Lithobiotic cyanobacteria diversity of the Karelian Isthmus

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Abstract

This work presents data obtained as a result of studying the composition of cyanobacteria in lithobiotic communities on various substrates (Ruskeala marble, rapakivi-granite, granite gneiss) in different light conditions on the territory of the Karelian Isthmus: Leningrad Oblast, Republic of Karelia, and South Finland. The species composition of cyanobacteria was revealed, and the species composition on certain types of substrates was analyzed. A total of 49 species of cyanobacteria were noted for the Republic of Karelia (13 of which were not previously recorded in this territory). The detailed taxonomic and environmental characteristics of species are given. Changes in the species diversity of cyanobacteria in connection with specific habitats are shown. The type of substrate, the degree of moisture, and illumination are noted as the main factors determining the diversity of cyanobacteria in lithobiotic communities.

Keywords: biofilms, cyanobacteria, lithobiotic communities, Ruskeala marble, rapakivi-granite

Introduction

Cyanobacteria are one of the most diverse groups of bacteria. They are often primary colonizers of bare areas of rock (Whitton, 1992; Gromov, 1996) because their life processes require only water, carbon dioxide, inorganic substances, and light.

Due to their efficient adaptive capacity, cyanobacterial colonies form frequent biofilms in different terrestrial habitats (Gorbushina, 2007; Rossi and De Philippis, 2015; Davydov and Patova, 2018). Different cyanobacterial species often were noted on infertile substrates such as desert sand or volcanic ash, at the stone-soil interface, and in endolithic niches in all Earth biomes (Jaag, 1945; Weber, Wessels and Büdel, 1996; Büdel, 1999; Mur, Skulberg and Utkilen, 1999; Pentecost and Whitton, 2000; Golubic and Schneider, 2003).

The functioning processes of lithobiotic systems and the various environments that influence these processes have not been sufficiently studied. The conditions of existence on the surface of the stone are considered close to extreme. Being in a thin surface layer, microorganisms are exposed to sharp fluctuations in humidity, temperature, pH, and light. Most often these are slow-growing organisms that are resistant to harsh environmental conditions. (Gorbushina, Lialikova, Vlasov and Khizhniak, 2002; Keshari and Adhikary, 2013).

The exopolysaccharide substance (EPS) of microbial origin contributes to the colonization of the mineral substrate by cyanobacteria and has an integrating function (Beech and Gaylarde, 1991). Cyanobacteria that actively produce EPS

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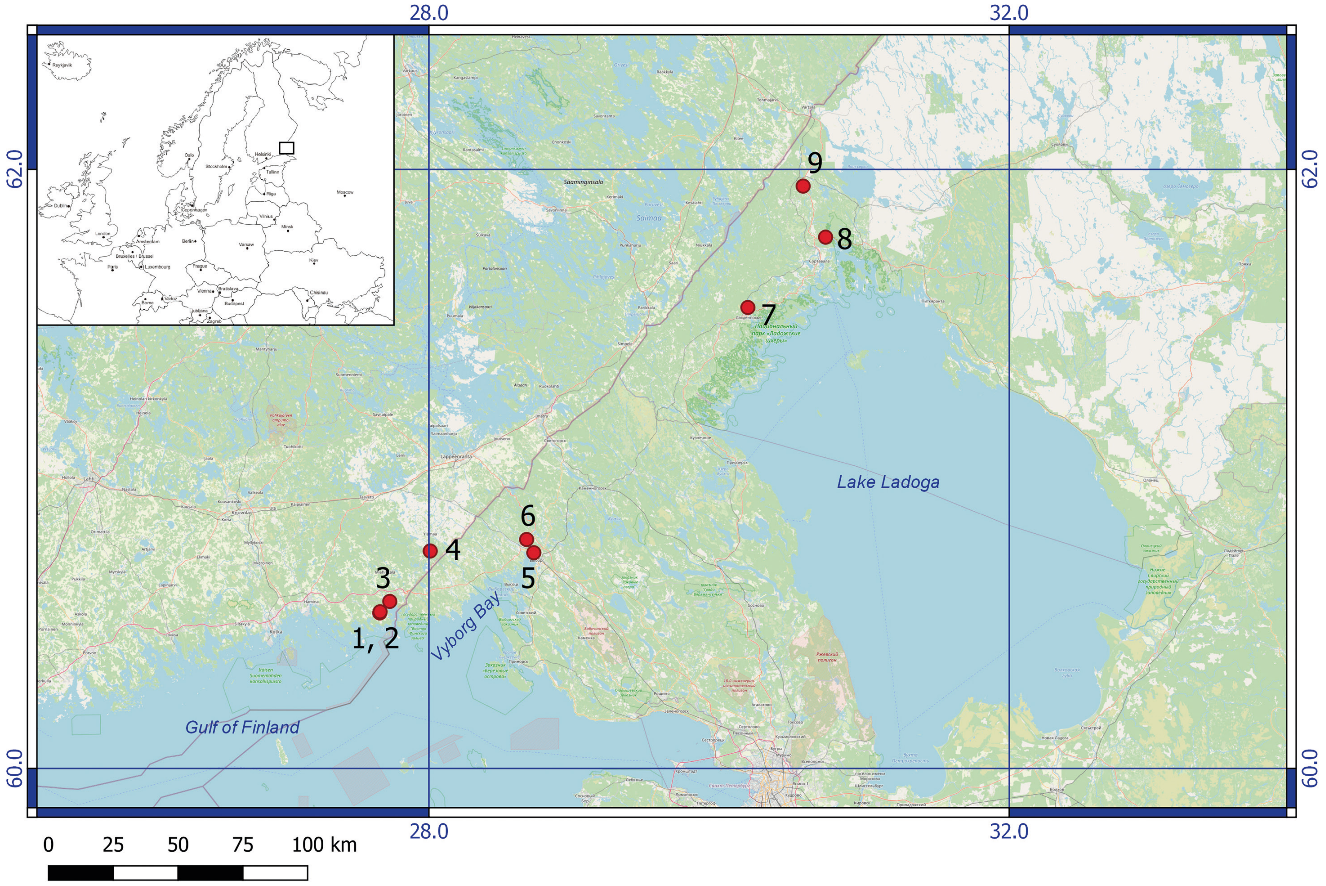

Fig. 1. Map of sampling sites: 1–4 are granite quarries, Southern Finland; 5 — Monrepos Park; 6 — Vyborg tunnels; 7 — Ristijarvi Park; 8 — Owl Mountain; 9 — Ruskeala Park. Numbers of sample plots as in Table 1.

contribute to the retention of moisture and the accumulation of organic matter, creating conditions for the development and accumulation of saprotrophic bacteria and fungi (Crispim, Gaylarde and Gaylarde, 2003).

