Geologically-inspired Constraints for a Potential Field Litho-inversion Scheme

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1. Abstract

We describe a gravity and magnetic potential field litho-inversion scheme to assist with 3D geological mapping. The use of 'litho-category' as the primary variable and 'density' and 'magnetic susceptibility' as secondary variables has a natural appeal for most geoscientists. This formulation eliminates the need for a post-inversion interpretation phase to distil physical property information into the form of a geological map, and provides a convenient framework for describing spatial and statistical prior physical property knowledge. One of the major obstacles to the litho-inversion approach, construction of an initial litho-model, has been largely removed by linking the inversion to a program that rapidly generates 3D geological maps. Utilising a Bayesian approach to inversion, a large number of models is generated, each with known likelihood with respect to the observed potential field data. We gradually modify the geometry of the litho-regions whilst respecting the elements of the model that the user has specified as being points of known litho-category. Secondary density and magnetic susceptibility models are produced by noting the category value for the selected model element and randomly re-sampling the physical properties from the statistical distribution supplied for the relevant litho-category. The present scheme would be significantly enhanced by the following; (1) a method for obtaining convergence during exploration of the very large parameter space, and hence allowing the full posterior probability density function to be computed, (2) a method to track changes in the axes that define any asymmetry in the physical property distributions as the boundaries of the litho-regions are modified, and (3) a suitable representation for tectonic surfaces in the litho-model.

2. The Contribution of Potential Field Data to Geological Mapping

We required a potential field inversion method to assist with geological mapping rather than the more common application of characterising the source of a discrete anomaly. Geological maps are a representation of the spatial elements of geological knowledge for a particular moment of past or present time (Perrin et al., 2005). This form of information is used as the foundation for many geoscience applications. Each map is conditional on a set of litho-categories, generally defined using a number of criteria (e.g., lithology, age, physical properties, structural properties, etc.). The spatial domain of the map is subdivided into litho-regions such that each region is occupied by material belonging to just one of the litho-categories. Geological maps have traditionally been 2-dimensional

(2D), not through choice but as a consequence of the difficulties in constructing and displaying 3-dimensional (3D) maps. Although tools have been developed to alleviate these difficulties (e.g., “3D GeoModeller”; Lajaunie et al., 1997; Chiles et al., 2004), a more fundamental issue for 3D mapping remains in that there are insufficient geological observations to unambiguously define the boundaries of the litho-regions.

This ambiguity can be reduced by inverting complementary datasets, provided (a) the data are a function of the 3D distribution of a source, (b) the response of a given 3D source distribution can be calculated, and (c) the source distribution shows some degree of correlation with the litho-regions. Gravity and magnetic potential field data generally satisfy these criteria. Unfortunately, these data do not allow source geometry to be uniquely resolved through inversion (Boschetti et al., 1999), nor is the source geometry likely to be perfectly correlated with the litho-regions. Even under these conditions, the expression for the posterior probability density function (PPD) for a Bayesian inversion procedure (Eq.1.2 of Gelman et al., 2004) can be used to demonstrate how prior geological knowledge is modified by investigating the fit to observed potential field data for various models;

$$P(\mathbf{m} \mid \mathbf{d_o}) = k\rho(\mathbf{m})L(\mathbf{d_o} \mid \mathbf{m}) \tag{1}$$

where k is a normalizing constant, $\rho(\mathbf{m})$ is the prior probability for the property model $\mathbf{m}$ based on geological knowledge, and $L(\mathbf{d_o} \mid \mathbf{m})$ is the likelihood function that reflects the agreement between the observed potential field response and the predicted response of the model. Litho-models that have reasonable probability based on prior knowledge are downgraded if the likelihood deduced from the associated potential field response is very low. Conversely, many so-called ‘mathematical’ solutions for the source geometry that have reasonable likelihood values can be discounted because they have very low prior probability based on available geological knowledge and hence low overall PPD.

3. Previous Approaches to Potential Field Inversion

Many potential field inversion schemes have been developed to allow different representations of geological prior information to be supplied (Jessell, 2001). Pratt et al. (2001) describe a deterministic discrete object method that automates many aspects of model building and parameter optimisation once a class of geological object has been specified by the user. Although this approach is an efficient way to model individual features, it is not designed as a general mapping technique. Li and Oldenburg (1996, 1998a) describe a more general deterministic approach for inversion of magnetic and gravity data using a mesh of rectangular prisms. Geological information is supplied via reference magnetic susceptibility and density models that can be constructed by populating regions within a geological model with appropriate physical property values (Williams et al., 2004). This form of inversion does not support simultaneous inversion of gravity and magnetic data, and requires an additional interpretation phase to convert the physical property perturbations that are defined during the inversion into a series of modifications to be made to the initial geological model.

A litho-model approach for parameterization of the model can be used to avoid the vexed interpretation step of inferring geological units from physical property values. By making the physical property values conditional to the litho-categories, it is also possible to simultaneously invert multiple data types (e.g., gravity and magnetics). Fullagar et al. (2004) describe a deterministic litho-inversion method where the model volume is discretised into a series of close-packed vertical rectangular prisms. Since the primary model remains in litho-format, the results are readily integrated back into a 3D geological map and transferred to other applications. Farrell (2000) describes a genetic inversion method that refines “geological history” parameters based on a potential field likelihood function. This work builds on the “kinematic” or “history” modeling approach for generating a 3D geological map described by Jessell and Valenta (1996). Unfortunately, it is conceptually difficult to prescribe a sequence of overprinting events that combine to accurately reproduce the litho-regions shown in a geological map.

