ADVANCED GEOPHYSICAL INTERPRETATION CENTRE

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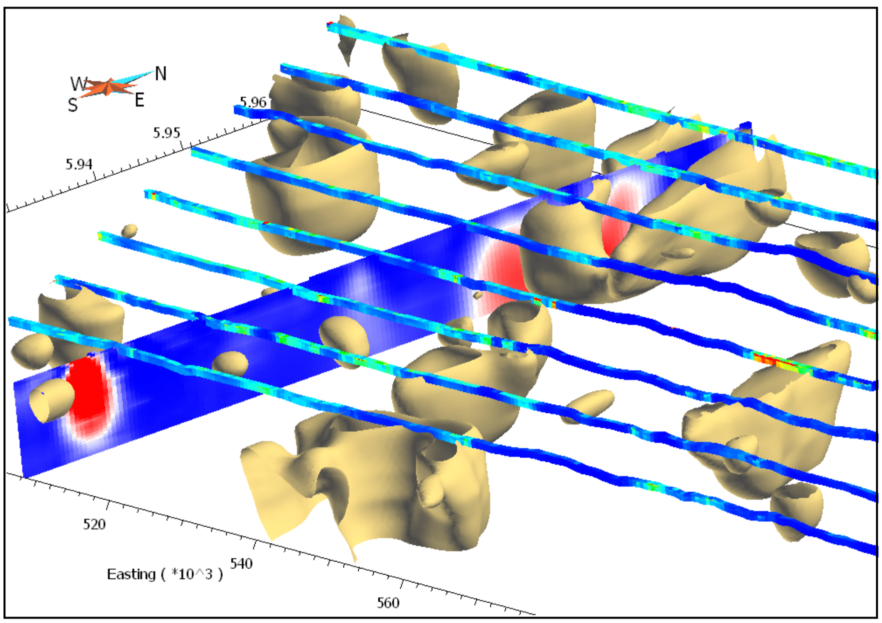
QUEST Project: 3D inversion modelling, integration, and visualization of airborne gravity, magnetic, and electromagnetic data, BC, Canada.



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Executive Summary

The Mira Geoscience Advanced Geophysical Interpretation Centre has completed 3D inversion modelling, integration, and visualization of airborne gravity, magnetic, and electromagnetic data for the QUEST project area, BC, Canada. This was undertaken for Geoscience BC as follow-up analysis of QUEST project geoscience data. The objective of this work is to provide useful 3D physical property products that can be directly employed in regional exploration to target prospective ground based on different exploration criteria.

This work considers all airborne gravity, magnetic and electromagnetic data available for the QUEST project area. The inversions were performed using the UBC-GIF GRAV3D, MAG3D, and EM1DTM, suite of algorithms for the gravity, magnetic, and AEM data respectively. The products are 3D inversion models of density contrast, magnetic susceptibility, and electrical conductivity, and integrated products combining the individual physical property models. These are provided for each of the five regions of the project area (A, B, C, D, and NT).

The gravity and magnetic data were modelled in 3D using several smaller tiles after separation of regional signal. The tiles were combined to construct a detailed model over the whole area. The conductivity data were inverted for 1D (layered earth) models using a laterally parameterized method and subsequently interpolated in 3D. A late-time, background conductivity map has also been produced for the survey area. An estimate of the depth of penetration has been provided for the AEM conductivity models. The resulting models provide guidance to the regional structure and prospective geology and location of alteration and mineralization.

Final density contrast, magnetic susceptibility, conductivity models have been integrated into a Common Earth Model ready for 3D GIS analysis, interpretation, and integration with geologic, drill-hole, and other geophysical information. 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 different, commonly used formats. A suite of 3D PDF scenes have been produced to aid in visualization and communication.

The resulting physical property models 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, drill-holes, 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.

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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, magnetic susceptibility, and conductivity inversion modelling for Geoscience BC. This was modelled from airborne gravity, airborne total field magnetic, and airborne EM data respectively. The data were collected as part of the Geoscience BC's QUEST Project; a program of regional geochemical and geophysical surveys designed to attract the mineral exploration industry to an under-explored region of British Columbia between Williams Lake and Mackenzie (Geoscience BC QUEST Website). The survey area and data blocks are shown in Figure 1. The software used for the inversion were the University of British Columbia – Geophysical Inversion facility (UBC-GIF) program suites GRAV3D, MAG3D, and EM1DTM, and Gocad was used for data preparation, model integration, visualisation, and interpretation.

Information about the methods employed for the inversion modelling, the geophysical data used, and the data processing are presented in Sections 2, 3, and 4.

Section 5 details the modelling results. Regional 3D potential field inversion modelling used a coarse discretization with cells sizes of 2000m x 2000m x 500m 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 500m x 500m x 250m cell dimension. The smaller, local inversion cell size is appropriate for the airborne survey data line spacing of 2000 m and 4000 m.

A 3D conductivity model which conforms to topography was constructed by interpolating 1D conductivity models produced from the AEM data at each station along and across survey lines. An estimate of the depth of investigation has been produced for the AEM 1D modelling results.

Topography was used at all stages of the inversion modelling, and the inversions are unconstrained by geologic or physical property information.

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 6. Section 7 details the digital modelled, integrated, and visualization deliverables. Conclusions and recommendations are provided in sections 8 and 9, respectively. Several pieces of background and reference material are provided in the appendices.

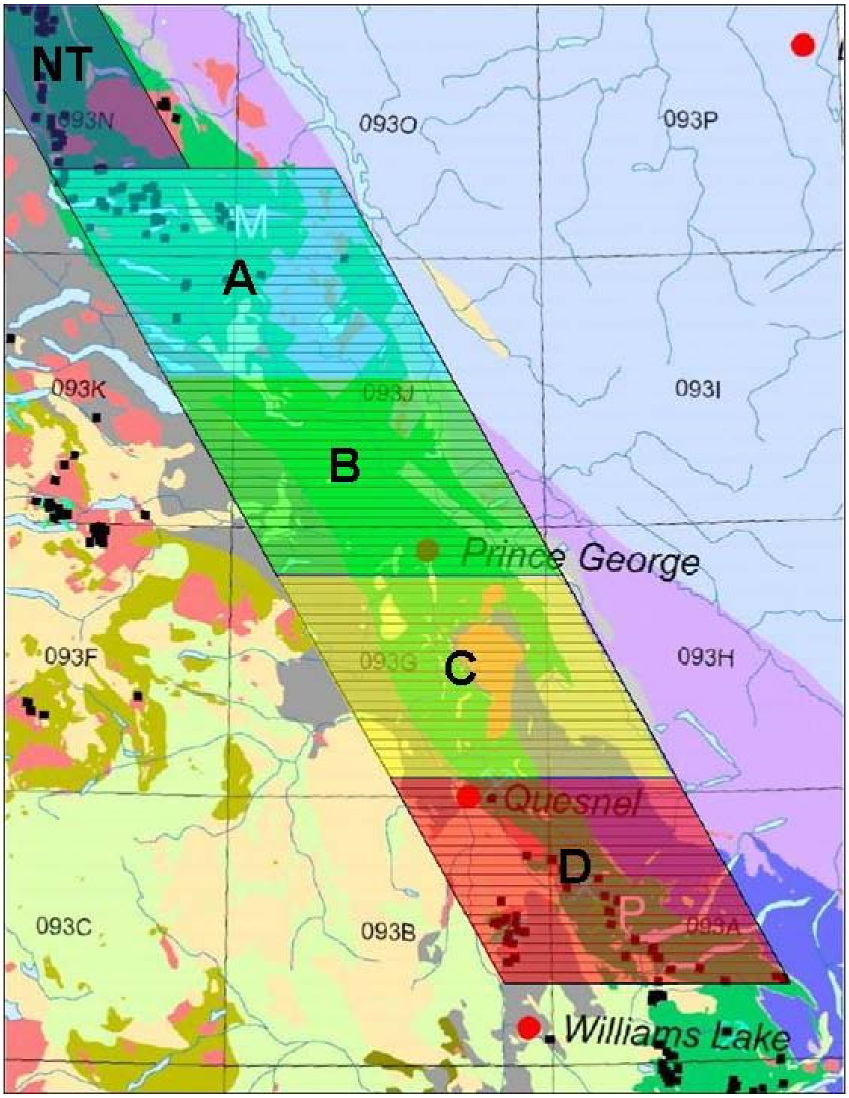

Figure 1 Regional geology base with NTS map sheets showing coverage of the airborne geophysical data split into 5 blocks: A, B, C, D, and NT.

1.1. Geologic Setting

The primary focus is the Quesnel Terrane which is prospective for copper and gold porphyry deposits, and is locally covered by a thick layer of glacial sediments (Geoscience BC website). A bedrock geology map, without a geologic legend, is shown below (BCGeoMap 2009).

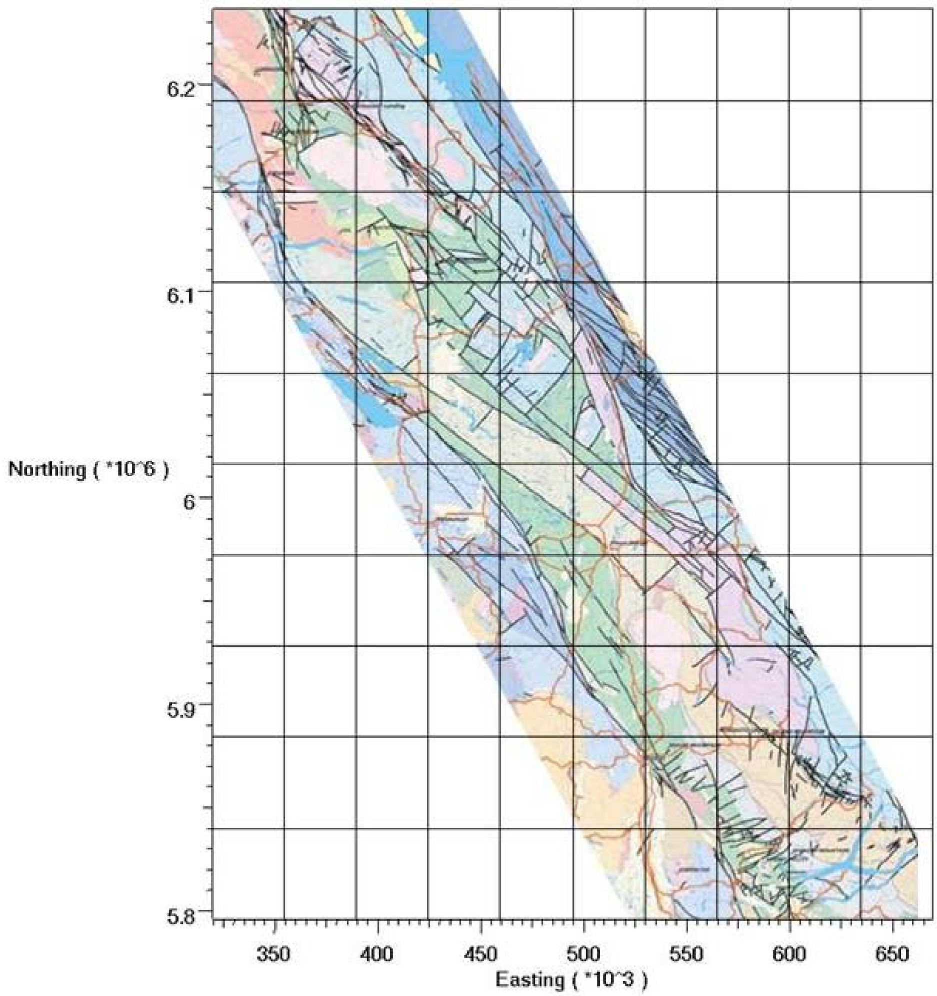

Figure 2 Interim Bedrock Geology Map of the Quesnel Terrane.

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 to target prospective ground based on different exploration criteria. This is done using physical property-based inversion to determine 3D distributions of density contrast, magnetic susceptibility, and electrical conductivity for a 390 km x 460 km area located in centre of British Colombia, to a depth of 8 km. 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 data acquisition campaigns in favourable areas.

2. Methodology

The workflow for producing density contrast, magnetic susceptibility, and conductivity models of the QUEST 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, removal of negative EM decays, and regions of high power-line effects).

2. Data preparation involving down-sampling or re-gridding, upward-continuation of gravity data, and creation of inversion input files.

3. Regional and background inversion modelling which are 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, PDF and 3DPDF.

2.1. 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 3).

2.2. Magnetic Modelling

Total Field Magnetic data are inverted for a 3D susceptibility model of the earth using the UBC-GIF MAG3D inversion code (Appendix 3). 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. Topography is included in the inversions. The character of the recovered model is determined by a versatile model objective function based on L2 (smooth) measures.

2.3. 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 data set 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.

For a detailed explanation of the regional removal process see the paper by Li and Oldenburg, 1998a.

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 data set prohibitively slow. By calculating a regional response for different local volumes of interest (tiles), a separate local inversion can be performed on each residual data set. A detailed model of the entire area can then be constructed by merging the local inversion models.

2.4. Airborne EM Modelling

The AEM inversions were performed using the 1D electromagnetic inversion program EM1DTM, developed at the University of British Columbia – Geophysical Inversion facility (UBC-GIF). This program is a versatile inversion code capable of inverting data from 3 component magnetic-dipole sources. The algorithm is designed to invert for a model with many more layers than input data so that the character of the recovered model is determined by a model objective function and not solely by the goal of fitting the data.

The input to the algorithm is the time-domain EM data for each channel, assigned data uncertainties, transmitter and receiver positions and altitude, transmitter waveform, system information, and model and inversion parameters (e.g. layer thicknesses, background conductivity, and level of desired data misfit). The outputs are: a finely discretized 1D conductivity model for each sounding, the predicted data, and a number of measures which can be used to evaluate the quality of the inversion results. The recovered conductivity is smoothly varying in depth while at the same time it is minimally different from the prescribed reference conductivity. It predicts the observed data to an appropriate degree that is justified by the assigned errors in the data. The algorithm is capable of producing L2 (smooth) and L1 (blocky) model results but the L2 option is most commonly used. This means that sharp boundaries will appear somewhat smoothed in the final model although increased structure can be infused by use of a layered reference model. Appendix 3 provides more detailed information on the EM inversion software.

Each sounding is inverted individually. The 1D conductivity models are presented side-by-side along line and also interpolated between lines to create approximate 3D conductivity models of the earth.

2.5. Laterally Parameterized AEM Inversions

There are many input data and parameters for the 1D EM inversions and it is often difficult to optimize these parameters for every sounding in a large survey. When the parameters are not appropriate, artifacts can appear in the resulting models that can be misleading to the interpreter.

Two of the parameter selection issues faced are explained below:

1. Due to the large area covered by AEM surveys, the host geology, in which anomalous zones are being sought, will often vary considerably. In terms of the EM survey this means the background conductivity will change over the survey area. For the inversions being performed on these data, the reference conductivity model should be varied accordingly.

