Magnetic field visualization of magnetic minerals and grain boundary regions using magneto-optical imaging

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[1] Magneto-optical imaging based on the Faraday effect has been used to characterize magnetic minerals embedded in a nonmagnetic matrix. We have studied magnetite grains and magnetite-magnetite grain boundary regions in samples of skarns and serpentinites. Distributions of the remanent magnetic field were measured across at the surface of polished thin sections kept at room temperature. The magneto-optical images resolve directly magnetic structures on length scales ranging from millimeter down to micrometer, thereby revealing the shape and arrangement of the magnetite grains and allow determination of the grain magnetization. We find that (1) for the skarns the intergrain interactions do not affect the magnetic properties of magnetite grains within 0.6–60 μm of each other, while the saturation remanence decreases weakly with increasing grain size from 40 μm to 0.6 mm, and (2) for the serpentinites the magnetic properties of the stripes are size-dependent due to variations in chemical composition.


1. Introduction

[2] Magnetic minerals are common in most rock types and their associated magnetizations represent the basis for paleomagnetic reconstructions, and thus serve as a key source of information for plate tectonic studies. Rock magnetic properties also provide valuable insight into the thermal history of a variety of geological systems [Dunlop and Özdemir, 1997]. It is therefore of great interest to study processes affecting rock magnetic properties, such as diagenetic and metamorphic reactions and thermal resetting. This interest stimulates development of techniques for spatial imaging of a rock’s magnetic properties at various scales. Although several methods, such as Bitter pattern imaging, magnetic force microscopy and electron holography allow a direct imaging of magnetic domains at the micrometer [Dunlop and Özdemir, 1997] and nanometer scales [Harrison et al., 2002; Dunin-Borkowski et al., 2002; Feinberg et al., 2005], a fast way to quantitatively characterize the magnetic properties of minerals on length scales from millimeter to submicrometer is still lacking.

[3] Significant recent advances in magneto-optical imaging (MOI) based on the Faraday effect in ferrite garnet films (FGF), have made it possible to directly visualize static and dynamic magnetic behavior over a wide range of length scales and temperatures. So far, the technique has been applied with greatest success in studies of superconducting materials, see Jooss et al. [2002] for a review. The main advantages of MOI in the context of rock magnetism are that (1) MOI is a very simple technique, requiring only a polarization microscope and a magneto-optical sensor film, (2) the imaging requires only a standard polished thin section sample, (3) the sample size can range from centimeters to fractions of a millimeter, (4) one can observe magnetic structures on scales from the sample size and down to submicrons, and it is very easy to switch between resolutions by changing objective lens in the microscope, (5) MOI can be performed with sample temperatures from below 4 K to above room temperature, (6) MOI is a quantitative technique since the gray level on the images can be directly mapped to the local value of magnetic field, and (7) MOI is a fast technique that allows one to follow dynamics of magnetic field distribution in real time (from hours to nanoseconds), e.g., under varying magnetic field or temperature.

[4] These advantages should allow MOI to fill an important niche among other magnetic imaging methods used for rock studies. In particular, electron holography may have a better spatial resolution, but does not cover a wide range of length scales, require much more sophisticated equipment, and ultra thin samples. The scanning probe techniques, magnetic force microscopy and scanning SQUID and Hall probe magnetometry are all slow, and hence far less efficient, e.g., when a series of images under different external conditions are recorded. Bitter pattern imaging and the Prussian blue method may be used for approxi-
In this paper we describe the application of MOI to magnetic mapping of rock samples: magnetite-bearing skarn samples from the Oslo region and serpentinized ultramafic rocks from the Solund Devonian Conglomerate, western Norway. The spatial distributions of local magnetic fields generated in response to an applied magnetic field were measured on thin sections. The measured distributions allow us to identify magnetite grains and the complex arrangement of magnetic domains within them. In the first part, we describe how MOI can easily be applied to thin sections and analyze the magnetic field distributions produced by magnetite grains and gaps between such grains. In the second, we discuss how to determine the true magnetic properties of the magnetite particles that are masked by their surroundings. The examples serve to illustrate the important role that MOI can play for future work on rock magnetism.