The lithobiotic organisms could be considered as several different groups: chasmoendoliths and cryptoendoliths occupy preexisting fissures and structural cavities in the rocks, whereas euendoliths penetrate soluble carbonate and phosphate substrates (Golubic, Friedmann and Schneider, 1981).

If the biofilm is formed on a rock surface (at the boundary of the solid and air phase), it is called a subaerial biofilm (SAB). In natural conditions, such biofilms are hard, dry plates or biological soil crusts. On vertical surfaces, they form films in the form of colored smudges (Gorbushina and Broughton, 2009). Biofilms occupy a significant part of the earth's surface and play a significant role in the circulation of matter and energy, in the weathering of rocks and soil formation processes (Krasilnikov, 1949; Glazovskaya and Dobrovolskaya, 1984; Grbić et al., 2010; Sancho, Maestre and Büdel, 2014; Davydov and Redkina, 2021).

In general, the analysis of the literature data indicates the important role of cyanobacteria in primary lithobiotic communities formed under a wide variety of environmental conditions.

The relevance of the topic is associated with the fundamental role of cyanobacteria in the colonization of the mineral substrate. At the same time, a comparative study of the composition and structure of cyanobacterial communities on different rocks under different environmental conditions may be of particular interest. Based on the results of such a study, it is possible to answer the question of what factors most affect the diversity of this group of prokaryotes inhabiting carbonate and silicate rocks. These issues still remain insufficiently studied. The biodiversity of cyanobacteria can be very high, including in poorly studied geographic regions (Nabout, Da Silva Rocha, Carneiro and Sant'Anna 2013; Gaysina, Bohunická, Hazuková and Johansen, 2018). Since morphological features have traditionally been the main criterion for the classification and identification of cyanobacteria, most of the studies conducted to date have relied almost entirely on morphology-based methods

Table 1. Description of localities studied

Substrate	Place	Location	Description of localities	Number of samples
Marble	Ruskeala (9)*	N 61°56'45" E 30°34'49"	The Ruskeala quarry is located in the Northern Ladoga region (the Republic of Karelia, near Sortavala town). Currently, it is a monument of mining. We examined this area for the first time to determine the composition of cyanobacteria in lithobiotic biofilms at open rock surfaces in 2016 (Kuznetsova et al., 2016). For this research, sampling was carried out in open areas of rock surfaces and in tunnels with artificial lighting and poorly lit areas.	40
Granite and Granite gneiss	Southern Finland (1–4)*	Montferrand quarry (Quarry I) (3) N 60°34'12,4", E 027°43'50.1"; Quarry II (2) N 60°31'51,3" E 027°39'41.9"; Quarry III (1) N 60°32'6,1" E 027°39'49.4"; Quarry IV (4) N 60°44'24,8" E 028°0'33.8".	For the study of granites, four rapakivi-granite quarries were selected on the territory of Finland, where a stone was extracted for the construction of famous architectural structures in St Petersburg. Montferrand Quarry is one of the famous quarries. Granite mining here was stopped in the 19th century. The quarry was preserved as a mining monument. Now the quarries are privately owned by the Finns, and they are open to visitors. The quarry is located in the forest near the settlement of Peterlahti (Virolahti) on the shore of the Gulf of Finland in southeastern Finland, almost on the border with Russia. Currently, the quarry is undergoing gradual natural overgrowth. In addition to the Montferrand Quarry, which was the main focus, there are other granite outcrops in the same area, which were also investigated.	24
	Ristijarvi (7)*	N 61°46'48" E 30°44'6"	About two billion years ago, this area was the mouth of the Kiryavolakhtinsky volcano (Ladoga volcano of the Lower Proterozoic era). Its length reached 60–80 km, width was 30–40 km, and height — 2.5 km. Over the past two billion years, under the influence of the sun, wind, and precipitation, the mighty Kiryavolakhtinsky volcano was largely destroyed. Its central part, which was in the zone of tectonic-magmatic uplift of the granite gneiss dome, was completely eroded, up to the granite base. It is here, in the center of the former volcano, that the modern Ristijarvi Lake is located. The lake is surrounded by high (up to 100–140 m) and steep rocks, composed of granites and granite gneisses, formed in the Archean.	6
	Monrepos Park (5)*	N 60°44'01" E 28°43'29"	Rock landscape park on the shore of the Protective Bay of the Vyborg Bay, on Tverdysh Island in the northern part of Vyborg town, Leningrad Oblast, located on the territory of the State Historical, Architectural and Natural Museum-Reserve Monrepos Park. The territory of the park consists of two large sections, adjacent to the south and north to the historical core of the park. It is characterized by unique Ice Age stone ridges of rapakivi-granite (Karel. rapakivi — “rotten stone”), in some areas reaching a height of 20 m.	2
	Vyborg tunnels (6)*	N 60º46'23" E 28º40'13"	Biofilms from poorly lit and heavily shaded (underground) areas of the rapakivi-granite rock surface were studied in the territory of three tunnels near the “Iron Forest” Museum (“Rautakorpi”), Vyborg District. These are tunnels cut out of the rock, from the time of the First World War, which served as Finnish artillery depots. Sampling was at a depth of 3 to 5.5 m from the entrance with a gradient decrease in illumination.	13
	Owl Mountain (8)*	N 61º32'59.9" E 30º11'56.9"	Owl Mountain is a military-historical and geological museum, located in South Karelia in Lahdenpokhya town. The location of the object is unique — it is a huge man-made bunker inside a powerful granite rock with two entrances inside. On the vertical walls at the entrance to the bunker, biofilms with the participation of cyanobacteria are actively formed. The substrate is a gray granite gneiss (close to the rapakivi-granite).	8

*The numbers in brackets correspond to the points in Fig. 1.

