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Numerical Simulation of Thermoremanent Magnetization in Intrusions

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1 **Abstract**—This paper is devoted to the possibility of inverse remanent magnetization that is acquired in intrusive rocks due to a magnetic field that is produced by a sum of the normal core field and an anomalous effect induced by solidified rocks. A computer program has been created to simulate the process of solidification of
1 intrusive body rocks from its edges to the center. The computing results showed the possibility of remanent magnetization that is acquired, which can have a different direction as compared to the external magnetic field, up to the inverse one.

1 *Keywords:* remanent magnetization, direct problem of magnetic exploration

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INTRODUCTION

Thermoremanent magnetization has a higher
1 information content among different types of remanent magnetization. Thermoremanent magnetization occurs during solidification of magmatics in a geomagnetic field and carries data on the character of this field (its variation, inclination, and strength) during
1 the formation of these rocks. The value of the remanent magnetization can exceed the induced magnetization by several tens of times; the latter exists in all rocks and is produced by the current magnetic field. At the same time, a detailed analysis of the behavior of thermoremanent magnetization in different intrusive rocks shows that the direction and value of this magnetization in samples taken from one intrusive body can change significantly, up to the occurrence of reverse magnetization. The period of formation of rocks of this intrusion was comparatively short and there is no reason to believe that the Earth's magnetic field changed significantly in this period. The causes of
1 such behavior of the remanent magnetization can be different. Sometimes it can be explained by the properties of minerals that compose this intrusion and the probable effect of magnetization reversion (Trukhin and Bezaeva, 2006). However, the mineral composition of rocks that are sampled from one intrusion is the same in most cases and the different character of their magnetization is difficult to explain in this case.

1 As has been already mentioned, remanent magnetization is acquired under the effect of a geomagnetic field where a cooling rock exists. This field is composed of the vector sum of the external Earth's magnetic field and a field induced by magnetized solidified rocks, and this component can be comparable in value with the external field and different in direction at a short distance from the magnetized rocks. The aim of this work is to model conditions for the occurrence of thermoremanent magnetization in magmatics with a direction that is different from that of the geomagnetic field due to already magnetized rocks of the intrusion. This study was carried out on the basis of a numerical simulation of the remanent magnetization that is 1
acquired in solidifying intrusive rocks.

MODEL DESCRIPTION

Let us assume the following.

1. The process of remanent magnetization acquisi- 1
tion occurs in a dike whose length is much larger than its thickness. The dike thickness is larger than 10–20 m. This representation of the environment allows 2D simulation.

2. The external magnetic field T_0 is characterized by the strength H_0 and the inclination i_0, i.e., the vector field $\vec{H}_0$.

3. An endocontact zone of a certain thickness with magnetization co-directed with the external magnetic field and strength defined by the equation $\vec{I} = \kappa\vec{H}_0$ is formed at the instant of dike intrusion into nonmagnetic enclosing rocks. The value of κ can attain 5 SI units for solidifying rocks.

4. The magnetized rocks of the endocontact zone will further homogeneously thicken due to cooling of an adjacent molten mass. The newly solidified rocks acquire the magnetization $\vec{I} = \kappa(\vec{H}_0 + \vec{H}_a)$, where

