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Biomineralization and Magnetism in Magnetotactic Bacteria

M. Pósfai*, R. E. Dunin-Borkowski**, T. Kasama**, R. K. K. Chong***, E. T. Simpson*** and P. R. Buseck****

* Department of Earth and Environmental Sciences, University of Pannonia, Veszprém, POB 158, H8200 Hungary

** Center for Electron Nanoscopy, Technical University of Denmark, DK-2800 Kongens Lyngby, Denmark

*** Department of Materials Science and Metallurgy, University of Cambridge, Pembroke Street, Cambridge CB2 3QZ, United Kingdom

**** School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287-1404, USA

Many organisms are known to contain ferrimagnetic nanocrystals. However, with the exception of magnetotactic bacteria and homing pigeons, the relationship between the presence of the ferrimagnetic crystals and navigation in magnetic fields remains poorly understood.

The magnetic properties of biogenic iron oxide and sulfide nanocrystals are determined by their sizes, morphologies, crystallographic orientations and arrangements. We have used off-axis electron holography in the transmission electron microscope to characterize the magnetic fields of iron oxide and iron sulfide nanoparticles in magnetotactic bacteria in order to understand nanoparticle magnetism in the cells and to draw conclusions about possible mechanisms of magnetoreception in structurally more complex organisms.

We studied a variety of wild and cultured magnetotactic bacteria. Figure 1 shows an example of a bacterial cell that contains two double chains of slightly elongated magnetite (Fe_3O_4) magnetosomes (membrane-bound magnetic nanocrystals). The [111] directions of the crystals are parallel to the lengths of the chains. Electron holograms were used to construct a magnetic induction map (Fig. 1e), which shows that each crystal contains a single magnetic domain and that the magnetization directions of the individual crystals are parallel to each other. Similar maps from magnetosomes with different sizes, morphologies, orientations and spacings suggest that shape anisotropy is the most important factor that controls the magnetic microstructure of such chains of crystals, followed by interparticle interactions, with magnetocrystalline anisotropy being the least important [1]. Some species of magnetotactic bacteria produce greigite (Fe_3S_4) magnetosomes. Figure 2 shows that the morphologies and arrangements of iron sulfide magnetosomes are typically less strictly constrained than are those of magnetite magnetosomes, resulting in a lower magnetic moment per volume of magnetic material. The organism compensates for this reduced efficiency by synthesizing a correspondingly larger number of magnetosomes. Even though the magnetosome chains that we studied differed in the number, sizes, shapes, and arrangements of magnetosomes, their magnetic moments per unit length were similar. In all cells that were studied using electron holography, the magnetosomes were observed to result collectively in a permanent magnetic dipole moment that is sufficient for efficient alignment of the cell in the Earth's magnetic field.

References

[1] E. T. Simpson et al., J. Phys. Conf. Ser. 17 (2005) 108.
[2] T. Kasama et al., Amer. Mineral. 91 (2006) 1216.
[3] We thank Richard Frankel, Damien Faivre, and Dirk Schüler for contributions to this work.

