months, including 2 months with day temperatures ranging between 20 and 30 °C. On the rocky slopes of southern aspect, the temperature conditions are colder and are approximately the same as in loose substrates of the local valleys: the period with $T > 0$ °C lasts up to 2.5 months, and the surface soil (rock) day temperature reaches 10 °C during 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 longer, and the absolute summer day temperatures are 2–3 times higher than those on other surfaces in oases.

We sampled multicomponent formations at the bedrock surfaces, including (1) exfoliation plates with endolithic communities on the bottom sides and rock varnish/silica glaze on the upper sides, (2) mineral fine earth and biomass of the endolithic organisms from the system of fractures immediately under such plates, and (3) nondisturbed rock interior under the plates without endolithic organisms. Totally, 10 target sites were sampled on granitoids from Larsemann Hills and Thala Hills oases. Among them, three were specially selected for excavation of micromonoliths (0.7–1.5 cm^3 in volume) for microtomography survey.

To set the framework of research, we suggest that these three components together can be designated as an endolithic system. The structure and morphology of this system resemble a soil microprofile, and a preliminary term—endolithic soils—was suggested earlier (Mergelov et al. 2012). This proposal was more thoroughly examined in the course of our study.

The morphology of samples was studied on different hierarchical levels—under Leica MZ6 binocular, Nikon Eclipse E200 microscope both with digital cameras, and under a scanning electron microscope JSM-6610LV with an X-ray microanalyzer by Oxford Instruments making it possible to determine elemental composition of the substrate. The samples were observed both in native state and in thin sections (under incident light in parallel nicols). Internal structure and fracture network of rock micromonoliths were studied using X-ray high-resolution computer microtomography on SkyScan 1172. The carbon and nitrogen contents in 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 (we included data obtained by this method from our previous publication—Mergelov et al. 2012).

3 Results

Macrostructure of endolithic system in its native state and its schematic representation are shown in Fig. 1. The removal of an exfoliation plate (0.5–1.0 cm) covered with rock varnish and/or silica glaze reveals a community of endolithic organisms including green algae and cyanobacteria as primary components, their mort biomass, and fine earth mainly of coarse silty and fine sandy fractions. Fine earth material partly penetrates into the deeper rock zone along vertical fissures. We argue for mostly in situ origin of the fine earth since the attachment of exfoliation plates was very strong and the transverse size of superficial fractures was less than the size of observed fine earth fractions. Mineral grains are covered by biofilms, which are thick enough to be visible even at macro level. Endolithic biota and fine earth material compose together a specific layer, which we called endolithic organo-mineral horizon. Its thickness varies between 0.1 and 1.0 cm.

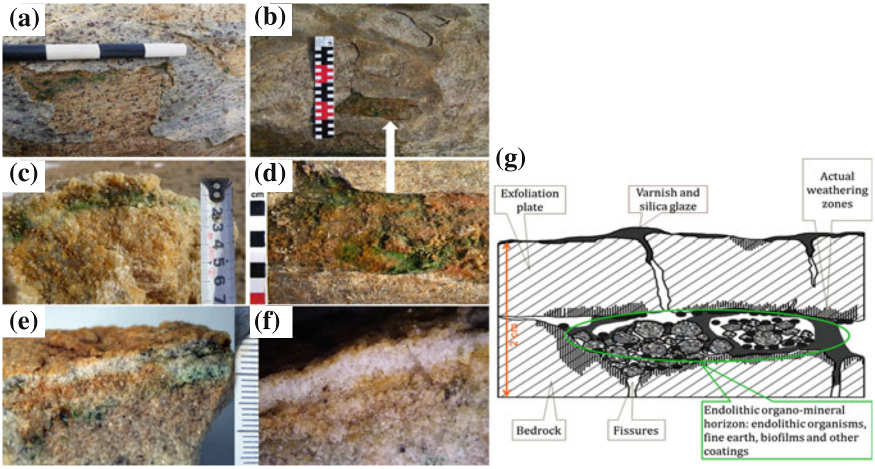

Fig. 1 Macromorphology of endolithic system on granitoids: **a** exfoliation patterns on granites in Larsemann Hills; **b** exfoliation patterns on orthogneiss in Thala Hills; **c** vertical section with distinct organo-mineral horizon but without bleached zone on gneiss in Larsemann Hills; **d** horizontal section through endolithic organo-mineral horizon on orthogneiss in Thala Hills; **e**, **f** eluvial–illuvial differentiation and distinct bleached horizon on granites with high quartz content in Thala Hills; **g** schematic structure of endolithic system

Mesomorphological features of exfoliation plates and endolithic organo-mineral horizon. Mesomorphological study suggests the association of Fe-loci to microdepressions at the surface of exfoliation plate. Fe-film does not have a continuous distribution and only partially cover mineral grains (10–60 % of the surface) (Fig. 2a). On the contrary, the lower part of the exfoliation plate is depleted in iron compounds (Fig. 2b): Fe-locus are absent, some mineral grains are covered by cyanobacterial biofilm and fossilized organo-mineral coatings. Endolithic organo-mineral layer reveals several features usually attributed to organogenic horizons of a common soil: (1) it is a hot spot of biota-to-rock interactions with most rapid mineral transformations (Fig. 2c); (2) it is a locus of fine earth formation mainly fine sand and coarse silt; (3) it has blocky subangular and up to granular structure, where major aggregation agents are cyanobacterial and green algae biofilms rich in EPS (Fig. 2d).

Micromorphology of endolithic system is exemplary in terms of visualization how cyanobacteria colonize mineral surfaces at more intimate level and even produce pseudomorphic features (Fig. 3a). Sites of intensive weathering and accumulation of Fe-(hydr)oxides are closely associated with cyanobacteria loci (Fig. 3b, d). These degraded zones are confined to the upper limit of bleached eluvial layer in profile of endolithic system. In a horizontal cross-section, an extensive network of fractures was revealed (Fig. 3c) indicating possible migration of Fe-(hydr)oxides along fissures between quartz and feldspar grains taking source in biotite degradation loci.

