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Yukon Geological Survey Miscellaneous Report MR-10

Geologically-constrained inversion of magnetic and gravity data over parts of the Yukon-Tanana terrane and Whitehorse trough

Prepared for Yukon Geological Survey

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Yukon Geological Survey

Yukon Energy, Mines and Resources

Canadian Northern Economic Development Agency

Agence canadienne de développement économique du Nord

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Preface

In the winter of 2013 the Yukon Geological Survey (YGS) contracted Mira Geoscience to undertake a 3D geologically constrained modelling exercise to take advantage of a wealth of new geological and geophysical data. These data include new gravity and aeromagnetic surveys, new bedrock geology maps, rock property data and a seismic survey. The area of interest covers much of the northern Whitehorse trough south and east of Carmacks and extends west to Aishihik and Sekulmun Lakes. The goals of this project were to develop a better understanding of the geological relationships in an area of poor bedrock exposure, extending this knowledge to the subsurface and ultimately to provide insight into targeting for mineral and oil and gas exploration.

This report documents in some detail the approach used by Mira Geoscience. A new 3D geological model was constructed for the area using GOCAD's SKUA and Sparse advanced 3D modelling modules that integrated all available geologic and geophysical data. From this model two inversion techniques were used to better resolve subsurface 3D geometries. VPmg inversion was used to better constrain stratigraphic subsurface contacts, especially within the Whitehorse trough; while UBC-GIF magnetic inversion was used to constrain the 3D geometry of large plutonic bodies such as the Aishihik and Ruby Range batholiths.

The two different inversion techniques resulted in the recognition of geologic elements with significant implications for both oil and gas and mineral potential. Within the Whitehorse trough the subsurface geometry imaged by the VPmg inversion shows evidence for dome structures and 'crested anticlines' which could be traps for conventional hydrocarbons. The base of the trough (Laberge Group) is also modelled to be shallower than previous estimates. The UBC-GIF inversion exhibits an array of west-northwest trending magnetic highs that coincide with the distribution of several known mineral occurrences. However, a number of interesting magnetic anomalies occurring along these trends are not associated with known mineralization; these represent potential exploration targets.

This project was funded under the SINED (Strategic Investments for Northern Economic Development) program. The new aeromagnetic surveys used in the development of the inversion models were products of the GEM (GeoMapping for Energy and Minerals) program of Natural Resources Canada. Detailed gravity surveys were funded through SINED and new bedrock mapping through YGS's internal operating budget.

Steve Israel and Maurice Colpron

1. Overview

In April 2013, the Mira Geoscience Advanced Geophysical Interpretation Centre (AGIC) was commissioned by the Yukon Geological Survey (YGS) to conduct 3D geologically-constrained modelling of airborne magnetic and ground gravity data over parts of the Yukon-Tanana terrane, the Whitehorse trough, and Stikinia in southwest Yukon Territory (Figure 1).

