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Middle Darriwilian Small Stromatolite Bioherms and Spheroids (Oncoids) From the Moyero River Section (Siberian Platform)

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The article presents results of studies of the stromatolites from Middle Ordovician deposits of the Moyero River section (Siberian platform). It demonstrates that despite the growing dominance of skeletal metazoans against the backdrop of Great Ordovician Biodiversification Event (GOBE) in Siberian Platform reef systems, microbial communities remained integral components of reef formation from the Middle Ordovician onward. These communities functioned both as crucial auxiliary elements and as sole framework builders. Stromatolites are associated with bioherms dominated by skeletal metazoan reef-builders (*Angarella sp.*, *Moyeronia sp.*, tabulate coral, *Cryptolichenaria miranda*, and stromatoporoid, *Priscastroma gemina*). This indicates that in some parts of the platform, due to regional peculiarities, microbial communities not only retained their role in Middle Ordovician reef systems, but also formed bioherms without symbiosis with other reef builders. Microbial communities form two distinct stromatolite types: less numerous spheroidal forms (SS and SS-I) and more prevalent stromatolite bioherms (SS → LH). The persistence of microbial influence in this region is attributed to specific depositional environment conditions. Due to their morphology and diagenetic alterations, these stromatolites have a potential for hydrocarbon reservoir formation. The study highlights that while contemporary reef zones in the Ordovician of West Taimyr are prospective yet poorly understood reservoirs, the Moyero River organogenic build-ups serve as valuable geological models. Further research into their structure, texture, and genesis is essential to refine predictions for Ordovician reservoir distribution. These findings emphasize the need to consider stromatolites as significant targets in reservoir exploration.

Keywords: Middle Ordovician, Siberian platform, stromatolites, oncoids, microbialites, Great Ordovician Biodiversification Event (GOBE), reservoirs.

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Research Article

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Introduction

Stromatolites are laminated benthic microbial deposits [*Riding*, 1991]. That type of microbialites is widespread for Precambrian and Early Paleozoic deposits of the Siberian paleocontinent [*Belenitskaya et al.*, 1990]. In the same way as on other platforms microbial organisms of stromatolite structure were a major type of reef-builders until the Great Ordovician Biodiversification Event [*Kuznetscov and Zhuravleva*, 2022]. Along with the increase in marine invertebrate biodiversity, the main reef-builders also changed during this event. The Ordovician witnessed a remarkable change in reef composition [*Lee and Riding*, 2018; *Webby*, 2002] – a transition from microbial dominated to metazoan dominated frameworks. However, due to a variety of regional factors (water depth, salinity and temperature), this transition was not a one-step process.

Stromatolites of the Siberian Platform have been the subject of numerous studies since the mid-20th century [*Kuznetscov and Zhuravleva*, 2022]. The major interest of past researchers was mainly focused on the Cambrian reefs as they were seen as a possible reservoir for oil and gas. The main results of their study are summarized in the fundamental work – Stratigraphy of oil and gas basins of Siberia (Cambrian of Siberian Platform) in two volumes [*Pegel et al.*, 2016; *Sukhov et al.*, 2016]. However, the Ordovician stromatolite organogenic buildups have received immeasurably less attention. Lower Ordovician hemispheroidal type stromatolites that extend across the Siberian Platform from the Yenisey River to the Lena River [*Krylov*, 1975; *Maslov*, 1960; *Sychev et al.*, 1982] are well known. Previously, it was assumed that the distribution of stromatolites in the Lower Ordovician was limited only to the south of the Siberian Platform, where they formed a reef system [*Yadrenkina et al.*, 1979]. However, the recent discovery of Lower Ordovician stromatolite bioherms in the Moyero River section, which are a prolongation of the Upper Cambrian ones, challenges this statement. It shows that the reef system in the north of the Siberian platform, which started in the Cambrian, continued its development. The characterization of Lower Ordovician stromatolite bioherms is published in a recent paper by the authors [*Lykov et al.*, 2024b]. It was also considered that stromatolite bioherms didn't form the Middle Ordovician [*Kanygin et al.*, 2007], because previously it was thought that their formation had completed by the end of the Lower Ordovician. Nevertheless, the authors found small stromatolite bioherms in the Middle Ordovician of the Moyero River section during fieldwork. However, they were first noted by E. I. Myagkova and co-authors [*Myagkova et al.*, 1977] as algae bioherms. But due to the lack of time and different focus of the work, they did not make a detailed characterization. The purpose of this study is to elucidate the features of middle Ordovician small rounded stromatolites in order to reconstruct the conditions of their growth and formation. Their detailed description has not been provided before.

Geological Setting

In the middle Ordovician time Siberian Platform was situated in low latitudes, closer proximity to the equator [*Cocks and Torsvik*, 2021]. It gradually migrated from the Southern Hemisphere during the Early Ordovician to the Northern Hemisphere by the Late Ordovician [*Cocks and Torsvik*, 2007]. The Siberian paleocontinent at that tame embraced several basins, the largest of them is the Tungus Syneclise (or the Tungus basin) [*Kanygin et al.*, 2007]. The Moyero river section is located in the northern part of the Siberian Platform in modern coordinates adjacent to Anabar land (Figure 1A).

