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Micromagnetic Tomography: toward a useful tool for paleomagnetic and rock-magnetic studies

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Introduction

Micromagnetic Tomography (MMT) allows to reconstruct magnetic moments of individual grains embedded in a sample. It relies on combining a magnetic surface scan with a spatial characterization of the iron-oxide grains from a MicroCT scan (Fig. 1). The spatial information on the magnetic sources helps to constrain the mathematical inversion and to overcome the traditional non-uniqueness of potential field inversion problems.

Since its proof-of-concept in 2018 MMT has seen rapid development. In 2018, we were able to determine the magnetic signals of a few individual grains in a synthetic sample. Over the past years, there has been considerable progress. First, we are now able to describe complex magnetic signals of grains in spherical harmonics. Second, improvements in computational routines increased the speed of the inversion, so we can now invert for thousands of grains at once. Third, improvements in the QDM set-up and resolution of microCT machines now enable us to detect much smaller grains, which further improves the accuracy of MMT results.

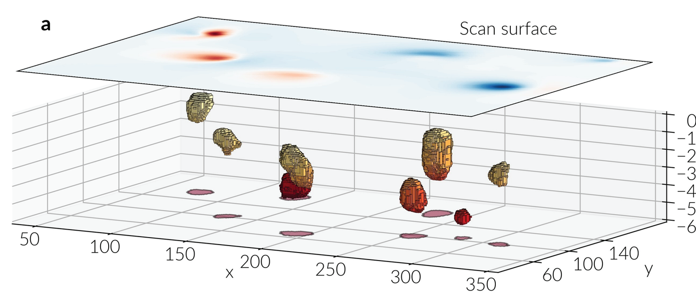


Fig. 1: Concept of MMT

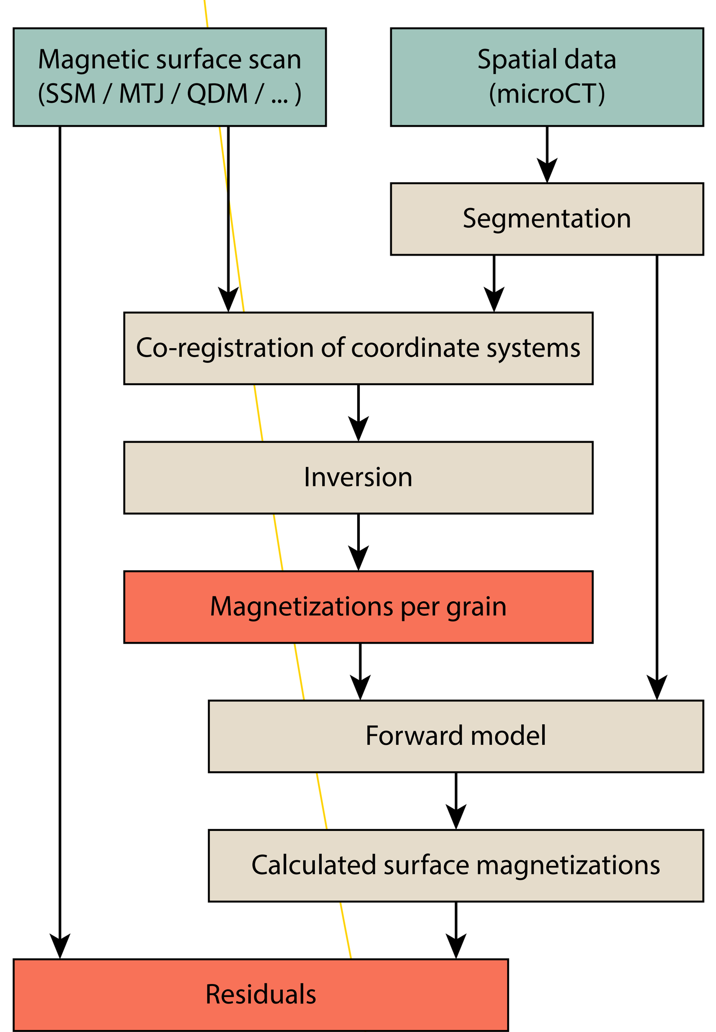


Fig. 2: Workflow of Micromagnetic Tomography experiments. The input (measurements) is in the green boxes; computational steps are in the tan boxes and the output is in the red boxes.

Methods

MMT combines two datasets obtained from each sample or region of interest: a magnetic surface scan and a spatial characterization of the iron-oxide grains obtained from a microCT scan (Fig. 2). These datasets have to be co-registered in the same coordinate system, before a mathematical inversion produces the magnetic moments of the individual grains in the system.