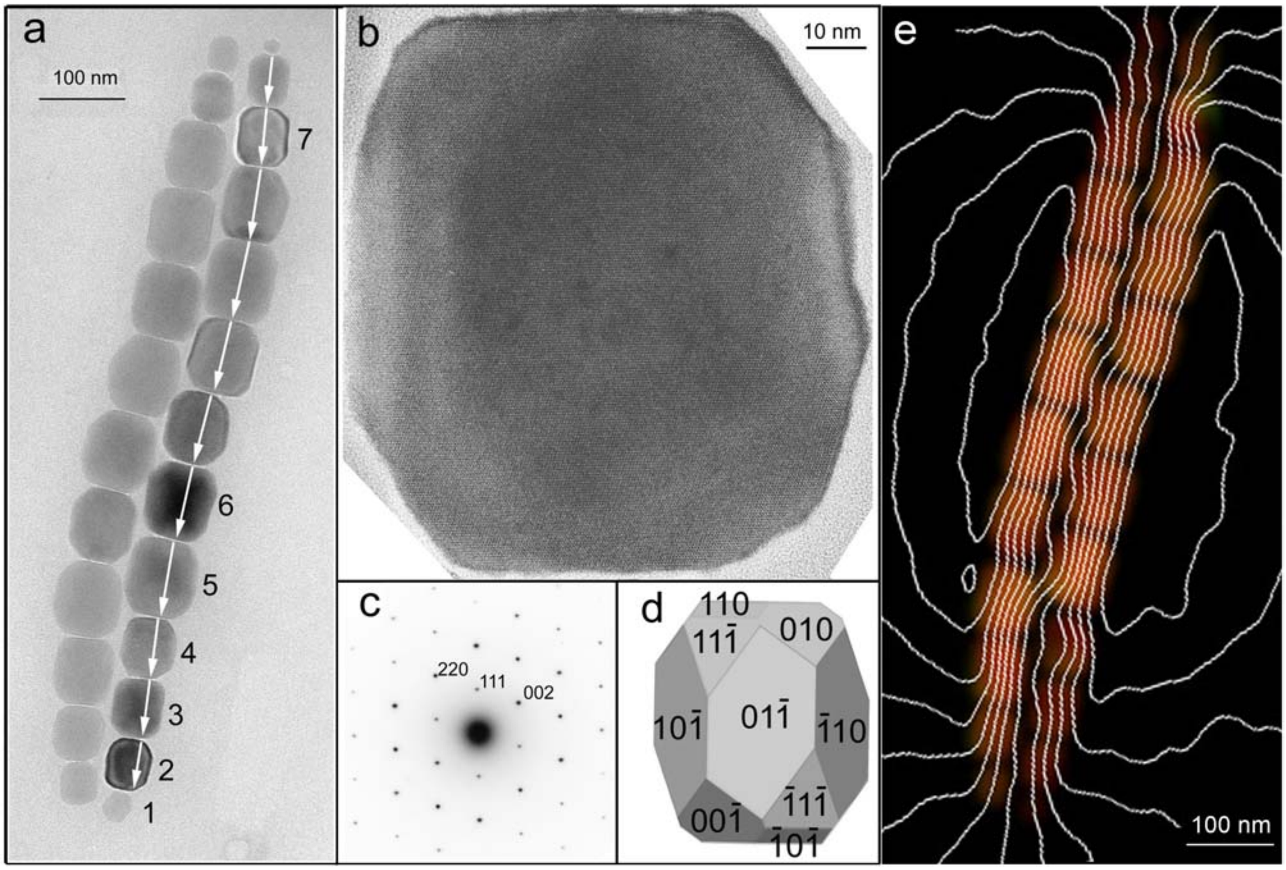

Fig. 1. (a) Bright-field image of a double chain of magnetite magnetosomes from a bacterial cell. The orientations of the crystals that are marked 1-7 were determined by using electron diffraction. The white arrows are parallel to [111] in each crystal. (b) High-resolution TEM image, (c) selected-area electron-diffraction pattern, and (d) morphological model of crystal 4 in (a). (e) Magnetic induction map recorded using off-axis electron holography from the double chain of magnetite magnetosomes in (a). The magnetic phase contours show that each particle is a single magnetic domain, uniformly magnetized parallel to the chain. The contour spacing is 0.3 rad.

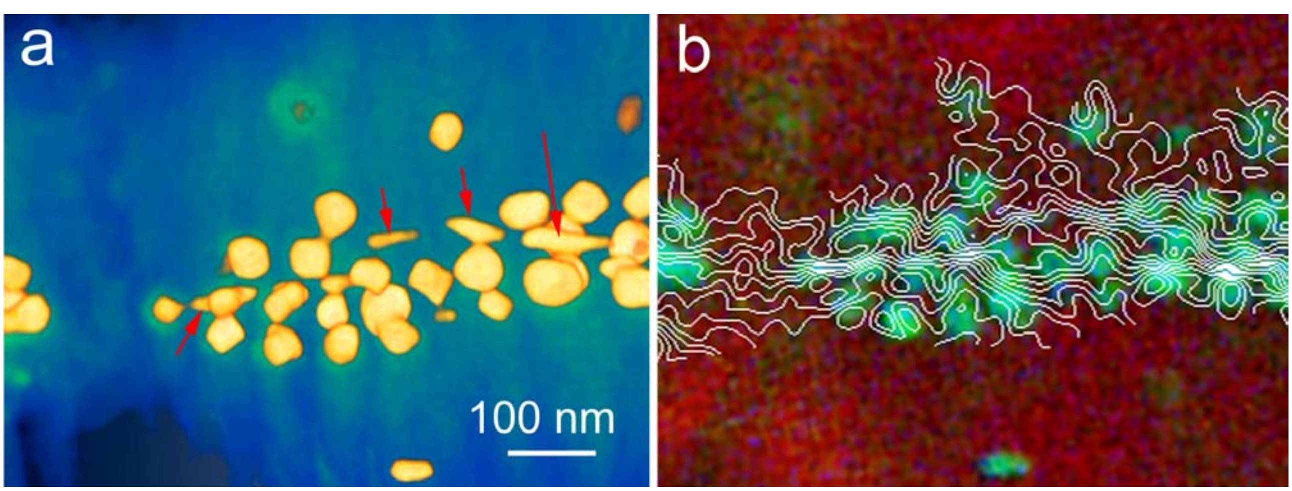

Fig. 2. (a) High-angle annular dark-field tomographic reconstruction of part of a multiple magnetosome chain from a magnetotactic cell. Although most of the magnetosomes are greigite, the arrowed, elongated particles are magnetite. (b) Composite of three-window energy-loss maps (red: C; green: S; blue: Fe) and a magnetic induction map recorded using off-axis electron holography.

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