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Genesis of carbonate precipitate patterns and associated microfossils in Mesoproterozoic formations of India and Russia—a comparative study

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Abstract

The Jaradag Fawn Limestone Formation (∼1.6 Ga, Semri Group, Vindhyan Supergroup, India) contains abundant microfossils and precipitates in early diagenetic (bedded and stromatolitic) cherts. The silicified carbonate precipitates and associated micritic event laminae were formed at or near the sediment–water interface and presumably lithified very rapidly. The precipitates, deposited inorganically without active participation of cyanobacterial mats, can be grouped into three morphological categories: radial-fibrous fans, microlaminated stratiform laminae and poorly differentiated laminated stratiform laminae. A diverse assemblage of cyanobacteria is preserved both within precipitates where preservation is excellent, and in other synsedimentary textures. Precipitates and microfossil assemblages from four Mesoproterozoic formations of Siberia are described and compared with those from Jaradag Fawn Limestone. Comparison of the Indian and the Siberian precipitates and associated microfossil assemblages reveals an almost identical pattern for contemporaneous Mesoproterozoic carbonate precipitates and microbiotas in cherts. The microbial assemblages, almost exclusively composed of the remnants of cyanobacteria, are dominated by entophysalidacean members and short trichomes, and can be termed as “typical Mesoproterozoic microbiotas”. Co-occurrence of these microbiotas and precipitates is probably related to the depositional environment of the Mesoproterozoic tidal flats, with high carbonate saturation. Neoproterozoic depositional conditions changed drastically, as did the composition of microbial communities.

Keywords: Mesoproterozoic; Cyanobacteria; Precipitates; Semri Group; India; Russia

1. Introduction

The microorganisms evolved significantly in the Mesoproterozoic (1.6–1.0 Ga) as is evidenced by the sharp changes in microbiota and explosive diversification of morphologically complex eukaryotes (Knoll,

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1992; Knoll and Sergeev, 1995; Sergeev et al., 1995, 1996; Javaux et al., 2001). The morphological diversification was accompanied by environmental evolution, which ultimately resulted in virtual disappearance of inorganic precipitates in the Neoproterozoic (Grotzinger, 1986, 1989, 1993, 1994; Grotzinger and Read, 1983; Grotzinger and Kasting, 1993). The precipitates are of interest because: (1) they are superficially similar to organo-sedimentary structures, i.e. stromatolites, (2) they incorporate, or are closely associated with many silicified microbiotas, suggesting a significant influence of environment on metabolic activity of ancient microorganisms and taxonomic composition of preserved microbiotas, and (3) their geological history, considered together with the fossil record, significantly improves information on the evolution of early life (Grotzinger, 1993; Kah and Knoll, 1996). Studies of numerous Proterozoic and Archean radial-fibrous and laminated textures carried out during past two decades have brought the diversity and complexity of the pre-Neoproterozoic sedimentary precipitates into sharper focus. Exceptionally well-preserved silicified fossil assemblages are, in almost all cases, closely related to these sedimentary textures (Knoll et al., 1993; Knoll and Sergeev, 1995; Sergeev et al., 1994, 1995; Seong-Joo and Golubic, 1999, 2000; Bartley et al., 2000). Therefore, investigation of the Mesoproterozoic silicified carbonate precipitates and associated microbiotas is very important, both to understand the carbonate precipitation patterns and the role of evolving ancient microorganisms in biostratigraphy. We further expanded research on precipitates from the Mesoproterozoic carbonate microfabrics to test the hypothesis that secular variations in taxonomic composition of microfossil assemblages principally reflect environmental changes governing substrate conditions, rather than biological evolution (Knoll and Sergeev, 1995; Sergeev et al., 1995; Kah and Knoll, 1996).

The Jaradag Fawn Limestone Formation (JFLF) in central India contains, many such precipitates/stromatolites preserved in early diagenetic cherts, which provide new information on these sedimentary textures. We have deciphered the morphology of the JFLF precipitates within the framework of their relationship to the remnants of cyanobacteria, which are abundant in the same microfabric. We have also analyzed the data on precipitates from the Mesoproterozoic fossiliferous cherty-dolomitic formations of Siberia and evaluated the similarities between the compositions of these microbiotas and associated sedimentary textures. The Indian and Siberian precipitates and associated microbiotas have been compared to the contemporaneous silicified sedimentary textures and microfossil assemblages from other areas of the world. The comparison has revealed that the presence of entophysalidacean cyanobacteria is the most typical feature of all these microbiotas. The precipitates provide information on the particular environments of microbial colonization, growth and fossilization, and also an opportunity to decipher the nature of ancient microorganisms and to explain why particular types of evolutionarily conservative cyanobacteria (e.g. entophysalidacean and nostocacean) dominated some of the Proterozoic microbial assemblages.

2. Materials, methods, and terminology and classification

2.1. Materials

The study is based on original material from the JFLF of India and the Kotuikan, Yusmastakh, Sukhaya Tunguska, Svetlyi and Debengda Formations of Siberia. Sharma collected chert samples from the JFLF exposed in eastern fringe of the Vindhyan basin, Rohtas District, Bihar (Fig. 1). A total of 51 rock samples were obtained from three localities covering base to top of the formation. Samples of silicified microfossils and precipitates from the Siberian formations were arranged by Sergeev (see Sergeev et al., 1994, 1995, 1997; Sergeev and Seong-Joo, 2001). We also studied one sample of chert collected by T.A. Ivanovskaya (Geological Institute of RAS) from the uppermost part of the Debengda Formation, along the east bank of the Khorbusuonka River, approximately 25 km below the mouth of Khatyspyt Stream (see Sergeev et al., 1994).

2.2. Methods

All precipitates and microfossils were investigated in petrographic thin sections. The silicified stratiform laminated rocks were cut perpendicular to bedding in series of slabs, each about 0.5 cm thick. Ground thin sections were prepared from each slab. Microfossils and precipitates were photographed in transmitted light with a Leitz and a REM-5 microscope and

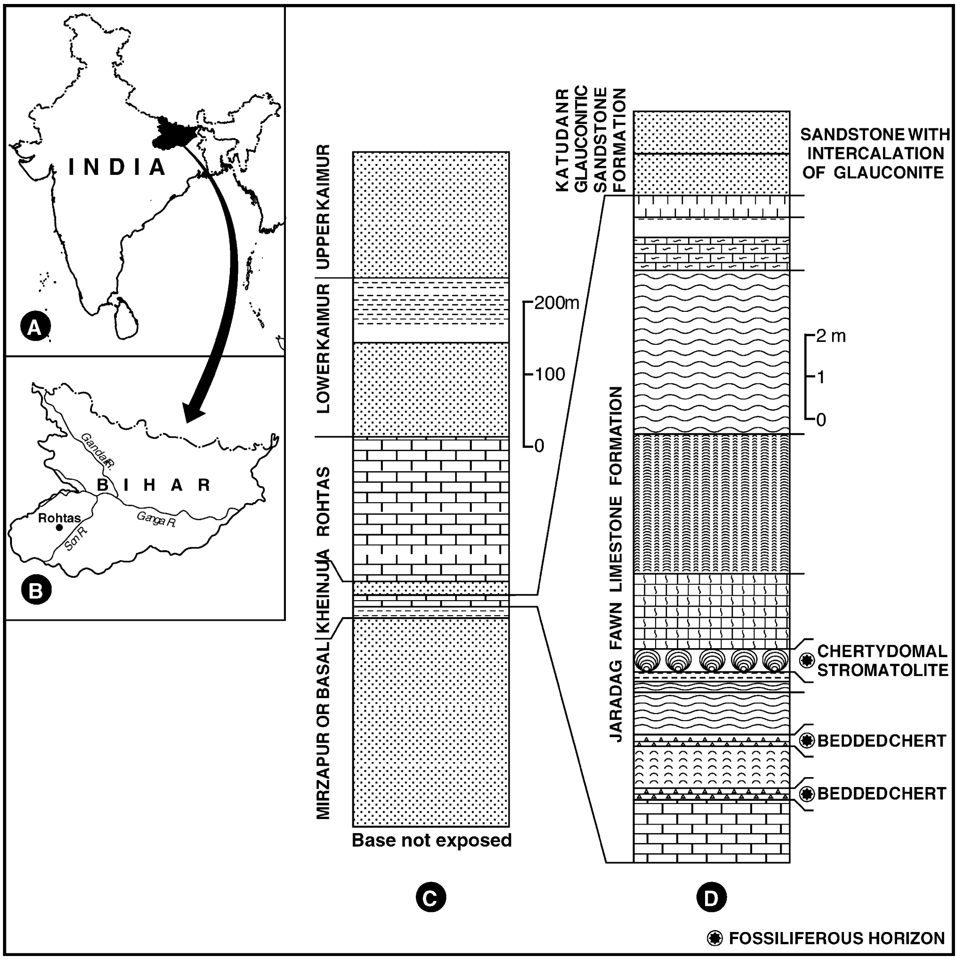


Fig. 1. Geographic and stratigraphic location of fossiliferous cherts from the Jaradag Fawn Limestone Formation. (A) Index map of India with position of Bihar state. (B) Outline map of Bihar showing position of Rohtas District where locations of the microfossiliferous outcrops of the JFLF occur. (C) Generalized stratigraphic column of the Semri and Kaimur Groups exposed in Rohtas. (D) Detailed litholog of JFLF, showing location of fossiliferous horizons.

measured with an eyepiece reticule to the nearest micrometer. For most specimens, England Finder coordinates and slide numbers are provided. For some specimens, the coordinates cited refer to the numbers of the points at the strips of paper attached at the end of the slides. A strip of paper is glued covering the thin section and the locations of the microorganisms are marked numerically by a sharp pencil. Specimens are deposited in the Paleobotanical Collection of Birbal Sahni Institute of Palaeobotany, Lucknow (BSIP 10905, 10906, 10907, 12872, 12873, 12874), and in Paleontological Collection of the Geological Institute of the Russian Academy of Sciences, Moscow (PCGI of RAS), Collection #4689, 4690 and 4694.

2.3. Terminology and classification

The terms “stromatolite” and “precipitate” have not been defined satisfactorily; even terminology for their description is not quite clear. For a long time, all laminated sedimentary structures found in the Precambrian rocks were supposed to be of organo-sedimentary origin, i.e. stromatolites, that formed as a result of trapping, binding and precipitation of carbonate sediments by colonies of microorganisms, presumably the blue–green algae (Walter, 1976). In recent years, it has been found that many microlaminated structures found in the Archean and Paleoproterozoic rocks and previously termed as “microdigitate stromatolites” formed as a result of calcium carbonate precipitation from oversaturated seawater (Grotzinger and Read, 1983; Hofmann and Jackson, 1987; Grotzinger, 1986, 1989, 1994; Kah and Knoll, 1996; Seong-Joo and Golubic, 1999, 2000; Bartley et al., 2000). These predominantly inorganic structures were named “precipitates” in contrast to “stromatolites” which are presumed to have deposited mainly as a result of metabolic activity of cyanobacteria. It is not still quite clear how to appreciate influence of biological activity on the precipitate formation and what percentage of biological influx is necessary to call the microlaminated sedimentary texture as “stromatolite” (Riding, 1999). The recognition of these structures, and use of various terminology and classification schemes to describe precipitated textures have been amply discussed (Seong-Joo and Golubic, 1999, 2000; Grotzinger and Knoll, 1999).

We consider laminated or radial-fibrous microbiolites with fine, extremely even and uniformly thick lamination, regardless of depositional orientation, as “precipitates”. These precipitates formed almost exclusively by inorganic deposition of calcium carbonate, with little evidence of involvement of cyanobacteria. Unambiguous remnants of cyanobacterial communities, that could be responsible for

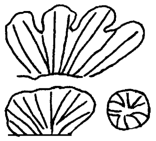
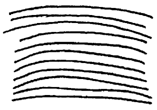
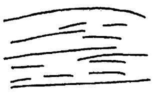
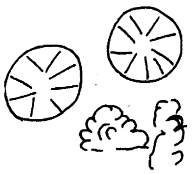
Type of Texture	This paper	Bartley et al 2000	Lee-Seong and Golubic, 1999, 2000	Grotzinger and Knoll, 1996	Kah and Knoll, 1999
	Radial fibrous fans	Radial fibrous texture	Upward radiating crystal fans	Microdigitate stromatolites	Laminated tufa microfacies
	Microlaminated stratiform laminae	Macrolaminated texture		Precipitated stratiform stromatolites	Microbe-bearing tufa
	Poorly laminated stratiform laminae	Poorly laminated to fenestral te			Microfacies coccoidal rich
		Laminated micritic texture (Yusmastakh Formation)			Microbial mats-Filament rich microbial mats
			Spherulites and botryoids		

Fig. 2. Terminology and classification of Precambrian precipitate structures.

accretion of precipitates by deposition, trapping or binding of sediments, have not been observed within these textures. The cyanobacteria or heterotrophic bacteria, as a result of their metabolic activity, probably changed the environments and indirectly facilitated the carbonate precipitation (Chafetz and Buczynski, 1992; Grotzinger and Knoll, 1995; Seong-Joo and Golubic, 1999, 2000; Bartley et al., 2000), but the microorganisms were not actively involved in formation of these finely laminated textures.

No standardized precipitate classification, like that developed for stromatolites, has yet been evolved. A number of classifications based either on morphology of these textures (Seong-Joo and Golubic, 1999, 2000; Bartley et al., 2000), or presence of any kinds of microbial remnants (Kah and Knoll, 1996) or other peculiarities have been proposed. We have preferred to follow the classification proposed by Bartley et al. (2000) that is based mainly on gross morphology of the primary textures and their relation to the microenvironments of their deposition (Fig. 2).

3. Geological setting and age of the Jaradag Fawn Limestone Formation

3.1. General geology

The Vindhyan Supergroup is unmetamorphosed, tectonically little disturbed in most of the areas and one of the best-preserved Proterozoic sedimentary sequences in India. It unconformably overlies the slightly metamorphosed Bijawar Group (∼2500 Ma, Crawford and Compston, 1970). The Vindhyan sediments comprise a thick pile of sandstones, shales and limestones spread over a large area extending from Sasaram, Rohtas District (Bihar) in the east to Chittorgarh (Rajasthan) in the west and Dholpur (Rajasthan) in the north to Hoshangabad (Madhya Pradesh) in the southwest. The sediments are distributed in an exposed area of about 1,04,000 km^2 and almost 65,000 km^2 area under alluvial cover (Auden, 1933; Ahmad, 1971; Krishnan and Swaminath, 1959; Mathur, 1981; Jokhanram et al., 1996; Sengupta, 1996). The Vindhyan Supergroup is divided into four groups, namely Semri, Kaimur, Rewa and Bhander, in ascending order. The lithostratigraphic succession in the area of study has been worked out by several workers (Sarkar, 1981; Sharma, 1993; Das Gupta, 1997). Here, the estimated thickness of the different formations is 935 m (Prakash and Kumar, 1980). The generalized lithostratigraphic succession of the Vindhyan Supergroup in the eastern part of the Vindhyan basin is given in Table 1. The Semri Group is divided into three Subgroups, viz. Mirzapur, Kheinjua and Rohtas. Kheinjua and Rohtas Subgroups of the Semri Group and Lower Kaimur and Upper Kaimur Subgroups of the Kaimur Group are well developed in the Rohtas area.

