Biomineral attractions: magnets in organisms

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Many organisms contain ferrimagnetic nanocrystals. Bacteria, pigeons and fish are known to use magnets for navigating in the Earth's magnetic field, whereas some animals use the iron minerals for hardening or protection. However, in most cases the biological functions of magnetic crystals remain unknown.

Magnetotactic bacteria are the best known examples of organisms that contain nanoscale magnets. Specific strains of bacteria form magnetite (Fe_3O_4) or greigite (Fe_3S_4) crystals, or both, in their cells. The membrane-bound, ferrimagnetic nanocrystals (magnetosomes) have species-specific sizes and morphologies and various arrangements, most often 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, including off-axis electron holography, to study the structural, magnetic and chemical properties of magnetic nanocrystals inside magnetotactic bacteria. The samples studied included uncultured magnetotactic cells collected from both marine and freshwater environments, and cultures of the strain *Magnetospirillum gryphiswaldense* and its genetically-modified mutants.

We studied the fine details of magnetic induction maps determined from electron holograms obtained from magnetosomes with a range of sizes and spacings. Based on these results, an experimental "magnetic-state phase diagram" was constructed that highlights the delicate balance between the magnetic state of a crystals, its size, shape and orientation, and the chain configuration, and illustrates graphically whether cells are able to respond effectively to the geomagnetic field. In general, the shape anisotropy of each crystal is the most important factor in controlling the magnetic microstructures of ferrimagnetic crystals in bacteria, followed by interparticle interactions and, least important, magnetocrystalline anisotropy. Despite significant variations in the magnetic properties of magnetosome chains, all of the wild-type cells had permanent magnetic dipole moments that were sufficient for magnetotaxis.

Biogenic magnets exhibit fascinating combinations of magnetic properties and biological functions. However, except for ferrimagnetic particles in magnetotactic bacteria, relatively little is known about them. Further work is needed to understand magnetic sensing in animals and the functions of magnetite particles in humans. A key challenge is the localization and preparation of tissues that contain ferrimagnetic particles. Once such samples are available, advanced analytical techniques, including off-axis electron holography, can be used to provide detailed characterization of the structures, compositions, arrangements and magnetic properties of biogenic nanomagnets.