

Biogenic Structures in the Silurian Stromatolites (Timan-Northern Ural Region)

V. A. Matveev*

Yushkin Institute of Geology, Komi Science Center, Ural Branch, Russian Academy of Sciences, Syktyvkar, 167982 Russia

**e-mail: vamatveev@geo.komisc.ru*

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Abstract—The study of the Silurian stromatolites revealed the diversity of biogenic structures and similarity of their morphology to that of the bacterial forms found in the ancient Archean stromatolites and modern cyanobacterial mats. The diversity of biogenic structures indicates high activity of microorganisms that formed cyanobacterial mats and confirms the microbial nature of the Silurian stromatolite buildups of the Timan-Northern Ural region.

Keywords: Silurian, stromatolites, biogenic structures, Timan-Northern Ural region

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Morphology of the biogenic structures of the Silurian stromatolites (Timan-Northern Urals) was found to be similar to that of the bacterial forms of the ancient Archean stromatolites and modern cyanobacterial mats, which confirms the microbial nature of the Silurian stromatolite buildups studied.

G.A. Chernov carried out the first detailed study of the Silurian stromatolites at the Chernov Swell (Chernov, 1963). He described them for the first time and proposed systematics based on the classification by V.P. Maslov (1960).

The author carried out a new study of stromatolites of the Silurian sections in the Padimeytyvis River basin at the Chernov Swell, as well as at the western slope of the Subpolar Urals in the Kozhym River basin (Fig. 1). This study indicated significant diversity of shapes and sizes of buildups from a few centimeters to tens of meters (Matveev, 2011, 2013). The main morphological types of stromatolites are stratiform, nodular, and columnar buildups. The nodular type is the most widespread morphotype; it is subdivided into disc-shaped, spherical, loaf-shaped, and domical forms.

The stratigraphic sequence of stromatolite buildups made it possible to identify three main stages of stromatolite formation in the Timan-Northern Ural sea basin in the Silurian: in the Llandovery, Wenlock, and Ludlow (Matveev, 2016).

The beginning of the stromatolite formation was associated with the Middle Llandovery (Early Telychian). At that time, the most high-capacity stratiform and flattened domical stromatolite buildups were formed. They are quite well traced in the studied sections of the western slope of the Subpolar Urals in the

Kozhym River basin (Matveev, 2013). The Wenlock stage of development of stromatolites is characterized by the formation of small-capacity loaf-shaped, domical, and stratiform buildups. This stage can be traced in the Bezymyannyj section of the Chernov Swell (Matveev, 2011). The Ludlow buildups of the Chernov Swell are characterized by significant morphological and size diversity (Matveev, 2016). The greatest diversity of biogenic structures was observed in the Wenlock stromatolites (Matveev, 2017).

Good preservation of microorganisms was believed to be characteristic only of siliceous rocks for a long time, while detection of bacterial formations in carbonate rocks was considered to be almost impossible. The diversity of bacterial structures in all sedimentary formations was determined using a scanning electron microscope (Gerasimenko et al., 1999; *Bakterial'naya paleontologiya...*, 2002; Rozanov, 2003; Litvinova, 2009; *Iskopaemye bakterii...*, 2011; Zavarzin, 2015; Kovalevskii and Makarikhin, 2016; Litvinova and Sergeev, 2018; Schopf, 2009; etc.).

Biogenic structures in the Silurian stromatolites were studied under a TescanVega 3 LMH scanning electron microscope (SEM) with an OXFORD Instruments X-MAX energy dispersive spectrometer in the Laboratory of Experimental Mineralogy at the Institute of Geology of Komi Science Center (Ural Branch, Russian Academy of Science) (carbon coating). Prior to the test, the samples were washed sequentially with distilled water and alcohol and treated with hydrochloric acid in order to exclude surface contamination. As a result, biogenic structures, which are considered as remnants of fossilized micro-

