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Magnetotactic Bacteria and Biomagnetism: Criteria of Sample Selection for the National Biobank–Depository of Living Systems

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Abstract—Magnetotactic bacteria that produce nanosized crystals of magnetite or greigite (or both minerals) inside cells in the processes of life play an important role in the biogeochemical processes, for example, in the iron and sulfur cycle, as well as in natural residual magnetization of sedimentary rocks. Despite decades of investigation, knowledge of their abundance and ecology is still limited. The principles of sample selection for the national biobank–depository of the living systems are described on the basis of petro- and paleomagnetic methods for the investigation of biomineralization.

Keywords: biomagnetism, magnetotactic bacteria, biobank–depository of the living systems
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INTRODUCTION

Recently, magnetotactic bacteria are increasingly used in various fields of science, including geoecology, mineralogy and biomagnetism, crystallography, biochemistry and biomedicine, physics, and even astrobiology. The discovery of magnetotactic bacteria by a graduate of the University of Massachusetts, R. Blakemore, in 1975 stimulated the development of biomagnetism, which is a new field of science (Blakemore, 1975). The studies showed that several species of bacteria that were extracted from swamp mud migrated mostly to the north along the magnetic meridian and towards the surface-water layers (Blakemore, 1975). Pure magnetite (Fe_3O_4) that is synthesized by bacteria from iron during the processes of life is the source of their magnetism (Evans and Heller, 2003).

There are two pathways of the formation of magnetite by bacteria: BIM (*biologically induced mineralization*) and BOM (*biologically organized mineralizaton*). The composition, crystal habit, and spatial organization of magnetic grains is not controlled by bacterial activity during the formation of BIM magnetite. Magnetotactic bacteria of this group (e.g., *Geobacter metallireducens*) use amorphous iron (Fe^{3+}) hydroxide in the processes of life and produce reduced iron (Fe^{2+}), which is precipitated in the environment as magnetite (Evans and Heller, 2003). Magnetic grains produced by such bacteria are poorly crystallized and have an irregular shape and a wide range of grain sizes (Evans and Heller, 2003).

The formation of magnetic minerals in BOM occurs inside magnetotactic bacteria cells. The composition, crystal habit, size, and spatial organization of magnetic grains is controlled by bacterial life activities (*Aquaspirrilum magnetotacticum* is the best studied among them). Magnetite crystals that are produced in such a way usually form chains, in which each crystal occupies its own cytoplasmatic section (magnetosome). Magnetosomes are protrusions of the cytoplasmatic membrane that surround iron particles. An actin-like protein in *Magnetospirillum magneticum* is responsible for the "correct" position of magnetosomes. If the protein is absent, the distribution of the magnetosome over the cell surface is disordered (Shih and Rothfield, 2006).

Depending on the habitat of magnetotactic bacteria, classification by the crystal shape of magnetic minerals has been suggested (Bazylinski and Williams, 2007): the freshwater *Magnetospirillium* species produce cubo-octahedral crystals; *D. magneticus*, which are sulfate-reducing magnetotactic bacteria, synthesize elongated magnetite crystals; magnetotactic bacteria in marine environments form elongated cubo-octahedral magnetosomes. Magnetotactic coccus synthesize pseudohexagonal elongated prismatic crystals, whereas magnetotactic vibrio forms elongated cubo-octahedral crystals.

However, the term "magnetotactic bacteria" does not have a taxonomic sense. As was demonstrated in (Bazylinski and Frankel, 2004), magnetotactic bacteria should be considered as a diverse set of prokaryotes with a common feature, namely, biomineralization of magnetosomes. In spite of the differences, magnetotactic bacteria have a number of common features: they are gram-negative prokaryotes that are phylogenetically related to the bacterial domain. They move using flagella and are microaerophiles or anaerobes; they have the respiratory form of metabolism (with one exception); they are active and, thus, may fix atmospheric nitrogen; they are mesophilic in relation to a temperature increase and have magnetosomes (Bazylinski and Frankel, 2004). At the same time, the physiology and metabolism of magnetotactic bacteria differ strongly and depend on the conditions of cultivation as well, which often impacts their magnetic characteristics (Bazylinski and Williams, 2007).