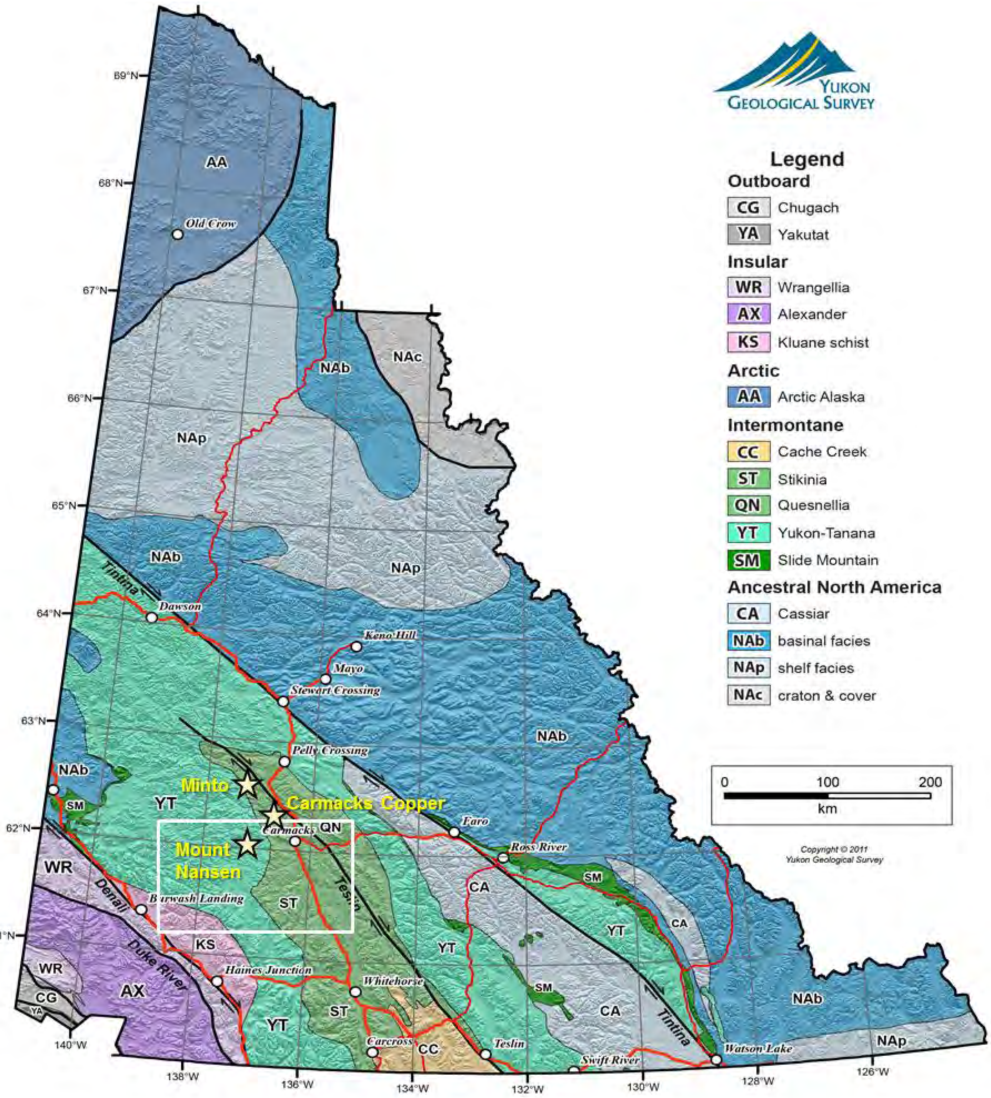

Figure 1. Terrane map of the Yukon Territory (Colpron and Nelson, 2011) showing project area (white outline), and showing nearby mineral deposits, including the producing Minto Cu-Au-Ag mine.

The area of interest was chosen for several reasons. Firstly, the project area has limited bedrock exposure, making geologic mapping challenging. Inversion of geophysical data and generation of a geophysically-constrained geologic model will improve understanding of the distribution of geologic units and structures under surficial cover, and at depth, and will provide insight into the nature of boundaries between important geologic domains. Secondly, both mineral, and oil and gas potential exists within the project area. The Minto mine occurs immediately north of the project area (Figure 1), and is hosted by Jurassic plutonic rocks that are also represented within the area of interest. Paleocene intrusives occurring in the west of the area of interest are also prospective for porphyry and epithermal mineralization. The Whitehorse trough represents a faulted Jurassic to Cretaceous sedimentary basin, which has potential to contain oil and gas resources (White et al., 2012; Hayes, 2012; Hayes and Archibald, 2012). The geophysical and geologic models resulting from this work will help to inform future natural resource exploration within the area.

Several geophysical and geological datasets overlap in the area of interest. The main objectives of this project are to compile and assess the different data sets and various geological and geophysical interpretations. A 3D geology model is built from mapped information and geophysical interpretations, and is then populated by rock property values to facilitate geologically constrained inversion of the total magnetic intensity and gravity data. The modelling process aims to reconcile the constraints provided by geologic mapping, physical property data, and seismic interpretations with gravity and magnetic data in order to understand and refine the structural interpretation of the area, and geologic unit composition and geometry.

The key stages of this project are listed below:

1. Data compilation, assessment and preparation for modelling
2. Interpretation of deep geology from geophysical datasets
3. Physical property data assessment
4. 3D geologic model construction
5. Population of the 3D starting geologic model with constraining rock property information

6. Geologically constrained inversion and modelling of the magnetics and gravity data using two different inversion methods
7. Reporting and generation of a comprehensive suite of 2D and 3D deliverable products

In this project, the VPmg 3D potential fields forward modelling and inversion software (Fullagar et al., 2000, 2004, 2007, 2008) was used for initial gravity and magnetic modelling. The VPmg software permits a wide variety of inversion styles and model options and is well suited to geologically constrained inversion. A key feature of VPmg for this project was its ability to perform geophysical inversion within a geological framework.

The final result is an updated 3D geologic model with lithological domains characterized by physical property values which are consistent with magnetic and gravity data. Geological domains exhibiting anomalous density and susceptibility may signify that additional geological complexity is required in the model.

A second inversion method using University of British Columbia – Geophysical Inversion Facility (UBC-GIF) inversion codes was applied to generate an alternative smooth magnetic susceptibility model which can be used to investigate depths and extents of magnetite-bearing intrusive and volcanic rocks within the study area.

Data and model preparation for VPmg and UBC-GIF inversion, and assessment of inversion results, was undertaken in the GOCAD Mining Suite software.

In summary, key outcomes from the integrated modelling project include:

- Summary of physical property characteristics of geologic units present in southwest Yukon Territory
- Interpretations of deep geology guided by processed regional gravity and magnetic data
- 3D geologic model validated against 3D magnetic and gravity models encompassing:
    - Geophysics-driven update of geometry of units within the Whitehorse trough
    - Updated subsurface distributions/depths of intrusive units which could have exploration significance
    - Update of rock properties associated with modelled geologic units within the project bounds

- Identification of areas where the geological model contradicts geophysical data, suggesting areas of interest and future focus where inferred physical property distributions are not of the range expected (different intrusive phases, or alteration?), or geophysical responses are not explained by geology mapped at surface
- Generation of an alternative smooth magnetic susceptibility model which may help improve interpretation of geology at depth, and act as a guide for any future constrained 3D geologic modelling or geophysical inversion in the project area

The purpose of this report is to document the methodology and results from this project. It is assumed that the reader will have access to the accompanying digital model results, as listed at the end of this report.

2. Data compilation and assessment

Compilation of all relevant data into a 3D GIS package expedites integrated interpretation and helps to rapidly identify relationships (and any inconsistencies) between different data sets.