In the Ordovician of Siberian Platform two carbonate series of contrast lithology could be distinguished: 1) warm water tropical carbonate series (Tremadocian-Floian) and 2) cool-water carbonate series (Sandbian-Katian) [*Dronov*, 2013]. These two series are separated in the Moyero river section by a relatively thick and well-developed transitional interval (Dapingian-Darriwilian) with alteration of cool water and warm water carbonates. The latter become less and less abundant upward the section. The authors consider the influence of cold currents (upwelling) to be one of the main reasons for the change in the type of carbonate sedimentation [*Dronov*, 2013; *Lykov et al.*, 2024a].

The Moyero river reference section is one of the most complete and continuous Ordovician sections on the entire Siberian platform [*Myagkova et al.*, 1963]. Thus, the study of Great Ordovician Biodiversification Event (GOBE) manifestation in the reef community's development against the background of facies peculiarities of the Siberian paleobasin is most promising in the Moyero River section deposits. However, due to its remoteness, it remains rarely visited by researchers, as a result of which many aspects of Ordovician paleogeography, sedimentary and paleoecology conditions are insufficiently studied. Outcrops along the Moyero River are traditionally marked with specific numbers such as Nos. 69, 70, 71,72 (Figure 1B) and so on given to them by O. I. Nikiforova in 1951 [*Myagkova et al.*, 1977]. The Ordovician strata are almost horizontal or slightly tilted (2° to 3°) to the

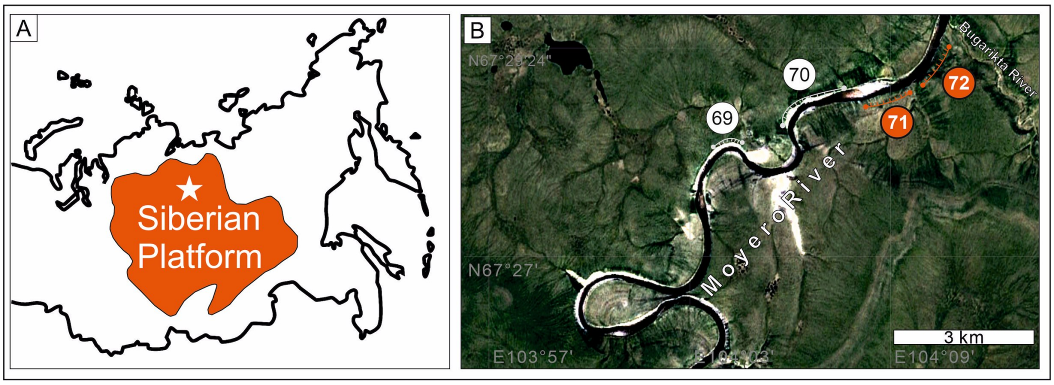

Figure 1. Geographical position and outcrops of the studied deposits. A. Position of the Moyero section on the Siberian platform indicated with a white star. B. Map, showing locations of the 69 to 72 outcrops along the Moyero river. The studied outcrops, marked in orange color.

south. The Ordovician succession of the Moyero river is subdivided into four formations (from the base upward): Irbukli, Kochakan, Moyero, and Dzheromo formations [*Kanygin et al.*, 2016; *Pokrovsky et al.*, 2018]. The studied objects here come from the upper part of Kochakan formation (Figure 2A), which crops out along the right bank of the Moyero River (outcrops Nos. 71 (Figure 2B); 72; 72A separated by the Bugarikta river). That whole formation includes the upper Ugorian, Kimaian, Vikhorevian, and Mukteian Regional Stages (upper Floian–lower Darriwilian stages) [*Bergström et al.*, 2009; *Kanygin et al.*, 2007]. The small rounded stromatolites are found only in two layers related to the uppermost Mukteian Regional Stage (Figure 2). To be precise they are available for observation in the lower part of outcrop Nos. 71; middle part of outcrop Nos. 72, upper part of Nos. 72A. The part of the section in which they occur is represented by variegated violet-red, more rarely green siltstones (aleurolites) and calcareous (less frequently dolomitised) mudstones intercalated with greenish gray bioclastic limestones with numerous bioherms of different size (Figure 2A, C).

Materials and Methods

Fieldwork was conducted in July 2013, August 2020, July 2021, and July 2022, during which a total of 50 samples were collected by A. Dronov and N. Lykov. These samples were processed into longitudinal and tangential thin sections for lithological and paleontological identification and from two of them polished slabs were made. In total, forty-eight 2.5×2.5 cm and five 5×5 cm thin sections were prepared in the thin section laboratory of the Geological Institute of the Russian Academy of Sciences. Eight of these samples were taken from the stromatolite bioherms, half of them were prepared using blue colored epoxy resin to mark pores. Microphotographs were captured using a 6.3 Mpx, USB 3.0 Aptina camera.