It is assumed that the mechanism of magnetotaxis is necessary for transition to the area of optimal conditions at the bottom sediment–water boundary; however, this hypothesis does not explain all of the peculiarities of magnetotactic bacteria. In particular, this mechanism is effective only at high latitudes, whereas the magnetic field near the equator does not allow bacteria to distinguish “top” and “bottom.”

The study of magnetotactic bacteria in the solution of geological tasks. Bacteria that produce magnetic minerals are widely abundant on almost all continents. However, magnetotactic bacteria exist in the water environment mostly under the conditions of a quite sharp redox boundary (ROB) and directly near this boundary (Kopp and Kirshvink, 2008). The concentration of bacteria near this boundary may reach 100 cells per mL (Bazylinski and Schübbe, 2007).

Sediments of modern lakes are wonderful paleogeographic archives that usually contain high-resolution records of changes of climate, geomagnetic field, other events, and, as a whole, the evolution of the environment over the last thousands of years (Evans and Heller, 2003). Biogenic magnetic minerals that are abundant in sediments and sedimentary rocks play an important role in this.

BOM magnetism. Magnetotactic bacteria that produce magnetosomes have been described in detail during petro- and paleomagnetic investigations of modern lake sediments (Peck and King, 1996; Snowball et al., 1999; Peng et al., 2000; Nurgaliev et al., 2009). The data were used for estimation of the time at which the rocks acquired characteristic components of magnetization and for correlation of the data that are obtained with global cycles, including the Milankovich cycles (Evans and Heller, 2003). In addition, the study of biomagnetism provides evidence for climate change (warming/cooling) and for variation of the entire geoecological situation in the studied sedimentary basin (various types of pollution).

However, the orientation/reorientation of magnetosomes along the direction of the modern geomagnetic field and preservation of this direction occur only in the process of the life activities of magnetotactic bacteria. After the death of a BOM bacteria, it becomes a “magnetic” sediment and ordering of magnetic minerals is violated in the course of the formation of orientation (detrital) residual magnetization. The data that were obtained during the study of lithified Holocene lake sediments provide evidence for a decrease in inclination, which is typical of sedimentary rocks at the postdiagenetic stage. It has also been established that the strong decrease of the natural residual magnetization and change of the vector of natural residual magnetization (NRM) in shallow marine carbonates occur in the course of diagenesis and dolomitization (Evans and Heller, 2003).

Solution of paleoecological/paleogeographic tasks on the basis of BOM magnetism. Since each species of magnetotactic bacteria of the BOM type has a clear response to redox conditions and to the concentration of sulfur in water, they are widely applied for paleogeographic reconstructions, and not only modern ones. Study of magnetic minerals that were produced by magnetotactic bacteria in Cambrian limestone of Siberia provided the data on environments of sedimentation at that time (Changetal, 1987).

BIM magnetism. The study of paleosoils is the main direction in the investigation of magnetism of this type. Since BIM bacteria die after the production of iron, and further reactions that result in the formation of new magnetic minerals proceed without the participation of magnetotactic bacteria, the value and direction of the geomagnetic field that is recorded in magnetized minerals do not change significantly after the formation of sediment/paleosoil. In this case, one more method of petro- and paleomagnetic investigations, namely, the study of the anisotropy of magnetic susceptibility (AMS), plays an important role, which provides data on the direction and regularities in the sources of magnetized minerals.

Modern studies show that sediments often contain both BIM and BOM minerals, which are distinguished reliably by the petromagnetic parameters (coercive spectra, hysteresis loops, magnetic susceptibility, etc.). The data from the correct assessment of the total natural residual magnetization in rocks based on understanding of the nature of BIM and BOM magnetism provide a more reliable reconstruction of paleogeographic events.

Petro- and paleomagnetic studies of magnetotactic bacteria in modern lakes. Application of petro- and paleomagnetic methods allows us to study the distribution of biogenic magnetic minerals in columns of soils and bottom deposits and to understand the evolution of a sedimentary basin. In addition, the extraction of magnetotactic bacteria from natural environments is simplified by their motion in a magnetic field. For this purpose, bottom sediment and near-bottom water are collected in a vessel in which bacteria may be cultivated for a long time. To obtain the fraction that is enriched in magnetotactic bacteria, a constant magnet is placed externally at the level of the water/sediment boundary. After 1–3 hours, a visible spot of the concentrated fraction of the magnetotactic bacteria is formed near the north magnetic pole from the inner part of a vessel wall (Gorlenko et al., 2011). Extraction of species may be carried out by magnetic separation. Such studies were performed for some freshwater basins in Russia. As a result, communities of the lakes Seliger and Pshada were distinguished.

