Applying UBC-GIF potential field inversions in greenfields or brownfields exploration

Nicholas C. Williams
Mineral Deposit Research Unit
Dept. Earth and Ocean Sciences
The University of British Columbia
6339 Stores Road
Vancouver, BC, V6T 1Z4
Canada
nwilliams@eos.ubc.ca

SUMMARY

The University of British Columbia – Geophysical Inversion Facility software for deriving physical property models that explain observed gravity and magnetic data provide a quick way of extracting default physical property distributions in the absence of geological constraints. This gives an acceptable first pass model but is unlikely to be geologically realistic.

Even in greenfields mineral exploration there will be some geological information available in addition to the geophysical data. These constraints can be supplied to the inversion software, with adjustable levels of certainty, via a reference model of expected properties, bounds on the expected properties, or smoothness weights based on positions and orientations of the rocks. The constraints can come from mapping, sampling, analogous areas, or neighbouring regions. In later stages of exploration and development additional information from drilling, detailed structural interpretation, trenching, and even preliminary mining will also be available.

The UBC-GIF inversion software will produce holistic physical property models consistent with all the supplied information. The recovered models may be predictive about the geology of a region because they are consistent with the geology and geophysics. The types of constraints that can be included, and their effectiveness, can be demonstrated using a simple geologically-based synthetic example which provides a far superior recovered model than the default, geologically-unconstrained inversion.

Key words: Inversion, gravity, constraints, geology.

INTRODUCTION

Mineral exploration produces a large amount and variety of geological and geophysical data, yet it has always proved difficult to combine all of that information into consistent holistic models of subsurface geology. Traditionally, 2D or 3D forward modelling, calculating the geophysical response of some model based on observed or expected geology, has been used to identify discrepancies between inferred geological scenarios and the geology required to reproduce observed geophysical data. In recent years advances in computing power have facilitated the forward computation of the geophysical responses of very large 2D and 3D models. Methods have also been developed to calculate inverse solutions that predict physical property distributions that give rise to the observed geophysical responses.

Two of the most common geophysical tools used in exploration for many styles of ore deposit are gravity and magnetic data. Even in greenfields exploration these datasets may be available from government surveys or previous companies’ work. An increasingly common step in many exploration programs, especially in areas where prospective basement rocks are covered, involves inversion of gravity and aeromagnetic datasets to obtain estimated models of physical properties within a region. The recovered inverse models can be used to target regions of anomalous physical properties for further data acquisition or drilling.

Inversion of potential field data is impeded by several numerical difficulties:

1. *Non-existence*: Due to the ubiquitous presence of noise in geophysical and geological observations, there may not exist a single model capable of fitting the measured data.
2. *Instability*: Small changes in the data, such as noise, can result in large changes in the recovered model since the inverse problem is ill-conditioned.
3. *Non-uniqueness*: There are two sources of non-uniqueness. (1) A finite number of any noise-free data can be reproduced in an infinite number of ways. (2) Any potential field response can be reproduced by an equivalent layer of sources (by Green’s third identity), so there are an infinite number of physical property models that could reproduce gravity or magnetic datasets.

To recover a physical property model, some type of regularisation is required to mitigate these problems. Regularisation typically imposes a set of mathematical constraints that stabilise the problem and recover a model that fulfils certain criteria. The regularisation imposed by the University of British Columbia Geophysical Inversion Facility (UBC–GIF) inversion approach seeks a model that is small, containing as little deviation from a reference model as possible, and smooth, with any deviations spread over a number of cells rather than concentrated in individual cells.

While these mathematical constraints can recover visually pleasing physical property models and may provide broad geological insight, used in isolation they can never recover an accurate physical property model because there is no direct link between the mathematics and the geology. A holistic model, consistent with all observed information, can only be
recovered by including geology-based constraints in addition to the mathematical constraints.