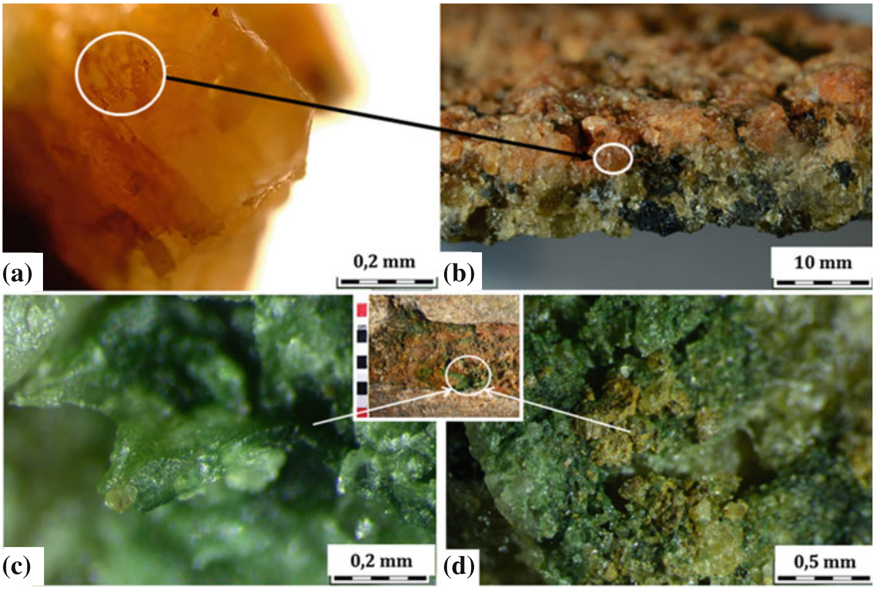

Fig. 2 Mesomorphology of endolithic system. **a** Fe film on mineral grains in oxidized part of exfoliation plate; **b** two zones in exfoliation plate: oxidized top with varnish and silica gaze and depleted in iron bottom with minerals coated by cyanobacterial biofilms and fossilized organo-mineral films; **c** cyanobacterial biofilm on highly degraded quartz grain; **d** sandy/silty fine earth aggregated by cyanobacterial biofilm

Submicromorphology. Figure 4a show biofilms with cyanobacterial cells embedded in extracellular matrix, which covers most mineral surfaces in the photic part of endolithic organo-mineral horizon. The loci of melanin and hyaline pigmented fungal hyphae (Fig. 4b) are attributed to the top of the bleached eluvial zone with strong weathering patterns, most pronounced along the whole system (Fig. 4c). Hyaline hyphae also spread deeper and penetrate into green cyanobacterial loci. Some hyphae are closely associated with single algae or cyanobacterial cells suggesting that observed part of community is an endolithic protolichen. Particular coatings are fossilized to a great extent (Fig. 4d in blue color).

The most common case is when relatively fresh biofilms (green color on Fig. 4e) alternate in space with mineralized/fossilized coatings (blue color). The extracellular matrix is also subjected to mineralization (Fig. 4f, g). Silicon predominates in the composition of these bodies. In general, organo-mineral films are mainly composed of C, O, Si, Al, Fe, K, Ca, Na, and Mg. Their elemental set reflects the chemical composition of biofilms and primary minerals interacting with each other. From our point of view, the newly formed organo-mineral films represent in situ microproducts of pedogenesis. Figure 4h shows how cells and clay-sized particles penetrate through fractures between mineral grains. Elemental map of the thin section (Fig. 4i) vividly demonstrates that quartz (shown in red color) and feldspar