(Alvarenga, Rigonato, Branco and Fiore, 2015). Nienow (1996) indicates 70 cyanobacteria genera involved in the formation of subaerial communities. Of these, the order Chroococcales is the leader in the number of species—34 genera (49 %) (Nienow, 1996). In this order, the genus *Gloeocapsa* is represented by the greatest variety of species for the carbonate substrates of caves in Bulgaria (a total of 59 cyanobacteria species were noted) (Draganov and Dimitrova-Burin, 1977). For speleoobjects, the intensity of illumination is also a key factor in the algae distribution. For example, green algae predominate in grottoes, as ecologically more comfortable habitats, while the algoflora of caves was characterized by lower species diversity and a significantly higher proportion of cyanobacteria (40–70 % of the species composition) (Vinogradova and Mikhailyuk, 2009). In the Left-bank cave in Leningrad Oblast, nine cyanobacteria species (31 % of the species composition of algae) were identified (Abdullin, 2012). The flora of lithobiotic communities on the territory of the Karelian Isthmus remains poorly studied. For the Republic of Karelia and Leningrad Oblast, the flora of aquatic habitats is mainly known.

The aim of our work was to identify the species composition of cyanobacteria on rock surfaces (Ruskeala marble and rapakivi-granite) under various environments (rock outcrops, quarries, and tunnels).

Materials and methods

The investigated area is situated on the northeastern part of the Baltic region. We studied cyanobacterial diversity of the Karelian Isthmus: Leningrad Oblast, Karelia, and South Finland. All samples were collected by the senior author in 2015–2018 (Fig. 1, Table 1).

Samples were taken at the sites of color and surface substrate changes. Wet samples were collected in sterile containers and tubes with a volume of up to 120 ml. Dry samples were collected in sterile containers and Kraft envelopes. Samples were taken with a sterile scalpel, because biofilms dominated by cyanobacteria are most often easily separated from the substrate. Where possible, biofilms were taken together with small pieces of substrate. The storage of samples is provided by the herbarium of the Polar-Alpine Botanical Garden-Institute (KPABG).

Characteristics of the studied substrates

In the study area, there are rocks of different geological origin. Most of the territory of study is located within felsic rocks. In contrast, the Ruskeala marble quarry site belongs to **carbonate rocks**. It includes not only calcite but also dolomite, unlike numerous analogs. The color of Ruskeala marble varies from dark gray and black to snow-white, sometimes with greenish stripes and nests up to several centimeters wide; the structure is fine-grained. Ruskeala marble is divided into 3 groups: calcite, dolomite, and calcite-dolomite (Bulakh, 1999).

The physical and mechanical properties of Ruskeala marbles are the following: density 2750–2820 kg/m^3; water absorption 0.1–0.2 %; compressive strength from 200 MPa to 80 MPa (Borisov, 2001).

A greater variety of substrata were found among **felsic rocks**.

Rapakivi-granite (Finnish "rapakivi", of "rapa" (meaning mud or sand) and "kivi" (meaning rock or stone)) refers to double-feldspar granites of high alkalinity with a characteristic structure due to the presence of large ovoids of potassium feldspar, usually surrounded by oligoclase borders. This structure causes the relatively rapid destruction of the rock to which it owes its name, which in Finnish means "rotten stone". The color of rapakivi is gray and pink. Dark-colored minerals are represented by biotite and high-ferruginous hornblende; accessory minerals are titanomagnetite, olivine, fluorite, apatite, and zircon. In composition, rapakivi belongs to alkaline granites or granosienites with a high content of Fe. Rapakivi density is about 2650 kg/m^3, porosity is 0.3 %, water absorption is 0.15–1.30 %, and compression resistance is 100–200 MPa.

Granite gneiss is full-crystalline banded or shale rock, and its composition is similar to granite. Granite gneiss structure occupies an intermediate position between granite and gneiss. The texture is due to the subparallel arrangement of tabular and prismatic crystals (mica, hornblende, feldspar) and elongated inclusions, as well as the accumulation of individual minerals in alternating bands or interlayers (the so-called gneiss-like texture). Most researchers consider granite gneisses as granites that crystallized in the deep zones of the earth's crust during the cooling of the magmatic melt under conditions of directional pressure or during the movement of magma, resulting in a parallel orientation of minerals. The bodies of such granite gneisses have secant contacts with the host rocks.

Laboratory research methods

Species identification was carried out using light microscopy (Leica DM 1000 microscope) by direct microscopy of samples. Cultural methods were also used. To obtain accumulative cultures, fragments (biofilm pieces or fragments of the substrate with biofilms on their surface) of all samples were placed in distilled water, in the liquid Gromov-6 medium, as well as in the medium Z8 and BG-11 (Kotai 1972; Rippka, 1988; Waterbury, 2006). Isolation of pure cultures was carried out from accumulative cultures by successive inoculations onto BG-11 agar medium. The cultures were stored on BG-11 agar medium and Z8 liquid medium.

Part of the material was examined under a scanning electron microscope in the magnification range from 100x to 10,000x. SEM studies were performed on a TM 3000 electron microscope (HITACHI, Japan, 2010) with an OXFORD energy-dispersive microanalysis device at the SPbU Microscopy and Microanalysis Resource Center.

The species composition of cyanobacteria was determined by morphological characteristics, using identification guides (Komárek and Anagnostidis, 1998, 2005; Komárek, 2013). Data on the geographical distribution of the species and their ecological characteristics are provided in accordance with CRIS database (Melechin, Davydov, Shalygin and Borovichev, 2013; Melekhin et al., 2019). The names of geographical elements are cited according to Konstantinova (2000). The geographical elements are distinguished by Davydov (2010b).

The principal component method was performed using the Statistica 8.0 software. Samples were selected as objects (n = 76), and the presence of species taxa in the sample (90 species in total) was selected as features.

Flora similarity was determined by the ExcelToR software (Novakovskiy, 2016) based on the Sørensen index: KS = 2a/(2a + b + c), where a is the number of species common to both sets, b — the number of species unique to the first set, and c — the number of species unique to the set.

Results and discussion

Taxonomic analysis of cyanobacteria diversity in lithobiotic communities

In this research, 90 species taxa of cyanobacteria belonging to 4 orders, 17 families, and 31 genera were identified by morphological features. A complete taxonomic list of identified cyanobacteria is given in Table 2.

The order Nostocales is represented by the largest number of families (6). The smallest number of genera (4) is represented by the order Oscillatoriales; the other orders contain 9 genera each. A total of 30 taxa at the species level were identified in Chroococcales; in Synechococcales — 33 taxa. Of the 17 families, the most widely represented is Leptolyngbyaceae (16 species). *Leptolyngbya* is the genus with the most species diversity and occurrence frequency (Fig. 2), which includes 13 species (14 % of the identified diversity). The taxonomic analysis of the identified cyanobacteria of the lithobiotic communities is given in Table 3.