Table 1
Lithostratiphic succession of Vindhyan Supergroup exposed on easternmost fringe of the Vindhyan basin (modified after Das Gupta, 1997)

	Group	Subgroup	Formation
VINDHYAN SUPERGROUP	Kaimur	Upper Kaimur	Adhaura Quartzite and Sandstone
			Amjhore Scarp Sandstone and breccia
			Bijaigarh Shale (Amjhore Shale)
		Lower Kaimur	Matiama Quartzite and Sandstone
			Silicified Shale and Breccia
			Madhukupia Quartzite and Sandstone
	Semri	Rohtas	Scarp Limestone with inter bedded Shale
			Chuntia Shale
			Calcnodular Shale
			Pipradih Limestone
		Kheinjua	Katudanr Glauconitic Sandstone
			Jaradag Fawn Limestone
			Jadunathpur Olive Shale
		Porcellanite	Porcellanite
		Basal (Mirzapur)	Not Exposed

The JFLF is a part of the Kheinjua Subgroup. It is a thickly bedded fawn-coloured limestone exposed as small hillock and overlying the Jadunathpur Olive Shales with gradational to sharp contact. The chert bands stand out in weathered limestone. These bands are black to dark greenish black, gradually changing from bedded lithologies to massive stromatolitic. The individual bands of limestone at places are up to 3.5 m thick. *Irregularia* and *Stratifera* groups of stromatolites are dominant and *Pseudogymnosolen*, *Rohtasia harnaensis* and cryptalgal laminite stromatolites occur occasionally (Sharma, 1996). The total thickness of the JFLF is 50 m (Das Gupta, 1997).

3.2. Depositional environment

The JFLF consists of light-gray, thick-laminated, wavy-bedded dolosiltites and stromatolitic, oolitic and intraclastic dolomites and limestones interbedded with fine-grained doloarenites, edgewise conglomerate, and fine-grained siliciclastic lithologies. Presence of stratiform precipitats, flaggy fine-grained clastic carbonates, small-scale symmetrical ripples, mudcracks and voides supports interpretation of the fossiliferous facies as tidal flat deposits.

The JFLF chert is dominated by entophysalidacean cyanobacteria *Eoentophysalis belcherensis*, which by analogy with its modern counterpart *Entophysalis major* is considered to indicate the presence of an intertidal zone, i.e. a periodically emergent depositional environment (Golubic, 1976; Hofmann, 1976; Golubic and Hofmann, 1976; Knoll and Golubic, 1979; Sergeev, 1994; Sergeev et al., 1995). Modern *Entophysalis* dominate in warm, shallow hypersaline bodies of quite water in the intertidal zone or in coastal ponds that have only limited access to the open ocean. Another criterion suggesting episodic emergence is brown pigment that marks the surface of fossil entophysalidacean mats. Such yellow–brown extracellular pigment (scytonemine) is produced by cells of modern *Entophysalis* in response to high light intensity (Fritsch, 1945; Golubic and Hofmann, 1976). The upper margins of *Eoentophysalis* from the JFLF are frequently marked with similar dark-brown pigments (Fig. 5C).

No relicts of evaporite minerals have yet been found in the JFLF though a few voids, vugs and replacement sequence of carbonates to chert occurring in some bands are indicative of the existence of evaporitic conditions. Somewhat similar successive replacement features have been noted by Milliken (1979) in the chert nodules replacing Mississipian evaporites of southern Kentucky and northern Tennessee.

Sedimentological and paleontological data taken together thus suggest that the JFLF accumulated in arid, intertidal to supratidal, probably sabkha-like environment where some evaporitic minerals could have formed contemporaneously with cyanobacterial mats.

3.3. Age constraints

Radiometric dating, stromatolites and biostratigraphy of Lower Vindhyan deposits have lead to contradictory age determination (see Vinogradov et al., 1964; Tugarinov et al., 1965; Valdiya, 1969; Kumar, 1978a; Barman, 1981; Srivastava and Rajagopalan, 1988; Venkatachala et al., 1996). U/Pb isotope studies of galena collected at the contact of Bijaigarh Shale and Amjhore Scarp Sandstone (upper Kaimur) suggest an age of 725 Ma, probably indicating the age of galena mineralization, which is distinctly syngentic (Balasubrahmanyan and Chandy, 1976).

Recent radiometric dating suggests an older age for the Vindhyan Supergroup. Rasmussen et al. (2002) have generated a robust data set for the Lower Vindhyan using SHRIMP U–Pb zircon geochronology to date two silicified tuffs bounding the Chorhat Sandstone. Their studies have shown that the tuffs were deposited 1628 ± 8 Ma and 1599 ± 8 Ma. Ray et al. (2002) dated two rhyolitic volcanic horizons from the Deonar Formation, one between the Kajrahat and Rohtasgarh Limestone and the other below the unit containing trace fossils (Seilacher et al., 1998). These rhyolites yielded U–Pb zircon ages of 1631 ± 5 Ma and 1631 ± 1 Ma, respectively. Ray et al. (2003) worked out Pb–Pb age of the Rohtasgarh Limestone as 1601 ± 130 Ma. Of all these lithologies, the Kajrahat Limestone belongs to Basal Subgroup whereas the JFLF is a part of Kheinjua Subgroup, which is overlain by Rohtas Subgroup. These geochronological analysis suggest that the Kajrahat Limestone is of latest Palaeoproterozoic age and the Rohtasgarh Limestone of Rohtas Subgroup is of Mesoproterozoic age. The fossil-yielding horizon of Jaradag Limestone is therefore early Mesoproterozoic. Kumar et al. (2001) dated glauconites occurring in the basal shale of the Mirzapur Subgroup exposed in the Chitrakut area in central India and suggested a 1600 ± 50 Ma minimum age for the onset of Vindhyan sedimentation (for present status of the age of different formations of the Vindhyan Supergroup, see Venkatachala et al., 1996; Sharma, 2003a).

It can thus be deduced that the age of Semri Group exposed on the eastern-most fringe of the Vindhyan Basin ranges between ∼1600 and 1000 Ma. The fossiliferous JFLF is considered older than 1400 Ma and about 1600 Ma.

4. Precipitates and microfossils in cherts of the Jaradag Fawn Limestone Formation

4.1. *Brief history*

Stromatolites from the equivalent Fawn Limestone Formation in central India were first reported by Mathur (1965) and Valdiya (1969). Some of these 'stromatolites' have definite precipitated components (see Sharma, 1996), which were described either as stromatolites (Kumar, 1976, 1978a) or as microbialites (Sharma, 1996). Certain precipitates from Paleo- and Mesoproterozoic deposits of India were identified as microdigitate stromatolites (Sharma and Shukla, 1998; Riding and Sharma, 1998; Sharma et al., 1998). Silicified microfossils were discovered in cherts in the Son Valley by Kumar (1978b) and later described in detail by McMenamin et al. (1983) and Kumar and Srivastava (1995). Microfossils and precipitates have also been found in cherts from contiguous outcrops of the JFLF in Bihar (see Venkatachala et al., 1990; Sharma, 1993). Subsequent studies of the chert samples from this area resulted in a detailed description of the Jaradag microbiota (Sharma, 2003b).

4.2. *Description of precipitates*

Precipitates of JFLF vary in morphology and can be grouped into three main types, similar to those described from other Mesoproterozoic formations (Knoll et al., 1993; Bartley et al., 2000). These

Table 2
Comparative characteristics of the precipitates and associated silicified microfossils from the various Mesoproterozoic formations

Unit name	Age	Location	Type of texture	Dominant and conspicuous microfossil taxa
Jaradag Fawn Limestone Formation	Early Mesoproterozoic	Bihar, India	RFF, MSL, PDSL	*Eoentophysalis belcherensis*, *Archaeoellipsoides* spp., Short trichomes
Kotuikan and Yusmastakh Formations	Early Mesoproterozoic	Anabar Uplift, Siberia	RFF, MSL, PDSL, LMT	*Eoentophysalis belcherensis*, *Archaeoellipsoides* spp., *Myxococcoides grandis*
Kyutingda Formation	Early Mesoproterozoic	Olenek Uplift, Siberia	RFF, MSL	*Eoentophysalis belcherensis*, *E. dismallakesensis*, Short trichomes
Debengda Formation	Mesoproterozoic	Olenek Uplift, Siberia	RFF, MSL, PDSL	*Eoentophysalis belcherensis*, *E. dismallakesensis*, *Siphonophycus typicum*
Svetlyi Formation	Mesoproterozoic	Uchur-Maya Region, Siberia	RFF, MSL	*Siphonophycus robustum*, *S. typicum*, *S. solidum*
Dismal Lakes Group	Mesoproterozoic	Northern Canada	Present but not described or illustrated	*Eoentophysalis dismallakesensis*, *Archaeoellipsoides* spp.
Gaoyuzhuang and Wumishan Formations	Mesoproterozoic	Northern China	RFF, MSL	*Eoentophysalis belcherensis*, *Coccostratum dispergens*, *Archaeoellipsoides* spp., *Siphonophycus* spp.
Sukhaya Tunguska Formation	Late Mesoproterozoic	Turukhansk Uplift, Siberia	RFF, MSL	*Eoentophysalis dismallakesensis*, *Polybessurus bipartitus*, *Siphonophycus* spp.
Society Cliff Formation	Late Mesoproterozoic	Northern Canada	RFF, MSL, PDSL, LMT	*Eoentophysalis belcherensis*, *Polybessurus bipartitus*, *Siphonophycus* spp.,

Abbreviations: RFF: radial fibrous texture; MSL: microlaminate stratiform laminae, PDSL: poorly differentiated stratiform laminae, LMT: laminated micritic texture. Data about the precipitate types and dominated taxa of microfossils from the Kyutingda Formation is a result of personal investigation of one of authors (VNS) in the thin sections of cherts from M.S. Yakschin's collection and differ from those described in the relevant publications (Yakschin, 1990, 1999).

are: radial-fibrous fans, microlaminated stratiform laminae, poorly differentiated stratiform laminae (Fig. 2, Table 2). In describing Jaradag Fawn Limestone sedimentary structures, emphasis is laid on the precipitate morphology and its relationship to the microorganisms rather than on sedimentological analysis of depositional environments.

4.2.1. *Radial-fibrous fans*

The radial-fibrous textures are composed of radiating to subparallel blades of fibrous crystals. The fibers are 2–5 μm across and 200–2000 μm long; their thickness is consistently uniform along the long axis (Fig. 3C). Microfossils are relatively abundant in this texture and are usually very well preserved, often occurring within crystal bundles. Laminae within the radial-fibrous textures are delineated by layers of well-preserved microfossils as well as by finely dispersed organic matter distributed perpendicular to the direction of the crystal growth. The finely dispersed organic matter apparently may have provided nucleation sites for the crystal growth. If nucleation sites are distributed continuously over a horizon, palisade laminae develop (Fig. 6A). The radial-fibrous fans, when stacked vertically, produce irregular microdigitate stromatolite-like structures (Fig. 4B and E).

The radial fibrous crystals, when discretely nucleated, form bundles growing upward and sideward and interpenetrate laterally (Fig. 7A and C). Spherical oncolite-like textures sometimes occur where the crystal growth is in downward and upward as well as in lateral directions (Fig. 3E). In regions where the sideward growing bundles of crystals interfere, colonies of *Eoentophysalis* and *Eosynechococcus* (2–8 μm diameter) are trapped inside the precipitates (Fig. 6C and D). Sheaths of *Siphonophycus* also occur within the fans and are often oriented vertically reaching the fans' upper surface. Beautifully preserved trichomes occur inside the radial-fibrous fans also (Fig. 5E; Fig. 6B, D and E). Otherwise, the microorganisms occur inside the growing upward tubes, either reaching the upper surface of the fans (Fig. 6B and E; Fig. 7F) or terminating inside in hemispherical structures (Fig. 8A, B and D). Most probably, the sheaths of cyanobacteria that escaped burial by precipitates formed these tubes. Sometimes, the terminal parts of the sheaths near the upper surface of fan, without filaments, act as tubes that allow dwelling space for coccoid microfossils.

Crystal bundles either terminate sharply, or interpenetrate for a small distance before termination. The upper surface may be flat/to wavy, laminated or mammilated (Fig. 3A and D), in which the precipitates resemble comb-like structures. The deep tube-like structures penetrate to several hundreds of microns downward from the fans' surface containing inside sheaths of *Siphonophycus*, and coccoidal forms.

4.2.1.1. Interpretation. Bartley et al. (2000) suggested that morphologically identical radial-fibrous fans were located near the intertidal and supratidal facies of an arid tidal flat, where evaporation of seawater resulted in significant carbonate oversaturation. The growth of radial-fibrous structures was quenched by a change in water chemistry, resulting from flooding, reduced concentration of inorganic carbon or overgrowth of cyanobacterial mats. The decomposed mats probably were the centers for initial carbonate precipitation because organic molecules that inhibited this process were consumed heterotrophically making the microenvironments favourable for carbonate precipitation. In some cases, nucleation occurred directly at the sediment–water interface and the fans grew rapidly, penetrating the mats and entombing allochthonous microorganisms. When discretely nucleated, bundles of radial fibrous crystals grew sidewards and interfered, the trapped microorganisms probably tried to escape upwards, changing the shape of the fans. The filamentous microorganisms also tried to avoid burial by carbonate cement and moved upward leaving behind abandoned sheaths (see Seong-Joo and Golubic, 1998) preserved inside the precipitates (Fig. 6B and E; Fig. 7F).

The growth of radial-fibrous textures was intermittent, with periods of low precipitation punctuated by rapid growth of the radial-fibrous fabric. When the nucleation occurred slightly below the sediment–water interface, the radial fan-like structures were formed (Bartley et al., 2000). The size and shape of fibrous crystals resembles the fibers that constitute botryoidal aragonite (Ginsburg and James, 1976; Folk and Assereto, 1976; Grotzinger and Read, 1983; Hofmann and Jackson, 1987), although this growth habit may also occur in calcite (Bartley et al., 2000).