A strength of the UBC–GIF inversion programs is that they allow the inclusion of as much or as little geological information as is available, in the form of a reference model of physical properties or bounds on the range of expected physical properties. The inversion will return a solution that is within the bounds and as close as possible to the imposed reference model while still fitting the geophysical data to within the accepted uncertainty levels.

THE UBC-GIF INVERSION METHOD

A solution to a linear inverse problem aims to find a model, \( \mathbf{m} \), which satisfies:

\[
\mathbf{Gm} = \mathbf{d}^{obs}
\]

where \( \mathbf{G} \) is the forward operator, or kernel, that describes the physics of the problem, and \( \mathbf{d}^{obs} \) is the observed data. For potential field data in mineral exploration, where the subsurface is discretised into a model \( \mathbf{m} \) containing \( M \) individual cells, the number of cells in the model is greater than the number of data, \( N \), available \( \mathbf{d}^{obs} \). This results in an \( N \times M \) (\( M > N \)) matrix \( \mathbf{G} \) that is not square and therefore not invertible. Instead, the problem becomes an optimisation problem, seeking a solution that minimises both a numerical measure of the model and the misfit between the observed and predicted data.

The details of the UBC–GIF inversion approach for potential field data (MAG3D and GRAV3D) are given in Li and Oldenburg (1996, 1998a), and in the software user manuals (UBC–GIF, 2005a, 2005b). A brief summary is included here. In both the inversion programs and the following method and discussion, all distance quantities are measured in metres, all gravity observations and predictions are in mGal, all densities are in g/cm³, all magnetic field observations are in nT, and all magnetic susceptibilities are induced susceptibilities with units of SI. All other quantities (such as weightings) are effectively unit-less.

Model Objective Function

The UBC–GIF magnetic and gravity inversion codes use a model objective function to quantify the model. The regularisation applied includes a term that measures the smallness, or difference between the recovered model and some reference model, and terms that measure how the difference between recovered and reference models varies between cells in each of three orthogonal directions. The reference model may be as simple as a uniform (usually zero) half-space, in which case the returned model may be expected to contain the minimum amount of detail necessary to reproduce the observed data. But the reference model may be more complicated, and in situations where there already exists a strong understanding of the subsurface physical property distribution, a full model of the expected physical properties could be used. The model objective function is designed to match the supplied reference model as closely as possible ensuring that the extracted inverse model is consistent with existing \textit{a priori} knowledge. The model objective function used is:

\[
\phi_m(m) = \alpha_s \int_V w_s \left( \frac{\partial}{\partial x} w_r(z)(m - m_{ref}) \right)^2 dV + ...
\]

\[
\alpha_s \int_V w_s \left( \frac{\partial}{\partial y} w_r(z)(m - m_{ref}) \right)^2 dV + ...
\]

\[
\alpha_z \int_V w_z \left( \frac{\partial}{\partial z} w_r(z)(m - m_{ref}) \right)^2 dV
\]

The first component measures the smallness. The last three components measure the smoothness of the difference between the recovered model and the reference model in each of the three axes and ensure that any discrepancies between the recovered model and the reference model are spread over a region rather than concentrated in individual cells. The adjustable parameters \( \alpha_s, \alpha_r, \alpha_x, \) and \( \alpha_z \) are used to balance the contributions of the smallness and smoothness components. The function \( w_r \) may be used to force the physical property of cells to be closer to the supplied reference model where the physical properties are better understood. The parameters \( w_s, w_r, > w_x, \) and \( w_z \) can be used to make the model-difference more or less smooth across cell boundaries to reproduce geological continuity or boundaries. The function \( w_s \) is a depth weighting function.