The study of bioherms was carried out according to the methodology suggested by [*Yao et al.*, 2023], definition and classification of bioherms and carbonate rocks to [*Dunham*, 1962; *Frolov*, 1993; *Logan et al.*, 1964; *Riding*, 1991, 2002]. Detailed studies of the structure of rocks were performed on a scanning electron microscope JSM 6610 LV (JEOL, Tokyo, Japan), equipped with an energy dispersion spectrometer IE350 (OXFORD INSTRUMENTS, Abingdon, Oxfordshire, England), which was used to determine the elemental composition of individual nanocrystals. Small samples of rocks measuring 8 by 10 mm were glued to the holder with electrically conductive carbon tape before being viewed with an electron microscope. Then, to remove the charge formed due to the interaction of the electron beam with the sample surface, they were sprayed with a thin conductive platinum coating. The thickness of the platinum coating was 20 nm. The coating was produced in the JFC-1600-JEOL device (JEOL, Tokyo, Japan). The samples were examined in the secondary electron mode ("secondary electron image", abbreviated "SEI"). The observation mode is indicated as a stamp on the pictures. In the secondary electron mode, the topographic contrast of the sample surface is clearly visible. In this mode, the maximum resolution is reached. The

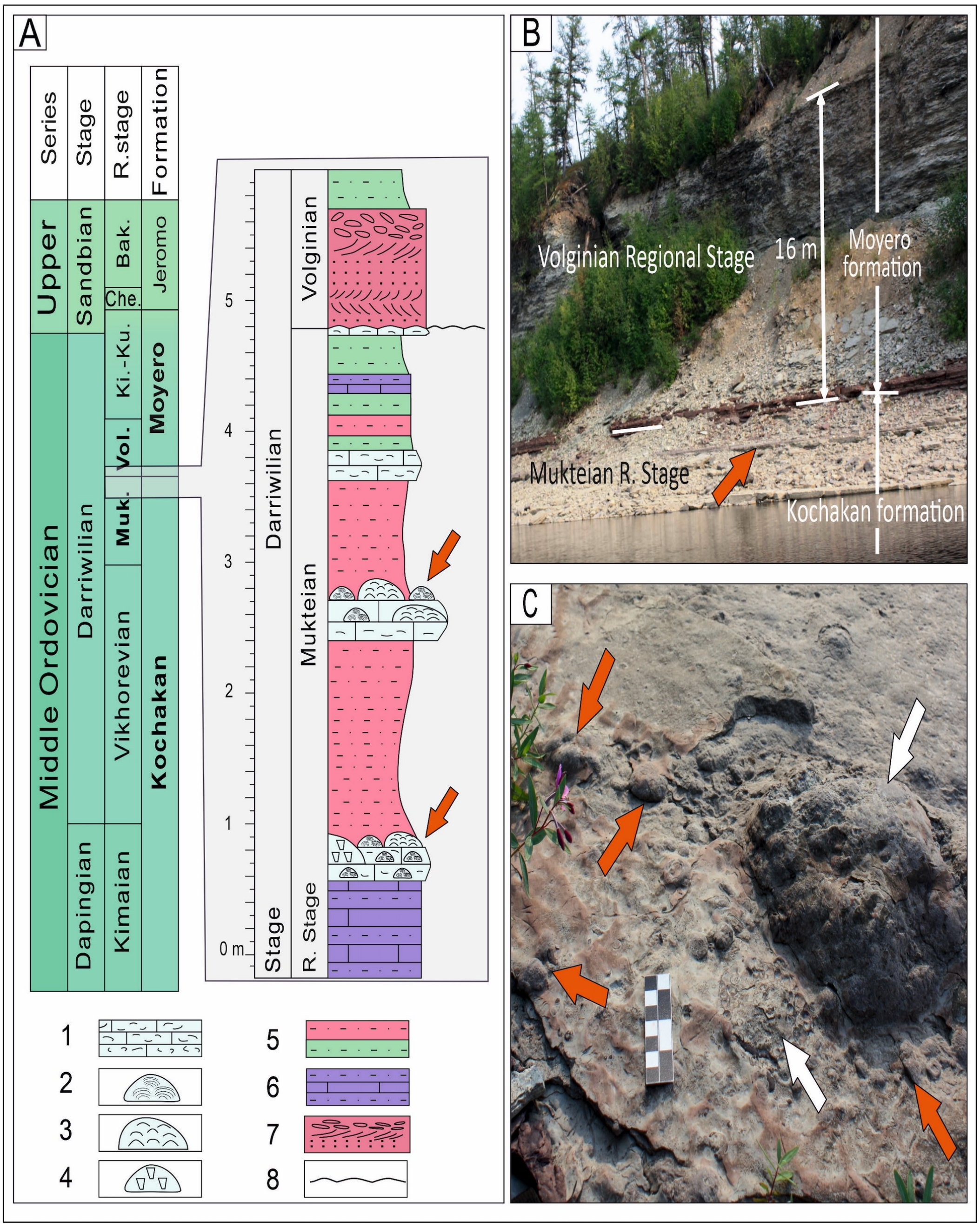

Figure 2. A. Simplified lithology and stratigraphy column of the studied section (stromatolite bioherms and oncoids marked with orange arrows). Abbreviations: R. stage – Regional stage; Muk. – Mukteian; Vol. – Volginian; Ki. – Ku. – Kirensko – Kudrinian; Che. – Chertovskian; Bak. – Baksian. Legend: 1) bioclastic grainstones; 2) stromatolite bioherms and oncoids; 3) *Angarella* and *Moyeronia* bioherms; 4) tabulate coral (*Cryptolichenaria miranda*) and stromatoporoid (*Priscastroma gemina*) bioherms; 5) variegated violet-red, more rarely green siltstones; 6) intercalation of peloidal wackestones and calcified or dolomitised siltstones; 7) reddish iron oolites; 8) erosion boundary. B. Field photo of Nos. 71st outcrop (upper layer with stromatolite bioherms marked with an orange arrow). C. Field photo of the upper (second) layer with studied objects (stromatolite bioherms marked with orange arrows; Metazoan skeletal dominated bioherms are marked with white arrows).

analytical conditions for studying the samples were an accelerating voltage 30 kV, spot size 40–45, and working distance 10–14 mm.

