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Three-dimensional inverse modelling of magnetic anomaly sources based on a genetic algorithm

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ABSTRACT

We present a modelling method to estimate the 3-D geometry and location of homogeneously magnetized sources from magnetic anomaly data. As input information, the procedure needs the parameters defining the magnetization vector (intensity, inclination and declination) and the Earth's magnetic field direction. When these two vectors are expected to be different in direction, we propose to estimate the magnetization direction from the magnetic map. Then, using this information, we apply an inversion approach based on a genetic algorithm which finds the geometry of the sources by seeking the optimum solution from an initial population of models in successive iterations through an evolutionary process. The evolution consists of three genetic operators (selection, crossover and mutation), which act on each generation, and a smoothing operator, which looks for the best fit to the observed data and a solution consisting of plausible compact sources. The method allows the use of non-gridded, non-planar and inaccurate anomaly data and non-regular subsurface partitions. In addition, neither constraints for the depth to the top of the sources nor an initial model are necessary, although previous models can be incorporated into the process. We show the results of a test using two complex synthetic anomalies to demonstrate the efficiency of our inversion method. The application to real data is illustrated with aeromagnetic data of the volcanic island of Gran Canaria (Canary Islands).

1. Introduction

Magnetic surveying has been widely used over the years to map geological structures, especially through the reconnaissance and analysis of magnetic anomalies. Recently, Nabighian et al. (2005) reported the historical development of the magnetic method in exploration, including a review about techniques for estimating the depth to source and performing physical property mapping and inversion. Among the different approaches that aim to invert magnetic anomaly fields, the identification and characterization of magnetic source bodies in a three-dimensional context remains a difficult and challenging task due to several limitations: the inherent non-uniqueness of potential field inversion; the finite number of inaccurate measurements; and the vector nature of magnetization (the physical property responsible for crustal magnetic anomalies), which makes source modelling even more complex than when other fields are used, such as the gravity field.

To deal with the non-uniqueness problem, different strategies can be applied, such as imposing simple restrictions on admissible solutions based on the available geologic knowledge, integrating the magnetic data with other independent data sets or including constraints into the inversion procedure (e.g. Pilkington, 2009).

In recent decades, different potential field inversion techniques have been proposed, providing increasingly successful results. On the one hand, many magnetic modelling methods search for analytical solutions by means of linear optimization techniques, where the magnetization intensity of each cell in the subsurface model is to be found (e.g. Li and Oldenburg, 1996, 2003; Bhattacharyya, 1980; Portniaguine and Zhdanov, 2002). Some limitations of linear techniques are their dependence on the accuracy of the initial estimation of the model parameters and the decrease of resolution with depth (e.g. Fedi and Rapolla, 1999). On the other hand, non-linear modelling carried out with local optimization techniques (steepest descent, conjugate gradients, etc.) also shows some drawbacks due to the high non-linear mathematical formulation. In particular, non-linear techniques engender inherent discontinuities and local optima in the function to be minimized, where local

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optimization methods are likely trapped. For these reasons, local methods need to introduce particular constraints to manage the inherent ambiguity in the inversion of potential fields (e.g., Fullagar et al., 2008; Fedi and Rapolla, 1999; Pilkington, 2009).

Global optimization techniques constitute other approach to solve the inverse problem. Among them, genetic algorithms have been successfully used in several areas of geophysics and, in particular, for the inversion of potential fields (Boschetti et al., 1997; Chen et al., 2006; Montesinos et al., 2005; Currenti et al., 2005, 2007; etc.). Because the parameter space is typically very large, multimodal, and poorly understood, genetic algorithms have the advantage of performing a much broader search over the parameter space using a random process with a greater likelihood of finding a near optimal solution (Holland, 1975). Moreover, some genetic algorithms have been found to be more efficient than other global optimization methods (Grandis et al., 2002) and are more robust in finding the global minimum than local optimizations such as conjugate gradient methods (Wang and Lilley, 1999; Handa, 2005).

In particular, to solve the magnetic inverse problem, we propose a method based on a genetic algorithm to identify the 3-D geometry and location of magnetic anomaly sources with known magnetization. Due to the similar formulation of the gravitational and magnetic inverse problem, many methods that were developed for gravity prospecting have been applied to magnetic exploration and vice versa. Our method is based on the gravity inversion algorithm of Montesinos et al. (2005), which minimizes a misfit function to find a source model that fits the magnetic data and is reasonable from a geological point of view.

