

CONSTRAINING GRAVITY AND MAGNETICS INVERSIONS FOR MINERAL EXPLORATION USING LIMITED GEOLOGICAL DATA

Nicholas Williams^{1*}, Douglas Oldenburg², Peter Lelièvre³

The University of British Columbia – Geophysical Inversion Facility, Dept. Earth & Ocean Sciences, 6339 Stores Road, Vancouver, V6T 1Z4, Canada, nwilliams@eos.ubc.ca¹

Geoscience Australia, GPO box 378, Canberra, ACT, 2601, nick.williams@ga.gov.au¹

The University of British Columbia – Geophysical Inversion Facility, Dept. Earth & Ocean Sciences, 6339 Stores Road, Vancouver, V6T 1Z4, Canada, doug@eos.ubc.ca²

The University of British Columbia – Geophysical Inversion Facility, Dept. Earth & Ocean Sciences, 6339 Stores Road, Vancouver, V6T 1Z4, Canada, plelievre@eos.ubc.ca³

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INTRODUCTION

Mineral exploration produces a large amount of diverse geological and geophysical data, yet it can be difficult to combine all of this information into integrated models of subsurface geology. Gravity and magnetic data are the two most common geophysical datasets used in mineral exploration. They are commonly interpreted by developing 2D or 3D geological models, forward modelling the geophysical response, and modifying the models until they explain the observed data. Inversion techniques have also been developed to calculate 2D or 3D physical property models that explain observed geophysical responses. However, inversion of potential field data is hindered by the non-uniqueness of solutions.

Application of default, geologically-unconstrained inversions to obtain estimated subsurface physical property models from gravity and aeromagnetic datasets is a common step in many exploration programs. Although the recovered models can help target anomalous features in the subsurface, a reliable model, consistent with all observed geological and geophysical information, can only be recovered by including geology-based constraints with the standard mathematical constraints.

The University of British Columbia – Geophysical Inversion Facility's (UBC-GIF) GRAV3D and MAG3D gravity and magnetic inversion packages (Li and Oldenburg, 1996, 1998) are particularly well suited to early stages of exploration where prior geological knowledge is limited. They seek density or magnetic susceptibility models that minimise the function:

$$\phi = \phi_d(\mathbf{m}) + \phi_m(\mathbf{m}) \quad (1)$$

where $\phi_d(\mathbf{m})$ measures the geophysical data misfit associated with the model, and $\phi_m(\mathbf{m})$ is an objective function that describes a model \mathbf{m} that is small, containing as little deviation from a reference model (m_{ref}) as possible, and has certain smoothness characteristics. It is:

$$\begin{aligned} \phi_m(\mathbf{m}) = & \alpha_s \int w_s w^2(z) (m - m_{ref})^2 dv + \alpha_x \int w_x \left(\frac{\partial \{w(z)(m - m_{ref})\}^2}{\partial x} \right) dv \\ & + \alpha_y \int w_y \left(\frac{\partial \{w(z)(m - m_{ref})\}^2}{\partial y} \right) dv + \alpha_z \int w_z \left(\frac{\partial \{w(z)(m - m_{ref})\}^2}{\partial z} \right) dv \end{aligned} \quad (2)$$

where $m - m_{ref}$ is the deviation from the supplied reference model in each cell, w_s , w_x , w_y , and w_z are weights indicating the relative importance of smallness and smoothness throughout the model, α_s , α_x , α_y , and α_z are global smallness and smoothness weights, and $w(z)$ is a depth weighting function. The recovered model must also lie between specified bounding values in each cell.

THE UBC-GIF GEOLOGICAL CONSTRAINTS

Common located geological information that can be incorporated as inversion constraints includes: surface information, drilling, cross sections, and volume interpretations. Surface samples, maps, and drill holes may supply actual physical property measurements, or geological observations and interpretations from which physical property values can be estimated. Cross sections and lithological volumes represent 2D and 3D interpretations of subsurface geology for which physical property estimates can be specified.

Available geological information must be translated into a reference model, bounds, and smallness and smoothness weights. Default values are assigned where information is unavailable. The reference model consists of the best estimate of the arithmetic mean physical property value in each cell in the model. Smallness weights (w_s) specify the reliability of the reference model in each cell. The weights are unit-less; the default is unity, but increased confidence in the reference property estimate for each cell can be indicated with higher values.

