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Inversion of magnetic data to fully reconstruct the Magnetization vector and its application to mineral exploration

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ABSTRACT

We develop a fast sequential inversion method (M-IDI) for 3D inversion of distribution of total magnetization vector to estimate both direction and intensity of magnetization. First, the magnetization intensity is retrieved by inversion of the magnitude magnetic anomaly using preconditioned conjugate gradient method. Then, the inclination and declination of magnetization are recovered either using the conjugate gradient algorithm like that is done to recovery of magnetization intensity by inverting the total field data (M-IDCG) or computing the correlation coefficients between the observed and predicted total field anomalies where the most correlated anomaly corresponds to the optimal magnetization direction (M-IDC). The new algorithm is evaluated by applying to synthetic and real data examples, and the results are compared with a previous important method i.e., the magnetization vector inversion in Cartesian framework (MMM) and spherical framework (MID).

Keywords: magnetic data, magnetization vector, remanent magnetization, remanence, inversion, Galinge

INTRODUCTION

The magnetization vector inversion (MVI) for recovering the distributions of total magnetization vector (TMV) is a well-known tool to solve the problems involving the remanence and self-demagnetization effect (Guo et al., 2001; Lelièvre and Oldenburg, 2006). Wang et al. (2004) derive the equations required in magnetization vector inversion and recover the horizontal and vertical magnetization components of a 2D theoretical model. Lelièvre and Oldenburg (2009) employ more complicated scenarios and improve the aforementioned methods and calculate the three components of magnetization vector in Cartesian and spherical frameworks. This method finds a widespread application in magnetic data inversion under the influences of significant remanent magnetization. Liu et al. (2015) propose a 2D sequential inversion method (M-ID) for inverting the total magnetization vectors. This algorithm is based on the fact that in 2D case the magnitude of magnetic anomaly is independent of the magnetization direction. Accordingly, first, the magnetization intensity is retrieved by inversion of the magnitude magnetic anomaly using preconditioned conjugate gradient method. Then, the inclination and declination of magnetization are recovered either using the conjugate gradient algorithm like that is done to recovery of magnetization intensity by inverting the total field data (M-IDCG) or computing the correlation coefficients between the observed and predicted total field anomalies where the most correlated anomaly corresponds to the optimal magnetization direction (M-IDC). Contrary to the 2D case, the magnitude magnetic anomaly is not completely independent of magnetization direction for 3D sources (Stavrev and Gerovska, 2000; Gerovska and Araúzo-Bravo, 2006). For this purpose, we develop the 2D algorithm and propose a fast iterative method (M-IDI) to retrieve the distribution of the magnetization vector. The results of this new algorithm is compared with that of an important method *i.e.*, the magnetization vector inversion in Cartesian framework (MMM) and spherical framework (MID) introduced by Lelièvre and Oldenburg (2009).