The presented results are corresponding with some published data. For example, species of the genera *Gloeocapsa*, *Gloeothece*, *Chamaesiphon*, *Calothrix*, *Tolypothrix*, and *Scytonema* are especially characteristic of irrigated rocks (Wasser, Kondratyeva and Masyuk, 1989), most of which were noted in our studies.

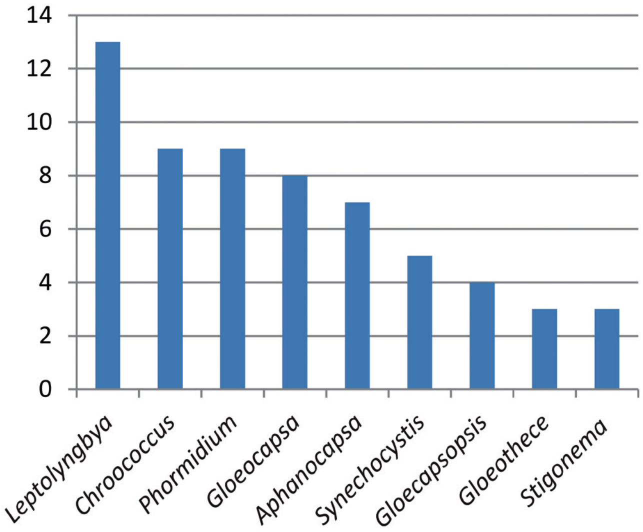

Fig. 2. The number of species taxa for the most widely represented genera of cyanobacteria.

However, when compared with a specific region (Murmansk Oblast), the most studied in relation to terrestrial cyanobacterial communities, we noted some differences, primarily related to the diversity of species within genera. Thus, the genera *Gloeocapsa* (7 species), *Nostoc* (7), *Phormidium* (7), *Leptolyngbya* (6), *Chroococcus* (5), and *Calothrix* (5) are widely represented in this territory (Davydov, 2010a). In the present study, the genus *Leptolyngbya* (13 species) is in the first place. The genera *Nostoc* and *Calothrix* contained only two species of taxa each. Such differences are most likely associated with the characteristics of the studied biotopes. In this study, only lithobiotic (epilitic) communities were considered, while in Murmansk Oblast, soil habitats were also studied. As an example, the genus *Nostoc*, which is more typical for soils, falls out of our general list.

We found 38 species on marble and 76 on granite. A comparison of the species lists of cyanobacteria found on carbonate and silicate rocks using the Sørensen index of species similarity shows a medium degree of similarity — 53 %.

The distribution of cyanobacteria species by geographical elements (Davydov, 2010b) shows that among species with a known geographical distribution (49 species), there is a predominance of cosmopolitan species (Fig. 3). Stony substrates can be classified as difficult for living organisms. These substrates are usually colonized by either highly specialized species or species with a wide range of resistance to environmental factors. Only 11 % of identified species are associated with mountain habitats (montane, arctomontane, arctoborealmontane (Davydov, 2010b)).

Table 2. Cyanobacteria species composition on rock surfaces from Ruskeala marble and granite of Leningrad Oblast, Karelia and South Finland

Taxon	Ruskeala (marble)	Common For Granite	Vyborg tunnels	Quarry I	Quarry II	Quarry III	Quarry IV	Ristijarvi	Owl mountain	Monrepos Park
Anabaena sp.	1									
Aphanocapsa fusco-lutea Hansg.		1	1							
Aphanocapsa parietina Näg.		1			1			1		
Aphanocapsa sp. 1	1	1	1					1		
Aphanocapsa sp. 2		1	1							
Aphanocapsa sp. 3		1	1							
Aphanocapsa holsatica (Lemm.) G. Cronb. et Komárek		1					1			
Aphanocapsa muscicola (Menegh.) Wille		1			1	1				
Aphanothece castagnei (Bréb.) Rabenh.		1							1	
Aphanothece saxicola Näg.		1						1		
Calothrix parietina Thur. ex Born. et Flah.	1	1	1		1		1	1	1	
Calothrix sp.		1					1		1	
Chalicogloea sp.	1	1	1						1	
Chondrocystis dermochroa (Näg.) Komárek et Anagn.		1		1						
Chroococcus cohaerens (Bréb.) Näg.	1									
Chroococcus minor (Kütz.) Näg.	1	1			1		1			
Chroococcus minutus (Kütz.) Näg.	1	1					1			
Chroococcus pallidus (Näg.) Näg.		1						1	1	
Chroococcus sp.	1									
Chroococcus spelaeus Erceg.	1	1						1		
Chroococcus turgidus (Kütz.) Näg.	1									
Chroococcus varius A. Braun		1						1	1	
Cyanobium gaarderi (Ålvik) Komárek et al.		1			1					
Cyanothece aeruginosa (Näg.) Komárek	1	1					1			
Eucapsis sp.	1									

Taxon	Ruskeala (marble)	Common For Granite	Vyborg tunnels	Quarry I	Quarry II	Quarry III	Quarry IV	Ristijarvi	Owl mountain	Monrepos Park
Gloeocapsa alpina (Näg.) Brand	1	1					1			
Gloeocapsa compacta Kütz.	1	1			1			1		
Gloeocapsa kuetzingiana Näg.	1	1	1						1	
Gloeocapsa punctata Näg.	1	1					1			
Gloeocapsa rupestris Kütz.		1			1					
Gloeocapsa sp.	1									
Gloeocapsa violascea (Corda) Rabenh.	1	1	1							
Gloeocapsa atrata Kütz.	1	1		1	1	1	1			
Gloeocapsopsis magma (Bréb.) Komárek et Anagn.	1	1	1	1	1	1	1			
Gloeocapsopsis sp. 1		1							1	
Gloeocapsopsis sp. 2	1									
Gloeocapsopsis crepidinum (Thur.) Geitl. ex Komárek		1			1					
Gloeothece palea (Küzt.) Rabenh.	1	1		1						
Gloeothece rupestris (Lyngb.) Born.	1	1							1	
Gloeothece sp.	1									
Hapalosiphon pumilus Kirchn. ex Born. et Flah.		1		1						
Jaaginema geminatum (Menegh. ex Gom.) Anagn. et Komárek		1					1			
Jaaginema pseudogeminatum (G. Schmid) Anagn. et Komárek		1			1					
Johannesbaptistia pellucida (Dickie) W. R. Taylor et Drouet		1				1				
Johannesbaptistia schizodichotoma (J. J. Copeland) Komárek et Anagn.		1				1				
Leptolyngbya amplivaginata (Van Goor) Anagn. et Komárek		1				1				
Leptolyngbya cebennensis (Gom.t) I. Umezaki et M. Watanabe		1					1			
Leptolyngbya foveolarum (Rabench. ex Gom.) Anagn. et Komárek	1	1						1	1	
Leptolyngbya gracillima (Hansg.) Anagn. et Komárek	1	1		1	1	1	1			
Leptolyngbya lagerheimeii (Gom.) Anagn. et Komárek		1			1					