Depth Weighting

The depth weighting function is designed to counteract the decay of the potential field response with distance from the source so that all cells have an equal likelihood of containing sources. This is necessary as there is no inherent depth information contained in the observed potential field response and a default solution to the inverse problem would result in a model with sources clustered near the surface. The depth weighting function has the form (Li and Oldenburg, 1996):

\[
w^2(z) = \frac{1}{(z + z_0)^\beta}
\]

where \( z \) is the depth to the centre of the cell and \( z_0 \) and \( \beta \) are adjustable parameters used to match the weighting function to the kernel’s decay with depth. If the distance between a cell and observation point is large relative to the dimensions of the cell, as will be the case for most cells in the model, then \( \beta \) will approach the exponential decay of the gravity or magnetic response of a sphere: \( \beta = 2 \) for gravity data and \( \beta = 3 \) for magnetic data. The parameter \( z_0 \) is usually calculated automatically to match the kernel’s decay.

Data Misfit

For the recovered inverse model to be capable of reproducing the observed data there must also be a measure of how closely the predicted response of the recovered model matches the observed data. Geophysical experiments will obtain measurements:
Several additional constraints, the implementation of which is described by Li and Oldenburg (1996, 1998a), are also applied when calculating a solution: positivity and bounds. Logarithmic barrier functions are used in the MAG3D code to ensure that only positive magnetic susceptibilities are obtained. They are also applied in both MAG3D and GRAV3D to ensure that the recovered properties lie between specific bounds. In default inversions wide bounds are allowed, but when including geological constraints, narrow bounds can be supplied to restrict the properties to some expected range. The bounds can be set for the whole model or for individual cells.

PREPARING INVERSIONS

A number of steps are required to prepare data and a mesh for an inversion. These steps are covered by Li and Oldenburg (1996, 1998a, 1998b) and UBC–GIF (2005a, 2005b). In summary they include:

• Definition of the problem to be addressed
• Definition of the volume of interest (depth, width and length of desired mesh)
• Definition of the data area
• Definition of the cell sizes to match the resolution of the data, the desired resolution of the recovered model, and available computing power (currently about 1.5 million cells is a reasonable upper limit for tenable computation on standard desktop PCs)
• Padding the mesh with a buffer of additional cells to prevent boundary effects where anomalies are located near the edge of the mesh
• Upward continuation of the potential field data to the width of the cells to ensure that high frequency information that could only be reproduced by smaller cell sizes is not included
• Calculation and removal of a regional data trend that accounts for all sources located outside of the volume of interest that have responses captured by the observed data

CHOOSING OPTIMAL PARAMETERS

The implementation of the UBC–GIF inversion method requires selection of appropriate values for a large number of parameters. Each choice can cause large differences in the model, and although use of the default values may be acceptable in some situations, more reliable models will be obtained by tuning the parameters to a particular problem. One exception is the depth weighting which has a basis in the physics of potential fields; the default values are usually best, and if the results are deemed to be inappropriate then a reference model or bounds should be employed.

Noise

It is critical to assign appropriate noise levels to the observed data used in the inversion. If the assigned noise levels are too low, then too much of the noise will be reproduced as noise in the model (Figure 1). If the assigned noise levels are too high then too much of the observed data will be treated as noise, and information will be lost in the model. Unfortunately potential field data rarely comes with robust uncertainty estimates, and additional uncertainties are introduced by data processing, using a discretised representation of the earth, and numerical inaccuracies.
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If an estimate of the noise level is available it can be included in the data file. For inversions gravity will commonly have standard deviations of 1–2 % of the data range, expressed as a constant (i.e. 0.1 mGal). Due to its higher dynamic range, aeroemagnetic data may have standard deviations on the order of a couple of percent plus a couple of nT (i.e. 5 % + 5 nT). Older surveys may require higher noise levels than newer surveys, depending on the methods used, and this can be accommodated in the UBC–GIF inversions where data from the two surveys are combined. Likewise, upward continued data will have a lower dynamic range and should have lower standard deviations applied.