4.2.2. *Microlaminated stratiform laminae*

The microlaminated stratiform laminae are not abundant in JFLF chert. This texture consists of al-

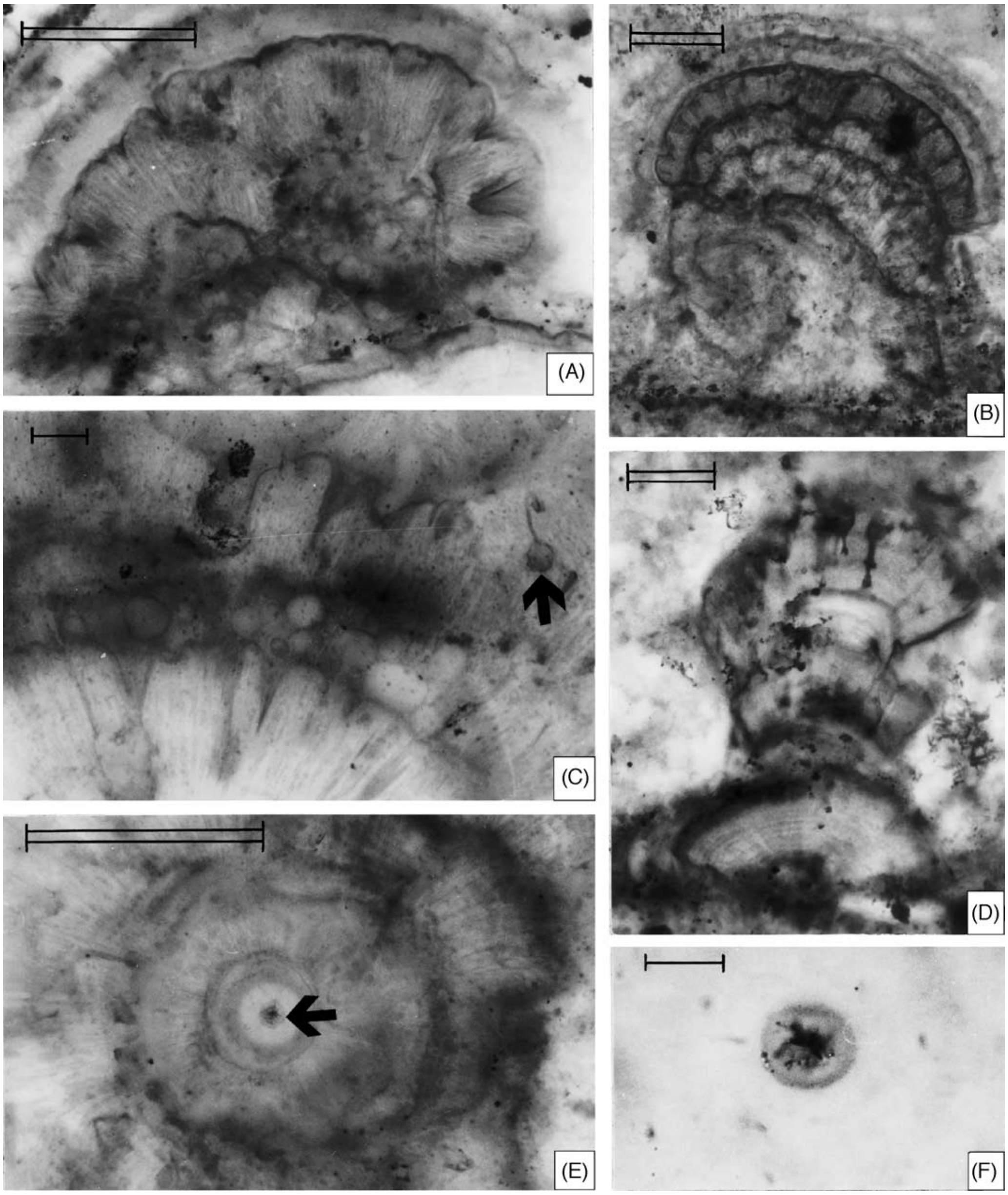


Fig. 3. Radial-fibrous fans from the Jaradag Fawn Limestone Formation. All materials illustrated in Figs. 3–12 came from the thin sections of black cherts. For all specimens shown on Figs. 3–10, the microscope stage coordinates and England Finder coordinates (in brracketes) are provided. (A) Radial- fibrous fan with mammilated surface. Sample #3949, slide no. BSIP-10907, coordinates 28.0 × 97.5 (S-28-3). (B) Low-magnification view of radial-fibrous fan with mammilated surface. Sample #3949, slide no. BSIP-10905, coordinates 31.0 × 101.0 (P-31-1). (C) Radial-fibrous fan with apparently discrete bundles of crystals growing upward and sideward. Sample #3949, slide no. BSIP-10905, coordinates 31.4 × 101.4 (O-31-2). Note the microfossil with a "tail" in the upper right corner of the picture (arrow) formed as a result of superimposition of a coccoidal *Myxococcoides* sp. over a filamentous sheath of *Siphonophycus robustum*. (D) Radial-fibrous fan with mammilated surface growing atop of the radial-fibrous fan with smooth surface. Sample #3949, slide no. BSIP-10905, coordinates 32.1 × 93.7 (W-32-3). (E and F) The three-dimensional radial-fibrous crystal with *Myxococcoides* sp. (F, indicated by an arrow in E) A nucleation site. Sample #3949, slide no. BSIP-10905, coordinates 33.0 × 105.5 (K-33-2). Single scale bar represents 20 μm, double 200 μm.

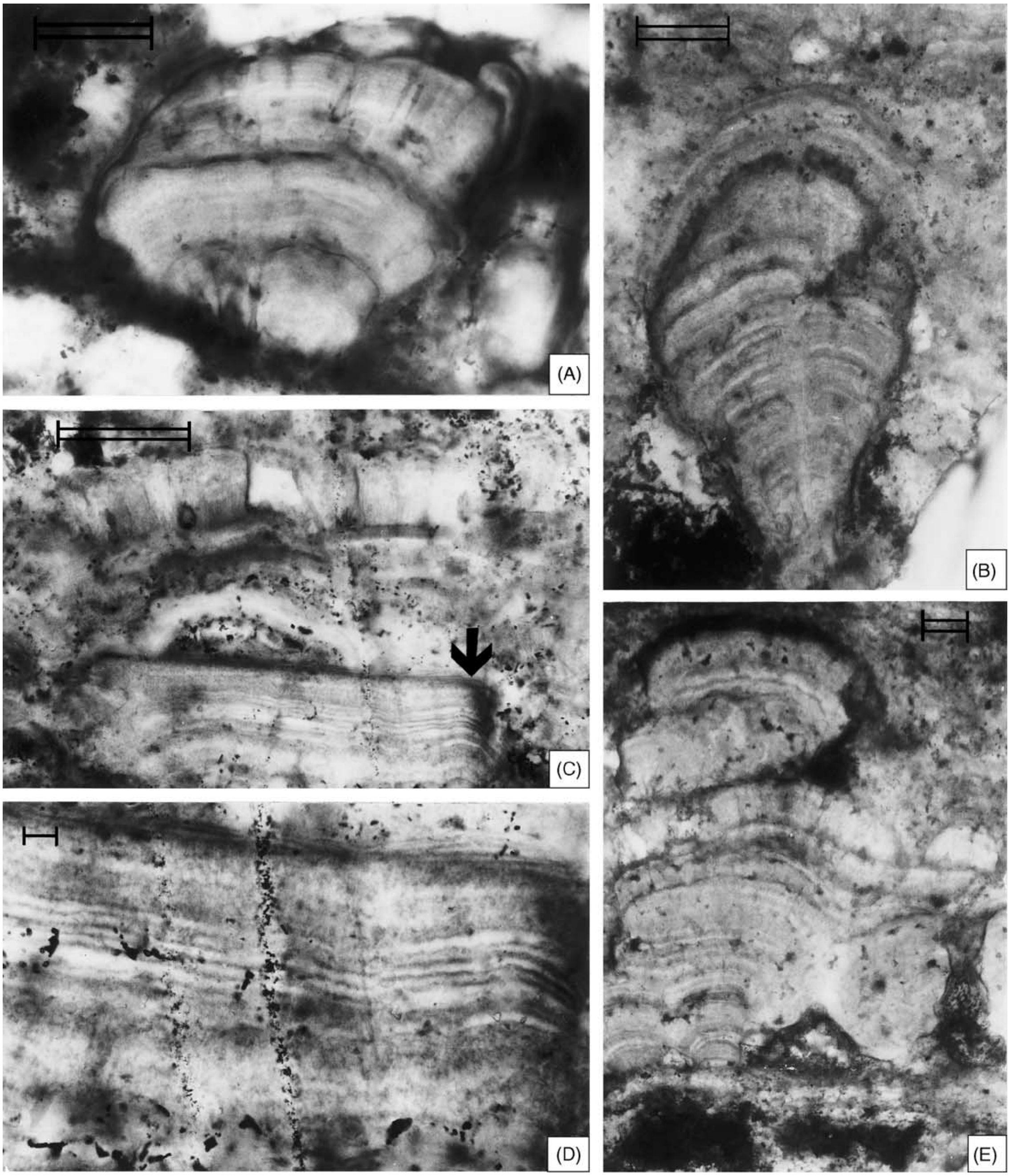


Fig. 4. Radial-fibrous fans and microlaminated stratiform laminae from the Jaradag Fawn Limestone Formation. (A) Radial-fibrous fan with vertically oriented sheaths of *Siphonophycus robustum* preserved inside. Sample #3949, slide no. BSIP-10907, coordinates 36.7 × 95.6 (U-37-4). (B) Radial-fibrous fan of irregular "microdigitate stromatolite" shape. Sample #4280, slide no. BSIP-12872, coordinates 60.4 × 106.5 (J-61-4). (C and D) Microlaminated stratiform laminae (D, indicated by an arrow in C) Overgrowing by the radial-fibrous fan of palisade appearance. Note the isopachous character of the laminae. Sample #4280, slide no. BSIP-12872, coordinates 49.4 × 106.5 (J-50-4). (E) Radial-fibrous fans stalked vertically. Sample #4280, slide no. BSIP-12872, coordinates 49.0 × 104.7 (L-49-2). Single scale bar equals to 20 μm, double to 200 μm.

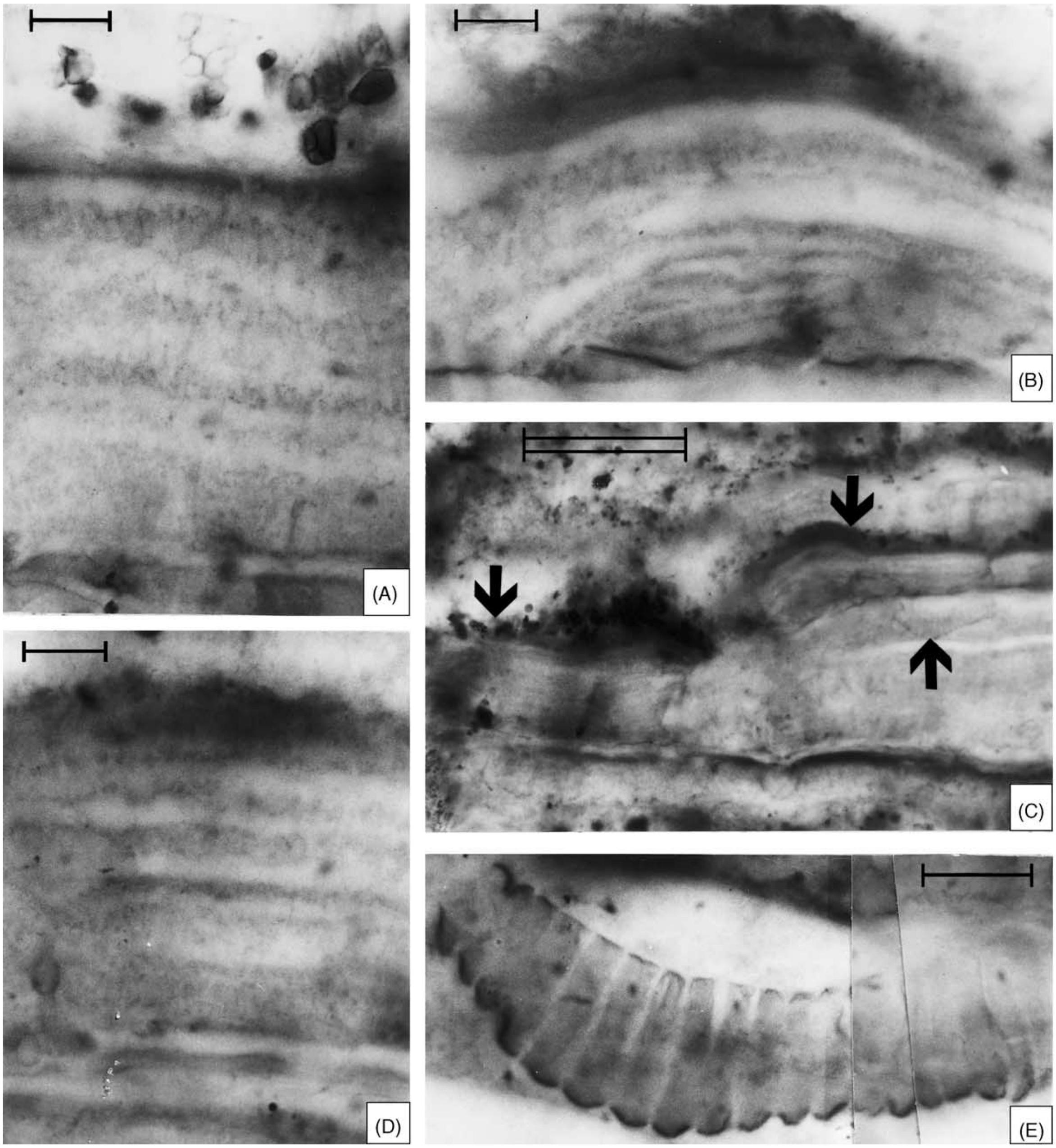


Fig. 5. Radial-fibrous fans and microlaminated stratiform laminae from the Jaradag Fawn Limestone Formation. (A–C and E) Radial-fibrous fan (C, low-magnification view) overgrowing by microlaminated stratiform laminae (B, indicated by the upper right arrow in C) and colony of *Eoentophysalis belcherensis* (A, indicated by the upper left arrow in C). Radial-fibrous fan containing the trichome of *Oscillatoriopsis longa* (E, indicated by the lower right arrow in C). Sample #3949, slide no. BSIP-10907, coordinates 43.2 × 98.8 (R-44-3). (D) Microlaminated stratiform laminae, sample #3949, slide no. BSIP-10907, coordinates 43.3 × 98.0 (S-44-1).). Single scale bar equals to 20 μm, double to 200 μm.