Taxon	Ruskeala (marble)	Common For Granite	Vyborg tunnels	Quarry I	Quarry II	Quarry III	Quarry IV	Ristijarvi	Owl mountain	Monrepos Park
Leptolyngbya perelegans (Lemm.) Anagn. et Komárek		1					1			
Leptolyngbya sieminskae D. Richter et Matula	1	1						1	1	
Leptolyngbya sp. 1	1	1	1					1	1	
Leptolyngbya sp. 2	1									
Leptolyngbya sp. 3	1									
Leptolyngbya valderiana (Gom.) Anagn. et Komárek		1			1					
Leptolyngbya angustissima (W. West et G. S. West) Anagn. et Komárek		1			1		1			
Leptolyngbya tenuis (Gom.) Anagn. et Komárek		1			1					
Lyngbya martensiana Menegh. ex Gom.		1								1
Lyngbya sp.		1		1						
Microchaete tenera Thur. ex Born. et Flah.		1							1	
Microcoleus paludosus Gom.		1					1			
Microcoleus vaginatus Gom. ex Gom.		1								1
Microcystis pulverea (H. C. Wood) Forti		1			1					
Nostoc commune Vauch. ex Born. et Flah.	1	1	1					1	1	
Nostoc microscopicum Carm. ex Born. et Flah.		1					1			
Petalonema incrustans Komárek	1									
Phormidesmis molle (Gom.) Turicchia et al.		1				1				
Phormidium breve (Kütz. ex Gom.) Anagn. et Komárek		1					1			
Phormidium corium Gom. ex Gom.		1					1			
Phormidium granulatum (N. L. Gardner) Anagn.		1				1				1
Phormidium interruptum Kütz. ex Forti		1					1			
Phormidium inundatum Kützi. ex Gom.t		1					1			
Phormidium papyraceum (C. Ag.) Gom.	1	1					1			
Phormidium sp.	1									

Taxon	Ruskeala (marble)	Common For Granite	Vyborg tunnels	Quarry I	Quarry II	Quarry III	Quarry IV	Ristijarvi	Owl mountain	Monrepos Park
Phormidium tergestinum [Kütz.] Anagn. et Komárek	1									
Phormidium puteale (Mont. ex Gom.) Anagn. et Komárek	1									
Planktolyngbya bipunctata (Lemm.) Anagn. et Komárek		1			1					
Planktolyngbya limnetica (Lemm.) Kom.-Legn. et G. Cronberg		1					1			
Scytonema hofmanii C. Ag. ex Born. et Flah.		1	1							
Stigonema hormoides Kütz. ex Born. et Flah.		1						1		
Stigonema mesentericum Geitler		1						1		
Stigonema ocellatum Thur. ex Born. et Flah.		1		1						
Synechococcus sciophilus Skuja		1								1
Synechocystis aquatilis Sauv.	1	1		1			1			
Synechocystis parvula Perfiliev		1					1			
Synechocystis pevalekii Ercegović		1								1
Synechocystis salina Wislouch		1		1						
Synechocystis minuscula Woronichin	1	1			1		1			
Tolypothrix tenuis Kütz. ex Born. et Flah. f. *terrestris* J. B. Petersen		1							1	
Total	38	76	12	10	19	9	26	14	15	5

Table 3. Taxonomic structure of identified cyanobacteria of lithobiotic communities

ORDER	NUMBER OF FAMILIES	FAMILY	NUMBER OF GENERA	GENUS	NUMBER OF SPECIES TAXA
Chroococcales	4	*Aphanothecaceae*	2	*Aphanothece*	2
				Gloeothece	3
		Chroococcaceae	4	*Chalicogloea*	1
				Chondrocystis	1
				Chroococcus	8
				Gloecapsopsis	4
		Cyanothrichaceae	1	*Johannesbaptistia*	2
		Microcystaceae	2	*Gloeocapsa*	8
				Microcystis	1
Nostocales	6	*Hapalosiphonaceae*	1	*Hapalosiphon*	1
		Nostocaceae	2	*Anabaena*	1
				Nostoc	2
		Rivulariaceae	2	*Calothrix*	2
				Microchaete	1
		Scytonemataceae	2	*Petalonema*	1
				Scytonema	1
		Stigonemataceae	1	*Stigonema*	3
		Tolypothrichaceae	1	*Tolypothrix*	1
Oscillatoriales	4	*Cyanothecaceae*	1	*Cyanothece*	1
		Leptolyngbyaceae	3	*Leptolyngbya*	13
				Phormidesmis	1
				Planktolyngbya	2
		Microcoleaceae	1	*Microcoleus*	*2*
		Oscillatoriaceae	2	*Lyngbya*	*2*
				Phormidium	9
Synechococcales	3	*Merismopediaceae*	3	*Aphanocapsa*	7
				Eucapsis	1
				Synechocystis	5
		Pseudanabaenaceae	1	*Jaaginema*	2
		Synechococcaceae	2	*Cyanobium*	1
				Synechococcus	1

