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Refinement of three-dimensional multilayer models of basins and crustal environments by inversion of gravity and magnetic data

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Abstract

The sensitivity of gravity and magnetic data to deep structures and the broad availability of regional data sets and surveys of high resolution make them suitable for determining detailed three-dimensional (3D) models of the subsurface. However, the sole consideration of gravity and magnetic information cannot properly resolve heterogeneous 3D environments. Advocated to solve this problem, we present an automated refinement technique for three-dimensional multilayer models as conditioned by gravity and magnetic data and by meaningful geometrical and physical constraints. We construct our model by an aggregate of rectangular prisms and aim to estimate their bottom depths, which define the geological layers. We summarize mathematically our concept of refinement in an objective function that includes the misfit to the data, the similitude to an a priori geological–geophysical model, and the smoothness of the relief of the layers. Importantly, our objective function also includes inequality constraints that prevent the superposition of layers and integrate the surface and borehole geology with the multilayer deep model. The objective function is solved using quadratic programming in a stable iterative scheme. The resulting algorithm is tested on synthetic data and applied to crustal and sedimentary basin environments from southern Baja California, Mexico. The assimilation of the geological and geometrical constraints to the inversion process produces models that correlate with the surface geology and reveal the three-dimensional features of the subsurface.

Keywords: Gravity data; Magnetic data; Joint inversion; Sedimentary basins; Integration of geophysical data

1. Introduction

The sensitivity of gravity and magnetic data to deep structures, along with the relatively low surveying costs, have made these data widely available and appropriate to the study of sedimentary basins and deep structure of oceanic and continental crust. For these environments, the full potential of the data is exploited only when the geophysical model incorporates all the geologically meaningful elements available using heterogeneous three-dimensional (3D) models.

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Unfortunately, the capability of resolution of gravity and magnetic data for this type of models is limited, since they can have different structures that equally reproduce the data. Additional geological–geophysical information plays then an important role as it narrows the range of possible models. A successful procedure to integrate complementary geophysical data of high-resolution, namely, seismic or electromagnetic data, are found in algorithms of joint inversion of disparate data sets (e.g., Lines et al., 1988; Haber and Oldenburg, 1997; Gallardo and Meju, 2004). However, such information is not easily acquired in the form of 3D surveys, and 3D joint inversion algorithms for this type of data remain to be developed.

A more conventional procedure to incorporate alternative geophysical information is the use of an a priori model, that is refined using trial-and-error forward modeling techniques (e.g., Götze and Bernd, 1988). Although the trial-and-error techniques have the advantage that independent geological information can be easily included, the simultaneous fit of gravity and magnetic data in 3D environments becomes a difficult task. A desirable procedure should be to extend this flexibility to inverse or automatic-fitting algorithms, which would fit gravity and magnetic data swiftly but still control a relatively complex 3D model. However, to our knowledge, there is no computational algorithm available with these characteristics, and a preferred option is still the simultaneous use of multiple forward and inverse modeling techniques (e.g., Anderson et al., 2004). We aim to solve this problem by developing a flexible inversion algorithm for gravity and magnetic data using complex 3D models.

To focus on an appropriate model, we consider that there are two main approaches for converting gravity and magnetic data into subsurface models. In a first approach, the subsurface is defined as an aggregate of basic elements (usually small prisms) with fixed geometries and dimensions whose individual values of density and magnetization are the object of the inversion. Safon et al. (1997), Bear et al. (1995), and Li and Oldenburg (1998) follow this approach and show appropriate models only for massive (one-body) structures. The second approach also relies on similar elements, but their geometries or dimensions are varied and improved in an iterative process. The list of inversion procedures that follow this second approach is significantly large (e.g., Cordell and Henderson, 1968; Chai and Hinze, 1988; Barbosa et al., 1997, 1999; Gallardo-Delgado et al., 2003). However, despite the variety in the model formulation and regularization techniques applied, none of them can be proclaimed as appropriate for heterogeneous 3D models.

In this work, we follow the second approach, aiming to improve the definition of the geometry of 3D structures in the form of multiple layers. A major complication for an inversion procedure that follows this approach is the incorporation of an a priori model and its appropriate guiding constraints that lead the process towards geologically meaningful models. In our perspective, this problem limits to a great extent the use of gravity and magnetic data in three-dimensional environments and its solution constitutes the main thrust of this paper.

In what follows, we first define the conceptual multilayer model and describe how it is parameterized into a quantitative model. We then briefly describe formulae to compute its gravity and magnetic responses and show how to incorporate alternative information effectively into an objective function. There follows a short account of the solution of the objective function to refine the a priori model. The algorithm is tested on a synthetic example and applied to gravity and magnetic data from southern Baja California, Mexico in a regional (crustal) case and in a basin scale example.

2. The three-dimensional multilayer model

A gather of geological layers constitutes our basic model, where each layer is assigned a depth-dependent density and a vector of magnetization, both constant along the layer. Letting density vary with depth accommodates the fact that the density of a sedimentary filling behaves predictably with depth and can reduce the number of layers required. On the other hand, the use of magnetization vectors rather than susceptibilities allows its application to permanently magnetized environments, e.g., spreading centers or rifts.