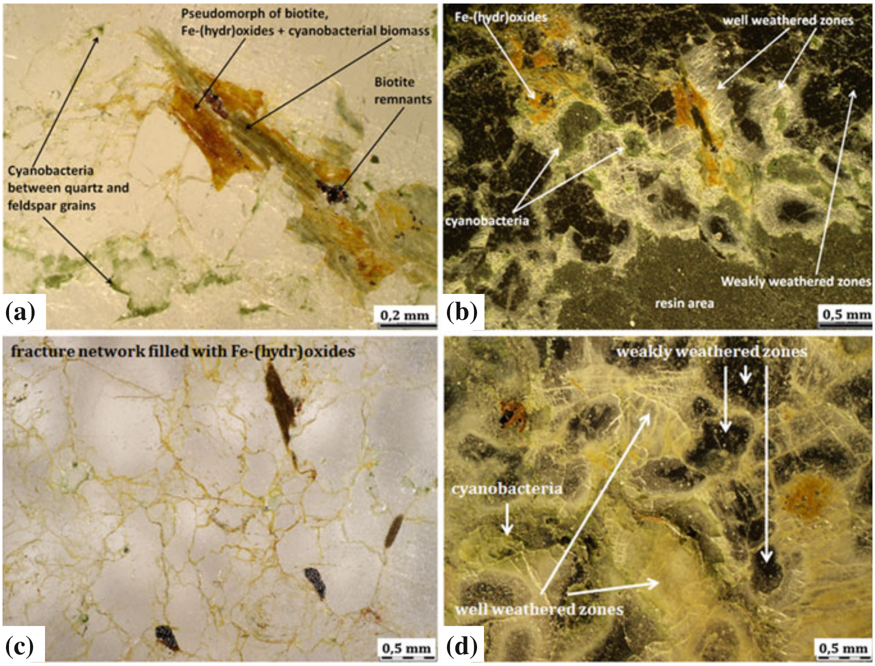

Fig. 3 Micromorphology of endolithic system with eluvial–illuvial differentiation and bleached horizon in Thala Hills. *Left part* (reflected light)—thin sections are illuminated by incident light from above, *bright white background* is used. *Light areas* indicate grains of quartz and feldspar. *Rusty-brown zones* are non-silicate iron compounds and *green-olive patterns*—areas of cyanobacteria colonization. *Right part* (reflected light)—thin sections are illuminated by incident light from above, black background is used—*dark areas* indicate that light passes well through the mineral grains and is absorbed by the black background of the substrate. *Bright areas* indicate that the light is well reflected due to strongly weathered surfaces, developed fracture network, and high specific surface area. Such bright sites correspond to the bleached eluvial zones. *Rusty-brown patterns* indicate non-silicate iron compounds. *Green-olive patterns*—areas of cyanobacteria colonization. Further explanations are given in the text

(brown) particles are ubiquitously interlayered with biofilms and organo-mineral coatings (blue).

Thus, one of the major products of endoliths-rock interaction are the numerous coatings and films covering the inner rock surfaces under exfoliation plate. In all the films, the major role is played by Si and Al compounds and by C. As follows from the morphological analysis of the films, Si and Al compounds are present in them in the predominantly amorphous forms, including silica.

Some chemical and isotopic properties of endolithic horizon. Reaction of the medium in bulk samples is close to neutral (Table 1). The carbon content varies within 0.2–3.3 %, and nitrogen—0.02–0.47 %. These values are usually higher on stable horizontal surfaces than on the vertical ones, where exfoliation is enhanced by the gravitational force. The same is true for warmer slopes of the northern aspect

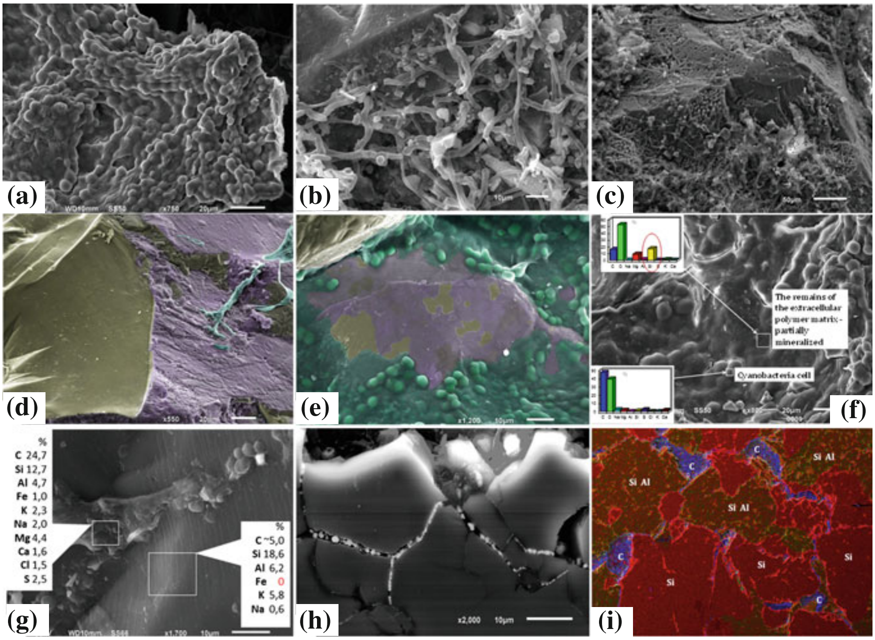

Fig. 4 Endolithic biofilms and fossilized organo-mineral films inside the rocks—products of endolithic pedogenesis. Explanations are given in the text

Table 1 Some properties of endolithic organo-mineral horizon (Larsemann Hills oasis)

No.	Sample	pH	C (%)	N (%)	C/N	δ13C (‰)
1	10-45 B	6.4	3.33	0.47	7.1	−23.7
2	10-47 2B1	6.8	1.54	0.21	7.3	−21.0
3	10-45 B1	6.5	0.21	0.02	10.5	–
4	10-47 B2	6.7	1.71	0.09	19.0	–
5	10-54 B1	7.8	1.04	0.12	8.7	−22.0
6	10-58 B1	6.8	2.76	0.25	11.0	–
7	10-64 B1	7.8	3.01	0.39	7.7	−23.4
8	10-64 B2	7.6	0.86	0.08	10.8	−22.0
9	10-61 B1	6.3	2.48	0.27	9.2	−19.6
10	10-65 B2	6.8	1.69	0.14	12.1	–
	μ	6.9	1.86	0.20	10.3	–

in comparison to colder ones of the southern aspect. Under stable and thermally favorable conditions the C/N ratio decreases to 7.1, which probably indicates more "mature" state of endolithic systems in such environment. Variability of measured parameters in bulk samples of organo-mineral horizon always depends on the ratio between organic and mineral components. We are dealing with very small quantities of a substrate and very thin organic coatings, so that just several silt-size mineral grains without biofilms could significantly affect the total estimate. More than that the integral chemical parameters measured in bulk samples by standard methods may be misleading for describing interactions of the biofilms with minerals which occur mostly at the microlevel. For example, neutral reaction observed in endolithic horizon could not explain morphology of quartz as shown earlier in Fig. 2c, as well as various forms of secondary organo-mineral coatings produced via transformation of minerals by biofilms (Fig. 4). The presence of biofilms on the mineral surface supports a specific geochemical microenvironment that may enhance or retard weathering processes. The capacity of biofilms to alter the mineral surface is enormous. Some works attest to the possibility of the local decrease of pH values to 3.0–4.0 directly in the endolithic cyanobacterial biofilms covering mineral grains (De los Rios et al. 2003). It was also shown that cyanobacterial biofilms are capable to initiate quartz dissolution via shifting pH in small loci from 3.4 to 9.0 during photosynthesis (Brehm et al. 2005).