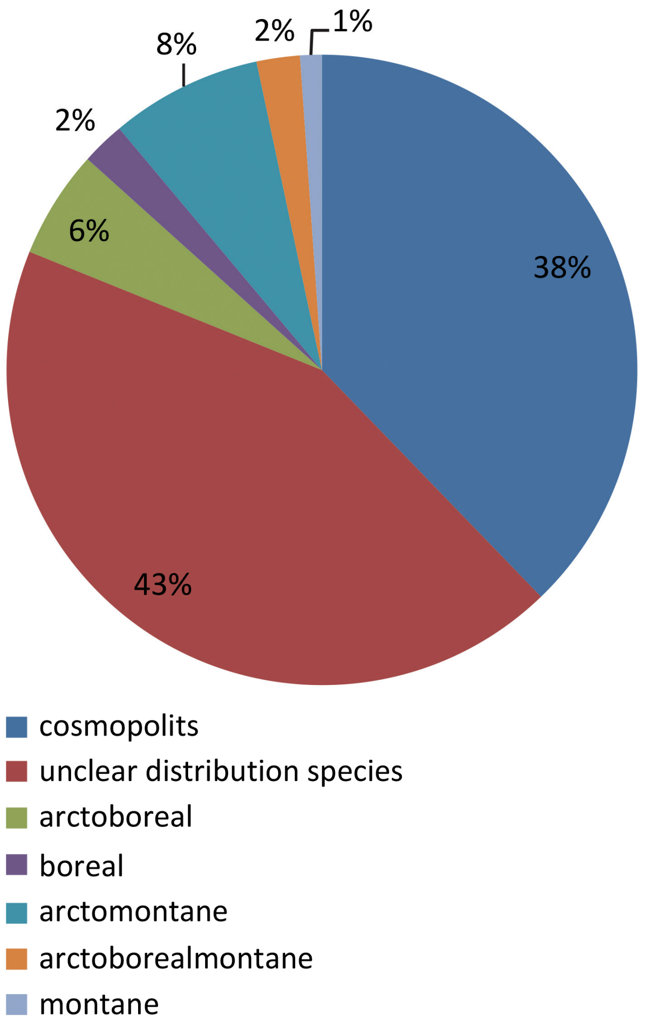

Fig. 3. Distribution of identified cyanobacteria species by geographical elements.

The assessment of the distribution of the found species by type of habitat also shows the predominance of cosmopolitan species (37 % of the total number). It is interesting to note that one species we found, *Gloeocapsopsis crepidinum*, belongs to the amphioceanic type (found in terrestrial habitats along the sea coast, the supralithoral zone, or along the shores of brackish reservoirs); at the same time, we found it on granites irrigated with fresh water. This species was previously recorded in Russia on Kamchatka, on Medny Island (arch. Commander Islands, Kamchatka) and in Murmansk Oblast (Davydov, 2010a). In this research, the presence of 49 species of cyanobacteria was noted for the Republic of Karelia (13 of which were not previously recorded in this territory).

A floristic comparison of the studied territories with each other according to the identified species of cyanobacteria was carried out. In addition, for comparison, we selected territories where the composition of lithobiotic cyanobacteria in mountain conditions had been studied: the flora of ravines in the Vatsuoi River valley (Sal'nye Tundra ridge), Kerkchorr (Chunatundra ridge) (Shalygin, 2012), and the Aikuaivenchorr ravine (Davydov, 2018). The number of species in the studied territories is comparable: for Aikuivenchorr flora 36 species were found; the Vatsuoi Valley flora includes 23 taxa; and for Kerkchorr ravine, 26 species were noted. With other territories, the comparison can only be made conditionally, since the substrates and environmental conditions are very different. The similarity coefficient for the studied territories is low. The highest Sørensen index of 0.48 was obtained when comparing Ristijarvi and Owl Mountain (Fig. 4). The flora are clustered according to the geographical principle. The territories are close to each other geographically and have a similar substrate in general. Since there was only one collection area for Ruskeala marble, it is not possible to trace the clustering by substrate when comparing the studied territories.

Component analysis (the principal component method) was used to identify the possible association of cyanobacteria with certain types of habitats. The analysis results show that the entire sampling is practically homogeneous. The first two factors together reflect only a little less than 12 % of the explained variability. The first factor is most likely associated with the type of substrate (granite, marble); the second—with the degree of saturation. On the graph (Fig. 5) most species are grouped in the central part of the graph (located in the area of zero coordinates), which is due to their rare and rather random finds. There is also a division of species in three directions. In the first sector, the species common to marble and granite are grouped. Sector II is occupied by species typical of granites. In the third sector, the species of marble are grouped.

On the surface of rocks, both monospecific and multi-species communities can form. For example, a rich biofilm with *Stigonema ocellatum* dominance was found on granite in the Montferrand Quarry at the site of natural water seepage (Fig. 6). This species forms a biofilm of tightly intertwined threads, which is clearly visible on the SEM image. As you can see in the figure, the biofilm from green to black is represented by *Stigonema ocellatum*, and in the wetter part of the biofilm, you can see a change in color to brown-red, which is associated with the replacement of the dominant species by *Gloeocapsopsis magma*. In addition, other cyanobacteria also appear: *Lyngbya* sp., *Leptolyngbya foveolarum*. For this case, the degree of moisture can be noted as the leading factor affecting the biofilm composition.

Lighting also plays an important role in the formation of biofilms. For comparison, we studied communities from the surface of Ruskeala marble and rapakivi-granite in open areas and in tunnels (under artificial lighting and in shaded areas).

For biofilms on open rock surfaces under natural light on the surface of marble, the list of species included 21 taxa. For open areas of granite quarries, 63 species of cyanobacteria were identified.