The following data were provided for this project:

- Geology maps
- Geological cross-sections
- Topographic data
- Airborne magnetic data
- Gravity data
- Seismic data and interpretations
- Physical rock property data

2.1. Geology data

Several geology maps exist covering the project area. Four maps were specifically referred to for 3D geologic model building (Figure 2):

1. Bedrock Geology, Yukon Territory map, 1:1,000,000 (compiled by Gordey and Makepeace, 2001) – covers entire Yukon Territory and provides lower resolution geology in areas not covered by more detailed geological maps.
2. Bedrock Geology, parts of Carmacks and Glenlyon, 1:250,000 (compiled by Maurice Colpron, 2011) – includes north Whitehorse trough and covers NE corner of the project area.
3. Bedrock Geology, Lake Laberge and part of Quiet Lake and Aishihik Lake, 1:250,000 (compiled by Maurice Colpron, 2011) – includes central Whitehorse trough and covers SE corner of the project area.
4. Preliminary geological map of the northwestern Aishihik Lake area, 1:50,000 (compiled by Israel and Westberg, 2012) – maps portions of the Ruby Range and the Yukon-Tanana terrane and covers the west-central project area.

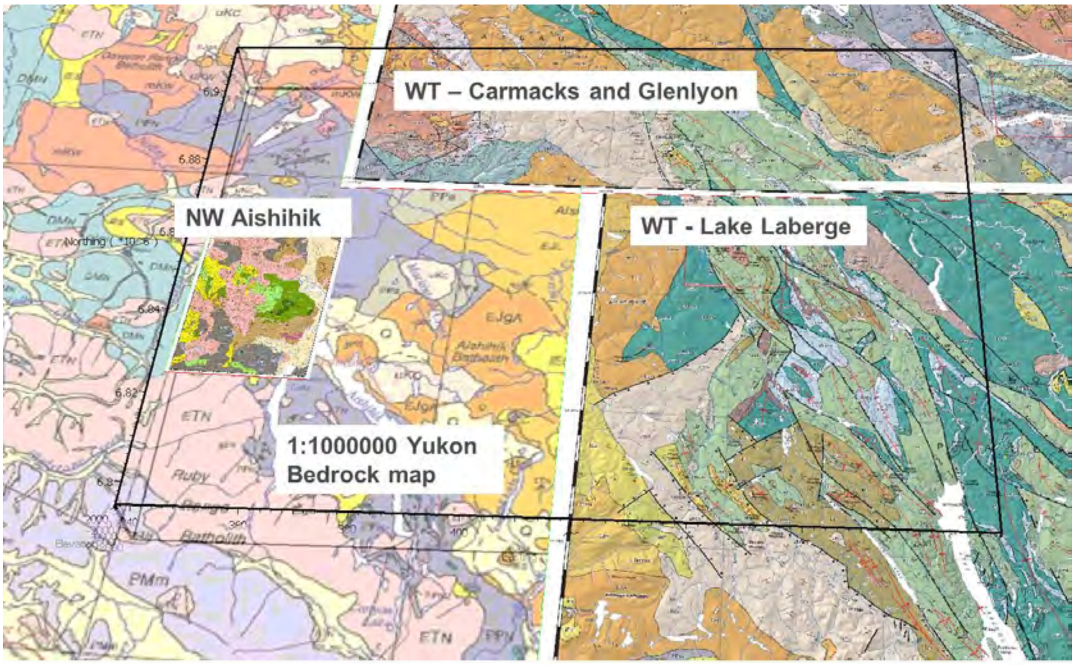

Figure 2. Snapshot from GOCAD showing the four principle maps used in the construction of the 3D geologic model of the northern Whitehorse trough (WT) and parts of the Yukon-Tanana terrane. 3D volume of interest is shown outlined in black.

2.1. Geological cross-sections

Three sets of geological cross-sections were used to guide 3D geologic modelling (Figure 3). These are:

1. Deep geologic sections extending across the area of interest. Three geologic cross-sections were prepared by Steve Israel from YGS to use as a guide for building the 3D geologic model. The sections correlate with mapped geology from the four bedrock maps, and extend to depths of greater than 10 km.
2. Sections crossing the central Whitehorse trough. Three geologic sections from White et al. (2012) indicating geology and structure at depth, up to 1500 m, interpreted based on mapped geology.
3. Seismic sections. Migrated seismic data were provided in SEGY format, as well as seismic interpretations published in White et al. (2012). For modelling, geologic contacts and structures interpreted on the seismic section were transferred onto the 3D objects in GOCAD (Figure 4).