2. Samples

Magnetite-bearing skarn samples from the Oslo region and serpentinized ultramafic rocks from the Solund Devonian Clast were selected for MOI investigation. The thin sections were prepared by standard polishing techniques used for optical microscopy, and slurry was avoided during preparation. They had mirror-like surface quality. It was checked by reflecting light, Newton ring analysis and SEM.

3. Experimental Procedures

In a conventional MOI setup a 1–5 µm thick ferrite garnet film (FGF) is used as a Faraday active indicator [Indenbom et al., 1990]. We used a Bi-substituted yttrium iron garnet film with in-plane magnetization [Johansen et al., 1996] deposited on an optically transparent gadolinium gallium garnet substrate using liquid phase epitaxy growth. Details about how this FGF responds to magnetic fields, i.e., serves as a local field sensor via the Faraday effect, is found in the Appendix A. The FGF is covered with a thin reflecting layer of Al resulting in a Faraday rotation of incident light. As shown in Figure 3, the film is placed with the mirror side down on the flat sample and mounted in an incident light polarization microscope. Light of 546 nm wavelength comes from a 100 W Hg lamp, and with a crossed polarizer/analyzer setting the contrast in the transmitted light intensity becomes a direct map of the magnetic field in the plane of the FGF. The images were recorded with a digital camera (RETIGA Exi FAST1394, Cooled Mono 12-bit) and transferred to a computer for processing (ImageJ 1.35g, Adobe Photoshop 6.0). The highest magnification in the microscope gives a spatial resolution of ~10 pixel/µm. External magnetic fields were applied perpendicular to the sample plane using a Cu-wire solenoid.

To increase the MOI sensitivity, we used a subtraction procedure. Difference images are obtained by subtracting two images recorded with the sample in two opposite remanent magnetization states. Those states were prepared by applying large pulses of opposite perpendicular fields (~160 mT). The analyzer is here set slightly out of crossing with respect to the polarizer, i.e., at an angle of 90° ± ϕ. According to Malus’ law, the transmitted light intensity, I, then becomes

\[ I/I_0 = \sin^2(θ_F - ϕ) + E \approx (θ_F - ϕ)^2 + E, \]

where \( θ_F \) is the Faraday rotation in the FGF, \( I_0 \) is the light intensity before the analyzer, and \( E \) is the extinction ratio of the optical system. For the difference image, obtained for \(+θ_F\) and \(-θ_F\) the intensity becomes

\[ ΔI(x,y) = |I_+ - I_-| \approx 4L_0|θ_F[B(x,y)]|, \]

where it is expressed explicitly that \( θ_F \) depends on the spatial distribution of the magnetic field. It should be emphasized that the image subtraction also filters out the effect of nonuniform illumination, and reduces irrelevant visible features like defects and magnetic domain walls frequently present in the FGF.

The electron microprobe analyses were carried out on a Cameca SX100 instrument. The analyses were performed by an accelerating voltage of 15 kV and a beam...
The excited volume decreases with increasing density of the analyzed phase and decreases with the increasing excitation energy of the line analyzed. At the operating conditions FeKα were excited in a spherical volume with a diameter of \( \sim 1 \) μm in magnetite (density 5.2 g/cm³) while MgKα was excited in a spherical volume of \( \sim 2 \) μm in serpentine (density 2.5 g/cm³). Hematite (Fe₂O₃) was used as a standard for Fe and MgO for Mg.

**Figure 1.** Magnetite-bearing skarn samples from the Oslo region. (a) Transmissive optical image of thin section 16 × 32 × 0.03 mm³, together with (b) a reflective optical and (c-f) magneto-optical images of a smaller region containing several magnetite inclusions. In Figure 1b the bright, light gray, and dark regions correspond to magnetite, quartz, and surface defect, respectively. The MO images in Figures 1c and 1d were recorded after applying a perpendicular magnetic field of +160 and −160 mT, respectively, resulting in oppositely magnetized remanent states. The white arrows show the direction of the in-plane grain magnetization. Figure 1e shows the difference MO image obtained from Figures 1c and 1d. The region marked in Figure 1e by a rectangle is seen magnified in Figure 1f, where the magnetite-magnetite grain boundary marked by a small rectangle is shown in even more detail in Figure 4.
Matrix corrections were carried out according to the PAP procedure [Pouchou and Pichoir, 1984].