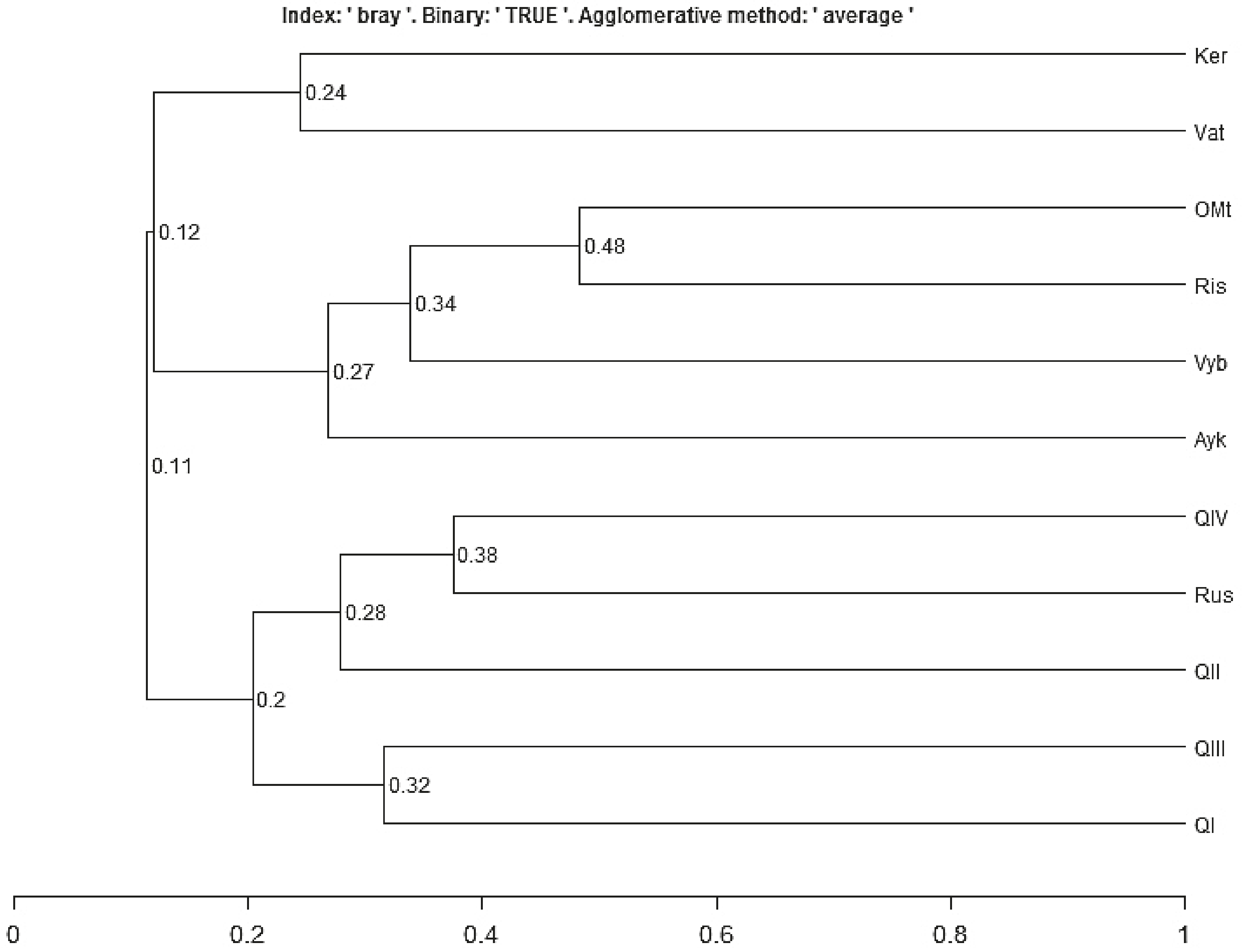

Fig. 4. Graph of similarity of cyanobacteria flora on rock surfaces from Ruskeala marble (Rus) and granite of Leningrad Oblast (Vyborg tunnels — Vyb), Karelia (Ristijarvi Park — Ris, Owl Mountain — OMt, South Finland quarries — Q I-IV and in the ravines of Aykuivenchorr — Ayk (Davydov, 2018), Vatsuoi — Vat, Kerkchorr — Ker (Shalygin, 2012). Sørensen's similarity coefficient, clustering by average method.

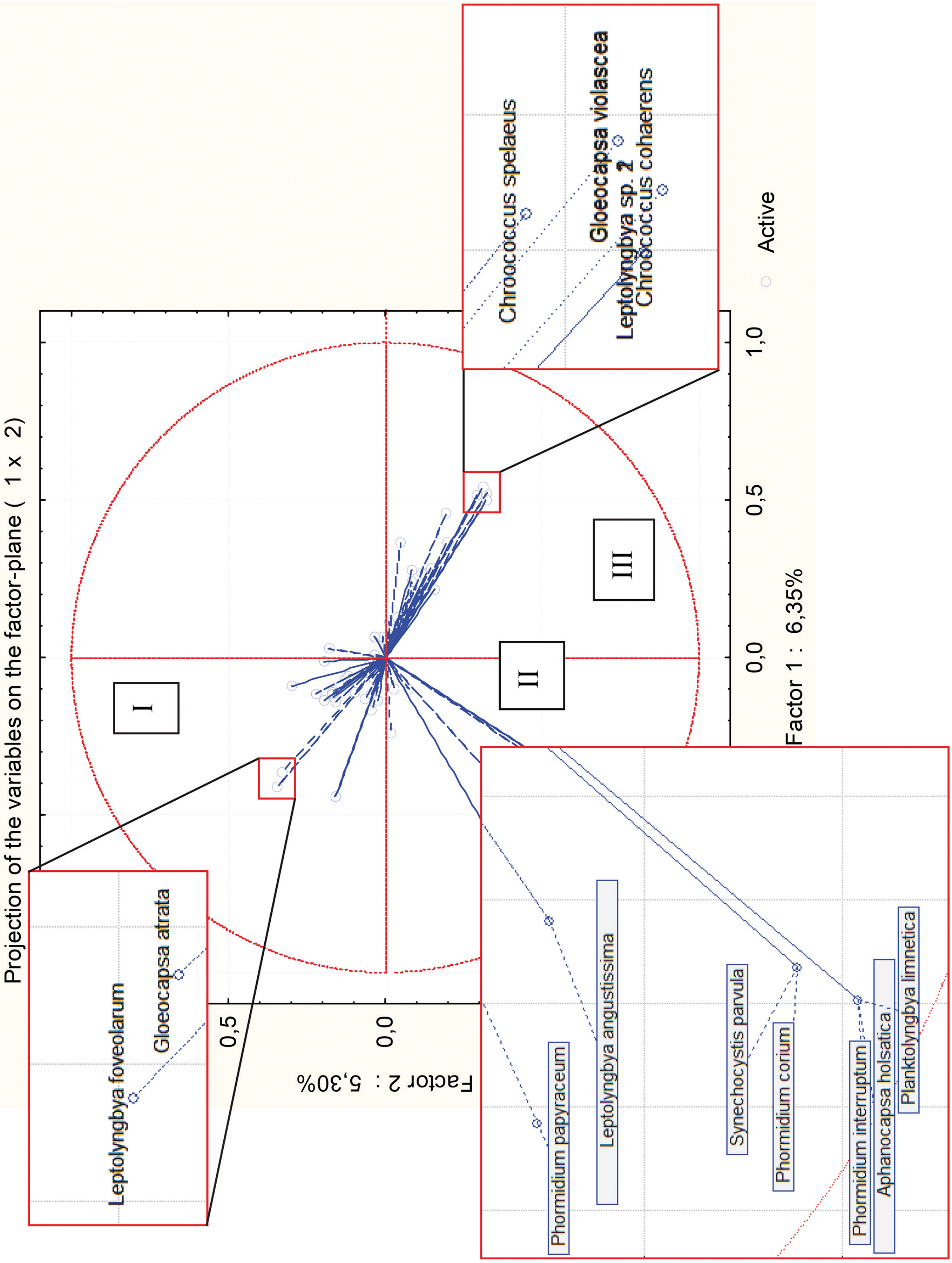

Fig. 5. Ordination of features (occurrence of species in samples) in the space of the first and second factors (I, II, III — sector number).