The accuracy of the inversion is assessed by considering the residuals of the inversion. First, all grains in the system are assigned their calculated magnetic moments. Then these are used to calculate the surface magnetizations in a forward model. The residual is the difference between the measured surface magnetizations and the calculated magnetizations, i.e. the residual magnetization that is unexplained by the results of the MMT inversion.

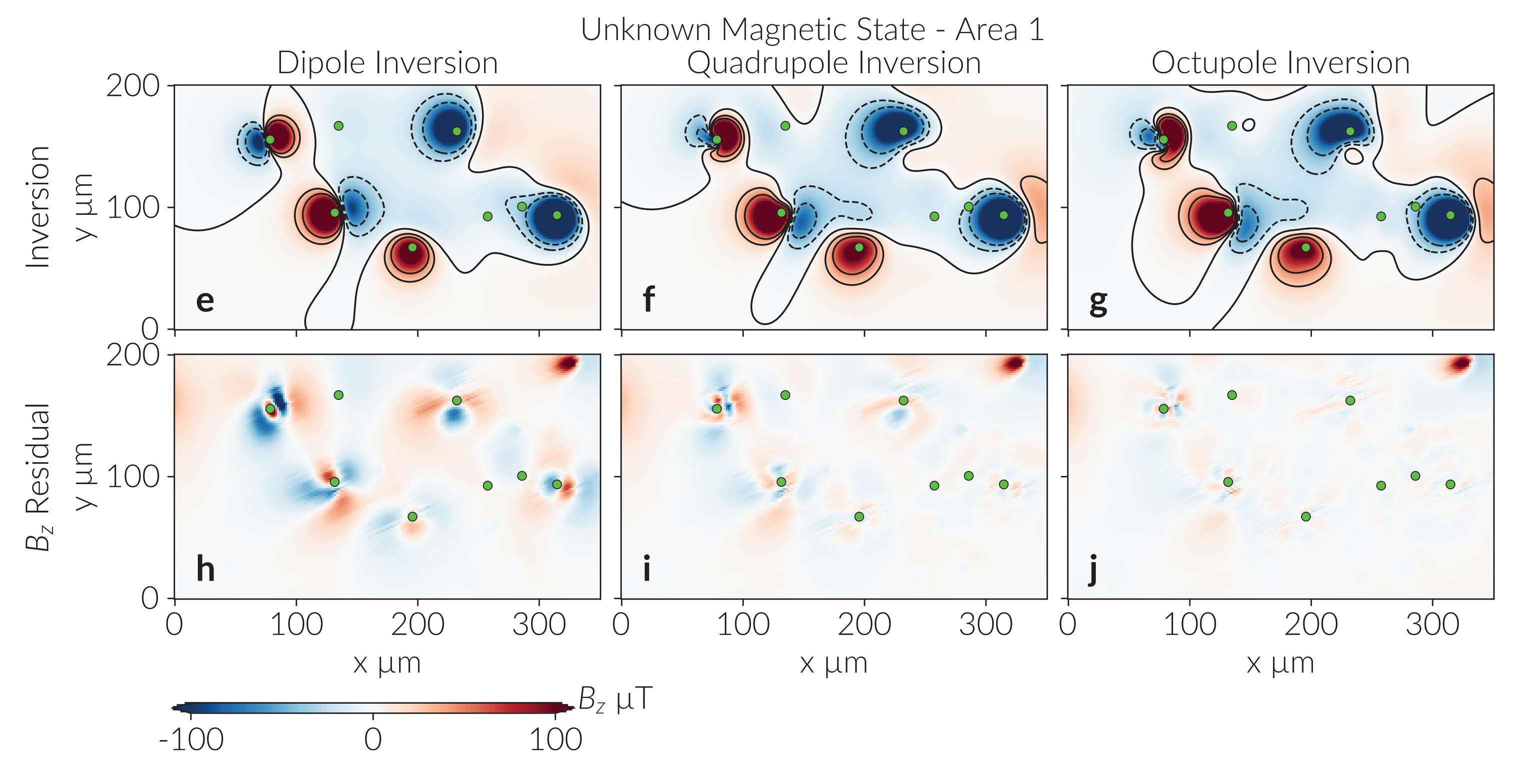
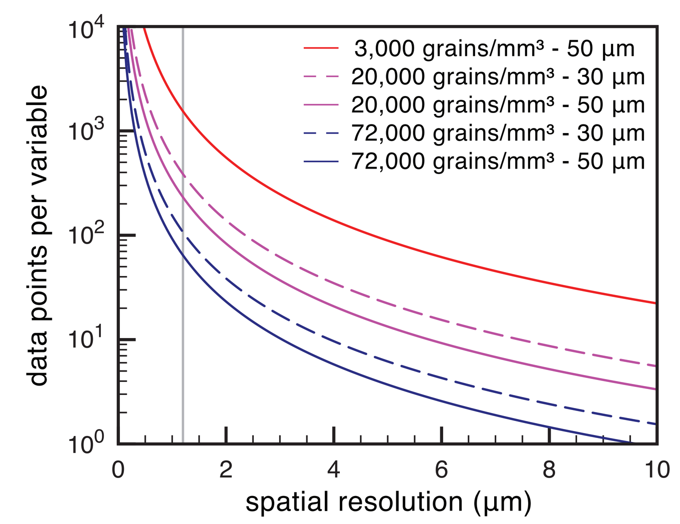


