ELECTRON HOLOGRAPHY OF NANOMAGNETS IN ROCKS AND BACTERIA

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Small particles of magnetite(Fe_3O_4) are the dominant carriers of strong and stable remanent magnetization in rocks. We have used off-axis electron holography in the transmission electron microscope (TEM) to image the magnetic remanent states of a natural, finely-exsolved intergrowth of submicron magnetite blocks in an ulvöspinel (Fe_2TiO_4) matrix. The magnetic microstructure of the sample, measured using electron holography, reveals single-domain and vortex states in individual magnetite-rich blocks, as well as magnetostatic interaction fields between them, at a spatial resolution approaching the nanometer scale. The images reveal an extremely complicated magnetic microstructure, in which both the shapes of the blocks and magnetostatic interactions between them are responsible for the stability of the remanent magnetization. Magnetic superstates, in which clusters of blocks act collectively to form vortex and multi-domain states that have zero net magnetization, are also observed. At remanence, the magnetic microstructure is never saturated in the applied field direction. The magnetic microstructure of a small magnetite-rich region is observed to follow the flux return paths of the larger adjacent blocks. This observation may provide insight into one of the causes of self-reversed thermo-remanent magnetization.

Magnetotactic bacteria provide the simplest example of the use of magnetic iron minerals by an organism for navigation. Each bacterial cell contains one or more chains of ferrimagnetic magnetite or greigite crystals, which are 20-200 nm in size, have well-defined morphologies, and impart a magnetic moment to the cell that results in its alignment parallel to geomagnetic field lines. We have used electron holography to record images of magnetic field lines in bacterial cells at nanometer spatial resolution. Such measurements allow the magnetization, coercivity and magnetic moment of the crystals to be measured directly. Experimentally, magnetite and greigite crystals in bacterial cells are always observed to contain single magnetic domains when they are arranged in chains. The magnetization directions of crystals that would normally be multi-domain or superparamagnetic are then constrained as a result of magnetic interactions with their neighbors. Surprisingly, the magnetization of greigite is found to be more variable between crystals than that of magnetite, perhaps as a result of differences in the iron to sulfur ratio between adjacent crystals in the bacterial cell.