

Significance of Bacteria in Natural and Experimental Sedimentation of Carbonates, Phosphates, and Silicates

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Abstract—The role of bacteria in sedimentation of phosphorites, siliceous and carbonate rocks is discussed. Preservation of bacterial bodies in fossil condition, even in very ancient deposits, is connected with their very early mineralization. A series of laboratory experiments allowed conditions to be reproduced that could have led to mineralization of cyanobacteria and their preservation in sedimentary deposits. The experiments have also shown the important role of cyanobacteria and their metabolic products in the formation of some carbonate minerals, as well as in the accumulation of stromatolites.

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INTRODUCTION

Bacteria are the most ancient, numerous, and diverse life forms on our planet. They have most successfully utilized the space of the Earth, far surpassing more complex organisms, and they have the greatest diversity of metabolism forms (Zavarzin and Kolo-tilova, 2001). In modern conditions, bacterial life exists nearly everywhere: on land, in the aquatic environment where they can tolerate a temperature range from -7 up to $+120^{\circ}\text{C}$, deep under ice in Antarctica, and in the upper layers of the atmosphere. The environment determines only what forms will be able to reproduce in given conditions. Up to now, bacteriomorphic fossils have been found in deposits of almost the entire geological record starting from the middle part of the Lower Archean (Walsh, 1992, Astafieva et al., 2005). The best preserved fossilized bacteria and cyanobacteria occur in phosphorites, siliceous rocks, and high carbon

deposits (Pl. 1, figs. 1–6). Less often their mineralized bodies occur in carbonate and clayey deposits (Pl. 1, fig. 7). The preservation of bacteria as fossils depends on their very early mineralization, which should have occurred prior to the decomposition of bacterial bodies. Fossilized bacteria usually have identical mineral composition with hosting rocks, i.e., their posthumous fossilization should actually have proceeded simultaneously with the accumulation of the enclosing deposits. It is a very important feature in determining the role of bacteria in the genesis of host rocks. Various bacterial metabolites quite often promote deposition of sedimentary rocks. For example, the day-time growth of photosynthesizing cyanobacteria strongly increases the pH level of the environment that stimulates sedimentation of phosphates and carbonates (Gerasimenko and Orleanskii, 2004). The activity of sulfate-reducing bacteria in anoxic conditions promotes sedimentation of dolomite (Lith et al., 2003). The increased concentra-

Explanation of Plate 1

Photographs of mineralized cyanobacteria and bacteria in various ancient rocks and those obtained in laboratory conditions.

Fig. 1. Fragment of phosphorite from the Khubsugul deposits (Lower Cambrian, Mongolia) with phosphatized cells of bacteria.

Fig. 2. Mineralized cells of bacteria and detached threads of cyanobacteria from clayey-carbonate high carbon rocks of the Sinyaya Formation (Lower Cambrian, Siberian Platform, photo by M.M. Astafieva).

Fig. 3. Silicified bodies of cyanobacteria and bacteria in siliceous interlayers of the Khubsugul phosphorites (Lower Cambrian, Mongolia).

Fig. 4. Fragment of the Khubsugul phosphorite composed of a phosphatized cyanobacterial mat (Lower Cambrian, Mongolia).

Fig. 5. Aggregate of phosphatized bacterial cells in Pliocene phosphorites of Sakhalin Island.

Fig. 6. Modern silicified cyanobacterial mat from a stromatolite near the Uzon Caldera, Kamchatka (specimen of G.A. Karpov).

Fig. 7. Mineralized carbonate cells of cyanobacteria in Sarmatian stromatolites of the Taman' Peninsula (materials of Yu.V. Rostovtseva).