All the samples (polished slabs and thin sections with stromatolites) are stored in Mineralogical and petrographic museum named after L. V. Pustovalov (Gubkin Russian State University of Oil and Gas).

Description

The part of the section (Figure 2A) under consideration contains two layers with metazoan dominated bioherms and stromatolites (Figure 3A, B, C). Stromatolites are represented by two main variations (Figure 4) – spheroidal and hemispheroid structures. According to Logan's classification [*Logan et al.*, 1964] – SS → LH (the form of transition from spheroids to laminated hemispheroids). Less common is the spheroidal type (oncoids) and inverted stacked hemispheroids (SS and SS-I types according to 18]). Each stromatolite small bioherm and oncoid are roughly 2–3 cm in size. The largest observed measures are 3 cm in height and 7 cm in diameter. a shallow pit resembling an indentation is occasionally noted in their central part.

Metazoan dominated bioherms are represented by a combination of skeletal metazoan and microbial reef builders (in a subordinate position). These bioherms are underlain by bioclastic limestones with wave ripple marks noted on the top surface of them, indicating shallow water conditions at the time of the beginning of bioherm formation. In the lower (first) layer skeletal metazoan reef-builders are *Angarella* sp. (Figure 3D), *Moyeronia sp.*, and *Cryptolichenaria miranda* (tabulate coral) [*Myagkova et al.*, 1977]. Later, in some bioherms V. G. Khromych found and identified stromatoporoids, represented by a single species *Priscastroma gemina* [*Khromykh*, 1999]. Their average thickness is about 0.5 m. In the upper (second) layer the largest number of bioherms is composed by *Angarella sp.* and *Moyeronia sp.* with the auxiliary role of microbe communities. Their morphologies are convex-upward and have the largest dimensions of all bioherms (maximum height 0.5–0.8 m, maximum diameter up to 3 meters).

Most often, the location of stromatolite bioherms is not accidental. They form clusters both independent and confined (Figure 3A, B) to the periphery of metazoan dominated bioherms (Figure 3C, D). In clusters, their number varies from several units to dozens. Typical stromatolite bioherms with underlying deposits are well represented on a polished slab (Figure 4), which consists of three layers.

Layer 1 is represented by reddish cross-laminated quartz siltstones (Figure 4, 5A–B) with different carbonate clasts – large (0.5×1 cm) *Angarella* shells, ooids, microbial peloids and intraclasts; their reddish color is presumably due to the abundance of hematite envelopes covering quartz grains and in the matrix. Towards the top of the layer, the number of carbonate clasts increases (Figure 5B). a few thin empty cracks are also noted in the layer. The contact of layers 1 and 2 is gradual in terms of predominance shift from terrigenous to carbonate components.

Layer 2 (Figure 4, 5C, D) is grayish-green ooidal-bioclastic limestone (grainstone) with sparite matrix, numerous shell fragments (mostly *Angarella*), oolites, and microbial peloids and intraclasts, admixture (10%) of quartz grains is noted in thin sections of that layer. The size of bioclasts varies from 0.1 to 1 mm, ooides – 0.1–0.15 mm. They are formed mainly by ostracod shells. In addition, there are also large (up to several cm) hematitized fragments (Figure 5E) of stromatolite oncoids (spheroids). There are a few empty pores, clearly distinguishable due to staining (blue color), in the thin sections.

Layer 3 (Figure 4, 5H) is greenish gray limestone, mostly hemispheroidal and less spheroidal (boundstone), with a stromatolite structure (Figure 5F–H, 6). In the basal parts there are large (2–5 cm) Angarella shells, on the surface of which the growth of microbial colonies begins (Figure 4). In bioherms, microbial colonies grow upward from shells or redeposited spheroids. Numerous branching low-amplitude stylolites are noted (Figure 5H), which together form a system of fractures. In the latter, dark brown clayey matter with residual hydrocarbons is observed within them. The columnar forms of stromatolites with a layered texture are composed of micrite (calcite) and have dark gray color. Between them there is sparite which recrystallized from micrite in the rock matrix. There are leaching

