Journal of Applied Geophysics 111 (2014) 121–128

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

Three-dimensional correlation imaging for total amplitude magnetic anomaly and normalized source strength in the presence of strong remanent magnetization

Lianghui Guo [a,*], Xiaohong Meng [a], Guoli Zhang [b]

[a] Key Laboratory of Geo-detection (China University of Geosciences, Beijing), Ministry of Education, Beijing 100083, China
[b] Tianjin Center, China Geological Survey, Tianjin 300170, China

ARTICLE INFO

Article history:
Received 20 July 2014
Accepted 6 October 2014
Available online 16 October 2014

Keywords:
Magnetic anomaly
Correlation imaging
3D
Remanent magnetization
Mineral exploration

ABSTRACT

We present the 3D correlation imaging approach for the total magnitude magnetic anomaly and the normalized source strength data for reducing effects of strong remanent magnetization. We divide the subsurface space into a 3D regular grid and then calculate the cross correlation between the observed total magnitude magnetic anomaly or normalized source strength and the theoretical total magnitude magnetic anomaly or normalized source strength at each grid node due to a magnetic dipole. The resultant correlation coefficients are used to describe the equivalent magnetic dipole distribution underground in a probabilistic sense. The two approaches were tested both on the synthetic magnetic data and the real magnetic data from a metallic deposit area in the middle-lower reaches of the Yangtze River, China. The results show that the two approaches can considerably reduce effects of remanent magnetization and delineate magnetic sources in the subsurface, and that the approach for the normalized source strength is less sensitive to strong remanent magnetization than that of the total magnitude magnetic anomaly.

1. Introduction

Quantitative interpretation of magnetic data plays an important role in mineral exploration, to which inversion of physical properties in the subsurface (Li and Oldenburg, 1996; Pilkington, 1997) is a primary approach. Such procedure includes linear or nonlinear inversion, which is based on the inversion theory and makes the target function reach minimum in the least squares sense. In the condition of adequate constraints, the inversion can reveal distribution of physical properties and geometries in the subsurface approximating the real geology. Traditional approaches of the physical property inversion usually assume the field source does not contain remanent magnetization and the self-demagnetization effect can be ignored, i.e., the magnetization direction is in accordance with the geomagnetic field. Such a hypothesis is, however, not always valid because of complicated real geologic settings. For instance, when there exists strong remanent magnetization, the magnetization direction of the source differs much from that of the geomagnetic field. In this case, if inversion is based on the direction of the geomagnetic field as the effective magnetization direction, its results will have big errors or are even completely wrong (Li et al., 2010; Shearer, 2005). Therefore, how to reduce or even remove the effect of remanent magnetization become a focused issue in the magnetic data inversion in recent years.

Several techniques have been proposed for physical property inversion of magnetic data with strong remanent magnetization. In terms of principles, these techniques can be classified into the following three classes. The first is to estimate magnetization direction of magnetic source from magnetic anomalies, which facilitate further inversion of physical properties. Helbig (1963) suggested the integral approach based on the integral relationship between magnetic anomaly rotary inertia and magnetic moment of dipole. Roest and Pilkington (1993) pointed out the magnetization direction of magnetic source can be estimated using cross-correlation between analytical signal of magnetic anomaly and horizontal gradients of pseudo-gravity anomaly. Medeiros and Silva (1995) described how to estimate the magnetization direction using equivalent source magnetic moment. Phillips (2005) gave direct and indirect algorithms for the Helbig's integral method to estimate magnetization directions. The approach of Dannemiller and Li (2006) is built on correlation between the vertical gradient and the analytical signal of reduction to the pole magnetic anomaly. A similar idea was given by Gerovska et al. (2009) that uses cross-correlation between reduction to the pole and total magnitude magnetic anomaly. These methods can be applied to magnetic sources with arbitrary shapes but require they produce isolated magnetic

* Corresponding author.
E-mail address: guo_lianghui@163.com (L. Guo).