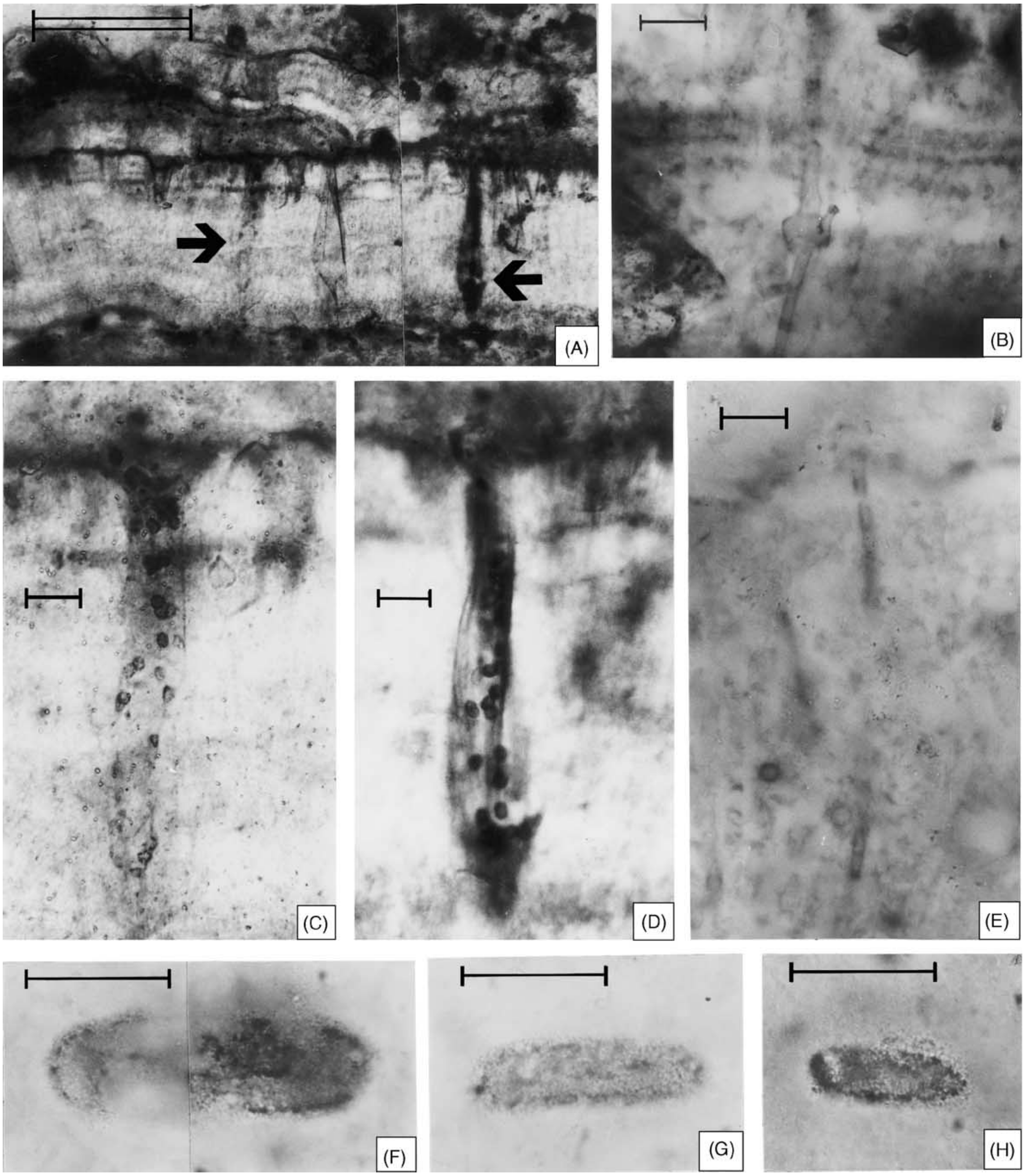


Fig. 6. Radial-fibrous fans and akinetes *Archaeoellipsoides* from the Jaradag Fawn Limestone Formation. (A, C, and D) The palisade texture (A, low-magnification view) containing colonies of *Eosynechococcous* and *Eoentophysalis* (C and D, indicated by the relevant arrows in A). Sample #3949, slide no. BSIP-10907, coordinates 42.4 × 102.4 (O-44-1). (B and E) The vertically oriented sheath of *Siphonophycus robustum* trapped inside the radial fibrous fans. Sample #4280, slide no. BSIP-12872, coordinates: B—40.5 × 99.5 (R-41-J); E—47.0 × 106.0 (K-48-1). (F) *Archaeoellipsoides major*. Sample #4256, slide no. BSIP-12873, coordinates 23.2 × 111.8 (D-23-1). (G and H) *Archaeoellipsoides minor*, sample #4256: G—slide no. BSIP-12873, coordinates 22.0 × 112.1 (C-21-4); H—slide no. BSIP-12874, coordinates 39.6 × 96.8 (U-40-1)). Single scale bar equals to 20 μm, double to 200 μm.

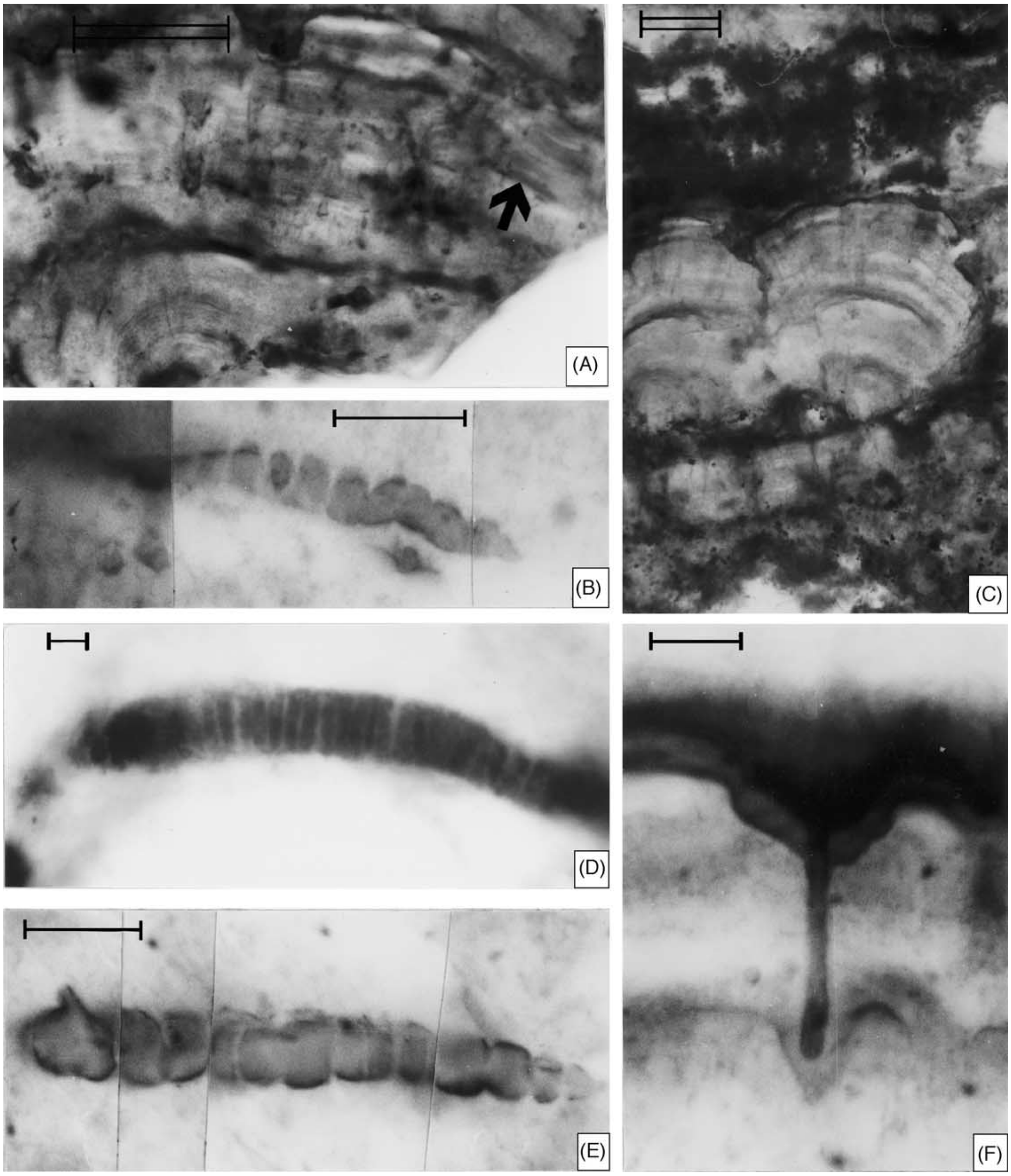


Fig. 7. Radial-fibrous fans and trichomes from the Jaradag Fawn Limestone Formation. (A and B) A trichome of *Filiconstrictosus majusculus* contained inside a radial-fibrous fan (B, indicated by an arrow in A). Sample #3949, slide no. BSIP-10905, coordinates 41.0 × 108.3 (G-40-4). (C) The doubled radial-fibrous fan containing vertically oriented sheaths of *Siphonophycus robustum*. Sample #3949, slide no. BSIP-10907, coordinates 42.9 × 104.6 (Q-35-2). (D) *Oscillatoriopsis longa*. Sample #3949, slide no. BSIP-10906. (B) Coordinates 36.8 × 106.9. (E) The trichome *Filiconstrictosus majusculus* preserved inside a radial-fibrous fan (neighboring and morphologically almost identical to specimen shown on Fig. 7C. Sample #3949, slide no. BSIP-10907, coordinates 35.7 × 99.0 (R-36-3). (F) The pseudoendolithic filaments of *Siphonophycus robustum* penetrating downward from the surface of radial-fibrous fan (located near trichome shown in Fig. 7E. Sample #3949, slide no. BSIP-10905, coordinates 35.7 × 98.9 (R-36-3). Single scale bar equals to 20 μm, double to 200 μm.

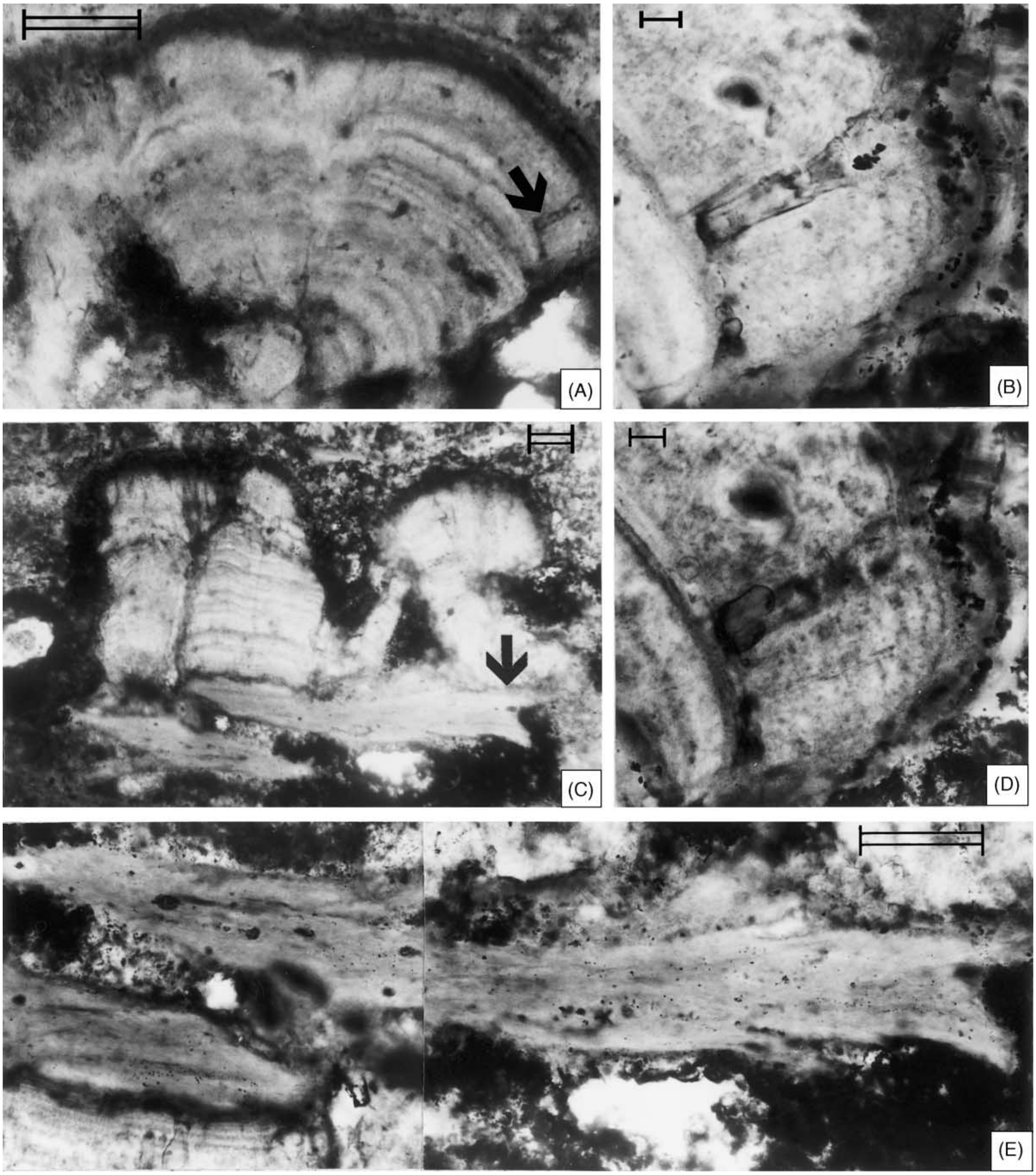


Fig. 8. Radial-fibrous fans and poorly differentiated stratiform laminae from the Jaradag Fawn Limestone Formation. (A, B, and D) Radial-fibrous fan (A, low-magnification view) containing inside a trapped colony of coccoidal microfossils—*Eoentophysalis*? (B, D, indicated by arrow in A). The colony shown on (B) and (D) is terminated by hemispherical dome-like structure that probably documents the unsuccessful attempt of microorganisms to escape burial by growing aragonite fan. Sample #4280, slide no. BSIP-12872, coordinates 34.6 × 103.3 (M-35-4). (C and E) The poorly differentiated stratiform laminae (E, indicated by arrow in C) overgrowing by the radial-fibrous fan. Sample #4280, slide no. BSIP-12872, coordinates 37.0 × 103.3 (M-37-4). Single scale bar equals to 20 μm, double to 200 μm.

ternating dark and light individual microlaminae, respectively, 1–4 and 4–7 μm thick, much thinner than those of typical microbial mats, with planar to convex-upward shape (Fig. 4C and D). When curved, laminae form overlapping or onlapping domes, with younger laminae truncating against older structures (Fig. 5A and D). Individual microlaminae are of uniform thickness, traceable throughout their length, and are defined by concentration of organic matter, producing an alternating pattern of thin dark and thicker light microlaminae. Microfossils are not abundant in the microlaminated laminae, but sometimes have excellent preservation. Fossils of spherical shape are entirely uncompacted inside this texture.