One approach to estimating the noise levels in the absence of good estimates is to perform a Generalised Cross Validation (GCV) inversion, an option within the UBC–GIF codes, supplying a standard deviation of 1 (mGal or nT) to all data. This chooses a trade-off parameter \( \beta \) based on how dependent the model is on individual data points. The completed inversion log file reports a final Achieved Misfit. Dividing this misfit by the number of data points gives a rough estimate of the average standard deviation for the dataset. However, GCV inversions commonly fit the data a little too closely so the actual standard deviation chosen should be slightly higher than this estimate, and should be compared to other estimates of the noise in the data.

Alphas

The balance of smoothness versus smallness for the whole model is controlled by the \( \alpha \) values: \( \alpha_x, \alpha_y, \alpha_s \), and \( \alpha_c \). Since the values are combined in the minimisation, it is only the balance between them that is important. A smaller model may contain more structure, manifested as excess detail at depths within the model, whereas a smoother model may exhibit less detail. By simplifying the model objective function and considering the case of only two adjacent cells, the balance between smoothness and smallness can be evaluated:

\[
\phi_m(m) = \alpha_s \int m^2 \, dA + \alpha_s \int \left( \frac{\partial m}{\partial \Delta x} \right)^2 \, dA
\]

If each cell is the same size, with area \( A = \Delta x \Delta z \) (where \( \Delta x \) is the cell width, and \( \Delta z \) is the cell height, in metres) and physical properties \( m_1 \) and \( m_2 \), the model objective function for the two cells becomes:

\[
\phi_m = \alpha_s \left( m_1^2 + m_2^2 \right) A + \alpha_s \left[ \frac{m_2^2 - m_1^2}{(\Delta x)^2} \right] A
\]

It is possible to evaluate the \( \alpha \)'s so as to balance smallness and smoothness by equating the two terms:

\[
\alpha_s \left( m_1^2 + m_2^2 \right) A = \alpha_s \left[ \frac{m_2^2 - m_1^2}{(\Delta x)^2} \right] A
\]

Equality is reached when their ratio is unity:

\[
\alpha_s = \frac{\alpha_s \left( m_1^2 + m_2^2 \right) A}{\alpha_s \left[ \frac{m_2^2 - m_1^2}{(\Delta x)^2} \right] A} = \alpha_s \cdot c_s \left( \Delta x \right)^2
\]

where:

\[
c_s = \frac{m_2^2 + m_2^2}{m_2^2 - m_1^2}
\]

The constant, \( c_s \), controls the desired proportionality of the properties of the two cells if all other constraints, such as data misfit, allow. For a full 3D mesh, the constant is more complex and is generalised to an arbitrary model smoothness parameters which can be applied in each direction to also yield:

\[
\alpha_y = c_y \cdot \alpha_s \left( \Delta y \right)^2
\]

\[
\alpha_z = c_z \cdot \alpha_s \left( \Delta z \right)^2
\]

If \( c = 1 \), the smoothness and smallness should balance. Experimentation shows that better inversion results are usually obtained when \( c \) is between 4 and 25, causing a slight bias towards smoother models. In older versions of the UBC–GIF inversion codes, this corresponded to length scales:

\[
L_x = \Delta x \cdot \sqrt{c_s}
\]

The crucial aspect of the above analysis is that the balance of smoothness versus smallness is controlled by the square of the cell sizes, so it is important to adjust the \( \alpha \) parameters to suit the size of the cells in the centre of the model.

The smoothness parameters, \( c_s \), can also be used to supply some geological information about the continuity of strike in a given area. Higher values can be used to indicate that geology is more continuous in a particular direction, for example, east-west strike can be reproduced by disproportionately higher \( c_s \).
values. An empirical rule of thumb, based on the results of synthetic inversions, takes the form:

\[ c_x \geq 2 \cdot (n_x - 7) \]

where \( n_x \) is the number of cells in a row in the \( x \)-direction that are influenced by a tight constraint on the property of one cell in the middle of that row, where allowed by the geophysical data. This estimate only works for \( n \geq 9 (c \geq 4) \), but the effect on all but those cells closest to the constrained cell is usually minimal. Such tuning is subjective and may be improved by trial and error, and comparison of inversion results with known geology.