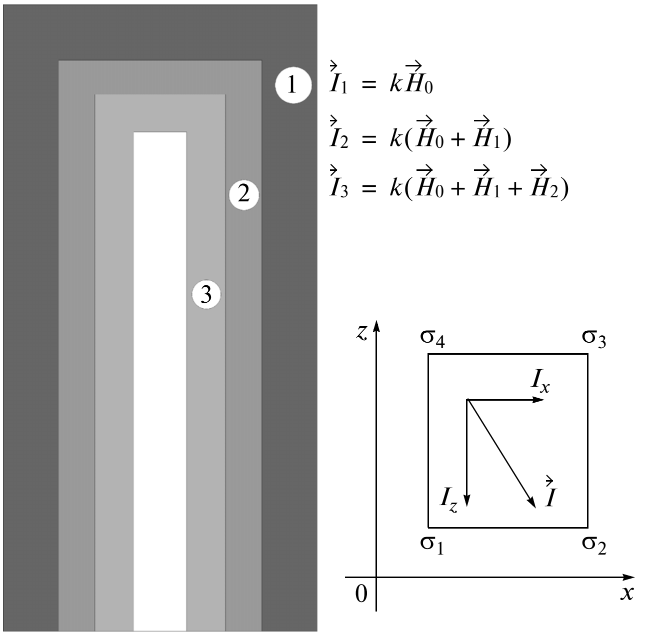

Fig. 1. The schematic of the computational model: an endocontact zone that originates during dike intrusion (1), intrusion layer that originates during a certain period of its cooling (2), the next intrusion layer (3).

$\vec{H}_a$ is the anomalous magnetic field induced by rocks that solidified earlier with the thermoremanent magnetization acquired in them. This process continues until the entire dike solidifies.

5. The time of dike cooling is such that the external magnetic field remains invariable, as well as the value and direction of the thermoremanent magnetization that is acquired. In addition, we assume that rocks with a temperature higher than the Curie temperature have zero magnetic susceptibility, i.e., they are nonmagnetic. We also assume that the induced magnetization of cold rocks is negligible in comparison with the thermoremanent magnetization. This means that the anomalous field $\vec{H}_a$ is induced by rocks that acquire only thermoremanent magnetization, while the induced magnetization of the cold rocks can be neglected.

The principle scheme of the model is shown in Fig. 1, where the endocontact zone that forms at the instant of dike intrusion is marked by 1. The magnetization of rocks of this zone is $\vec{I} = \kappa\vec{H}_0$. An intrusion layer that originated during a certain period of cooling of this zone is marked by 2; the magnetization of this layer is defined by the equation $\vec{I} = \kappa(\vec{H}_0 + \vec{H}_1)$, where $\vec{H}_1$ is the strength of the magnetic field induced by layer 1. The next intrusion layer is marked by 3; its magnetization is defined as $\vec{I} = \kappa(\vec{H}_0 + \vec{H}_1 + \vec{H}_2)$, where $\vec{H}_2$ is the strength of field induced by layer 2, and so on.

COMPUTATIONAL ALGORITHM

Let us represent the intrusion model as a vertical 2D right-angle prism with a horizontal width d and vertical thickness h. For numerical calculations, we approximate this prism with a set of right-angle prisms with the sizes dx and dz ($dx = dz$ is assumed during the calculations). The number of these prisms $N_x = d/dx$ along the horizontal axis Ox and $N_z = h/dz$ along the vertical axis Oz.

The strength of the magnetic field from a right-angle prism was considered in the SI system via the equation (Strakhov, 1984)

$$H(s) = \frac{1}{4\pi} I \sum_{\nu=1}^{N} \alpha_\nu \ln\frac{\sigma_{\nu+1} - s}{\sigma_\nu - s},$$

where $N = 4$; H is the complex magnetic field strength, $H = Z + iX$, where X and Z are the horizontal and vertical components of the strength vector; i is an imaginary unit; I is the complex magnetization of a prism ($I = I_x + iI_z$); I_x and I_z are the horizontal and vertical components of the magnetization vector; $s = x + iz$ is the complex coordinate of a point where the right-angle prism effect is calculated; and $\sigma_\nu = \xi_\nu + i\zeta_\nu$ is the complex coordinate of a prism vertex. The parameter α_ν is defied as

$$\alpha_\nu = \frac{\bar{\sigma}_{\nu+1} - \bar{\sigma}_\nu}{\sigma_{\nu+1} - \sigma_\nu},$$

where the bar means complex conjugation.