The EM inversion code has functionality for calculating the best-fitting conductivity halfspace for the data at each sounding along a line. Often this value is a reasonable representation of the bulk conductivity at the sounding location. The best fitting halfspace can be used as a reference model. However, if the conductivity varies greatly with depth, or if the conductivity has large changes in the lateral direction (as would be the case for a contact zone) then the best fitting halfspace is not an adequate representation of the local geology. A more robust procedure is required to compute a background reference model for each station.

2. The level of data misfit is often hard to determine for each sounding along a line because noise levels in the data vary and because 3D conductivity features may be encountered that may not be explained with a 1D model. Thus choosing the level of data-misfit can be difficult. Strategies such as finding a model that fits to a predefined misfit value, or a strategy of inverting the entire line using a fixed value of the regularization parameter, can lead to poor results in locations where the noise is large and variable.

In order to help avoid these problems, a laterally parameterized methodology is followed for the inversion of AEM data.

First the best-fitting half-space models are calculated using only later times in the EM decay. These half-space values are smoothed along line and then used as reference model inputs for the layered inversions. This provides a gradually changing background conductivity, results in more consistent models from sounding to sounding, and reduces misleading conductivity modelling artifacts. The smoothed background conductivity model is also a useful exploration product when displayed as a map as it shows lateral variations in conductivity that can be a guide to deeper, underlying geology.

A level of balance between data misfit and model complexity is defined by a trade-off parameter. This trade-off parameter is calculated by first determining the appropriate level for each sounding, and then smoothing it along line. The inversions are subsequently re-run with the smoothed trade-off parameter used at each sounding. The resulting models are much more consistent from sounding to sounding and allow for geologic features to be more easily interpreted. While some soundings will still be either over- or under-fit with the predicted data, the inconsistency is greatly reduced from when a fixed trade-off parameter is used, and generally more appropriate models are produced.

This method of determining inversion parameters by considering lateral background conductivity and data-misfit levels produces models that avoid misleading artifacts and hopefully reveal more reliable geologic information.

2.6. Estimate of AEM Depth of Investigation.

The meshes used in the inversion extend to considerable depth but conductivities in the lower region are determined by the reference model and not by the observations. Effectively they are beyond the depth of investigation of the survey and hence do not contain reliable information. These sections of the model should be removed from images that display final conductivity profiles. The depth of investigation depends upon the EM instrumentation and survey parameters, and also upon the conductivity structure. The depth of investigation can be estimated by carrying out multiple inversions using different backgrounds (as is done in DC resistivity inversion) but it can also be estimated using cumulative conductance rules. This does not require additional inversions. Rather, it specifies the depth of investigation to be that depth at which the cumulative conductance reaches a target value. We use that method here and the resulting models are cut-off below this depth and provide a guide to the depth to which more reliable interpretation can be made. For details refer to Appendix 6.

3. Data

All data were provided, and the modelling results are delivered in, the NAD83 UTM Zone 10N Datum and Coordinate System. Due to the large area covered by the survey, the area was split into five blocks – A, B, C, D, and NT.

3.1. Topographic Data

Topographic data were obtained from the SRTM database on a 90m grid. This was used for the gravity and magnetic modelling and interpolation of the 1D conductivity models in 3D under topography. Figure 3 shows the topography data. The survey area exhibits some areas of rugged terrain.

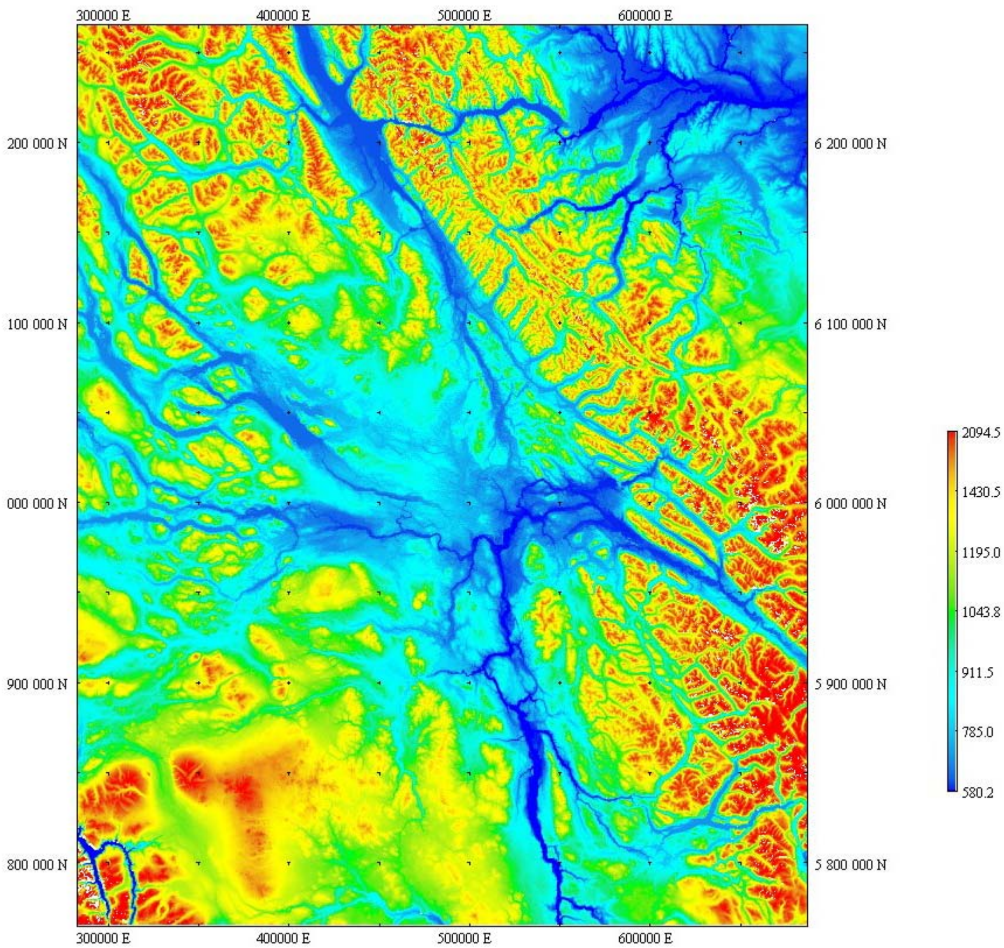

Figure 3: QUEST topography data [m]. Source SRTM World Elevation 90m.

3.2. 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 250m grid size. This gravity data set consists of Quest, Quest West, and Nechako Basin surveys (Figure 4) collected by Sander Geophysics in 2008 at a line spacing of 2000m (East-West flight lines). Additional information regarding the data can be found in the Sanders acquisition report for this survey.

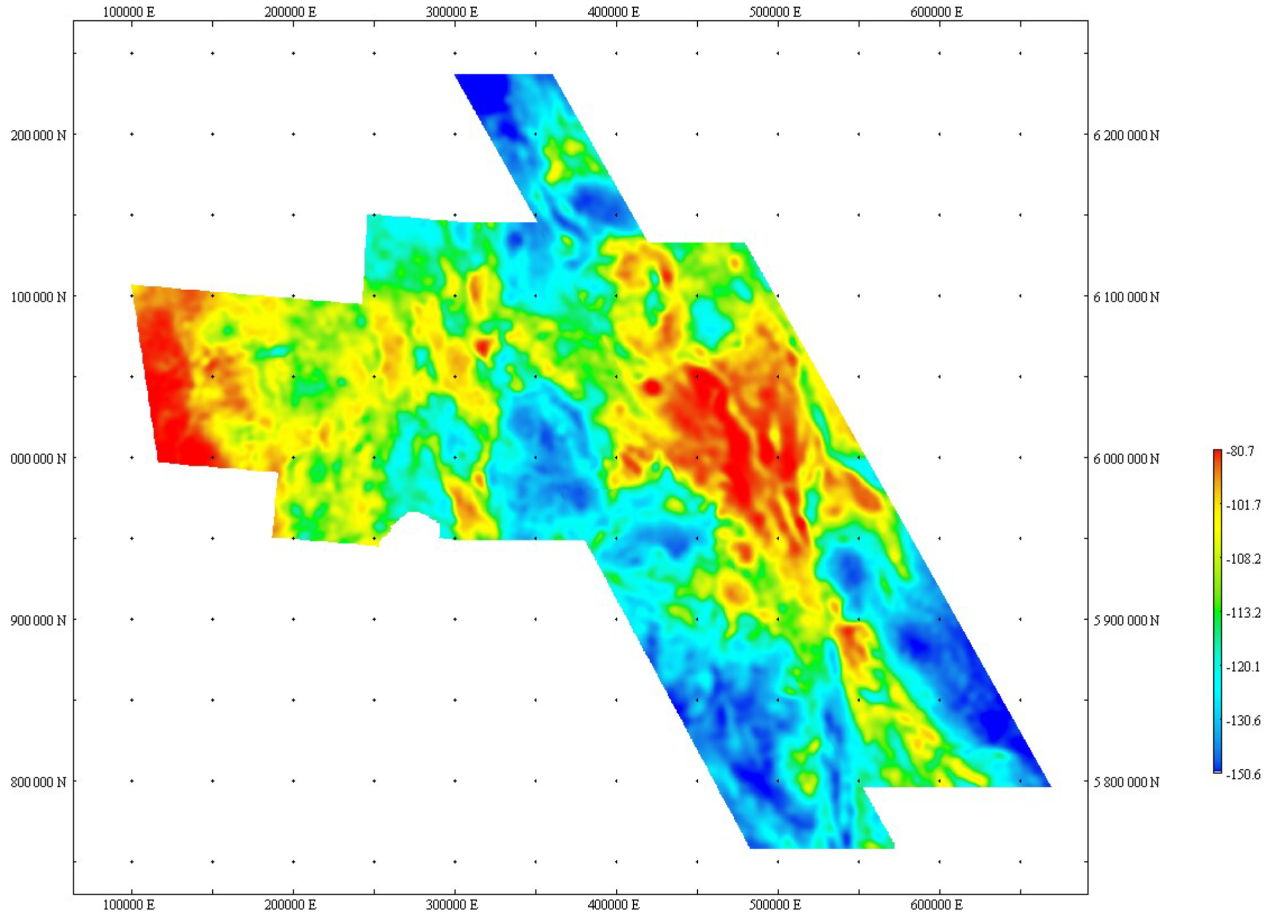

Figure 4 Bouguer gravity of Quest, Quest West and Nechako Basin surveys [mGal]

Surface gravity data for the study area, obtained from the GSC, have also been downloaded from Canadian depository databases. This data set was utilized to complete the airborne gravity so as to obtain full coverage of the study area for the regional inversion prior to regional removal.

3.3. Airborne Magnetic Data

Geoscience BC has provided a regional airborne magnetic database and gridded GSC magnetic data. The magnetic database consists of helicopter-borne data collected by Geotech Ltd. from July to November 2007 on East-West lines at a line spacing of 4000m (collected in conjunction with a VTEM survey). The data were provided in an ASCII column format with diurnal corrections and leveling applied to the total field observations, location information, and sensor height (nominal 75m flight height). Magnetic survey specifications are detailed in Appendix 2, and more information regarding the survey can be found in the Geotech survey acquisition report.

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 regional inversions (Figure 5).

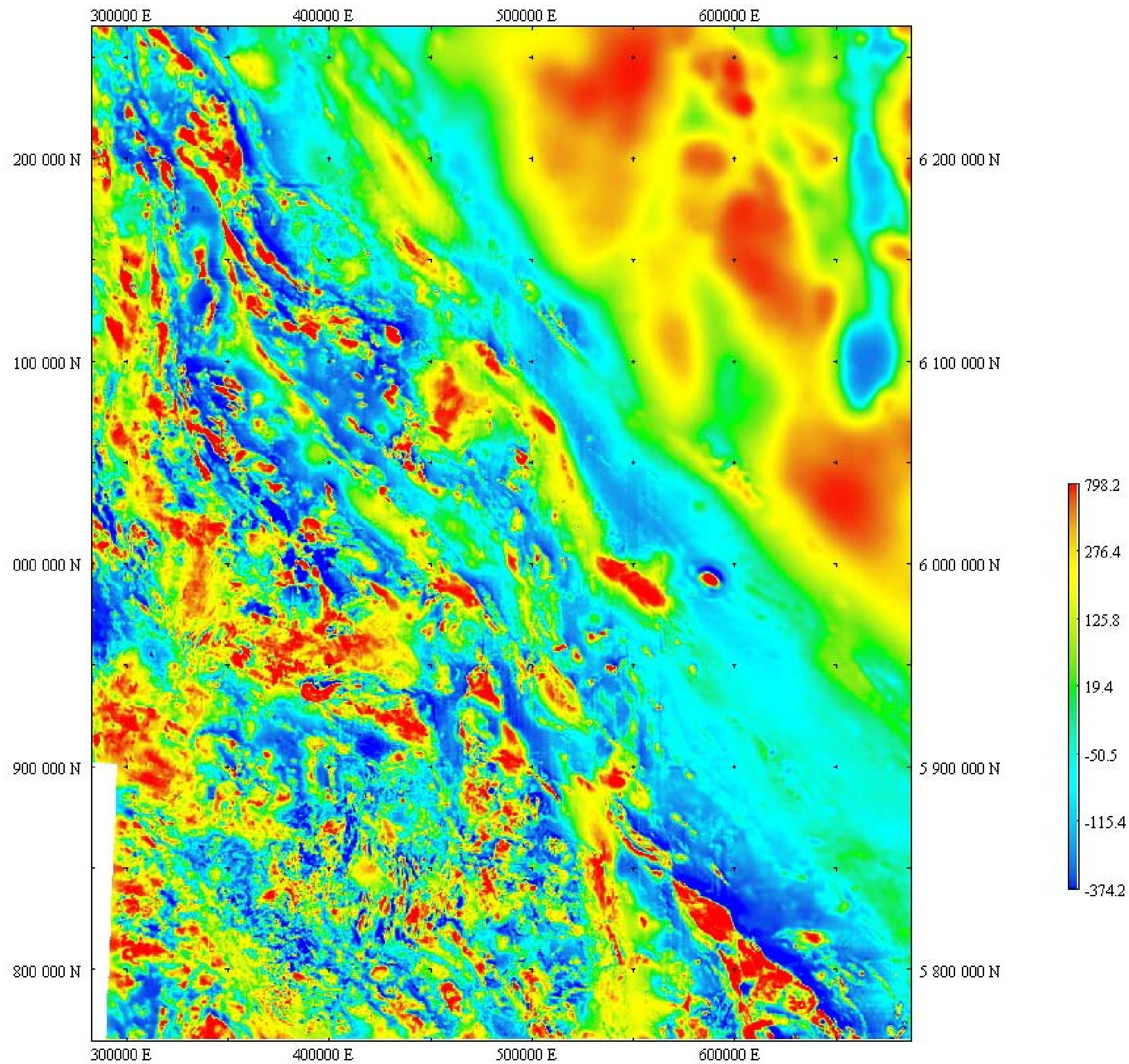

Figure 5 Combined QUEST and GSC Total Magnetic Intensity data [nT].

3.4. Airborne EM Data

Helicopter-borne VTEM data were collected by Geotech Ltd. concurrently with the airborne magnetic data acquisition and has the same data coverage. The survey covered 46,500 km^2 in area and over 11,600 line kilometres.