Bounds provide a powerful means of enforcing a particular range of properties within a region or unit where the physical properties are known to vary, or are difficult to define exactly. They can be supplied with or without a non-default reference model. Since the reference property in each cell should be an estimate of the mean property, it is useful to consider the bounds as a confidence interval on that estimate of the mean at a particular confidence level, such as 95 %.

Directional smoothness weights (w_x , w_y , and w_z) can be defined for each individual cell face. This helps define the texture of the model. The default values are unity. Values < 1 encourage breaks in model smoothness across known faults or lithological boundaries; values > 1 indicate that properties in adjacent cells are expected to be correlated.

Where constraint information is only available in a limited number of cells, a smooth model style of inversion is required to help extrapolate observations into adjacent cells that lack constraints. The existing UBC-GIF software normally uses a smooth model-difference style that ensures that differences between the reference model and the recovered model are distributed over a number of cells. This approach reproduces any sharp breaks in the reference model as sharp breaks in the recovered model. However, smooth model inversions can be achieved in the existing software by specifying a uniform (zero) reference model everywhere, and supplying the geological constraints using only tight bounds where observations are available.

SYNTHETIC GEOLOGICALLY-CONSTRAINED INVERSION EXAMPLE

A synthetic example based on a nickel sulphide exploration scenario is used to demonstrate the benefits of including even a small number of typical geological constraints in gravity inversions. The area has a dipping, north-south-striking granite-greenstone basement, but extensive regolith cover limits basement outcrop (Figure 1). The gravity data for the area was calculated from the true density contrast model on a regular grid with noise added. The smooth model style of inversion is used in all inversions. All inversions presented below show acceptable data misfits and reproduce the observed gravity data.

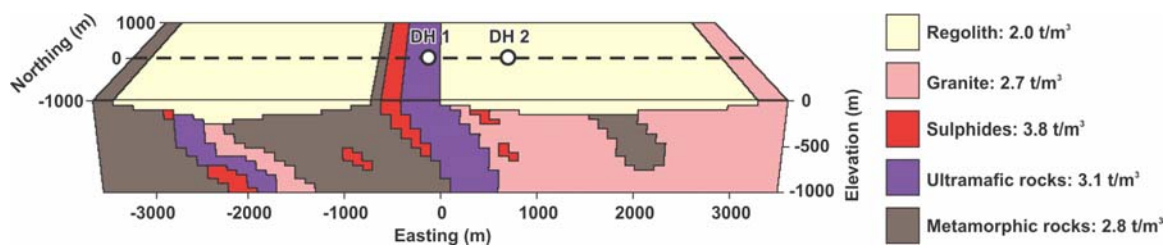


Figure 1: Perspective view of the actual synthetic geology model, looking down to the north. The dashed black line shows the position of the cross-sections shown in later figures, and the two white circles indicate the collar locations of two drill holes. The legend indicates the actual densities assigned to each rock unit in the true density model. The UBC-GIF inversion and forward modelling packages expect density contrasts rather than densities; density contrasts are obtained by subtracting a constant 2.8 t/m^3 from all densities prior to modelling.

The only geological information available to the explorer is from surface mapping, density measurements, two deep drill holes, and structural observations. A greenstone belt outcrops above the centre of the volume to be modelled. An ultramafic unit with significant massive nickel sulphide mineralisation is present in this belt, but rocks are deeply weathered on both sides. The explorer wants to delineate the main sulphide body, and hopes to identify additional resources below cover.

Default, Geologically-Unconstrained Inversion

A geologically-unconstrained gravity inversion was performed using default settings. A vertical cross-section is shown in Figure 2 alongside the true densities from the geological model. The result is an acceptable first pass reproduction of the real geology. It captures the position and dip, but not the shape and size of the main sulphide body (A). It also suggests the presence of the central main ultramafic that hosts the main sulphide body, but its extent, properties and dip are poorly defined. An explorer's interest may be drawn to the location and extent of any shallow density anomaly which might provide a prospective mineralisation target. Anomalies at positions B-C do correspond to buried sulphide bodies, but there are several anomalies of similar size and magnitude that do not correspond to sulphide bodies (D). These are false positive targets. Without any knowledge of the subsurface, the most obvious deficiency in this recovered model is the absence of low density zones at surface where well developed regolith profiles are known to exist at surface (E). The extremely large low density features at depth (F) are geologically unrealistic as is the extreme size and depth extent of the density anomaly associated with the main sulphide body (G). Although the result could be used to plan exploration targets (A-D), it seems unwise given that the result is not consistent with the geological information that is available from mapping, even at shallow levels (E).