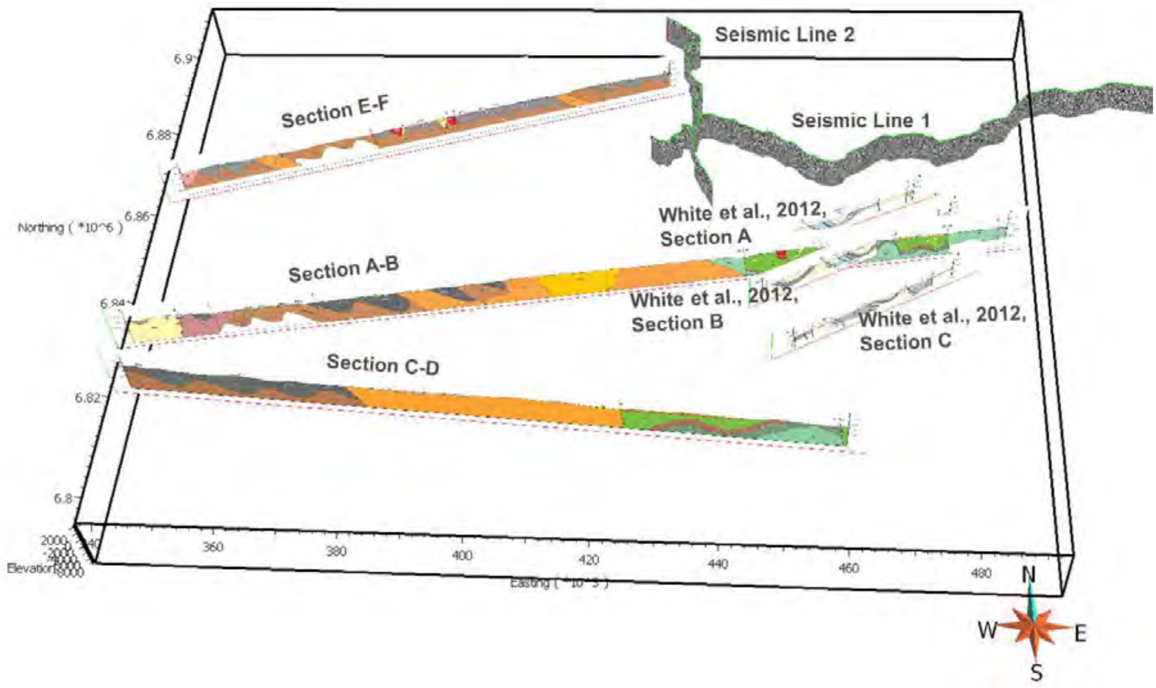

Figure 3. Snapshot from GOCAD showing the cross-sections used to guide the construction of the 3D geologic model of the northern Whitehorse trough and parts of the Yukon-Tanana terrane. Volume of interest is shown.

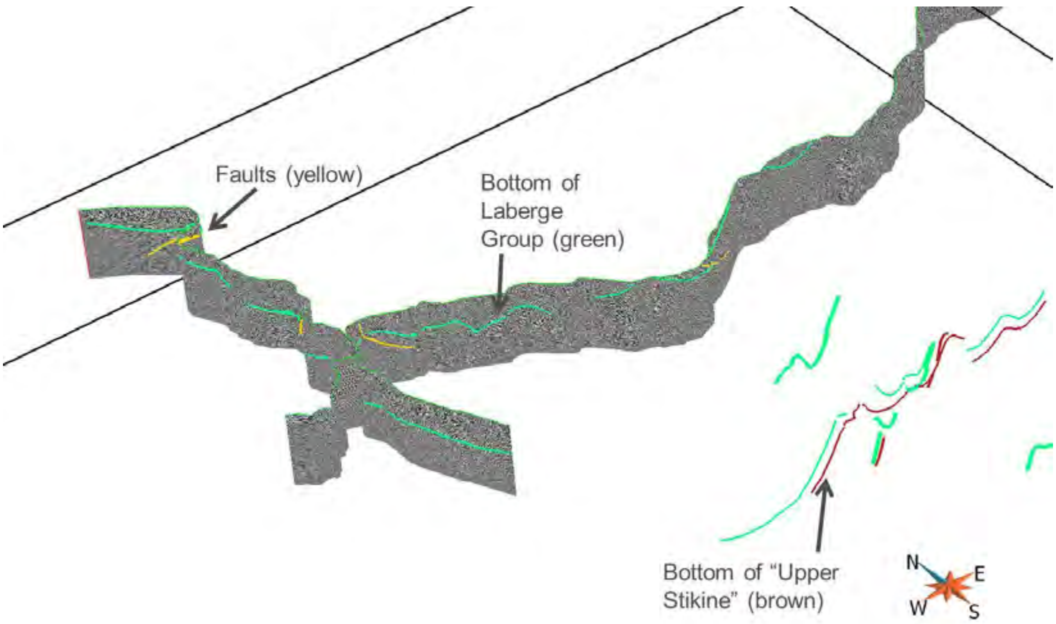

Figure 4. Snapshot from GOCAD showing seismic data with interpretations from White et al. (2012) digitized. Curves digitized from other geological sections are also shown.

2.1. Topography data

A digital elevation model (DEM) was extracted from the Space Shuttle radar data set (SRTM) in the NAD83 UTM Zone 8 coordinate system. The data have a resolution of 30 m (Figure 5). Elevations within the current study area range from around 400 m to 2300 m. The average elevation of the study area is 1059 m.

