Lorentz electron microscopy of exsolution lamellae in ilmenite-hematite

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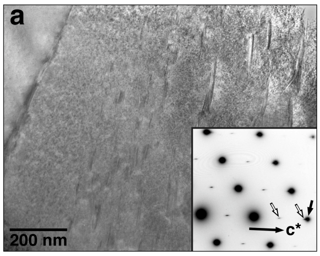
Abstract

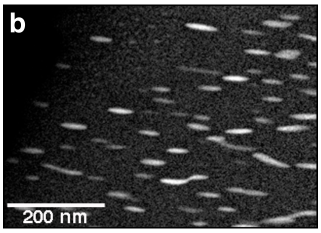
McEnroe et al. (2002) found fine exsolution lamellae of hematite (Fe_2O_3) and ilmenite ($FeTiO_3$) in rock samples with high coercivities and stable natural remanent magnetizations (NRMs). They suggested that the exsolution lamellae may be related to the acquisition of NRM. Robinson et al. (2002) used Monte Carlo simulations to suggest that the ferrimagnetic moment of an intergrowth of hematite and ilmenite could be associated with the arrangement of cations and spins at the interface between hematite and ilmenite. They described this "lamellar magnetism" as being due to "contact layers", which are cation layers at the interface between hematite and ilmenite that do not correspond to the chemistry of either hematite or ilmenite.

Transmission electron microscopy (TEM) is a powerful tool for the examination of the magnetic properties of mineral samples at high spatial resolution, as well as their crystallographic and chemical structures. Lorentz electron microscopy (LEM) allows magnetic microstructure to be observed directly at the nanometer scale. Here, we apply this technique to the examination of the magnetic properties of rock samples that contain fine ilmenite lamellae within hematite hosts. Our preliminary results support the lamellar magnetism hypothesis. Since lower crustal rocks can contain hematite and ilmenite lamellae that exsolved during slow cooling, the formation of lamellae may be a predominant factor responsible for magnetism in the crust.

Microstructure of ilmenite lamellae in hematite hosts

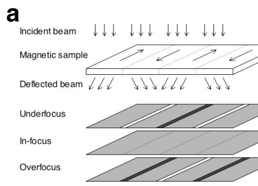


A bright-field (BF) TEM image of typical fine ilmenite lamellae in a hematite host and its electron diffraction pattern are shown in (a). The finer lamellae, which are present between coarser lamellae and are < 50 nm in length, are observed abundantly and are surrounded by strain contrast. The <100> electron diffraction pattern reveals that the ilmenite lamellae and hematite host share (001) planes. The smaller solid arrow in the diffraction pattern shows a reflection due to hematite. The open arrows show reflections due to ilmenite.

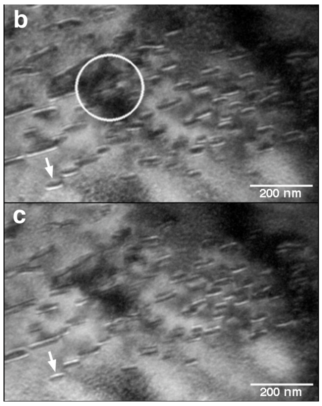


A Ti map of fine ilmenite lamellae (5-10 nm in thickness) within a hematite host was acquired using energy-filtered TEM and is shown in (b). The ilmenite lamellae have lens-like or sometimes kinked shapes and are usually thinner than corresponding hematite lamellae observed in ilmenite. The chemical compositions are $Ilm_{13-19}Hem_{87-81}$ for hematite lamellae and $Ilm_{97-99}Hem_{3-1}$ for ilmenite lamellae, as measured using energy-dispersive X-ray spectrometry (McEnroe et al. 2002).

Lorentz electron microscopy

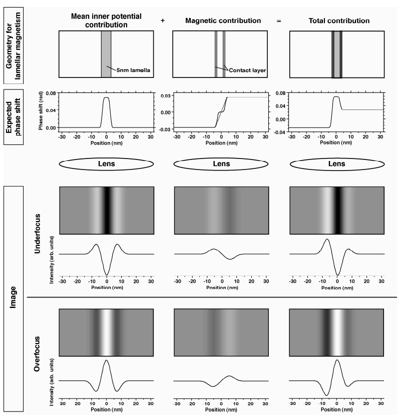


The diagram in (a) outlines the approach used to image magnetic microstructure using Fresnel (defocus) imaging. The Lorentz force associated with the in-plane component of the magnetization in the specimen deflects the incident electron beam. By analyzing the resulting contrast, information about the local directions of the magnetic moments can be obtained.



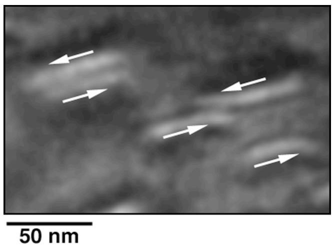
Lorentz images of ilmenite lamellae in hematite, acquired after saturating the sample magnetically in a direction parallel to the a-axes of hematite and ilmenite, are shown in (b) and (c) for overfocus and underfocus imaging conditions, respectively. Asymmetric contrast at the position of each lamella reverses between the images. Since the contrast is parallel to the interfaces of the lamellae, we suggest that it is not associated simply with the canted magnetization of hematite but that it results from the presence of additional magnetic moments at each interface. The images suggest that the net magnetic moment of each lamella orients to its long axis (perpendicular to the c-axis). Diffraction contrast in the region marked by a circle makes the magnetic contrast in this region invisible.

Lorentz image simulation for lamellar magnetism



LEM image simulations that take the presence of lamellar magnetism into account (Robinson et al. 2002) are shown above for a sample of thickness 150 nm and a defocus of 50 μm. Mean inner potential (MIP) simulations correspond to the images that would be recorded from non-magnetic lamellae, while the "total" images incorporate the magnetic moments that are expected to be present in the contact layers between hematite and ilmenite. In the "total" images, the asymmetric contrast associated with the magnetic signal appears clearly, and is consistent with that observed in the experimental LEM images.

The presence of in-phase and out-of-phase lamellae



The LEM image shown on the left, which was acquired at a defocus of -50 μm, suggests that the ilmenite lamellae have two directions of their magnetic moments. While some of the lamellae are magnetized in the direction in which a large (5 T) magnetic field was applied to the sample ("in-phase"), the remainder have moments that point in the opposite direction ("out-of-phase"). The number of lamellae pointing in each direction is summarized in the table.

Table Number of measurements and ratio of in-phase to out-of-phase ilmenite lamellae

	In-phase	Out-of-phase
No. of counts	34	31
Ratio	52%	48%

For ilmenite lamellae in a hematite host, Monte Carlo simulations have been used to predict that the moments associated with lamellar magnetism are related to the physical positions of the lamellae, and that the directions of the resulting moments may be approximately random (Robinson et al. 2002). Our observations are in agreement with this prediction.

Although the difference between the directions of the observed moments is only a few percent, the resulting net magnetization would be 4-8 times larger than that of hematite. The fine lamellae may therefore be responsible for the acquisition of stable magnetization.

References

McEnroe et al. (2002) Geophysical Journal International 151, 890-912.
Robinson et al. (2002) Nature 418, 517-520.

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