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The Special Features of the Interaction between Iron-Manganese Stromatolites and the Environment

V. V. Avdonin[a], N. E. Sergeeva[a], and K. V. Van[b]

[a] *Department of Geology, Moscow State University, Moscow, Russia*
[b] *Institute of Experimental Mineralogy, Russian Academy of Sciences, Chernogolovka, Moscow Oblast, Russia*
e-mail: avdonin@geol.msu.ru; nat@geol.msu.ru; kvv@iem.ac.ru

Abstract—The analysis of the submicroscopic textures of the cobaltiferous crusts from the Magellan Seamounts has shown that biofilms—ferromanganese stromatolite builders absorb petrogenic components (SiO_2, Al_2O_3, P_2O_5, etc.) from the environment and use them for the formation of a columnar structure.

Keywords: stromatolites, cobaltiferous crusts, Magellan Seamounts
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INTRODUCTION

Ferromanganese stromatolites are assumed to have appeared after the Great Mesozoic extinction at the boundary between the Mesozoic and the Cenozoic periods and were widely distributed through the ocean bottom as crust coverings and fields of nodules (Avdonin et al., 2013 a, b).

The cobaltiferous crusts from the ore region of the Magellan Seamounts form extensive coverings on the parent rocks of the near-to-summit slopes of the guyot seamounts. The crusts have a layered structure; in their section, there are several ore layers with an average thickness of 2–3 cm that differ in their appearance, structure, physical properties, and nonmetallic admixtures.

The layered section of the crusts is a peculiar chronicle of the Mesozoic–Cenozoic ferromanganese ore genesis that covers the time period from the Campanian–Maastrichtian until the present time (Melnikov, 2005). The section of the crusts from the Magellan Seamounts contains four macro-layers: the Late Paleocene–Early Eocene (I-1), the Middle–Late Eocene (I-2), the Miocene (II), and the Pliocene–Quaternary (III). At times the main section was underlain by the relicts of the layers that had existed before (relict layers, R) with the two age ranges: the Campanian–Maastrichtian and the Late Paleocene (?). The typical associations of microtextural elements were identified for each layer.

The crust growth was often halted, sometimes for a long period, but was always resumed. As a rule, in this case, the macrolayers of the crusts were not interlayered with sediments. A definite evolution of the structural forms of stromatolites can be traced in the crust section. It consists in the consecutive alternation of the various columnar textures.

The detailed study of the crust section made it possible to establish that all of the macrolayers are sets of textural elements that form associations that are typical of each layer. The evolution of these associations is the following.

The relict layers are characterized by wavy-layered forms and large radial-layered "structures." The pattern that reflects the intergrowth of oxide ferromanganese microforms through phosphate sediment can be considered as the leading texture of this layer.

The I-1 layer is represented by fine-flaky homogeneous masses with wavy-layered forms that have features of columnar buildups. The short-columnar and festoon forms are also recorded.

The I-2 layer consists of tree-shaped columnar aggregates with large cavities between them. The base and the top of the layer contain rows of closely spaced short columns.

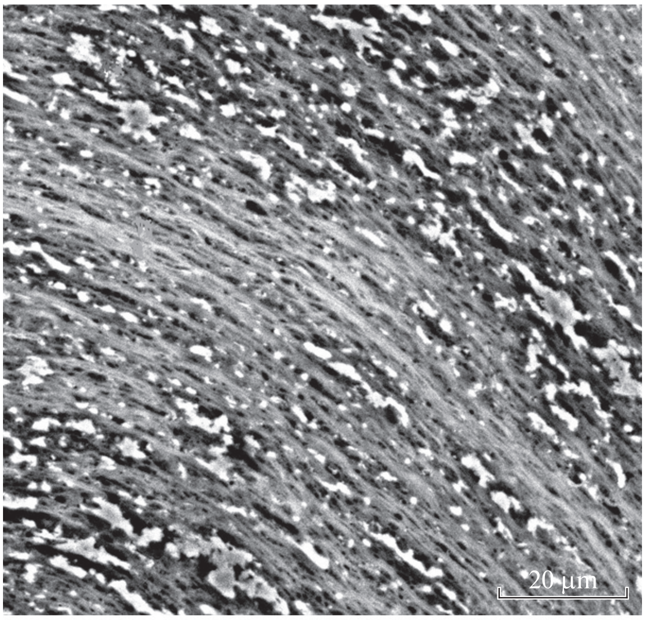
The II layer has a three-member structure: compact rows of columns are located at the top and at the bottom; the bushy intergrowths of branching columns dominate in the center.