4. Results and Discussion

[12] Figure 1c shows a magneto-optical image of the magnetite-bearing skarn sample in the remanent state after applying perpendicular fields of +160 mT. The area seen in the image is the same as in the optical image of Figure 1b. The brightness in the MO image represents the perpendicular component of the local magnetic field, with black and white regions corresponding to +3 and −3 mT, respectively. The nonmagnetic matrix is seen as a featureless background.

[13] Evidently, the large-scale grain structure shows a close resemblance to that of the optical image. In addition to the grain contours, the MO image shows that the grains have a brighter left edge and a darker right edge. This is a direct result of the grains being magnetized, and that the magnetization vector, $\mathbf{M}$, lies predominantly in the sample plane, with a direction as indicated by the white arrow. The stray magnetic field of each grain, i.e., from the magnetic surface charges, $\mathbf{M} \cdot \mathbf{n}$, where $\mathbf{n}$ is the unit normal to the grain contour, has then opposite perpendicular components where $\mathbf{M}$ and $\mathbf{n}$ are parallel and antiparallel, as we indeed observe. Gray level in the grain central area essentially coincides with gray level far from grain suggesting that the out-of-plane component of $\mathbf{M}$ is negligible. Note also from the MO image that the small dark particles seen in the optical image do not show up in magneto-optical images. Hence magnetic properties of these particles do not differ from those of their surrounding.

[14] The MO image in Figure 1d shows the remanent state after a maximum field of −160 mT was applied. Since the intensity contrast is here opposite to that in Figure 1c, we conclude that this field was sufficiently large to reverse the magnetization vector.

[15] To illustrate the advantages of the subtraction scheme, we show in Figure 1e the calculated difference between the grey levels in the images in Figures 1c and 1d. The difference image allows a very precise identification of the grain edges, which appear bright, and the gap between the grains which appear black. Actually, the contrast is even better than in the optical image, and implies that MOI is able to resolve intergrain gaps more clearly than conventional optical microscopy. This is due to the “magnetic

Figure 2. Serpentinized ultramafic rock sample. (a) Optical images of the rock and (b) reflective optical images of its thin section 16 × 32 × 0.015 mm$^3$, used for optical and magneto-optical studies. (c) Optical and (d–f) magneto-optical images of smaller regions of the thin section containing several magnetite stripes. Bright and dark regions on Figure 2c are quartz and magnetite, respectively. Figures 2d and 2e show remanent magnetization images after applying a perpendicular magnetic field of +160 and −160 mT, with bright and dark regions in Figures 2d and 2e corresponding to local magnetic fields of +5 and −5 mT, respectively. Figure 2f is the difference image obtained by subtracting Figure 2e from Figure 2d. The magnetite stripe marked by arrow in Figure 2d is shown in detail in Figure 8.
lens’’ effect, i.e., the fact that stray magnetic fields extend far beyond the gap. It allows detection of gaps down to 100 nm as estimated in Appendix B.

[16] Zooming in on a small region of a grain boundary marked with a rectangle in Figure 1f, we show in Figure 4 the slice of the optical image together with magnetic field profiles. The profiles $H_+(x)$, $H_-(x)$, and $|H_+(x) - H_-(x)|$ correspond to the MO images of Figures 1c, 1d, and 1e, respectively. Figure 4 also shows chemical composition profiles for Si and Fe collected using the electron microprobe. The composition of the grains is essentially uniform, with a high Fe content. Between the grains, in a region of $\approx 15$ micron width, the Fe content abruptly drops to zero, consistent with the optical micrograph.