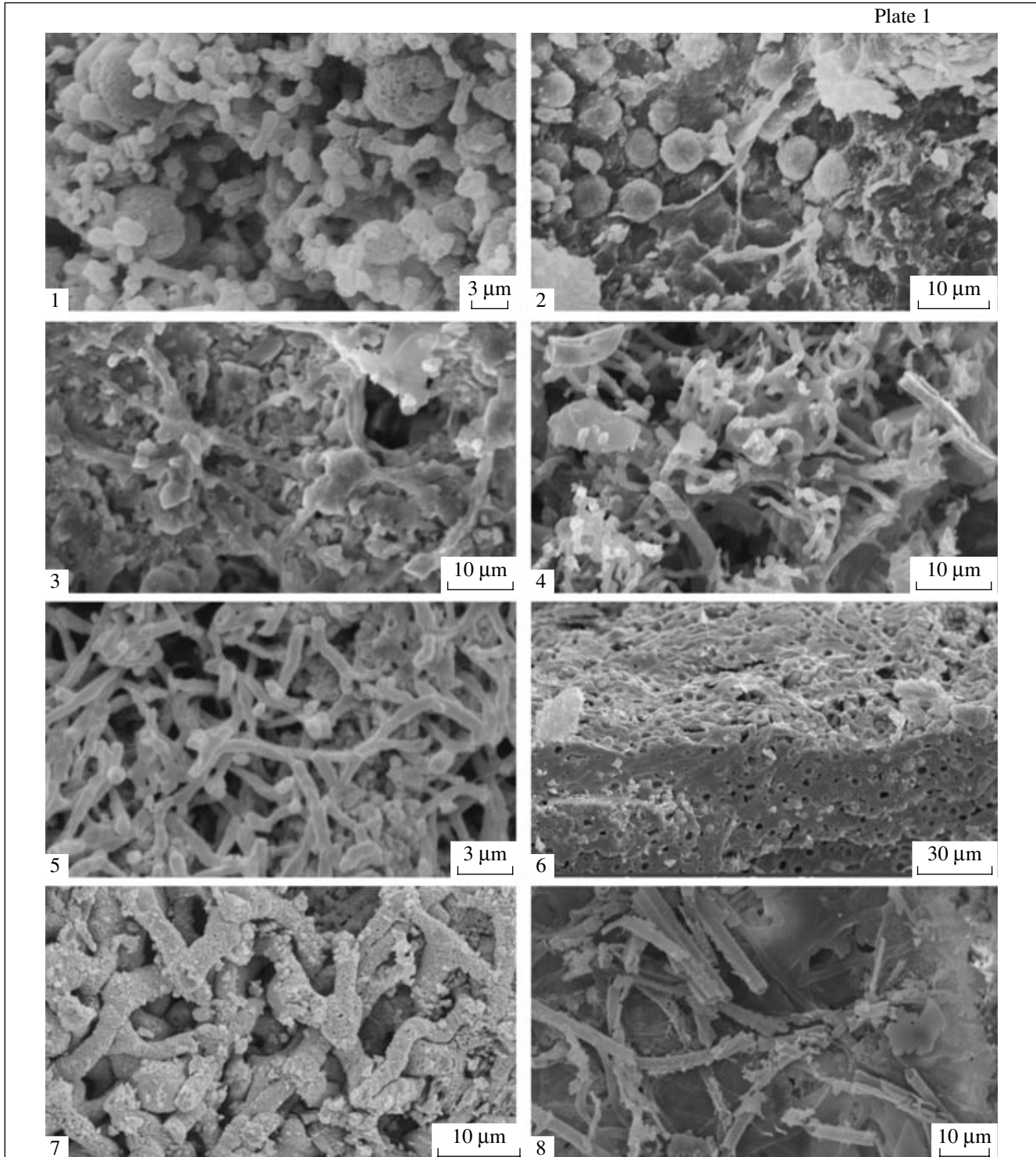
Fig. 8. Modern cyanobacterial mat consisting of threads of *Microcoleus*, partly phosphatized.

tion of silicon in the environment causes a strong mucus production by cyanobacteria, and the slime formed intensively sorbs silicon (Gerasimenko et al., 2004). More examples can be given. In addition, cyanobacterial mats, their fragments, and bacterial bodies (recently dead or already decomposing) frequently become centers of nucleation of minerals from the ambi-

ent medium, resulting in the formation of layered deposits of variable structure that contain numerous fossilized microorganisms (Sharma and Sergeev, 2004).