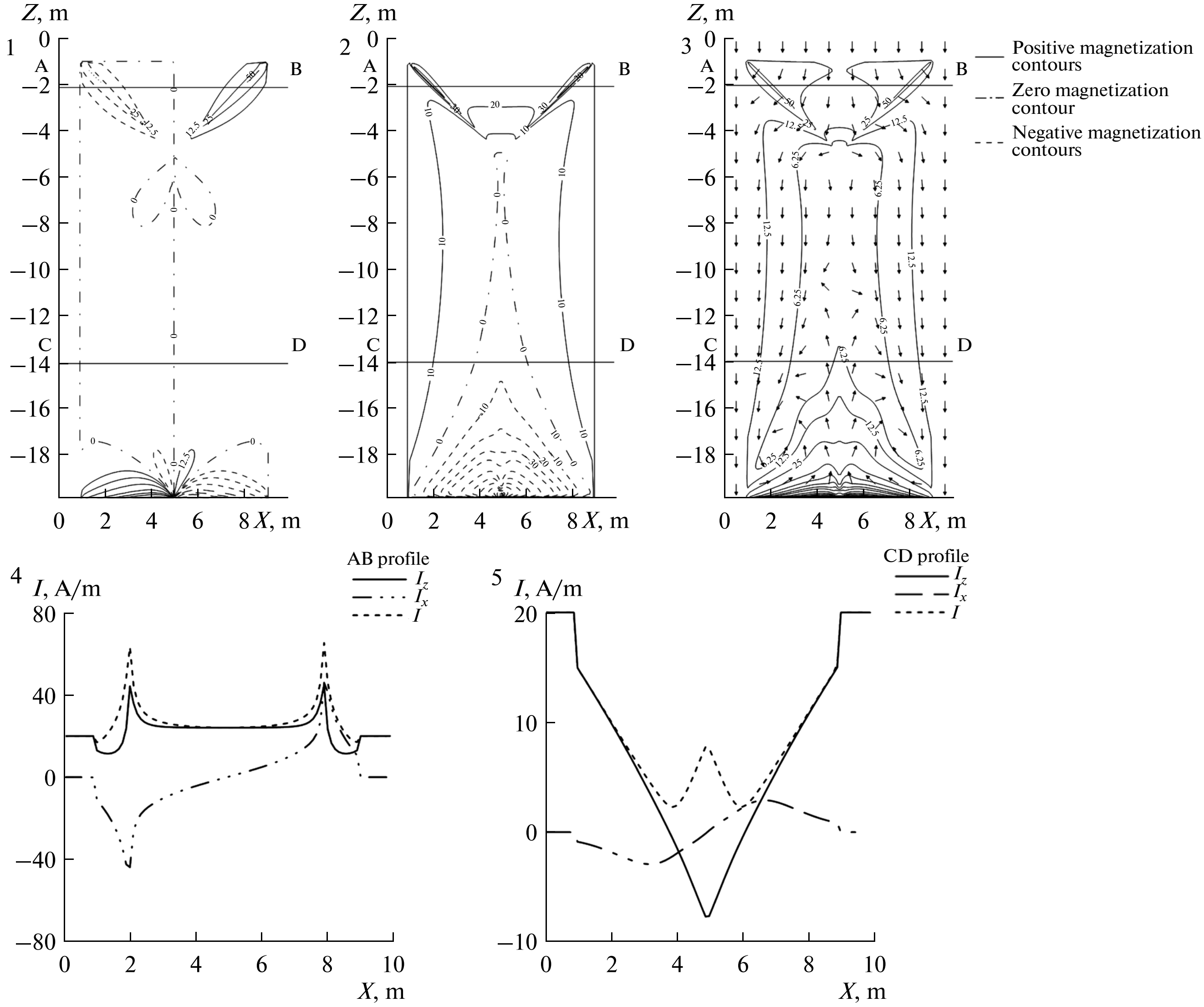

Fig. 2. Model κ = 5.026 Si units, $i_0 = 90°$, and $\vec{I} = 200$ A/m: map of the horizontal magnetization component *Ix*, variable step of contours (1); map of the vertical magnetization component *Iz*, variable step of contours (2); map of the magnetization modulus, variable step of contours, the arrows show the magnetization direction (3); plots of the vertical and horizontal magnetization components and modulus in terms of the AB profile (4); plots of the vertical and horizontal magnetization components and modulus in terms of the CD profile (5).