Line spacing for the survey was flown at 4000 m. Lines were flown East-West and split into two parts, west and east, with each part approximately 62 km in length. No tie lines were flown. The last 27 of the 35 data channels were used for the inversion. The airborne electromagnetic data are assumed to have had adequate quality control procedures applied although some bad data were removed during additional quality control processing.

The VTEM survey specifications are detailed in Appendix 2, and more information regarding the survey can be found in the Geotech survey acquisition report.

4. Data Processing

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 and 1D EM 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.

4.1. 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 with one data point at the horizontal center of each cell.

4.2. Gravity Data Processing

The GSC surface gravity data were upward continued 125 m above topography to reduce cell effects from the discretization of the model. These upward continued data were used with the airborne gravity to obtain a full coverage of study area from 290250 to 680250 Easting and from 5784250 to 6248250 Northing (Figure 6).

The gravity data were re-gridded at 2000 m sample interval for the regional inversions and at 500m for the detailed inversions. A standard deviation of 1 mGal was assigned to the data. This value is ~ 2% of the total range of terrain corrected data.

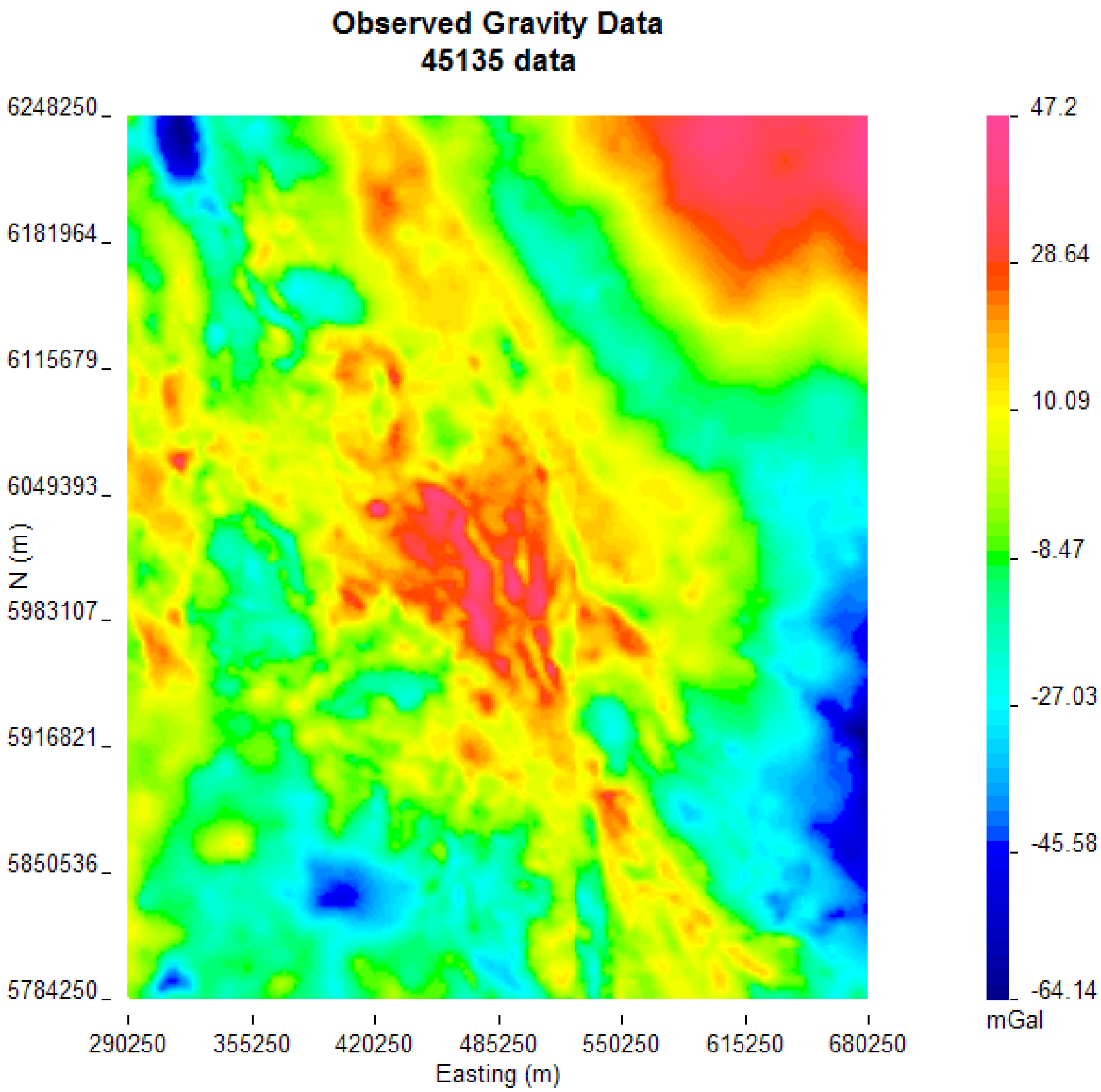

Figure 6 Terrain Corrected gravity data prepared for regional inversion modelling.

4.3. 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 IGRF value was removed from the data and the data were then down-sampled along line. The distance between sampled points was approximately equivalent to half the nominal flight height.

A standard deviation of 100 nT was assigned to the data. The data were prepared in UBC ASCII data format. Appendix 2 details the processing applied to the data.

The TMI data were re-gridded at 2000 m intervals for the regional inversion, and at 500m for the detailed inversions. Interpolated flight height information was merged with the data. The inducing field parameters used were those appropriate for the centre of the survey area (longitude 123"13'30 E and latitude 54''17'39 N) and a date halfway through the acquisition (15th of September 2007). The inducing field doesn't vary more than one degree 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 7.

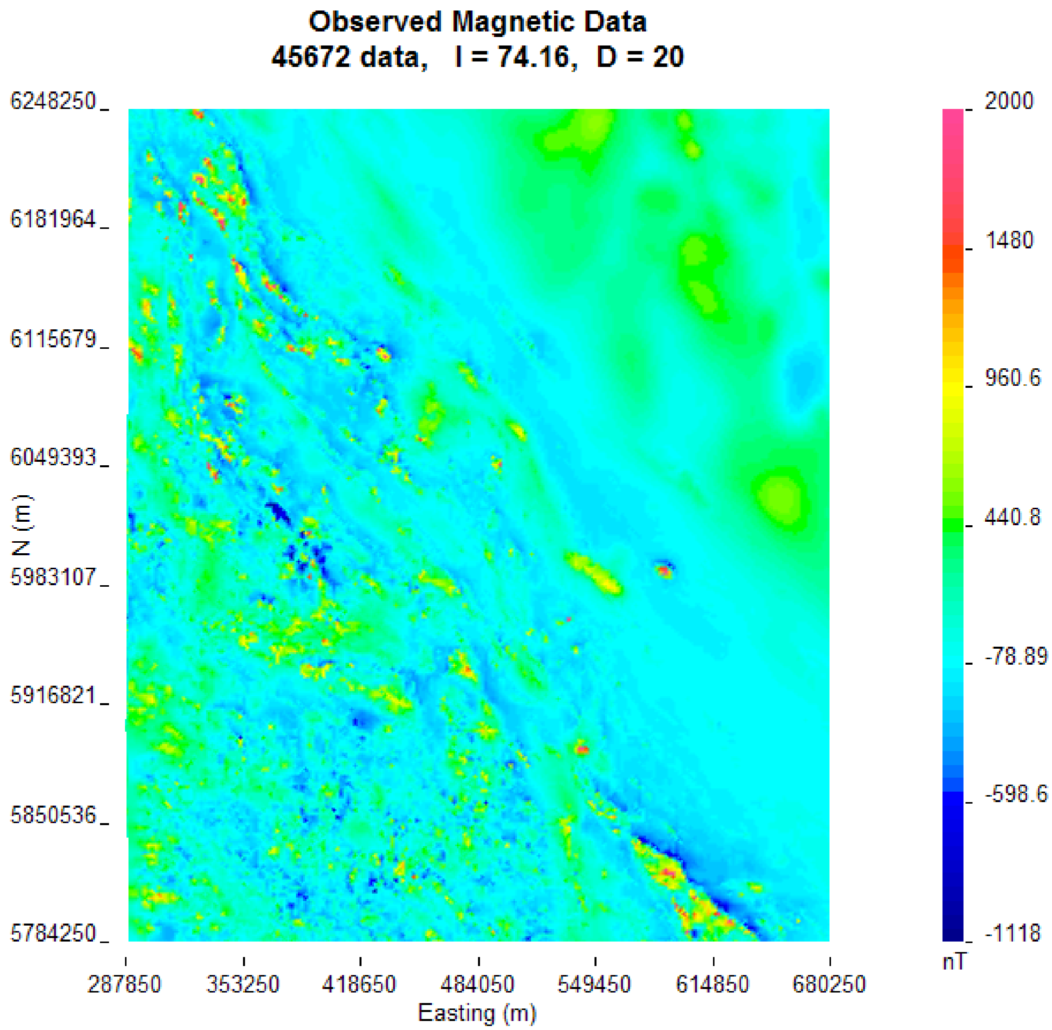

Figure 7 Total Field Magnetic Intensity data prepared for regional inversion modelling.

4.4. AEM Data Processing

Due to the high rate of data sampling with airborne EM systems, the VTEM data were averaged before inversion to reduce the data spacing and achieve a suitable along-line sampling rate. In this case, the data were averaged using 5 soundings on each side of the central sounding. This achieves a spatial resolution similar to the nominal flight height (~60m) and is a value similar to the size of the EM system footprint for the VTEM system.

The airborne electromagnetic data are assumed to have had adequate quality control procedures applied. It is noted however, that the surveyed area contains a railway line as well as pipelines and high voltage electrical transmission lines. The data were filtered to minimize effects associated with culture by applying a frequency cut-off filter. The cut-off was derived from the power line monitor data, which measures the 60 Hz EM frequency during the flight. The units on the monitor are relative, and thus on an un-calibrated scale. When a value is close to zero, it means there was no 60 Hz EM field close to the EM receiver. A cut-off of 700 was chosen for the filter.

Some data were also omitted from the final inversions because of system errors (e.g. incorrect radar altimeter data on Line 1780). In addition, decays with significant negative data were removed.

Noise and errors in the data can be caused by a number of issues. The most common are equipment and system errors, operator errors, GPS location errors, and modelling errors. It is important to assign uncertainties to the data when modelling the data to account for noise and errors present in the data. We assume that the data errors are Gaussian and independent and have a standard deviation equal to a percentage of the magnitude of the datum plus a floor. The percentage value is needed to account for errors on data with a large dynamic range. The floor value is needed when data are small compared to the noise. The uncertainties are assigned as standard deviations (Table 1).

Table 1 Data standard deviations for each channel.

Channels	Assigned STD DEV (%)	Minimum Absolute Uncertainty (ppm)
1-6	10	5e-7
5-10	15	5e-7
11-27	20	5e-7

5. Geophysical Inversion Modelling

5.1. 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 thin horizontal layers of infinite lateral extent for the 1D electromagnetic modelling. This discretization 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 don't introduce additional regularization in the inverse problem. Discretization parameters are tabulated in Appendix 5 for both the regional and detailed 3D gravity and magnetic inversions, and for the 1D EM 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.

The 1D conductivity mesh consists of layers with slowly increasing thickness with depth. The maximum depth exceeds the depth of penetration of the survey equipment.

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. The conductivity model comprises a much shallower part of the earth and so it isn't effectively represented on the same 3D mesh as the gravity and magnetic models. However the basement conductivity values (Section 5.5) have been gridded into a 2D map that has been subsequently represented on the same 3D mesh with a constant conductivity as a function of depth. This representation of different physical property models (and different earth properties in general) allows quantitative 3D GIS analysis of the modelling results (Section 6).

5.2. Separation of Regional Signal

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

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.

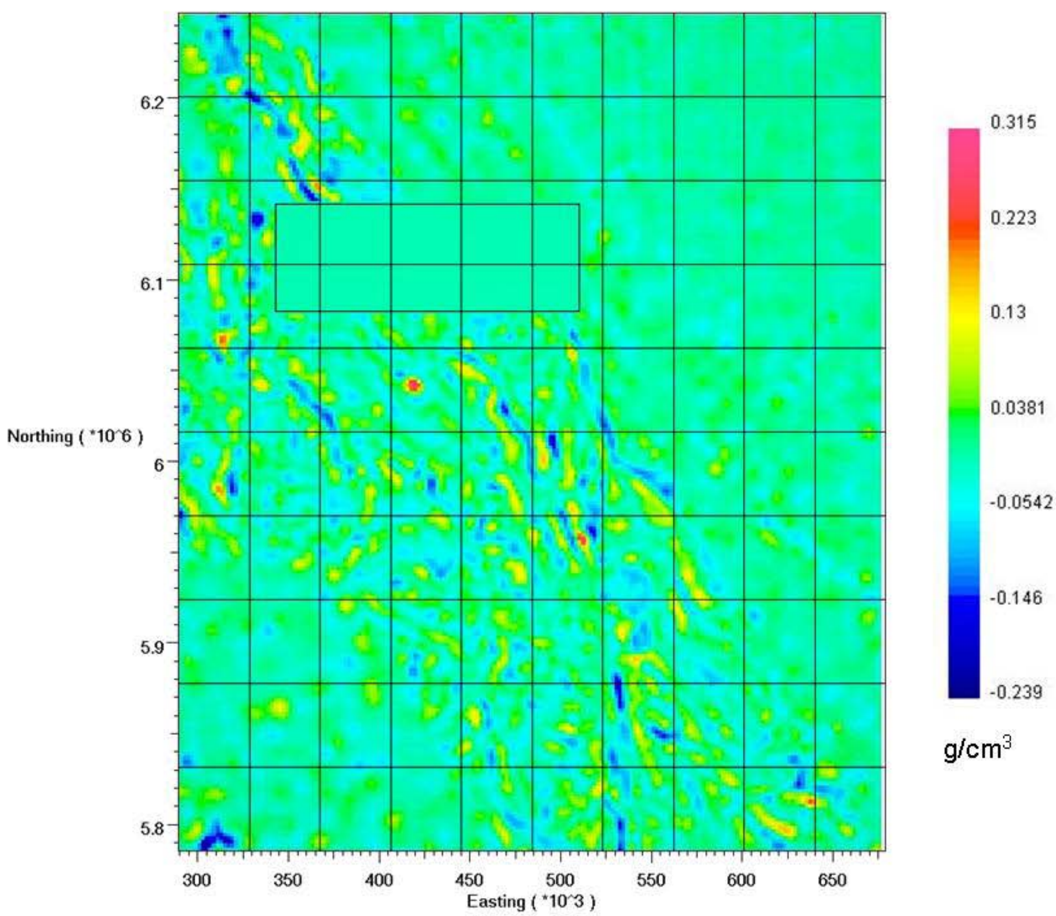

Figure 8 Plan section of regional density contrast model with one local model region removed (cells set to zero density contrast) [g/cc].

Figure 9 shows the gravity anomaly of sub-segment A1 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.