4.2.2.1. Interpretation. The microfossils are entirely encompassed and microlaminae onlap the margins of cell walls and then overstep the top of cells. The deflection of laminae away from the cell wall probably reflects the hydrophobic properties of certain organic compounds, which prevented the buildup of fluids. At the same time, the seawater became oversaturated as a result of evaporation, but primarily calcium carbonate concentration was not sufficient for precipitation. The extraordinary thin individual lamina suggests that accreted carbonates were covered by extremely thin film of water, possibly in supratidal environment, wetted only by ocean spray during storms or unusually high tides. Therefore, the microlaminated texture was precipitated at the sediment–water interface, and the allochthonous planktonic microorganisms were rapidly entombed as they settled on the accumulating carbonate crust. Bartley et al. (2000) suggested that microlaminated stratiform laminae probably are of supratidal origin and formation of this texture was highly episodic.

4.2.3. Poorly differentiated stratiform laminae

This texture comprises irregular flat lying to gently convex upward laminae of relatively dense finely divided organic matter, but without many recognizable structurally preserved microfossils. Thin individual organic laminae are discontinuous and often invisible. Poorly laminated laminae can be replaced upwards or laterally by fibrous and microlaminated textures (Fig. 8C and E).

4.2.3.1. Interpretation. This particular texture is inferred to have been produced during relatively slow accumulation of carbonate sediments. The mat-building cyanobacteria were decomposed and buried before lithification. Occasionally, the decomposed mats turned into sites of nucleation of the radial-fibrous fans. The remnants of benthic cyanobacteria and planktonic allocthonous microorganisms were lithified early and preserved almost undeformed suggesting instantaneous formation of this texture.

4.3. The composition of the Jaradag Limestone microbiota

The Jaradag Limestone microbiota is represented by at least 18 genera and 27 species of morphologically simple, filamentous and coccoidal fossils (Sharma, 2003b). These are interpreted as cyanobacterial cells, trichomes and sheaths, except for some simple spheroids, which may be eukaryotic. Five taxa, viz. *Filiconstrictosus majusculus* Schopf and Blacic (Fig. 7E), *Oscillatoriopsis longa* Timofeev and Hermann, *Oscillatoriopsis* sp., *Eomicrocoleus crassus* Horodyski and Donaldson and *Orculiphycus* sp. are assigned to the Oscillatoriales. *Archaeoellipsoides major* Golovenoc and Belova and *A. minor* Sergeev and Knoll are interpreted as the preserved akinetes of the nostocalean cyanobacteria. *Siphonophycus robustum* Schopf, *S. thulenema* Butterfield may belong to either the Oscillatoriales or the Nostocales. *E. belcherensis* Hofmann, *Coniunctiophycus gaoyuzhuangense* Zhang, *Palaeoanacystis vulgaris* Schopf, *Sphaerophycus parvum* Schopf, *S. medium* Horodyski and Donaldson, *Tetraphycus hebeiensis* Liu, and *T. major* Oehler represent the Chroococcales. *Eosynechococcus grandis* Hofmann, *E. medius* Hofmann and *Diplococcus* sp. may also belong to this order.

The Jaradag Limestone assemblage does not contain remains of unequivocal eukaryotic microorganisms. *Myxococcoides minor* Schopf, *M. muricata* Schopf and Barghoorn, *Myxococcoides* sp. and *Leiosphaeridia* sp. are all simple spheroidal fossils, which, however, may represent preserved cells of protista, cyanobacterial cell walls, or extracellular envelops of coccoidal cyanobacteria. Colonies of spherical unicells surrounded by common sac-like or amorphous envelope, e.g. *Clonophycus elegans* Oehler, *C. ostiolum* Oehler, *Conhemisphaera pendula* Luo and Wang and *Leptoteichos golubicii* Knoll, Barghoorn and Awaramik may have been formed as a result of multiple division of protoplasts of cyanobacterial or eukaryotic cells. However, we are rather inclined to interpret the Jaradag Limestone microbiota as totally prokaryotic, composed only of non-nucleated simple microorganisms. The dominance of cyanobacteria in Jaradag Limestone cherts reflects the formation of these particular early diagenetic-bedded cherts in peritidal environments of a type dominated today as well as in the Mesoproterozoic by prokaryotes. Recently it has been shown that nucleated organisms, unambiguous eukaryotic acritarchs, were conspicuous in early Mesoproterozoic ecosystems also (Xiao et al., 1997; Javaux et al., 2001; Prasad and Asher, 2001; Sergeev and Seong-Joo, 2004).

4.3.1. *Mat-forming cyanobacteria*

The Jaradag precipitates were not though accreted by microbial mat communities, yet mat horizons can be identified by the occurrence of dense populations spread over bedding surfaces. At least two distinct mat-building populations, viz. *E. belcherensis* and *S. robustum* (Fig. 4A), are present in Jaradag Limestone cherts. The billowing pigmented colonies of *E. belcherensis* are located mainly on the surfaces of and above radial-fibrous fans and microlaminated stratiform laminae, sometimes following the truncating bedding surfaces (Fig. 5C).

4.3.2. *Associated cyanobacteria*

Due to high polymorphism of *Eoentophysalis* colonies and very complicated life cycle, these cyanobacteria exhibit different morphologies that can be described as separate taxa. Some of the taxa reported from the Jaradag Limestone, e.g. *C. gaoyuzhuangense*, *P. vulgaris* and *S. parvum*, may be developmental or taphonomic variants of *E. belcherensis*. On the other hand *Eosynechococcus medius*, *E. grandis*, *T. hebeiensis*, *T. major*, *Sphaerophycus medium* and *Diplococcous* sp. are independent taxa of chroococcacean cyanobacteria.

4.3.3. *Trichomes*

Trichomes constitute a rare but distinctive element of the Jaradag Limestone assemblage. Most of the specimens are quite short. Several taxa, e.g. *Filiconstrictosus*, *O. longa* (Fig. 7D), *Oscillatoriopsis* sp. and *Orculiphycus* sp. have been reported. These trichomes may represent hormogonia and hormocysts or germinated akinetes of nostocalean cyanobacteria.

4.3.4. *Planktonic microfossils*

Ellipsoidal microfossils *A. major* (Fig. 6F) and *A. minor* (Fig. 6Gn and H) may be akinetes of nostocalean cyanobacteria. Of several dozen specimens observed, not a single pair represents dividing cells. The affinities of simple spheroidal fossils *M. minor*, *Myxococcoides* sp., *Leiosphaeridia* sp. and spheroidal colonies of *C. elegans*, *C. ostiolum*, *Conhemisphaeria pendulua* and *L. golubicii* are uncertain. These may represent planktonic prokaryotic or eukaryotic microorganisms, or even benthic settlers.

4.4. *Relationship between the Jaradag Limestone precipitates and associated microfossils*

The precipitates that are part of the cherts of the JFLF are not stromatolites in the sense that they were not formed through the routine activity of cyanobacteria. The carbonates deposited neither as a result of metabolic activity of cyanobacteria nor by trapping and binding of particles of carbonates by cyanobacterial mats. The carbonates rather precipitated from highly oversaturated seawater as a result of change in its chemical composition. In some cases, it is evident that decomposed cyanobacterial mats were nucleation sites for upward growing radial-fibrous fans (Fig. 3C–E). Some fossils, including spherical or filamentous cyanobacteria were often preserved inside precipitates that in some cases evidently facilitated their very good preservation. Absence of *Eoentophysalis* nor *Siphonophycus* mats within the radial-fibrous fans or stratiform laminae evidently indicates that they did not build the precipitates. While bacterial metabolism may have played a role in carbonate nucleation, cyanobacterial mats did not and therefore these structures are non-stromatolites. However, formation of the Mesoproterozoic precipitates was not only due to the change in the local environmental chemistry. These precipitates were widely distributed in Archean, Paleo- and Mesoproterozoic basins; they almost completely disappeared in the Neoproterozoic. The Mesoproterozoic precipitates were widely localized in intertidal and supratidal environments while during the Archean and Paleoproterozoic, precipitates formed in a variety of environments, including open-marine settings (Grotzinger, 1986, 1989, 1993; Sumner and Grotzinger, 1996; Sumner, 1997; Kah et al., 2001).

5. Comparison with other Mesoproterozoic precipitates and microfossil assemblages

5.1. The Kotuikan and Yusmastakh Formations, Anabar Uplift, Siberia

The Kotuikan and Yusmastakh, predominantly carbonate facies, and the underlying terriginous-carbonate Ust'–Il'ya Formation comprise the Billyakh Group. This group contains abundant stromatolites, organic-walled and silicified microfossils. Considering all biostratigraphic data on the stromatolitic and microfossil assemblages and new chemostratigraphic and isotopic-geochronological dating, the age of Billyakh Group may be bracketed between 1500 and 1250 Ma (Gorokhov et al., 1991, 1995; Semikhatov et al., 2001; Bartley et al., 2001).

The upper member of the Kotuikan Formation is interpreted to have deposited principally in restricted marine, peritidal and probably supratidal environments. The Yusmastakh Formation represents alternation of restricted marine tidal-flat environments with less restricted shallow marine setting. The distinctive beds of its lower member contain cherts with abundant microfossils and precipitated textures that also deposited in the peritidal environments with subaerial exposure (Sergeev et al., 1995; Bartley et al., 2000).

Bartley et al. (2000) have recognized four different textures in the Kotuikan and Yusmastakh silicified carbonates, viz. radial-fibrous, microlaminated, poorly differentiated (poorly laminated to fenestral) and laminated micritic. The radial-fibrous fans and microlaminated fabrics are easily recognizable and almost identical with those in the Jaradag Limestone. However, in the Kotuikan Formation this fabric is comparatively better developed and abundant (Fig. 9A–D; Fig. 10A–D). The radial-fibrous fans with mammilated surfaces are present only in the JFLF. The poorly differentiated laminae also are easily recognizable and not very abundant in the Kotuikan and Yusmastakh Formations (Fig. 10E and F). But laminated, micritic texture abundant in the Yusmastakh Formation was not detected in the Jaradag Limestone.

The taxonomic composition of the Kotuikan and Yusmastakh microbiotas is very similar to that of the Jaradag Limestone, and the three can be named as "typical Mesoproterozoic microbiotas". The entophysalidacean cyanobacterium *E. belcherensis* is the dominant element of these microbiotas and other taxa share similar proportions among fossilized microorganisms. *Archaeoellipsoides* and *Myxococcoides* are widely distributed in cherts of Russian formations (Fig. 9C and D; Fig. 10D and F). *S. robustum* (Fig. 9E) is common, but it is not a predominant element of these microbiotas. The small coccoidal microfossil taxa *Sphaerophycus*, *Eosynechococcus* and *Coniunctiophycus* often occur in the Jaradag Limestone as well as in the Kotuikan and Yusmastakh Formations.

Some differences nonetheless exist. The ellipsoidal microfossil *Archaeoellipsoides* and coccoidal microfossils *Myxococcoides* are common in the Kotuikan and Yusmastakh microbiotas, but in the Jaradag Limestone remnants of these microorganisms are relatively poorly represented. The short trichomes are typically present in the Kotuikan and Jaradag Limestone microbiotas, whereas in the Yusmastakh Formation these forms are almost absent. The short trichomes are presumed to represent the initial stage of akinetes germination (Knoll and Sergeev, 1995; Sergeev et al., 1995; Sergeev, 1997). The abundant presence of *Archaeoellipsoides* fossils in these cherts suggests a taphonomic bias. The Kotuikan and Yusmastakh microbiotas contain filaments of *Circumvaginalis elongatus* (Fig. 9F) that are missing in the Jaradag Limestone.

5.2. The Debengda Formation, Olenek Uplift, Siberia

The Solooliiskaya Group contains some 1500 m of quartz arenites, shales and carbonates and is divided into the Sygynakhtakh, Kyutingda, Arymas, Debengda and Khaipakh Formations. The Debengda Formation (ca. 200–250 m thick) comprises sandstones, siltstones, and argillites, as well as abundant limestone and dolomite with stromatolites, oolites, pisolites and intraformational conglomerates. The fossiliferous cherts and precipitates occur in its upper member (Sergeev et al., 1994). Debengda fossiliferous facies are tidal flat deposits (Sergeev et al., 1994). The age of the Solooliiskaya Group is principally based on stromatolite and microfossil biostratigraphy. The Solooliiskaya and Billyakh Groups occur in the same basin and their intrabasinal correlation is secure. Stromatolite assemblages permit reliable correlation of the Khaipakh Formation with the upper member of the Yusmastakh Formation, and microfossils favour of a Mesoprotero-