**REFERENCE MODELS, BOUNDS AND WEIGHTINGS**

The UBC–GIF inversion approach is flexible enough to include a wide range of geological information, if available. Without including this information, no inversion method will return a model that is consistent with existing geological knowledge since there are an infinite number of mathematically-feasible, but geologically-unlikely models available. Geologically-unconstrained inversions are unlikely to be consistently predictive about the subsurface physical property distribution.

**Types of Geological Constraints**

In general the geological information that can be included as constraints falls into five types (Figure 2). Surface data and drill holes may supply actual physical property measurements, possibly even multiple measurements within a single model cell. By assigning a reference model, with appropriate levels of certainty supplied by \( w_x \), or by assigning bounds, these properties can be used to fix the property of cells containing outcrop or drill holes in the recovered inversion model.

All five types can provide geometrical lithological constraints indicating the positions and extents of particular units or types of rocks. With appropriate selection of a physical property or property bounds for each unit, their positions and extents, where known, can be recovered in the inversion model.

In addition to actual observations and measurements, hypotheses can also be tested. Hypothetical bodies or regions can be created and included in the inversion. The recovered model will show if the hypotheses are possible given the supplied constraints and observed data, or require geologically-unrealistic changes within the recovered model to compensate.

![Figure 2. Schematic representations of the styles of geological constraints that can be included in a reference model as viewed in a 2D cross section through a 3D mesh. Red cells are those where information is available to assign either property bounds or a reference property; white cells remain geologically-unconstrained.](image)

While most of the geology types are self-explanatory, the last category, zones, is more general. One situation where zones can be defined is where a detailed 3D physical property model is already available for some small region based on a synthesis of all available data (physical property measurements, mapping, drilling, structural interpretation, seismic data, etc.). This information can be "painted" into the reference model with reference properties, high \( w_x \) values, and narrow bounds. The inversion can then extrapolate that information outwards into unknown areas based on the geophysical data.
Another type of zone places certain restrictions on the types of rocks that may be present in an area based on geological principles and variability. An example would be where there is weathering at surface, but the depth to basement is uncertain. Based on an understanding of the regolith, or drilling and seismic data in other areas, an inference might be made that all rocks below a certain depth (perhaps 250 m) must be unweathered basement rocks and therefore will not have the low densities typical of weathered material. Although the actual geology of the basement may be poorly known, densities less than 2 g/cm³ would be unlikely, and this can be included as a constraint by applying a slightly narrower range of bounds than the default. In another example, dense carbonates may only be expected in a particular portion of a basin, based on sequence stratigraphic work, and this can be reflected in the inversion by allowing higher bounds in that area, even if the exact location and properties of the rocks are unknown.

Implementing constraints

As mentioned above, the α values can be used to reproduce strike continuity. But much more information can be included in the definition of the reference model, bounds, and wₓ, wᵧ, and wₚ weightings. All are used in any inversion, however, if they have not been supplied by the user then default values are assigned. If a reference model file, bound file, or weighting file is to be supplied, it must be defined for every cell in the model, but the user can use appropriate default values anywhere where they have insufficient information.

The reference model consists of a single physical property value for each cell in the model. The default values are 0 g/cm³ and 0 SI. It is used in conjunction with a set of wₓ values, also defined for each cell in the model. These smallness values indicate a level of certainty in the physical properties assigned in the reference model. The wₓ values are unit-less; the default is unity, but increased certainty 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 are powerful because they can be supplied with or without a reference model. If a reference model is not supplied, or default values are used for a particular region within the reference model, then bounds can be supplied to restrict the physical properties in that region to some approximate limits based on known, or expected, geology. Where a reference model is supplied, the reference model might be used to define the expected physical property value (perhaps with a low certainty, or wₓ value), but the bounds can be used to allow the likely range of values, even if the physical properties are skewed (Figure 3) or bimodal.

