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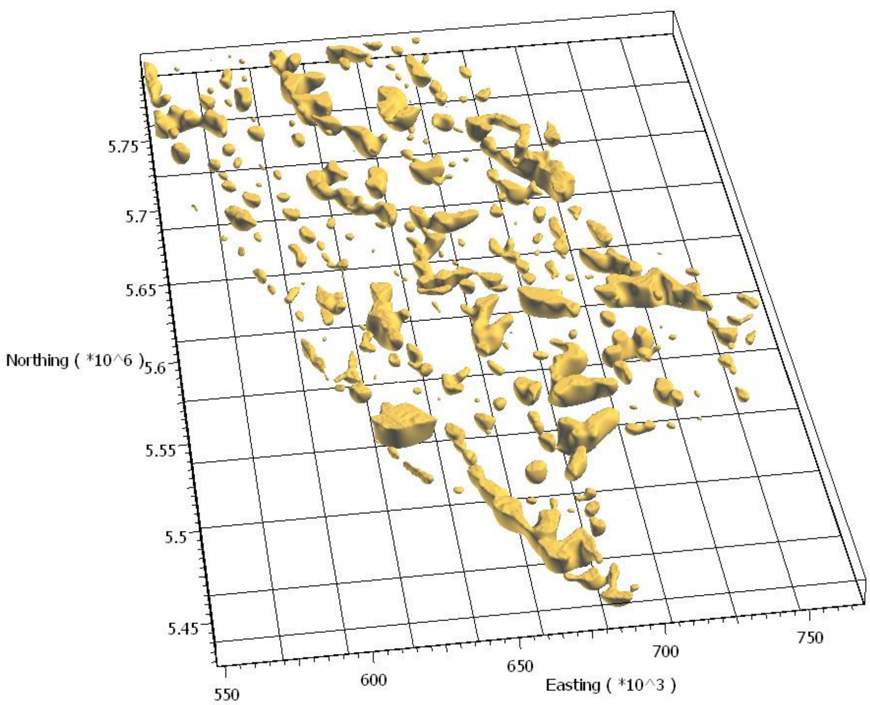
# Regional 3D inversion modelling of airborne gravity and magnetic data: QUEST-South, BC, Canada

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## Executive Summary

The Mira Geoscience Advanced Geophysical Interpretation Centre has completed 3D inversion modelling, integration, and visualization of airborne gravity and magnetic data for the QUEST-South regional area in south-central British Columbia, Canada. This project is an enhanced continuation of the completed Geoscience BC inversion modelling report 2009-15 for the QUEST survey area. The objective of this work is to provide useful 3D physical property products and accessible knowledge for the exploration of different resources in BC following the release of the datasets.

This work considers all airborne gravity and magnetic data available for the QUEST-South project area. The inversions were performed using the UBC-GIF GRAV3D and MAG3D suite of algorithms. The products are 3D inversion models of density contrast, magnetic susceptibility and integrated products combining the individual physical property models. The extensive set of digital deliverable products that accompany this report include: physical property cut-off iso-surfaces, observed and predicted data, and the inversion models in several commonly used formats. A suite of 3D PDF scenes has been produced to aid in visualization and communication. The deliverables from this project are consistent with past project deliverables allowing seamless regional exploration in south-central BC.

The gravity and magnetic data were modelled in 3D using 9 tiles after separation of regional signal. The tiles were combined to construct a detailed model over the whole area. Final density contrast and magnetic susceptibility models were integrated into a Common Earth Model ready for 3D-GIS analysis, interpretation, and integration with geologic, drillhole, and other geophysical information. The resulting physical property models provide guidance to the regional structure, prospective geology and location of alteration and mineralization and can be used to guide regional targeting and help design more detailed, follow-up data acquisition. The inclusion of geologic or physical property information in the inversion from maps, drillholes, and samples was not within the scope of this project, although it is expected that the integration of these data would improve the resulting models, especially at the local scale.

## Table of Contents

## List of Figures

# List of Tables

# 1. Introduction

Geophysical prospecting methods used in exploration provide information about the physical properties of the subsurface. These properties can in turn be interpreted in terms of lithology and/or geological processes. Moreover, the geometric distribution of physical properties can help delineate geological structures and may be used as an aid to determine mineralization and subsequent drilling targets.

The Advanced Geophysical Interpretation Centre at Mira Geoscience has completed 3D density contrast and magnetic susceptibility inversion modelling for Geoscience BC. This was modelled from airborne gravity and airborne total field magnetic data. The data were collected as part of Geoscience BC's QUEST-South Project; a program of regional geochemical and geophysical surveys designed to provide new geoscience information to industry from a region of British Columbia between Williams Lake and the Canada-United States border. This region of the province has been explored and mined for decades and remains one of the most actively explored and prospective areas for discovery of new Cu, Mo and Au resources in British Columbia (Simpson, 2010). The QUEST-South project is the third of a series of large-scale regional geoscience studies designed and managed by Geoscience BC since 2007. The survey areas of these projects (QUEST, QUEST-West and QUEST-South) are shown in Figure 1. The software used for the inversion was the University of British Columbia – Geophysical Inversion Facility (UBC-GIF) program suites GRAV3D and MAG3D. Gocad was used for data preparation, model integration, visualisation, and interpretation.

Information about the geophysical data used and the data processing is presented in Section 5. Section 3.1 details the modelling methodology and results. Regional 3D potential field inversion modelling used a coarse discretization with cells sizes of 2000 m x 2000 m x 500 m in the east, north and vertical directions respectively. This was used for separation of a regional signal prior to detailed local inversion. Detailed local inversions used a more finely discretized 3D mesh with 500 m x 500 m x 250 m cell dimension. The smaller, local inversion cell size is appropriate for the airborne survey data line spacing of 2000 m and 4000 m. Topography was used at all stages of the inversion modelling, and the inversions are unconstrained by geologic or physical property information.

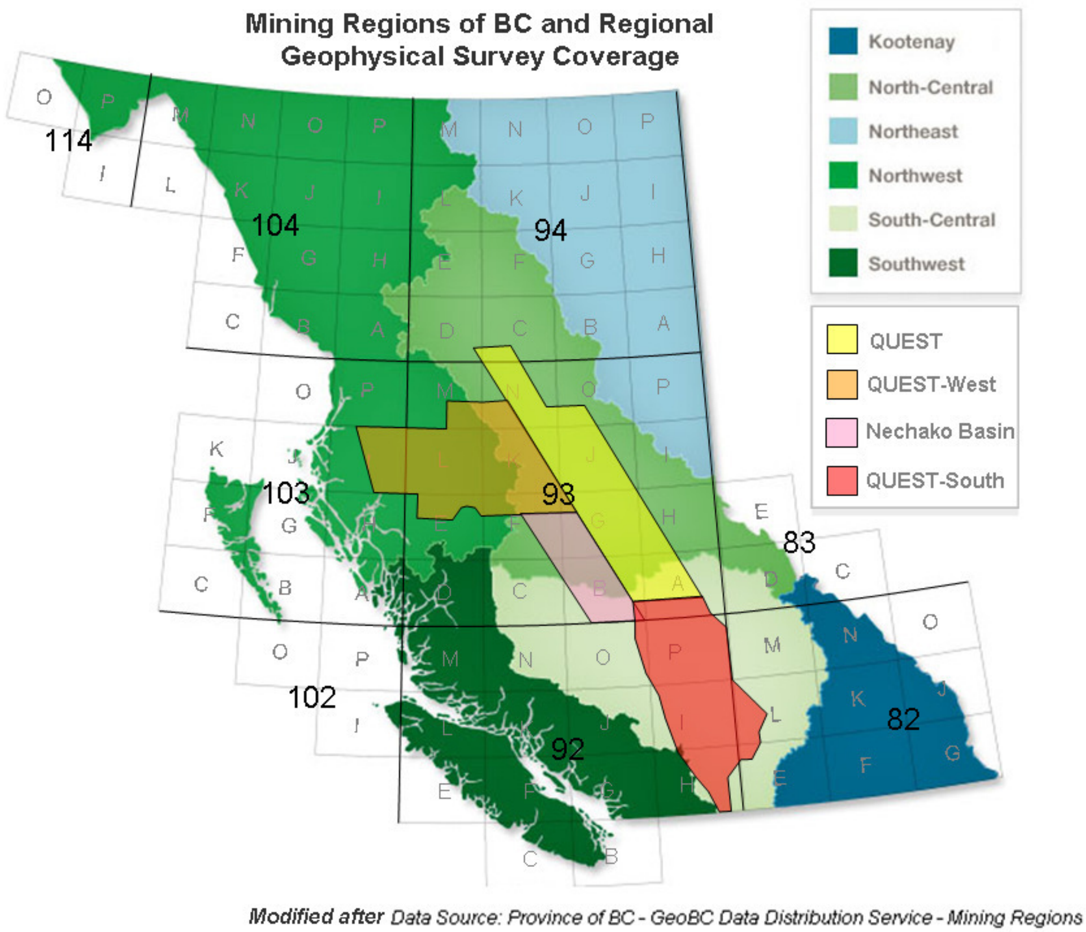


**Figure 1: Map of BC showing the areas covered by Geoscience BC's regional geophysical surveys (including QUEST-South) as well as the mining regions and NTS map sheets.**

The resulting models have been integrated into a Common Earth Model ready for quantitative 3D-GIS analysis and integration with additional geoscientific data. An example of integrated interpretation using simple 3D-GIS property query functionality is provided in Section 4. Section 5 details the digital modelled, integrated, and visualization deliverables. Conclusions and recommendations are provided in sections 6 and 7, respectively. Several pieces of background and reference material are provided in the appendices and as accompanying files, including a Glossary of Useful Terms (Appendix 1) and an inventory of Project Deliverables (Appendix 2).

### 1.1. Geologic Setting

The geophysical component of the QUEST-South project covers a 45,000 $km^2$ area in south-central British Columbia extending south of Williams Lake to the US border (Figure 1). The area is located within the Interior Plateau of southern British Columbia, containing the southern part of the Fraser Plateau and much of the Thompson Plateau, and lies between the Monashee Mountains to the east and the Coast and Cascade mountain ranges to the west.

QUEST-South focuses on the Quesnel Terrane, an assemblage of Late-Triassic to Early-Jurassic arc volcanics, volcaniclastics, and co-magmatic intrusive rocks overlain by Jurassic arc-derived clastics. The southern part of the Quesnel Terrane is largely dominated by the Late-Triassic Nicola Group. The Nicola arc sequences are composed of submarine basaltic to andesitic lavas and associated volcaniclastic rocks (Bissig et al., 2010).

The region has had a successful history of mineral exploration and mining, specifically for alkalic porphyry Cu-Au, and hosts many notable deposits and prospects including Mt. Milligan, Lorraine, Mt. Polley, Afton/Ajax, Highland Valley, and Copper Mountain. However, exploration success has been limited by the presence of an extensive veneer of till and other glacially derived sediments, which cover much of the area (Bobrowsky et al., 2002). The QUEST-South project aims to characterize the underlying bedrock and stimulate further mineral exploration in the area.

### 1.2. Objectives

The objective of this modelling work is to provide useful 3D physical property products that can be directly employed in regional exploration programs to target prospective areas. This is done using physical property-based inversion to determine 3D distributions of density contrast and magnetic susceptibility to a depth of 8 km for a 220 km x 380 km area located in southern British Columbia. The models will more easily facilitate geologic interpretation and definition of favorable geology than the data alone, and they can be used in a quantitative manner using 3D-

GIS analysis. The models can provide important information for determining the depth of overburden and designing appropriate follow-up airborne or ground data acquisition campaigns in the favourable areas.