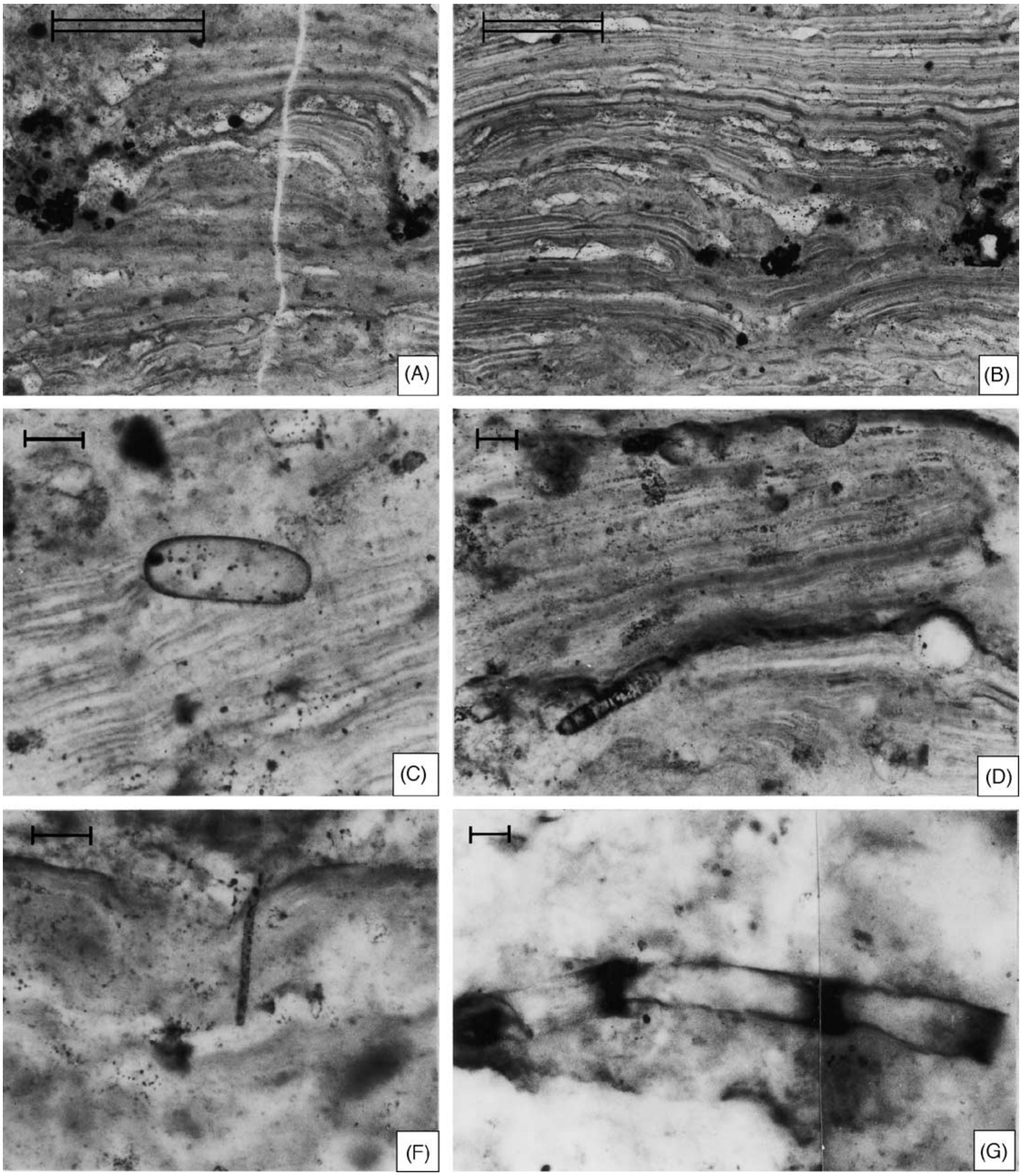


Fig. 9. Microlaminated stratiform laminae and trichomes from the Kotuikan Formation. (A) The convex-upward curved microlaminated stratiform laminae with colonies of *Eoentophysalis belcherensis* occupying depressions between the domes, sample #4689-7e, slide no. PCGI-482-90, coordinates 31.6 × 104.0 (M-32-1). (B) The microlaminated stratiform laminae containing scattered colonies of *Eoentophysalis belcherensis* and primarily dolomite rhombohedrons. Sample #4689-7e, slide no. PCGI-482-90, coordinates 34.1 × 104.0 (M-33-2). (C) The akinete *Archaeoellipsoides grandis* preserved inside microlaminated stratiform laminae. Sample #4689-7e, slide no. PCGI-482-90, coordinates 41.5 × 98.0 (S-42-3). (D) A germinating akinete with prominent ribs preserved inside microlaminated stratiform laminae. Sample #4689-7e, slide no. PCGI-482-90, coordinates 34.2 × 98.5 (S-34-2). (E) Pseudoendolithic filaments of *Siphonophycus robustum* penetrating downward from the surface of microlaminated stratiform laminae. Sample #4689-7e, slide no. PCGI-482-90, coordinates 32.1 × 106.1 (K-32-2). (F) *Circumvaginalis elongates*. Sample #4689-7d, slide no. PCGI-471-90, coordinates 42.4 × 101.0 (L-33-2). Single scale bar equals to 20 μm, double to 200 μm.

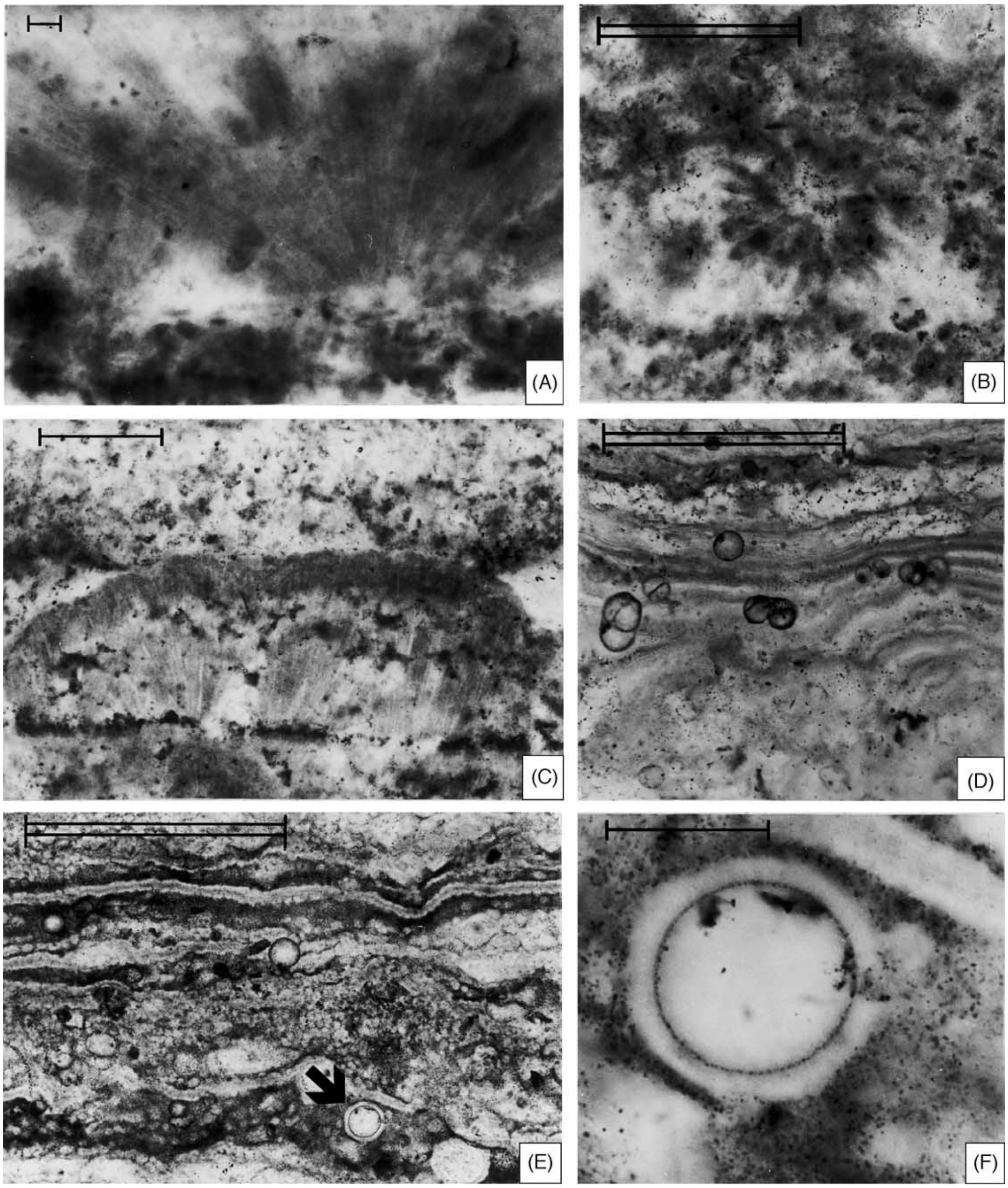


Fig. 10. Radial-fibrous fans, microlaminated stratiform laminae and microfossils from the Kotuikan Formation. (A) Radial-fibrous fan growth from organic-rich laminae. Sample #4689-53, slide no. PCGI-580-93, coordinates 34.7 × 104.0 (M-36-1). (B) Radial-fibrous fan growing downward from the surface three-dimensional radial-fibrous crystals. Sample #4689-53, slide no. PCGI-580-93, coordinates 42.5 × 110.0 (F-43-1). (C) Radial-fibrous fans forming a dome-like structure above organic-rich laminae. Sample #4689-53, slide no. PCGI-480-53, coordinates 33.4 × 108.5. (D) Microlaminated stratiform laminae containing inside several specimens of *Myxococcoides grandis*. Sample #4689-7e, slide no. PCGI-482-90, coordinates 33.2 × 97.3 (T-33-2). (E and F) Poorly differentiated stratiform laminae containing inside *Myxococcoides grandis* (F, indicated by arrow in E). Sample #4689-7e, slide no. PCGI-470-90, coordinates 30.9 × 99.8 (Q-31-3). Single scale bar equals to 20 μm, double to 200 μm.

zoic age for the Kyutingda and Debengda Formations (Semikhatov, 1991; Sergeev et al., 1994). Considering new data on the Anabar Uplift, the age of the Solooliskaya Group may also be bracketed between 1500 and 1250 Ma (Gorokhov et al., 1991; Semikhatov et al., 2001).

The radial-fibrous fans and microlaminae and poorly differentiated stratiform laminae are easily recognizable and abundant. Here, too, *Eoentophysalis* did not build the laminae and, indeed, does not occur within the radial-fibrous fans and microlaminae (Fig. 11A). In general, these fossils occur as small colonies of a few to more than one hundred cells scattered along bedding surfaces, but contiguous populations that form thin mats occur locally. While bacterial metabolism may have played a role in carbonate nucleation of radial-fibrous fans, cyanobacterial mats definitely did not.

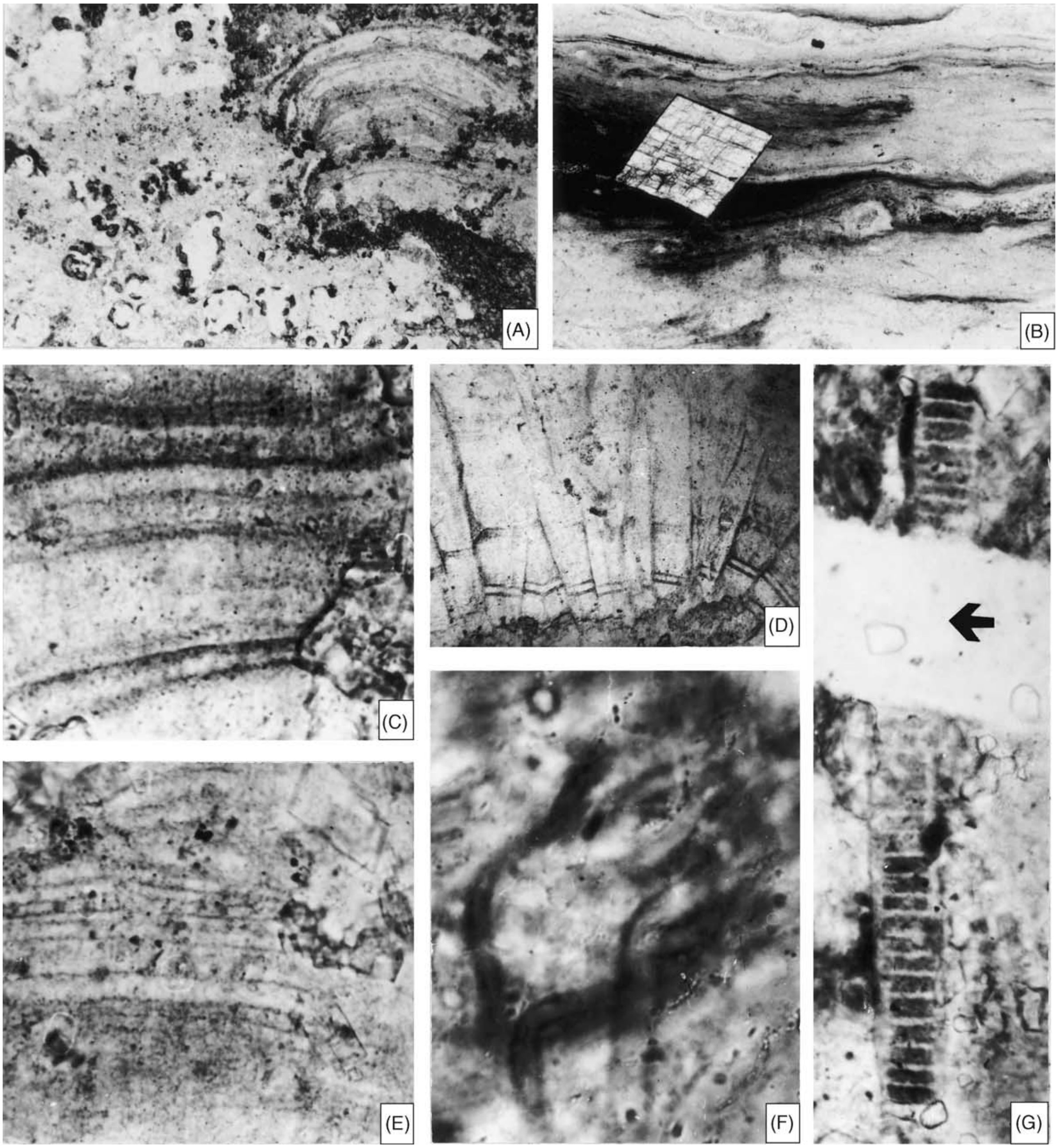
The taxonomic composition of the Debengda assemblage is also similar to that of the Kotuikan and Jaradag Limestone, but with some differences. The Debengda microbiota, like that of the Kotuikan and the Jaradag Limestone, is dominated by entophysalidacean cyanobacteria; *Eoentophysalis dismallakesensis* and *E. belcherensis* constitute more than 50% of all individuals. In contrast, sheaths of *Siphonophycus* are also abundant and rarely intercalated with *Eoentophysalis* populations' laminae, display mats containing mainly *Siphonophycus typicum* and less common *S. kestron* and *S. robustum*. In some cases, it is evident that only decomposed *Siphonophycus* mats formed the poorly differentiated stratiform laminae (Fig. 11B). Other less abundant taxa, viz. *Gloeodiniopsis* aff. *lamellosa*, *G. gregaria*, *E. medius* and *Clonophycus* sp. occur as loose colonies between filaments of *S. robustum* or in close association with *Eoentophysalis*. *Palaeolyngbya catenata* and *Archaeoellipsoides grandis* are represented by single individuals; the short trichomes are absent in the Debengda assemblage. Most types of precipitated textures known in the Kotuikan and JFLF are observed in the cherts from the Debengda Formation.

5.3. The Svetlyi Formation, Uchur-Maya Region, Siberia

The Svetlyi Formation consists of mixed siliciclastic and carbonate sediments; first and third units are predominantly dolomitic whereas the second and fourth are composed of shales and sandstones. The Svetlyi and the underlying Talynskaya Formations comprise the Aimchan Group, which is separated from underlying Uchur and overlaying Kerpyl Groups by an angular unconformity. Recent U–Pb geochronology yielded a 1.7 Ga age for the volcano-plutonic deposits underlying the Uchur-Maya Proterozoic sedimentary succession (Larin et al., 1997) and 1.3 Ga for the basal horizons of the Kerpyl Group (Khudoley et al., 2001). Therefore, the Svetlyi Formation seems to be bracketed probably between 1.6–1.5 and 1.3 Ga.

