Quantitative Transmission Electron Microscopy of Magnetic Minerals

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Magnetite (Fe_3O_4) is ubiquitous in igneous, metamorphic and sedimentary rocks and can be used as a primary paleomagnetic recorder in rocks on the Earth and on other planets [1]. Magnetite is also found in magnetotactic bacteria and many animals, although its function is often poorly understood [2]. Greigite (Fe_3S_4), which is an isomorphic mineral to magnetite, is less common in nature but is sometimes found in magnetotactic bacteria. It is important to investigate the fundamental magnetic properties of these magnetic minerals. Here, we use transmission electron microscopy (TEM) to study (1) greigite-containing magnetotactic bacteria and (2) titanomagnetite inclusions in a silicate host. We use electron holography, energy-filtered elemental mapping and electron tomography to examine magnetic microstructures, chemical compositions and three-dimensional morphologies.

(1) Rod-shaped greigite-containing magnetotactic bacteria were prepared for TEM examination by air drying and found to contain multiple chains of approximately equidimensional magnetosomes, which had no preferred crystallographic orientations. The chains also contained elongated magnetite crystals, which were interspersed between the greigite crystals and elongated both along [100] and along the axis of the magnetosome chains. The magnetic induction of the crystals measured using electron holography is consistent with that expected for greigite and magnetite (Fig. 1). Although the crystals in such a cell are less well organized in terms of their crystallography, morphology and position than in solely magnetite-producing bacteria, they provide a collective magnetic moment (9 x 10^{-16} Am^2) that is sufficient for magnetotaxis and allows the cell to migrate along geomagnetic field lines at more than 90% of its forward speed. These results provide an improved understanding of magnetotaxis in iron sulfide-producing magnetotactic bacteria.

(2) Needle-shaped titanomagnetite inclusions with stable magnetic remanences, which had formed epitaxially by exsolution from their clinopyroxene host, were studied using electron holography and elemental mapping. The internal microstructure comprised magnetite crystals and ulvöspinel (Fe_2TiO_4) lamellae, which formed as a result of phase unmixing during initial cooling (Fig. 2a). Closely-spaced magnetite crystals were fournd to exhibit strong magnetostatic interactions, occasionally forming magnetic vortices. (Figs 2b and c). These interactions were strong enough to dominate both the shape and the magnetocrystalline anisotropies of individual crystals. The observed collective behavior undoubtedly has an influence on the overall magnetic behavior of the needle-shaped titanomagnetite inclusion, including its stable remanence [3].

References

[1] D.J. Dunlop & Ö. Özdemir, *Rock Magnetism*, Cambridge Univ. Press, 1997.
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[3] We thank R.K.K. Chong, R.B. Frankel, J.M. Feinberg, N.S. Church and R.J. Harrison for discussions and ongoing collaborations.