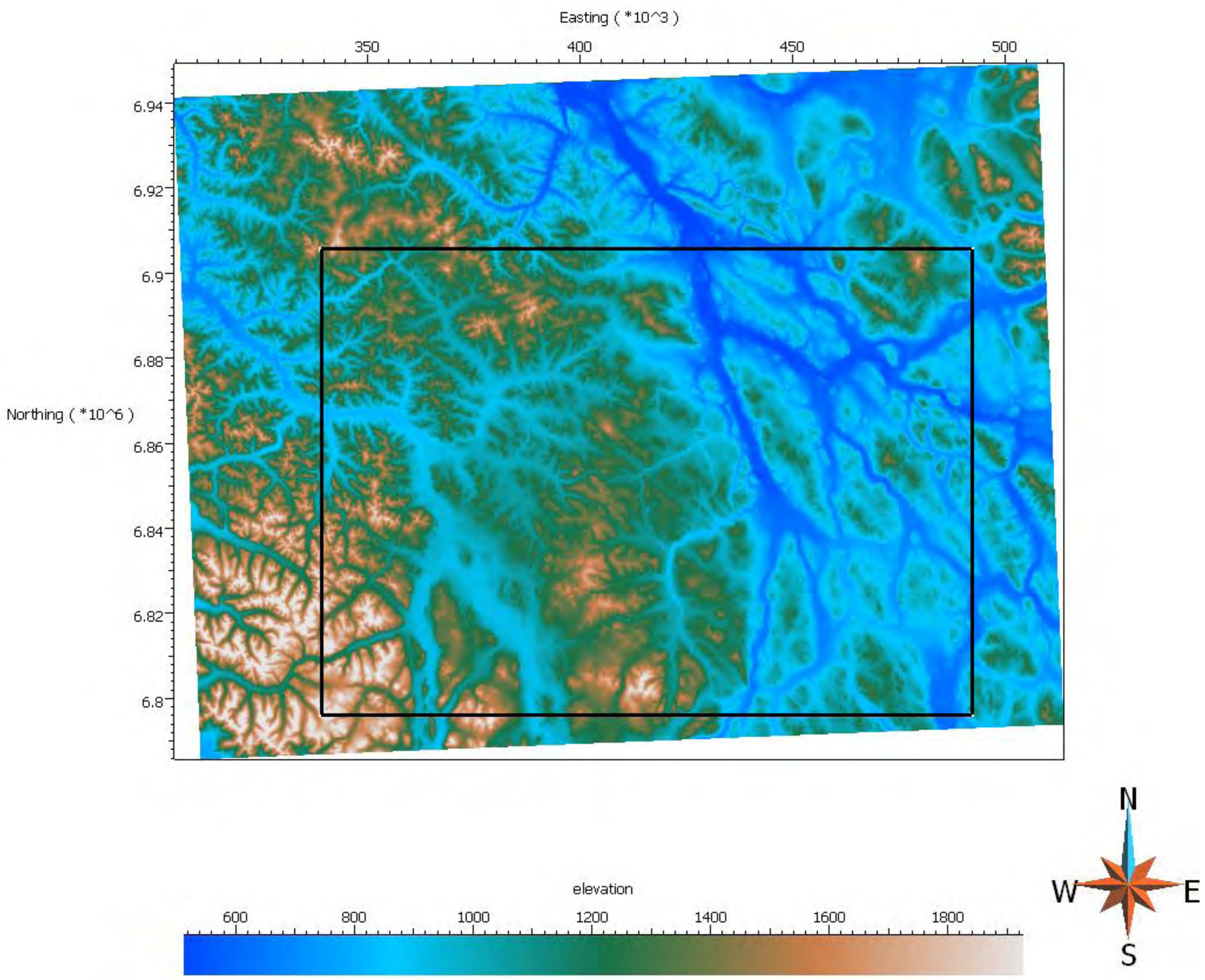

Figure 5. SRTM data at 30 m resolution. The project area is indicated by the black outline.

2.2. Airborne magnetic data

The airborne magnetic data utilised in this project comes from the Geological Survey of Canada, and is a merged dataset compiling various magnetic data collected over the Yukon Plateau (Hayward et al.,. 2011). Within the project area, two high resolution airborne magnetic datasets are represented, the Kluane survey data (Kiss, 2010), and the Nisling River survey data (Kiss and Coyle, 2011). These surveys were flown in 2010 and 2011 by Fugro Airborne Surveys, at line-spacings of 400 m. The remainder of the grid is filled by regional magnetic data, which were collected between 1961 and 1966 at a line-spacing of 1207 m. The data was provided as a grid file with a 100 m cell size (Figure 6).