Different approaches have been proposed in the literature for the same purpose. Many authors suggested minimizing an objective function (error or misfit function) comprising two terms: the data misfit and the model norm (e.g., Li and Oldenburg, 1996; Portniaguine and Zhdanov, 2002). Chasseriau and Chouteau (2003) proposed a stochastic approach, whereas Van Zon and Roy-Chowdhury (2006) used linear programming, and Pilkington (1997) applied a generalized conjugate gradient solver. Recently, Kim et al. (2014) solved the magnetic inverse problem by systematically searching for a model that minimizes an error function adapted from the method developed by Camacho et al. (2000) for gravity data.

In this paper, we assume that the sources are characterized by a constant magnetization value, both in intensity and direction, which must be understood as a bulk magnetization that is known in advance. Obviously, actual geological sources are made up by portions that can be heterogeneous from the magnetic point of view, with remanent magnetizations and susceptibilities that can vary within their volume. However, the sampling of the magnetic anomaly of a geological structure at a certain height over its top results in a 'filtering' of local heterogeneities, so that the effect is that of a nearly homogeneous body characterized by a bulk (average) magnetization. This is a usual assumption in magnetic inversion. Therefore, our method is useful for interpreting magnetic maps consisting of a limited number of dipolar anomalies, so that each of them can be modelled by a homogeneously magnetized body.

In addition, the method allows consideration of different directions for the source magnetization and the Earth's magnetic field. This extends the applicability of the method to geological contexts in which the remanent part of the magnetization vector is not negligible, such as in volcanic areas. In these situations, we suggest the estimation of the magnetization direction as a first step of our modelling procedure to be used as input information for the inversion.

As a second step, our inverse approach models the geometry of magnetic sources in a 3-D context from non-gridded and/or non-planar anomaly data. The parameterization of the subsurface consists in a partition of cells with non-regular or regular sizes. No constraints for the depth to the top of the sources are necessary and although an initial model is not needed, a priori models can be incorporated into the process.

We tested the efficiency of the proposed inversion method with several complex synthetic anomalies and real datasets. Here, two examples and the application to aeromagnetic data from the volcanic island of Gran Canaria (Canary Islands) are shown.

2. Methodology

The proposed inversion method is based on the hypothesis that no information about the geometry and location of the magnetic anomaly source is available. Instead, the parameters that define the magnetization vector (intensity, declination and inclination) must be known in advance. In the following paragraphs, we explain the modelling approach that we propose for interpreting magnetic anomaly sources, which comprises, as a first step, the total magnetization vector estimation, and then the 3-D inversion by means of a genetic algorithm.

2.1. The total magnetization vector of the source

The physical property of rocks that is responsible for the magnetic field of crustal origin (or magnetic anomaly field) is magnetization ($\mathbf{J}$), which is related to the presence of small quantities of magnetite and other magnetic minerals. It consists of two terms: induced and remanent. Induced magnetization ($\mathbf{J_i}$) is parallel to the Earth's present magnetic field and can be calculated as the product of the rock's magnetic susceptibility (χ) and the magnetic field intensity ($\mathbf{H}$):

$$\mathbf{J} = \mathbf{J_i} + \mathbf{J_r} = \chi\mathbf{H} + \mathbf{J_r}$$

where the bold letters are vector quantities. Remanent magnetization ($\mathbf{J_r}$) is acquired by different mechanisms (thermoremanent, depositional, chemical, etc.) throughout the rock's past history. Therefore, its direction is, in the general case, different from the Earth's present magnetic field direction. Thus, the total magnetization vector is the sum of the induced and remanent magnetizations with a direction defined by a declination (D) and an inclination (I), which are generally different from the declination and inclination of the Earth's present magnetic field, which can be calculated with the International Geomagnetic Reference Field, IGRF (see Finlay et al., 2010, for information regarding the eleventh generation of the IGRF).

Most inversion methods assume that magnetization is parallel to the Earth's magnetic field, then neglecting the remanent part of the vector. In many geological contexts, this assumption may be reasonable but cannot be generalized. For instance, in volcanic environments, remanent magnetizations are usually several orders of magnitude larger than induced magnetizations (Hunt et al., 1995) and its effect on the anomaly pattern is crucial (e.g. Roest and Pilkington, 1993). Therefore, when the magnetization direction is expected to differ significantly from the direction of the Earth's magnetic field, it is essential to gather some information about it prior to the inversion. To do this, the interpreter can choose among different options. One way to estimate the total magnetization direction is the use of paleomagnetic data. However, this approach has some limitations because paleomagnetic data are not always available, and when they are, the magnetic properties of outcropping geologic units can be quite different from the magnetic properties of the subsurface bodies, which many times are the main sources of the observed anomalies. Another procedure is to calculate the magnetization direction from