The radiocarbon "age" of organic matter was determined in two samples from: (a) vertical surface of rock cliff of the warm northern aspect and (b) horizontal surface of the same rock (Table 2). Though the volumes of the analyzed biomass and fine earth were approximately the same, the first sample had very young radiocarbon "age" (less than 60–80 years), whereas, in the second one the mean residence time (MRT) of organic matter reached 480 ± 25 years.

This result is quite reasonable considering that the lifetime of endolithic system at the north facing vertical cliff is reduced due to more intensive exfoliation driven by gravitation. Besides that, favorable thermal conditions promote here biochemical weathering and increase rate of organic matter turnover. In case of stable horizontal surface, the MRT of organic matter suggests endolithic organo-mineral horizon is not an ephemeral body. And even more, some part of organic matter in this endolithic system is much older than obtained MRT value, however, it is mixed with younger components (e.g., biomass of the living organisms) that rejuvenate the average 14C "age." Therefore, we may conclude that the absolute age of endolithic systems under stable conditions, i.e., the time that has passed since endolithic organisms inhabited the rock, is more than 500 years. However, this assumption needs additional verification. The literature data indicate that some endolithic systems formed on stable surfaces (without active exfoliation) in Antarctic oases may be very old; their age is estimated as several thousand years (Johnston and

Table 2 14C "age" of organic matter in endolithic organo-mineral horizon (Mergelov et al. 2012)

Material	Sample	% of modern C	14C "age"/ MRT, years
Organic matter from endolithic horizon	10-45 B warm northern aspect, vertical surface	102.86 ± 0.28	Modern
	10-47 2B1 horizontal surface	94.19 ± 0.26	480 ± 25

Vestal 1991; Sun and Friedmann 1999). In this case, we operate almost at geological timescale, and this allowed Johnson and Vestal to suppose that endolithic microecosystems might be the slowest growing communities on Earth. However, taking into account the observed intensity of exfoliation and the "ages" estimated by us, including the date attesting to the modern radiocarbon age of organic matter, such old endolithic systems may represent an exception rather than the rule. In Antarctica extreme environment, they may only be developed in relatively rare "shelters." The values of δ13C obtained for the samples being dated (Table 1) 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 to the values obtained for endolithic material from the Dry Valleys of Antarctica (Hopkins et al. 2009). 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.

Potential carbon stocks and pools in endolithic systems. We have obtained the preliminary estimate of average endolithically generated organic C stock in granites of Larsemann Hills which is 0.037 ± 0.019 g C/cm^2 (3,7 Mg C/ha). We also calculated the potential total carbon pool of endolithic systems at a key site in the wet valley of Larsemann Hills (S69° 20′, E76° 20′, 27 ha area), which is 36 Mg C (Fig. 5). It is comparable with the carbon pool of the same site created by bryophyte communities in loose soils (40 Mg C). More than that, endolithic carbon pool occurred to be significantly higher than in soils on lacustrine sediments (9 Mg C) and ornithogenic soils (2 Mg C), and in comparison to epilithic (<1 Mg C) and hypolithic (8 Mg C) pools.

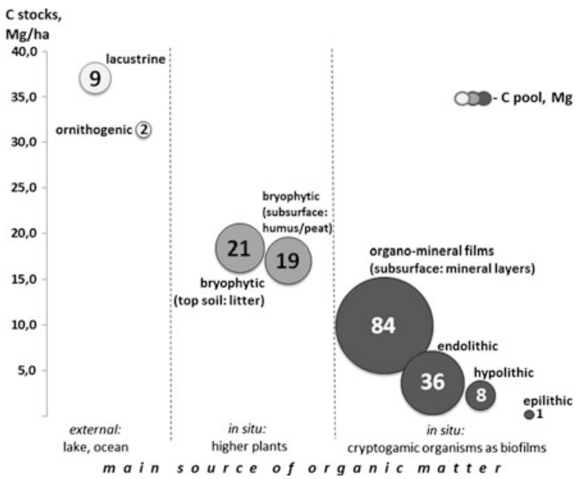

Fig. 5 Carbon stocks and pools at the key site in Larsemann Hills (S69° 20′, E76° 20′, wet valley, 27 ha area)

Specific* in situ *products of weathering and pedogenesis that contain carbon in organic or inorganic form are frequently encountered in the interior of endolithic system. Among them are carbonates which accumulate on an external surface of cyanobacterial biofilms (Fig. 6a); crystals of carbonates could also be found embedded in the cyanobacterial EPS (Fig. 6b). Recent studies widely confirm possibility of carbonates precipitation by cyanobacteria. Two mechanisms are involved: $CaCO_3$ crystals precipitation on the cell surface layer and extracellular sheath calcification in situ promoted by pH rise due to CO_2 depletion and OH^- increase during photosynthesis (Dupraz et al. 2009; Fundamentals of Geobiology 2012). Common features of a bleached eluvial zone and its vicinities are the oxalates crystals produced when exudates of endolithic fungi including oxalic acid and its derivates react with silicates and/or nonsilicate Fe compounds (Fig. 6c, d). The main sources of cations stabilizing oxalate and carbonate ions could be the feldspars. New born oxalates and carbonates are the products of pure in situ bio-mineral interactions, thus may also be considered as a proper pedogenic attribute.