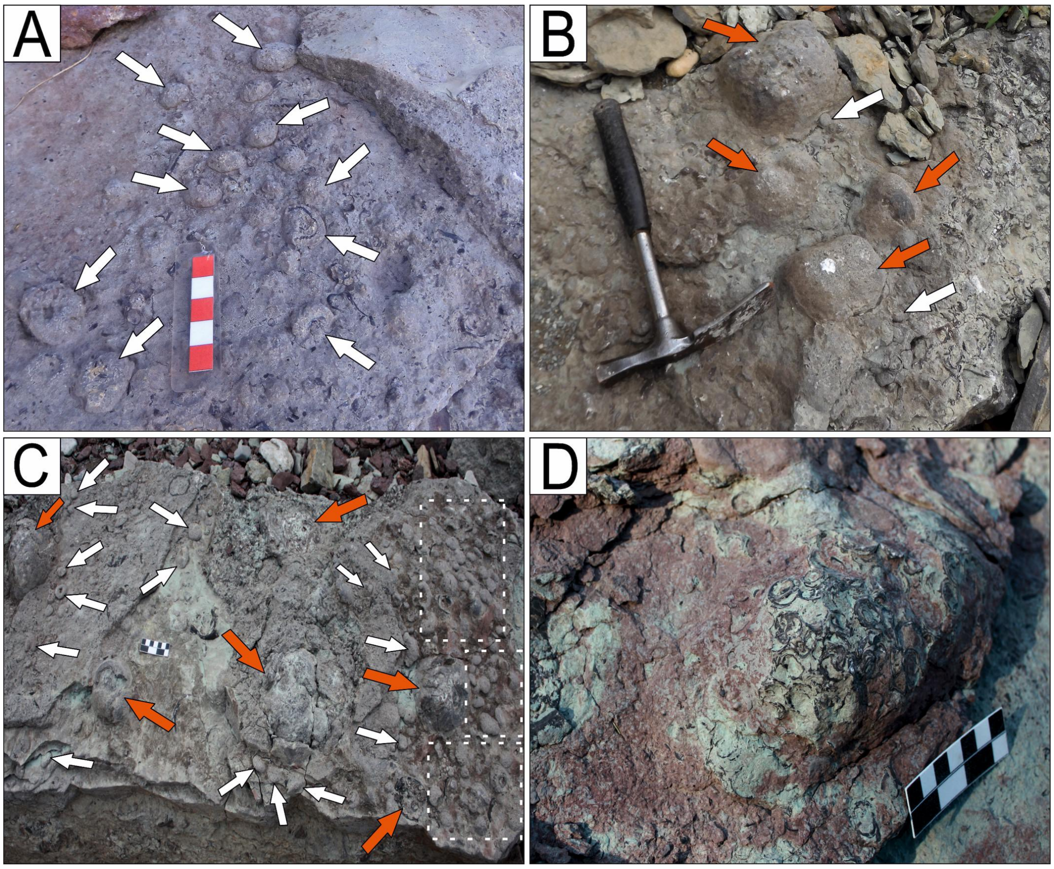

Figure 3. Field photographs of the studied layers with the bioherms: white arrow indicates the stromatolite bioherms and oncoids, orange arrow – metazoan dominated bioherms. (A) The stromatolites on top of the bioclastic grainstone from the bottom (first) layer; (B, C) General view of the inter-location of stromatolite and metazoan dominated bioherms, showing that the stromatolites are confined to larger metazoan dominated bioherms (tabulate coral, *Angarella sp.* and *Moyeronia sp.*) from the upper (second) layer; Cl – white dotted boxes indicate areas of stromatolites clusters; (D) Angarella bioherm from the upper (second) layer. The hammers in (B) are approximately 30 cm high. The entire length of the scale bar in (A, C, D) are 5 cm, and each square indicates 1 cm.

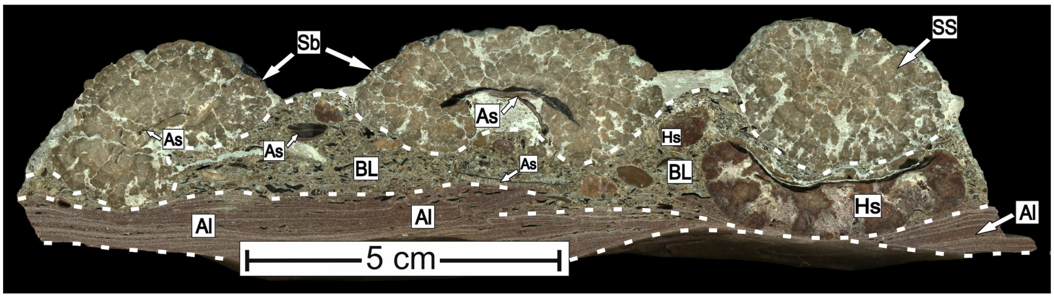

Figure 4. The Polished slab with three layers is highlighted (white a dotted line): layer 1 (Al): reddish cross-laminated siltstones with rare bioclasts; layer 2 (BL): grayish-green bioclastic limestone with large *Angarella* shells (As), microbial peloids and intraclasts, ooides, ostracod shells, and bryozoan fragments, secondary hematitized clasts of stromatolites (Hs); layer 3: small hemispheroidal stromatolite bioherms (Sb) and stromatolite spheroids (SS), according to [*Logan et al.*, 1964] SS and SS → LH types of stromatolite structures.

pores that are now filled with secondary calcite. Finally, single quartz grains occur in the matrix between stromatolite columns.