The III layer is mostly composed of compact rows of rectilinear fine columns.

Thus, in total, we have quite a definite picture of the existence and development of a common structure according to the general laws. The columnar textures vary but the columns always grow synchronously at an equal rate.

By studying the ferromanganese crusts from the guyots of the Magellan Seamounts in the Pacific Ocean with a scanning electron microscope we found

(a)



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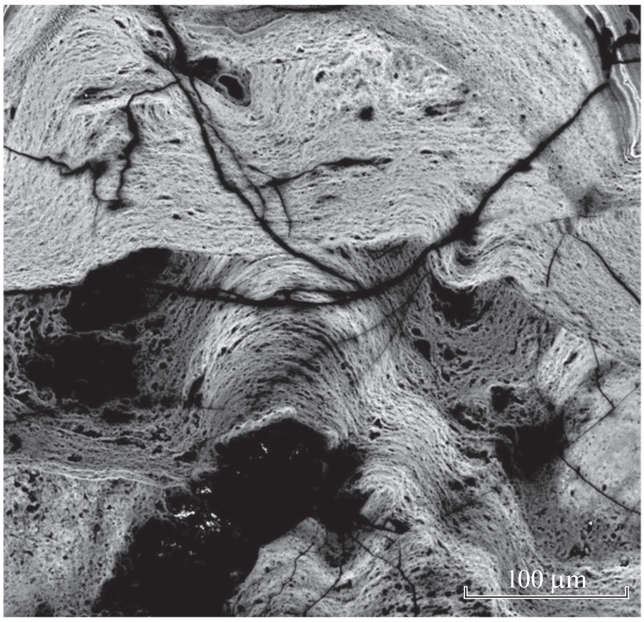

Fig. 1. Bacterial tufts: A is the alternation of the fossilized biofilms, the white lumps are phosphate particles that were captured during growth; B is the interrelationships of bacterial tufts of various generations in the columnar structure of a ferromanganese stromatolite that shows inconsistent overlying of the more recent layer on the truncated surface of the earlier formations.

that they represent a special type of ferromanganese stromatolites. The columnar textures of stromatolites are bacterial tufts formed by the alternation of fossilized relicts of bacterial films (Fig. 1). The textural pattern of the crust stromatolites greatly resembles the well-known carbonate stromatolites (Bacterial..., 2002; Zavarzin, 2003). The relicts of bacterial films are morphologically similar to the modern cianobacterial films, where the intersection of filamentous and coccoid forms of cianobacteria can be traced, which was first recorded by Chinese geologists (Bian Lizeng et al., 1996; Hu Wenxuan et al., 2000).

The ferromanganese stromatolites are built by biofilms, which are communities of microorganisms that are attached to a solid substrate. The biofilms form bacterial tufts, which are stratified macrocolonies that consist of prokaryotic organisms (Fossils..., 2011; Pinevich, 2005). The biological body of a tuft includes horizontal layers with a thickness from 1 μm to several millimeters. A bacterial tuft grows as its microorganisms develop. A tuft impregnated with iron and manganese oxides is a ferromanganese stromatolite.

Deposition interferes with the growth of the crusts. Upon being buried under heavy deposits, after quick attempts to continue their growth in a state of repression these biofilms—stromatolite-builders die. The facial environments of the crust formation indicate that at early stages (the formation of relict layers and I-1 and I-2 layers), the growth of stromatolites is accompanied by the accumulation of carbonate—phosphate sediments. Therefore, the mass of a bacterial tuft often contains small phosphate inclusions in alternating biofilms (Fig. 1). At more recent stages, the growth of the upper crust layers was accompanied by the deposition of siliceous material.