The earliest bacteriomorphic organisms that have been found in greenstone belts of southern Africa and Australia are usually confined to siliceous rocks. According to the researchers who studied them (Hof-

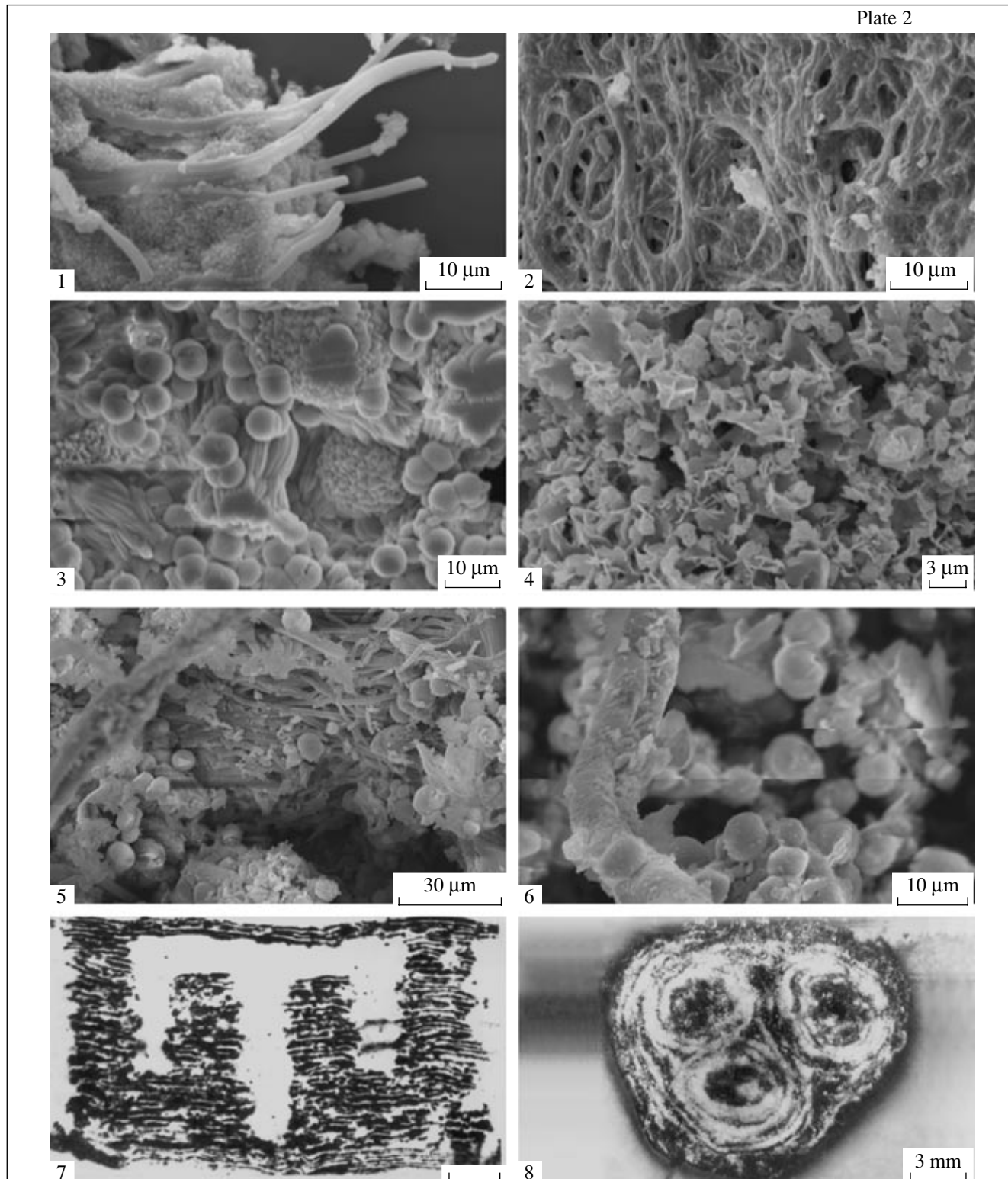
Plate 1



mann and Schopf, 1983; Walsh, 1992), the formation of microbial communities occurred in shallow water conditions near to hydrothermal sources. By now, the role of hydrothermal sources in localization, mineralization, and preservation of bacteriomorphic structures is relatively well studied (Orleanskii and Gerasimenko, 1982;

Phoenix et al., 2000; Gerasimenko and Orleanskii, 2004; and many others). Communities of cyanobacterial mats and bacteria usually occupy significant areas around hot sources. Sometimes they form stromatolite constructions there. Silicification of bacteria and cyanobacteria is primarily connected with a constant

Plate 2



supply of silicon-rich solutions from the Earth's interior and with the increased concentration of silicon in the solution due to evaporation. Silicification is a very fast process, which begins during the life of the microorganisms. At first, mineral silicon coatings are formed around bacterial bodies (Pl. 1, fig. 6). After the death of the bacteria, their bodies are frequently completely replaced with silicon. However, incrustation and replacement do not always preserve morphological characters, thus hampering their exact comparison with living forms (Renaut et al., 1998; Jones et al., 1998; etc.). The persistence of hydrothermal areas, their size and intensity of activity determine the thickness and distribution of locally accumulating siliceous sequences composed of silicified bacteria.

Studies of phosphorites, both ancient, Lower Cambrian (Rozanov and Zhegallo, 1989; Zhegallo et al., 2000), and younger, Mesozoic and Cenozoic (Shkol'nik et al., 1999), carried out using SEM, has shown that the bulk of these deposits is composed of fragmentary parts of different phosphatized organic communities with a dominant role of phosphatized cyanobacterial mats consisting of cyanobacteria proper and an assemblage of other microorganisms, primarily purple bacteria (Pl. 1, figs. 1, 4). This suggests that the biogenic factor was the most important for the origin of phosphorites.