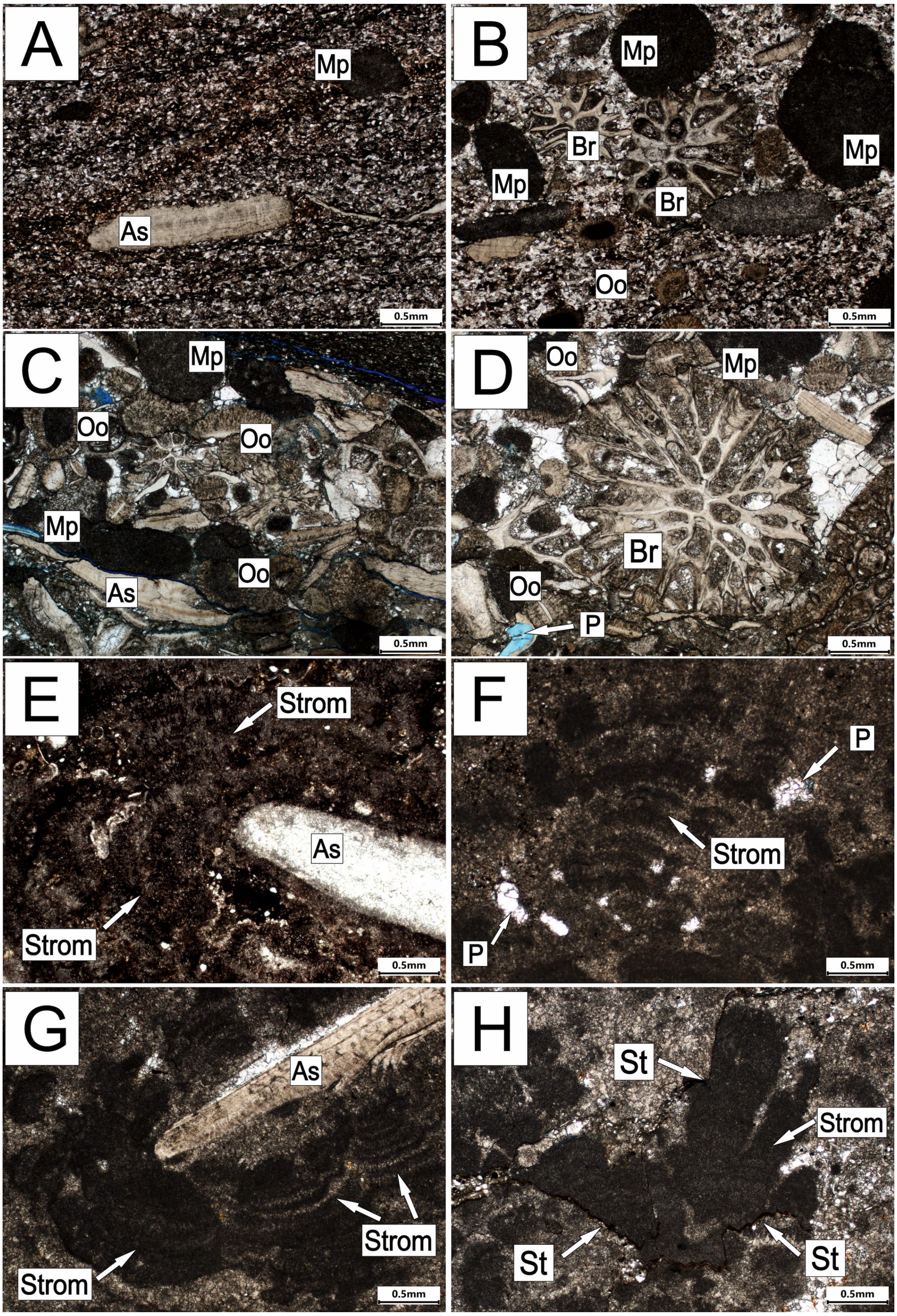

Figure 5. Photos of the thin sections in plane polarized light: As – Angarella shells; Mp – microbial peloids and intraclasts; Br – fragments of bryozoans; Oo – ooids; P – pores with or without calcification; Strom – stromatolites (laminated microbialites); St – stylolites. A – cross-laminated quartz siltstones; B – uppermost part of siltstones with an increased amount if bioclasts; C-D – ooidal-bioclastic limestone (pack-grainstone); E – hematitized fragments of stromatolite oncoids (spheroids); F–G – bioherms and oncoids (spheroids) with marked stromatolites textures; G – center part of oncoid limestone; H – stylolites in stromatolite bioherms.