Like similar biofilms of other species, the biofilms that form stromatolite cianobacterial tufts are a well-organized interacting community of microorganisms (Maltsev, Mansurova, 2013). The formation of biofilms is a result of the coordinated group behavior of bacteria and is controlled by so-called quorum sensing. This is one of the basic concepts of modern microbiology (Gruzina, 2004). It is most probable that all of the features of the textural characteristics of oxide ores are to a large extent the manifestation of this phenomenon.

The synchronous growth of the columns and the formation of ordered dendrite-like structures can be caused by the specific social behavior of bacterial communities.

The base structure of a crust is a buildup that consists of consecutively alternating layers. However, this structure is complicated by numerous small secondary elements, such as cavities, fractures, and inclusions of foreign materials and faunal remains. Some of these secondary elements have features of autonomous existence with restrained conditions. These microtextural elements are especially important for determining the conditions and the results of the interaction of the environment with the growing organisms.

Cavities of different natures, types, and sizes constantly occur during the growth of the crusts. The cav-

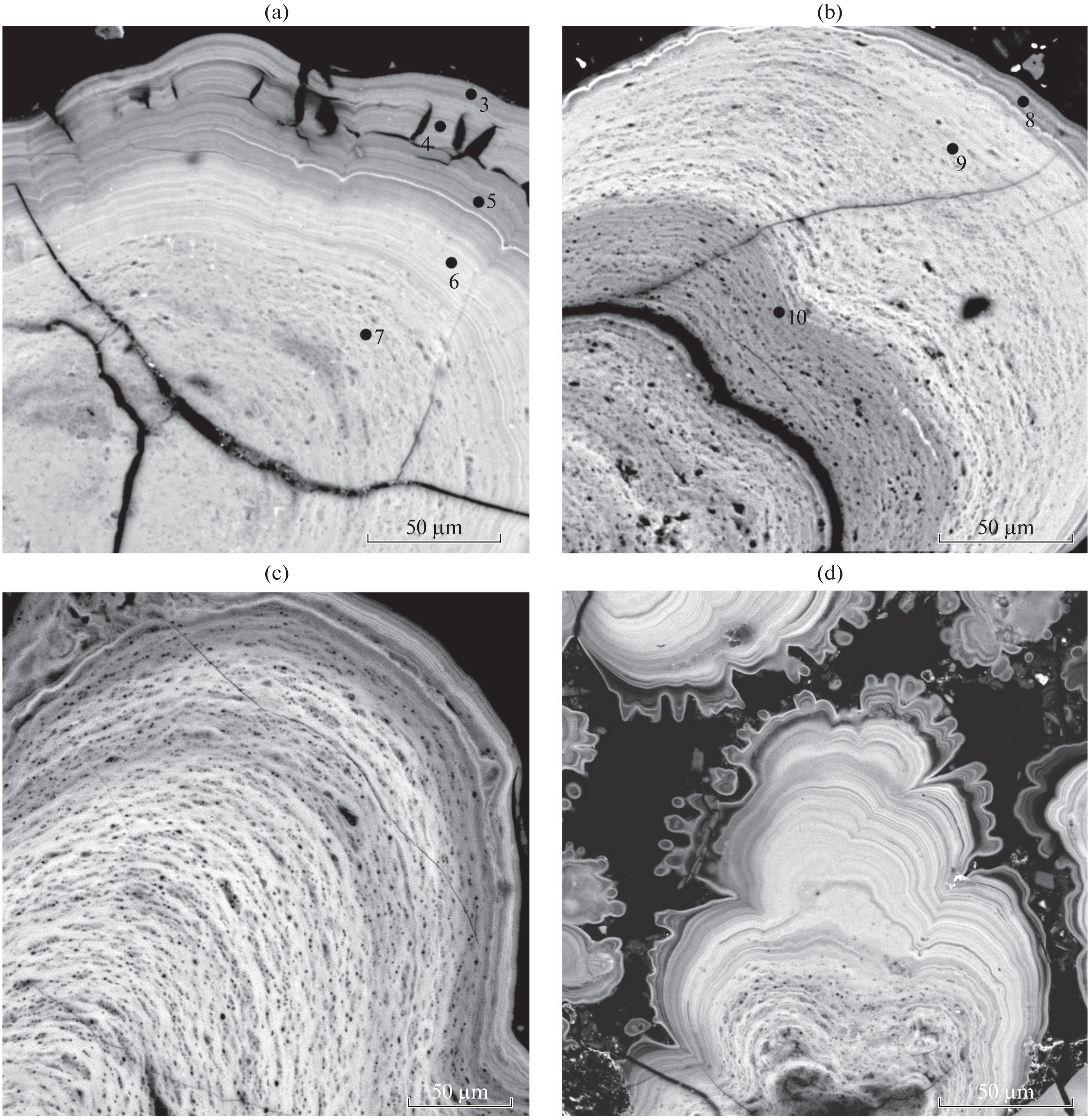

Fig. 2. The nodules in the cavities of the crust layers: A and B are the nodules of the layered texture, as they grow, the thickness of the bacterial films decreases; the extreme layers are impregnated with silicone dioxide, aluminum silicate, and iron (Table 1); C is the alternation of fossilized films of two types: homogeneous manganese (light) and spindle-shaped (gray) with rounded pores (cocci traces); D is the nodule in a free cavity; the bacterial films become thinner from the base to the periphery; the nodule has a margin with a scalloped crown.

ities in the interstices between the columns are recorded most frequently. These occur at the boundaries of macrolayers; therefore they mark gaps in ore accumulation, etc.

Some cavities remain open for a long time and are subject to active environmental action, other ones close quickly and the processes that occur in them are not affected by the environment.

The origination of the cavities is clearly associated with the growth stages of stomatolites; the filling of the cavities corresponds to the environment that dominated at a given stage. Cavities that are filled with sed-

Table 1. The composition of laminas in the nodules from the microanalysis data (mass %), 38-2 sample, Fig. 2

Composition	Analysis number							