The use of reduced formulas for the calculations assumes the introduction of Cartesian coordinates with the *Ox* axis directed to the right and *Oz* axis directed upward. The polygon is counterclockwise traversed. (Fig. 1), The inclination angle i_0 of the external magnetic field is considered to be positive in the coordinates introduced if the vector $\vec{H}_0$ is downward directed. In this case, the components of its strength are defined as $X_0 = H_0 \cos i_0$ and $Z_0 = -H_0 \sin i_0$.

To represent the results, we turn back to the common coordinates, where the *Oz* axis is downward directed and consider the magnetization vector components as positive if they are co-directed with the coordinate axes in these common coordinates.

COMPUTATION RESULTS

Model 1. The external magnetic field $T_0 = 50000$ nT, which corresponds to the strength $H_0 = 39.79$ A/m (0.5 Oe in the CGS system); it is vertical (the inclination $i_0 = 90°$). For definiteness, let the dike width $d = 10$ m and its vertical thickness $h = 20$ m. The dike model is represented by a set of square prisms with sizes $dx = dz = 0.1$ m. During dike intrusion into enclosing rocks, an endocontact zone of 1 m in thickness is formed from the top and sides of the intrusion.

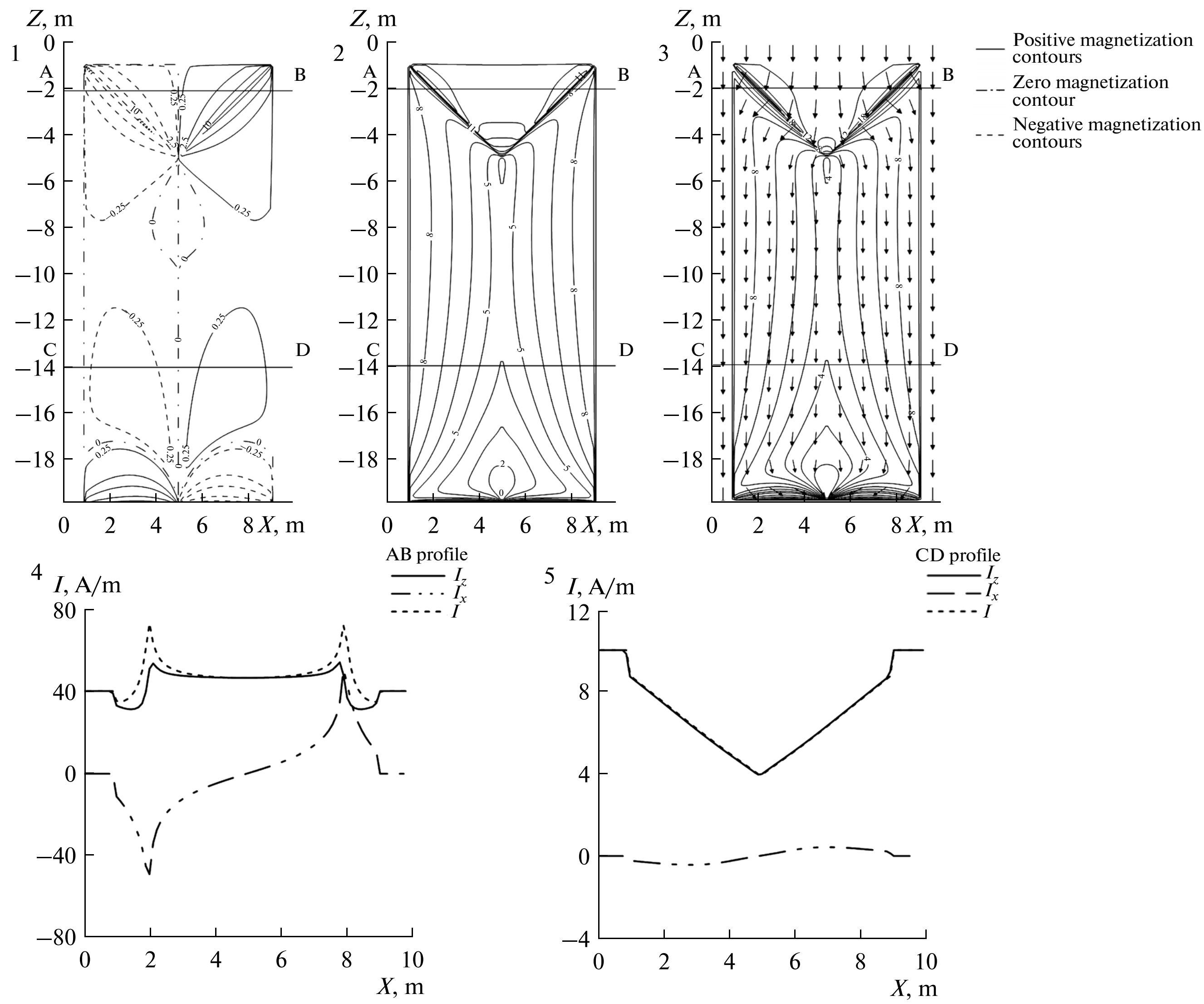