Silicified microfossils and carbonate-precipitated textures are known in cherts of the first and third units (Sergeev and Seong-Joo, 2001). The precipitates here are not associated with any microfossils. There are two kinds of precipitates in the Svetlyi Formation, viz., the radial fibrous fans and the microlaminated stratiform laminae. The radial-fibrous texture is composed of radiating blades of fibrous crystals 50–100 μm across and 800–2000 μm long. Laminae within these radial-fibrous textures are delineated by layers of finely dispersed dark organic matter distributed perpendicular to the direction of crystal growth. Laminae are discon-

Fig. 11. Radial-fibrous fans, microlaminated stratiform laminae, poorly differentiated stratiform laminae from the Debengda (A and B, after Sergeev et al., 1994) and Svetlyi formations (C–G). The coordinates cited in brackets for Figs. 11 and 12 refer to the numbers of the points at the strips of paper attached at the end of the thin sections. For some specimens, the England Finder coordinates are provided as well. (A) Microlaminated stratiform laminae and scattered colonies of *Eoentophysalis dismallakesensis*. Note that colonies of *E. dismallakesensis* do not occur inside the precipitates. Slide no. 2-91-3, coordinates N-44-0 (Paleontological Collection of the Yakutian Institute of Geological Sciences of RAS, Yakutsk, Russia). (B) Poorly differentiated stratiform laminae composed of the compressed sheaths of *Siphonophycus typicum*. Note the euhedral dolomite crystal grown after silicification. Slide no. KG-91-11-FL, coordinates U-46 (Harvard University Herbarium Paleobotanical Collection, Cambridge, USA). (C–E) Microlaminated stratiform laminae with euhedral dolomite crystals. Note lack of microfossils nearby or inside precipitates. Sample #4698-28, slide no. PCGI-847-98, point 1. (D) Radial-fibrous fan with layers of finely dispersed dark organic matter distributed perpendicular to the direction of crystal growth. Sample #4698-28, slide no. PCGI-847-98, point 3. (F) Cyanobacterial mat formed by sheaths of *Siphonophycus typicum* and *S. robustum*. Sample #4698-18, slide no. PCGI-788-98, point 9. (G) A filament of *Palaeolyngbya catenata* cut in halves by the cracks in the thin sections (indicated by an arrow). Sample #4698-18, slide no. PCGI 788-98, point 10. Single scale bar equals to 20 μm, double to 200 μm.


(A)
(B)
(C)
(D)
(E)
(F)
(G)

tinuous and broken by crystals into separate chord-like segments (Fig. 11D). The upper surfaces of the fans are wavy- or flat-laminated; sometimes significant deepening and elevations are observed. The planer shaped microlaminated stratiform laminae consist of alternating dark and light individual microlaminae, 4–7 and 10–15 μm thick, respectively (Fig. 11C and E). Often these microlaminated laminae are associated with rhombohedra of dolomite crystals, probably grown after silicification. The precipitates of the Svetlyi Formation are supposed to be purely inorganic due to lack of any fossils inside or nearby these sedimentary structures. The presence of fine dispersed organic matter in the laminae, however, suggests that the decomposed cyanobacterial mats may have been sites for the initial nucleation of precipitates growth.

The Svetlyi microbiota is represented almost exclusively by empty sheaths of *Siphonophycus* (Fig. 11F); only a few well preserved filaments of *P. catenata* (Fig. 11G) have been recorded. This community probably thrived in very harsh environments because, “... species diversity is inversely proportional to harshness of environmental conditions” (Golubic, 1976, p. 166). But taphonomical bias can also not be ruled out as a factor for low diversity. These communities of cyanobacteria inhabited tidal-flat or upper tidal flat environments where high evaporation provided requisite conditions for precipitate growth. Microbial mats built by filamentous cyanobacteria, comparable to modern species of *Lyngbya* and *Phormidium*, dominated these peritidal environments. Densely woven mats of thick-sheathed *Siphonophycus* with few associated taxa characterize more restricted parts of tidal flats. These are comparable to sheaths of oscillatorian cyanobacteria found in frequently exposed portions of other ancient (e.g., Oehler et al., 1979; Knoll et al., 1991) and modern tidal flats; thick sheaths appear to provide protection from dessication and harmful radiation.

All the Svetlyi carbonates were not tidal-flat deposits. The thick succession of the Svetlyi carbonates, traceable over a vast area, along with the occurrence of siliciclastic deposits, which contain glauconites help in interpretation of its depositional environment. The other geochemical evidence viz. $\delta^{13}C$ of the carbonates varies between 0 and 1‰ that is typical of marine rocks of that age; $\delta^{18}O$, Sr, Mg/Ca, Ca/Sr, etc. (see Bartley et al., 2001, p. 183) are also in favour of marine genesis of the carbonate. The absence of the entophysalidacean cyanobacteria, one of the best paleoenvironmental indicators of the intertidal range, can be explained either due to subtidal or supratidal setting of Svetlyi carbonates or climatic variations.

5.4. The Sukhaya Tunguska Formation, Turukhansk Uplift, Siberia

The Sukhaya Tunguska Formation (530–670 m thick) consists mainly of limestones and dolostones, with abundant nodular chert in the upper part. Pb–Pb age dates for early diagenetic carbonates within the formation are 1017 ± 91 Ma and 1035 ± 60 Ma (Ovchinnikova et al., 1994, 1995). Biostratigraphic and chemostratigraphic data are broadly consistent with Pb–Pb data. For the most part, the Sukhaya Tunguska cherts preserve fossil populations and precipitates from a limited range of peritidal environments (Petrov et al., 1995; Sergeev et al., 1997).

Precipitates are not very common in the Sukhaya Tunguska Formation. These precipitates consist of microlaminated stratiform laminae, each 2–3 to 5–7 μm thick (Fig. 12A–C). Individual laminae are defined by concentration of organic matter, producing an alternating pattern of thin dark and relatively thick light layers. The laminae are of uniform thickness and traceable throughout their lengths. Microfossils are not preserved in this texture, but colonies of *Eoentophysalis arcata* are closely associated and sometimes overgrow the laminae (Fig. 12D and E). *Eoentophysalis* did not build these laminae; it does not occur within the stratiform lamina.

On one hand, the Sukhaya Tunguska microbiota contains such “typically” pre-Neoproterozoic fossils as *E. arcata* and *E.* cf. *belcherensis*, on the other hand, the stalked pleurocapscalaen *Polybessurus bipartitus* occurs here as well (Fig. 12F). In contrast to other Mesoproterozoic precipitate-bearing formations, mats formed by *Siphonophycus* (*S. robustum*, *S. typicum* and *S. solidum*) are abundant and contain remains of chroococcacean dwellers, viz., *Eoaphanocapsa oparinii*, *G. lamellosa*, *Eosynechococcus moorei*, *E. medius*, *S. medium* and *S. parvum*. Sheaths and trichomes of other hormogonian cyanobacteria (*Calyptothrix* sp., *Eomicrocoleus* sp., *Uluksanella* sp., *Oscillatoriopsis media*, *Palaeolyngbya* sp.) constitute less than 1–2% of all individuals. The planktonic forms are represented by eukaryotic/prokaryotic (*M. minor*,

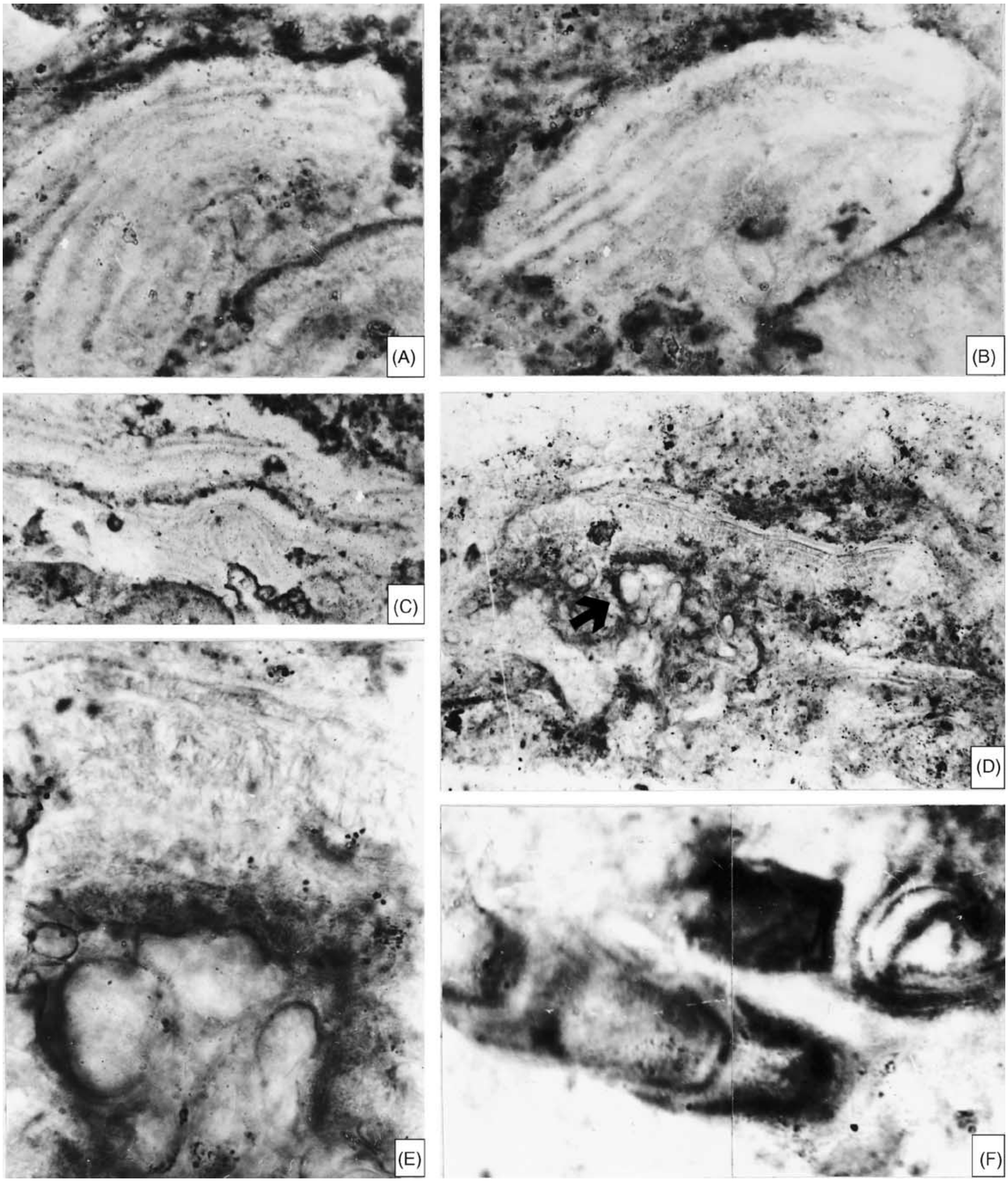


Fig. 12. Microlaminated stratiform lamina and microfossils from the Sukhaya Tunguska Formation. (A–C) Microlaminated stratiform laminae. (A) Sample #4694-28, slide no. PCGI-600-94, point 13. (B) Sample #4694-28, slide no. PCGI-600-94, point 14. (C) Sample #4694-28, slide no. PCGI-602-94, point 12. (D and E) Microlaminated stratiform laminae overgrowing the colony of *Eoentophysalis arcata* (E, indicated by an arrow in D) demonstrating polarized, unidirectional growth as an attempt to escape burial. Sample #P 4398, slide no. PCGI-664-94, point 16. (F) Stalked cyanobacterium *Polybessurus bipartitus*. Single scale bar equals to 20 μm, double to 200 μm.

M. inornatum, *M. grandis*, *Myxococcoides* sp., and *Leiosphaeridia* sp.), as well as, cyanobacterial remains (*Gyalosphaera golovenokii* and *Archaeoellipsoides dolichum*). *A. dolicum*, interpreted as akinete of a nostocalean cyanobacterium, is a minor component of the Sukhaya Tunguska microbiota.

The Sukhaya precipitates are closely associated with colonies of entophysalidacean cyanobacteria; populations of *E. arcata* extended into upper subtidal environment as identified by sedimentological evidence (Petrov et al., 1995; Sergeev et al., 1997). Therefore, the upper subtidal position can be suggested for the most Sukhaya Tunguska precipitates. As discussed above, the microlaminated stratiform laminae probably are of subtidal to supratidal origin and the formation of this texture was highly episodic.

Petrov et al. (1995) inferred that the entophysalidacean colonies lived in restricted coastal environments within local depressions, separated by elevated ridges and subjected to subaerial exposure. Possibly, the oversaturation of calcium carbonate resulted inside these small insignificant deep pools or ponds separated by polygonal bars. In any case, modern *Entophysalis* species live near the air/water interface (Golubic, 1983) and their extension to subtidal waters could be explained by seasonal changes in sea level. After reaching supersaturation level, the microlaminated laminae could start to grow. The origin of this texture in the Sukhaya Tunguska Formation probably was similar to that in the Kotuikan Formation. That the instantaneous rate of the precipitated structures formation was high is clear from unidirectional polarized orientation of *E. arcata* colonies probably reflecting an attempt to escape burial.

5.5. Other Mesoproterozoic precipitates-bearing formations

The Mesoproterozoic Salkhan Limestone Formation of the Vindhyan Supergroup exposed in Son Valley, India also contains abundant microfossils (Kumar, 1978b; McMenamin et al., 1983; Kumar and Srivastava, 1995) and precipitates (Singh and Rai, 2001). This limestone is considered to be older than ∼1400 Ma. Salkhan microfossil assemblage is dominated by *E. belcherensis* and *E. magna*, which occur as billowy irregular patches of densely packed colonial aggregates that have been attributed to mat building activity by Kumar and Srivastava (1995). *Archaeoellipsoides*, *Bactrophycus*, short trichomes, *M. minor*, *M. grandis*, *S. parvum*, *S. medium* and remains of other cyanobacteria are in general quite similar to the microbiotas known from the JFLF, Kyutingda, Debengda, Kotuikan and Yusmastakh Formations. Kumar (1978c) has suggested a tidal flat environment for deposition of the Fawn Limestone Formation of the Son Valley.

Yakschin (1990, 1999) described silicified microfossils and precipitates (as stromatolites) from the Kyutingda Formation of the Solooliiskaya Group. These precipitates probably are also associated mainly with entophysalidacean cyanobacteria (see Sergeev et al., 1995). The taxonomic composition of the Kyutindga microbiota however needs a restudy.