	3	4	5	6	7	8	9	10
SiO_2	14.04	4.45	5.16	2.99	1.47	6.25	1.87	5.40
Al_2O_3	4.71	1.51	1.57	0.57	1.18	2.16	0.46	1.00
FeO	19.80	23.26	23.41	18.80	11.46	30.02	14.80	23.34
MgO	1.65	0.27	1.04	1.87	1.95	1.57	2.16	1.05
MnO	23.83	25.88	23.73	33.56	41.81	17.41	37.70	24.86
CaO	2.34	2.67	2.97	4.07	3.98	2.45	3.58	3.53
Na_2O	0.39	0.27	0.99	2.70	2.74	1.19	2.37	0.99
K_2O	0.83	0.19	0.21	0.38	0.76	0.30	0.47	0.19
P_2O_5	0.76	0.90	0.56	0.81	0.45	1.16	0.77	0.59

imentary material give us a reason to evaluate the facial conditions for the layer formation. In particular, it was established that the basal layers of these crusts contain a large quantity of phosphate material almost everywhere. The top layers do not usually have phosphate material; they accumulate noncalcareous and phosphate-free silicate silts.

Along with the fragments of sedimentary material, the cavities contain microfaunal remains, including the microflora that is fundamental for the calculation of the age of crust layers, and accessory minerals. Over the entire period of growth of the crust, the cavities are inhabited by various microorganisms, including biofilms—stromatolite-builders. The process of biofilm activity continues in the cavities. The biofilms that develop in a free space inside the cavities form various shapes: solid edges on the walls, semispherical nodules, paw-shaped outgrowths, and spherical segregations.

Since certain types of cavities are closed spaces, the processes that occur in them are not influenced by external factors. This makes it possible to consider them as natural cells for experimental studies on the details of stromatolite growth processes, in particular, for studying the interaction between biofilms and sediments.

We consider the most typical cases. The walls of the cavities that are free from sediments begin to develop nodule formations with well-pronounced features of the stromatolite structure. Their texture is similar to that of the bacterial tufts that compose the crust columns, which is the rhythmic alternation of fossilized biofilms. Homogeneous extended manganese stripes (which appear to be lighter in the microphotographs) alternate with ferriferous spindle-shaped stripes that contain numerous rounded pores. It is clearly seen that as a nodule grows, the thickness of the laminas decreases to vanishingly small values gradually from the base to the surface. At the same time, the marginal stripes increase the contents of silicone dioxide, aluminum silicate, as well as iron. This is most likely to be related to the depletion of the nutrient solution in the closed space and to the fact that manganese is the first to be spent (Fig. 2, Table 1).