### 1.3. Scope of Work

The workflow for producing density contrast and magnetic susceptibility models of the QUEST-South data involves data processing, inversion modelling and finalizing the deliverables. The steps are outlined below:

1. Data quality control, where the data, and survey and instrument parameters are carefully checked for consistency and suspect data are removed. This includes inspection and analysis of geophysical and geodetic data (e.g. analysis of positional and radar altimeter information).
2. Data preparation involving down-sampling or re-gridding, upward-continuation of gravity data, and creation of inversion input files.
3. Regional inversion modelling, which is needed to reduce data, or to provide constraints or background models for local inversions.
4. Detailed inversion modelling at the required resolution using carefully chosen inversion parameters to produce high quality physical property models which, when forward modelled, predict the observed data to an appropriate degree.
5. Construction of final 3D model products through merging and interpolation of detailed models in 3D, and basic analysis and integration of the detailed inversion models.
6. Preparation of deliverables in various formats including Gocad, UBC-GIF, general ASCII, Geosoft grids and 3D PDF.

# 2. Data and Processing

All data were provided in the NAD83 UTM Zone 10N Datum and Coordinate System; the modelling was carried out in the same coordinate system.

## 2.1. Topographic Data

Topographic data were obtained from the Shuttle Radar Topography Mission (SRTM) database on a 90 m grid (Figure 3). This data was used for the gravity and magnetic modelling. The survey area exhibits some areas of rugged terrain.

### *2.1.1. Topographic Data Processing*

For both the regional and detailed unconstrained gravity and magnetic inversions the topography data were re-gridded to cover the full mesh. The topographic elevation of a surface cell is equal to that of the data point at the horizontal center of the cell.

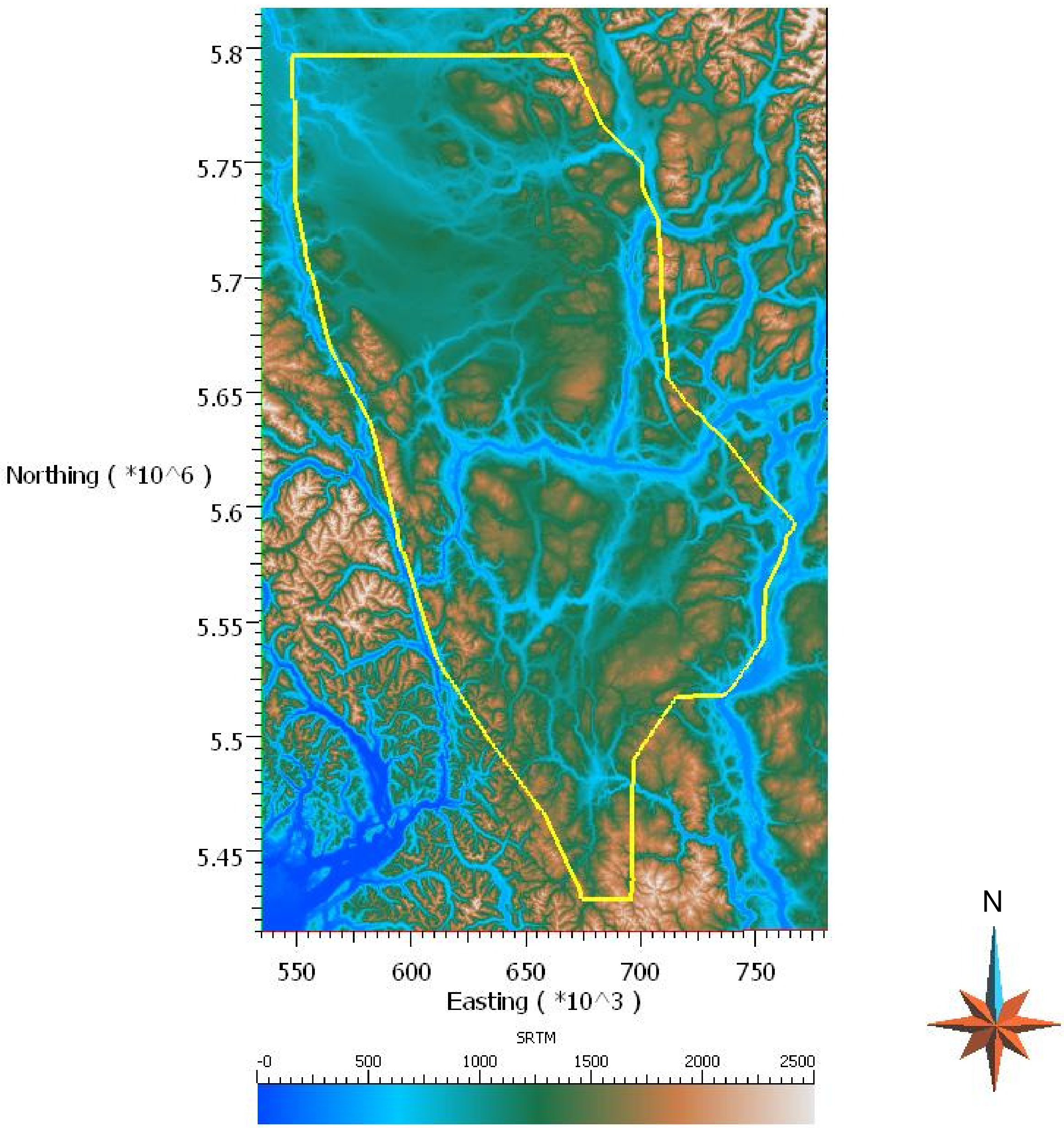


**Figure 2: SRTM topography data (90 m grid) for the QUEST-South area (yellow outline).**

## 2.2. Gravity Data

Geoscience BC has provided airborne gravity data with a terrain-correction applied at a density of 2.67 g/cm$^3$, in a gridded format with a 500 m grid size (Figure 4). This gravity dataset was collected by Sander Geophysics in 2009 at a line spacing of 2000 m (east-west flight lines). Gravity survey specifications are detailed in Appendix 3 and additional information regarding the data can be found in the Sanders acquisition report for this survey.

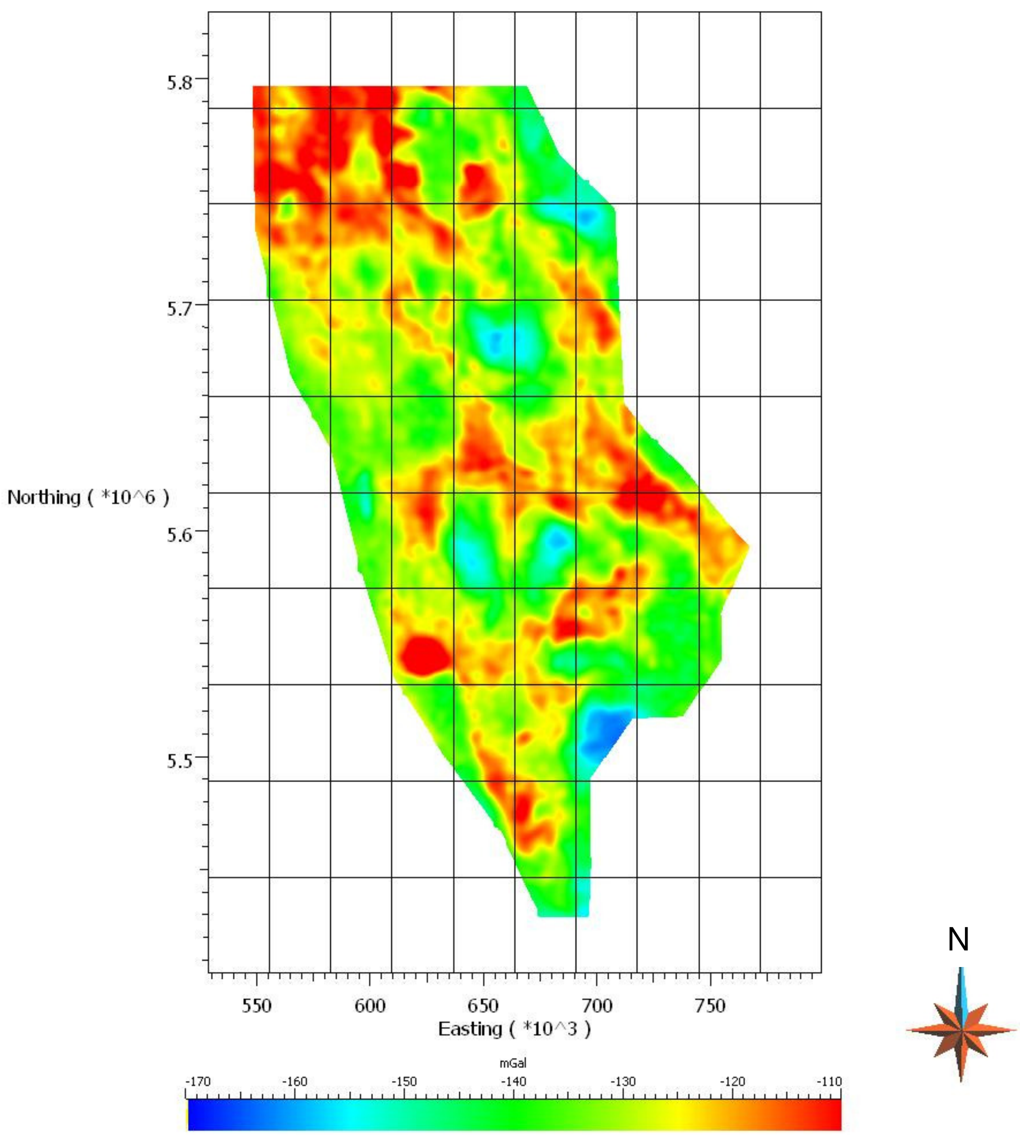


**Figure 3: QUEST-South Bouguer gravity [mGal].**

Surface gravity data for the study area, obtained from the GSC and USGS, have also been downloaded from the Canadian repository and USGS databases (Hildenbrand, 2002). These datasets were used to complete the airborne gravity in order to obtain full coverage of the study area for the regional inversion prior to regional removal.

### *2.2.1. Gravity Data Processing*

For regional inversion, the GSC surface gravity data were upward continued 250 m above topography to reduce cell effects from the discretization of the model. These upward continued data were merged with the airborne gravity to obtain full coverage of QUEST, QUEST-West and QUEST-South projects areas from 94450 to 774050 Easting and 5417650 to 6160050 Northing. The gravity data were re-gridded at 2000 m sample intervals for the regional inversions. A standard deviation of 4 mGal was assigned to the data. This value is ~ 2% of the total range of terrain corrected data.

For the detailed inversions, the GSC surface gravity data were upward continued 125 m above topography and the gravity data were re-gridded at 500 m sample intervals.