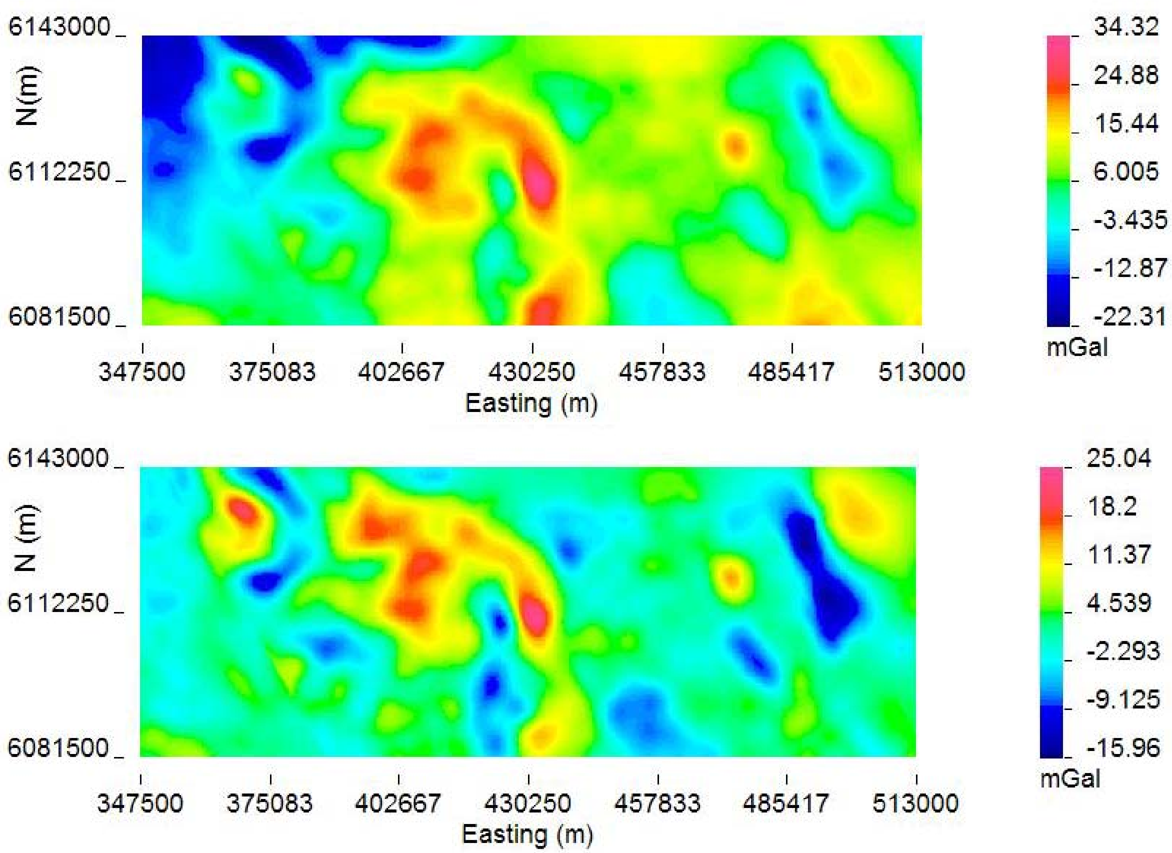

Figure 9 Regional gravity data (upper panel), and local gravity data after regional separation (lower panel).

5.3. Detailed Gravity Inversion Modelling

Ten 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 32 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. The density model was cut at an elevation of 8km below sea level.

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; the second is the contrast at 2500 meters below sea level. These are presented in Figure 10 and Figure 11 respectively. 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 gm/cc is shown in Figure 12. All anomalous densities with a value less than this threshold are transparent.

Details of the inversion parameters used for the detailed inversion blocks are shown in Appendix 4.

Observed and predicted data for each tile are included in the suite of digital deliverables for comparison and analysis.

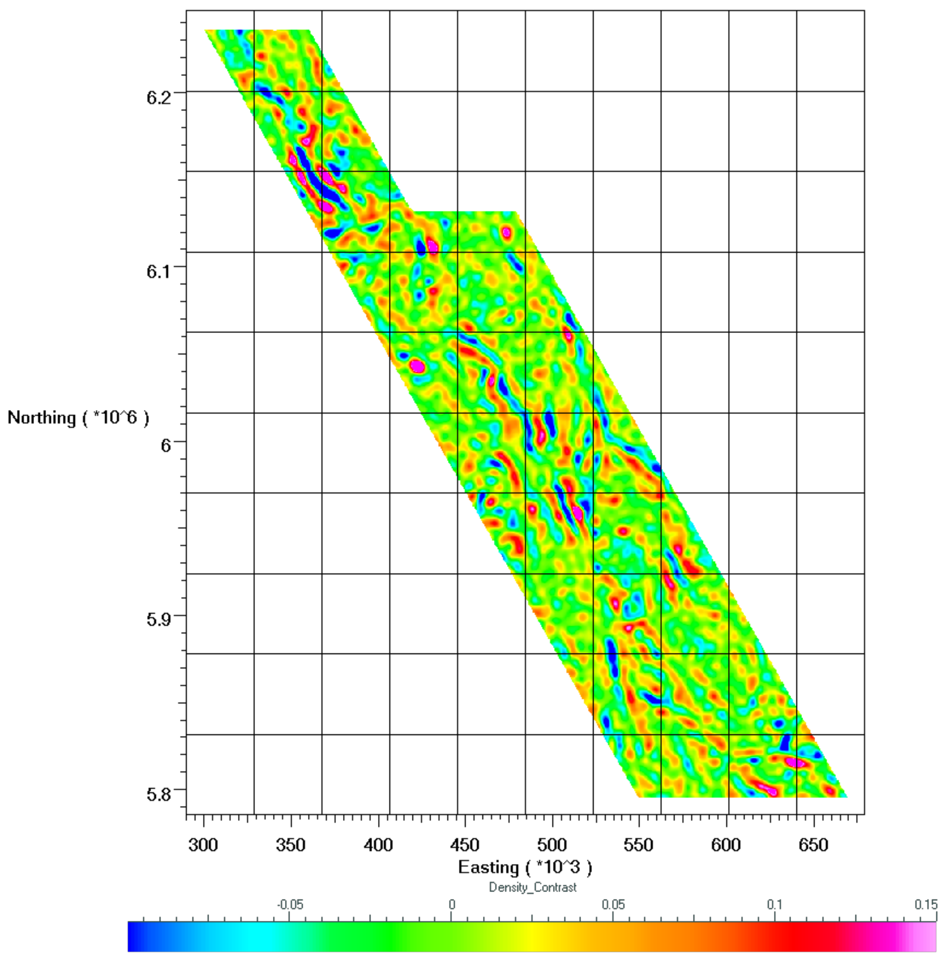

Figure 10 Plan view of QUEST detailed density contrast model at sea level.

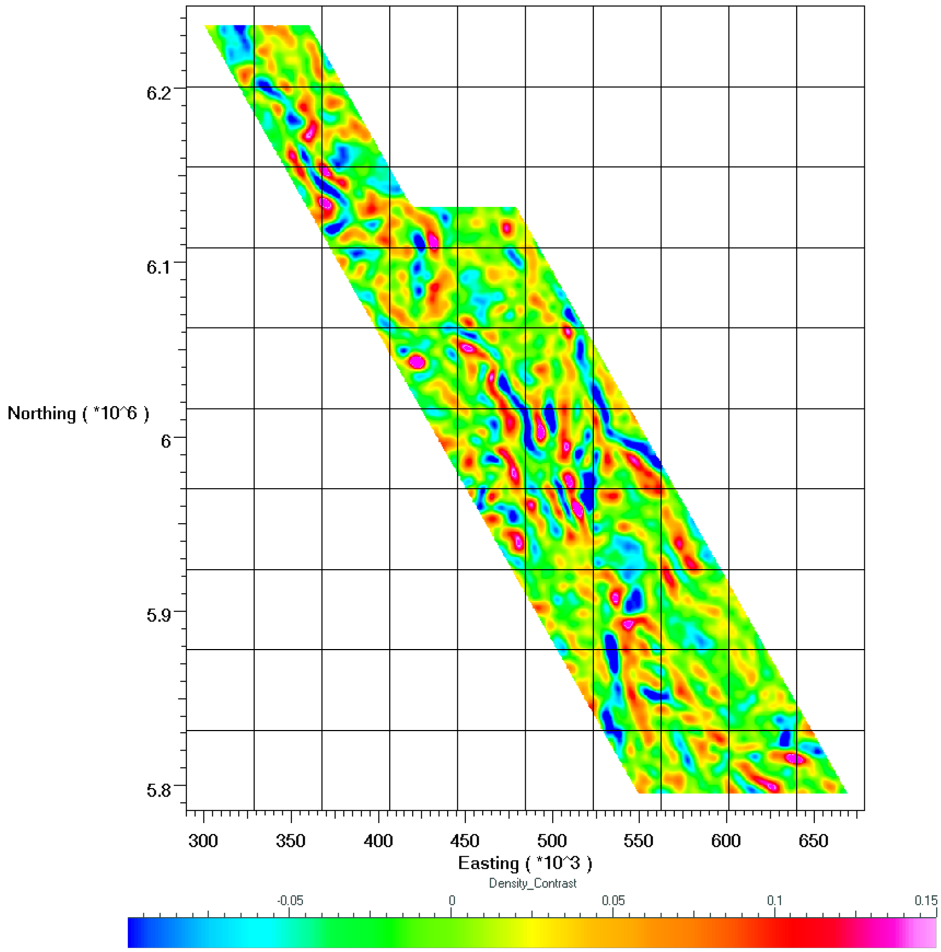

Figure 11 Plan view of the QUEST detailed density contrast model at an elevation of 2500m below sea level.

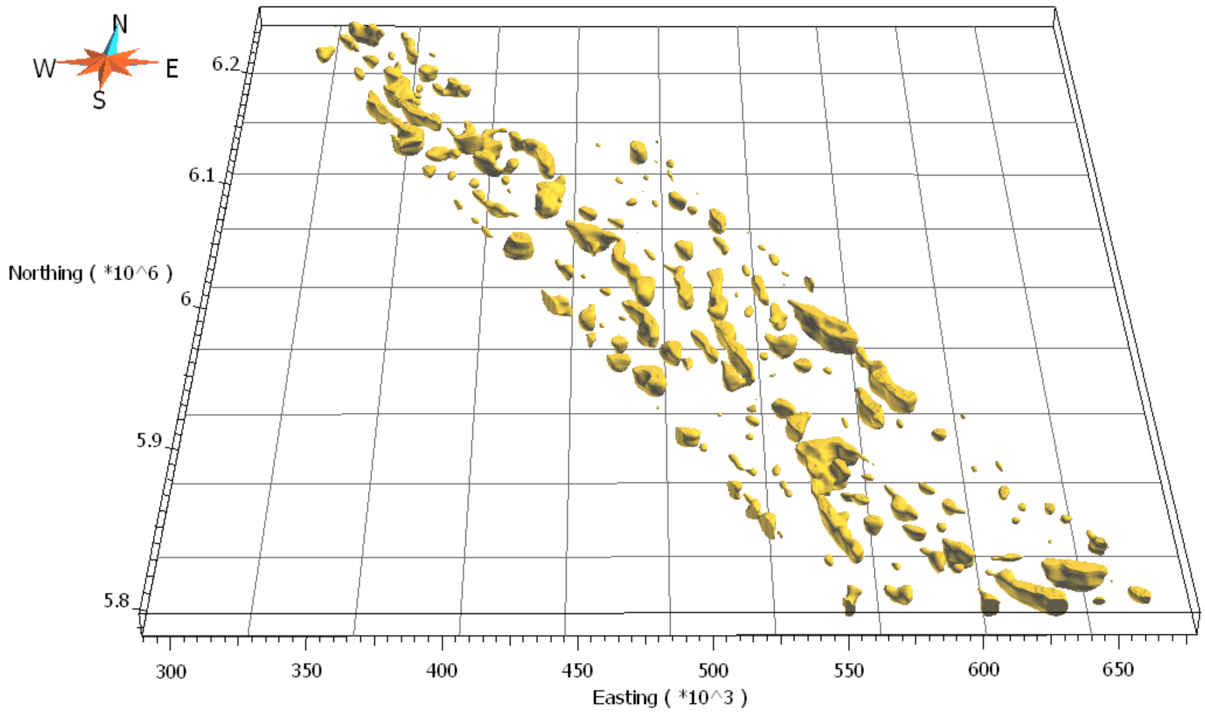

Figure 12 Perspective view of the QUEST density contrast model showing an iso-surface at 0.05 g/cm^3.

5.4. Detailed Magnetic Inversion Modelling

Figure 13, Figure 14, and Figure 15 shows 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 values reach 0.405 SI. This high value could be sufficient for self-demagnetization effects to be considered in some regions. Higher susceptibilities of the rock than this are probable as the model value represents the bulk volume susceptibility for the entire 500m, x 500m x 250m 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 500m). The models show detailed structure near the surface and gradually more smooth structure with depth. From the iso-surface cut-off value presented in

Figure 15, there is a lack of large, deep, susceptible bodies in the center of the survey area in relation to structures at the north and south (unlike the density contrast model).

Observed and predicted data for each tile are included in the suite of digital deliverables for comparison and analysis.

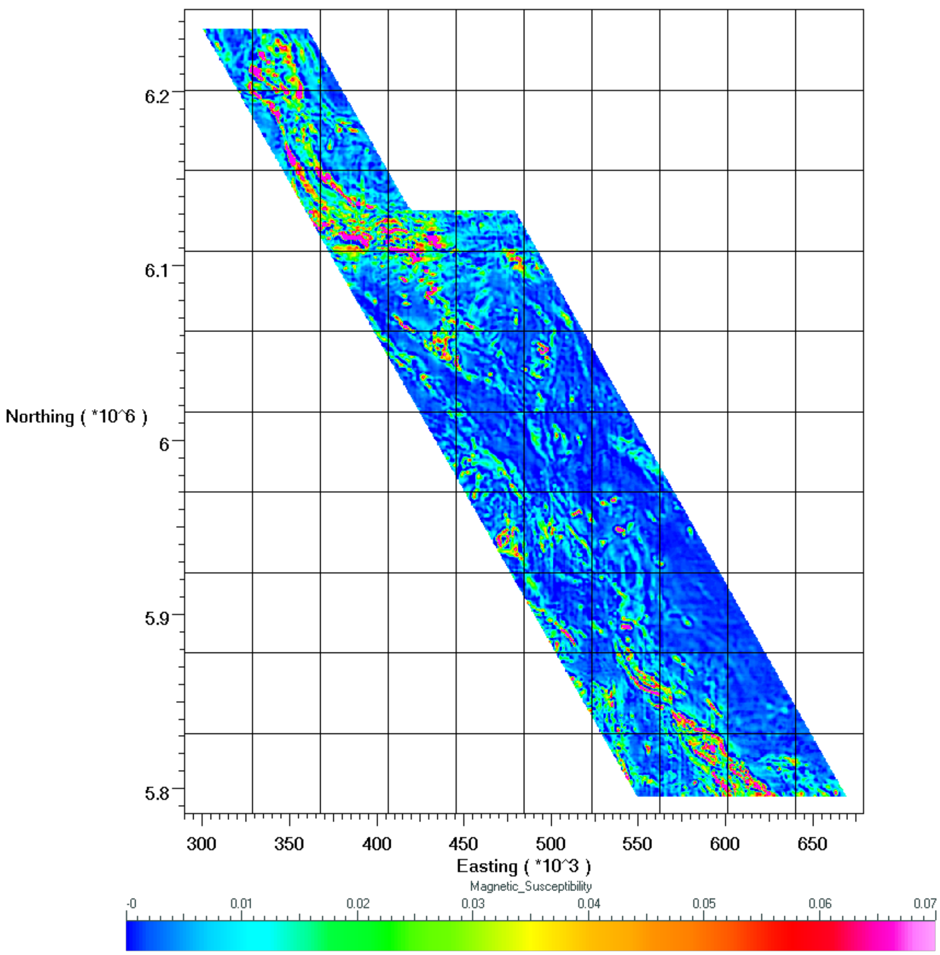

Figure 13 Plan view of the QUEST detailed magnetic susceptibility model at sea level.