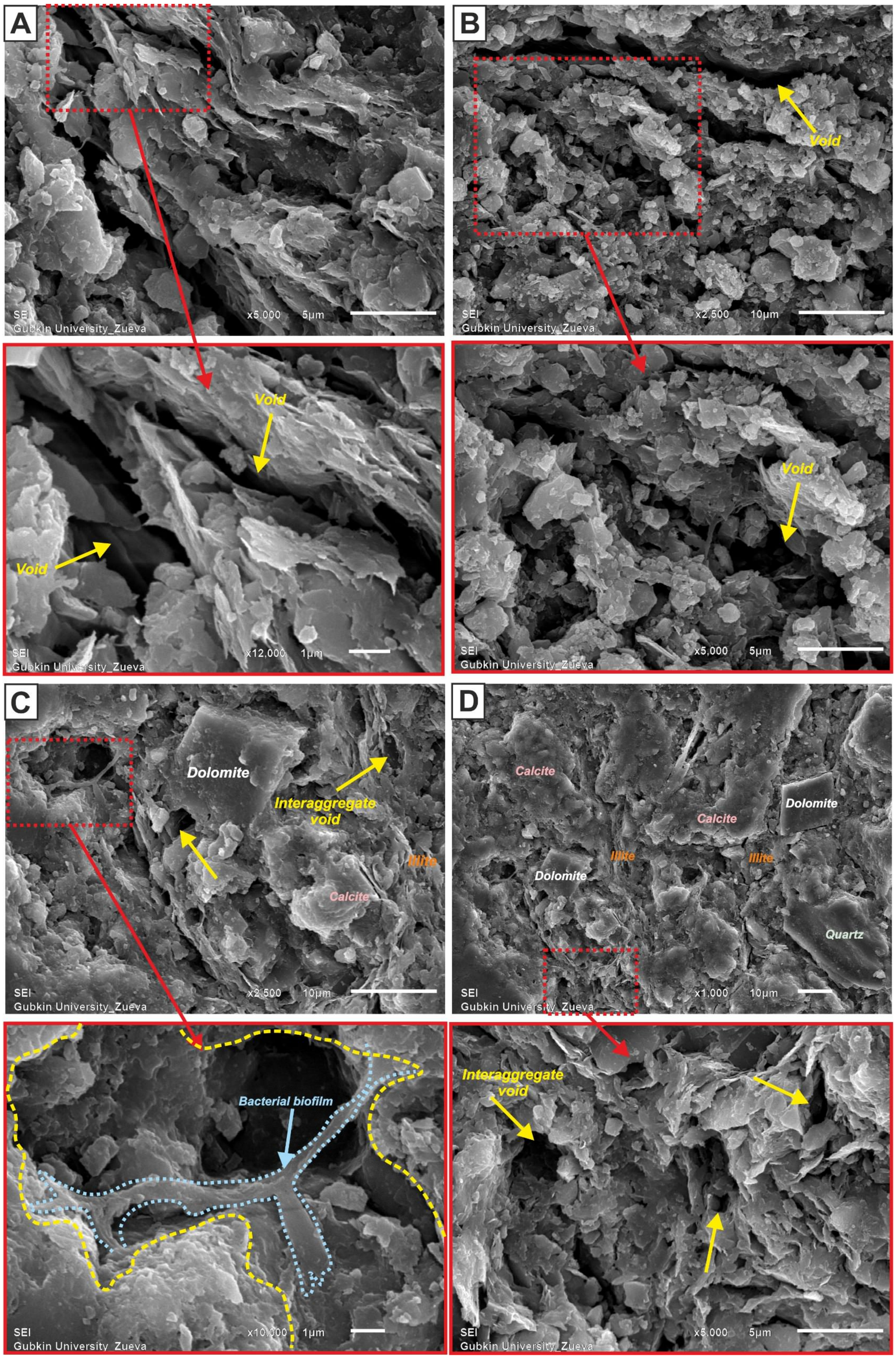

Figure 6. Bacterial calcite biofilms found in microbial limestones with a stromatolite texture (layer 3) (SEM photos, EDS spectrum of the calcite).

Stromatolites have a rather peculiar type of void space. The determining factor of its formation is the layered texture of stromatolite formations. The largest voids are confined to the interlayer space, along which fracturing and leaching voids develop (Figure 7A–B).

It should be noted that abundant calcite mineralized bacterial biofilms are prominent in the void space (Figure 7C). The bacterial origin of these structures is confirmed not only morphologically, but also by the increased carbon content. Significantly smaller voids 1–2 microns in size are confined to the interaggregate space inside the stromatolite layers (Figure 7D). Numerous stylolite seams filled with transformed organic matter are noted in the rocks, which form a system of connected channels.

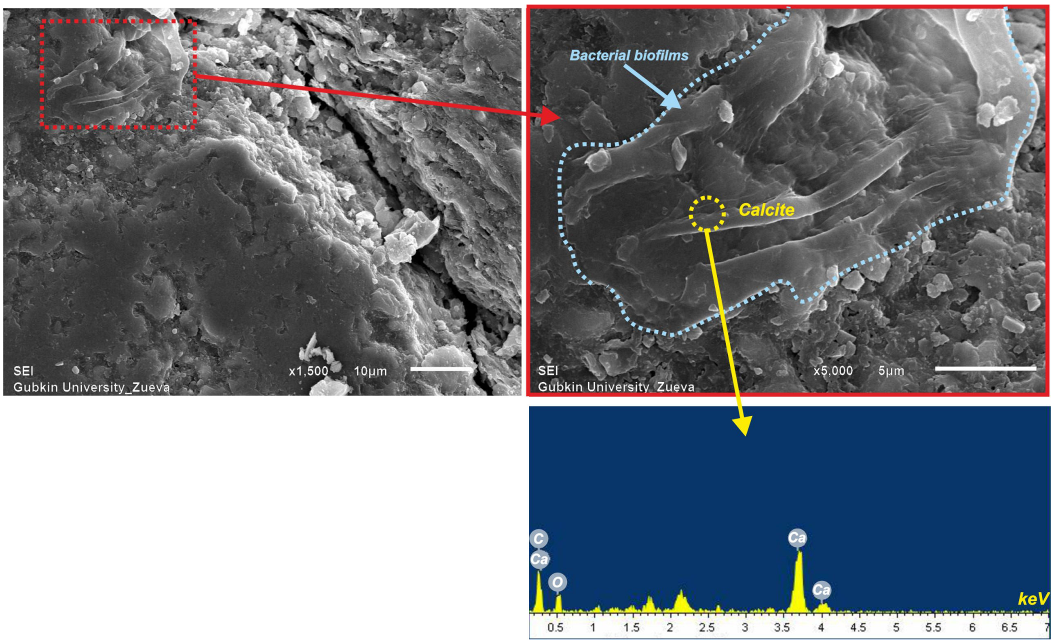

Figure 7. SEM photos of the microtextures of stromatolites. A, B – voids confined to the interlayer space; C – bacterial calcite biofilms in the void; D – interaggregate voids 1–2 microns in size.