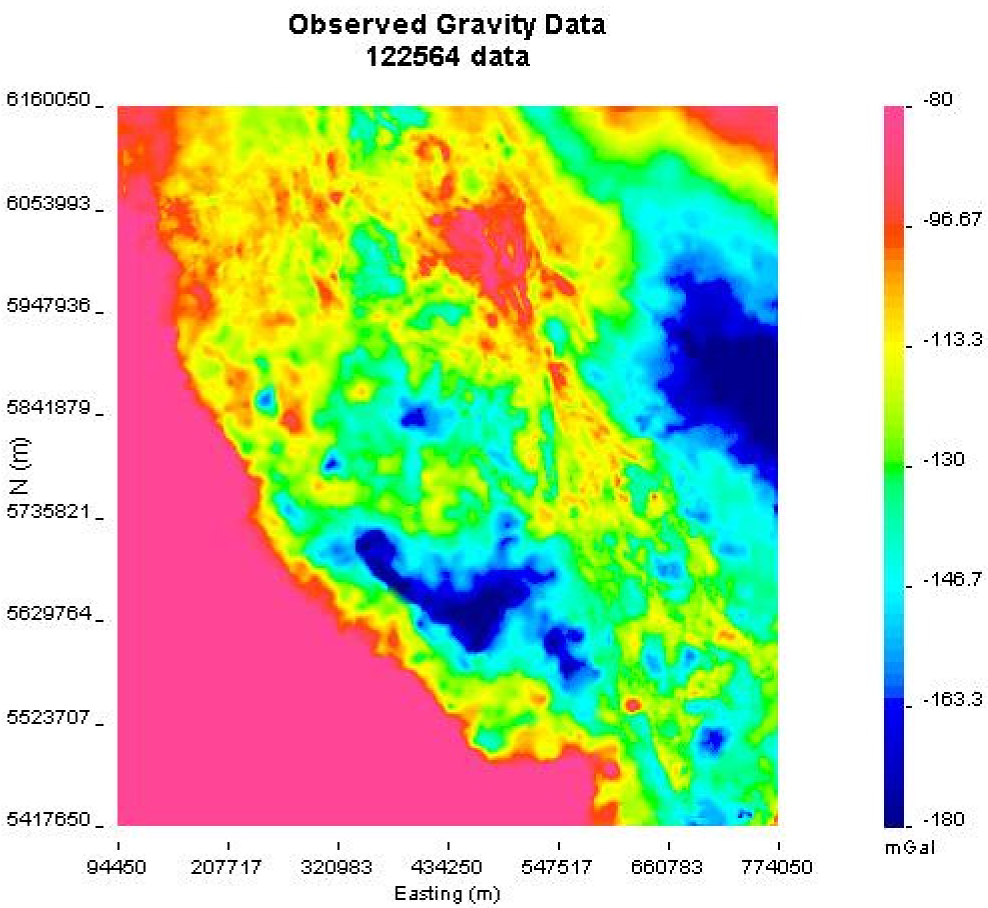


**Figure 4. Terrain-corrected gravity data prepared for regional inversion modelling.**

### 2.3. Magnetic Data

Magnetic data downloaded from the GSC Canadian repository databases and USGS magnetic data (USGS Open-File Report 2002–361) have been used for magnetic inversion.

The GSC magnetic data were collected from 1947 to the present and consist of 500 surveys generally with a line spacing of 800 m and an altitude of 305 m above the ground (available from the Geophysical Data Repository at Natural Resources Canada).

The two data sources were combined to form the final Total Magnetic Intensity magnetic data coverage for the inversions (Figure 5).

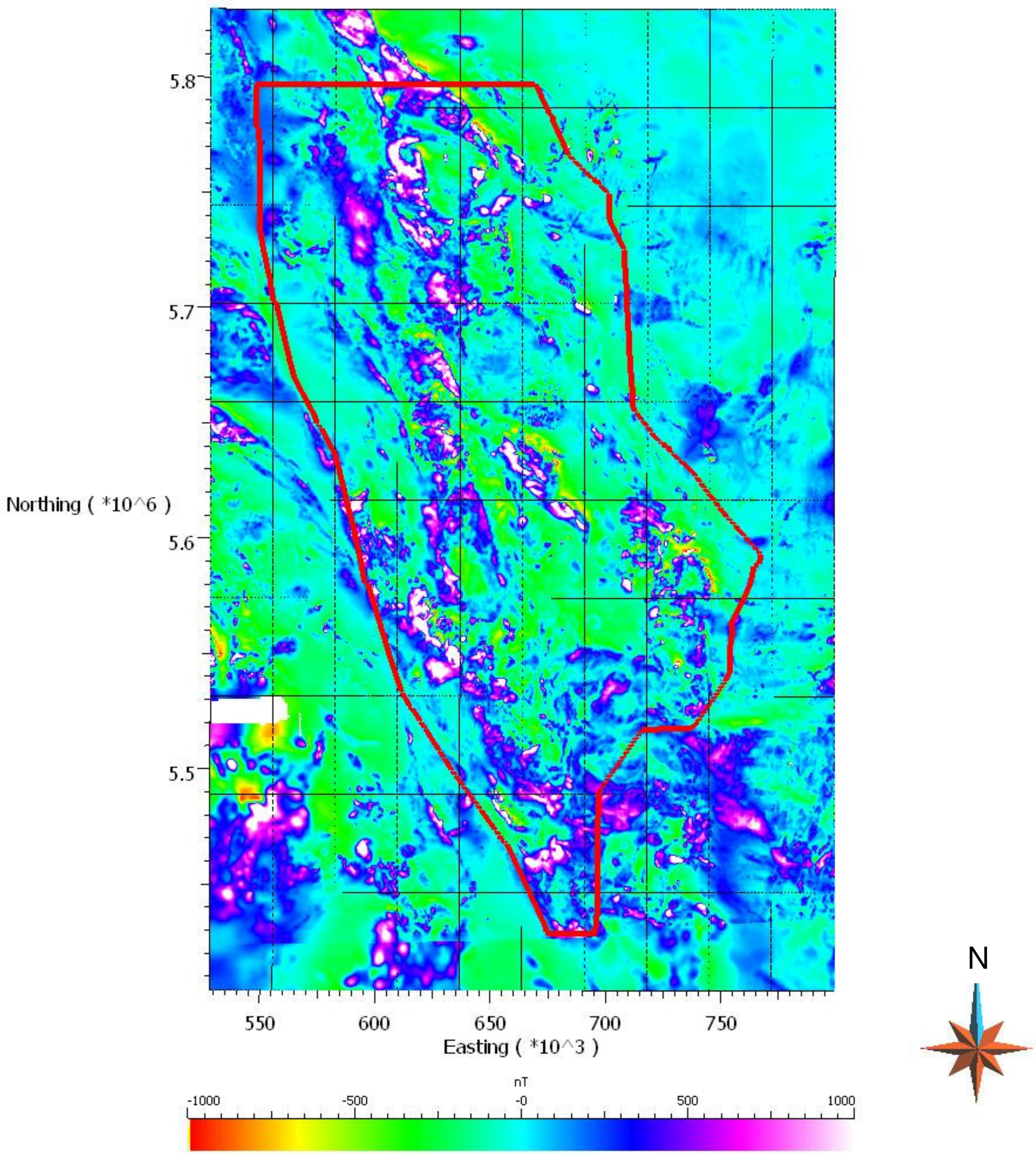


**Figure 5. QUEST-South Total Magnetic Intensity data (CGRF removed nT) and the outline of the airborne gravity survey (red).**

All supplied data were imported into Gocad. They were checked for quality and consistency, processed and edited if necessary, re-sampled, and converted to a format suitable for unconstrained 3D gravity and magnetic inversions.

A standard deviation is assigned to the data for inversion modelling purposes. The standard deviation represents an estimate of all possible sources of data uncertainty including: sensor sensitivity and noise, GPS location uncertainty, modelling uncertainties (topographic representation in the model or small sources that cannot be accounted for in the discretization). The assigned value is a starting estimate and the actual level of data misfit is determined during inversion.

### *2.3.1. Magnetic Data Processing*

Data were examined and edited for bad data points. Data for which there was no elevation information in the data base were discarded. The USGS data were merged with the GSC gravity data to obtain full coverage of QUEST, QUEST-West and QUEST-South projects areas from 94450 to 774050 Easting and 5417650 to 6160050 Northing. However there are two areas in the west and south-west that have no magnetic data.

The Canadian Geomagnetic Reference Field (CGRF) value was removed from the data. A standard deviation of 100 nT was assigned to the data. The data were prepared in UBC ASCII data format.

The total magnetic intensity (TMI) data were re-gridded at 2000 m intervals for the regional inversion, and at 500 m for the detailed inversions. The inducing field parameters used were those appropriate for the centre of the QUEST, QUEST-West and QUEST-South survey areas (longitude 123”13’30 E and latitude 54”17’39 N) and a date halfway through the acquisition of the QUEST magnetic data (September 15, 2007). The inducing field does not vary more than 1.5 degrees throughout the whole expanse of the survey area so using a single direction for the inducing field was felt to be a reasonable assumption. The magnetic data, as prepared for the regional inversions, are presented in Figure 6.

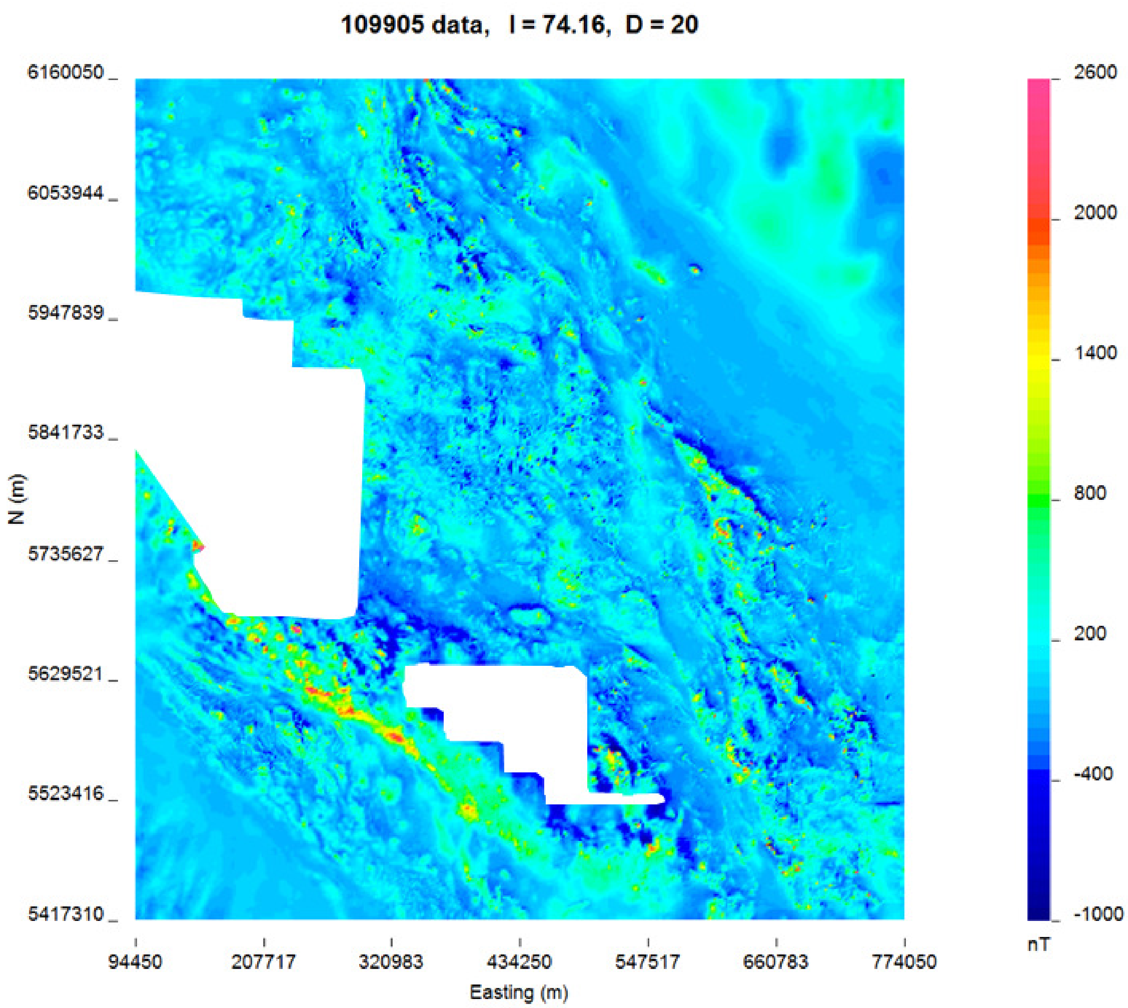


**Figure 6: Total Field Magnetic Intensity (CGRF removed nT) data prepared for regional inversion modelling.**

# 3. Geophysical Inversion Modelling

## 3.1. Methodology

### *3.1.1. Gravity Modelling*

Terrain-corrected gravity data are inverted to recover a 3D distribution of density contrast. The contrast is referenced to the density at which the terrain correction is applied. Topography is included in the inversion. The models are produced using the UBC-GIF inversion GRAV3D code (Appendix 4).