Methodology and examples

The method is explained in more detail by synthetic and real case examples. The synthetic model is consisted of a rectangular (*i.e.*, A) and two dipping prisms (*i.e.*, B and C) (Liu et al., 2017). The inclination and declination of Earth's magnetic field are $I_0 = 45°$ and $D_0 = 90°$ (east to north). The model has a constant TMV with intensity $M = 1$ A/m, inclination $I = 45°$ and declination $D = 60°$, where the remanent magnetization components are: $M_r = 0.56$ A/m, inclination $I_r = 38.90°$ and declination $D_r = 36.21°$. In the MID method, the retrieved parameters *i.e.*, magnetization intensity, inclination and declination have different units, and consequently their sensitivity to magnetic anomaly is also different. Therefore, it is essential to use weighting coefficients to balance the parameters (Lelièvre and Oldenburg, 2009). The MMM method tends stable convergence of iterations, because three inverted components of magnetization intensity have the same unit and weighting, the convergence of iteration is less affected by the initial model. In the synthetic example in Figure 1b, for instance, the magnetization intensity, inclination and declination of magnetization are weighted by $w_M = 10^{-6}$; $w_I = w_D = 1$, respectively. The M-ID includes three methods (i.e., M-IDCG, M-IDC, and M-IDI). When recovering the magnetization direction distributions in M-IDCG, the initial model is set to parallel the Earth's magnetic field which shows a lower dependency than MID method. The M-IDCG inversion results (Figure 1c) is less scattered compared with that of MMM, but they show a less concentration than MID results. The more exhaustive methods, M-IDC and M-IDI, provide the same magnetization direction with error < 5° (Figure 1d). However, these methods are more appropriate for simple and isolated anomalies because only one optimal magnetization inclination and declination are estimated. For multiple sources or complicated magnetic anomalies a window-based strategy is usually used to separately investigate the anomalies. The Galinge iron-ore deposit, located at the centre of Qimantage metallogenic belt, is one of the important skarn iron deposits in Qinghai province (NW China) (Liu et al., 2017). The contour map of the total field anomaly reveals that the length and width of anomaly reach to 1200 m and 500 m showing ellipsoid shape and prolonging NW-SE direction whose amplitude exceeds 1500 nT (Figure 2). M-IDC and M-IDI methods are used to recover the distributions of magnetization intensity and to estimate the magnetization vector direction. The inversion recover two magnetite belts at the north and south of the mining area, striking NW-SE direction (Figure 3a). The northern one is the main orebody with a 200 m average depth to top and approximately a 150 m true thickness. The orebody is inclined to south-west direction with dipping angle 70-80° and extension of 250-300 m. The northern orebodies are verified by series of drillholes (Figure 3a). The drillhole logs reveal that the thickness of Quaternary gravels reach to 117-210 m and the magnetite ores are occurred in the bedrocks. The top depth of the buried orebodies is 200 m in average .For example, in ZK21201 drilled magnetite ore belt indicates an apparent thickness of 169.23 m (i.e., from 189.61 m to 358.84 m depth). Based on the drillholes ZK21202, ZK21203 and ZK21204, it is inferred that the magnetite orebodies dip to south-west direction around 70° and extending length is nearly 300 m. The southern explored magnetic source is estimated at the 300-350 m depth. This is a concealed and potential iron orebody which has not been verified by drillings, but the size of the orebody is expected to be smaller than northern ore belts. Subsequently, the correlation coefficient method (M-IDC) and iteration method (M-IDI) are used to determine the magnetization direction. The magnetization inclination and declination are constrained as: $0° \leq I \leq 90°$, $0° \leq D \leq 90°$, varying with a 1° step when calculating the total field anomaly. The correlation coefficients at A ($I = 71°$, $D = 70°$) reach to the maximum value, $R = 0.96907$. The estimated optimal inclination and declination by means of M-IDC method are $I = 71°$, $D = 70°$, respectively (Figure 3b). The M-IDI method finally is converged on $I = 68.4°$, $D = 70.77°$ in 5 iterations with the initial values of $I = 0°$, $D = 0°$. M-IDI and M-IDC return the similar results. Combining with the magnetization intensity distributions (Figure 3a) and the magnetization direction (Figure 3b), finally, the distribution of magnetization vector can be deduced.

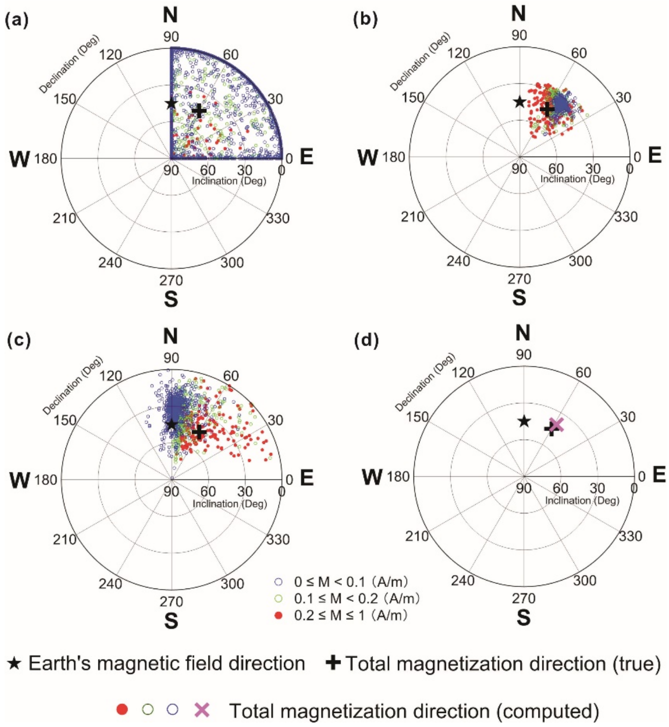

Figure 1. Scatter plots of inverted magnetization inclination and declination of synthetic mode using (a) MMM, (b) MID, (c) M-IDCG, (d) M-IDC, and M-IDI methods

