Direct visualization of CRM and TRM of pseudo-single-domain magnetite particles

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In order to reliably interpret palaeomagnetic measurements, the mechanisms of chemical remanent magnetization (CRM) and thermoremanent magnetization (TRM) must be fully understood. Currently, most models of CRM and TRM processes only exist for the smallest, uniformly magnetized grains, termed single domain (SD). However, the magnetic signal from rocks is often dominated by slightly larger grains containing non-uniform magnetization states, termed pseudo-SD (PSD) grains.

Magnetite (Fe3O4) is the most magnetic naturally occurring mineral on Earth, carrying the dominant magnetic signature in rocks and providing a critical tool in palaeomagnetism. The oxidation of Fe3O4 to other iron oxides, such as maghemite (γ-Fe2O3) and hematite (α-Fe2O3), is of particular interest as it influences the preservation of remanence of the Earth's magnetic field by Fe3O4. Further, TRM in Fe3O4 grains is acquired in the direction of the ambient geomagnetic field as they cool below their Curie temperature (TC) of ~ 580 ˚C. The latest transmission electron microscopy (TEM) techniques like electron holography and environmental TEM (ETEM) allows for the imaging of magnetization in nano-scale minerals during in situ heating under vacuum and controlled atmospheres.

In the present study, synthetic Fe3O4 particles in the PSD size range (< 200 nm) were heated in situ in an ETEM under an O2 atmosphere. Close examination of Fe3O4 particles after in situ heating revealed surface degradation, whilst electron energy-loss spectroscopy confirmed their oxidation. The effect of CRM was visualized using electron holography, in the form of reconstructed magnetic induction maps, where the oxidized grains exhibited a loss of overall remanence and change in remanent direction.

The thermomagnetic behaviour of Fe3O4 particles in the PSD size range is also investigated using off-axis electron holography. Magnetic induction maps, which are recorded during in situ heating up to above the TC, reveal the PSD nature of several Fe3O4 grains by visualizing their vortex domain states. The vortex states in small Fe3O4 grains are shown to rotate close to its unblocking temperature, rather than remaining thermally stable as seen in the vortex states of larger Fe3O4 grains.