Fig. 3. Model κ = 2.513 Si units, $i_0 = 90°$, and $\vec{I}$ = 200 A/m: map of the horizontal magnetization component *Ix*, variable step of contours (1); map of the vertical magnetization component *Iz*, variable step of contours (2); map of the magnetization modulus, variable step of contours, the arrows show the magnetization direction (3); plots of the vertical and horizontal magnetization components and modulus in terms of the AB profile (4); plots of the vertical and horizontal magnetization components and modulus in terms of the CD profile (5).

This zone immediately acquires the magnetization $\vec{I} = \kappa\vec{H}_0 = 200$ A/m under the effect of the external magnetic field $\vec{H}_0$ and the field initiated by the solidified rocks $\vec{H}_a$:

$$\vec{I} = \kappa(\vec{H}_0 + \vec{H}_a).$$

As has been already mentioned, magnetized rocks
1 acquire only remanent magnetization, i.e., the induced magnetization component is absent. The computation results are shown in Fig. 2. It is seen that cells with even reverse magnetization can appear in the rocks.

Let us note that an increase in the detail of the intrusion model representation by a set of right-angle prisms does not change the computation results qualitatively.

Model 2. The same calculations were performed but with κ = 2.513 SI units (i.e., two times lower), which results in the fact that although the magnetization vector does not reverse its direction, it can be directed differently than the external magnetic-field vector (Fig. 3).

Model 3. This model differs from model 1 in that the vector of the normal magnetic field has an inclination angle i_0 of 60°, with the other parameters being invariable. The results of these computations show