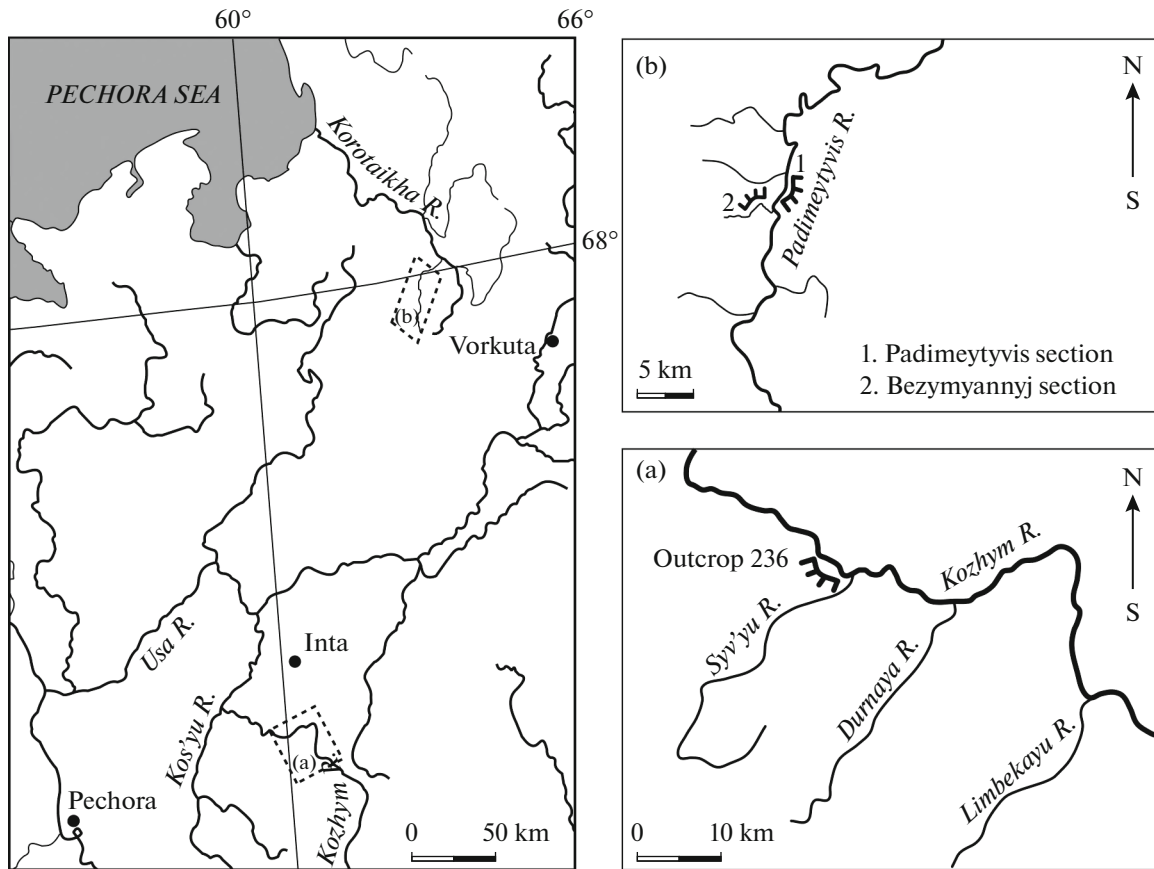


Fig. 1. The layout of the studied sections: (a) the Kozhym River basin, the western slope of the Subpolar Urals; (b) the Padimeytyvis River basin, Chernov Swell.

organisms that were involved in stromatolite formation, were revealed.

Biogenic structures of stromatolites are divided into five main forms:

I. Filaments are the most widespread forms, which are present in rocks. These are sheaths of tubular filamentous forms (possible cyanobacteria) that reach 60 μm in length and 4 μm in diameter and have a wall of up to 2 μm thick. Both single filaments closely connected with the rock (Fig. 2a) and aggregates of several filaments on the rock surface are observed. These intertwining filaments form a cobweb resembling mycelium of modern actinomycetes (Fig. 2b). In some cases, septa are observed in filaments (Fig. 2c). Filaments, the surface of which is covered with tiny globules of up to 0.5 μm in diameter, are also present in the rock (Fig. 2d). Such filaments resemble modern hyphae of micromycetes with warty outgrowths and were probable contamination (*Iskopaemye bakterii...*, 2011, pp. 106–107).

