

## SCANNING MAGNETIC MICROSCOPES FOR ANALYZING GEOLOGICAL SAMPLES

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### ABSTRACT

We have developed two scanning magnetic microscopes for separately mapping remanence and magnetic response to an applied field in rock thin sections at high spatial resolution. The first instrument utilizes a magnetic tunnel junction (MTJ) sensor to detect the normal component of the remanent magnetic field of a sample at close proximity in an environment free of background fields. Spatial resolutions better than 7  $\mu\text{m}$  were typically achieved for a magnetic field sensitivity of about 150 nT/Hz<sup>1/2</sup>. The second instrument is based on a Hall-effect sensor, which remains operational in the presence of a background field. By applying a known magnetic field and detecting the sample's response, we can measure magnetic properties such as hysteresis curves and susceptibility. Our current prototype can apply magnetic fields up to 450 mT, and attains spatial resolution of 200  $\mu\text{m}$  and magnetic sensitivity of 350 nT/Hz<sup>1/2</sup>. We performed combined tests using both instruments on a 30 micrometer thin section of granulite-gneiss from the Vredefort impact crater in South Africa.

**Keywords:** instrumentation, scanning magnetic microscopy, magnetic susceptometry,

### RESUMO

Dois microscópios magnéticos de varredura de alta resolução vêm sendo desenvolvidos para mapear, independentemente, remanência e resposta a campos aplicados em seções delgadas de rochas. O primeiro instrumento utiliza um dispositivo junção de túnel magnético (MTJ) para detectar, próximo à superfície, a componente normal do campo magnético remanente de uma amostra em um ambiente sem campos externos. Resoluções espaciais superiores a 7  $\mu\text{m}$  têm sido obtidas regularmente, sendo a sensibilidade a campos magnéticos deste instrumento aproximadamente 150 nT/Hz<sup>1/2</sup>. O segundo microscópio baseia-se em um dispositivo de efeito Hall, o qual permanece operacional mesmo na presença de campos externos. Ao aplicar-se um campo conhecido e detectar-se a resposta da amostra a este campo, é possível medir propriedades magnéticas como curvas de histerese e suscetibilidade. O protótipo atual pode aplicar campos magnéticos de até 450 mT, dispondo de uma resolução espacial de 200  $\mu\text{m}$  e sensibilidade de 350 nT/Hz<sup>1/2</sup>. Testes combinados foram realizados com os dois microscópios magnéticos de varredura em uma lâmina delgada de granulito-gnaiss proveniente da cratera de impacto Vredefort na África do Sul.

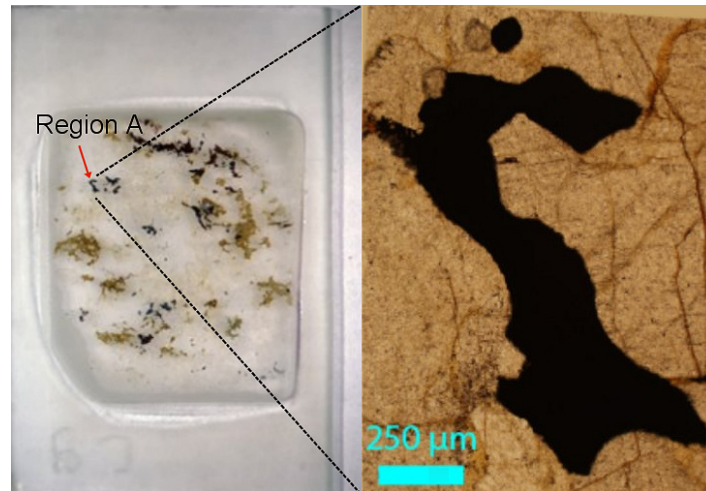
**Palavras Chave:** instrumentação, microscopia magnética, susceptometria magnética.

### Introduction

To access the spatial distribution of magnetization and magnetic properties in rock thin sections at room temperature, we have developed two scanning magnetic microscopes using non-cryogenic sensor technology. These instruments are intended to complement the capabilities of well-established scanning SQUID microscopes by providing higher spatial resolution for measurements of remanent magnetic fields and the ability to detect the sample's response to applied magnetic fields for characterizing its magnetic properties. Combined tests using both instruments were carried out on a 30- $\mu\text{m}$  thin section of a granulite-gneiss from the Vredefort impact crater in South Africa (Carporzen *et al.*, 2005) (Fig. 1). In particular, we



analyzed a specific section of the sample denoted as “Region A”. The dark regions contain ferromagnetic minerals that carry remanence (mainly magnetite), and are surrounded by nonmagnetic plagioclase feldspar and quartz.