Transportation network of endolithic system. Microtomography study helped to reveal the fractures, weathering foci and areas colonized by biofilms inside sampled monoliths, which were invisible from the surface. It is important that diagnostics

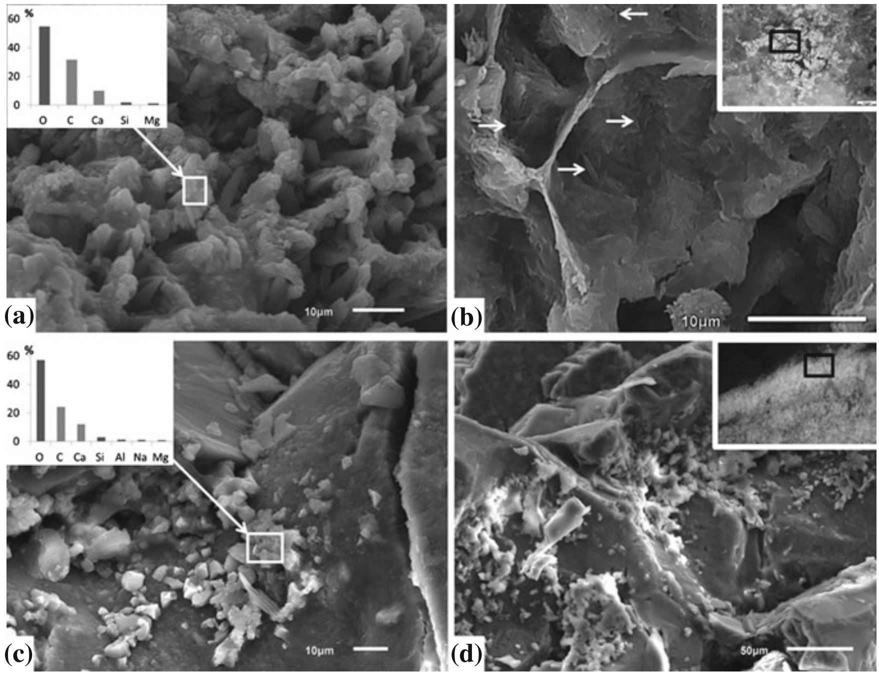

Fig. 6 Specific in situ products of endolithic weathering and pedogenesis. **a** Carbonates on an exterior of cyanobacterial biofilm; **b** carbonates formed within cyanobacterial EPS (pointed by *arrows*); **c**, **d** oxalates in bleached eluvial horizon

was held by noninvasive way without exfoliation plate being detached or destroyed. Target areas for further qualitative and quantitative study on SEM were identified.

The fracture network (Fig. 7) can clearly be divided into (a) perforating slightly branched subhorizontal fractures (20–200 μm) and (b) filamentous highly branched subvertical fractures (2–20 μm). Exfoliation of 10 mm thick plate occurs along major subhorizontal fissures which are populated by endolithic organisms to a maximum extent in comparison to the rest of the rock. The weathering zones of 0.1–1.0 mm size are formed here and can be clearly distinguished on tomography image due to the well-established grid of microfractures and numerous roundish pores creating a "perforated" microcellular pattern (Fig. 7a). The most advanced stage would have endolithic organomineral horizon formed along subhorizontal fractures which consists of individual mineral grains, dead and living biomass of endoliths, and sometimes even aggregates (according to mesomorphology study—Fig. 2d).

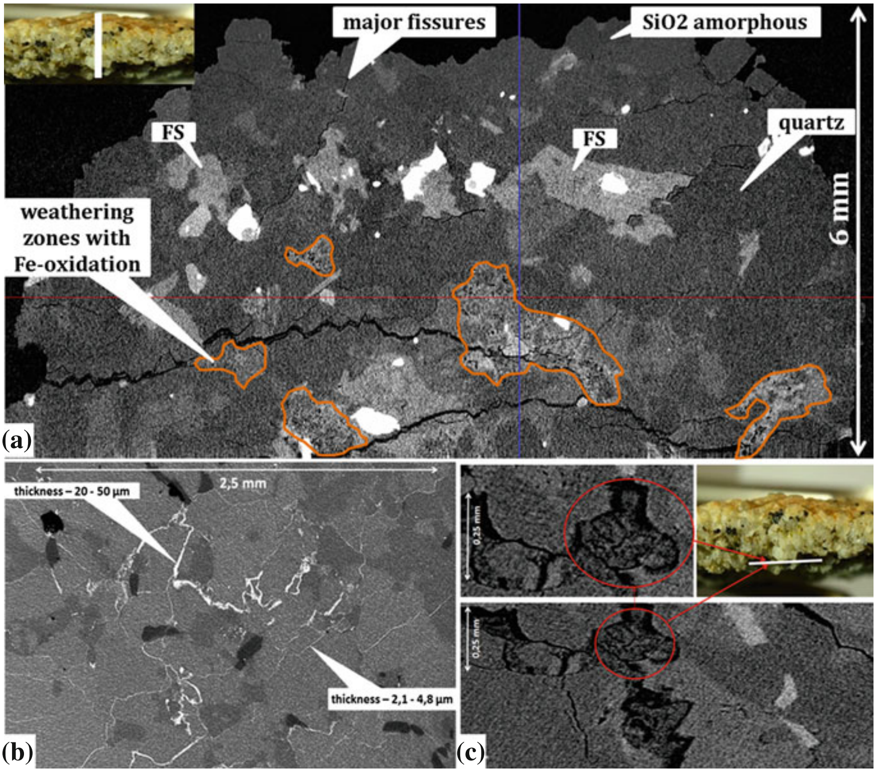

Fig. 7 X-ray microtomography (max resolution 1 μm) of endolithic system. **a** Vertical profile of exfoliation plate; **b** horizontal cross section—fissures network raising to the day surface of rock (image is in inverted color and fractures are shown in *white*); **c** pocket-like microzones with initial stage of fine earth formation on the lower surface of exfoliation plate

The most significant finding was the thin subvertical fractures in exfoliation plate rising to its current day surface (Fig. 7a, b) and connected to each other with thin subhorizontal ones. The fractures size may decrease to 1–2 μm, i.e., right to the limit resolution of the tomograph. The broken fractures that penetrate between the individual grains of minerals are widespread. 5–20 % of fractures have smoother pattern, they dissect weathered grains, mainly of feldspars. Weathering zones with microcellular patterns are formed in points of intersection between subvertical and subhorizontal fractures right in the body of exfoliation plate (Fig. 7a). According to X-ray microanalyzer (SEM), such areas have a higher content of Fe and C. Morphologically, either true biofilm or their derivatives—organomineral coatings containing, as impurities, Si, Al, C, K, Ca, Mg (thickness—1 or more microns) are present here. Initial stages of in situ fine earth formation were detected in pocket-like microzones (Fig. 7c).