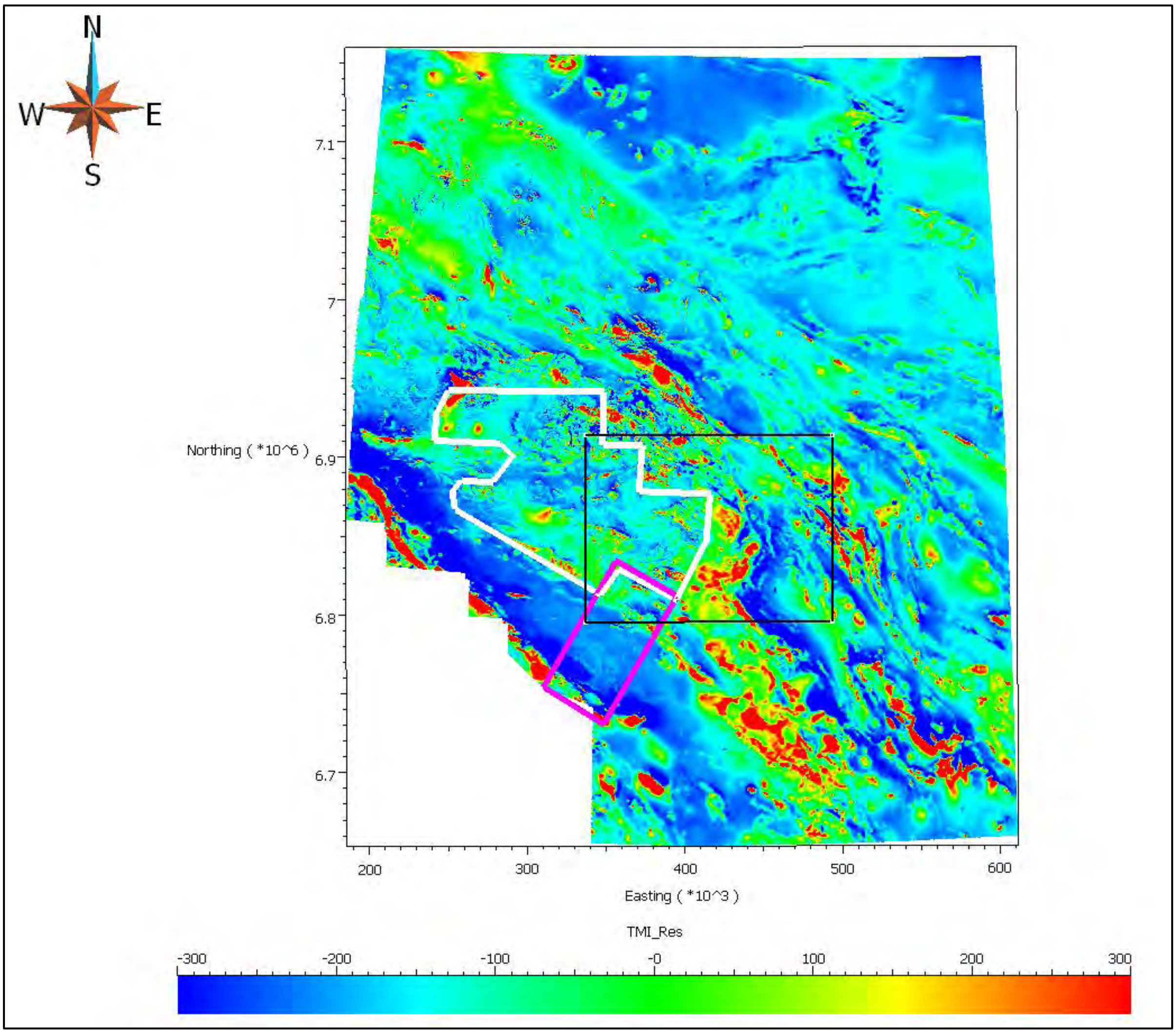

Figure 6. Image of Yukon Plateau aeromagnetic total magnetic intensity (TMI) grid, with project area indicated by the black outline. High resolution Nisling and Kluane magnetic surveys are outlined in white and magenta, respectively.

During the inversion processing of the magnetic data, magnetic data were draped 100 m above topography for the near surface inversions, and 10750 m above the topography for upward continued data used for modelling regional sources below the extents of the model.

Ambient magnetic field parameters of 56,298 nT, 76.83° inclination and 28.68° declination were adopted for modelling. All processing was done in the NAD83 UTM Zone 8 projection and coordinate datum system.

2.3. Gravity data

Two gravity datasets were used. The first is a regional gravity dataset from the Geological Survey of Canada (Canadian Geodetic Information System, 2008), with data collected on a 10 km grid. The dataset included Free Air and Complete Bouguer data, which are gridded at 2860 m × 2860 m. Regional data is compiled from gravity surveys run between 1944 and 1999. The second dataset is derived from a survey completed by Aurora Geosciences between 2011 and 2012 (Yukon Geological Survey, 2011). The dataset included Free Air and Complete Bouguer Anomaly (2.67 g/cm^3) data. This survey covers the northern and western parts of the area of interest, and has a data station spacing of approximately 2 km.

Complete Bouguer data was re-calculated for Geological Survey of Canada regional gravity data to ensure that local topography was accounted for. The GSC Free Air data were terrane corrected using 30 m DEM downloaded from SRTM. A density value of 2.67 g/cm^3 was applied to generate the Complete Bouguer data (Figure 7). To level the Aurora Complete Bouguer data to the terrain corrected GSC data a DC shift of 92.3569 mGal was applied to the Aurora survey data (Figure 8). All data were gridded at 500 m and draped 1 m above the DEM (10750 m above DEM for upward continued data used for basement inversions). Although the regional GSC gravity data were gridded at 500 m to match the resolution of geologic modelling and modelling of magnetic and Aurora gravity data, the regional data does not support this high resolution interpolation, and features outside the extents of the more detailed Aurora gravity survey (see Figure 8) should be interpreted with caution.