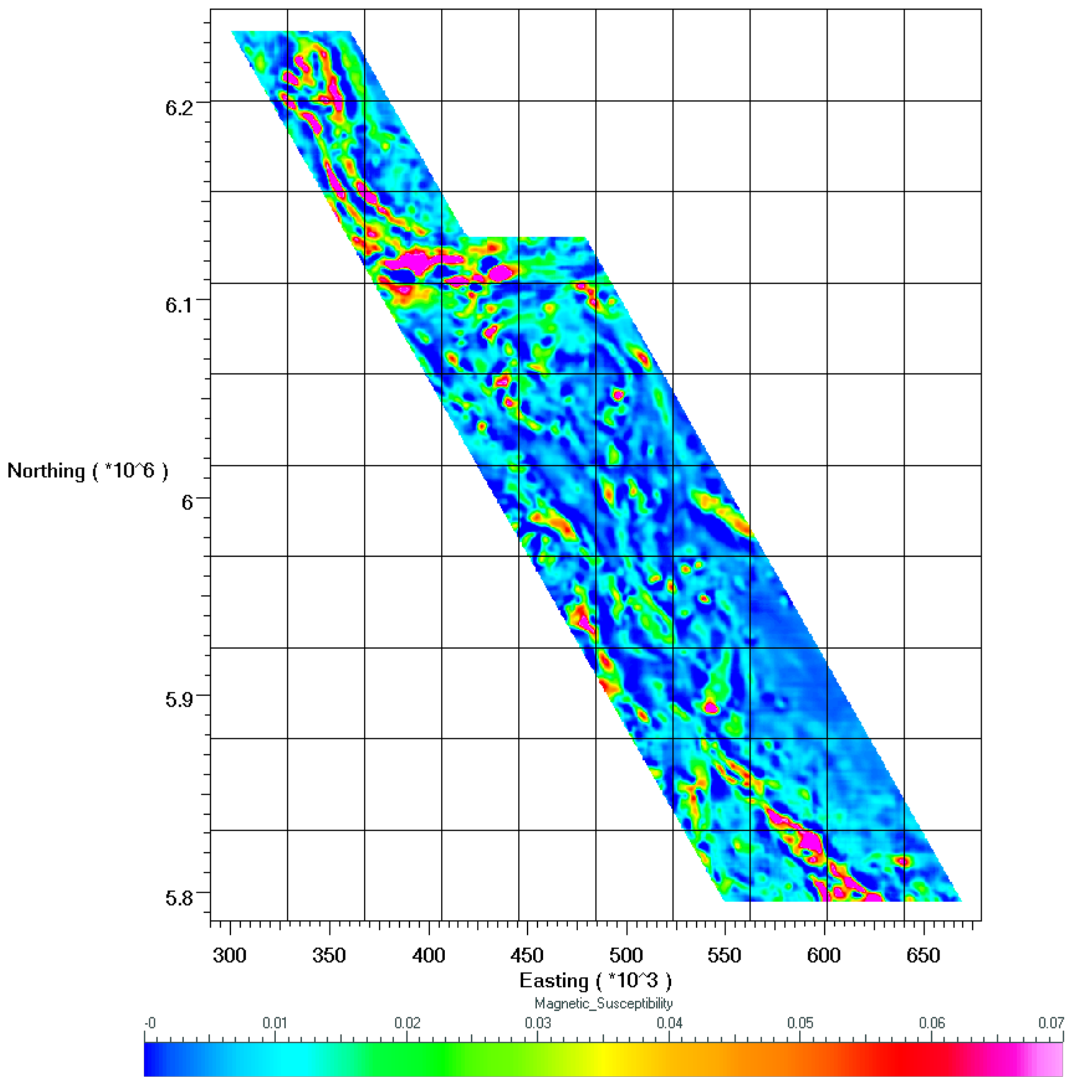

Figure 14 Plan view of the QUEST detailed magnetic susceptibility model at an elevation of 2500m below sea level.

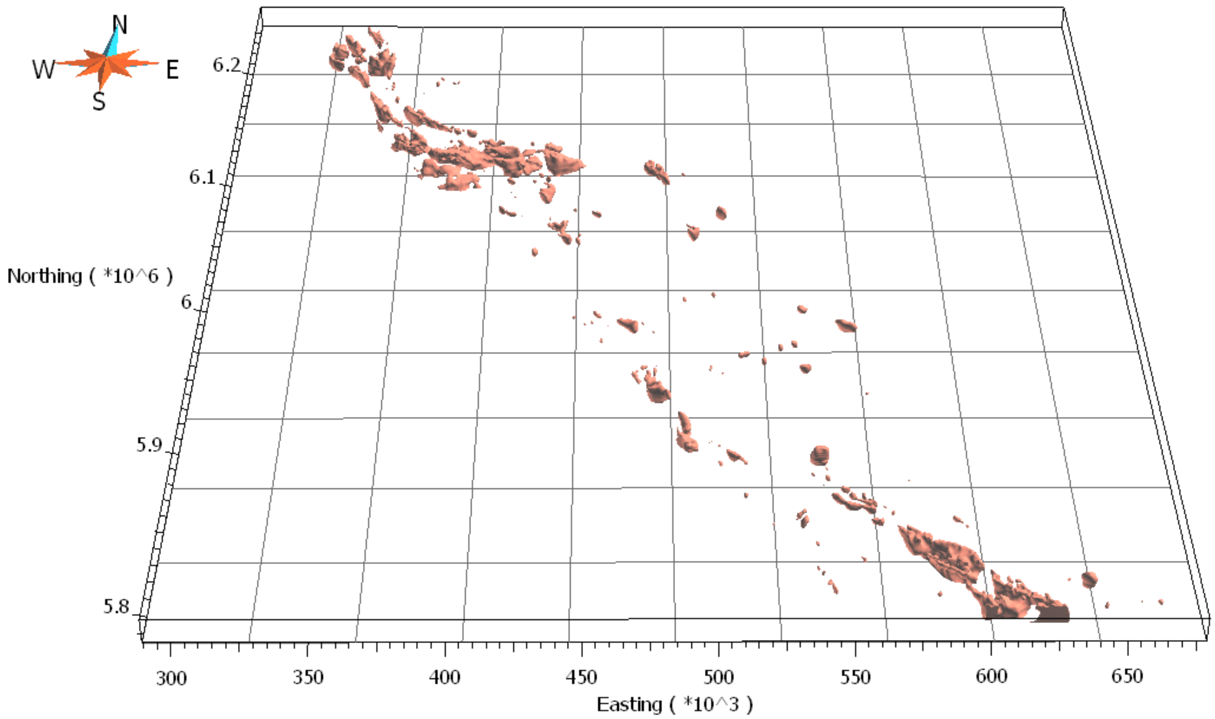

Figure 15 Perspective view of the QUEST magnetic susceptibility model showing an iso-surface at 0.05 S.I.

5.5. AEM Background Inversion Modelling

The background conductivity model is shown in Figure 16. The model shows the best-fitting half-space conductivity calculated from late-time data (last 13 channels) smoothed along line. This model is used as an input reference model for the 1D EM inversions, and provides a useful guide to lateral variations in deeper geology.

The background model shows some correlation to the geologic map (Figure 2) but will not show the bedrock where overlying conductive units are present.

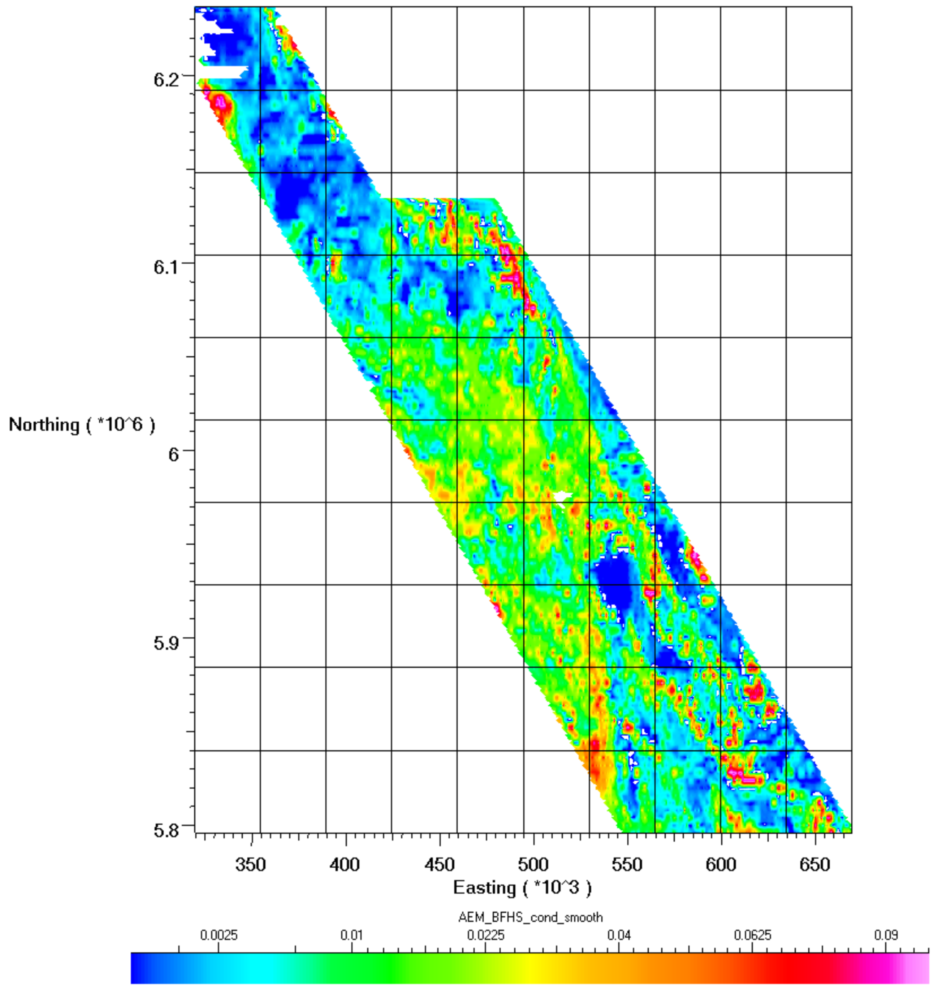

Figure 16 Background conductivity model [S/m].

5.6. AEM Inversion Modelling

VTEM dBz/dt data are inverted for a 1D (layered earth) conductivity model using the UBC-GIF EM1DTM inversion code. 379,481 stations were inverted for a 1D earth distribution of conductivity using 30 layers increasing in thickness from 2.7m to 50m with a total depth of 700m. The inversion parameters for each sounding are tabulated in Table 13 in Appendix 4.

An example of the observed and predicted data for 6 channels throughout the EM decay for a single flight line is shown in Figure 17. The predicted data show a good fit in general with observed data. The fit is better at the mid- and late times than the early times, and is slightly worse where the data have larger amplitude.

Note these comments refer to the data in general and may not be true for all soundings because different convergence and data misfit parameters were chosen for each station based on a balance between fitting the data and minimizing unnecessary structure in the model.

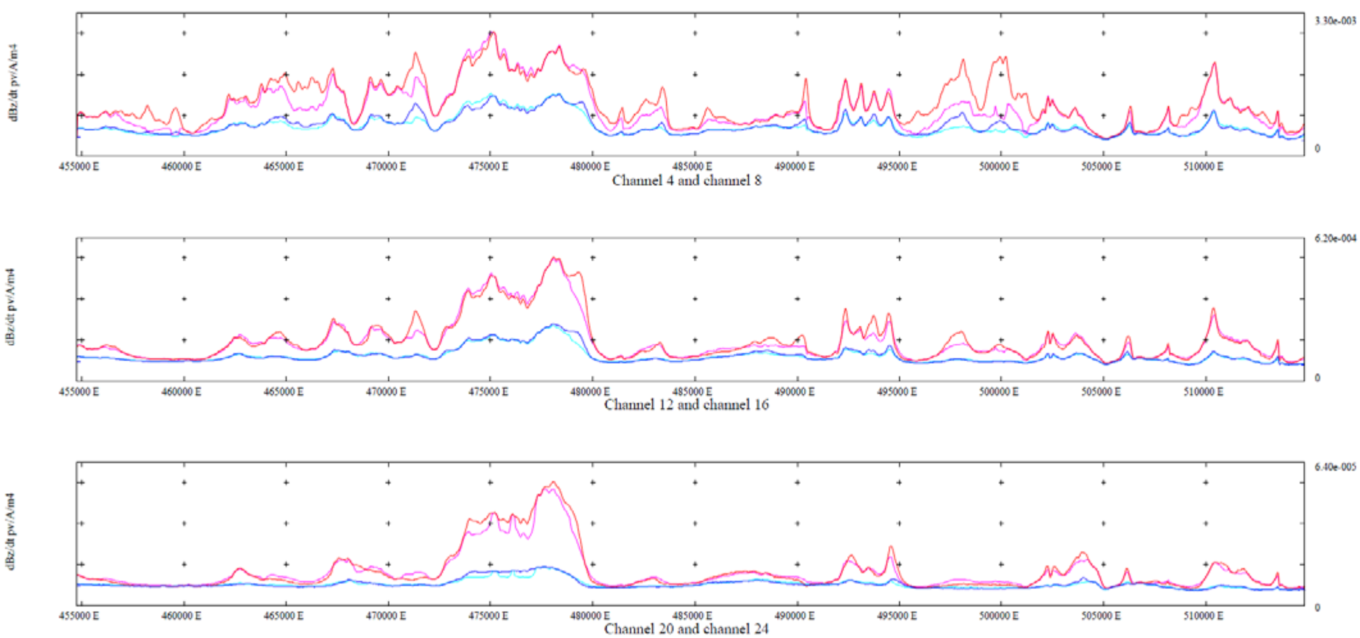

Figure 17 VTEM data profile for Line 1425. The channels shown are: 4 and 8 (upper panel), 12 and 16 (middle panel), and 20 and 24 (lower panel). The earlier channel observed data is in red, and the predicted data in magenta. The later channel observed data is in blue, and the predicted data in cyan.