[17] By analyzing the magnetic field profiles the magnetization of magnetite grains can be estimated as follows. Assuming that two grains are uniformly magnetized with an in-plane magnetization, $M$, one can calculate the field distribution in the whole space; see Appendix B. Figure 5a shows the corresponding field lines as well as field profile $H(x)$ evaluated in the FGF sensor plane. Such a profile always has a peak and a dip near the gap, quite similar to the experimental curves in Figure 4. The peak-to-dip field difference $\Delta H$ and the peak-to-dip distance $D$ can be readily extracted from the experimental field curves, and then $M$ is determined using formulas derived in Appendix B.

[18] The analysis can be performed graphically as illustrated in Figure 6, where in Figure 6a the calculated curves $D$ versus gap width, $d$, are plotted for different values of the a priori unknown distance $z$ between the thin section and the FGF. Also included are experimental data points, $D(d)$, obtained at different places along the boundary between the same two grains, with $d$ determined from optical image, and $D$ from field profiles. It is seen that all the data fall consistently on the same curve for $z = 2.5 \mu m$. Figure 6b shows $\Delta H/M$ versus the gap width using this $z$, which then allows us to determine uniquely the grain magnetization $M$. The data obtained at the different locations result in $\mu_0 M = 8$ mT with a spread of approximately 20%. The variation might be caused by an actual nonuniformity of the magnetization within the grains or by grain-grain interaction. However, the spread is fairly small, and suggests that the crosstalk is negligible even at short intergrain distances. Furthermore, the result justifies the assumption of a uniform $M$. This is further justified by Figure 1f, where one can see that the field distribution within $\sim 15$ microns from the grain edge is essentially featureless.

[19] Note from Figure 1f, that contrary to the edge region, the internal parts of the grains have a distinct magnetic fine structure. A detailed study of these intragrain magnetic domains is subject of a future paper.

[20] Equipped with the MOI method to determine the grain magnetization, we have investigated how the satura-
Magnetization remanence, $M_{\text{rm}}$, of magnetite depends on the sizes of grains. Plotted in Figure 7 are results obtained for a number of free standing grains of sizes ranging from 40 $\mu$m to 0.6 mm. They show a weak tendency of decreasing remanence with increasing size. Included in the plot are also two dashed lines indicating the upper and the lower boundary for an extensive collection of data presented by Dunlop and Özdemir [1997]. Our data fall nicely within this range, and agree particularly well with previous measurements on crushed grains and glass ceramics. Thus our results give additional evidence for strong deviation of natural magnetite properties from predictions based on micromagnetic and domain theories.

[21] We performed a similar analysis of magnetite in the serpentinized ultramafic rock sample shown in Figure 2. The remanent state MO images obtained after applying perpendicular fields of $+160$ mT and $-160$ mT, are shown in Figures 2d and 2e, with their difference presented in Figure 2f. The magnetite grains appear in Figure 2d as bright quasi one-dimensional structures, implying that they were formed by crystallization in a nonmagnetic matrix. Moreover, from the MO images it also follows that they are magnetized perpendicular to the thin section. This is not surprising since magnetic shape anisotropy is here negligible.

[22] Shown in Figure 8 is the backscattered electron (Figure 8a), optical (Figure 8b) and MO images (Figure 8c). Schematics of MOI as applied to our two model cases. (a) Field lines showing the stray magnetic field generated near the boundary between two magnetite grains with in-plane magnetizations, as in the magnetite-bearing skarn. The magneto-optical indicator film, placed above the sample responds to the distribution of the perpendicular field, shown on top. (b) Corresponding situation for the serpentinized ultramafic rock sample modeled with one stripe with perpendicular magnetization embedded in a nonmagnetic matrix. The brightness in the MO images represents the value of the perpendicular component of the local field in the plane of magneto-optical indicator.

Figure 5. Schematics of MOI as applied to our two model cases. (a) Field lines showing the stray magnetic field generated near the boundary between two magnetite grains with in-plane magnetizations, as in the magnetite-bearing skarn. The magneto-optical indicator film, placed above the sample responds to the distribution of the perpendicular field, shown on top. (b) Corresponding situation for the serpentinized ultramafic rock sample modeled with one stripe with perpendicular magnetization embedded in a nonmagnetic matrix. The brightness in the MO images represents the value of the perpendicular component of the local field in the plane of magneto-optical indicator.