### *3.1.2. Magnetic Modelling*

Total Field Magnetic data are inverted for a 3D susceptibility model of the earth using the UBC-GIF MAG3D inversion code (Appendix 4). The correct inducing field parameters are needed as well as the data. The assumption has been made that no self-demagnetization or remanent magnetization effects are present (see Appendix 5 for further discussion). Topography is included in the inversions.

### *3.1.3. Separation of Regional Potential Field Signal*

A method for separating regional and residual gravity and magnetic fields using an inversion algorithm was presented in Li and Oldenburg (1998). The separation is achieved first by inverting the observed gravity or magnetic data from a large area to construct a regional physical property distribution (usually with a more coarsely discretized model). The local volume of investigation is removed from the regional model (model cell values in that volume are set to 0) and the gravity or magnetic fields are calculated and then used as the regional field. The residual data are obtained by simple subtraction of the regional field from the original data.

These residual data reflect the response from local and shallower geology that are often dominated by stronger regional sources, and they can be subsequently inverted on the local volume of interest (usually with a more detailed model discretization). The residual data may also be useful for qualitative interpretation of geology within the volume of interest.

This modelling-based approach to regional signal removal provides a robust result that is consistent with the modelling objectives. The modelling workflow is outlined below:

1. *Regional Inversion*: Invert the entire dataset using a coarse mesh to produce a regional model.
2. *Regional Response:* Define a local volume of interest. Set the physical property value to zero inside this volume and forward model to obtain the regional response.
3. *Regional Removal:* Calculate a residual by subtracting the regional response from the original data.
4. *Detailed, local Inversion:* Invert the residual data using a refined mesh over the local volume of interest.

The regional separation method can be employed to help inversion of very large areas of data where the number of model parameters at the desired detail of discretization would make the inversion of the entire dataset prohibitively slow. By calculating a regional response for different local volumes of interest (tiles), a separate local inversion can be performed on each residual dataset. A detailed model of the entire area can then be constructed by merging the local inversion models.

### 3.2. Model Discretization

Geophysical inversion modelling has been performed using a parameterization of the earth which employs many finely discretized cells or layers, each of which has a constant physical property value. The discretization is in the form of cuboid cells for the 3D gravity and magnetic inversions, and is commonly referred to as a mesh. The mesh parameters are based on the survey and system parameters, and are made small enough to reduce modelling errors due to discretization (such as the topographic representation) and are also small enough so that they do not introduce additional regularization in the inverse problem. Discretization parameters are tabulated in Appendix 6 for both the regional and detailed 3D gravity and magnetic inversions.

The 3D models have a core mesh of regularly sized cells corresponding to the lateral extents of the data. Padding cells of increasing dimensions extending east, west, north, south, and vertically down complete the volume used in the inversion. The padding cells help accommodate signal (often regional) that cannot easily be accounted for in the core mesh. Padding cells are removed for deliverable model products.

Both the gravity and magnetic inversions use the same 3D mesh, so direct evaluation can be made between the density contrast and magnetic susceptibility models. This representation of different physical property models (and different earth properties in general) allows quantitative 3D-GIS analysis of the modelling results (Section 4).

### 3.3. Separation of Regional Signal

Regional density contrast and susceptibility models have been used for regional removal. Seven local inversion volumes, or 'tiles', were used for the detailed inversions (Figure 7).

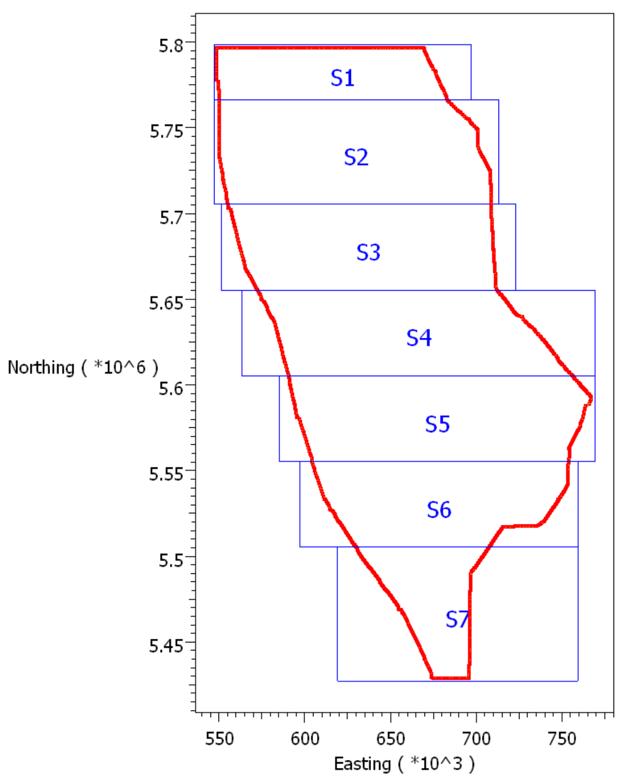


**Figure 7: Quest South survey area and model tiles.**

Figure 8 shows a plan section of the regional density contrast model with one local model region (tile) removed by setting the cells to zero density contrast. This is used in forward modelling the regional gravity response for the local region.

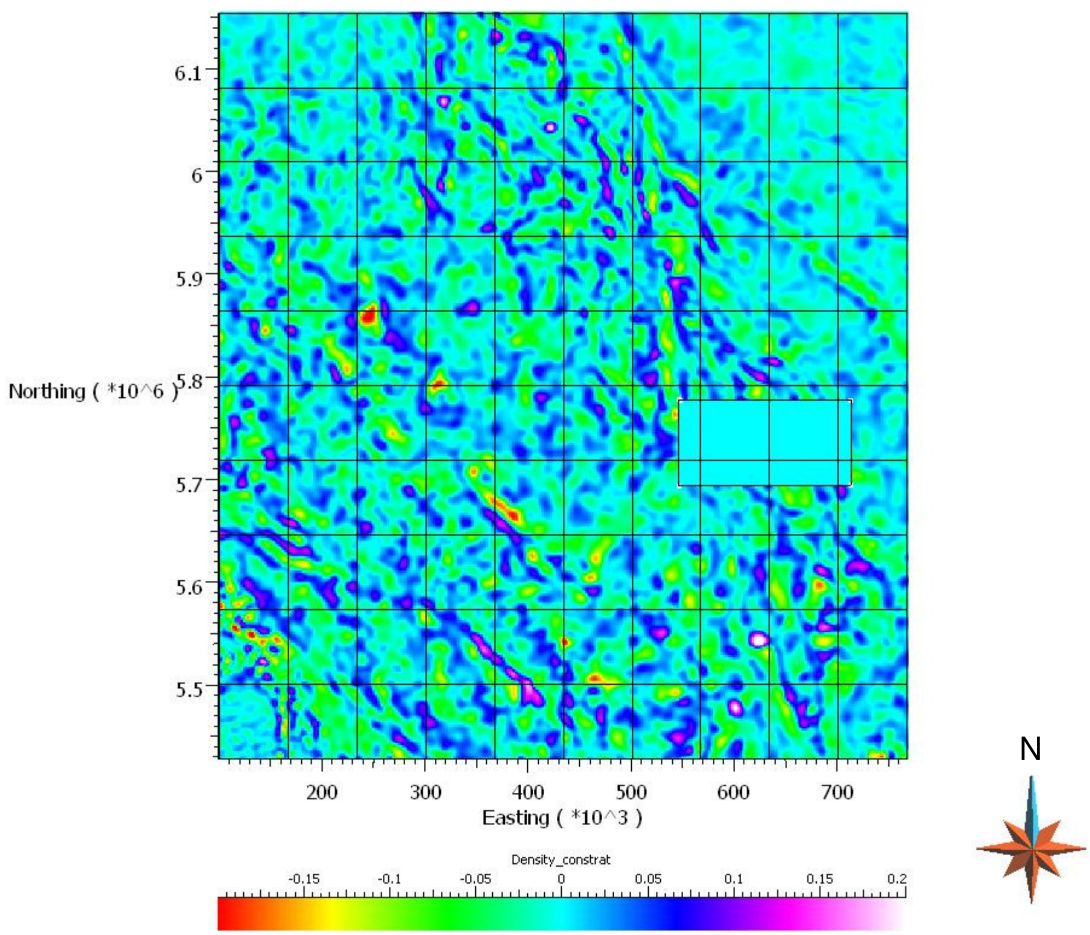


**Figure 8: Plan section of the regional density contrast model ($g/cm^3$) with one local model region removed (cells set to zero density contrast).**

Figure 9 shows the gravity anomaly of a sub-segment before and after regional removal. After regional removal, gravity anomalies show more detail as most long-wavelength signals are removed from the data. The signal in the residual data should contain information only from the associated detailed model region.

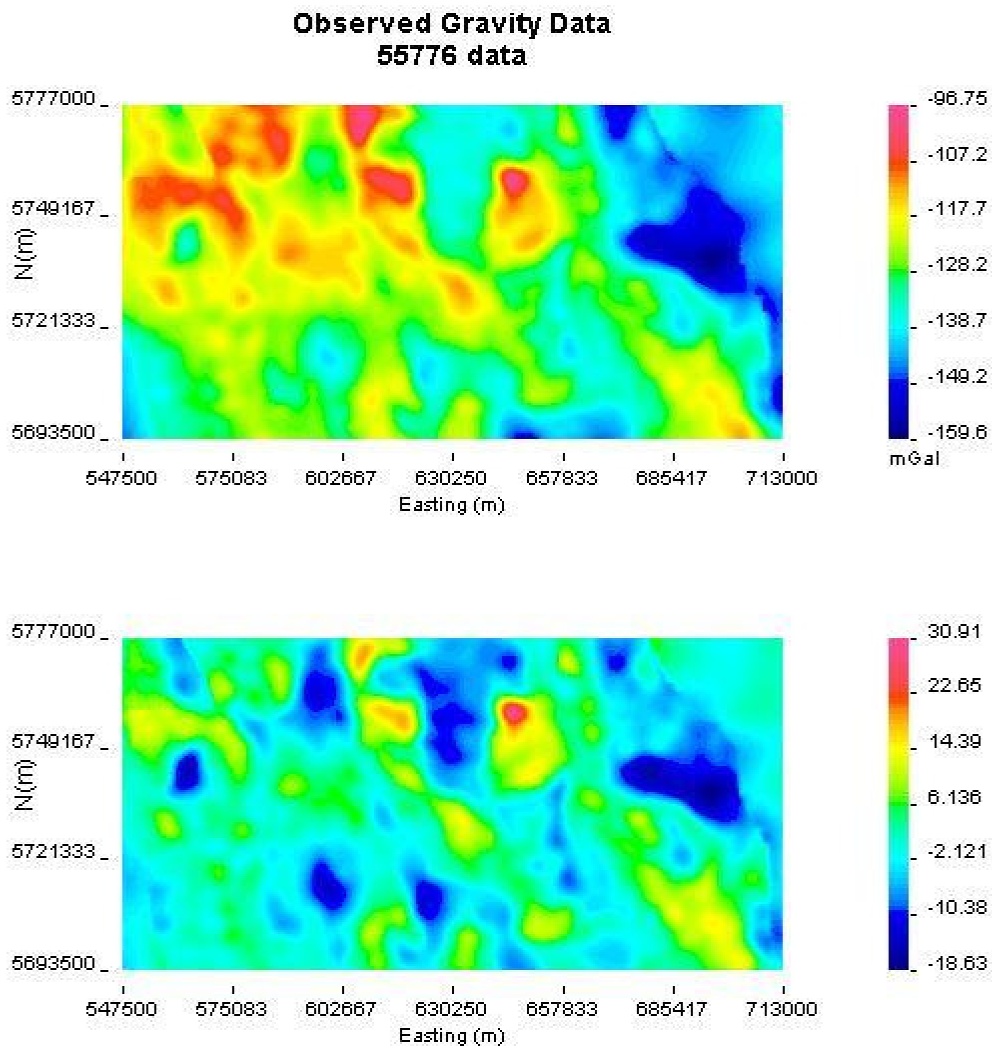


**Figure 9: Regional gravity data (upper) and local gravity data after regional separation (lower).**

### 3.4. Detailed Gravity Inversion Modelling

Seven detailed, local density contrast models have been produced from different local inversions. The models have been examined for consistency and merged to construct a detailed density contrast model for the entire survey area.