Such phenomena are more pronounced in the cavities that have silicon dioxide sediment at the moment of nodule growth. The external layers of the nodules that grow under these conditions are impregnated with silicone dioxide and aluminum silicate from the sediment. We may assume that the petrogenic components are absorbed by biofilms together with manganese and iron.

However, the relationships between biofilms and phosphate sediments demonstrate the most interesting and complicated phenomena. Both columnar structures and nodules often have phosphate microlaminas in the basal layers of the crusts, which were formed simultaneously with the accumulation of carbonate—phosphate sediments (Fig. 3a). We revealed the nature of these formations after the sequence of the processes that occurred in some cavities had been reconstructed. First, the columnar structures from the alternating ferromanganese laminas grew in the free space. The entry of sedimentary phosphate material interfered with the growth of the columns. During the struggle with unfavorable conditions, the biofilms often partially absorbed sedimentary material, by attaching it to its structure as a microlamina. Before the biofilms terminated their activity completely, small repressed nodules had been formed; at the end of

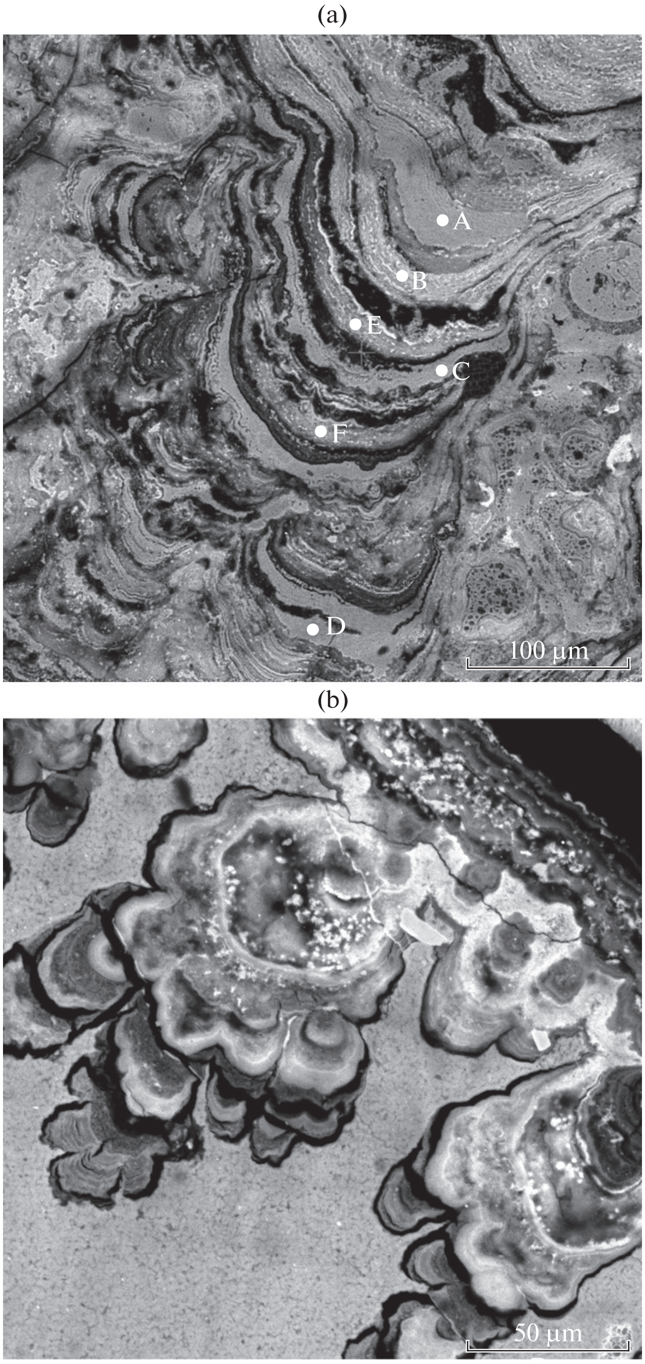

Fig. 3. Nodules in a phosphate medium: A is the alternation of ferromanganese and phosphate layers in a nodule: A, C, and D are phosphate laminas (the content of P_2O_5 varied from 25 to 32%), B, E, and F are ferromanganese layers (the content of P_2O_5 was up to 5.2%); B is the phosphate material that fills the cavity and erodes ferromanganese nodules.

