American Mineralogist, Volume 89, pages 725–747, 2004

Nature and origin of lamellar magnetism in the hematite-ilmenite series

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ABSTRACT

Grains consisting of finely exsolved members of the hematite-ilmenite solid-solution series, such as are present in some slowly cooled middle Proterozoic igneous and metamorphic rocks, impart unusually strong and stable remanent magnetization. TEM analysis shows multiple generations of ilmenite and hematite exsolution lamellae, with lamellar widths ranging from millimeters to nanometers. Rock-magnetic experiments suggest remanence is thermally locked to the antiferromagnetism of the hematite component of the intergrowths, yet is stronger than can be explained by canted antiferromagnetic (CAF) hematite or coexisting paramagnetic (PM) Fe-Ti-ordered ($R\overline{3}$) ilmenite alone. In alternating field demagnetization to 100 mT, many samples lose little remanence, indicating that the NRM is stable over billions of years. This feature has implications for understanding magnetism of deep rocks on Earth, or on planets like Mars that no longer have a magnetic field.

Atomic-scale simulations of an $R\overline{3}$ ilmenite lamella in a CAF hematite host, based on empirical cation-cation and spin-spin pair interaction parameters, show that contacts of the lamella are occupied by "contact layers" with a hybrid composition of Fe ions intermediate between Fe^{2+}-rich layers in ilmenite and Fe^{3+}-rich layers in hematite. Structural configurations dictate that each lamella has two contact layers magnetically in phase with each other, and out of phase with the magnetic moment of an odd non-self-canceling Fe^{3+}-rich layer in the hematite host. The two contact layers and the odd hematite layer form a magnetic substructure with opposite but unequal magnetic moments: a lamellar "ferrimagnetism" made possible by the exsolution. Because it is confined to magnetic interaction involving the moments of just three ionic layers associated with each individual exsolution lamella, lamellar magnetism is unique and quite distinct from conventional ferrimagnetism.

Simulation cells indicate that the magnetic moments of contact layers are locked to the magnetic moments of adjacent AF hematite layers and are parallel to the basal plane (001). Thus, lamellar magnetism is created at the temperature of chemical exsolution, and is a chemical remanent, rather than thermal remanent, magnetization. However, in thermal demagnetization experiments, too short for lamellar resorption, demagnetization temperatures are those of the CAF hematite, considerably higher than temperatures of original lamellae formation.

Internal crystal structure cannot dictate that the contact layers of different lamellae will form magnetically in phase with each other to give the highest net magnetic moment, but magnetic moments of lamellae can be made to form in phase by the external force of the magnetizing field at the time of exsolution. A thesis of this paper is that an external magnetic field can dictate the magnetic moments and hence the chemical location of ilmenite lamellae in a hematite host, and that once in place, neither the location nor the magnetic moment will be easily disturbed. In an ilmenite host, the external magnetic field cannot control the chemical location of a hematite lamella, which is dictated by the enclosing ilmenite, but once lamellae have formed, the field can dictate their magnetic moments. These moments, however, are not locked chemically to the host, resulting in lower coercivity. The effectiveness of the external force in single crystals is dictated by their orientation with respect to the magnetizing field. In grains with (001) oriented parallel to the field, it would be effective in producing in-phase magnetic moments and very strong remanence. In grains with (001) normal to the field, the field would be less effective in producing in-phase magnetic moments, hence producing weak remanence.

The most intense lamellar magnetism per formula unit occurs with in-phase magnetization, high lamellar yields, and the largest number of lamellae per unit volume (i.e., smallest lamellar size). Compared to the magnetic moment per formula unit (M_{pfu}) and magnetic moment per unit volume (M_V) of end-member magnetite ($M_{pfu} = 4\ \mu_B$, M_V = 480 kA/m) and hematite ($M_{pfu} = 0.0115\ \mu_B$, M_V = 2.1 kA/m), results for some atomic models reasonably tied to natural conditions are $M_{pfu} = 0.46$–$1.36\ \mu_B$ and M_V = 84–250 kA/m.