The final detailed model containing all the inversion results contains over 14 million cells. Careful selection of the inversion parameters for each local inversion allowed the models to fit together very well with only limited artefacts at the model transition. Details of the inversion parameters used for the detailed inversion blocks are shown in Appendix 6. Observed and predicted data for each tile are included in the suite of digital deliverables for comparison and analysis. The density model was cut at an elevation of 8 km below sea level. The density contrast ranges from -0.259 to 0.385 g/cm$^3$ (densities from 2.414 to 3.055 g/cm$^3$).

Viewing the 3D inversion output is best done with proper visualization software. However, to provide some insight about the results we show two plan-view sections. The first is the density contrast at sea-level (Figure 10); the second is the contrast at 2500 m below sea level (Figure 11). The shape of geologic structures can sometimes be captured by volume rendering the image and plotting iso-surfaces for a given threshold. The final image is critically dependent upon the threshold value for the iso-surface and so the interpreter will want to view the model with different thresholds. An image with an iso-surface value of 0.05 g/cm$^3$ is shown in Figure 12. All anomalous densities with a value less than this threshold are transparent.

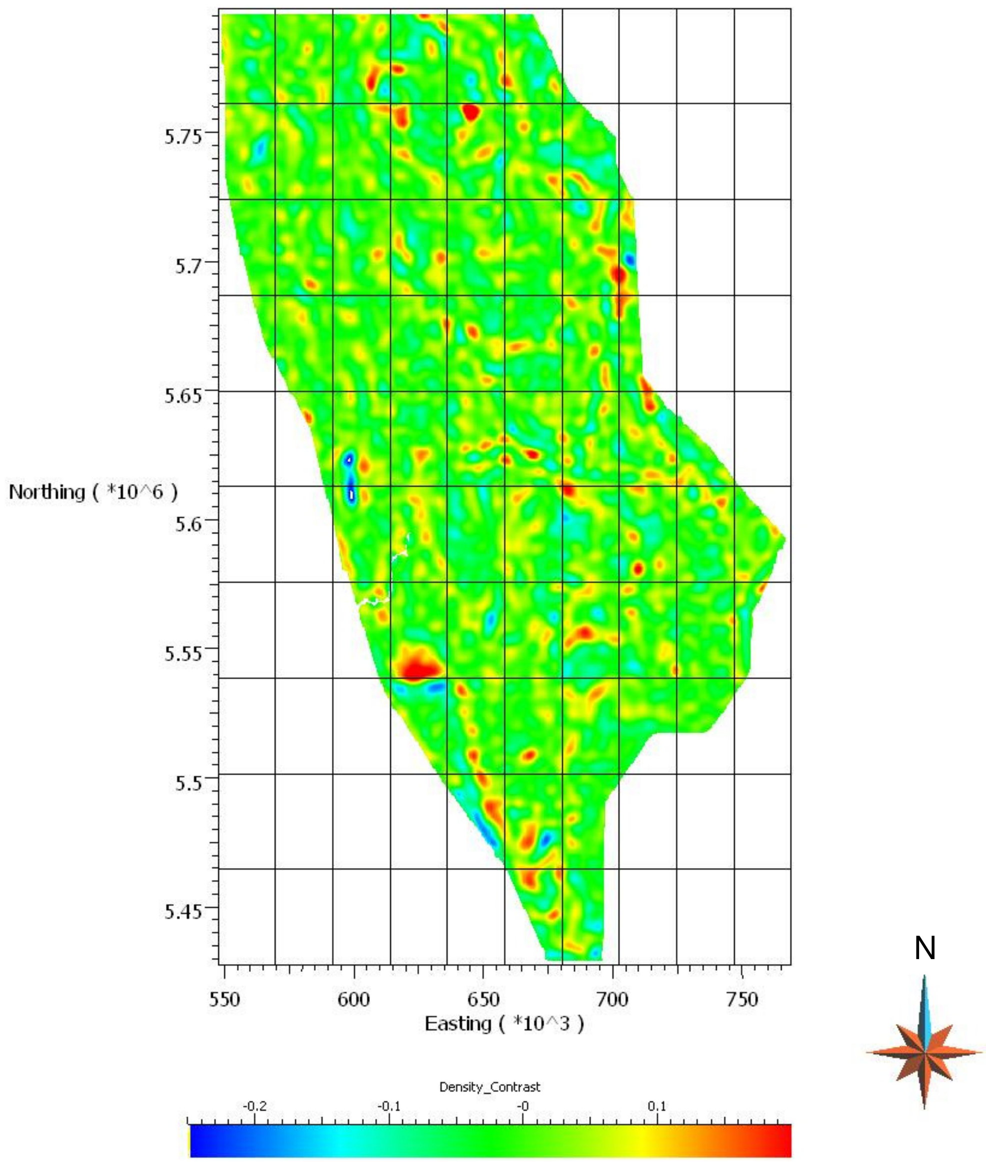


**Figure 10: Plan view of the QUEST-South detailed density contrast model at sea level.**

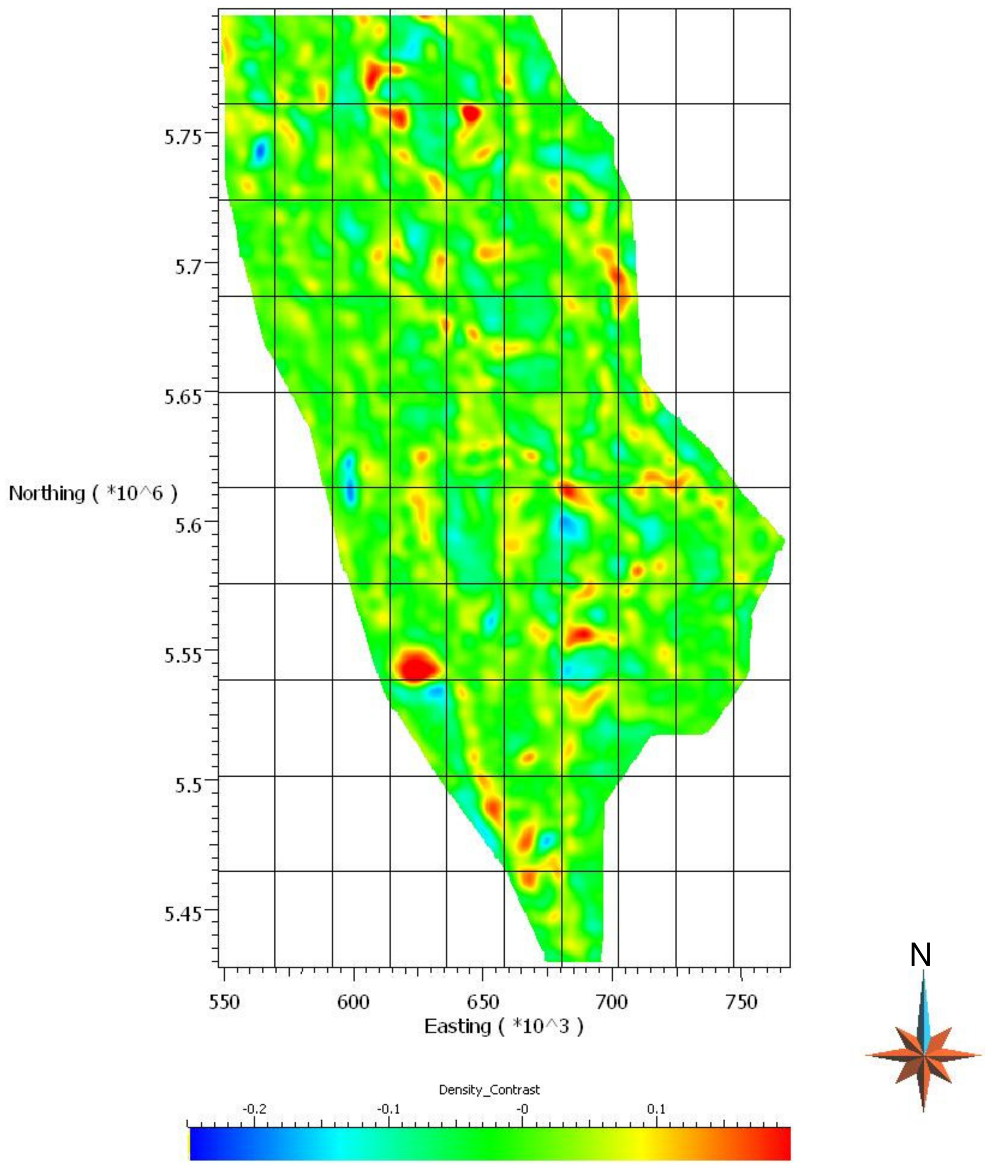


**Figure 11: Plan view of the QUEST-South detailed density contrast model at 2500 m below sea level.**

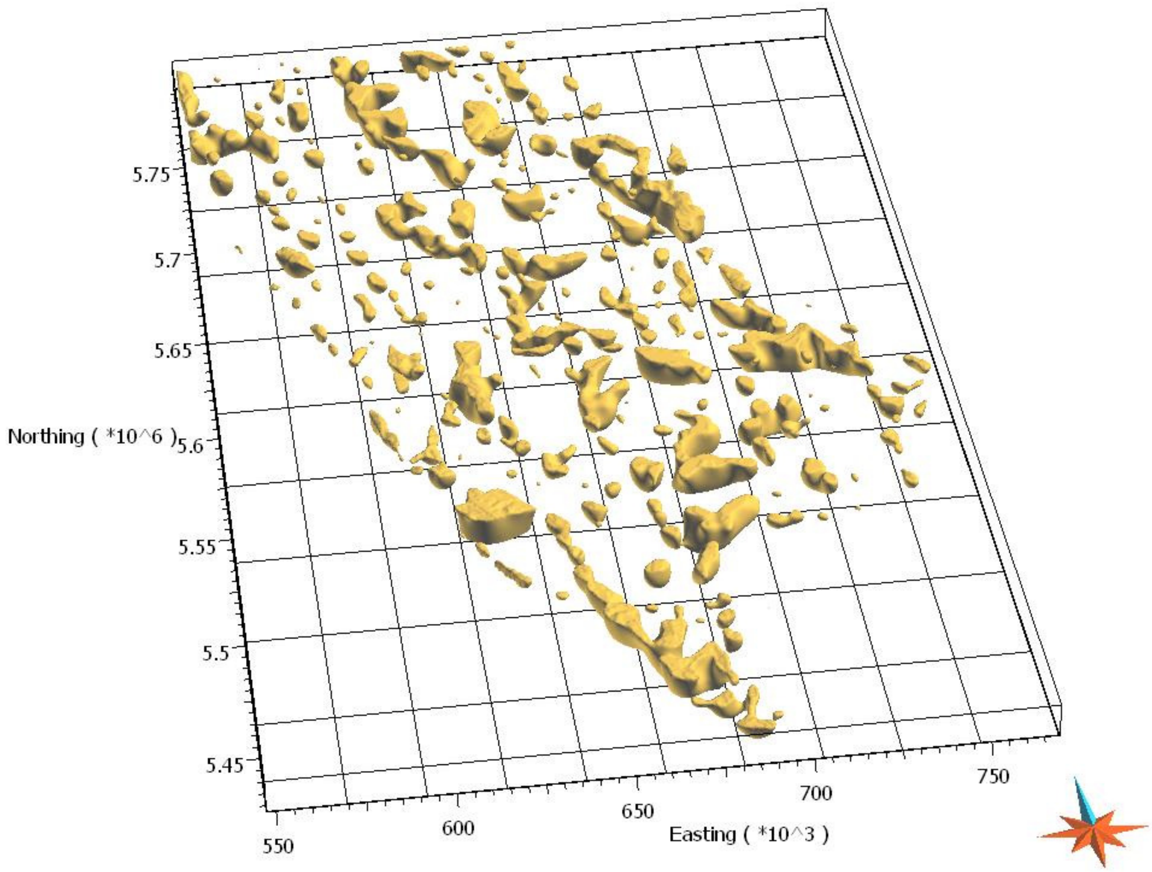


**Figure 12: Perspective view of the QUEST-South density contrast model showing an iso-surface at 0.05 g/cm$^3$.**

### 3.5. Detailed Magnetic Inversion Modelling

Figure 13, Figure 14, and Figure 15 show 3D distributions of magnetic susceptibility anomalies. As with the density contrast model, the magnetic susceptibility model is best viewed in 3D using a variety of views with different slices, cut-off values, and colour-scales. The two plan views and the one iso-surface presented convey the main features of the magnetic susceptibility model.