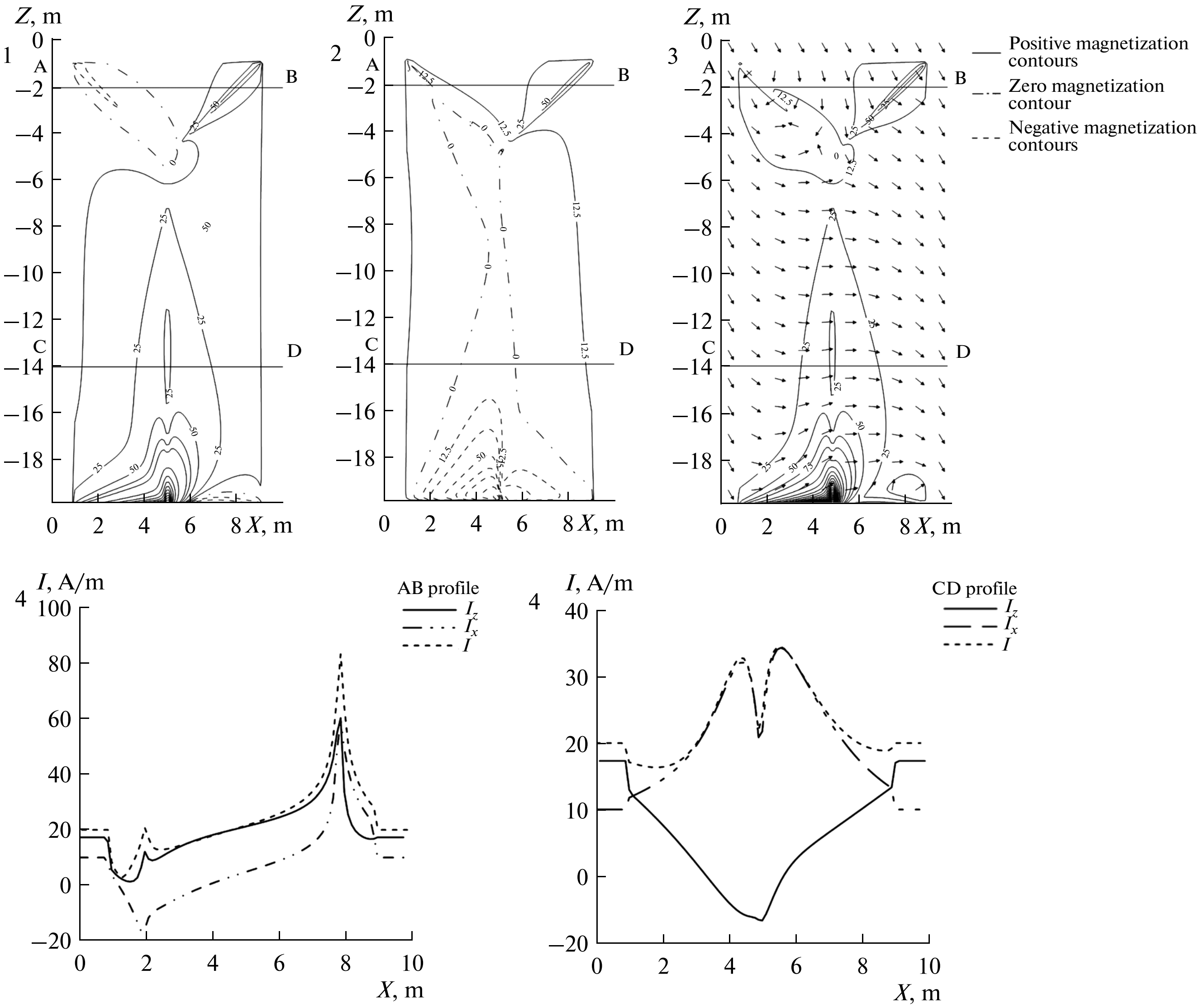

Fig. 4. Model κ = 5.026 Si units, $i_0 = 60°$, and $\vec{I} = 200$: map of the horizontal magnetization component *Ix*, variable step of contours (1); map of the vertical magnetization component *Iz*, variable step of contours (2); map of the magnetization modulus, variable step of contours, the arrows show the magnetization direction (3); plots of the vertical and horizontal magnetization components and modulus in terms of the AB profile (4); plots of the vertical and horizontal magnetization components and modulus in terms of the CD profile (5).

that the magnetization vector can become horizontal (Fig. 4).

CONCLUSIONS

Thus, the computation results show that the effect of solidifying rocks on the formation of a thermoremanent magnetization vector should be taken into account. In this case, the shape (geometry) of the solidifying intrusion is of significant importance.

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SPELL: 1. remanent