Figure 6. MOI data and results of calculations following the model of Appendix B for skarn thin sections with thickness $s = 30\mu$m. (a) Apparent gap width between magnetite-magnetite grains, $D$, as a function of the actual gap, $d$, for configuration shown in Figure 5a. (b) Peak-to-dip field difference $\Delta H$, is plotted in the same manner. The symbols show the experimental points, and from Figure 6a the distance between the sample and the MO indicator, $z \approx 2.5\mu$m, is determined. This value of $z$ is used in Figure 6b to determine $M$; see text for details.
(Figures 8c–8e) of a selected magnetite grain approximately 5 \( \mu \text{m} \) wide. Figure 9 includes profiles of the contents of Fe, Si, Mg, Mn, and Al. The backscattering image shows the area where the Fe content is uniform at depths on the order of a micron [Reed, 1996]. The scattered electrons are not sensitive to the spatial fluctuations of either the Fe valence or the electric resistance. The optical microscopy image shows an excessive amount of fine structure at the surface (at submicron depths) [Nesse, 1991]. It is very sensitive to the details of Fe 3d electronic states.

The MO images of Figure 8 were used to determine the magnetic field profiles across the grain, and analyzed according to the model shown schematically in Figure 5b. The model considers a free standing infinitely long grain with uniform out-of-plane magnetization. Using the formulas in the second part of Appendix B, the magnetization of several grains of various widths were obtained. The results are plotted in Figure 7 and show a different tendency compared to the magnetite grains in skarns; that is, the \( M_r \) increases with increasing grain size. We believe that this can be explained by variations in the Fe content with the grain size, as revealed by the probe analysis and indicated in the Figure 7.

5. Conclusions

[24] We have demonstrated that MOI method, which visualizes the spatial distribution of magnetic field, can be used to investigate rock magnetism. The images can directly reveal the shape of magnetite grains and their arrangement inside a nonmagnetic matrix, as was demonstrated by investigating thin sections of skarns from the Oslo region and serpentinitized ultramafic rocks from the Solund Basin. We have proposed a procedure that allows resolution of magnetite-magnetite grain boundaries and individual magnetite grains down to the submicron scale, and determine the grain magnetization. The saturation remanence of a number of magnetite grains were measured, and found that (1) for the skarns magnetic interactions do not effect the magnetic properties of magnetite grains within 0.8 to 60 \( \mu \text{m} \) of each other, (2) the saturation remanence decreases weakly with increasing grain size from 40 \( \mu \text{m} \) to 0.6 mm, in full agreement with previous results, and (3) for the serpentinites the magnetic properties of the stripes are size-dependent due to variations in chemical composition. Size effects of this type are usually studied using volume-averaging magnetometric methods, and we suggest that MOI with its space-resolved abilities can be an important source of supplementary information.

Appendix A: Response of MO Indicator to Magnetic Field

[25] The basic details of MOI that are important for studies of geological samples are as follow: Linearly polarized light propagating through the FGF will experience a rotation of its polarization vector if a magnetic field is present [Johansen et al., 1996; Goa et al., 2003]. The Faraday effect relates to the fact that the FGF is a ferrimag-

Figure 7. Saturation remanence \( M_r \) for skarn magnetite grains and serpentinitized veins vs. their sizes and widths, respectively. The dashed lines show the scatter of similar data from Dunlop and Özdemir [1997]. The variation in the Fe contents normalized to maximum is marked.