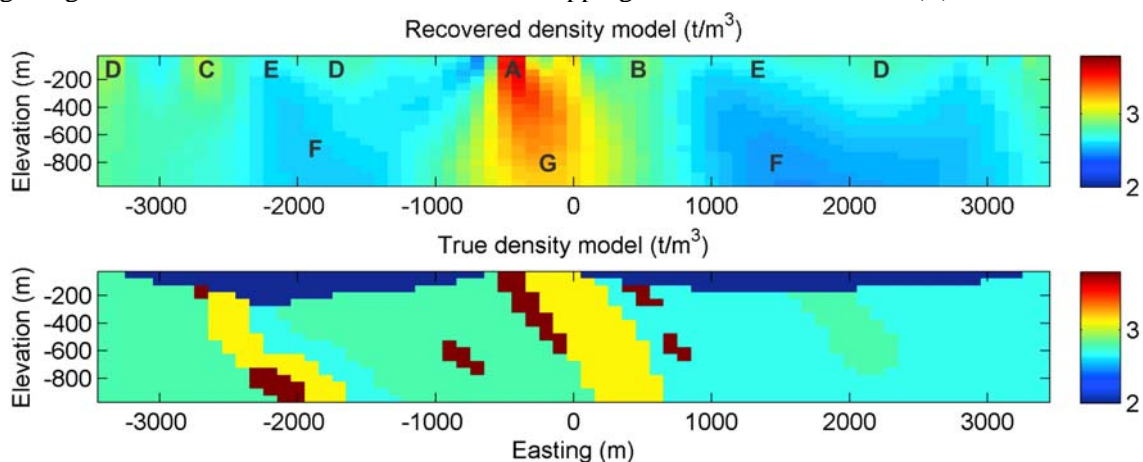


Figure 2: A default, geologically unconstrained inversion result compared against the true density model. Cross section is in the position of the dashed line in Figure 1. The result does capture some of the key features of the geology. Locations A-D shows possible target anomalies, however the three D locations

represent false positive anomalies with no sulphides present. Locations E-G show major discrepancies between the two models.

Geologically-Constrained Inversion

The geological information available includes surface mapping, two deep drill holes, density measurements and some understanding of the structural trends from mapping. This information can be translated into a set of geological constraints to enhance the reliability of the result. The reference model properties and bounds in the top layer of mapped cells and along the two drill holes are based on available physical property measurements and estimates. The constraints are developed automatically from the raw geological data using the methods of Williams (2008) and Williams and Oldenburg (submitted).

The observed structural orientations, a north-south strike and an easterly dip, are also translated into constraints. The observations provide information about the global geometry of the model which can be used to specify appropriate smoothness weights. Structural observations from mapping and drilling also provide information about local geological trends. The trends are used to extrapolate the geological constraints from those cells containing observations into adjacent cells that lack direct observations. This buffering technique is described in detail by Williams (2008) and Williams and Oldenburg (submitted) and uses distance weighting in ellipsoidal buffers defined by observed or inferred structural orientations. Without extrapolation of the constraints prior to inversion, only 5.0 % of the 42,000 cells in the volume of interest contain non-default constraints. Inversions using only these data-based constraints provide a much more reliable result than the default model in Figure 2. However, geological experience, structural observations, and other evidence suggest that the observations in one model cell may tell us something about adjacent cells in the directions of the observed structural orientations. The extrapolation seeks to reproduce this expectation and provides some form of constraint for 14.7 % of the cells.

The reference model, smoothness weights, and bounds used in the inversion are shown in Figure 3 alongside the recovered density model and the true model. The result is clearly a more accurate depiction of the true geology than the default result shown in Figure 2. The recovered model reproduces the known geology and has a geologically-realistic appearance. Without additional geological data it must be considered entirely plausible. Comparison with the default result (Figure 2) shows that all the previous false positive anomalies have been eliminated. All remaining anomalies are actually associated with sulphide bodies that have not yet been intersected. These should be considered as quality targets worthy of follow up.