Microorganisms also played a key role in the genesis and accumulation of carbonates, one of the most widespread sedimentary rocks on Earth. Their contribution to the formation of stromatolites, layered sedimentary structures resulting from interaction of microorganisms, their metabolites, and sedimentation processes, is especially well known. After their first appearance in the early Archean, stromatolites were particularly widely distributed in the Proterozoic. Cyanobacterial communities were the main stromatolite builders. In comparison with phosphorites and siliceous rocks, mineralized bodies of bacteria occur much less frequently in ancient carbonates. One of the explanations may be in the important role of sulfate-reducing bacteria in accumulation of carbonates, i.e., organisms that participate in the decomposition of organic matter. Dead bacterial cells have no time for mineralization

before decomposition. The fossilization of bacteria in carbonate rocks can also be deteriorated by a high speed of calcite crystallization at sedimentation, thus destroying bacterial cells. However, bacterial remains may also occur in carbonates. For example, Sarmatian stromatolites of the Taman' Peninsula perfectly preserve cells of cyanobacteria (Pl. 1, fig. 7).

Modern ocean water is strongly undersaturated with respect to calcium carbonate. However, studies of modern carbonate sedimentation in sites of locally high concentrations of Ca^{+2} , Mg^{+2} , and CO_3^{-2} ions elucidate the role of bacterial communities in the genesis of carbonate sequences in the past. Kazmierczak and Kempe (2002) list three examples of carbonate sedimentation in modern conditions: (1) High-alkaline waters of Lake Van are year-round oversaturated with respect to calcium carbonate and host benthic coccoid cyanobacterial mats. The sedimentation of unstratified aragonite micrites occurs in bacterially excreted glycocalyx or EPS (Extracellular Polymeric Substances). (2) In the medium alkaline Motitoi Lake (island of Satonda) with seasonal fluctuations of CaCO_3 level, metabolic activity of coccoid cyanobacteria produces layered stromatolites. They consist of alternating magnesian calcite, precipitated during the dry season, and aragonite, the sedimentation of which is stimulated by posthumous decomposition of dead cyanobacteria grown during the wet season. Finally, (3) cyanobacterial mats of Niva Bay (Denmark) show two different models of carbonate sedimentation: (1) layers of fine grains of magnesian calcite close to the cyanobacterial community and (2) layers of larger grains of magnesian calcite and aragonite precipitating below a layer of active cyanobacteria. They occur between layers of heterotrophic and phototrophic anoxygenic bacteria decomposing the dead cyanobacterial mass coming from above.