Fig. 3: MMT results using spherical harmonics with increasingly higher order multipole expansions: up to dipole (left), quadrupole (center), and octupole (right) order (e-g). Contour lines range from −50 µT up to 50 µT in steps of 25 µT. The residuals after removing the inverted magnetic fields from the measured data are in the bottom row (h-j). The particle centers are indicated by green circles.

Solving complex magnetic signals

Many grains in natural samples have grain sizes well above the range of single domain behavior. The magnetic moments of these grains can therefore not be properly described by a single dipole. Our inversion is now also capable of describing magnetic moments in terms of spherical harmonic expansions that are centered at the mid-points of the iron-oxide grains detected by the microCT (Fig. 3). Solving the magnetic moments of individual grains using also quadrupoles and octupoles reduces the residuals almost to zero, and hence provides a better description of the magnetic moments. It is important to keep in mind, however, that the MMT inversion performs best if the system is vastly overdetermined, i.e. when there are many more data points in the magnetic surface scan than variables to solve for (Fig. 4) in the system. Including higher order multipoles reduces this amount of data points per variable, as only 3 variables are solved for per grain for a dipole solution, 8 for a quadrupole solution, and 15 for an octupole solution.

Fig. 4: The theoretically available number of data points per variable that is to be solved by the MMT inversion is governed by the concentration of grains in the sample, the thickness of the sample, and the spatial resolution (i.e., step size) of the magnetic scan. The theoretically available number of data points per variable are given for the synthetic sample (3,000 grains/mm³, 50 µm thick, red line), and different grain concentrations and sample thicknesses for volcanic samples. The typical spatial resolution of the Quantum Diamond Microscope (1.2 µm) is indicated by the gray line. The number of data points are given for fitting dipoles for which 3 variables must be determined per grain.