this process, the tops of the columnar structures showed the features of destruction (Fig. 3B).

The buried concretions had the most interesting and most untypical behaviors in the struggle between the biofilms and the hostile phosphate environment; some buried concretions that occurred simultaneously with the early I-1 and I-2 crust layers are characterized by the crust formation mechanism of their shells. Like the crusts, they have a great many phosphates. In particular, they contain splitting layers or fractures that are similar to the interlayers formed by phosphates. These interlayers develop ferromanganese nodule formations. Analysis of this phenomena shows that nodules started to grow on the free surface and then were buried

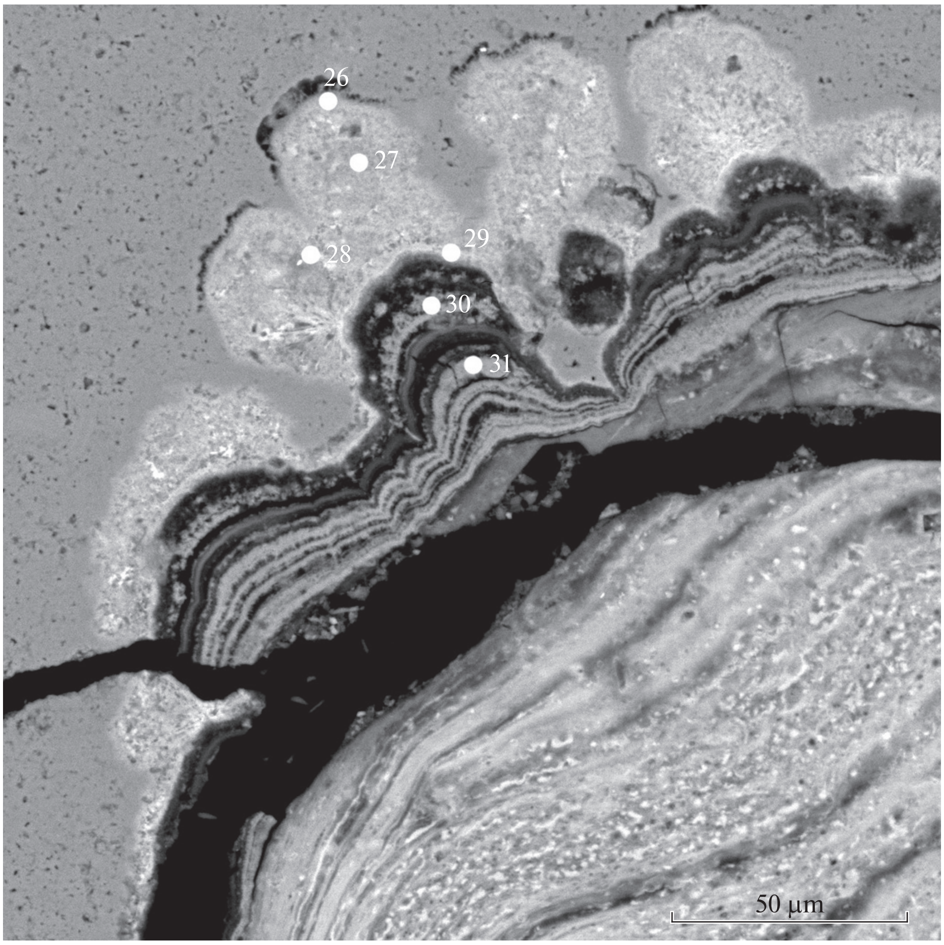

Fig. 4. Nodule-shaped growths in the phosphate interlayer of a buried concretion; the alternation of layers of different composition is shown (Table 2).

under the deposited phosphate material. The nodules continued to grow for some time, struggling for survival; the biofilms intergrew through the deposit and absorbed a certain amount of material. Further attempts to grow were manifested as the formation of peculiar phosphate–manganese caps (Fig. 4, Table 2). We note that nodules do not grow in the recent phosphate veins, which are fractures that intersect the earlier crust layers.