The directional smoothness weighting factors, wₓ, wᵧ, and wₚ, can be more difficult to apply since they are defined for dual meshes corresponding to the boundaries between cells (Figure 4). Low values can be used to encourage breaks in smoothness of the model across known faults or lithological boundaries; higher values can also be used to define regions where geological strike has different orientations on either side of a contact or fault, in much the same way as the α values except on a local scale.
Smooth Model or Smooth Model-Difference?

As described above, the model objective function smooths differences between the recovered model and the reference model over a number of cells. Where the reference model is the default zero model, or is constant through the model, this results in smoothly varying properties. However, if the reference model is defined differently in adjacent cells this can result in a discontinuous property variations (Figure 6). In some situations this may be desirable, but if only sparse information is available, such as along the surface row cells, or along drill holes, it is generally preferred that the inversion produce a smooth extrapolation of the assigned reference properties out some distance into the model as required by geophysical data and smoothness weightings.

One way to achieve this with the existing UBC–GIF inversion software is to only use the default zero reference model, in which case the model objective function effectively becomes:

\[
\phi_m(m) = \alpha_1 \int_V w_x [w_x(z)(m)]^2 dV + \ldots \\
\alpha_2 \int_V w_y \left[ \frac{\partial}{\partial x} w_x(z)(m) \right]^2 dV + \ldots \\
\alpha_3 \int_V w_y \left[ \frac{\partial}{\partial y} w_y(z)(m) \right]^2 dV + \ldots \\
\alpha_4 \int_V w_z \left[ \frac{\partial}{\partial z} w_z(z)(m) \right]^2 dV
\]

which will always result in a smooth model. This gives a geologically-unconstrained, default, result.

Since the reference model is zero, any available geological constraints must be applied using only upper and lower bounds. The bounds can be made very narrow if the property for a particular cell is well known, or wider if the property is less well known, equivalent to using \(w_y\) values to assign certainty to the property. This also allows the certainty to be more rigorously defined: perhaps \(2\sigma\) or \(3\sigma\) (where \(\sigma\) is the standard deviation of the available property measurements). In areas where no constraints are available, appropriate wide bounds are used.

A downside of using smooth model inversions is that the inversion is less able to recover sharp boundaries in the model. However, where the positions of boundaries are known, they can be recovered by defining different bounds ranges on either side of the boundaries, or by enforcing a break in smoothness with the \(w_x, w_y, \) and \(w_z\) weighting functions. In addition, situations commonly arise where the physical properties are not known well enough to enforce bounds and using a reference model and weightings would provide a better solution, hence the flexibility built in to the UBC–GIF software.

In general, the smooth model-difference approach, using a non-zero reference model, is ideal for regions where a full 3D geology model exists, or can be constructed. In other regions where the raw geological information (mapping, sampling, drill holes, cross sections, etc.) is all that is available, smooth model inversions using only bounds are preferable.

**EXAMPLE GEOLOGICALLY-CONSTRAINED INVERSION**

A simple, synthetic, but geologically typical, problem is used to demonstrate the benefits of including even a small number of geological constraints in a gravity inversion for mineral exploration.
exploration. This example is stylistically based on Ni-exploration in the Eastern Goldfield of Western Australia’s Yilgarn Craton. It consists of limited basement outcrop and extensive regolith cover, over a dipping, north-south-striking granite-greenstone terrain. To simplify building the true geology for this example, and to aid visualisation of the results using cross-sections, the north-south-strike is made perfect (similar to a 2.5D model) but full 3D constraints, data, and inversion are used. The topography is flat.

One greenstone belt outcrops near the centre of the proposed inversion volume, with significant massive sulphide Ni-mineralisation, but additional ultramafic horizons have been identified further to the southwest. It is hoped these may continue into the area of interest, and that there may be massive sulphide lenses that have been structural detached from their original ultramafic host rocks.