The network of fine fractures connects zones depleted in Fe at the bottom of exfoliation plate with the oxidized Fe-enriched loci at its surface. Perhaps such a network acts as a transport system when an upward migration of iron in dissolved form occurs toward the surface of the plate right to the oxidative geochemical barrier. Mobilization/deposition of Fe can occur during rare wetting events and subsequent long desiccation of the granitoids surface in Antarctica. Thermogradient forces can also be involved.

Soil-like eluvial–illuvial differentiation on granitoids. Even the first works by Friedmann and Ocampo (1976), Friedmann (1982) examining functioning of endolithic communities in Beacon sandstones in Dry Valleys of Antarctica indicated bright deprived of Fe-(hydr)oxides layers less than several millimeters thick. It was assumed that they are linked with the vital activity of fungi, cyanobacteria and lichens that live in the interior of sandstone. However, exact mechanisms of this phenomenon have not been investigated in details and no analogies with the formation of bleached eluvial horizons of classical soils have been drawn.

In 2000s, series of studies primarily relating to techniques adjustment for exploring organo-mineral substrates by the means of Raman spectroscopy used Beacon sandstone as a research material. The approach was more about methodology and did not address the genesis of material, its environmental or soil interpretations. A change in composition of non-silicate minerals including transformation of hematite to goethite received particular attention in these studies. Mechanism of Fe mobilization from hematite, its migration and subsequent immobilization as goethite was proposed. This process formed microzones depleted and enriched in Fe. Besides that, oxalates were detected as specific products of endolithic lichen interaction with the minerals of sandstone (Villar et al. 2005; Russell et al. 1998; Edwards et al. 2004, 2005). Some bleached eluvial layers described in these studies were very well developed and their thickness reached 1 cm (Edwards et al. 2005).

We propose that the observed eluvial–illuvial soil-like differentiation inside granitoids of Thala Hills (Fig. 8a) is driven by endolithic biogenic pump, possibly endolithic protolichen (as described in Wierzchos and Ascaso 2001) and to a less extent by classical gravitational mechanism. Establishment of perpendicular

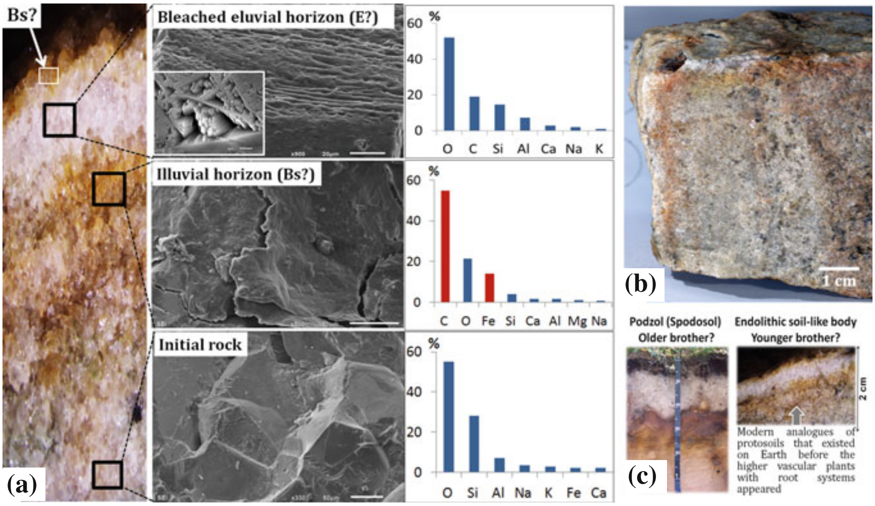

Fig. 8 Soil-like eluvial–illuvial differentiation on granitoids resembles “classical’ podzol. **a** Examples of morphology and elemental composition of bleached eluvial horizon, illuvial horizon and initial rock (*left* photo is out of scale and stretched vertically for display convenience); **b** monolith with endolithic system indicating that eluvial and illuvial horizons are established along perpendicular axes; **c** podzol and endolithic soil-like body with distinct eluvial–illuvial differentiation—older and younger “brothers”?

bleached horizons as well as oxidized ones in natural conditions is the best illustration of primarily nongravitational origin of this phenomenon (Fig. 8b).

Prior to this study, bleached layers of endolithic origin were described only for the sandstones (in Antarctica, Canada and South Africa), but never on granitoids. Could it be that common Podzol and endolithic soil-like body with distinct eluvial–illuvial differentiation—are the older and younger “brothers” (Fig. 8c)? It is disputable.