Table 2. The composition of laminas in the nodule from the microanalysis data (mass %), 14 D sample, Fig. 4

Composition	Analysis number					
	26	27	28	29	30	31
SiO_2	2.78	3.05	0.95	3.89	2.66	0.90
Al_2O_3	3.75	2.79	2.69	2.47	0.96	0.57
FeO	4.36	3.25	1.34	4.40	2.38	1.76
MgO	4.90	2.86	4.49	3.12	0.90	0.27
MnO	36.91	24.70	54.19	29.16	10.29	4.94
CaO	13.55	21.95	2.18	19.54	36.58	46.89
Na_2O	1.12	1.38	1.78	0.91	1.04	0.97
K_2O	0.66	0.50	0.86	1.02	0.62	0.40
P_2O_5	7.11	14.83	0.15	12.50	23.15	27.91

CONCLUSIONS

The results of these studies allowed us to conclude that biofilms–ferromanganese-stromatolite builders acquire the ability to absorb a certain amount of petrogenic components and to incorporate them into their structure when interacting with the environment (sediments) during the struggle for survival. New types of stromatolites occur due to this process.

REFERENCES

Avdonin, V.V., Eremin, N.I., Melnikov, M.E., and Sergeeva, N.E., Meso–Cenozoic ferromanganese oregenesis in the World Ocean, *Dokl. Earth Sci.*, 2013, vol. 451, no. 2, pp. 824–826.

Avdonin, V.V., Melnikov, M.E., and Sergeeva, N.E., The submicroscopic structures of Mesozoic–Cenozoic Fe-Mn stromatolites, *Moscow Univ. Geol. Bull.*, 2013, vol. 68, no. 5, pp. 289–294.

Bakterial'naya paleontologiya (Bacterial Paleontology), Rozanov, A.Yu., Ed., Moscow: Paleontol. Inst. Russ. Akad. Nauk, 2002.

Bian Lizeng, Lin Chengyi, Zhang Fusheng et al., Pelagic manganese nodules — a new type of oncolite, *Acta Geol. Sinica*, 1996, vol. 70, no. 3, pp. 287–294.

Gruzina, V.D., Bacterial communicative signals, *Antibiot. Khimioter.*, 2003, vol. 48, no. 10, pp. 32–39.

Hu Wenxuan, Zhou Huayang, Gu Lianxing et al., New evidence of microbe origin for ferromanganese nodules from the East Pacific deep sea floor, *Sci. in China. Ser. D.*, 2000, vol. 43, no. 2, pp. 187–193.

Iskopaemye bakterii i drugie mikroorganizmy v zemnykh porodakh i astromaterialakh (Fossil Bacteria and Other Microorganisms in Terrestrial Rocks and Astromaterials), Rozanov, A.Yu. and Ushatinskaya, G.T., Eds., Moscow: Paleontol. Inst. Russ. Akad. Nauk, 2011.

Melnikov, M.E., *Mestorozhdeniya kobal'tonosnykh margantsevykh korok* (Deposits of Cobalt-bearing Manganese Crusts), Gelendzhik: FGUGP GNTs "Yuzhmorgeologiya", 2005.

Mal'tsev, S.V. and Mansurova, G.Sh., What is a biofilm? *Prirodn. Meditsina*, 2013, vol. 1, no. 13, pp. 86–89.

Pinevich, A.V., *Mikrobiologiya zheleza i margantsa* (Iron and Manganese Micriobiology), St. Petersburg: St. Petersburg Gos. Univ., 2005.

Zavarzin, G.A., Lektsii po prirodovedcheskoi mikrobiologii (Lectures on Environmental Microbiology), Moscow: Nauka, 2003.

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