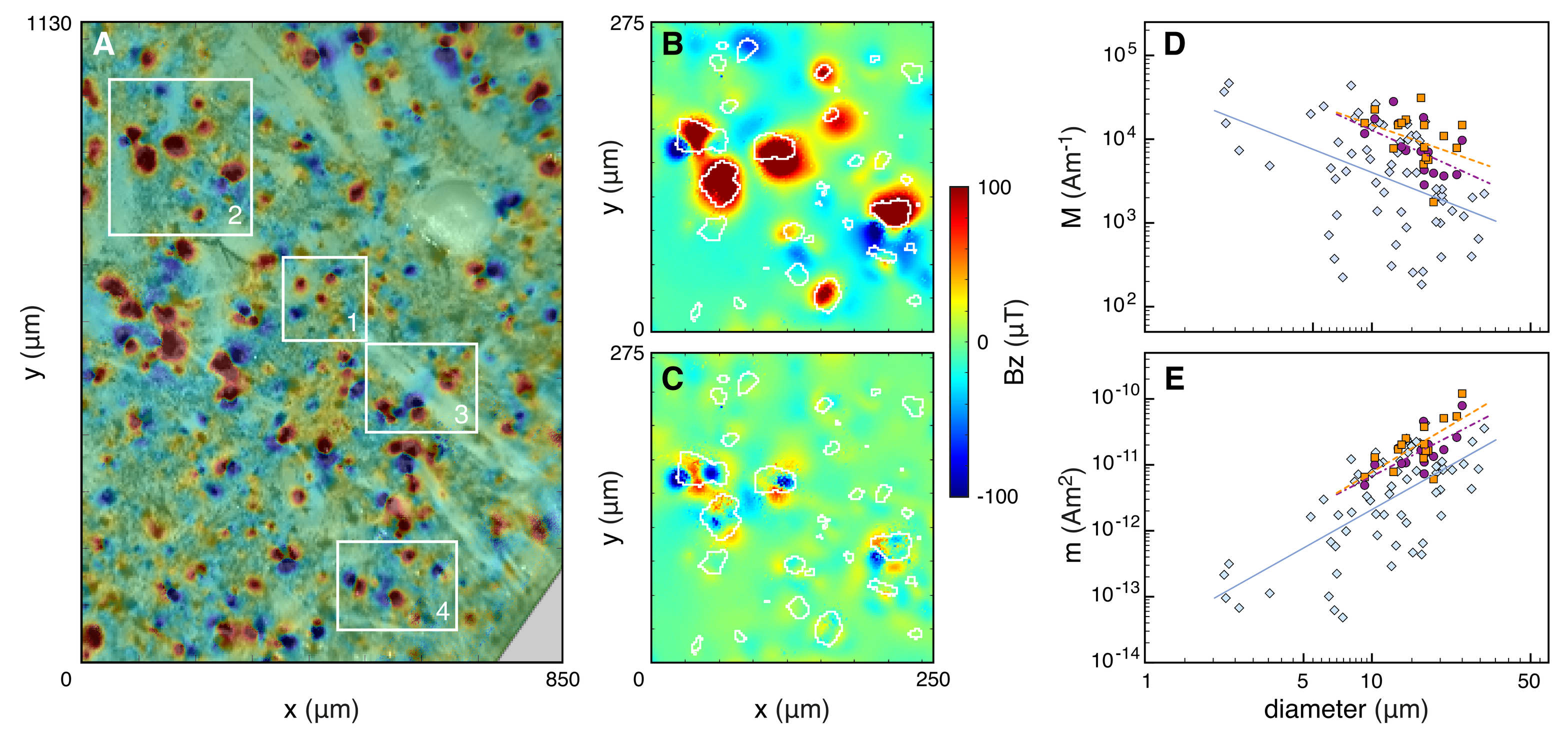
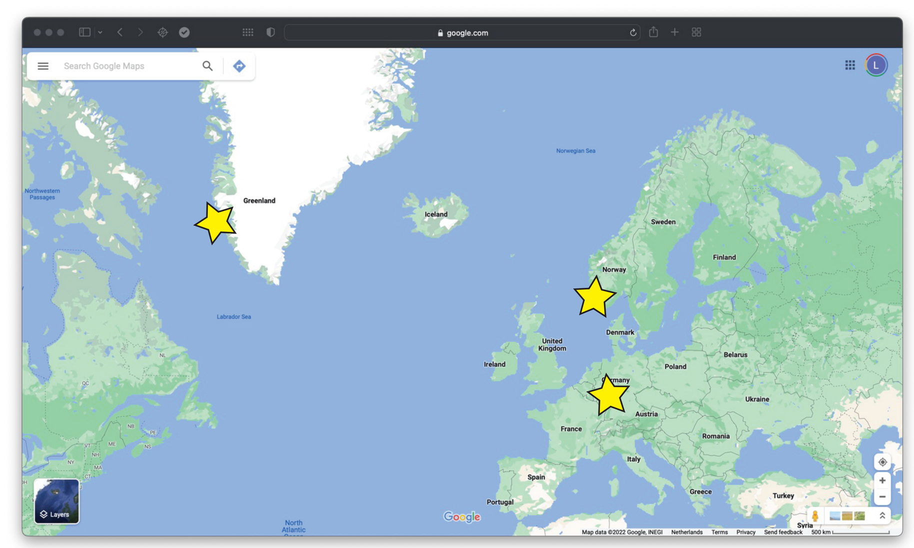


Fig. 5: Results of Quantum Diamond Microscope (QDM) experiments on a volcanic sample from Hawai'i. The optical microscopy image is in the background in gray-scale (a), the map of the magnetic flux density perpendicular to the surface (in color) is super-positioned with 50% transparency. The QDM data of area 2 (a) is in b, with the outlines of the iron-oxide grains as identified by microCT in white. The residual after the inversion to produce the individual magnetic moments per grain (c) are generally low and non-uniform, indicating a proper inversion result. The magnetizations (d) and magnetic moments (e) of grains with Mr/Ms ratios <0.10 are plotted as function of their diameter as blue diamonds, with their linear trend line in blue. The results of de Groot et al. (2018) are also included for comparison: the magnetizations arising from a "natural magnetic state" in purple circles/dashed trend line, and the magnetizations after applying an anhysteretic remanent magnetization with a bias field of 40 µT in orange squares/dashed trend line.

Conclusion and outlook



Here we showed that MMT is now capable of describing complex magnetic signals of larger iron-oxide grains embedded in natural, volcanic, material. Optimizations in the inversion code and computational routines allow to determine the signals of several thousands of grains at once. This implies that MMT is ready to start answering geological questions that previously could not be answered. We are currently working on magnetically complex samples from the Archean (Isua, collaboration with Claire Nichols, University of Oxford), Ediacaran (Norway, collaboration with Mat Domeier, University of Oslo), and Devonian (Germany, collaboration with Annique van der Boon, University of Oslo). These samples have in common that they yield ambiguous results in traditional paleomagnetic measurements, but seem to produce interpretable results when magnetic moments of individual grains are considered using MMT.

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