A Bayesian approach to potential field litho-inversion is described by Bosch (1999), Bosch and McGaughey (2001), Bosch et al. (2001) and Guillen et al. (2004). In these examples, both the geometry and properties of litho-regions are varied and hence, the inversion becomes a non-linear problem (Al-Chalabi, 1971). The authors argue that a better appreciation of the PPD is obtained by generating and storing a large number of models rather than using a deterministic approach to locate a single ‘optimal’ model, or possibly a small number of such models obtained with different start models or inversion parameters. In this paper, we present both implemented and proposed modifications to these Bayesian approaches whereby additional geological and physical property constraints can be incorporated.

4. Structure of the Present and Proposed Schemes

The most significant change from the approach described by Bosch et al. (2001) has been an extension from 2D to 3D, first described by Guillen et al. (2004). This enables effects of a 3D source that are expressed in the potential field data to be properly taken into account when adjusting the litho- and property models. A 3D geological map is supplied as the starting model in the form of a mesh of right rectangular prism elements. During inversion, the boundaries separating homogeneous litho-regions are progressively modified by re-assigning the litho-categories for voxels adjacent to the boundaries. To be confirmed as a suitable candidate, each new model is assessed with respect to a set of prior constraints.

Prior geological knowledge includes a specification for the degree of complexity that is most likely to be observed in the geometry of the litho-boundaries. If left unchecked, the method used to modify the boundaries of the litho-regions tends to produce highly convoluted boundaries. Bosch (1999) and Bosch et al. (2001) used volume and aspect ratio functions for the regions occupied by each litho-category to control the boundary complexity. To perform a similar task, Farrell (2000) used a “surface energy” function equal to the proportion of immediate neighbours with the same lithology (i.e., a value of X/26 where X is the number of prisms with the same lithology and a node in common with the prism under consideration). In the present scheme, morphological filtering is used to smooth the boundaries. Dilation, erosion, and their combinations, opening (i.e., erosion followed by dilation) and closing (i.e., dilation followed by erosion) are applied to entire litho-region boundaries using to a schedule defined by the user.

A range of options to hold elements of the model fixed during an inversion session are being implemented to make it easier to test different ‘hard data’ options; (a) all of the prism elements that form the surface layer (i.e., simulating a situation where the lithology is known at all surface locations), (b) all of the elements of a particular litho-category that lie on a boundary (i.e., testing an hypothesis that the geometry for this litho-category is known), and (c) all of the prisms that hosted a point observation used to build the initial 3D litho-model (i.e., representing scattered knowledge of lithology from surface outcrops and/or drill holes).

A degree of heterogeneity is generally expressed in the prior knowledge of the properties for each litho-category. Almost certainly, use of a single representative physical property value for each litho-class will compromise the fit to the observed potential field data. In some instances, use of simple distributions will suffice (e.g., normal, lognormal, etc.). In other cases, we need to be able to simulate more complex distributions. By incorporating composite distributions (i.e., the weighted sum of simple distributions) or a completely general probability density function, we can simulate quite complex distributions.

5. Unresolved Difficulties With Either the Present or Proposed Schemes

At present, there is no support for prior knowledge of spatial correlation for properties within a litho-region (e.g., layering, lenses, etc.). We are considering introducing sub-classes or ‘facies’ for each litho-category. Using a transition probability approach (Carle and Fogg, 1997), a relatively small number of parameters would be required to define both the stationary property distribution and the geometrical aspects for the facies within each litho-region. However, to simulate anisotropic property distributions, we must know the principal axes of orientation for each element in the mesh. In a general mapping application, the orientation will vary as a function of position within the model. The 3D mapping algorithm that we use to generate the initial litho-models could supply orientation information for the single axis perpendicular to the litho-region boundaries (Lajaunie et al., 1997; Chiles et al., 2004). This would be sufficient to simulate the most common situation where layering is parallel to the litho-region boundaries. However, the orientation information would only be relevant to the initial model. A method to update these orientations as modifications are made to the boundaries during an inversion session will also be required.

‘Tectonic surfaces’ such as faults and thrusts are an integral part of geological knowledge and 3D geological maps (Chiles et al., 2004; Perrin et al., 2005). In the present context, these surfaces would act as dislocations or complete discontinuities for spatial operations such as the assessment of topology and calculation of spatial correlation. We are yet to devise an appropriate paradigm that would define the representation, modus operandi and spatial perturbation mechanism of these features.

Except in the very simplest of examples, the extent of the parameter space for potential field inversion is such that the present method cannot hope to obtain convergence in statistics that would indicate adequate exploration of the space. This means that conclusions drawn from analysis of the model ensemble must be viewed as the product of a limited exploration in the vicinity of the parameters in the initial model.

The potential field response is calculated for a model of finite extent. Prior to inversion, adjustments need to be made to the geophysical data to remove the response of material that will not be considered during the inversion phase. This process is generally referred to as ‘regional removal’, and it is one of the most contentious steps in potential field modeling. Roach et al. (1993), Leaman (1994) and Li and Oldenburg (1998b) provide some guidance. The inversion approach described here doesn’t offer any new insight into this matter, and it is left to the user to justify any modification that is made to the observed data.

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