The Society Cliff Formation, late Mesoproterozoic (Kah and Knoll, 1996; Kah, 2000) of northern Canada also contains abundant precipitates and microfossils. The radial-fibrous fans are easily recognizable and were named as laminated tufa microfacies (Kah and Knoll, 1996). The Society Cliff microbiota comprising *Siphonophycus*- and *Eoentophysalis*-dominated mats or taxonomically diverse *Gloeodiniopsis*- or *Polybessurus*-rich assemblages relates well to its late Mesoproterozoic age. Mats of *Eoentophysalis* colonized upper lithified surface of radial-fibrous fans, whereas the *Polybessurus*-dominated communities are characteristic of micritic deposits on soft substrates. The major fosssiliferous carbonate microfacies (cement- and micrite-dominated) occur within a high intertidal to supratidal tidal regime. Locally microfacies are distributed as interfingering mosaic, reflecting relatively small differences in seawater level (Kah and Knoll, 1996). The precipitates are also known from the Dismal Lakes Group of Canada (Kah, personal communication to VNS), which is overlain by 1.27 Ga Coppermine Flood Basalts (LeChemiant and Heaman, 1989). The Dismal Lakes Group contains a microfossil assemblage dominated by *E. dismallakesensis*, akinetes *Archaeoellipsoides*, short trichomes, *Myxococcoides grandis*, remains of other cyanobacteria and in general is quite similar to the microbiotas known from the Jaradag Limestone, Kyutingda, Debengda, Kotuikan and Yusmastakh Formations.

Mesoproterozoic precipitates are also known from the Gaoyuzhuang and Wumishan Formations of China, where they are also associated with abundant entophysalidacean and other chroococcacean cyanobacteria, short trichomes, abundant *Archaeoellipsoides* and *M. grandis* (Zhang, 1981, 1985; Zhang et al., 1989; Cao, 1992). Radiometric dating of the Gaoyuzhuang Formation yielded an age 1434 ± 50 Ma (Yu and Zhang, 1985). No radiometric data are available on the Wumishan Formation; but its age is estimated as approximately 1200 Ma (Zhang, 1985; Seong-Joo and Golubic, 1999). The precipitates from the Gaoyuzhuang Formation are very similar to other Mesoproterozoic precipitates, especially from the Jaradag Limestone and Kotuikan Formations. Seong-Joo and Golubic (1999, 2000) have described the upward radiating crystal fans (=radial-fibrous fans), flat crustose coating (=microlaminated stratiform laminae) from Wumishan Formation and spherulites and botryoids which have been considered as variations of radial-fibrous fans. Unlike in the Jaradag Limestone and Kotuikan Formations, sheaths of *Siphonophycus* are abundant in the Gaoyuzhuang Formation. The mats formed by this taxon preferentially colonized soft substrates (loose micritic matrix) whereas entophysalidacean cyanobacteria colonized hard substrates (surface of the fans). Besides *E. belcherensis*, another colonizer of hard substrates, *Coccostratum dispergens*, which is not identified either in Indian or Siberian materials, has also been recorded (Seong-Joo and Golubic, 1999). The Gaoyuzhuang precipitates too deposited in peritidal environments, exhibiting evidence of frequent cyclic changes in water chemistry and sedimentation (Seong-Joo and Golubic, 1999, 2000).

6. Discussion

On the basis of material studied and analyzed, we conclude that all the assemblages contain only morphologically simple filamentous and coccoidal microfossils and can be termed as “typical” Mesoproterozoic microbiotas. Entophysalidacean and chroococcacean as well as oscillatoriacean and nostocalean cyanobacteria are present in almost in all the Mesoproterozoic silicified assemblages, whereas unambiguous protists are not reported.

The morphology of precipitates in all the Mesoproterozoic formations is almost the same, but some variants are observed. The radial-fibrous fans and microlaminated laminae occur everywhere, whereas fans with mammilated surface are reported only from the JFLF and the Salkhan Limestone Formation. The precipitate distribution pattern can be fortuitous because it is more or less evident that in most cases their formation was quite episodic (Bartley et al., 2000). Therefore, absence of the radial-fibrous fans and microlaminated laminae in some Mesoproterozoic formations, containing similar Mesoproterozoic microbiotas (e.g. the Yusmastakh Formation), could be related to taphonomic factors.

The most common feature of all Mesoproterozoic precipitate-dominated microbiotas is the dominance of entophysalidacean communities except in the Debengda Formation of Siberia. The occurrence of *Archaeoellipsoides* and associated short trichomes is one of the diagnostic features of these assemblages as well, but neither short trichomes nor akinetes are ubiquitous in all units due to probable variation in paleoenvironments and taphonomical bias. Taxa, such as, *Gloeodiniopsis*, *Eosynechococcus*, *Siphonophycus*, *Palaeolyngbya*, *Myxococcoides*, *Sphaerophycus*, etc. common to all these formations, are only indicative of broad stratigraphic distribution. These cannot be considered as diagnostic forms of the Mesoproterozoic microbiotas. All microfossils recorded in the precipitate associated microbiotas are considered to be cyanobacteria; no reliable remnants of eukaryotes are known.

There are three main factors, which could have influenced the taxonomical composition of microorganisms preserved inside silicified precipitates. Firstly, some fossils may have decomposed prior to precipitate formation; such tendency has also been observed in other Precambrian microbiotas as well where precipitates are missing. Secondly, the carbonate deposits may have recrystallised prior to precipitate formation and in this case all remains of microorganisms would have decomposed as well. Early lithification enhances the possibility for the microorganisms to be preserved in the fossil record and early recrystallisation in some fabrics equalizes fossilization potential for all microfossils. Lastly, silicification may not have occured in the particular fabric, in the particular unit. The last factor probably was the most important, and in this case the microfossils were not be preserved at all. It is understood that in most Mesoproterozoic carbonate rocks precipitates survived only in silicified parts of formations whereas in non-silicified parts subsequent recrystallisation erased the sedimentary patterns. Thus the taphonomy of microorganisms in precipitates did not differ significantly from that of the microorganisms from non-precipitates-bearing facies. Considering this, we mainly relied on the large number of studied thin sections that facilitated reconstruction of a representative picture of the silicified microbiotas associated with the precipitates with the same taphonomic restrictions as for other Proterozoic microfossil assemblages in cherts.

As mentioned above, *Eoentophysalis* is the dominant element of all microbiotas and; the abundance of this taxon is really correlatable to precipitates distribution in the fossil record. *Eoentophysalis*-dominated microfossil assemblages also are widely distributed in Paleoproterozoic strata (Hofmann, 1976; Muir, 1976; Oehler, 1978; Hofmann and Schopf, 1983), but have not been reported from Neoproterozoic marine rocks, where *Eoentophysalis* occurs as scattered colonies in assemblages dominated by other organisms (Knoll et al., 1991; Sergeev, 1992; Knoll and Sergeev, 1995). This seems anomalous in that entophysalid cyanobacteria are widespread mat builders in recent intertidal environments (Golubic and Hofmann, 1976). It has been suggested that the distinctive nature of Paleo- and Mesoproterozoic peritidal environments, with widespread deposition of seafloor precipitates, may explain the near absence of *Eoentophysalis*-dominated assemblages in Neoproterozoic successions (Knoll and Sergeev, 1995; Sergeev et al., 1995, 1997). *Eoentophysalis* clearly thrived in environments where the precipitates formed. When such precipitates ceased to form near the close of the Mesoproterozoic Era, *Eoentophysalis*-dominated assemblages disappeared along with them. Alternatively it is also possible that these environments were no longer being silicified, so entophysalidacean forms though present, were not preserved.

The carbonate precipitate evolution and seawater secular variation resulted in general replacement of hard grounds widespread in the Paleo- and Mesoproterozoic by soft substrates in the Neoproterozoic. These were responsible for the changes in the taxonomical composition of the silicified microbiotas. The biological evolution of Proterozoic microorganisms resulted in drastic changes in the Neoproterozoic microorganism communities. The explosive radiation of the unicellular eukaryotic microorganisms near the Mesoproterozoic–Neoproterozoic boundary resulted in appearance of morphologically complex microfossils (Knoll, 1992; Knoll and Sergeev, 1995; Sergeev et al., 1996). Remains of morphologically complex protists have been preserved in open-marine shelf deposits, but taxonomic composition of the microbiotas from the restricted peritidal environments changed as well. As a result, the Neoproterozoic microbiotas from the restricted shallow-water environments differ from those of the similar facial setting of older strata. This phenomenon can be explained not only by the evolution of grounds toward soft substrates in Neoproterozoic, but also by (hidden) expansion of morphologically simple eukaryotic unicellular microorganisms in cyanobacterial communities of peritidal setting (Knoll and Sergeev, 1995; Sergeev, 1997).

Archaeoellipsoides, *M. grandis*, and short trichomes are also widely distributed in the cherts of many Mesoproterozoic formations and can be considered as another diagnostic feature of these precipitate-dominated environments. The high levels of $CaCO_3$ supersaturation evident from the abundant precipitate structures probably triggered the full transformation of *Anabaena*-like filaments into chains of akinetes that additionally explain the abundance of the *Archaeoellipsoides* akinetes in the Mesoproterozoic. These chains of akinetes are present in the Kotuikan (Sergeev et al., 1995, Figs. 14.1–14.3, and 14.16) and Wumishan Formations (Zhang, 1985, Fig. 8B) and in the Dismal Lakes Group (Horodyski and Donaldson, 1980, Figs. 13.B, 13.E, and 13.F). The short trichomes are considered to be the early stage of akinete germination and their co-occurrence in *Archaeoellipsoides*-dominated microbiotas seems to be explainable (Knoll and Sergeev, 1995; Sergeev et al., 1995; Sergeev, 1997). Another explanation of short-trichome abundance in these Mesoproterozoic microbiotas also results from their co-occurrence with precipitates. It is evident that in the Jaradag Limestone and Kutuikan Formations, the short trichomes were entombed inside the radial-fibrous fans and microlaminated laminae. Therefore, it is reasonable to suggest that the cyanobacterial trichomes broke into hormogonias to escape burial by fast growing carbonate precipitates, but did not succeed and were entombed inside radial-fibrous or microlaminated textures.

The microfossil assemblages of Sukhaya Tunguska and Society Cliffs Formations are intermediate in composition between the Meso- and Neoproterozoic microbiotas. On one hand, these microbiotas contains such “typically” pre-Neoproterozoic fossils as entophysalidacean cyanobacteria, on the other hand, *Polybessurus bipartitus* is also found in the assemblage. The co-occurrence of entophysalidacean and stalked cyanobacteria provides the unique opportunity to evaluate the composition of microbiotas and their relationship to the inorganic precipitates near the Mesoproterozoic–Neoproterozoic boundary. Kah and Knoll (1996) have suggested that distribution of entophysalidacean and stalked cyanobacteria in the Proterozoic silicified microbiotas was related to the decline of precipitates in Neoproterozoic and, therefore, environmental evolution in Precambrian. While the entophysalidacean cyanobacteria preferentially colonize hard substrates, the stalked cyanobacterium prefers soft substrates. Therefore, after almost complete extinction of the precipitates in the Neoproterozoic carbonate record, the previously abundant entophysalidacean cyanobacteria became restricted, but *Polybessures* became widespread, preferentially colonizing the soft ground. This hypothesis suggests that the stalked cyanobacteria were present and probably widespread in pre-late Mesoproterozoic deposits, but these have not been preserved due to preferential silicification of hard grounds related to the precipitates. Almost all known silicified pre-Neoproterozoic microbiotas are of peritidal setting where the precipitates were abundant while the microbial communities from the deeper-water environments have been preserved as the organic-walled microfossils in fine-grained siliciclastic rocks. Knoll and Sergeev (1995) and Sergeev (1997) explain the lack of *Polybessurus* in pre-late Mesoproterozoic deposits by cyanobacterial evolution and “hidden” expansion of morphologically simple unicellular eukaryotes in cyanobacterial communities.

The Sukhaya Tunguska and Society Cliff microbiotas as well as some other latest Mesoproterozoic microbiotas provide a unique clear window for appreciation of both hypotheses. A contemporaneous silicified microfossil assemblage of similar composition is known from the Kataskin Member of the Avzyan Formation, southern Ural Mountains, Russia (Sergeev, 1992, 1994). In all microbiotas, both the entophysalidacean as well as stalked cyanobacteria occur, but the precipitates are absent in the Kataskin Member. As a result, the entophysalidacean cyanobacteria are abundantly recorded in both the Society Cliff and Sukhaya Tunguska microbiota, but in the Kataskin microbiota there are not many colonies of *E. belcherensis*. Undoubtedly, the early entrapment and early silicification had major role in the recovered microbial diversity. A little late silicification process would allow only those elements having sufficient strength to withstand the early digenesis. This pattern of distribution clearly demonstrates that hard substrate is really necessary for dominance of entophysalidacean cyanobacteria, but the stalks of *Polybessurus* are not abundant in the Kataskin microbiota as well where precipitates are absent. The only other possibility is that stalked cyanobacteria were abundant in offshore, muddy deposits, which were rarely silicified. But so far they are neither recorded nor reported in the assemblages of the shelf facies deposits suggesting their absence in the environment. Therefore, it seems plausible that substrates determined the cyanobacterial abundance through the Proterozoic. However, the stalked cyanobacteria are known only from the latest Mesoproterozoic and Neoproterozoic deposits. If their distribution is purely substrate controlled, one could expect the presence of stalked cyanobacteria in early Mesoproterozoic and Paleoproterozoic rocks and until relevant finds are known, we cannot accept the Kah and Knoll hypothesis. In our opinion, drastic changes in dominating substrates near the Mesoproterozoic–Neoproterozoic boundary possibly triggered the evolution of some forms of cyanobacteria, e.g. stalked cyanobacteria.

7. Conclusion

The precipitates from the silicified formations of the Mesoproterozoic are all similar and can be classified to a few forms. The Mesoproterozoic precipitates were localized only to particular intertidal and supratidal environments while during the Archean and Paleoproterozoic precipitated carbonate textures formed in a variety of environments, including open-marine setting. The precipitates almost completely disappeared in the Neoproterozoic. The Mesoproterozoic precipitates of the peritidal setting are associated with typical microbiotas composed of entophysalidacean cyanobacteria, assemblages of short trichomes, elongated akinetes and some other cyanobacteria. Unequivocal remnants of morphologically complex eukaryotes have not been reported, except for the report of *Bangiomorpha pubescens* from the Hunting Formation, Canada (Butterfield, 2001). Detailed analysis has revealed similarity of the Indian, Russian, Chinese and North American Mesoproterozoic silicified microorganism assemblages, associated with the inorganic precipitates. The composition of the microbiotas varies from one formation to other. In the late Mesoproterozoic assemblages, the stalked cyanobacteria *Polybessurus* appears, but the most common feature of all these associations is a dominance of the entophysalidacean forms. These cyanobacteria preferentially colonized hard substrates and, when in Neoproterozoic precipitates and associated microenvironments disappeared, the microorganism communities changed drastically. Nonetheless, the taxonomical composition of the peritidal facial setting Mesoproterozoic microbiotas differs from that of both older and younger microfossil assemblages and reflects the evolution of the Proterozoic biosphere as a whole. Subsequent changes among the microorganism communities near the Mesoproterozoic–Neoproterozoic boundary were related not only to seawater chemistry secular variation, but to evolution of Precambrian microorganisms as well, and to the explosive radiation of eukaryotic microorganisms and their expansion in prokaryotic ecosystems.

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