The study of modern carbonate biomineralization in hypersaline conditions shows that there is a close connection between sulfate-reducing bacteria and carbonate minerals. The coastal hypersaline Vermelha Lagoon (Brazil) gives an example of dolomite sedimentation in the period of the highest salinity mediated by sulfate-reducing bacteria (van Lith et al., 2003). It is remarkable that the same region gives another example of

Explanation of Plate 2

The mineralized cells of bacteria, cyanobacteria, stromatolites, and oncolites obtained in experiments.

Fig. 1. Silicification of the slime excreted by cyanobacteria. Trichomes are still alive (pH 10).

Fig. 2. Silicification of the slime and trichomes of cyanobacteria (pH 12).

Fig. 3. The carbonate deposit formed in the control solution (without cyanobacteria) in two weeks after the beginning of the experiment.

Fig. 4. The carbonate deposit formed after two weeks exposition of cyanobacteria and the solution (see also Fig. 1).

Fig. 5. Experiment in aerobic conditions in the light carried out for nine months. The carbonate compounds of calcium and magnesium formed in the presence of cyanobacteria (see also Fig. 2).

Fig. 6. Experiment in aerobic conditions in the dark carried out for nine months. The carbonate compounds of calcium and magnesium formed in the presence of cyanobacteria (see also Fig. 2).

Fig. 7. Laboratory biomodel of a stromatolite, vertical section.

Fig. 8. Laboratory biomodel of an oncolite, cross section.

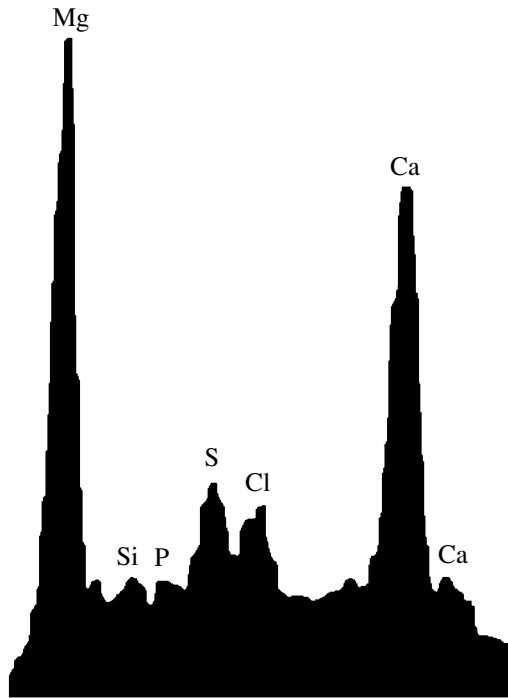


Fig. 1. Elemental composition of the carbonate deposit formed after a two-week-long exposure of cyanobacteria and the solution to light.

modern dolomite precipitating in aerobic conditions by the action of heterotrophic halophilic microorganisms (Roman et al., 2003). It means that sedimentation of dolomite can occur both under aerobic and anaerobic conditions, but the presence of microorganisms and strongly increased salinity are necessary.

EXPERIMENTAL

Experiments conducted in the laboratory allowed us to reveal some of the conditions favoring the mineralization (phosphatization, silicification, carbonation) of cyanobacteria and accumulation of sedimentary deposits containing bacterial fossils.