The 1D inversion models have been interpolated in 3D in two ways. The first is a simple lateral interpolation between cells at the same depth. This produces a 3D model where the vertical axis represents depth. Another 3D conductivity model has been produced for each survey block where the model is conformable to topography. This is shown in Figure 18 as a series of East-West and North-South cross-sections.

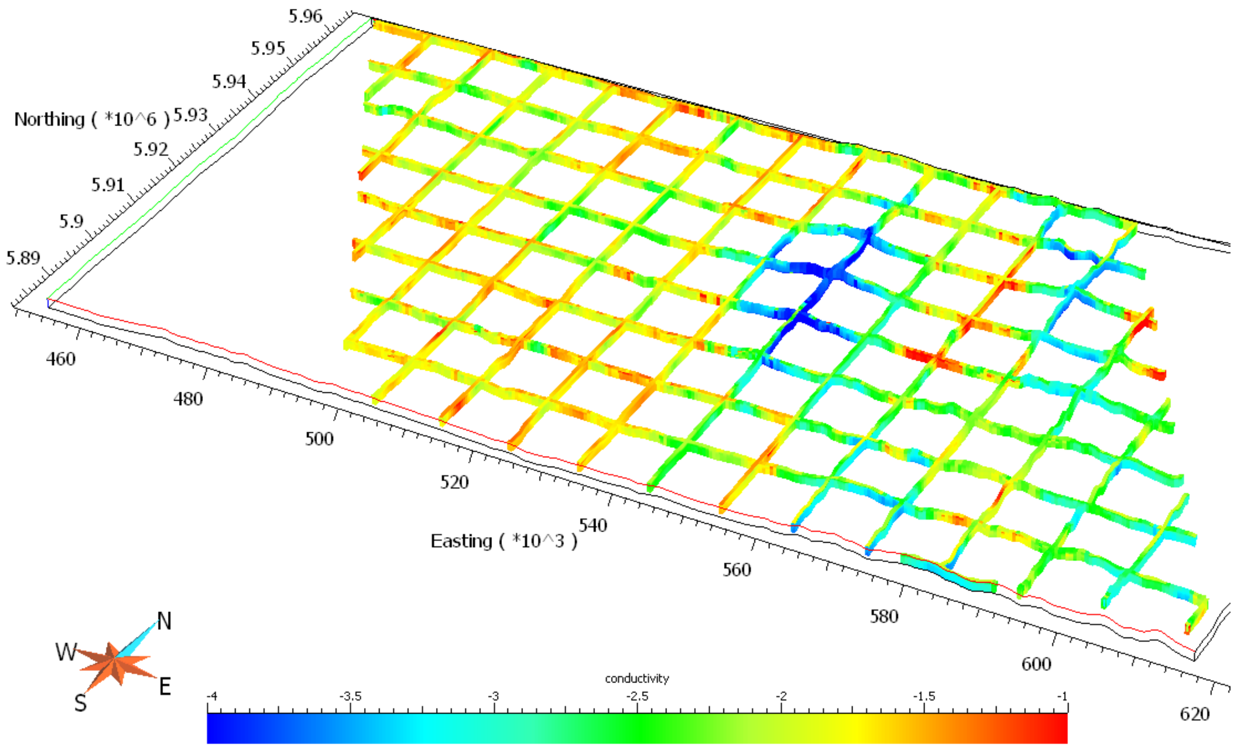

Figure 18 3D Conductivity model for Block C. East-West and North-South cross-sections shown. The model is interpolated between flight lines and conforms to topography.

5.7. AEM Depth of Investigation.

The method of estimating the depth of investigation from a vertical cumulative conductance has been applied to the QUEST AEM inversions. For the inversions of the QUEST VTEM data, a conductance of 6 Siemens was determined appropriate when compared to the alternative reference model depth of investigation approach. The resulting model for line 1425 is shown in Figure 19.

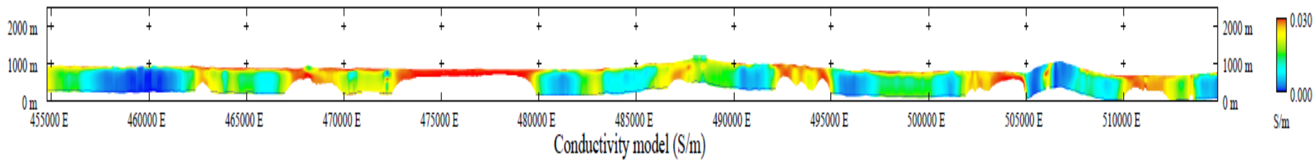

Figure 19 Line 1425 concatenated 1D conductivity model with depth of investigation cut-off applied. Displayed with 2x vertical exaggeration.

It can be seen that in areas of high surface conductivity the VTEM survey will have more limited penetration. In the resistive zones the penetration may be greater than the 700m shown in the figure. These results will help determine extents of resistive rock-types, and the depth of penetration will reduce misguided interpretations below conductive features. Without this depth-cut-off the model will continue to depth with a high conductivity value, which may not reflect the true earth model.

6. Common Earth Modelling

The inversion procedures produce 3D physical property models from gravity, magnetic, and AEM data, and allow quantitative analysis of the earth. The geophysical information, now spatially located, can be viewed and analyzed in conjunction with each other (Figure 20).

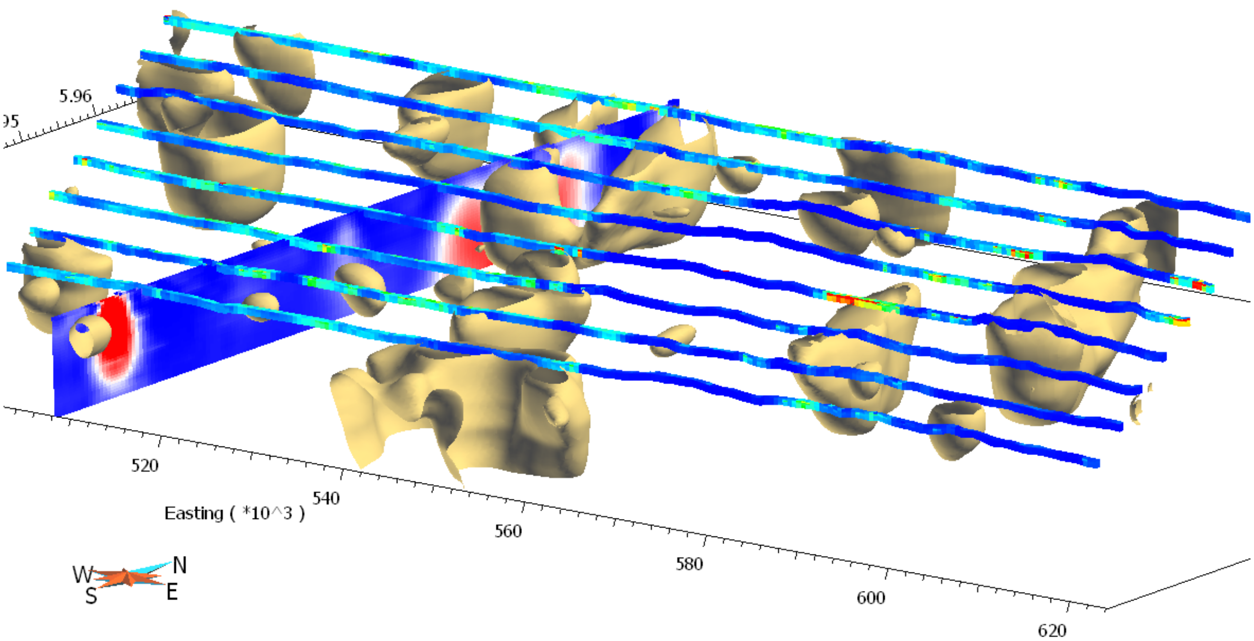

Figure 20 Perspective view of inversion modelling results for block C of the QUEST area. The conductivity model is shown as East-West cross-sections, the density contrast model is represented as iso-surfaces at a value of 0.05 g/cm^3, and a North-South cross-section displays the magnetic susceptibility values.

The next step in quantitative analysis of these models is to combine them in a Common Earth Model, where a common digital representation of the earth exhibits multiple earth properties. This can be used for regional targeting based on explicit exploration criteria using 3D GIS methods such as proximity, intersection, and property queries.

The density contrast and magnetic susceptibility models are already on a common 3D mesh structure so they can be directly evaluated together. The conductivity model accommodates a much shallower part of the earth due to the survey type, and so isn't well represented on this common 3D mesh structure. In order to have some form of the conductivity model in the Common Earth Model, the laterally varying basement conductivity values (Section 5.5) are sampled on the same lateral cell size and then extended vertically throughout the entire depth of the model.

An example of how QUEST physical property model information on a Common Earth Model can be used is shown in Figure 21 Physical property cross-plot of density contrast and magnetic susceptibility (log-scale) coloured by background conductivity with the hot colours reflecting higher conductivity. The figure shows results for the entire QUEST model volume with one symbol plotted for each cell (~32 million cells). Corresponding physical property information at known deposits and occurrences either within or external to, the QUEST survey area can be displayed on this plot to guide selection of physical property signatures. This can then be directly related to spatial targets in the QUEST survey area.

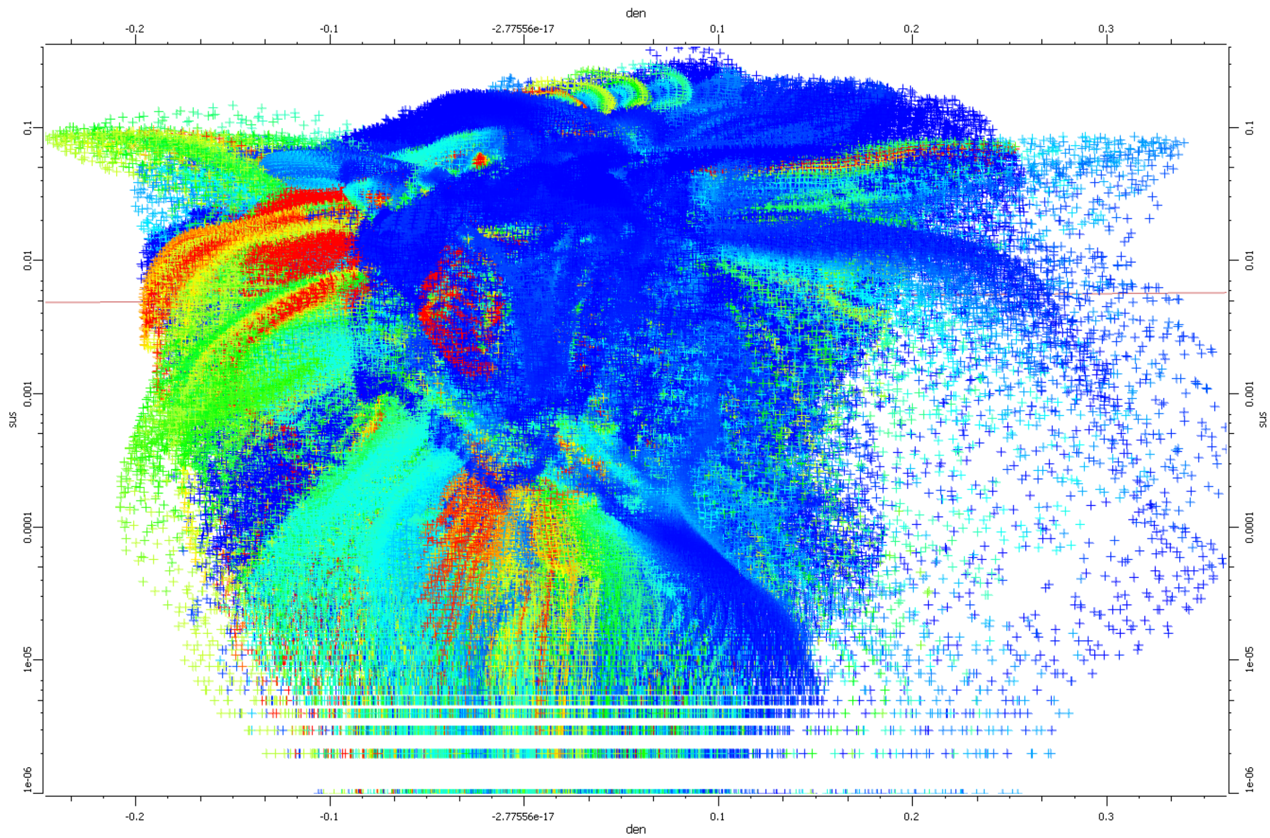

Figure 21 Physical property cross-plot of density contrast and magnetic susceptibility (log-scale) coloured by background conductivity with the hot colours reflecting higher conductivity.

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 (see Table 2), a 3D classified model is produced from the nine combinations of these model classes applied to the physical property models (see Figure 22). The resulting classified model is presented in Figure 23.

Table 2 Physical property class cut-off values.

	Density Contrast	Susceptibility	Conductivity
	g/cm^3	S.I.	S/m
Low	< -0.05	< 0.01	< 0.002
Medium	-0.05 to 0.05	0.01 to 0.05	0.002 to 0.03333
High	> 0.05	> 0.05	> 0.033333

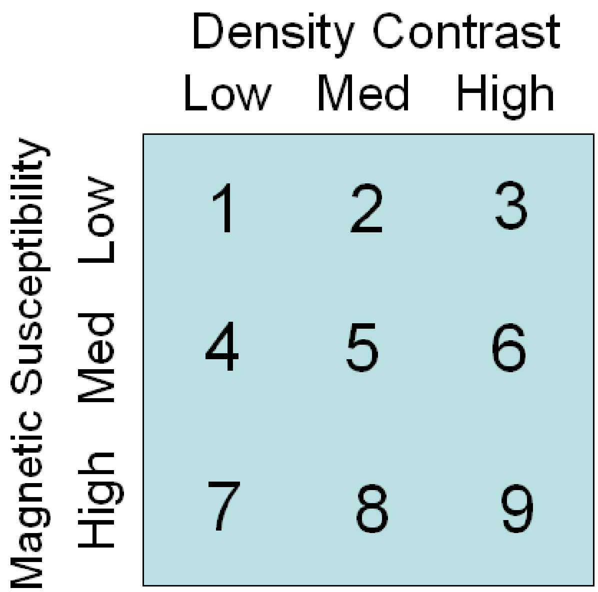

Figure 22 A Simple physical property classification matrix for a two phase system

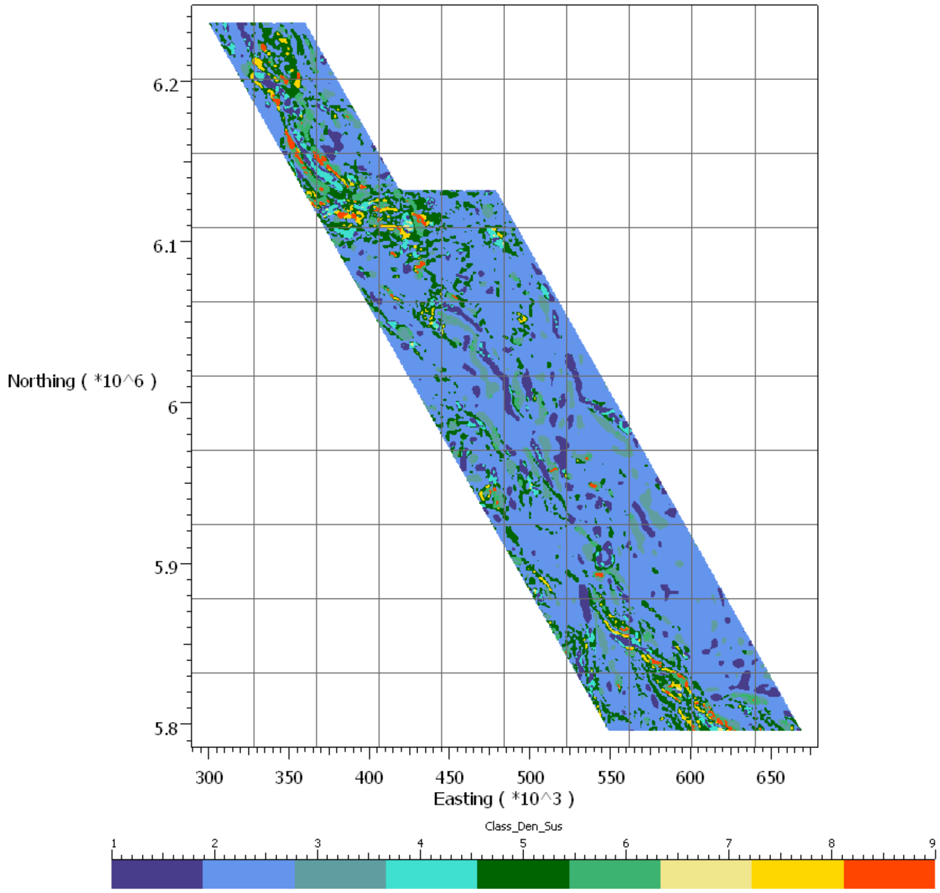

Figure 23 Surficial plan view of 9 discrete physical property classifications based on high, medium and low domains of density-contrast and magnetic susceptibility (file: domain.ds). See Figure 22 to interpret the color legend.