For the merged detailed local magnetic inversions, the maximum value reaches 0.42 S.I. This high value could be sufficient for self-demagnetization effects to be considered in some regions. Higher susceptibilities than this are probable as the model value represents the bulk volume susceptibility for the entire 500 m x 500 m x 250 m cell, and it is likely that it represents a combined effect of higher and lower susceptibilities at the sub-cell scale (a large range of sizes anywhere from the grain size up to 500 m). The models show detailed structure near the surface and gradually more smooth structure with depth. Observed and predicted data for each tile are included in the suite of digital deliverables for comparison and analysis.

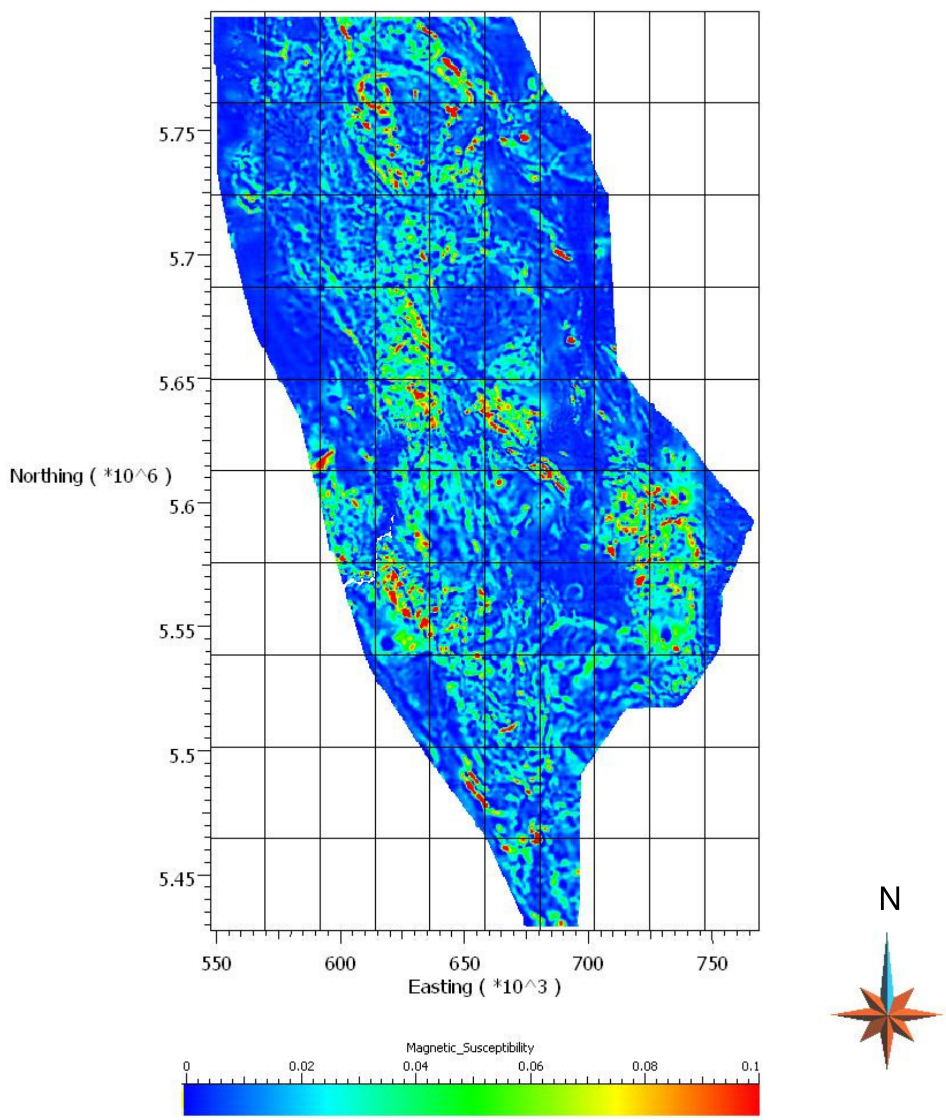


**Figure 13: Plan view of the QUEST-South detailed magnetic susceptibility model at sea level.**

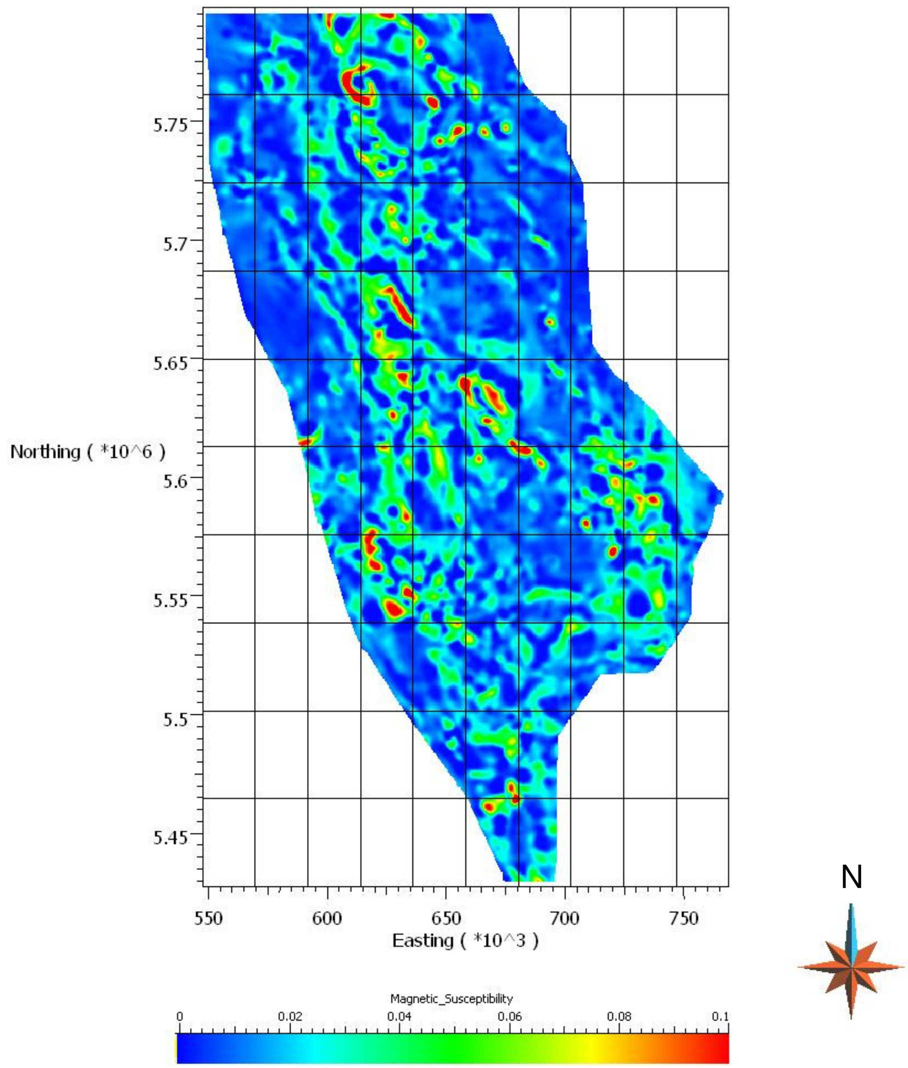


**Figure 14: Plan view of the QUEST-South detailed magnetic susceptibility model at 2500 m below sea level.**

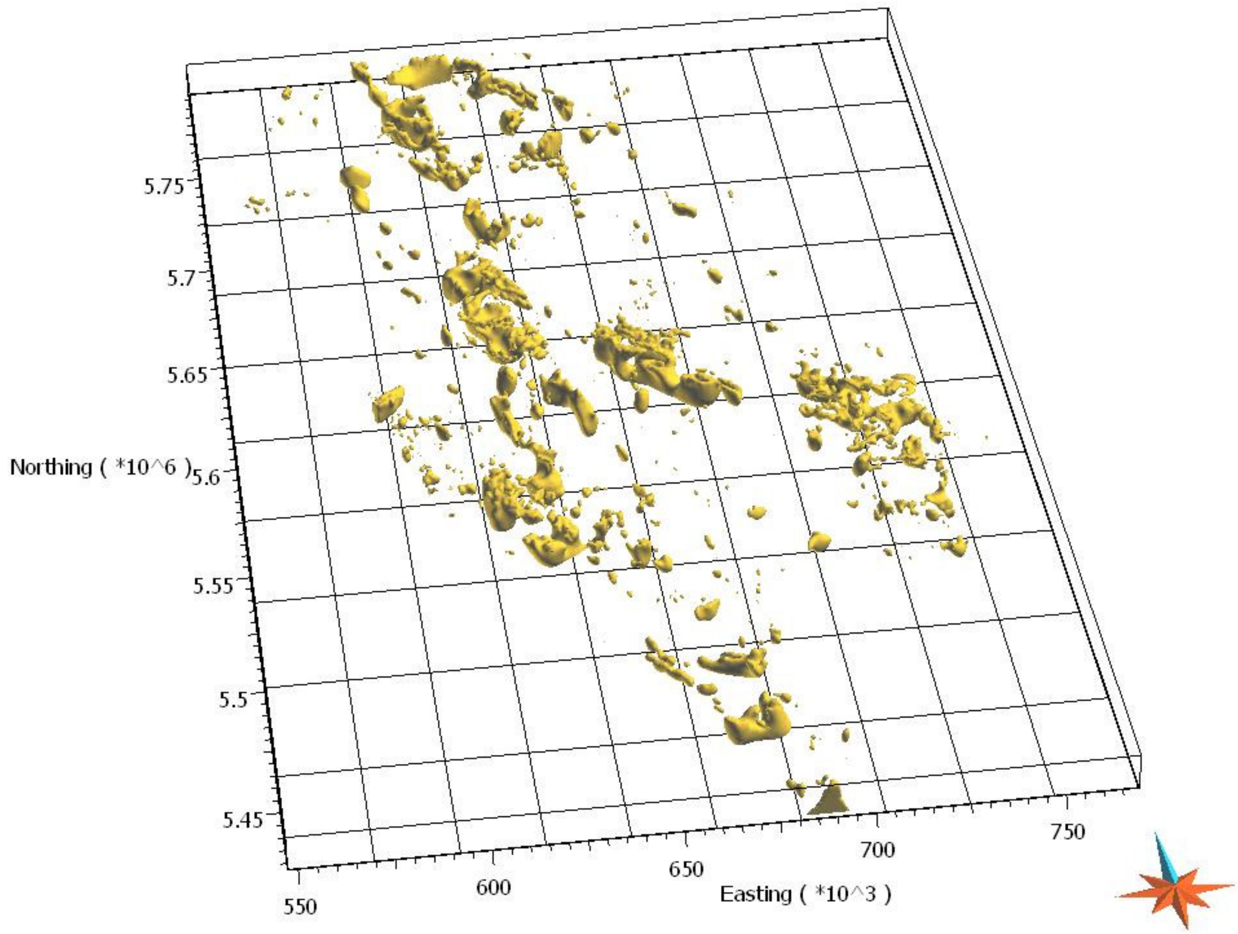


**Figure 15: Perspective view of the QUEST-South magnetic susceptibility model showing an iso-surface at 0.05 S.I.**

## 4. Common Earth Modelling

The inversion procedures produce 3D physical property models from gravity and magnetic data, which allow joint quantitative analysis to be carried out. The density contrast and magnetic susceptibility models are already on a common 3D mesh structure so they are spatially located and can be viewed and analyzed in conjunction with each other (Figure 16).

