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A stable downward continuation of airborne magnetic data: A case study for mineral prospectivity mapping in Central Iran

Maysam Abedi [a,*], Ali Gholami [b], Gholam-Hossain Norouzi [a]

[a] Department of Mining Engineering, College of Engineering, University of Tehran, Iran
[b] Institute of Geophysics, University of Tehran, Iran

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ABSTRACT

Previous studies have shown that a well-known multi-criteria decision making (MCDM) technique called Preference Ranking Organization METHod for Enrichment Evaluation (PROMETHEE II) to explore porphyry copper deposits can prioritize the ground-based exploratory evidential layers effectively. In this paper, the PROMETHEE II method is applied to airborne geophysical (potassium radiometry and magnetometry) data, geological layers (fault and host rock zones), and various extracted alteration layers from remote sensing images. The central Iranian volcanic-sedimentary belt is chosen for this study. A stable downward continuation method as an inverse problem in the Fourier domain using Tikhonov and edge-preserving regularizations is proposed to enhance magnetic data. Numerical analysis of synthetic models show that the reconstructed magnetic data at the ground surface exhibits significant enhancement compared to the airborne data. The reduced-to-pole (RTP) and the analytic signal filters are applied to the magnetic data to show better maps of the magnetic anomalies. Four remote sensing evidential layers including argillic, phyllic, propylitic and hydroxyl alterations are extracted from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) images in order to map the altered areas associated with porphyry copper deposits. Principal component analysis (PCA) based on six Enhanced Thematic Mapper Plus (ETM+) images is implemented to map iron oxide layer. The final mineral prospectivity map based on desired geo-data set indicates adequately matching of high potential zones with previous working mines and copper deposits.

1. Introduction

Mineral exploration aims to discover new mineral deposits in a region of interest. One of the main steps in mineral exploration is to distinguish prospective areas within the region of interest. Various thematic geo-data sets (e.g., geological, geophysical and geochemical data set) are collected, analyzed and integrated for mineral prospectivity mapping (MPM) to delineate prospective areas. Thus, MPM is a multiple criteria decision-making (MCDM) task and produces a predictive model for outlining prospective areas. There are several approaches to MPM, which can be categorized into data-driven and knowledge-driven methods (Bonham-Carter, 1994; Carranza, 2008; Pan and Harris, 2000). In data-driven or empirical techniques, the known mineral deposits in a region of interest are used as 'training points' to establish spatial relationships between the known deposits and particular geological, geochemical and geophysical features (Carranza et al., 2008a). The relationships between evidential maps and the training points are quantified and used to establish the importance of each evidence map (Carranza and Hale, 2002b, 2002c) and are finally integrated into a single mineral prospectivity map (Nykänen and Salmirinne, 2007). Examples of the empirical methods of MPM include weights of evidence (Bonham-Carter et al., 1989; Carranza, 2004; Carranza and Hale, 2000, 2002d; Porwal et al., 2006b), logistic regression (Agterberg and Bonham-Carter, 1999; Carranza and Hale, 2001b), neural networks (Abedi and Norouzi, 2012; Porwal et al., 2003a, 2004; Singer and Kouda,1996), evidential belief functions (Carranza and Hale, 2002a; Carranza et al., 2005; Carranza, 2008b), Bayesian classifiers (Abedi and Norouzi, 2012; Porwal et al., 2006a) support vector machines (Abedi et al., 2012b; Zuo and Carranza, 2011) and clustering methods (Abedi et al., 2012c). The other techniques, in which a geoscientist''s expert opinions are applied, are called knowledge-driven methods and include methods such as the use of Boolean logic (Bonham-Carter et al., 1989), index overlay (Bonham-Carter et al., 1989; Carranza et al., 1999), the Dempster–Shafer belief theory (Carranza et al., 2008b; Moon, 1990), fuzzy logic (An et al., 1991; Carranza and Hale, 2001a; Chung and Moon, 1990; Porwal et al., 2003b), wildcat mapping

* Corresponding author. Tel.: +98 9173124132.
E-mail addresses: MaysamAbedi@ut.ac.ir (M. Abedi), agholami@ut.ac.ir (A. Gholami), norouzih@ut.ac.ir (G.-H. Norouzi).

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(Carranza and Hale, 2002e; Carranza, 2010), and outranking methods (Abedi et al., 2012a, 2012d, 2012e).

Selecting the best area for exploratory drillings by considering many alternatives as a MCDM procedure is developed in our study, in which the results of application of a previously proposed approach that is called Preference Ranking Organization METHod for Enrichment Evaluation (PROMETHEE II) are considered (Abedi et al., 2012a). This method is applied to real data pertaining to the central Iranian volcanic-sedimentary belt located in Kerman. We have examined the application of the PROMETHEE II method to exploratory geo-data set including airborne geophysical data, geological layers (i.e., fault and host rock zones) and various extracted alteration layers from remote sensing images.

Porphyry-Cu deposits are associated with hydrothermal alterations such as phyllic/sericite, argillic, potassic and propylitic zones. Hydrothermal alteration minerals (i.e., sericite, biotite, K-feldspars and many K-bearing clay minerals) contain potassium (K) which is abundant particularly in the sericite zone. Therefore, K radiometric map can be as a tool for exploration of such geological feature (Ranjbar and Honarmand, 2004; Ranjbar et al., 2011). Airborne magnetic surveys, which are rapid and economic, have been traditionally employed for exploration of porphyry-Cu deposits. Porphyry intrusions and related alteration systems may have a characteristic magnetic signature, which can form a distinctive anomalous pattern in magnetic maps. These patterns may reflect the increased concentration of secondary magnetite in potassic alteration zones, or magnetite destruction in other lateral alteration zones or high magnetite in the original intrusive plutons responsible for mineralization (Daneshfar, 1997; Pazand et al., 2012).