Experimental phosphatization was studied using the cyanobacterium *Microcoleus chthonoplastes*, a common benthic organism of hypersaline basins of the arid zone. It can grow in a wide range of concentrations of inorganic phosphorus in the environment, with an optimum concentration of 18 mg/l. As the concentration of phosphorus increases above the optimum, its accumulation inside trichome cells begins in the form of easily soluble volutin granules. The further increase in the concentration of inorganic phosphorus leads to morphological modification of trichomes. They develop a slimy covering initially bearing separate plaques and globules of phosphate, which then merge into a uniform mineral cover. Trichomes could survive and creep out of the formed tubes. As the concentration of 36 mg/l is achieved, the destruction of the cells begins. The

decomposition of its biomass provides an additional amount of phosphorus to the medium, calcium phosphate replaces trichomes and decomposed matter, and its excesses are precipitated chemically. The aggregate formed is nearly identical to phosphorite nodules from the Lower Cambrian Khubsugul Basin (Pl. 1, fig. 8; compare to Pl. 1, fig. 4). All these processes proceed with great speed: the accumulation of volutin granules inside cells occurs during the first three hours, and the phosphatization of the trichomes mat takes one day—an insufficient time for decomposition of bacterial and cyanobacterial cells, thus resulting in their excellent preservation (Gerasimenko et al., 1993).

The laboratory modeling of silicification processes was based on the thermophilic cyanobacteria *Oscillatoria terebriformis* and *Phormidium angustissimum*. The experiment started with an initial concentration of silicon equal to its concentration in the hydrothermal source in Kamchatka (30 mg/l), then it was increased up to 500 mg/l. The initial pH level of the solution was 7.5, and at concentration of 500 mg/l it grew up to 12. It was shown that at pH 7.5 in the buffered solution, the growth of cyanobacteria was identical in the entire range of Si concentration. A high pH level and concentration of silicon higher than in the waters of the spring (conditions reached in nature by the evaporation) are needed to obtain silicified cyanobacteria. In two days of these conditions, cyanobacteria formed a thick mucous cover, which intensively sorbed silicon from the medium, while live trichomes remained free from it (Pl. 2, figs. 1, 2). The complete mineralization of trichomes occurs only after destruction of the culture caused either by high pH values or high concentrations of silicon. It appears that the degree of silicification is controlled by the concentration of silicon in the solution and the level of pH.

To determine the dynamics of silicon absorption by cyanobacteria with their subsequent silicification, cyanobacteria were raised in the laboratory in different concentrations of silicon. A high lability to silicon has been shown: *Mastigocladus laminosus* could grow in 30% silicon gel. The atomic absorption analysis showed that the silicon content of cells increases proportionally with its concentration in the environment. For natural Kamchatka samples, it is shown that the silicon content of cyanobacterial cells is four orders of magnitude higher than that of hydrothermal sources (Zelenkov et al., 2005). The ability of cyanobacteria to accumulate high concentrations of silicon explains why the mineral layer with cyanobacteria in modern stromatolites of Kamchatka is silicified.

Another set of laboratory experiments was conducted in order to clarify the role of cyanobacteria in the formation of magnesian calcite under variable conditions of cultivation (varied pH, light exposure, duration of incubation) (Zaitseva et al., 2006). The alkaliphilic strain of cyanobacteria *Microcoleus chthonoplastes* growing in favorable medium was taken. The