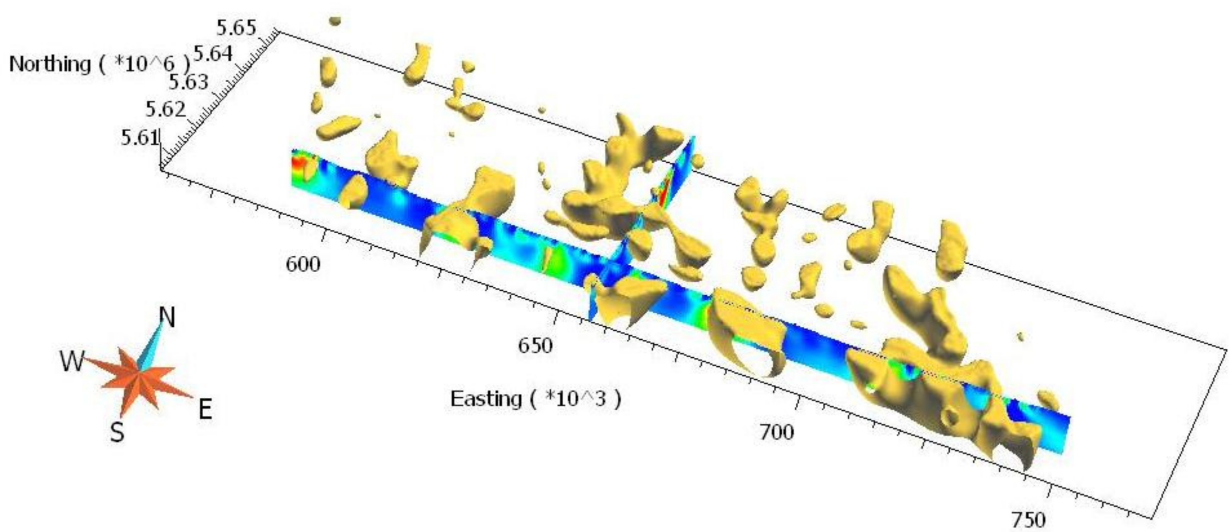


**Figure 16: Perspective view of inversion modelling results for Block S4 of the QUEST-South area. The density contrast model is represented as iso-surfaces at a value of 0.05 g/cm$^3$. North-south and east-west cross-sections display the magnetic susceptibility values.**

A simple example of 3D model interpretation is to classify regions in the model based on queries of physical property ranges that could relate to different geologic rock-types. With the density contrast and magnetic susceptibility models each divided into 3 arbitrary classes of high, medium, and low values (Table 1), a 3D classified model is produced from the nine combinations of these model classes applied to the physical property models (Figure 17). The resulting classified model is presented in Figure 18.

**Table 1: Physical Property Class Cut-Off Values.**

| | **Density Contrast ($g/cm^3$)** | **Susceptibility (SI)** |
|---|---|---|
| **Low** | < -0.05 | < 0.01 |
| **Medium** | -0.05 to 0.05 | 0.01 to 0.05 |
| **High** | > 0.05 | > 0.05 |

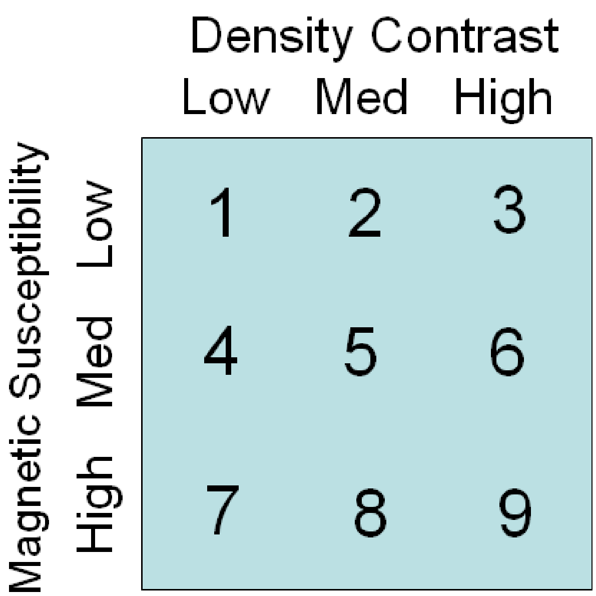


**Figure 17: A Simple physical property classification matrix for a two phase system.**

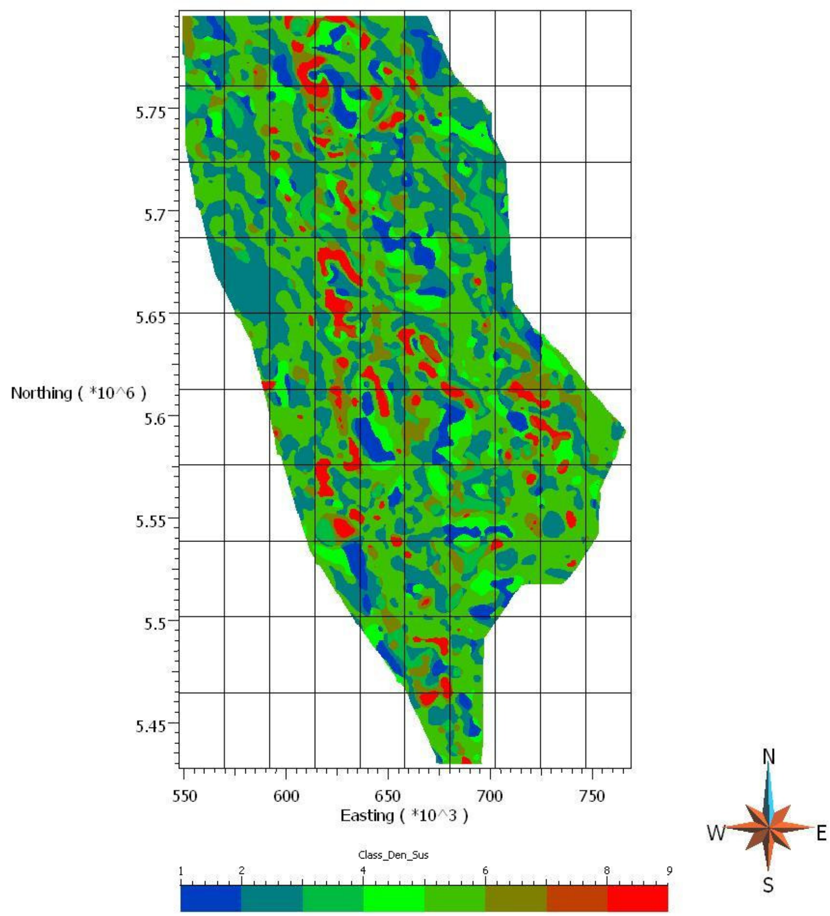


**Figure 18: Surficial plan view of 9 discrete physical property classifications based on high, medium and low domains of density-contrast and magnetic susceptibility (file: domain.ds). See Figure 17 to interpret the color legend.**

While it is not expected that these simple physical property classifications correlate directly with geology, it is hoped that some correlations with certain physical property ranges can be related to favorable lithology or alteration and then further refined.

The above examples demonstrate, in a very simplistic way, how the physical property models can be used together for exploration in a Common Earth Model using 3D-GIS methods. Given these models, more advanced 3D classification methods can now be employed to help identify lithology, alteration, or mineralization, based on model or data driven exploration criteria (e.g. Weights of Evidence, Multi-Class Index Overlay, Self Organising Maps, Neural Networks, etc.). The addition of more information in the Common Earth Model such as geology, geochemistry, drilling and other geophysical models will enable more accurate 3D targeting to be performed.

## 5. Deliverables

An extensive suite of digital deliverables have been prepared for distribution. The deliverables include several format types: Gocad, UBC, Geosoft, DXF, column ASCII, and PDF. The following products are provided:

- Observed and predicted data (gravity, magnetic))
- 3D density contrast and magnetic susceptibility models
- Several derivative products such as iso-surfaces, and a simple example of domain classification
- Gocad 2009.3 projects containing data and models for each survey block
- 3D PDF scenes for easy visualization and communication of the results. The 3D PDF display products are produced as an output from Gocad. These can be viewed in the freely available Adobe Reader (versions 8 and higher).
- This report in PDF format

Details of the deliverables are contained in an accompanying MS Excel spreadsheet:

Mira_AGIC_GeoscienceBC_Quest_South_Deliverables.xlsx

## 6. Conclusions

Detailed density contrast and magnetic susceptibility inversion models have been produced for the QUEST-South survey area. These models, and the extensive suite of associated digital deliverables, will aid visualisation, interpretation, and quantitative analysis of the data for regional exploration in the area. As well as the modelling products, the work undertaken in modelling preparation is valuable quality control of the data. This will be of benefit as exploration personnel use the QUEST-South geophysical dataset.

The deeper density contrast and magnetic susceptibility models can be interpreted within the context of geology in order to help define large structures and intrusives. Although a single density contrast and magnetic susceptibility model has been delivered, it is recognized that other models could have been chosen as appropriate model candidates. Inverse problems are non-unique and the output depends upon many factors which are difficult to quantify. The three main factors common to all inversions are: (a) how to estimate uncertainties in the data, (b) details of the model objective function and the *a priori* information, and (c) determining the appropriate value of the regularization parameter that balances misfit and the model objective function. Great care has been taken to winnow suspect data, remove regional fields for local inversions, estimate errors, incorporate reasonable information into reference models, and generate physical property models that fit the data well, but do not over-fit the data. In addition, because the inversion algorithms attempt to find the "simplest" (generally smooth) models that fit the data, the provided models will hopefully be representative of the larger scale features in the earth. They represent a first pass state-of-the-art estimate of the large scale distribution of density contrast and magnetic susceptibility in the QUEST-South region.

Rocks are not uniquely characterized by a single physical property. The importance of the work presented here is that there are now volumetric regions in the QUEST-South area that are characterized by two, and in some cases three, physical properties. These distributions can be used with 3D-GIS query technology to help identify potential exploration areas (as demonstrated). In follow-up work in these local regions, inclusion of additional *a priori* information in the form of geologic knowledge (conceptual model, overburden thickness, drilling, outcrop lithology, etc.), petrophysical information, and further geophysics, will help guide the selection of inversion parameters and constraints so that models with enhanced resolution can be obtained. This should make exploration more successful and cost effective.

