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Magnetic properties, microstructure, composition, and morphology of greigite nanocrystals in magnetotactic bacteria from electron holography and tomography

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Abstract

Magnetotactic bacteria comprise several aquatic species that orient and migrate along geomagnetic field lines. This behavior is based on the presence of intracellular ferrimagnetic grains of the minerals magnetite (Fe_3O_4) or greigite (Fe_3S_4). Whereas the structural and magnetic properties of magnetite magnetosomes have been studied extensively, the properties of greigite magnetosomes are less well known. Here we present a study of the magnetic microstructures, chemical compositions, and three-dimensional morphologies and positions of Fe-sulfide crystals in air-dried cells of magnetotactic bacteria. Data were obtained using several transmission electron microscopy techniques that include electron holography, energy-filtered imaging, electron tomography, selected-area electron diffraction, and high-resolution imaging. The studied rod-shaped cells typically contain multiple chains of greigite magnetosomes that have random shapes and orientations. Many of the greigite crystals appear to be only weakly magnetic, because the direction of their magnetic induction is almost parallel to the electron beam. Nevertheless, the magnetosomes collectively comprise a permanent magnetic dipole moment that is sufficient for magnetotaxis. One of the cells, which is imaged at the point of dividing, contains multiple chains of both equidimensional Fe-sulfide and elongated Fe-oxide crystals. The equidimensional and elongated crystals have magnetic properties that are consistent with those of greigite and magnetite, respectively. These results can be useful for obtaining a better understanding of the function of magnetotaxis in sulfide-producing cells, and they have implications for the interpretation of the paleomagnetic signals of greigite-bearing sedimentary rocks.

Keywords: Greigite, magnetotactic bacteria, transmission electron microscopy, electron holography, electron tomography, magnetic properties, biomineralization