II. Coccoid forms with a thin smooth sheath are often observed near filamentous forms. Their size, as a rule, does not exceed 2–5 μm (Figs. 2b, 2c). It is possible that coccoid forms associated with filamentous

builders of cyanobacterial mats are heterotrophic or chemolytic microorganisms (*Bakterial'naya paleontologiya*, 2002). It can also be assumed that such forms belong to spores of actinomycetes, being the result of modern contamination (*Bakterial'naya paleontologiya*, 2002).

III. Large spherical forms are represented by single remnants of three microbial groups. The first group consists of regular spherical forms with a diameter of up to 50 μm with smooth surface with small tubercles and single small pores with a diameter of up to 0.5 μm (Fig. 3a). The second group consists of spherical forms with spongy surface with a diameter of up to 50 μm (Fig. 3b). The third group is composed of oval forms (50 \times 70 μm) with smooth surface and numerous small pores with a diameter of up to 1 μm (Fig. 3c). All forms of biogenic structures revealed are enclosed in rock. We suggest their intravital burial.

IV. Domical forms have numerous tubercles and lintels. The dome diameter reaches 100 μm (Fig. 3d).

The size and the complex structure of spherical and domical forms suggest that they belong to the remains of eukaryotic microorganisms (*Iskopaemye bakterii...*, 2011).