An extension of this classification is to include the background conductivity model with high, medium and low cut-offs. This expands the physical property classifications to include 27 classes (see Table 3).

Table 3 Physical Property classification of low, medium, and high, density contrast, magnetic susceptibility, and conductivity models.

Domain_DSC	Density Constrast	Susceptibility	Conductivity
0	NDV	NDV	NDV
1	L	L	L
2	M	L	L
3	H	L	L
4	L	M	L
5	M	M	L
6	H	M	L
7	L	H	L
8	M	H	L
9	H	H	L
10	L	L	M
11	M	L	M
12	H	L	M
13	L	M	M
14	M	M	M
15	H	M	M
16	L	H	M
17	M	H	M
18	H	H	M
19	L	L	H
20	M	L	H
21	H	L	H
22	L	M	H
23	M	M	H
24	H	M	H
25	L	H	H
26	M	H	H
27	H	H	H

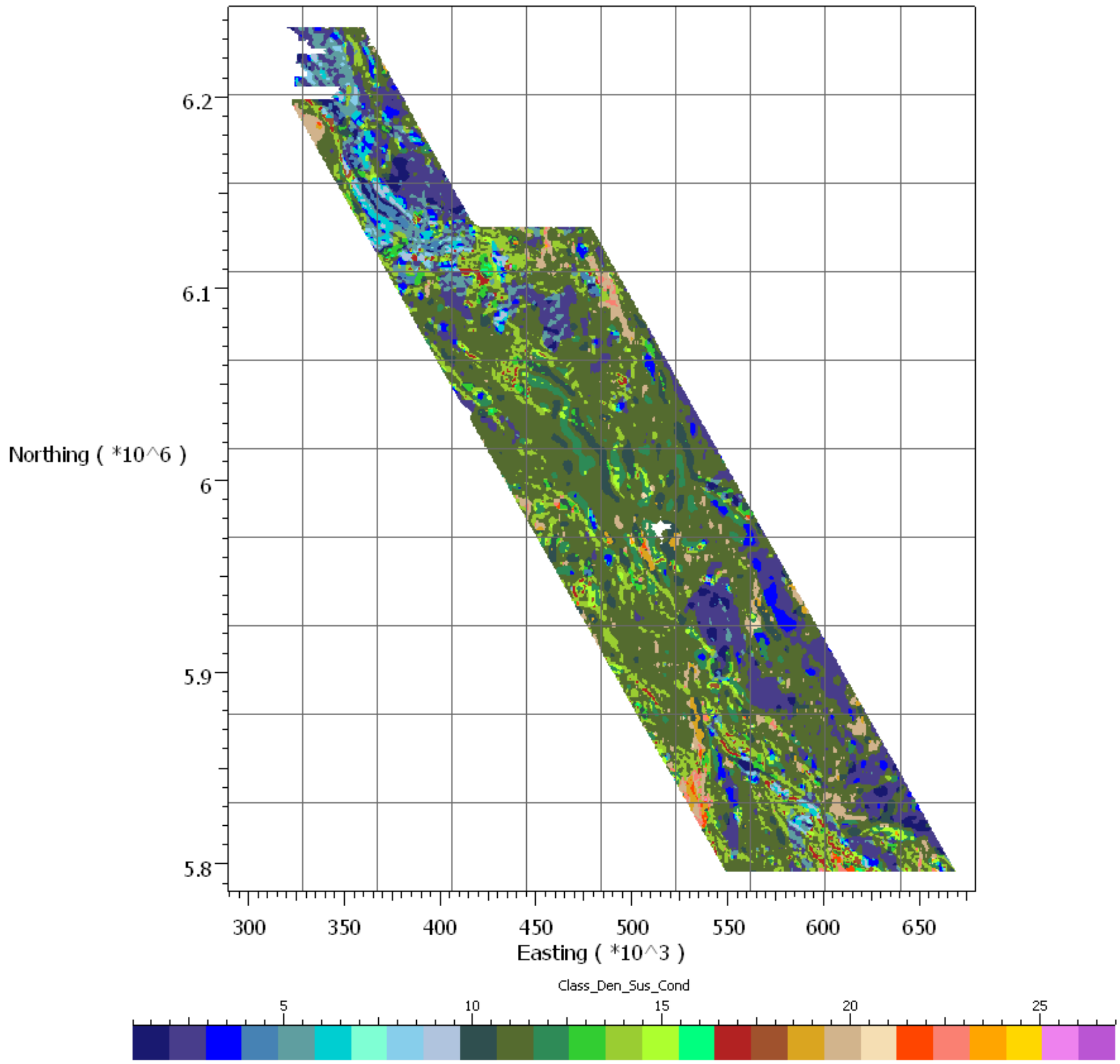

Figure 24 Surficial plan view of 27 discrete physical property classifications based on high, medium and low domains of density-contrast, magnetic susceptibility, and electrical conductivity (file: domain.dsc). See Table 3 to interpret the color legend.

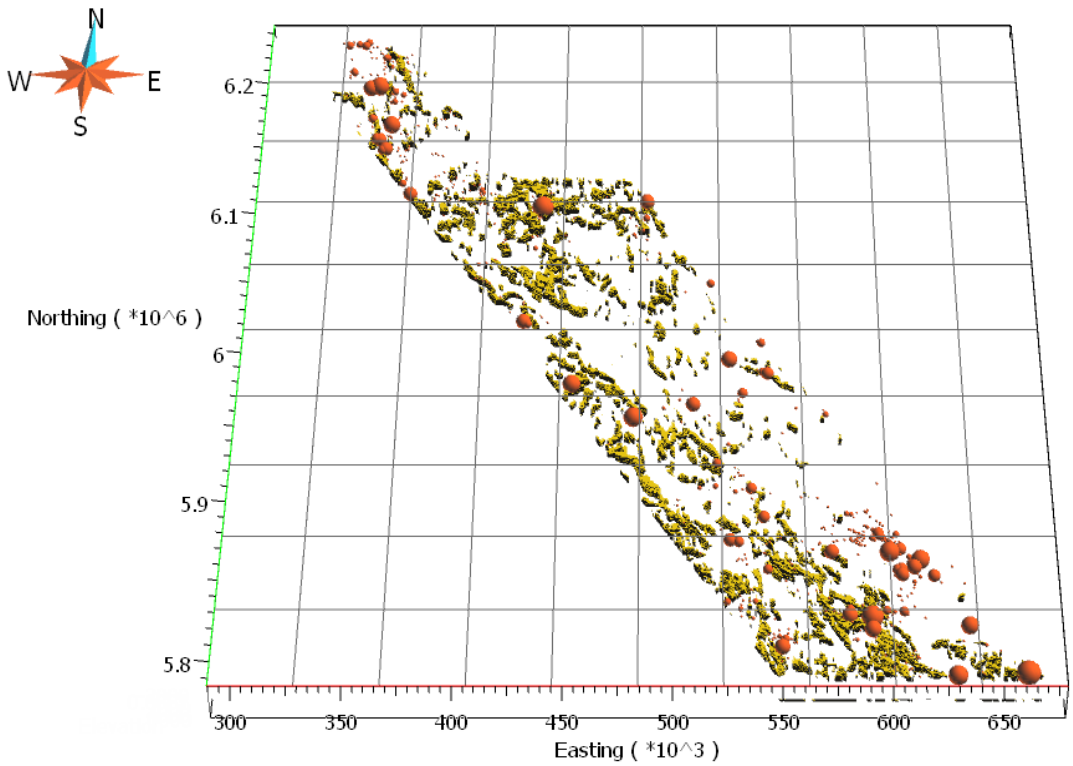

Figure 25 Perspective view of the 3D physical property classification (class 14) with mineral occurrences scaled by approximate volume.

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.

7. 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, electromagnetic)
- 3D density contrast and magnetic susceptibility models
- Conductivity models:
    - Background Conductivity Model
    - 1D models
    - 1D models presented along line and draped under topography
    - 3D interpolated conductivity model as a function of depth below topography
    - 3D interpolated conductivity model conformable with topography.
- Several derivative products such as iso-surfaces, interpolated 3D models, and a simple example of domain classification
- Gocad 2009 projects containing data and models for each survey block
- PDF3D 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_Geop_Modelling_Appendix1_Deliverables_2009-15-1.xls

8. Conclusions

Detailed density contrast, magnetic susceptibility, and conductivity inversion models have been produced for the QUEST 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 geophysical data set.

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. The laterally parameterized conductivity model will be useful in determining the thickness of the overburden and the depth of investigation estimate will guide reliability of the interpretations. Also, the background conductivity model may be useful in characterizing larger scale lateral variations of the near-surface.

Although a single density contrast, magnetic susceptibility, and conductivity 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, magnetic susceptibility, and near surface conductivity in the QUEST 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 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.

9. 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 data sets. 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 the three physical property models can be customized to specific exploration target criteria, such that a set of model queries suitable for massive sulphide exploration 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 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 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 with known conductive overburden present to a given 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 area such as the Mt. Milligan deposit where closer line-spacing infill AEM and magnetic data were collected.

6. ***Integrated Modelling:*** The density contrast, magnetic susceptibility, and conductivity models can be used to help constrain each other. Structures in the models that can be assumed common to both the gravity and magnetic inversions can be shared so that each model is consistent were possible. Also the 1D AEM modelling of overburden thicknesses could be used to constrain the potential field models at a smaller scale.

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 area.

8. ***Discrete AEM modelling:*** The 1D AEM inversion models may not be an appropriate model type for discrete 3D conductive bodies. Discrete 3D EM anomaly modelling with plates in conjunction with the 1D models may provide more information about the EM conductors.

9. ***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.

10. ***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 surveys and data analysis.

11. ***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. (0.4 S.I. encountered in the QUEST magnetic susceptibility model) and may become more apparent if the modelling discretization size is reduced.

Submittal

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

This report has been reviewed and approved by:

Doug Oldenburg, Principle Consultant.

30 July 2009

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Glossary of Useful Terms

A brief list of commonly used terms associated with geophysical inversion methods based on those available at http://www.eos.ubc.ca/research/ubcgif/.

Anomaly

Anomaly is a term that is used in two ways and therefore it is occasionally confusing. In general, the word means anything that is "not normal". In the context of data, we usually hope that the target or feature of interest will produce a measurable anomaly (variation in the data set) which can then be interpreted in terms of what caused it. In the context of the Earth's subsurface (or the geophysical model), a feature that can be detected or characterized may be referred to as an anomaly or an anomalous zone. For example, a subsurface void is a "density anomaly" that should produce a measurable "gravity anomaly" if a gravity survey is carried out over the void.

Data

Data are measurements of a physical phenomenon such as a field, or flux, or current, or force, etc. They should be accompanied by an estimated uncertainty. To understand and work with data in inversion, it is imperative that details of the survey and instrumentation are known, viz locations/orientations of transmitters and receivers, transmitter strength, receiver gains and any processing that has been done to the data.

Data misfit

Data misfit describes how close field measurements are to predicted (synthetic or calculated) data. Often we plot the real and synthetic data sets to compare for similarity. Sometimes a plot of the difference between the two data sets is generated to emphasis that variations between the two are small.

Discretization

Although the earth has a continuous distribution of physical properties we simplify this with a discretization that describes the earth as a model containing a number of cells each having a constant physical property. This model is defined on a 1D, 2D, or 3D grid or mesh. The size of the cells should reflect the resolving power of the survey. If the cells are too large important geologic features may not be adequately modeled, and also the discretization will act as a regularization in the inversion. If they are very small then many cells are required and hence the inverse problem will take longer to complete. Thus the cells should be small enough that they don't regularize the problem but their total number needs to be kept small enough so that the problem is numerically tractable.

Fitting the data

Any useful model of the Earth recovered by inversion must be capable of causing the data set that was observed. This is tested by comparing the measurements to a synthetic data set generated by forward modelling based upon this recovered model. We say the "model fits the data" if it is capable of generating data that match the field measurements to within a specified degree

Forward modelling

Forward modelling means simulating the data that would occur if a survey were gathered over a known model of the Earth. The reciprocal term, Inverse Modelling, describes the process of estimating a model of the earth from the data.

Geophysical model

A geophysical model is a simplified concept of how one physical property is distributed within the Earth. Geophysical models are generally either an object, a halfspace, 1D (layered earth), 2D, or 3D. Note that a "model of the Earth" can mean either a geological model in which the subsurface is described in terms of rock types, structures, fluids, etc., or a geophysical model defined here defined in terms of physical properties and physical property contrasts. Often a geologist and geophysicist must work together to reconcile these two ways of understanding the Earth.

Geophysics

A discipline of science which uses the tools of mathematics and physics to answer questions about the Earth.

Halfspace

A volume in which half is "air" and the other half is a constant value. Geophysicists consider the earth to be a "halfspace" when the whole volume that is visible has only a constant value of the relevant physical property.

Interpretation

Interpretation of geophysical data involves two steps. First the data must be interpreted in terms of a causative distribution of the relevant physical property. Then this "model" can be interpreted in terms of geology (structures, minerals, rock type alteration, etc). Geophysical interpretation may be carried out in many ways, ranging from simple data inspection to sophisticated inversion and modelling.

Inversion

Inversion (or inverse modelling) is the process of mathematically estimating one or more models of subsurface physical property distributions that could explain a data set that was gathered in the field.