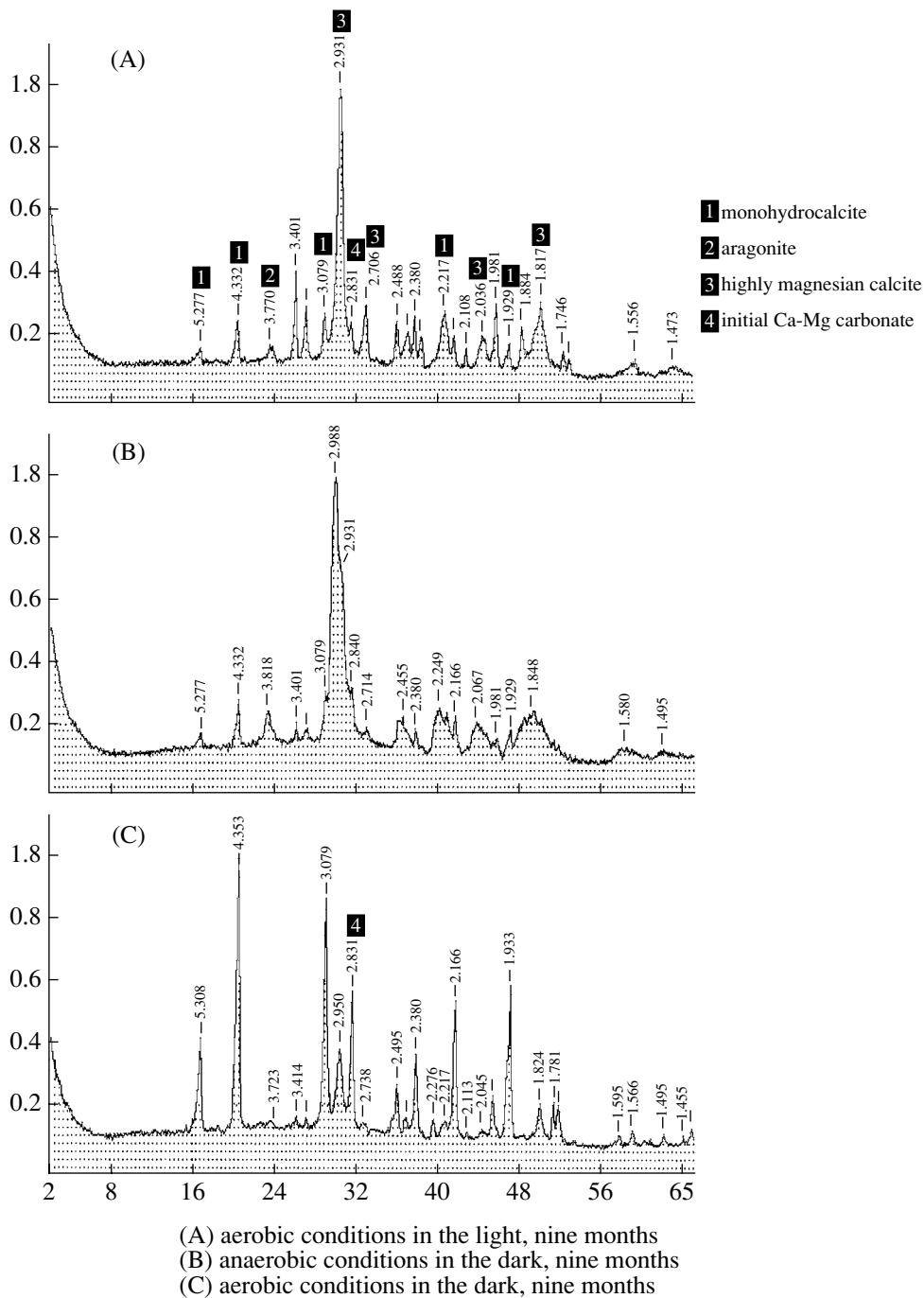


Fig. 2. Results of X-ray phase analysis of the carbonates transformed during laboratory modeling.

experiment utilized chloride-magnesian-calcium solutions with addition of sodium bicarbonate following the technique of Ohde and Kitano (1978). It was shown that the formation of sediment is strongly controlled, in addition to the presence of cyanobacteria, concentration of the solution and the level of pH, by the presence of cyanobacterial metabolites. The latter slow down the crystallization of magnesian calcite by the formation of exometabolites with a chelating effect. The exposure of

cyanobacteria to light or darkness considerably influences the structure of the deposit and the size and form of carbonate crystals (Pl. 2, figs. 3, 4). In conditions of photosynthesis, the mineral huntite, a probable predecessor of dolomite, is well represented. In the dark, the crystallization of carbonate deposit, along with a wide range of magnesian calcites, produces protodolomite.