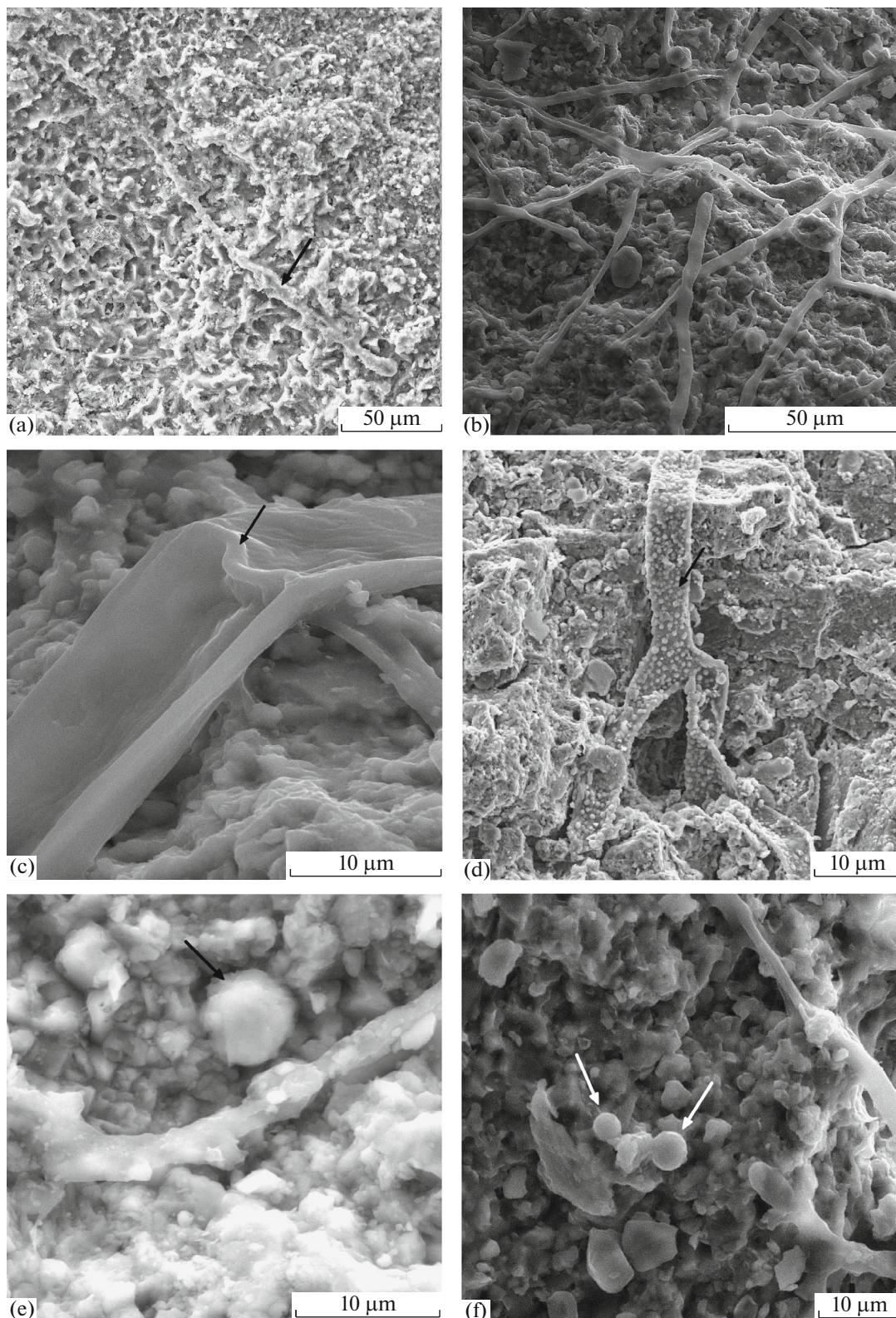


Fig. 2. Electron microscopic images of filamentous and coccoid microformations of the Silurian: (a–c, e, f) Wenlock, Chernov Swell and (d) Llandovery, western slope of the Subpolar Urals. All images are in secondary electrons: (a) mineralized sheath of the tubular filamentous formation (sample 90/1, no. 654/10-1); (b) intertwining filamentous forms composing a cobweb (sample 95/1, no. 654/10-2); (c) a fragment of the flattened single filament with a septum (sample 95/2, no. 654/10-3); (d) a fragment of the mineralized filament, covered with tiny warty outgrowths (sample 12/175, no. 654/3-3); (e, f) coccoid and filamentous mineralized microorganisms (sample 90/2, no. 654/10-4 and sample 95/3, no. 654/10-5).