A surface map of the area is shown in Figure 7. The gravity data for the area is on an even 100 m grid, and was upward continued to 100 m, the width of the inversion cells, to remove high frequency information that could only be accommodated by cells smaller than 100-m-wide. The data has a noise level of 0.1 mGal (added to the response of the true model prior to upward continuation). The black line indicates the position of the cross-sections shown in Figure 8.

Appropriate padding cells were added to the inversion volume. A uniform cell size of 100 m × 100 m × 50 m was used throughout. The smoothness parameters, $c_x$, were set to default values in the east-west and vertical directions, $c_x = c_y = 4$, but the known north-south strike suggests a higher value of $c_z$. It is estimated that rock properties may correlate over a north-south distance of 2 km, so using $n_y = 20$ cells, a smoothness parameter of $c_z = 2 \cdot (n_y - 7) = 26$ is obtained. Appropriate $\alpha$ values are therefore $\alpha_y = 0.0001$, $\alpha_x = 4$, $\alpha_z = 26$, and $\alpha_z = 1$.

A default, geologically-unconstrained GRAV3D inversion was performed on the data and the result is shown at the top of Figure 8, which also shows the geological information that is available. Comparison of the known geology with the default inversion result shows clear differences, but the known geological information can be developed into a set of constraints to guide the inversion and enhance the result.

The constraints shown in Figure 8 are combined with the measured densities shown in Table 1. Densities are converted to density contrasts by subtracting a rough estimate of the mean density (~2.8 g/cm$^3$) within the inversion volume. The central outcrop of ultramafic, sulphides, and minor metamorphic rock is well sampled for density, allowing narrow density bounds to be used. The surrounding regolith material and the small basement outcrops to the west and east have been sampled, but not in detail, so wider bounds are used. A 1 km$^2$, 250-m-deep 3D geological model is available for the central area. It is based on outcrop mapping, structural interpretation, and shallow drilling. There is high confidence in this model, and enough density measurements to assign narrow bounds on the expected densities. One 2-km-long exploratory drill hole was drilled from east to west through the ultramafic. Although it did not intersect any mineralisation, detailed density measurements were taken.

Table 1. Summary of the densities obtained from measurements of outcrop samples, drill hole samples, and similar rocks in other areas. The lower table shows the density contrast assigned for each unit based on a loosely estimated mean density for the inversion volume of 2.8 g/cm$^3$ given the expected rock types.

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Density (g/cm$^3$)</th>
<th>Minimum (g/cm$^3$)</th>
<th>Maximum (g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulphides</td>
<td>3.8</td>
<td>3.4</td>
<td>4.2</td>
</tr>
<tr>
<td>Ultramafic</td>
<td>3.1</td>
<td>2.75</td>
<td>3.2</td>
</tr>
<tr>
<td>Metamorphics</td>
<td>2.8</td>
<td>2.6</td>
<td>3.0</td>
</tr>
<tr>
<td>Granite</td>
<td>2.7</td>
<td>2.65</td>
<td>2.85</td>
</tr>
<tr>
<td>Regolith</td>
<td>2.0</td>
<td>1.7</td>
<td>2.4</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th>Rock Type</th>
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<th>Maximum (g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulphides</td>
<td>1.0</td>
<td>0.6</td>
<td>1.4</td>
</tr>
<tr>
<td>Ultramafic</td>
<td>0.3</td>
<td>-0.05</td>
<td>0.4</td>
</tr>
<tr>
<td>Metamorphics</td>
<td>0.0</td>
<td>-0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Granite</td>
<td>-0.1</td>
<td>-0.15</td>
<td>0.05</td>
</tr>
<tr>
<td>Regolith</td>
<td>-0.8</td>
<td>-1.1</td>
<td>-0.4</td>
</tr>
</tbody>
</table>

More general constraints, or zones, were also established. The depth of weathering and cover is not known, but is expected to be less than 250 m everywhere. Above a depth of 250 m there could be low density weathering or relatively high density basement. Below 250 m, only the higher density basement rocks are expected so the lower bound of density contrasts can be made more restrictive.