Airborne magnetic data due to multi-source anomalies may overlap at a given height above the ground surface. Therefore, a stable downward continuation (STDC) method is needed to separate anomalies of multiple magnetite targets in order to enhance those locations. The downward-continued field is sharper and consequently causes better resolution of multi-source anomalies. The main problem associated with the STDC is presence of noise. Since the STDC process is an inverse problem in the Fourier domain, the amplification of high frequency data corrupted by noise is such intense during downward continuation of airborne magnetic data that it quickly masks the information of original data. Low-pass filtering suppresses the noise but blurs the signal and defeats the enhancement of multi-source anomalies (Trompat et al., 2003). Various methods have been proposed to deal with the STDC, in all of which increasing the resolution of downward-continued data is the main purpose (Cooper, 2004; Li and Devriese, 2009; Trompat et al., 2003; Xu et al., 2007). In this study, the Tikhonov and edge-preserving regularizations methods are proposed for inversion of airborne magnetic data in the Fourier domain to enhance magnetite sources. The reduced-to-pole (RTP) and analytic signal filters are also applied to downward-continued magnetic data to show better maps of magnetic anomalies for MPM.

The common alterations associated with porphyry-Cu deposits are namely argillic, phyllic, propylitic, hydroxyl and iron oxide zones. Band ratios of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) images are used to map argillic, phyllic, propylitic and hydroxyl alterations in the study area. Because of the absence of an ASTER image in the blue region of the spectrum, iron oxide minerals cannot be enhanced from the ASTER data. Therefore, Enhanced Thematic Mapper Plus (ETM+) images are used to map iron oxide alteration (Ranjbar et al., 2011). To reduce redundancy in the ETM+ images, the principal component analysis (PCA) as a multivariate statistical technique is used to extract a principal component (PC) layer related to iron oxide alteration. The desired MPM based on prepared evidential data layers is generated and finally compared to locations of previous working mines and copper deposits in the study area.

2. Stable downward continuation

Downward continuation calculates the magnetic field that is closer to the sources of magnetic anomalies. Magnetic data at two observation heights are related by the upward continuation operation (Blakely, 1995; Li and Devriese, 2009):

$$T_{z_2}(x,y,\Delta z) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{T_{z_1}(X,Y)\Delta z}{[(X-x)^2+(Y-y)^2+\Delta z^2]^{3/2}}dXdY, \quad \Delta z = z_2 - z_1 \geq 0 \tag{1}$$

where $T_{z_1}(X,Y)$ and $T_{z_2}(x,y,\Delta z)$are, respectively, magnetic data at two different heights separated by a vertical distance Δz. Applying two-dimensional Fourier transform to Eq. (1), it yields a simpler form in frequency domain as:

$$\tilde{T}_{z_2}(K_x,K_y,\Delta z) = e^{-\Delta z K}\tilde{T}_{z_1}(K_x,K_y) \tag{2}$$

where $\tilde{T}_z$ denotes the Fourier transform of T_z, (K_x,K_y) are wavenumbers in x- and y-directions, $K=\sqrt{K_x^2+K_y^2}$ is the radial wavenumber, and $e^{-\Delta z K}$ is the upward continuation operator. If we consider the Fourier transform of observed magnetic anomaly at height z_2, i.e., $\tilde{T}_{z_2}(K_x,K_y,\Delta z)$, as the data, and the upward continuation operator $e^{-\Delta z K}$ as a forward operator, Eq. (2) is an inverse problem in the Fourier domain to find a regularized solution of downward continuation of $\tilde{T}_{z_1}(K_x,K_y)$ in that domain. Finally, the two-dimensional inverse Fourier transform of a regularized solution is the STDC of airborne magnetic data at height z_1. The downward continued solution is numerically unstable because of the presence of high-frequency noise. However, we can stabilize the solution of the inverse problem using a regularized operator. In matrix notation, considering that there are n observations magnetic data, Eq. (2) can be written as:

$$[\tilde{d}_{up}]_{n\times 1} = G_{n\times n} \times [\tilde{d}_{down}]_{n\times 1} \tag{3}$$

where $\tilde{d}_{up}$ and $\tilde{d}_{down}$ are, respectively, the Fourier transform of the airborne magnetic data and the downward solution. The forward operator G is a diagonal matrix in which it contains the values of $e^{-\Delta z K}$. We describe two regularization methods in the following sections.

2.1. Tikhonov regularization

The linear operator G has a multidimensional null-space. Indeed, the solution has to be regularized (Caratori Tontini et al., 2006; Tikhonov and Arsenin, 1977). We suppose that data are contaminated with white Gaussian noise of zero mean and finite variance σ^2. In order to be able to compute an appropriate solution of downward continuation in Eq. (3), the linear relation of this equation can be replaced by a less ill-conditioned nearby relation. Indeed, the unknown downward continuation vector can be estimated by optimizing a Tikhonov cost function as (Aster et al., 2003):

$$f\left(\tilde{d}_{down}\right) = \arg\left(\min_{\tilde{d}_{down}}\left\{\left\|\tilde{d}_{up}-G\times\tilde{d}_{down}\right\|_2^2+\lambda\sum_i \varphi_{\tilde{d}_{down}}\left([L\times\tilde{d}_{down}]_i\right)\right\}\right) \tag{4}$$

The notation $[L\times\tilde{d}_{down}]_i$ denotes the ith element of the vector $L\times\tilde{d}_{down}$ and $\varphi_{\tilde{d}_{down}}(x)$ is a potential function that is selected based on a priori information/assumptions about the sought solution. Conventional Tikhonov regularization (Tikhonov and Arsenin, 1977) can be obtained from Eq. (4) by choosing