The same cyanobacteria were used in the experimental modeling of the dolomitic stromatolite forma-

tion. The chemically precipitated deposit containing Ca-magnesian carbonate, $MgCO_3$ (65%), $CaCO_3$ (35%), and monohydrocalcite was placed between layers of an alkalophilic strain of *Microcoleus*. It was shown that the presence of a cyanobacterial mat produces a microhabitat where the Ca-Mg carbonate sediment endures changes with the formation of compounds that are more stable at this stage such as hydromagnesite, magnesian calcite with a high $MgCO_3$ content (up to 40%), aragonite, microscopic regions with dolomitic structure, and with remaining monohydrocalcite. In the dark and without oxygen, the recrystallization progresses faster than in the presence of oxygen (Pl. 2, figs. 5, 6; Fig. 2).

The use of cyanobacterial mats in the laboratory produced experimental models of stromatolites quite precisely mimicking sites of ancient constructions (*Bacterial Paleontology*, 2002). The very restricted distribution of stromatolites in modern conditions indicates that during their mass development in the Precambrian somewhat different geochemical parameters prevailed. It is supposed that the aquatic environment of cyanobacterial communities was more mineralized, which resulted in massive, constant precipitation of mineral deposits (carbonates, phosphates, etc.). This concept served as the basis for laboratory models morphologically similar to fossil stromatolites. Ancient stromatolites have a strongly pronounced lamination, which is treated as an alternation of organic and mineral layers. Therefore, the modeling was aimed at reproducing conditions favorable for alternation of cyanobacterial growth and mineral precipitation. In ancient sedimentary sequences, carbonate stromatolites occur most frequently. This is why we widely used carbonate materials in laboratory experiments. The precipitation of calcium carbonate from saturated solutions is achieved in many ways, such as the evaporation of the solution, increase in pH level of the medium, addition of excessive amounts of calcium chloride, etc. The experiments also produced other mineral interlayers, as layers of calcium phosphate, magnesium carbonate, calcium sulfate, and ferruginous compounds. In these experiments we used cyanobacteria isolated from mats of springs of the Uzon volcano (Kamchatka), *Oscillatoria terebriformis* and *Phormidium angustissimum*. These organisms have a number of interesting biological features that are essential for the biomodeling. They have mobile trichomes moving with a speed up to 100 μm per minute. This allows them to move between precipitating mineral particles. Filaments move purposefully towards the light, creeping on the surface of the formed sediment, occupying this surface, and forming a new clothlike film upon it. Less mobile threads stay buried by precipitated sediment and remain within its depth, indicating the former presence of cyanobacteria there.

After the stage of active growth of cyanobacteria with the formation of a uniform, dense film of interwoven trichomes, a calculated amount of powderlike calcium carbonate was added to the liquid medium. The

addition of carbonate on the surface of the growing bacterial film imitates a precipitation of carbonate deposit in the formation of stromatolite constructions under natural conditions. The average formation rate of paired layers in this intensive method ranges from several hours to one day, and models of differently shaped structures were produced from several weeks to about three months. Being buried by mineral deposit, mobile cyanobacteria repeatedly moved upwards to the light source, penetrated between grains of calcite and expanded on its layer, forming a new layer of cyanobacteria. Multiple alternations of addition of bacterial mass and calcium carbonate resulted in the formation of a multilayered mat (Pl. 2, fig. 7).

Experimental living models quite precisely reproduce reference constructions of ancient stromatolites. Therefore, there are reasons to believe that the laboratory processes are similar to the natural mechanisms of stromatolite morphogenesis.

Under laboratory conditions, it was also possible to produce oncolites nearly identical to fossil ones (Pl. 2, fig. 8) (*Bacterial Paleontology*, 2002).

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