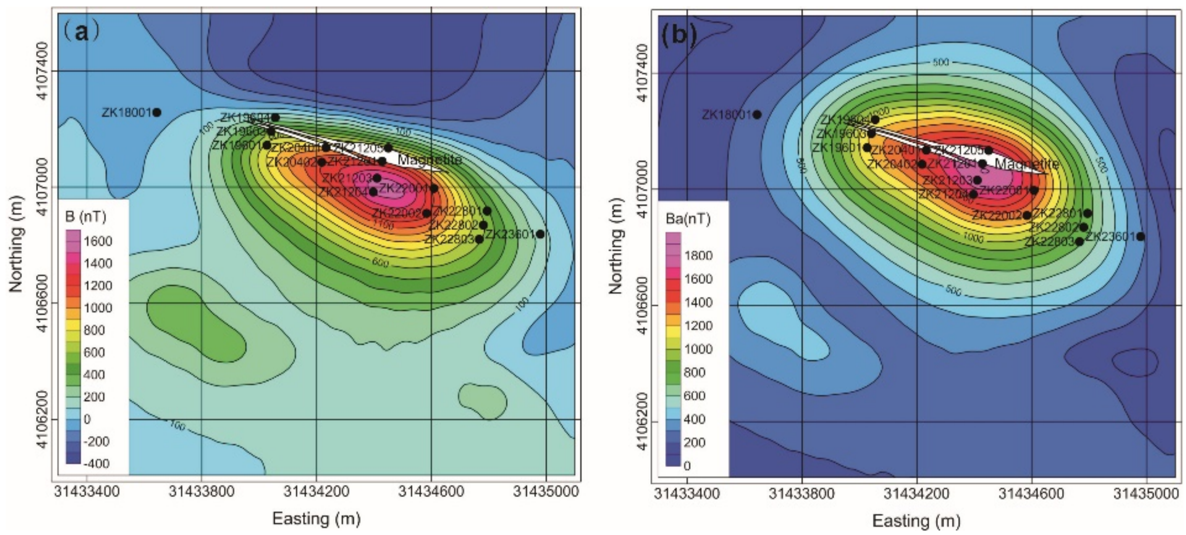

Figure 2. (a) Total field anomaly and (b) frequency-domain transformed magnitude magnetic anomaly of the Galinge iron-ore deposit, NW China. Black points and white-filled polygons show the drillholes and outcropped orebodies in bedrocks, respectively.

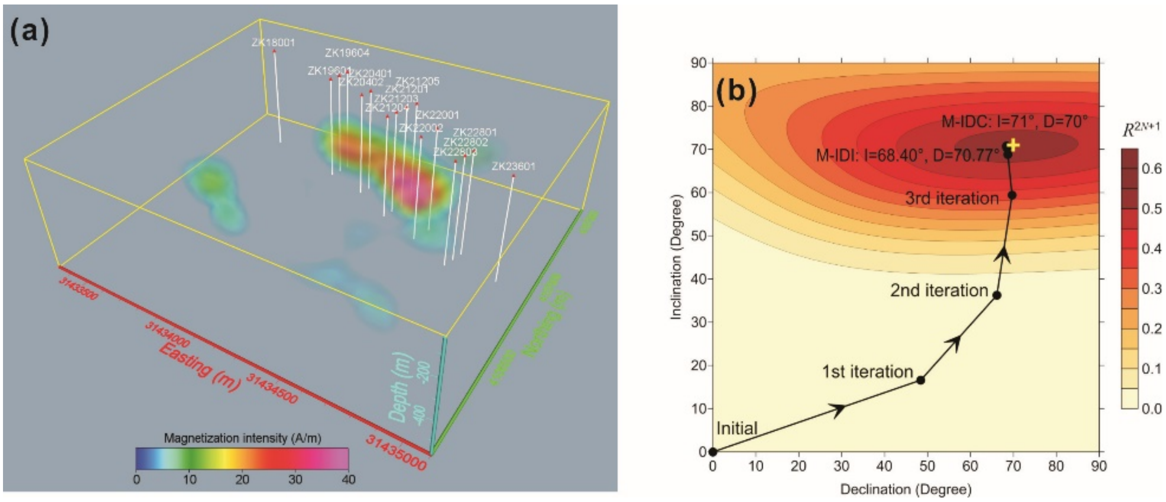

Figure 3. Computed magnetization (a) intensity and (b) direction using M-IDC and M-IDI methods of the Galinge iron-ore deposit, NW China.

CONCLUSION

The analysis of synthetic and real data reveal that MMM iteration has a stable tendency for convergence and also a low dependency on initial model. Without any constraint, the magnetization inclination and declination may be varied in a large range and magnetization vector will show a divergent behavior. However, incorporating geological and physical property information can improve the results effectively. For MID method of spherical framework, the magnetization intensity and direction have different units and sensitivities to magnetic anomaly. Therefore, it is critical to set appropriate weighting coefficients and initial values of inclination and declination. M-ID method can solve the magnetization intensity and direction sequentially. M-IDCG obtains the distributions of magnetization inclinations and declination, while M-IDC and M-IDI achieve an optimal magnetization direction which is more suitable for the isolated anomalies. The synthetic and field examples reveal that the isochronous MMM method worsens the geophysical non-uniqueness problem and the

MID suffers from the low stability of convergence because of the strong dependence on the starting models. The M-ID method of sequential inversion shows superior stability and precision since it makes successive use of the amplitude and phase information of magnetic anomaly.

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