Micromagnetics and hysteresis in rock magnetism

Karl Fabian[1]

[1] *Norwegian University of Science and Technology (NTNU), S. P. Andersens veg 15a, 7031 Trondheim, Norway*

Rock magnetism historically is the origin of western magnetic research, starting with the Epistola de magnete (1269) of Petrus Peregrinus and the first modern scientific treatise 'De Magnete, Magneticisque Corporibus, et de Magno Magnete Tellure' (1600) by William Gilbert. But also modern magnetic research is closely linked to rock magnetic questions. Néel developed his single domain theory in 'Théorie du traînage magnétique des ferromagnétiques en grains fins avec applications aux terres cuites' [1] and wrote an influential article on 'Some theoretical aspects of rock magnetism'[2]. Soon after Meiklejohn and Bean discovered exchange anisotropy in Co-CoO at 77 K[3], Meiklejohn and Carter reported exchange bias at room temperature in a natural dacite containing an Ilm60 ilmeno-hematite solid solution [4]. Nanoscale ilmenite lamellae coherently grown during slow cooling over millions of years within a hematite host mineral in a billion year old metamorphic rock even leads to a 1.3 T exchange bias due to natural interface exchange coupling[5].

Because rock magnetic interpretation initially was solely based on Néel's single-domain (SD) theory, but natural magnetic mineral grain size distributions usually peak well above the SD size region, the physics and micromagnetics of more complex magnetization structures became a key challenge in rock magnetism. The first three-dimensional micromagnetic models were published only months apart by Schabes and Bertram (1988) working on magnetic recording materials up to 55 nm in diameter and the geophysicists Williams and Dunlop (1989) aiming at 500 nm particle structures.

Currently, micromagnetic models are pushed forward to develop more realistic theories of rock magnetic measurements. For example, the study of thermoremanent magnetization in rocks requires to calculate large numbers of energy barriers in complex magnetite particles. As natural particle shapes can be experimentally recovered by focused-ion-beam (FIB) nanotomography, it now becomes realistic to compare bulk magnetic properties to averages over micromagnetic models [6, 7]. Such calculations are available to non-specialist geophysicists via the open-source micromagnetic modeling tool MERRILL[8] (https://blogs.ed.ac.uk/rockmag/), which uses an adapted nudged-elastic-band method for efficient energy barrier calculation [9].

Another challenge for micromagnetism is the interpretation of hysteresis measurements, which in rock magnetism are commonly influenced by high demagnetizing energies as well as by internal stress fields. To separate both contributions we recently developed a measurement procedure based on temperature dependent approach-to-saturation curves [10]. Here, micromagnetic modeling helps to interpret the transition from structurally related magnetization work in stressed particles towards uniform rotation away from anisotropy minima.

Another promising method for rock and paleomagnetism is to combine quantum-diamond magnetometers with X-ray nanotomography to reconstruct average magnetizations of partial natural magnetic grain ensembles with optimal recording properties [11]. This approach can also be used to reconstruct individual particle magnetic multipole expansions, and to exploit this information by micromagnetic modeling to narrow down or even identify possible internal magnetization structures [12].

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