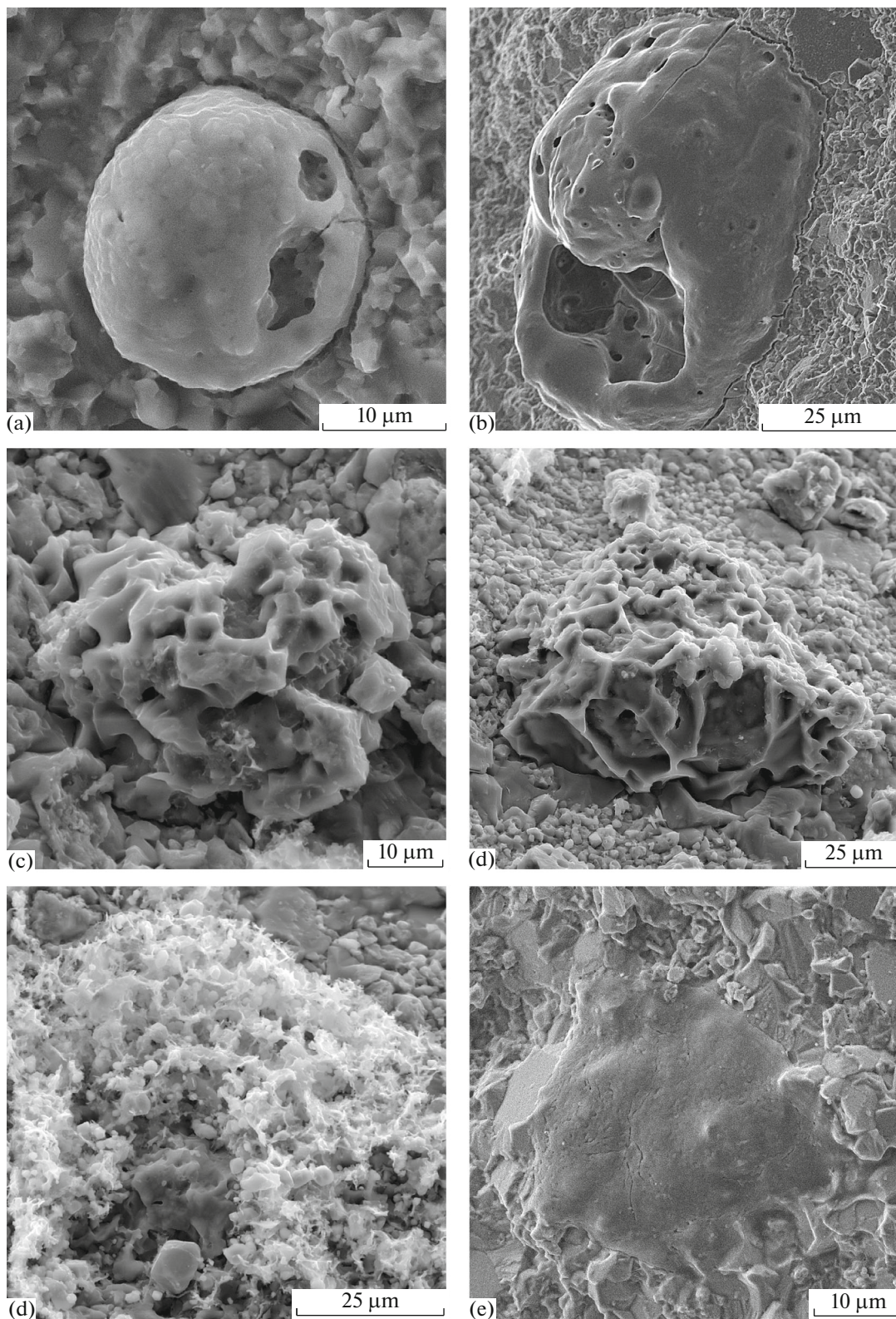


Fig. 3. Biogenic structures in the Silurian stromatolites, Wenlock, Chernov Swell. All images are in secondary electrons: (a) a spherical form immersed in the rock with a smooth surface with small tubercles (sample 90/3, no. 654/10-6); (b) an oval form with small pores on the surface (sample 90/4, no. 654/11-7); (c) a spherical form with spongy surface (sample 90/4, no. 654/10-8); (d) a domical form with numerous tubercles and lintels (sample 90/5, no. 654/10-9); (f) fossilized glycocalyx (?) with rounded cavities (sample 90/6, no. 654/10-10) (e); a fragment of the microbial biofilm (sample 90/7, no. 654/10).

V. Glycocalyx and biofilms. Glycocalyx is mucus secreted around the cells of bacteria and cyanobacteria; this mucus has a fibrillar structure and plays a protective role (*Bakterial'naya paleontologiya...*, 2002). The studied glycocalyx (?) has a fibrillar structure with rounded cavities. These cavities may contain bacterial coccoids (Fig. 3e) (*Bakterial'naya paleontologiya...*, 2011).

Biofilms with smooth surface and small cracks have dimensions of $40 \times 50 \mu\text{m}$ (Fig. 3f). Biofilms are known to be a result of interactions between bacterial colonies, water, and extracellular polymeric substance; they are often found in fossil stromatolite buildups (*Bakterial'naya paleontologiya...*, 2002).

Ca, Mg, and O predominated in the elemental composition of the rocks, in which biogenic structures were found. In addition to these elements, biophilic elements (K, Fe, S, Al, Na, Cl, etc.) are present in biogenic structures (Matveev, 2017).

Thus, for the first time, a diverse complex of biogenic structures was revealed in the Silurian stromatolites. These biogenic structures were found to be morphologically similar to the stromatolite-forming organisms of the ancient and modern stromatolites. New data on the morphological diversity of the biogenic structures of the Silurian stromatolites indicate high activity of microorganisms that formed cyanobacterial mats during the complex interaction of cyanobacterial communities, eukaryotic forms, and environmental conditions.

The collection no. 654 of the Silurian stromatolites of the western slope of the Subpolar Urals and Chernov Swell is stored in A.A. Chernov Geological Museum (Yushkin Institute of Geology of Komi Scientific Center, Ural Branch, Russian Academy of Sciences, Syktyvkar).

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