Given the sparse constraining information (the thin layer of outcrop, and the single deep drill hole), a smooth model style of inversion was chosen. This was done by using a default zero reference model and assigning all the physical property constraints using bounds. As described above and in Figure 8, varying certainties in the available physical properties were accommodated by using narrower or wider bounds. The results of the geologically-constrained inversion are shown towards the bottom of Figure 8 as well as the true density model. The geologically-constrained inversion fits the gravity data to the same accuracy as the default inversion.

Although the default inversion was able to identify the approximate lateral position of the two ultramafic units, the default settings pushed much of the mass of the central unit to depth, in contrast to the available geological information. It is also unclear which of the several moderate-density anomalies (~2.9 g/cm$^3$) lying near the surface are prospective.
By including the sparse constraints available from the outcrop, small 3D model, one deep drill hole, and some general expectations about the geology, the geologically-constrained inversion was able to reasonably recover the depth to basement (A in the lower panel of Figure 8), as well as the position, dip, and extent the central ultramafic unit (B). But the inversion still required some anomalous mass on the margins of the ultramafic (C, D) to fit the data. As there is currently no geological or geophysical explanation for these accumulations, they may provide targets for further drilling, which might prove successful given the presence of sulphides near C in the true geology model. Likewise, the anomalous mass accumulation at E is enhanced relative to the default inversion and relative to other shallow anomalies in the default inversion, making it more prospective.

CONCLUSIONS

In the development of this simple example, the importance of including surface information was clear, even if that surface information doesn’t come from outcropping basement rocks. The input of weathered material as a constraint is just as important as delineating basement units due to the low density (and commonly low magnetic susceptibility) of weathered material relative to basement rocks. The addition of deep drill hole data is also key, provided they are sufficiently sampled for physical properties, because that is the only method available for providing tight constraints for deep rocks. Small 3D models can be used to quickly define a relatively large volume of known geology, compared to the sparse outcrop and drilling data that might be available.

The use of geological zones comes directly from carefully assessing inversion results. A geoscientist may quickly dismiss a recovered inversion model as being “wrong”. The question should then be why? What information is available that proves the model to be wrong? If reliable, that information can and must be included as constraints to derive a realistic model. But often the criticism is based on less tangible observations, such as not expecting low density material below 250 m depth. Careful use of bounds, reference models, and weightings can allow this information to be included with the more obvious data. Together, these constraints help recover not only a more geologically-realistic model, but one that is also more accurate.

A specific capacity of the UBC-GIF inversion software is its flexibility to include as much or as little geological information as is available. 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. The constraints can easily be based on the raw geological data, without the additional interpretation required to build a full 3D model, however, 3D models are clearly a powerful dataset to include, if available.

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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Observed gravity profile

Recovered model: Default inversion

Constraints: Known geology

Constraints: Geological zones

Recovered model: Geologically-constrained smooth model inversion

True model: actual geology

Figure 8. East-west cross sections (along the black line in Figure 7) showing a profile through the gravity data, the default inversion result, available geological constraints, the geologically-constrained inversion result, and the true geology. The cross section extends from surface (0 m) to a depth of 1000 m, and is 7 km wide; cells are all 100 m × 100 m and 50 m high. All cells (except for the zones) are coloured by expected density contrast (converted from densities by subtracting an estimated mean density of 2.8 g/cm³) with the same scale. It is clear that the default inversion shows the positions of several major features, but lacks detail and vertical resolution, and does not allow clear ranking of targets, but the geologically constrained inversion result captures several of the key characteristics such as the depth to basement (A) and easterly ultramafic dip (B), and may suggest the presence of anomalous mass accumulations at C, D, and E.