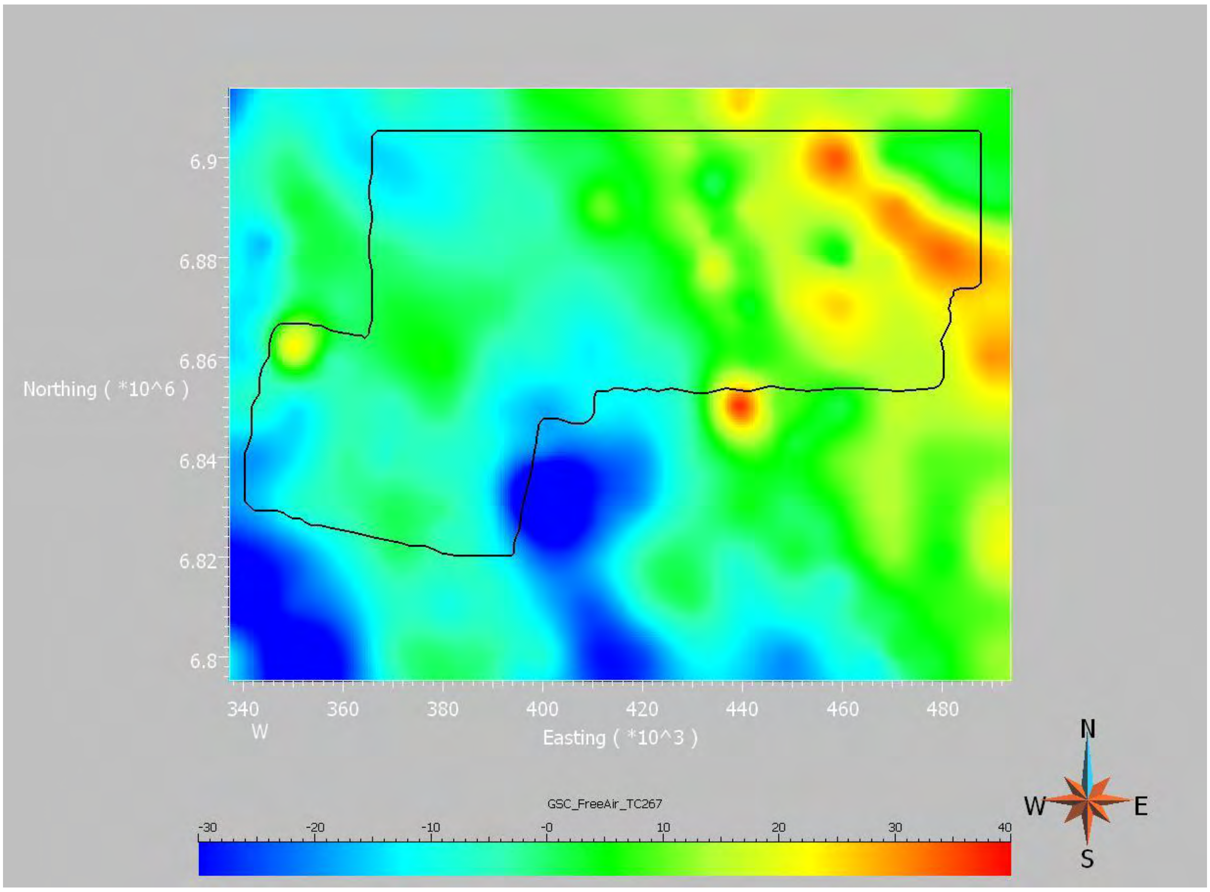

Figure 7. Image of GSC regional Complete Bouguer data over the project area. The black outline shows the extent of the Aurora gravity grid.

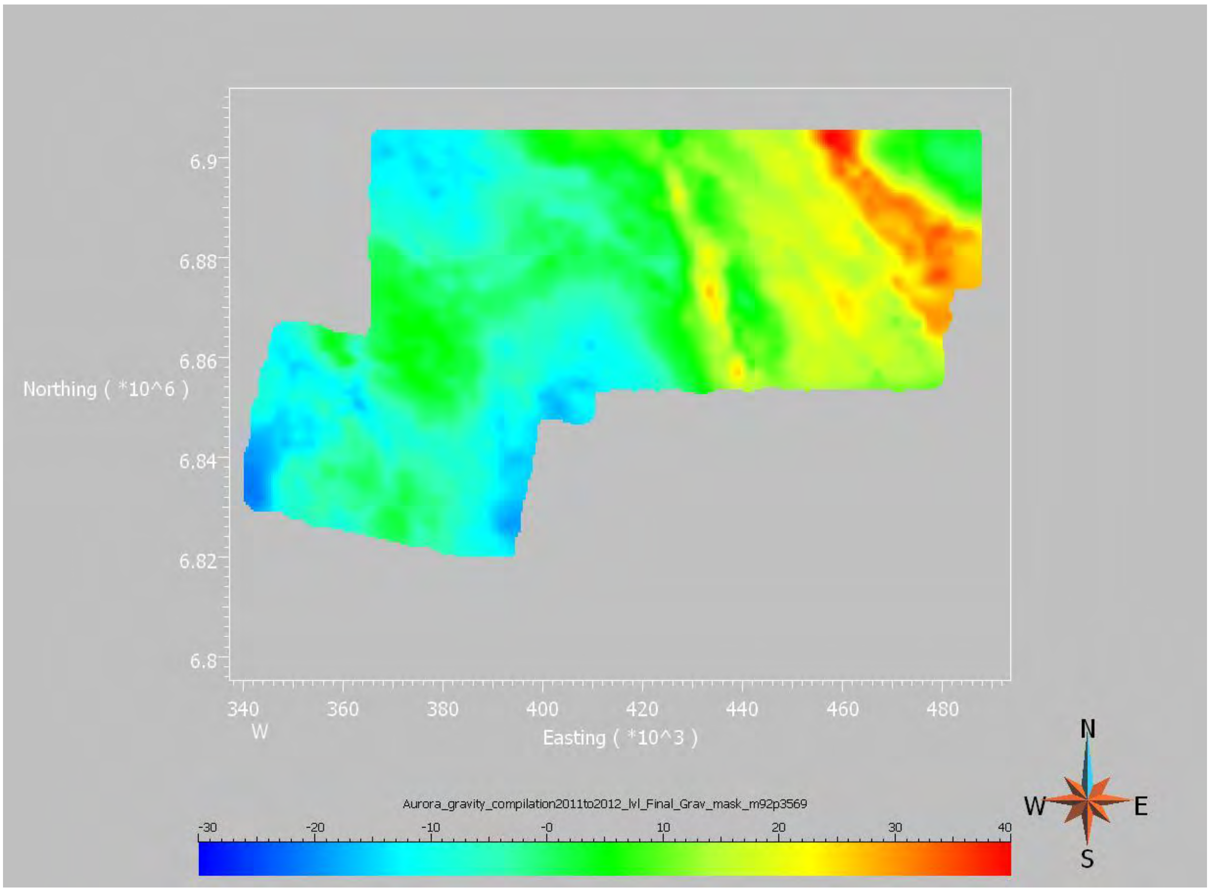

Figure 8. Image of Complete Bouguer data from the 2011-2012 A urora Geosciences survey. The Aurora survey covers ground within the northern and western parts of the project area.