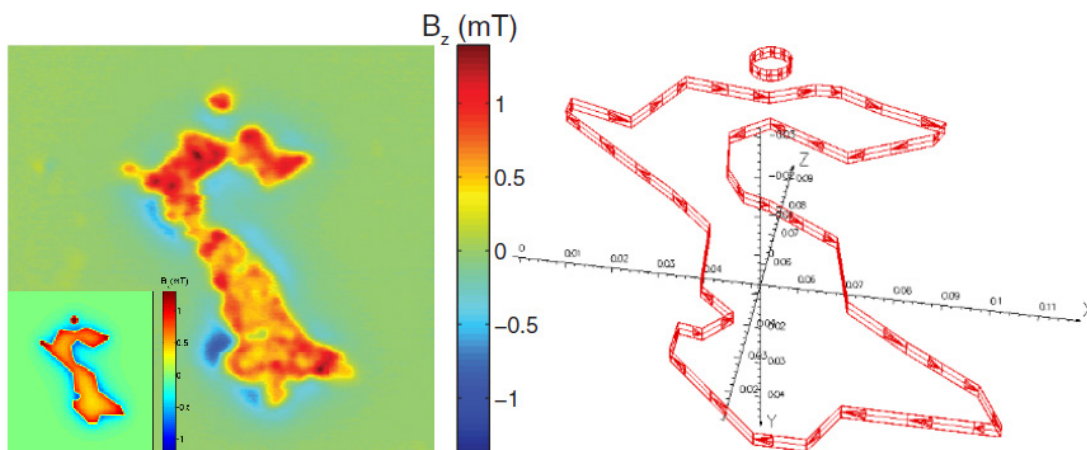


**Figure 1.** 30- $\mu\text{m}$  thin section of a granulite-gneiss extracted from the Vredefort crater in South Africa (left). We focused our analysis on a small region of interest denoted “Region A,” which is shown in detail (right).

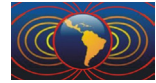
### Methods and Results

The magnetic microscope for measuring remanent magnetic fields is based on a commercial MTJ sensor and achieves spatial resolution better than  $7\ \mu\text{m}$  (Lima *et al.*, 2014). The sensor works as part of a Wheatstone bridge with modulated current injection. The signal detection and conditioning were performed by a custom-made low-noise preamplifier and a commercial lock-in amplifier. The magnetic field sensitivities obtained were better than  $150\ \text{nT}/\text{Hz}^{1/2}$ , which corresponds to a magnetic moment sensitivity on the order of  $10^{-14}\ \text{Am}^2$  for sources that are dipolar at this spatial scale.

Our first test consisted of measuring the out-of-plane component of the remanent magnetic field generated by Region A, after we imparted a strong-field isothermal remanent magnetization (IRM) by applying a  $0.4\ \text{T}$  field perpendicular to the thin section (Fig. 2a). In order to estimate the magnetization distribution in

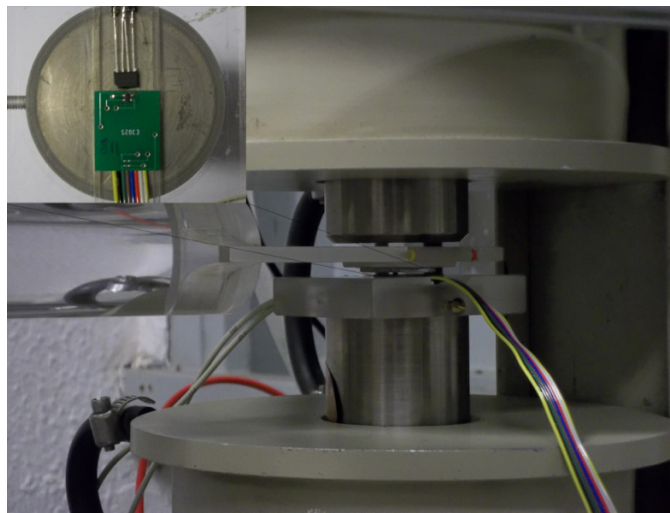


**Figure 2.** (a) MTJ microscope magnetic field map of the region of interest in the Vredefort sample (Region A – Fig. 1) after imparting a  $0.4\ \text{T}$  IRM. Inset shows the synthetic field map obtained by a current loop model fitting the experimental data. (b) Geometry of the finite-element mesh used to model the magnetization in the sample as equivalent current paths.



this region and its associated magnetic moment we modeled the magnetic features by equivalent current paths with  $30 \mu\text{m} \times 1 \mu\text{m}$  cross section area using a multiphysics finite element software (Fig. 2b). The corresponding magnetic field map generated by the model assuming uniform magnetization and fitting the experimental data strength is shown in the inset of Fig. 2a. This synthetic map agrees quite well with the MTJ microscope data and reproduces several features observed in the latter. Based on this model, we estimated a net magnetic moment for Region A of  $6.2 \times 10^{-8} \text{Am}^2$ .