Misfit

Misfit is a measure of how close one data set is to another. See also "Fitting the data".

Modelling

Modelling usually means the process of developing models of the Earth based upon measured geophysical data. It may be as simple as recognizing that an anomaly is likely caused by a buried pipe, or it may involve sophisticated data processing and/or inversion to mathematically build a range of plausible models. Sometimes also used to refer to Forward Modelling.

Optimization

A branch of mathematics related to determining the best or optimum choice from a large (possibly infinite) range of possibilities.

Physical properties

Physical characteristics of the ground being investigated, such as density, electrical conductivity, and others.

Prior information

Also referred do as *a priori* information. Additional information of the earth such as a known background or reference model, an expected structure or geometry, and known specific physical properties that can be assigned to cells can also be included in an inversion. These data can be used to constrain and guide the inversion. See also A Priori information.

Under-determined

A problem is said to be "under-determined" when there are more unknowns than data. There are not enough equations to obtain a unique solution. Under-determined problems are inherently "non-unique".

Appendix 1 Project Deliverables

See accompanying MS Excel file:

Mira_AGIC_GeoscienceBC_Quest_Geop_Modelling_Appendix1_Deliverables_2009-15.xls

Appendix 2 Data and Processing Specifications

Table 4 Sanders Gravity Survey Specifications:

Instrument	AIRGrav
Line spacing	2000m
Line-km	27,480
Line orientation	East-West
Nominal terrain clearance	125m

Table 5: Geotech Magnetic Survey Data Specification

Inclination	74.51 degrees
Declination	20.46 degrees
Inducing Field Strength	57254 nT
Acquisition Dates	July to November 2007
Line spacing	4000m
Corrections	Diurnal, flight levelling
Nominal Flight Height	75m
Station Spacing	2-3m
Down-sampling	11 (resulting in ~30m station spacing)
Assigned Standard Deviation	100nT

Table 6: VTEM System and Data Survey Specification

Transmitter coil diameter	26 m
Number of turns	4
Transmitter frequency	30 Hz
Peak current	235 A
Pulse width	4.5 ms
Duty cycle	27%
Peak dipole moment	503,000 NIA
Receiver coil diameter	1.1 m
Number of turns	100
Effective coil area	113.1 m^2
Wave form shape	approximate asymmetrical trapezoid
Sampling frequency	10 Hz
EM sensor vertical distance below helicopter (radar altimeter)	42m
Nominal airspeed	100 km/hr
Data recording rate	0.1 second (Magnetic and EM) 0.2 second (Altimeter and GPS)
Station Spacing	2-3m
Receiver – Transmitter configuration	Concentric
Coil orientation	Z-direction

Table 7 VTEM channel timing:

Channel	Time from bottom of ramp [µsec]
9	99
10	120
11	141
12	167
13	198
14	234
15	281
16	339
17	406
18	484
19	573
20	682
21	818
22	974
23	1151
24	1370
25	1641
26	1953
27	2307
28	2745

29	3286
30	3911
31	4620
32	5495
33	6578
34	7828
35	9245

The receiver decay recording scheme is shown diagrammatically in Figure 26.

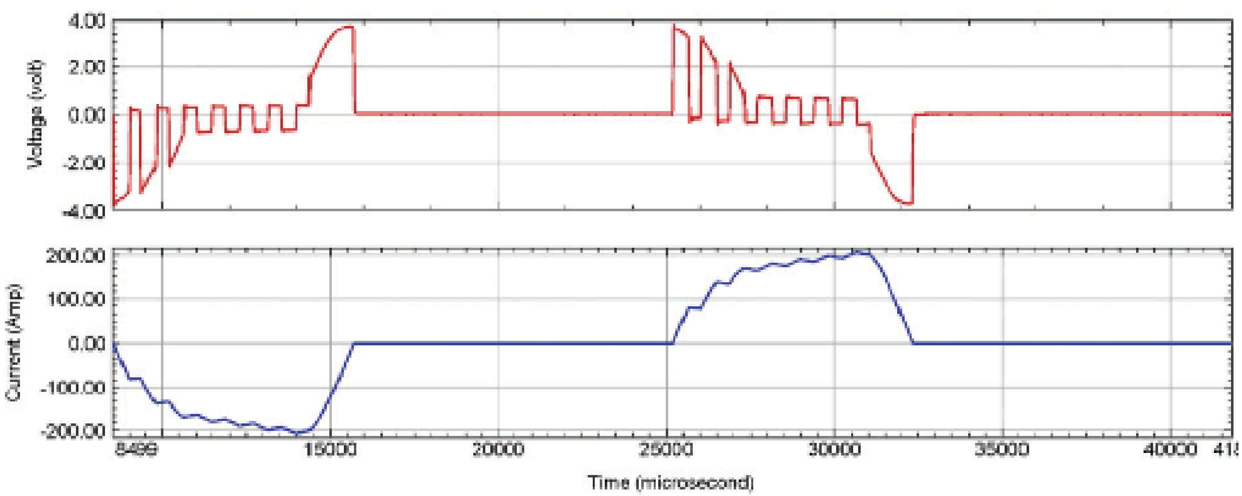

Figure 26: VTEM Waveform. The top panel is the voltage measured in the receiver coil in the absence of a conductive earth. Integrating and normalizing that produces the transmitter current. This is shown in the bottom plot.

For the inversion, each datum is assigned an uncertainty that is a percentage of the datum value plus a floor. Earlier time channels generally have greater accuracy than later time channels. The table below delineates the percentages and floor values for 3 groupings of time channels.

Table 8 VTEM assigned uncertainties

Channel	Assigned Standard Deviation (percent, floor [ppm])
1-5	10, 5e-7
6-10	15, 7e-7
11-27	20, 7e-7

Appendix 3 Modelling Software

GRAV3D

GRAV3D is a program developed by 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:

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.

Inversion of surface, airborne, and/or borehole 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 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.

(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:

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.

Assumptions: 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.

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).

EM1DTM

Program EM1DTM inverts time-domain electromagnetic data for one-dimensional earth models.

The observations: Off-time measurements (in the current version 1.0) are either voltage or B-field with an arbitrary current waveform flowing a horizontal transmitter loop. Receivers can be oriented in the x-, y- or z-directions, and they can be at any position relative to the center of the their transmitter loop. Transmitters are cab be any height relative to the ground surface. A "sounding" refers to all the time-decay data that correspond to what is going to be the same stack of layers at a particular horizontal location in the model. Measurement uncertainties can be provided in the same units as the observations or as as relative uncertainty in percent. Multiple soundings can be handled in a single run of the program.

Four possible inversion algorithms: 1) constant (user-supplied) trade-off parameter in the objective function being minimized; 2) the trade-off parameter chosen to achieve a user-supplied target misfit; 3) the trade-off parameter chosen using the GCV criterion; and 4) the trade-off parameter chosen using the L-curve criterion. Full flexibility of the l1 and the l2 measures of the model structure and data misfit is provided, adjustable balance between "flattest" and "smallest" components of conductivity model measure; inclusion of reference models; and inclusion of specialized weighting of the layers in the model.

The product: electrical conductivity models. The models are composed of (many) layers of uniform conductivity with fixed interfaces, and the value of the conductivity in each layer is sought in the inversion. For multiple soundings, a one-dimensional model will be produced for each sounding, and a composite two-dimensional model produced at the end of one run of the program.

(EM1DTM Manual)

Appendix 4 Modelling Parameters

Table 9 Regional 3D mesh parameters.

Cell size in East direction	2000 m
Cell size in North direction	2000 m
Cell size in vertical direction	250 m
Number of core cells in East direction	216
Number of core cells in North direction	253
Number of core cells in vertical direction	56
Number of padding cells in East direction	11
Number of padding cells in West direction	11
Number of padding cells in North direction	11
Number of padding cells in South direction	11
Number of padding cells in vertical direction (down)	19

Table 10 Detailed mesh parameters (single mesh)

Cell size in North direction	500 m
Cell size in North direction	500m
Cell size in vertical direction	250m
Number of core cells in East direction	333
Number of core cells in North direction	124
Number of core cells in vertical direction	56

Number of padding cells in East direction	11
Number of padding cells in West direction	11
Number of padding cells in North direction	11
Number of padding cells in South direction	11
Number of padding cells in vertical direction (down)	16

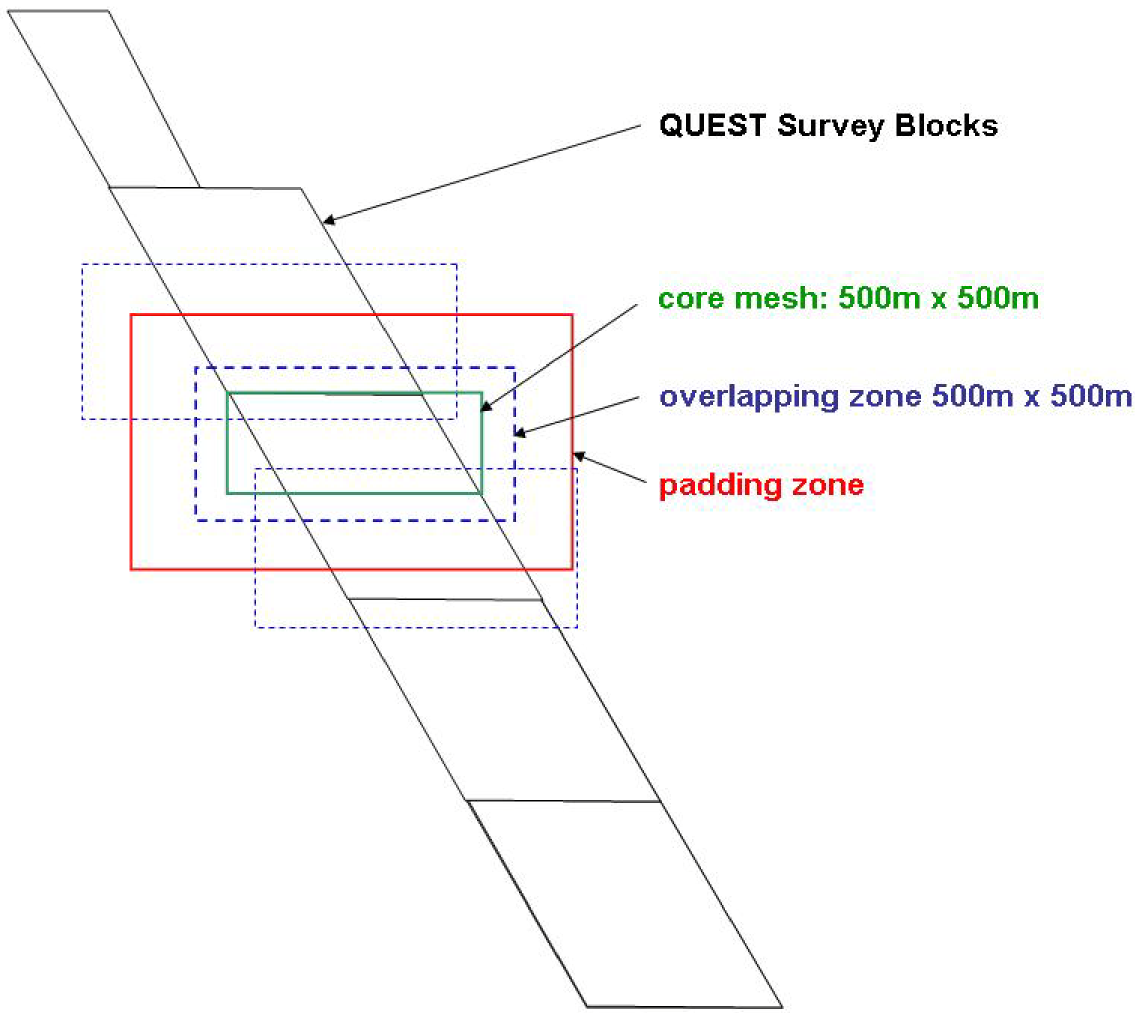

Figure 27 QUEST potential field lateral tiling of detailed inversions showing: the core mesh for each inversion, the overlapping zone used for the regional separation and used for the detailed inversion and merging afterwards, and the padding zone.

Table 11 Detailed Gravity Inversion Parameters (for parameters that were consistent between tiles)

Sensitivity wavelet relative threshold	0.002
Convergence mode	Fixed target misfit

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 12: Magnetic Inversion Modelling Specifications

Inversion Modelling Parameters	**Inversion Modelling Parameter Value**
Convergence Criteria	Chi-factor = 1
Length scales (Le, Ln, Lz)	1.500E+03, 1.500E+03, 1.000E+03
Number of data inverted	41168 (example for one tile)
Global Susceptibility Bounds	0, 1 S.I. (min, max)

Table 13 EM1DTM inversion input file parameters for each sounding

Root name	result
Observation file	obs.dat
Starting conductivity model	From smoothed half-space inversion of late-time data
Reference conductivity model	From smoothed half-space inversion of late-time data
Reference conductivity model (flat)	From smoothed half-space inversion of late-time data
Weights	None
Objective Function Parameters (hc, eps, ees, epz, eez, acs, acz)	1000 2 0.0001 2 0.0001 0.001 1
Inversion Type	Fixed beta
Trade-off parameter decrease	0.5

Maximum number of iterations	15
Convergence Test	0.0001
Hankel kernel evaluations	100
Fourier kernel evaluations	100
Level of output written to file	1

Appendix 5 Magnetization

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 SI) 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 Estimate of AEM Depth of Penetration

The effective depth of penetration of a geophysical survey will depend on the source of the anomalous signal and the configuration of the receiver. A commonly used technique for estimating the depth of investigation in inversion modelling of DC resistivity and IP data is to consider at what depth the recovered model returns to a reference model (Oldenburg and Li, 1999). The depth at which the model returns to the reference model is deemed the depth at which the observed data will no longer influence the model parameters, and hence reflects the maximum depth of investigation. A comparison of recovered models with different reference models can be used for determining a depth of investigation index.

The approach of using different reference models has been applied to 1D AEM inversions but this at least doubles the number of individual inversions required. An alternative method of estimating the depth of investigation has been applied where the cumulative conductance is calculated from the uppermost discretized layer downwards. (This is a much faster calculation which does not involve additional inversions.) The depth at which a given cut-off conductance is reached will provide an alternate estimate of the depth of penetration. Tests can be conducted on a single line of inversions in order to calibrate the cut-off conductance value with the reference model depth of investigation method described above. It should be noted that both methods are subjective as either a cumulative conductance cut-off or a depth of investigation index value has to be chosen.

The resulting models cut-off below this depth of investigation show reasonable and practical interpretation of the inversion models where resistive regions have deeper penetration (as there is nothing to hinder the rapid propagation of the electromagnetic fields), and conductive zones effectively shield the underlying earth and show shallow investigation.

The depth of investigation method presented here is purely an estimate of the depth to which the inversions models might be considered more reliable. While they seem to be a reasonable guide, they are not meant to reflect absolute penetration of the acquisition system. 1D AEM inversion conductivity models are provided with and without this cut-off applied.

Guidance on the application of this approach was provided by Peter Kowalczyk from Geoscience BC.