Discussion

The cross-bedding structures of siltstones and presence of ooides in bioclastic limestones indicate an active hydrodynamic environment before stromatolite's growth. It seems that in the final stage of bioclastic limestones formation (the time before they were fully cemented in early diagenesis) spheroid stromatolites (SS types) were transported and accumulated here. Inverted stromatolite structures (SS-I) most likely formed under the influence of short-term currents that facilitated a single overturning of stromatolites, which prevented the formation of a spheroidal type. In the aftermath, these sedimentary conditions were preserved at the time of formation of bioherms. Thus, spheroid stromatolites turned out to be the substrate for the bioherm form of stromatolites (SS → LH type). Similar modern stromatolites have been found in the intertidal zone of the Bahamas, where a variety of shells served as substrates for stromatolite growth [*Feldmann and McKenzie*, 1998].

Such small microbial (a number of authors attribute them to algal genesis) bioherms are extremely common in the Lower Paleozoic of the Siberian Platform [*Kanygin et al.*, 2007; *Luchinina et al.*, 2013], the greatest flowering of this type of bioherms occurred in the Early and Middle Cambrian and the beginning of the Ordovician. At some stages of sedimentary paleobasin development in the Cambrian age, they formed stromatolite fields within the "Sakhai organogenic strip" [*Kanygin et al.*, 2007; *Zhuravleva*, 1979]. In the second half of the 20th century, V. A. Luchinina [*Luchinina*, 1973] proposed a term for such spherical formations (small bioherms) on the example of the lower Cambrian – "Calyptra" (from Greek "cap"; corresponds to the dome in modern algae). This term entered the Russian-language literature. a characteristic feature of this type of bioherms is that they are located at the same level as their base, forming a field or "carpet". Meanwhile, the detected bioherms in the Moyero River section form 2 levels in study section that have been traced in several outcrops over a total length of more than 3 km. Therefore, it can be assumed that this term is also suitable for the described bioherms.

"Calyptras" (small stromatolite bioherms) found in the Middle Ordovician of the Moyero River section differ from those described by V. A. Luchinina in that they are not associated with larger stromatolite bioherms or form large fields exclusively by themselves. An important feature of the development of the studied stromatolites in the outcrops No. 71 and 72 is their co-occurrence with metazoan dominated bioherms. Microbial communities have equivalent significance in the structure of the studied levels, together with the predominant metazoan bioherms (*Angarella sp.*, *Moyeronia sp.*, tabulated corals and stromatoporoids). The combination of small bioherms with various reef-builders in one layer can apparently be explained by the unstable environmental conditions in the shallow part of the basin. Apparently, marine oxygenation [*Lee and Riding*, 2018] may provide more favorable conditions for the development of *Angarella sp.* and other new non-microbial reef-builders. However, at the middle Darriwilian of the Moyero river section, these conditions were not yet sufficient for a general ecological shift towards a microbial-metazoan consortia characteristic of more recent times [*Kröger et al.*, 2017; *Webby*, 2002]. Due to this, microbial communities did not lose their important role. In contrast, as a result of deteriorating environmental conditions at the end of the Middle Ordovician, microbial communities once again took a dominant position in reef building in the study part of paleobasin [*Jeon et al.*, 2025]. Further studies of the Ordovician of the Siberian Platform may provide a better understanding of the transition in the development of reef systems against the GOBE background in different parts of the paleobasin, showing the importance of taking into account regional differences.

Conclusions

Despite the appearance and increasing role of metazoan skeletal organisms in reef systems of the Siberian Platform, microbial communities continued their active development since the Middle Ordovician. They were included in reef formation both as auxiliary, but extremely important subjects, and acted as the main framework formers. The latter is directly evidenced by the finding of two types of stromatolites in association with bioherms dominated by other species. The first, less numerous one is represented by spheroidal stromatolites (SS and SS-I). The second, more numerous, is represented by stromatolite bioherms (SS → LH). Apparently, the preservation of the role of microorganisms in this part of the Siberian Platform is related to the depositional environment conditions. Due to the specificity of their morphology and secondary processes, they can be considered as potential hydrocarbon reservoirs.

Low Paleozoic carbonate deposits of the West Taimyr are potential oil and gas bearing area according to drilling data [*Vilesov et al.*, 2022]. Ordovician part is envisioned as a prospective complex with potential reservoirs confined to reef zones of the carbonate platform margin [*Bukatova et al.*, 2022]. However, given the peculiarities of the core material, organic build-ups from West Taimyr area are still poorly understood. But at the same time the organic build-ups of the same-age part of the Moyero River section can be considered as potential reservoir rock models. In this regard, it is necessary to further study their structure, texture and genesis, which will make it possible to refine the forecast of the development of Ordovician natural reservoirs. The new data obtained may encourage the following researchers to consider stromatolites as potential reservoirs when searching for potential reservoirs.

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