Figure 8. Details of serpentine vein with magnetite from ultramafic clast. The vein is indicated by arrow in Figure 2d. (a) Backscattering scanning electron microscopy, (b) optical, and (c-e) magneto-optical images. Figures 8c and 8d show remanent magnetic field images after applying out-of-plane fields of +160 mT and −160 mT, respectively. Figure 8e shows the difference image obtained from Figures 8c and 8d.
A net having a spontaneous magnetization, \( M_s \), with the easy axis lying in the film plane. An external magnetic field \( B \) at an angle \( \alpha \) will force the magnetization vector out of the plane, see Figure A1a, while the magnetization is essentially constant in magnitude. The equilibrium tilt angle \( \eta \) of \( M_s \) represents the balance between the magnetocrystalline anisotropy and the tendency to align with the external field. In the simplest form this can be expressed as a minimum of

\[
K \sin^2 \eta - BM_s \cos(\alpha - \eta),
\]

where \( K \) is the anisotropy energy. Minimizing (A1) with respect to \( \eta \) gives

\[
\frac{B_z}{\sin \eta} - \frac{B_x}{\cos \eta} = \frac{2K}{M_s} = B_{st},
\]

where \( B_{st} \) is the saturation field. The Faraday rotation, \( \theta_F \), is proportional to the component of \( M_s \) along the light beam direction, so that

\[
\theta_F = \theta_F^{sat} \sin \eta.
\]

Figure 9. Profiles of magnetic field and compound percents along a line crossing the central part of the vein shown on Figure 8: the profiles of \( H_+ \), \( H_- \) and \( H_+ - H_- \) correspond to Figures 8c, 8d, and 8e.

Figure A1. (a) Relationship between the directions of the spontaneous magnetization \( M_s \) of the in-plane indicator film and the magnetic field \( B \), which forces the magnetization vector away from the easy plane. (b) Indicator film’s Faraday rotation angle \( \theta_F \) versus the magnetic field component, \( B_z \), along the \( z \) direction.
After the light is rotated by the FGF and reflected by the mirror layer, the beam reenters the objective lens. In the microscope a second polarizer (analyzer) filters the light according to Malus’ law \[ \text{[Johansen et al., 1996]}. \] With the analyzer set at 90° relative to the original polarization, the intensity distribution arriving at the camera becomes

\[
I(x,y)/I_0 = \sin^2[\theta_F(x,y)] + E. \tag{A6}
\]

Here \( I_o \) is the intensity before the analyzer and \( E \) is the effective extinction ratio of the optical system, which is \( E = (1 - 3) \times 10^{-4} \). Combining this with the characteristics of the FGF it follows that at magnetic fields below \( B_{st} \) the light intensity versus magnetic field is a parabolic function. Note then that for small fields, the typical situation with mineral samples, the sensitivity \( \Delta I/\Delta B \) is low.

## Appendix B: Stray Fields From a Nonmagnetic Gap and a Magnetic Stripe

### B1. Nonmagnetic Gap

[27] Consider two thin grains uniformly magnetized with an in-plane magnetization of \( M \) and separated by a gap of width \( d \). To calculate the corresponding field distribution, we use a model based on positive magnetic charges (magnetic monopoles) at the left edge of the gap and negative charges at its right edge (see Figure 5a). Charges at the far edges of the grains can be ignored if the lateral dimensions of the grains are much larger than \( d \). When \( d \) is much larger than the grain thickness \( s \), we sum up fields generated by two infinite charged wires located at \( x = \pm d/2 \), \( z = 0 \). For the perpendicular component we obtain

\[
H = \frac{4\pi}{M} \frac{-2xz}{(z^2 + (d/2 - x)^2)(z^2 + (d/2 + x)^2)}. \tag{B1}
\]

An example of \( H \) profile is plotted in Figure 5a. It is clear that \( H \) changes from positive to negative values in the vicinity of the gap. Correspondingly, in a MO image a bright and a dark stripe should be seen (exactly what we find in Figures 1c and 1d). The distance between the stripes may be larger than the actual gap between the magnetite grains as evident already from Figure 5a. This distance is given by

\[
D(d,z) = \left( 2\sqrt{16z^4 + 4z^2d^2 + d^4 + d^2 - 4z^2} \right)^{1/2} > d. \tag{B2}
\]

For \( z < d \) one finds \( D \approx d \); however, for \( z \gg d \) one has \( D \approx 2z^{1/3} \). Another important quantity is the difference of \( H_z \) values in the peak and in the dip.