The microbiological methods for the study of bottom deposits are complicated and long. A complex of petro- and palomagnetic methods may be applied in order to determine the presence of magnetotactic communities and their characteristics in bottom sediments.

Petro- and paleomagnetic records in lake deposits are mostly controlled by sedimentation processes that result in the accumulation of iron-bearing minerals. Various lake types form the individual composition of magnetic minerals. Thermomagnetic analysis (TMA) or its modification (dependence of magnetic susceptibility on temperature) is a major method for the diagnostics of the composition of the ferromagnetic fraction in sediments. Both methods are based on the study of the dependence of inductive magnetization on temperature, in the first case, or magnetic susceptibility on temperature at a heating rate of 50–150°C/min. A high rate of heating is necessary for the elimination of the influence of oxidation and the formation of secondary (laboratory) magnetic minerals.

An important role in the study of lake deposits is played by measurements of magnetic susceptibility, which depends on the rate of sedimentation in a lake, sediment type, climate change, etc. Continuous measurement of the behavior of magnetic susceptibility with depth allows us to determine the proportions between contributions of the ferromagnetic, paramagnetic, diamagnetic, and superparamagnetic fractions to the bulk magnetic susceptibility. The paramagnetic fraction often characterizes the introduction of terrigenous material to a basin; the ferromagnetic fraction usually has a biogenic origin, whereas the superparamagnetic fraction may have a biogenic, as well as a terrigenous origin. Climatic conditions are one of the major factors that control lake sedimentation. Significant variations of the value of magnetic susceptibility in the column provide evidence for significant variations in the lake regime. The value of magnetic susceptibility mostly varies due to variations of the portion of introduced terrigenous material. Variations of magnetic susceptibility may result from the evolution of the ferromagnetic component, which is related to the dissolution of biogenic magnetite grains (Nurgaliev et al., 2009). A decrease in magnetic susceptibility with depth often results from oxidation. The sizes of magnetic particles that are produced by magnetotactic bacteria range from 35 to 120 nm (Diaz-Ricci and Kirschvink, 1992). After the death of magnetotactic bacteria, preservation of magnetic minerals depends on the environment. It has been demonstrated that large magnetite crystals are preserved for a long time, whereas small crystals undergo significant oxidation and are destroyed. Because of this, the upper part of the column is characterized by higher values of magnetic susceptibility (Nurgaliev et al., 2009).

The coercive spectra of the normal residual magnetization that are obtained by a coercive spectrometer in order to reveal the remnants of magnetotactic bacteria in the sediments of several modern lakes are currently applied for petro- and paleomagnetic studies (Nurgaliev et al., 2009). The method of wavelet analysis on a natural basis is used for analysis of the components of coercive spectra, which allows us to reveal magnetic assemblages of different origins in the sediments of modern lakes (Nurgaliev et al., 2010). The precise position of a maximum on a coercive spectra is not an indicator of the presence of magnetotactic bacteria relics in sediments. If the samples of deposits from modern lakes contain groups of components with a maximum position of coercive spectra from ~45–85 mT to ~25–55 mT it may indicate the presence of magnetosome relics in samples (Nurgaliev et al., 2010).

The magnetic characteristics of magnetosome remnants in sediments and products of the life activities of BIM bacteria have been poorly studied. The detailed study of the magnetic characteristics of sediments combined with investigation of the species composition of microbial communities will allow us to create a database that will broaden the area of application of paleomagnetic methods for paleoclimatic reconstructions and provide the ability to reconstruct the evolution of magnetotactic communities in the history of the Earth.

CONCLUSIONS

Investigation of the products of biomineralization using a complex of petro- and paleomagnetic methods allows us to classify samples prior to sample sequestration in order to determine the differences between the bacterial communities. Such an approach will allow us to collect a database on biogenic magnetic minerals that is supported by phylogenetic analysis of magnetotactic bacteria. This database will widen the possibilities for the application of biomagnetism to the solution of geological tasks and will allow us to study the evolution of bacterial communities over time, which is a very important task in the preparation of a bank–depository of living systems.

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