4 Discussion

Studies in East Antarctica oases propose that endolithic system has major features attributed to soils: (a) rock layer exposed to external abiogenic factors, (b) lithomatrix inhabited by living organisms which are synthesizing and decomposing organic matter, and (c) as a result initial parent rock (lithomatrix) is transformed in situ by biogenic and abiogenic factors, the products of transformation are retained and/or removed, the vertical heterogeneity is established in a form of microhorizons composing microprofile. Crucial feature also related to pedogenesis is the presence of endolithic organo-mineral horizon—the hotspot of biota-to-rock interactions, which is similar in its basic functions to organogenic and organo-mineral horizon of a common soil. Major products of endolithic rock transformation are the silty-sandy fine earth and abundant organo-mineral films that are formed within the porous space of endolithic system. Evidently, such films are the result of interaction between biofilms and mineral surfaces and reflect elemental composition of both components, mainly comprising C, O, Si, Al, Fe, K, Ca, Na, and Mg. Biofilms as complex formations create continuous organic layers, whose properties radically differ from the properties of the mineral matrix owing to the presence of polymeric substance. Biofilms on the mineral surface support a specific geochemical microenvironment that enhances substrate transformation. From our point of view, the newly formed organo-mineral films can be considered as in situ microproducts of pedogenesis.

Microtomography data shows that different layers of endolithic system are connected with the fracture network. Subtle branched subvertical (2–20 µm) and larger perforating subhorizontal fractures serve as a uniform network in the subsurface part of studied granitoids in East Antarctica. Thus, subaerial segment of explored rocks has mineral matrix, which is not sealed and is potentially permeable for dissolved products of endolithic weathering and pedogenesis. The fractures network is the possible transport system for the elements transfer in the interior of the upper 1–2 cm of granitoid that makes eluvial–illuvial differentiation possible. Differentiation occurs as a result of an upward and downward migration of solutions due to biogenic transfer of elements between components of endolithic systems (e.g., transfer between photobiont and mycobiont in endolithic lichen, siderophores carrier functions, etc.), hydro and thermal gradients, and to a less under the influence of downward gravity flows as common to "classic" Podzols. The real mechanisms should be confirmed by additional studies, including computer microtomography, SEM, Mössbauer spectroscopy, and chemical analysis of Fe compounds. But, in any case, the presence of an integrated transport system in hard rock, connecting the individual parts of endolithic system (e.g., organo-mineral horizons, exfoliation plates, bedrock, etc.) is a fact and it is crucial for relating such bodies to soils and soil-like bodies.

The more developed endolithic system becomes, the greater are the chances for its destruction and lower probability that initial endolithic soil-like body will turn into a common full-scale soil. Macrohorizons are never formed due to periodic rejuvenation of the rock surface by exfoliation. Besides that, the fine earth is removed by wind and allocated in accumulative positions where it enriches elemental and isotopic record of loose soils (Hopkins et al. 2009). Such kind of initial pedogenesis was called previously as "self-destructive" (Mergelov et al. 2012). Bleached eluvial microhorizons are the borderlines and weakest links that readily promote exfoliation and restrict full-scale pedogenesis in situ. This mode is common to other soils of extreme environment whose thin primitive profiles are often found in the quasi-equilibrium state with external conditions for hundreds and thousands of years. They are not transformed into the mature full-scale soil bodies because of the very low biogeochemical transformation rate and the high intensity of catastrophic processes and disturbances (exfoliation in our case). Such bodies can be referred as "infantile" soils: though their absolute age may be considerable

($n \times 10^2$–10^4 years), their morphology corresponds to the very initial stages of pedogenesis that are relatively quickly (in about $n \times 10^1$ years) replaced in more favorable environment by the more advanced stages. Such soils can be considered as modern analogues of protosoil bodies that existed on our planet before higher vascular plants with root systems appeared and contributed as major sources of humus (Kudinova et al. 2015).

5 Conclusion

The study of endolithic weathering front with the approaches of soil science showed that microprofiles established in granitoids morphologically and functionally are very similar to a common soil. Different horizons of this body are connected with the fracture network, which serves as a transport system for elements transfer. It leads to a unique result—the soil-like pattern is established inside the massive-crystalline rock. The profiles being examined have clear eluvial–illuvial differentiation patterns similar to macroprofile of a common Podzol (Spodsol) on loose substrates. It is unusual that this phenomenon is found in formally arid conditions and in the absence of higher plants. Due to the nature of the substrate (massive crystalline rock), position in the landscape (rock outcrops), and bioclimatic extremes (endolithic ecological niche), the thickness of profiles and horizons are one to three orders of magnitude less than in common Podzols. We propose quite a disputable statement that common Podzol and endolithic soil-like body with distinct eluvial–illuvial differentiation—are the older and younger "brothers." Besides that, endolithic soil-like bodies could be the modern closest analogues of protosoils that existed on Earth before the higher vascular plants with root systems established. More systematization and understanding of the place these objects occupy in the soils world is needed since endolithic weathering patterns are among the most spatially abundant soil-like bodies in extreme environment of Antarctica; besides that, they secure primarily-produced organic matter pool in these barren rocky landscapes.

Acknowledgments This work has been supported by the Russian Science Foundation; project no. 14-27-00133. Authors are grateful to Prof. Sofia Lessovaia and Prof. Dmitry Vlasov from Saint Petersburg State University for their assistance in micromorphology studies and inspiration.

References

Brehm U, Gorbushina A, Mottershead D (2005) The role of microorganisms and biofilms in the breakdown and dissolution of quartz and glass. Palaeogeogr Palaeoclimatol Palaeoecol 219 (1):117–129

De Los Ríos A, Wierzchos J, Sancho LG, Ascaso C (2003) Acid microenvironments in microbial biofilms of Antarctic endolithic microecosystems. Environ Microbiol 5(4):231–237

De Los Ríos A, Grube M, Sancho LG, Ascaso C (2007) Ultrastructural and genetic characteristics of endolithic cyanobacterial biofilms colonizing Antarctic granite rocks. FEMS Microbiol Ecol 59(2):386–395

De Los Ríos A, Wierzchos J, Ascaso C (2014) The lithic microbial ecosystems of Antarctica's McMurdo Dry Valleys. Antarct Sci 26(05):459–477

