The effects of nanometer-scale mineral structures on the magnetic remanence of silicate-hosted titanomagnetite inclusions: an electron holography study

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To successfully unravel the behavior of the Earth's ancient magnetic field, it is important to identify and characterize the minerals that record it. Titanomagnetite inclusions in pyroxene and plagioclase are carriers of stable magnetic remanence in some slowly-cooled rocks such as gabbros, anorthosites, granulites, and diorites, and can be excellent recorders of Precambian paleomagnetic information. Needle-shaped inclusions with average dimensions of 1 x 1 x >25 μm form epitaxially by exsolution from their host silicate. Close examination of clinopyroxene-hosted inclusions reveals an internal microstructure, which consists of magnetite (Fe_3O_4) prisms and ulvöspinel (Fe_2TiO_4) lamellae that formed as a result of phase unmixing during initial cooling. This internal structure exerts a profound influence on the magnetic remanence properties of each inclusion, primarily by transforming it from a multi-domain grain into an assemblage of magnetostatically interacting single-domain prisms. Here, we use off-axis electron holography to image the magnetization states of individual prisms and the magnetostatic interactions

between them. We show that the inclusions exhibit both single-domain and collective magnetic states that depend sensitively on a combination of: the magnetocrystalline anisotropy of the magnetite lattice, the shape anisotropy of individual magnetite prisms, magnetostatic interactions between closely-spaced prism stacks, and the shape anisotropy of the needle itself. Prisms that are separated by thick ulvöspinel lamellae show uniformly-magnetized and/or vortex states. In contrast, closely-spaced magnetite prisms behave as multi-part vortices or as long composite columns, whose strong net magnetization may not be related directly to the orientation and shape of either the needle or the constituent prisms. The overall remanence direction recorded by clinopyroxene crystals containing finely-exsolved inclusions is a reflection of both the inclusions' elongation directions and the prism arrangements within them.