# 7. Recommendations

This suite of physical property models provides an important foundation on which to base regional exploration analysis and follow-up surveys. Several points of recommendation are made for users of these models to consider:

1. ***Physical Properties:*** For 3D physical property models to be used effectively for interpretation and exploration targeting, a good understanding of the exploration target physical properties will be needed which can be related to geology and geologic processes.
2. ***Constraining Information:*** If geologic or physical property information is made available, the models can be recreated with this information acting as a constraint on the inversion process. This would produce more reliable models that are consistent with multiple datasets. This can be performed on smaller scale regions of the model. Such information could include drill holes, geologic maps, outcrop physical property samples, etc.
3. ***Target Customization:*** Integrated interpretation and 3D-GIS analysis on multiple physical property models can be customized to specific exploration target criteria, such that a set of model queries suitable for massive sulphide exploration, for example, would be different than queries designed for porphyry copper exploration.
4. ***Survey Design for Follow-up Data Acquisition:*** Data acquired as follow-up to targeting from the QUEST-South physical property models, or from other data (e.g. geochemical surveys), can be collected using effective survey designs based on physical property analysis and the QUEST-South models. This will ensure appropriate sensitivity to the exploration target is obtained. An example of this could be a DC Resistivity and IP survey being designed to target a magnetic susceptibility body at an estimated depth. This knowledge will allow feasibility studies to optimize the survey parameters so the goal of the survey is efficiently realised.

5. ***Detailed Data Acquisition:*** More detailed and possibly different geophysical data can be acquired in order to define the geophysical model targets at a higher resolution. This has already been done over some deposits and prospects in the QUEST and QUEST-West areas such as the Mt. Milligan deposit where closer line-spacing infill AEM and magnetic data were collected.

6. ***Integrated Modelling:*** The density contrast and magnetic susceptibility models can be used to help constrain each other. For example, if structures in the models are assumed to be at the same location, then the model obtained from inverting one data type can be used as a weighting or a constraint for a further inversion of the other data set. The end results are inversion models that individually fit the data and also incorporate a priori geologic knowledge about the relationship between the two physical properties shared so that each model is consistent where possible.

7. ***Common Earth Model Development:*** In order to continue the construction of a Common Earth Model with multiple earth properties useful for exploration targeting, more layers of information such as different geophysical data or models, geochemical data, drilling, assays, and geologic mapping and structural information can be added. This would help develop a Common Earth Model with all the important information needed to design comprehensive exploration search criteria in the QUEST-South area.

8. ***Classification Methods:*** A simple example of an integrated physical property query is presented. Classification of the models based on more advanced methods would produce a model that would relate more closely to geology, alteration, and mineralization for exploration targeting purposes.

9. ***Additional Regional Data Coverage***: Regional airborne data coverage can be extended to cover adjacent areas, or different areas in British Columbia. This will enable the same exploration resource as demonstrated from the success of the QUEST-South surveys and data analysis.

10. ***Accounting for Complicated Magnetization:*** The magnetic inversion modelling did not account for either remanent or self-demagnetization affects. In some areas, these may be present and it will be important to understand the effect more complicated magnetization has on the data in order to avoid misleading interpretations. This should be considered if recovered magnetic susceptibility values are above 0.2 S.I. (0.42 S.I. encountered in the QUEST-South magnetic susceptibility model) and may become more apparent if the modelling discretization size is reduced.

## Submittal

The work in this report has been completed by Nigel Phillips and Thi Ngoc Hai Nguyen of the Mira Geoscience Advanced Geophysical Interpretation Centre.

This report has been reviewed and approved by:

Doug Oldenburg, Principal Consultant

4 April 2011

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## Appendix 1. Glossary of Useful Terms

See accompanying document:

Mira AGIC Glossary of Useful Terms.pdf

## Appendix 2. Project Deliverables

See accompanying MS Excel file:

**Mira_AGIC_GeoscienceBC_Quest_South_Deliverables.xlsx**

# Appendix 3. Data and Processing Specifications

**Table 2: Sanders Gravity Survey Specifications.**

| | |
|---|---|
| Instrument | AIRGrav |
| Line spacing | 2000m |
| Line orientation | East-West |
| Aircraft Altitude | 200m |

# Appendix 4. Modelling Software

**GRAV3D**

GRAV3D is a program developed by the UBC Geophysical Inversion Facility (UBC-GIF) (an academic research unit within the Department of Earth and Ocean Sciences at the University of British Columbia) for carrying out forward modelling and inversion of surface, airborne, and/or borehole gravity data in three dimensions.

The program library carries out the following functions:

1. Forward modelling of the vertical component of the gravity response to a 3D volume of density contrast.

The model is specified using a mesh of rectangular cells, each with a constant value of density contrast, and topography is included. The gravity response can be calculated anywhere within the model volume, including above the topography simulating ground or airborne surveys, and inside the ground simulating borehole surveys.

2. Inversion of surface, and/or airborne gravity data to generate 3D models of density contrast.

The inversion is solved as an optimization problem with the simultaneous goals of (i) minimizing an objective function on the model and (ii) generating synthetic data that match observations to within a degree of misfit consistent with the statistics of those data. To counteract the inherent lack of information about the distance between source and measurement, the formulation incorporates a depth or distance weighting term. By minimizing the model objective function, distributions of subsurface density contrast are found that are both close to a reference model and smooth in three dimensions. The degree to which either of these two goals dominates is controlled by the user by incorporating *a priori* geophysical or geological information into the inversion. Explicit prior information may also take the form of upper and lower bounds on the density contrast in any cell. The regularization parameter (controlling relative importance of objective function and misfit terms) is determined in one of three ways, depending upon how much is known about errors in the measured data.

The large size of useful 3D inversion problems is mitigated by the use of wavelet compression. Parameters controlling the implementation of this compression are available for advanced users.

(GRAV3D Manual)

**MAG3D**

MAG3D is a program library (version 4.0 as of August 2005) for carrying out forward modelling and inversion of surface, airborne, and/or borehole magnetic data in the presence of a three dimensional Earth. The program library carries out the following functions:

1. Forward modelling of the magnetic field anomaly response to a 3D volume of susceptibility contrast.

Data are assumed to be the anomalous magnetic response to buried susceptible material, not including Earth's ambient field. The model is specified using a mesh of rectangular cells, each with a constant value of susceptibility, and topography is included. The magnetic response can be calculated anywhere within the model volume, including above the topography, simulating ground or airborne surveys, and inside the ground simulating borehole surveys. This code assumes susceptibilities are "small". This means results will be wrong when susceptibilities are high enough to cause self-demagnetization. There is no method for incorporating remanent magnetization in this code.

2. Inversion of surface, airborne, and/or borehole magnetic data to generate 3D models of susceptibility contrast.

The inversion is solved as an optimization problem with the simultaneous goals of (i) minimizing an objective function on the model and (ii) generating synthetic data that match observations to within a degree of misfit consistent with the statistics of those data. To counteract the inherent lack of information about the distance between source and measurement, the formulation incorporates a depth or distance weighting term. By minimizing the model objective function, distributions of subsurface susceptibility contrast are found that are both close to a reference model and smooth in three dimensions. The degree to which either of these two goals dominates is controlled by the user by incorporating *a priori* geophysical or geological information into the inversion. Explicit prior information may also take the form of upper and lower bounds on the susceptibility contrast in any cell (as of version 4.0). The regularization parameter (controlling relative importance of objective function and misfit terms) is determined in either of three ways, depending upon how much is known about errors in the measured data.

The large size of useful 3D inversion problems is mitigated by the use of wavelet compression. Parameters controlling the implementation of this compression are available for advanced users.

(MAG3D Manual).

# Appendix 5. Magnetization and Modelling

## Magnetization

Local magnetic anomalies in the data are due to the magnetic field produced by magnetically susceptible material beneath the surface that has been magnetized by the earth's ambient magnetic field. The majority of the response comes from shallow material due to the fast fall-off nature of the magnetic field. For low susceptibilities (< ~0.2 S.I.) the strength of the magnetization vector, and resulting field, is a linear relationship between the earth's field flux intensity and susceptibility. This makes interpretation relatively intuitive and modelling a less complex process.

## Self-Demagnetization

For high magnetic susceptibilities (> ~0.2 S.I.) the relationship between the strength of magnetization and susceptibility is non-linear. This non-linear relationship is the cause of the phenomena known as self-demagnetization where a component of the magnetization opposes the earth's field. The effect of self-demagnetization, which aligns the magnetization vector with the long-axis of the magnetic body, is to reduce the amplitude of the anomaly and change the anomaly location and shape, thus making traditional interpretation unreliable (Wallace, 2007). A typical result of considering only linear magnetization in modelling routines when non-linear magnetization is present is for the resulting dip of a magnetic body to be too shallow.

## Remanent Magnetization

Remanent magnetization (or remanence) is a permanent magnetization that can be obtained by ferromagnetic material through several phenomena including thermo-, chemical and detrital remanence. Often, the remanence obtained in the past becomes oriented in a direction different from the Earth's field today; this can occur through movement of the Earth's magnetic poles or through tilting of the stratigraphic units containing the permanently magnetized material. Hence, the induced and remanent components can be oriented in different directions.

Typical magnetic inversion routines assume no remanent component exists, employ a magnetization direction aligned with the current earth's inducing field, and erroneous results can be obtained from this incorrect assumption. (Lelievre et al., 2006). A typical result of not considering remanent magnetization is similar to that of the self-demagnetization effect, where the direction of inducing magnetization is incorrect and resulting dips of magnetic bodies can be incorrect or a diagnostic cone of zero magnetic susceptibility can propagate from the surface down through the model.

# Appendix 6. Modelling Parameters

**Table 3: Regional 3D Mesh Parameters**

| | |
|---|---|
| Cell size in East direction | 2000 m |
| Cell size in North direction | 2000 m |
| Cell size in vertical direction | 500 m |
| Number of core cells in East direction | 355 |
| Number of core cells in North direction | 384 |
| Number of core cells in vertical direction | 45 |
| Number of padding cells in East direction | 10 |
| Number of padding cells in West direction | 10 |
| Number of padding cells in North direction | 10 |
| Number of padding cells in South direction | 10 |
| Number of padding cells in vertical direction (down) | 16 |

**Table 4: Detailed Mesh Parameters (single mesh)**

| | |
|---|---|
| Cell size in North direction | 500 m |
| Cell size in North direction | 500 m |
| Cell size in vertical direction | 250 m |
| Number of core cells in East direction | 330 to 420 |
| Number of core cells in North direction | 116 to 188 |
| Number of core cells in vertical direction | 60 |
| Number of padding cells in East direction | 6 |

| | |
|---|---|
| Number of padding cells in West direction | 6 |
| Number of padding cells in North direction | 6 |
| Number of padding cells in South direction | 6 |
| Number of padding cells in vertical direction (down) | 16 |

**Table 5: Detailed Gravity Inversion Parameters (for parameters that were consistent between tiles)**

| | |
|---|---|
| Sensitivity Wavelet Relative Threshold | 0.002 |
| Convergence Criteria | Chi-factor = 0.2 |
| Global Density Contrast Bounds ($g/cm^3$) | -2, 2 (min, max) |
| Length Scales (Le, Ln, Lz) | 1.500E+03, 1.500E+03, 1.000E+03 |

**Table 6: Magnetic Inversion Modelling Specifications**

| | |
|---|---|
| Sensitivity Wavelet Relative Threshold | 0.002 |
| Convergence Criteria | Chi-factor = 0.1 |
| Number of Data Inverted | 41168 (example for one tile) |
| Global Susceptibility Bounds (SI) | 0, 1 (min, max) |
| Length Scales (Le, Ln, Lz) | 1.500E+03, 1.500E+03, 1.000E+03 |