Dmitriev EA (1996) Soils and soil-like bodies. Eurasian Soil Sci 29(3):275–282

Dupraz C, Reid RP, Braissant O, Decho AW, Norman RS, Visscher PT (2009) Processes of carbonate precipitation in modern microbial mats. Earth Sci Rev 96(3):141–162

Edwards HG, Wynn-Williams DD, Villar SEJ (2004) Biological modification of haematite in Antarctic cryptoendolithic communities. J Raman Spectrosc 35(6):470–474

Edwards HG, Moody CD, Villar SEJ, Wynn-Williams DD (2005) Raman spectroscopic detection of key biomarkers of cyanobacteria and lichen symbiosis in extreme Antarctic habitats: evaluation for Mars Lander missions. Icarus 174(2):560–571

Friedmann EI (1982) Endolithic microorganisms in the Antarctic cold desert. Science 215 (4536):1045–1053

Friedmann EI, Ocampo R (1976) Endolithic blue-green algae in the dry valleys: primary producers in the Antarctic desert ecosystem. Science 193(4259):1247–1249

Friedman I, Lipkin Y, Roseli OP (1967) Desert algae of the Negev. Phycologia 6:185–200

Gilichinsky D, Abakumov E, Abramov A, Fyodorov-Davydov D, Goryachkin S, Lupachev A, Mergelov N, Zazovskaya E (2010) Soils of mid and low Antarctic: diversity, geography, temperature regime. In: Proceedings of the 19th world congress of soil science. Published on DVD. www.iuss.org. Symposium WG 1.4. Cold soils in a changing world. Brisbane, Australia, pp 32–35

Glazovskaya MA (1958) Weathering and initial soil formation in Antarctica. Nauch Dokl Vyssh Shkoly Geol Geogr-Nauki 1:63–76 (in Russian)

Golubic S, Schneider J (2003) Microbial endoliths as internal biofilms. In: Fossil and recent biofilms. Springer, Netherlands

Golubic S, Friedmann I, Schneider J (1981) The lithobiontic ecological niche, with special reference to microorganisms. J Sediment Res 51(2):475–478

Hopkins DW, Sparrow AD, Gregorich EG, Elberling B, Novis P, Fraser F, … Greenfield LG (2009) Isotopic evidence for the provenance and turnover of organic carbon by soil microorganisms in the Antarctic dry valleys. Environ Microbiol 11(3):597–608

Horath T, Bachofen R (2009) Molecular characterization of an endolithic microbial community in dolomite rock in the Central Alps (Switzerland). Microb Ecol 58(2):290–306

Ivlev AM, Nesterova OV (2004) On the study of aquasols. Vestn DVO RAN 4:47–52 (in Russian)

Johnston CG, Vestal JR (1991) Photosynthetic carbon incorporation and turnover in Antarctic cryptoendolithic microbial communities: are they the slowest-growing communities on earth? Appl Environ Microbiol 57(8):2308–2311

Knoll AH, Canfield DE, Konhauser KO (eds) (2012) Fundamentals of geobiology. Wiley, New York

Kögel-Knabner I, Guggenberger G, Kleber M, Kandeler E, Kalbitz K, Scheu S, … Leinweber P (2008) Organo-mineral associations in temperate soils: integrating biology, mineralogy, and organic matter chemistry. J Plant Nutr Soil Sci 171(1):61–82

Kudinova AG, Lysak LV, Soina VS, Mergelov NS, Dolgikh AV, Shorkunov IG (2015) Bacterial communities in the soils of cryptogamic barrens of East Antarctica (the Larsemann Hills and Thala Hills oases). Eurasian Soil Sci 48(3):276–287

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

Roslikova VA (2006) Modern notions on the subaqual pedogenesis. Tikhookean Geol 25(4):97–103

Russell NC, Edwards HGM, Wynn-Williams DD (1998) FT-Raman spectroscopic analysis of endolithic microbial communities from Beacon sandstone in Victoria Land, Antarctica. Antarct Sci 10(01):63–74

Schmidt MW, Torn MS, Abiven S, Dittmar T, Guggenberger G, Janssens IA, … Trumbore SE (2011) Persistence of soil organic matter as an ecosystem property. Nature 478(7367):49–56

Semikolennykh AA, Targulian VO (2010) Soil-like bodies of autochemolithotrophic ecosystems in the caves of the Kugitangtau Ridge, eastern Turkmenistan. Eurasian Soil Sci 43(6):614–627

Sigler WV, Bachofen R, Zeyer J (2003) Molecular characterization of endolithic cyanobacteria inhabiting exposed dolomite in central Switzerland. Environ Microbiol 5(7):618–627

Sokolov IA (1996) The paradigm of pedology from Dokuchaev to the present day. Eurasian Soil Sci 29(3):222–232

Sun HJ, Friedmann EI (1999) Growth on geological time scales in the Antarctic cryptoendolithic microbial community. Geomicrobiol J 16(2):193–202

Targulian VO, Goryachkin SV (2011) The 19th world congress of soil science. Eurasian Soil Sci 44(9):1041–1047

Villar SEJ, Edwards HG, Cockell CS (2005) Raman spectroscopy of endoliths from Antarctic cold desert environments. Analyst 130(2):156–162

Walker JJ, Pace NR (2007) Phylogenetic composition of Rocky Mountain endolithic microbial ecosystems. Appl Environ Microbiol 73(11):3497–3504

Wierzchos J, Ascaso C (2001) Life, decay and fossilisation of endolithic microorganisms from the Ross Desert, Antarctica. Polar Biol 24(11):863–868

Wierzchos J, Sancho LG, Ascaso C (2005) Biomineralization of endolithic microbes in rocks from the McMurdo Dry Valleys of Antarctica: implications for microbial fossil formation and their detection. Environ Microbiol 7(4):566–575