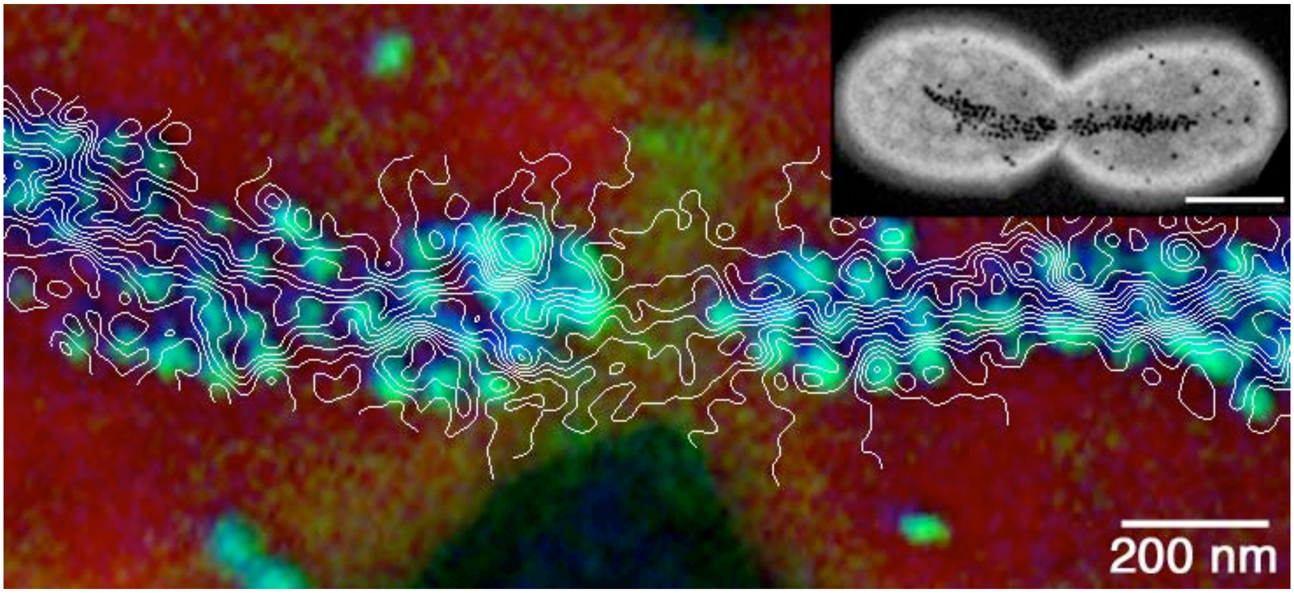

FIG. 1. Magnetic induction map of greigite (Fe_3S_4) and magnetite (Fe_3O_4) crystals in a dividing magnetotactic bacterial cell measured using electron holography, superimposed on an elemental map (red: carbon, green: sulfur, blue: iron). The rounded greigite crystals (light blue) are covered by amorphous iron oxides (darker blue). The phase contour spacing is 0.098 radians. The carbon map of the whole dividing cell is shown in the inset (the scale bar is 1 μm).

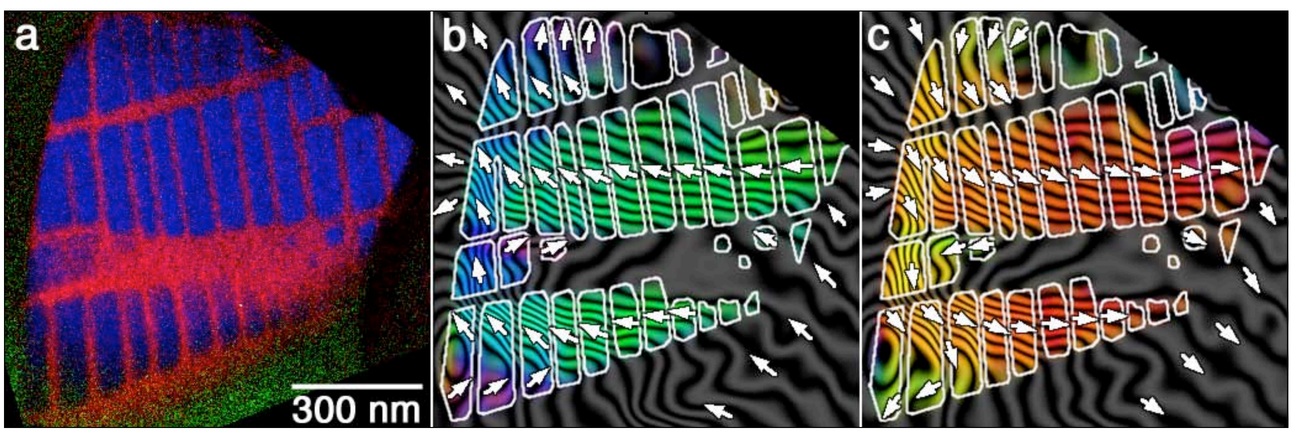

FIG. 2. (a) Energy-filtered elemental map of a titanomagnetite inclusion, acquired using three-window background-subtracted elemental mapping (red: titanium, green: calcium, blue: iron). Magnetite crystals are separated by paramagnetic ulvöspinel in a clinopyroxene host. (b) and (c) Magnetic induction maps recorded in magnetic-field-free conditions using electron holography, acquired after magnetizing the sample in different directions using the magnetic field of the conventional TEM objective lens. The colors represent the direction of the projected magnetic induction, while the arrows show approximate direction of the local magnetic field in each crystal. The phase contour spacing is 0.39 radians.