http://dx.doi.org/10.1016/j.jappgeo.2014.10.007
0926-9851/

anomalies and have homogeneous magnetization directions. The second is to transform magnetic anomaly into other quantities which are little affected by remanent magnetization and well related with the location of magnetic source and subsequently to do physical properties inversion on these transformed quantities. For instance, Shearer (2005) and Li et al. (2010) used 3D inversion of the amplitude of magnetic anomaly to reduce the effects of remanent magnetization. Pilkington and Beiki (2013) made 3D inversion using normalized magnetic source strength to suppress the influence of remanent magnetization. These methods are suitable to isolated magnetic sources as well as many magnetic sources with various magnetization directions, which generate a superimposed magnetic field. Their shortcomings include rough locations of magnetic bodies yielded by inversion, representing a vague result (Li et al., 2010; Pilkington and Beiki, 2013). And the third is to invert vectors of magnetization intensity directly, without needing any a priori information about remanent magnetization. Of this class, Wang et al. (2004) inverted 2D magnetization vector using a simple layered model. Lelièvre and Oldenburg (2009) suggested to invert magnetic data for a three-component subsurface magnetization vector in a Cartesian or spherical framework. Liu et al. (2013) employed magnitude magnetic anomaly to invert 2D magnetization vector from borehole magnetic data. Because of increased unknowns in inversions models, these approaches make intrinsic ill-conditioned and multiple-solution problems more severe. Overall, although all approaches of these three classes can reduce effects of remanent magnetization to some extent, they face some difficulties such as ill-conditioned equations, large calculation dimensions and huge computation amount in inversion. To tackle these problems, some algorithms were developed to further enhance inversion efficiency, such as data compression (Foks et al., 2014; Li and Oldenburg, 2003; Portniaguine and Zhdanov, 2002) and sparse-based inversion in the data space (Pilkington, 2009).

Based on the probability tomography approaches (Mauriello and Patella, 2001, 2008; Patella, 1997), Guo et al. (2011a, 2011b), Guo and Meng (2012) proposed the correlation imaging approach to achieve fast 3D imaging of gravity and magnetic data. This technique calculates the cross-correlation coefficients between theoretical and measured anomalies of the imaged points in the subsurface to characterize equivalent distribution of physical properties (in a probability sense). It does not require linear or nonlinear inversion calculation so that those problems in conventional inversion can be avoided, such as ill-conditioned equations, huge calculation dimensions and computation quantity. Up to now, this approach can be applied to fast imaging of various potential-field parameters such as gravity anomaly and its gradients, magnetic three components, total magnetic field anomaly and its gradients. Among them, the correlation imaging of total magnetic field anomaly and its gradients still need to know magnetization direction of the magnetic source. When the magnetic source contains strong remanent magnetization, its magnetization direction is much different from that of the geomagnetic field. Then if the direction of this geomagnetic field is simply used as the effective magnetization direction for correlation imaging, major errors would also appear in the results. In this situation, correlation imaging of the transformed quantity of magnetic anomaly become an alternative choice since it is little influenced by remanent magnetization and well corresponding to the location of the magnetic source.

As the total magnitude magnetic anomaly and the normalized magnetic source strength are little affected by remanent magnetization, and well corresponding to the location the magnetic sources (Li et al., 2010; Pilkington and Beiki, 2013), correlation imaging on both the parameters can yield better results. This work presents 3D correlation imaging approaches for these two parameters, respectively, which could reduce errors due to the influence of strong remanent magnetization. The synthetic data and real data from a metallic deposit in the middle-lower reaches of the Yangtze River are used to test the effectiveness of the approaches. The conventional 3D correlation imaging of vertical gradient of total magnetic field anomaly is also tested for comparisons.

