Magnetic microstructure of chains and clusters of iron oxide and sulfide nanocrystals in bacteria

M. Pósfai[1], T. Kasama[2], E.T. Simpson[2], D. Faivre[3], D. Schüler[4] and R.E. Dunin-Borkowski[5]

[1]Department of Earth and Environmental Sciences, University of Pannonia, Veszprém POB 158, H8200 Hungary, posfaim@almos.vein.hu
[2]Department of Materials Science and Metallurgy, University of Cambridge, Pembroke Street, Cambridge CB2 3QZ, United Kingdom
[3]Department of Biomaterials, Max Planck Institute of Colloids and Interfaces, Potsdam, Germany
[4]Department of Microbiology, Ludwig Maximilians-Universität, München, Germany
[5]Center for Electron Nanoscopy, Technical University of Denmark, DK-2800 Kongens Lyngby, Denmark

Magnetotactic bacteria contain intracellular, membrane-bound ferrimagnetic nanocrystals (magnetosomes) that have species-specific sizes and morphologies and are typically arranged in linear chains. Cells of magnetotactic bacteria provide a natural laboratory in which the magnetic properties of nanometer-sized particles can be studied.

We have used a combination of advanced transmission electron microscopy techniques to study the physical and chemical properties of magnetite (Fe_3O_4) and greigite (Fe_3S_4) nanocrystals inside magnetotactic bacteria. The relative orientations and morphologies of the nanocrystals were identified using electron diffraction, high-resolution electron microscopy and high-angle annular dark-field electron tomography. We used off-axis electron holography to record magnetic induction maps from the crystals. The samples included uncultured magnetotactic cells that were collected from both marine and freshwater environments, and cultures of the strain *Magnetospirillum magnetotacticum* and its genetically-modified mutants.

In magnetite-producing, uncultured cells, closely-spaced crystals were found to be magnetized parallel to each other and to the chain axes as a result of strong inter-particle interactions. In contrast, greigite-containing cells were found to contain disordered three-dimensional arrangements of multiple chains of crystals, with the magnetic field following a meandering path between adjacent crystals.

Wild-type cells of *Magnetospirillum gryphiswaldense* contained single chains of cubooctahedral magnetite crystals that were uniformly magnetized along the length of the chain. In contrast, magnetite crystals in mutant *ΔmamJ* cells, which lacked a magnetosome-associated protein thought to be responsible for assembling the magnetosomes into chains, occurred in clusters in each cell, producing a variety of magnetic microstructures. Other mutant cells contained chains of small (<30 nm), irregularly-shaped crystals, many of which did not produce a measurable magnetic signal and were inferred to be superparamagnetic at room temperature. By obtaining results from magnetosomes with a range of sizes and spacings, an experimental magnetic-state phase diagram was constructed. The phase diagram highlights the delicate balance between crystal size, shape, orientation and chain configuration and illustrates graphically whether cells are able to respond efficiently to an external geomagnetic field.