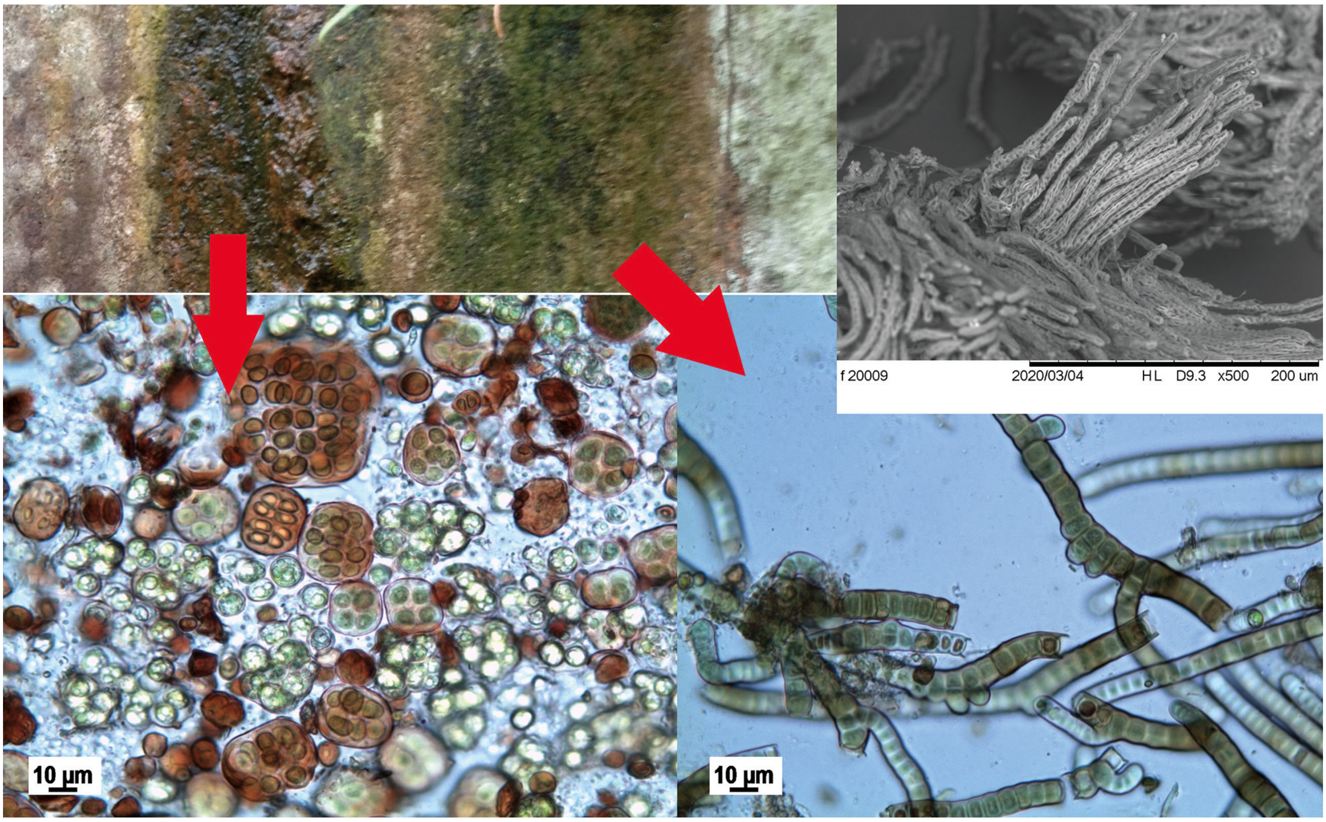

Fig. 6. Biofilm with a change of dominant species on the rapakivi-granite surface in the Montferrand Quarry (a — *Gloeocapsopsis magma,* b — *Stigonema ocellatum*).

Our studies have shown that the species composition in the tunnels is similar on different substrates and, at the same time, significantly poorer in comparison with open rock surfaces areas. In total, seven cyanobacteria species were detected on granites in conditions of limited light: *Chroococcus* sp. 1, *Gloeocapsa kuetzingiana*, *Gloeocapsopsis magma*, *Gloeocapsa violascea*, *Leptolyngbya* sp., *Aphanocapsa* sp., and *Aphanocapsa* cf. *fusco-lutea*. For comparison, six species of cyanobacteria were detected in one combined sample on open granite-rapakivi surface area near the tunnels (under natural light): *Gloeocapsopsis magma*, *Nostoc commune*, *Calothrix parietina*, *Scytonema hofmanii*, *Aphanocapsa* sp. 1, and *Aphanocapsa* cf. *fusco-lutea*.

Only six cyanobacteria species were identified in the marble tunnels: *Aphanocapsa* sp., *Chroococcus* sp. 1, *Chroococcus* sp. 2, *Gloeocapsa atrata*, *Leptolyngbya gracillima*, and *Leptolyngbya* sp.

The results show that biofilm diversity is significantly reduced in the absence of bright daylight. Light is the limiting factor in the distribution of phototrophs on rocky surfaces. This is typical not only for epilitic species in caves and tunnels, but, for example, for the desert regions of Antarctica, where the distribution of endolithic species also depends on the daylight penetration deep into the substrate (Nienow, McKay and Friedmann, 1988).

Conclusion

The conducted studies have shown that the cyanobacteria composition on rock outcrops (marble and granite) in Leningrad Oblast, Karelia and Southern Finland is characterized by significant diversity. The obtained data expand the information of cyanobacteria in lithobiotic communities, but further research in this direction is needed. The diversity of cyanobacteria on rapakivi-granite was two times higher than on Ruskeala marble, which is probably due to the more complex mineral composition of rapakivi-granite. Daylight, along with the degree of moisture, plays an important role in the species distribution on the rocky substrate's surface (the cyanobacteria diversity decreases significantly with a decrease in the illumination of the habitat, which is especially noticeable for tunnels). The revealed differences probably affect the composition of the metabolites of the lithobiotic biofilms. The role of cyanobacteria in geochemical processes and the destruction of stone requires in-depth study, and our work can be considered as a stage of this research.

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