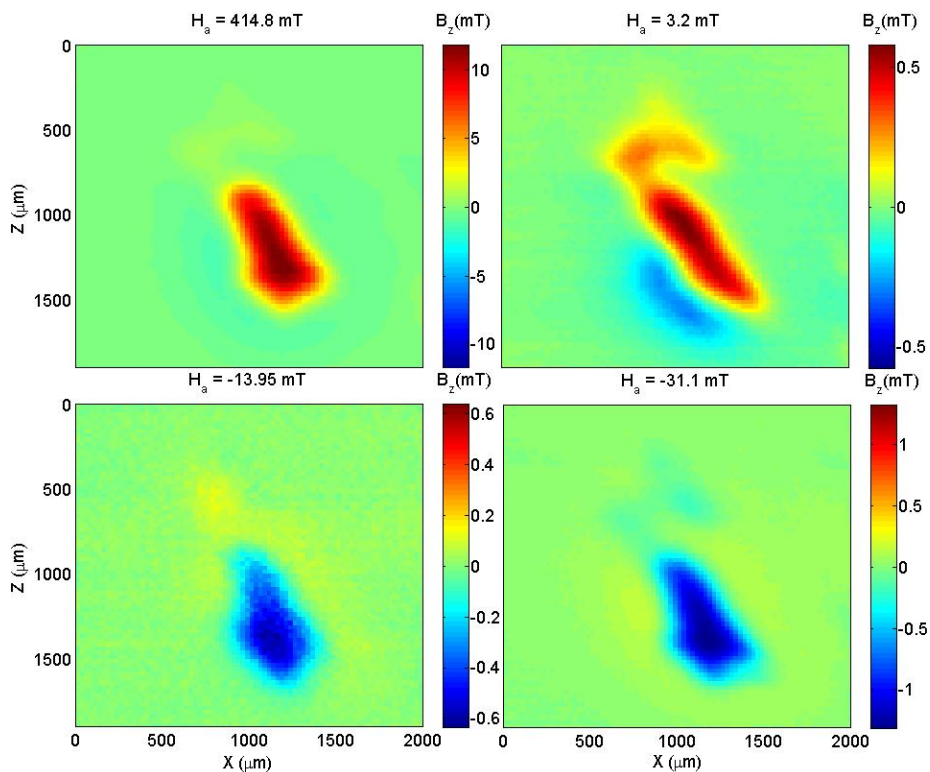
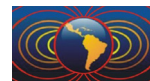
Next, we measured the Vredefort sample using the scanning Hall microscope with applied magnetic fields of different strengths. In this instrument, an acrylic tray carries the thin section and displaces it horizontally in the region between the 40 mm diameter poles of an electromagnet (Fig. 3). We used a first-order gradiometric sensor configuration comprised of two Hall sensors located at opposite sides of a printed circuit board (PCB; see inset in Fig. 3) to measure the sample's response, and a third Hall sensor mounted outside the PCB for monitoring the applied field. The bias in the gradiometer is also modulated to improve signal-to-noise ratio, and the signal of interest is detected using a lock-in amplifier. Whereas both the spatial resolution and the magnetic field sensitivity ( $200 \mu\text{m}$  and  $350 \text{nT/Hz}^{1/2}$ , respectively) are not as high as those of the MTJ microscope, this configuration allows us to apply magnetic fields of up to 0.45 T perpendicular to the sample.



**Figure 3.** Photograph of the measurement region in the scanning Hall microscope. Inset shows detailed view of the printed circuit board where two Hall sensors are mounted in gradiometric configuration and of the third Hall sensor that measures the magnetic field applied to the sample.

Four scans of the out-of-plane field generated by Region A for different applied fields (415 mT, 3.2 mT, -14 mT and -31 mT) are shown in Figure 4. It can be observed that the magnetic responses of the upper and lower portions of Region A depending on the applied field are rather distinct. This contrast between the two portions is barely noticeable in the IRM field map obtained with the MTJ microscope, in which a marginally stronger magnetization of the upper portion can be observed. This suggests that the upper portion contains magnetic minerals with higher remanence than the lower portion. However, the lower portion exhibits a much higher saturation magnetization compared to the upper portion, as seen in Figure 4.

Our combined tests demonstrate the complementary nature of these instruments and the invaluable information that can be obtained by conducting rock magnetic analysis at submillimeter scales. Our goal is to ultimately integrate the two instruments and expand the current capabilities to allow for anisotropy studies.



**Figure 4.** Hall microscope magnetic field maps of the region of interest in the Vredefort thin section for different applied magnetic fields.

### References

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