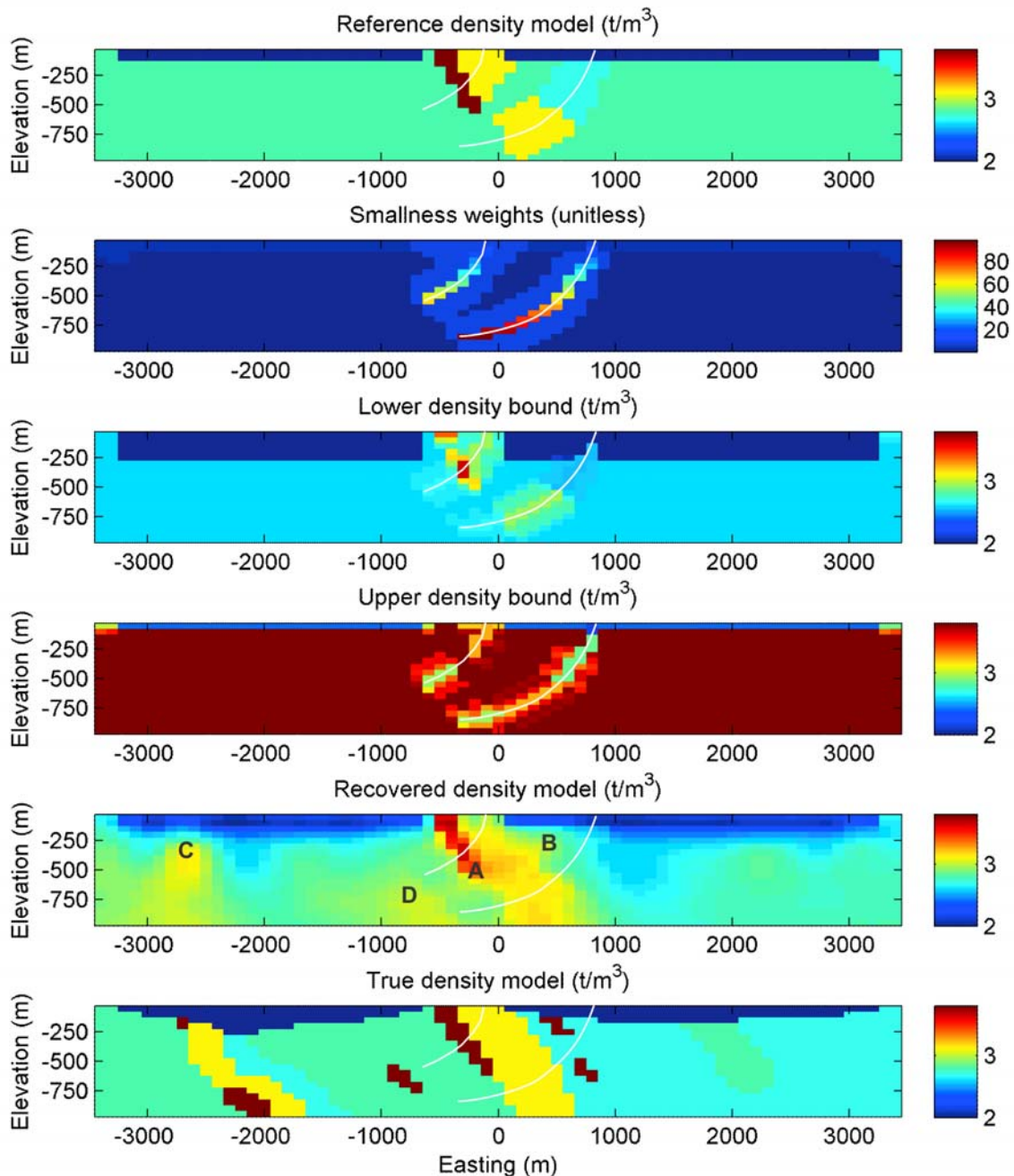


Figure 3: A geologically-constrained inversion result, showing the supplied reference model, smoothness weights, and bounds constraints based on mapping, drilling, and buffer extrapolation. The buffers represent ellipsoids defined by the measured or inferred strike and dip in each location. The strength of the constraints decreases with distance from the observation locations to indicate increasing uncertainty. The main sulphide body (A) is much more accurately resolved, and the smaller more subtle sulphide bodies at B-D are also well resolved.

CONCLUSIONS

A specific capacity of the UBC-GIF inversion approach is its flexibility to include as much or as little geological information as is available using a best estimate reference property model, limiting bounds, and weights for controlling smoothness or roughness. In early phases of exploration, default inversions may be used to locate possible anomalous regions. As more geological data becomes available during exploration, more constraints can be included to further refine the recovered physical property models, and therefore enhance their potential for targeting. Constraints based on the raw geological data can be included without the additional

interpretation required to build a full 3D model. The key to successful development and refinement of geophysical inverse models is to include all available information and to update the constraints as soon as new information becomes available.

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