2. Three-dimensional correlation imaging of total magnitude magnetic anomaly

At a survey area, we take a coordinate system with the (x, y)-plane at sea level and the z-axis positive downward. Suppose that an arbitrary magnetic dipole is presented at a point $q(x_q, y_q, z_q)$ in the subsurface, and its magnetic moment is $M_q = J_q v_q$ (where v_q is the volume and J_q is the magnetization intensity). The inclination and declination of the geomagnetic field are I_0 and A_0', respectively, while those of magnetization of the dipole are I and A' separately. The theoretical magnetic three components at an arbitrary station (x,y,z) on the observational surface caused by the dipole can be calculated by

$$\begin{cases} H_{ax,q}(x,y,z) = \dfrac{\mu_0 M_q}{4\pi} B_{x,q}(x,y,z) \\ H_{ay,q}(x,y,z) = \dfrac{\mu_0 M_q}{4\pi} B_{y,q}(x,y,z) \\ Z_{a,q}(x,y,z) = \dfrac{\mu_0 M_q}{4\pi} B_{z,q}(x,y,z) \end{cases} \tag{1}$$

where $r = \sqrt{\left(x_q - x\right)^2 + \left(y_q - y\right)^2 + \left(z_q - z\right)^2}$, $L = \cos I \cos A'$, $M = \cos I \sin A'$, $N = \sin I'$, μ_0 is the vacuum magnetic permeability and $B_{\alpha,q}(x, y, z)$ is the geometrical function of the dipole for magnetic α-component ($\alpha = x,y,z$) at the station,

$$\begin{cases} B_{x,q}(x,y,z) = \dfrac{1}{r^5}\Big[L\Big(2\left(x_q-x\right)^2 - \left(y_q-y\right)^2 - \left(z_q-z\right)^2\Big) \\ \qquad + 3M\left(x_q-x\right)\left(y_q-y\right) - 3N\left(z_q-z\right)\left(x_q-x\right)\Big] \\ B_{y,q}(x,y,z) = \dfrac{1}{r^5}\Big[3L\left(x_q-x\right)\left(y_q-y\right) \\ \qquad + M\Big(2\left(y_q-y\right)^2 - \left(x_q-x\right)^2 - \left(z_q-z\right)^2\Big) - 3N\left(z_q-z\right)\left(y_q-y\right)\Big] \\ B_{z,q}(x,y,z) = \dfrac{1}{r^5}\Big[-3L\left(z_q-z\right)\left(x_q-x\right) - 3M\left(z_q-z\right)\left(y_q-y\right) \\ \qquad + N\Big(2\left(z_q-z\right)^2 - \left(x_q-x\right)^2 - \left(y_q-y\right)^2\Big)\Big] \end{cases} . \tag{2}$$

Then the theoretical total magnitude (TM) magnetic anomaly at an arbitrary station (x, y, z) on the observational surface caused by the dipole can be expressed as

$$\begin{aligned} \mathrm{TM}_q(x,y,z) &= \sqrt{H_{ax,q}(x,y,z)^2 + H_{ay,q}(x,y,z)^2 + Z_{a,q}(x,y,z)^2} \\ &= \frac{\mu_0 M_q}{4\pi}\sqrt{B_{x,q}(x,y,z)^2 + B_{y,q}(x,y,z)^2 + B_{z,q}(x,y,z)^2} \end{aligned} . \tag{3}$$

The correlation coefficient between the real TM anomaly and the theoretical TM anomaly caused by the dipole is defined as

$$C_{\mathrm{TM},q} = \frac{\sum_{i=1}^{N_s} \mathrm{TM}(x_i,y_i,z_i)\mathrm{TM}_q(x_i,y_i,z_i)}{\sqrt{\sum_{i=1}^{N_s} \mathrm{TM}^2(x_i,y_i,z_i)\sum_{i=1}^{N_s} \mathrm{TM}_q^2(x_i,y_i,z_i)}}, \tag{4}$$

where $\mathrm{TM}(x_i, y_i, z_i)$ is the real TM anomaly at the station (x_i, y_i, z_i) and N_s is the total number of the observed stations.

In the above calculation, the magnetic moment of the dipole in Eq. (1) is supposed to be identical, i.e., $M_q = 1$.

The value of $C_{\mathrm{TM},q}$ in Eq. (4) reflects the cross correlation degree between the real TM anomaly and the theoretical TM anomaly due