[28] For small gaps, \( d \ll z \),

\[
\Delta H \equiv H_{|z=-D/2} - H_{|z=D/2} \approx \frac{3\sqrt{3}d}{2\pi} \frac{M}{4z^2}. \tag{B3}
\]

In a more realistic case when the grain thickness \( s \) is comparable to \( z \), the magnetic field is found by integrating equation (B1) over the thickness,

\[
H = \int_{z}^{z+s} \frac{M}{2\pi} \frac{-2xz}{(z^2 + (d/2 - x)^2)(z^2 + (d/2 + x)^2)} dz. \tag{B4}
\]

In a similar way we find the peak-to-dip distance and field difference, but now the exact expressions for \( D(d, z, s) \) and \( \Delta H(d, z, s) \) cannot be written down in a simple analytical form. However, a graphic analysis of these dependences plotted in Figures 6a and 6b allowed the determination of grain magnetization from measured field profiles in skarns; see the main text for details.

[29] Experimentally, the distance \( z \) between the sample and the MO indicator is about 1–4 \( \mu \)m due to imperfections and a slight curvature of the sample surface. Therefore, even a very small gap between magnetite grains produces two stripes in the MO image separated by a few microns, which is well within the spatial resolution of the technique. Remarkably, magneto-optical imaging thus can resolve gaps smaller than the optical wavelength. However, if the gap is too small, then the field contrast \( \Delta H \) is also very weak and may drop below our field resolution of 0.1 mT. It defines the minimal gap that can be detected with MOI; for example, for the present experiment on skarns where \( s = 30 \mu \)m, \( z = 2.5 \mu \)m and \( M = 8 \) mT, one obtains 200 nm. However, in an external magnetic field where \( M \) is larger, we can detect gaps down to 100 nm.

[30] Though the grain thickness is in practice not known, its uncertainty only slightly affects the results; for example, changing \( s \) from 30 to 15 \( \mu \)m for the gap shown in Figure 4 changes the resulting value of \( M \) by just 12%.

### B2. Magnetic Stripe

[31] Let us now consider a model for the case of magnetite stripes in the serpentinite. Here the narrow magnetic stripes are bound by nonmagnetic regions (see Figure 2). If the grain has a uniform magnetization in the perpendicular direction, it can be modeled by positive and negative surface charges at its top and bottom, as shown on Figure 5b. The perpendicular component of the magnetic field above such a grain is given by

\[
H = \frac{M}{2\pi} \left[ \arctan \frac{x - d/2}{z + s} - \frac{x - d/2}{z} \right. \\
\left. - \arctan \frac{x + d/2}{z + s} + \frac{x + d/2}{z} \right] \tag{B5}
\]

Obviously, \( H \) reaches the maximal value just above the center of the grain,

\[
H_{\text{max}} = 2 \arctan(d/2z) - 2 \arctan(d/2(z + s)). \tag{B6}
\]

If we shift horizontally some distance away from the stripe, the perpendicular component reverses direction, and the width of the region with positive \( H \) is given by

\[
D(d,z,s) = \sqrt{d^2 + 4z^2 + 4zs}. \tag{B7}
\]
Comparing with (B3), again we find that $D \approx d$ if the MO indicator is placed directly on the sample. However, for large $z$, $D$ is larger due to the magnetic lens effect. The dependences of $H_{\text{max}}(d)$ and $D(d)$ were used to extract magnetization of magnetite stripes in serpentinites from measured field profiles, see the main text for details.

[32] Interestingly, by combining equations (B4) and (B5) one can find the field distribution around a gap (or stripe) for an arbitrary direction of $\mathbf{M}$. It allowed us to find out that the proposed analysis is quite robust with respect to small deviation of $\mathbf{M}$ from the expected direction. For example, if $\mathbf{M}$ were 15° tilted away from the in-plane direction in the analysis of data in Figure 4, then the determined value of $M_{\text{max}}$ would be underestimated by only 4%. This robustness comes from the fact that $H(x)$ produced by an out-of-plane $\mathbf{M}$ is symmetric, while that by an in-plane $\mathbf{M}$ is antisymmetric, and hence they almost do not “interfere.”

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