2.4. Rock property data

The constrained inversion modelling completed for this project is strongly anchored on a collection of magnetic susceptibility and density measurements from southwest Yukon Territory that were originally published in 1978 by Tempelman-Kluit and Currie. A digital copy of this data was provided by the Geological Survey of Canada Pacific branch. The data covers a large portion of the SW corner of the area of interest chosen for the YGS modelling project. The digital database contained geographic coordinates, but it was necessary to append geologic formation and rock type information manually by referring to a scanned copy of the appendix of Tempelman-Kluit and Currie (1978). It is suspected that the geological formation names assigned to the samples may require updating to reflect current geologic understanding, however, they were kept as originally assigned for this work. It should be noted that the scanned .pdf appendix also contains metal assays and mineral estimates, which were not copied to the digital database, but which may be of interest to the mineral exploration community. Collated with Tempelman-Kluit and Currie data was additional magnetic susceptibility and density data generated during a field program led by Carmel Lowe in the early 1990's. The compiled physical property data can be found in Appendix C.

The availability of this physical property data made it possible to develop a robust characterization of the rocks within the area of interest that will allow magnetic and gravity models to be constrained.

This rock property information has been compiled and assessed and the average, minimum and maximum susceptibility and density per lithology is listed below in Table 1. Where no measurements were recorded for a lithology in the geology model, Mira Geoscience estimated values based on apparently similar rocks.

Table 1. Summary of density and susceptibility data used to constrain inversion modelling.

Geologic Formation	Density (g/cm^3)			Susceptibility (SI)		
	median	min	max	median	min	max
Rhyolite Creek Volcanics	2.64	2.48	3.21	0.00266	0	0.0752
Eocene Volcanics	2.64	2.48	3.21	0.00266	0	0.0752
Carmacks Volcanics	2.71	2.42	3.09	0.00522	0	0.124
Gabbro (Carmacks age)	2.71	2.42	3.09	0.00522	0	0.124
Mt. Nansen Volcanics	2.71	2.42	3.09	0.00522	0	0.124
Laberge	2.55	2.3	2.7	0.00136	0	0.012
Upper Stikine (Aksala fm)	2.65	2.4	3	0.00136	0	0.012
Stikine (Povoas fm)	2.89	2.73	3.02	0.00319	0	0.101
Boswell	2.7	2.6	3	0.002	0	0.04
Whitehorse Suite	2.7	2.58	3.17	0.00187	0	0.0696
Aishihik (+Long Lake) Batholith	2.65	2.52	2.95	0.00906	0	0.0654
McGregor Pluton	2.65	2.52	2.95	0.00906	0	0.0654
Tatchun Batholith	2.65	2.52	2.95	0.00906	0	0.0654
Ruby Range Batholith	2.6	2.32	3.1	0.00286	0	0.0712
Yukon-Tanana terrane	2.73	2.5	3.16	0.00103	0	0.126

3. Construction of a reference 3D geological model

3.1. Strategy

A 3D geologic model is constructed for two purposes. The first is to consolidate the current understanding of surficial and deep geology within the area of interest. The second is to provide a starting model for constrained inversion modelling. The 3D geologic model will guide the gravity and magnetic inversions toward a solution that is consistent with geologic knowledge, and will itself be iteratively updated to improve fit between the model and the observed geophysical data.

The choice of geologic units to focus on during 3D geologic modelling was determined both by relevance of the geologic unit to the project objectives, and by uniqueness of geophysical signature or physical property ranges. Because geophysical information is relied on to help update the interpreted geologic model, there must be distinct physical property contrasts between units; it is not possible to refine contacts between geologic units which are petrophysically similar. In general, regional scale geology is focused on, with less voluminous units ignored unless they have a significant and distinct geophysical response.

Sixteen units were modelled using two different GOCAD modelling tools. The modelling details are discussed in the following sections.

3.2. Model volume

One of the first, crucial steps to be undertaken when building a quantitative model of the Earth which is to contain multiple types of 3D geoscience data is to define the extents, depth, scale and resolution of the model. In GOCAD, this is typically a voxet object, which is a regular 3D-grid with constant cell sizes. The voxet cells are not required to be equal lengths along each (U, V and W) axis, allowing for flexibility when designing the model scale and resolution. Vertical or horizontal cells can be thinner to better resolve the smaller model details. The Yukon Geological Survey suggested preliminary extents for the project area. Mira Geoscience increased the suggested area slightly, and discretised the volume as appropriate for the detail of the geophysical and geological data. The geologic model was constructed using the NAD83 Zone 8N coordinate system to be consistent with data available for this location within the Yukon Territory. The project boundary runs east-west from 337250 m to 493750 m E, north-south from 6795250 m to 6913750 m N and from 2750 m to -19750 m elevation. This results in a 156.5 km x118.5 km x 22.5 km block model encompassing a volume of approximately 420,000 km^3 (Figure 9). The voxet was then discretized into 500 m x 500 m x 500 m cells resulting in a total of more than 3.4 million cells.

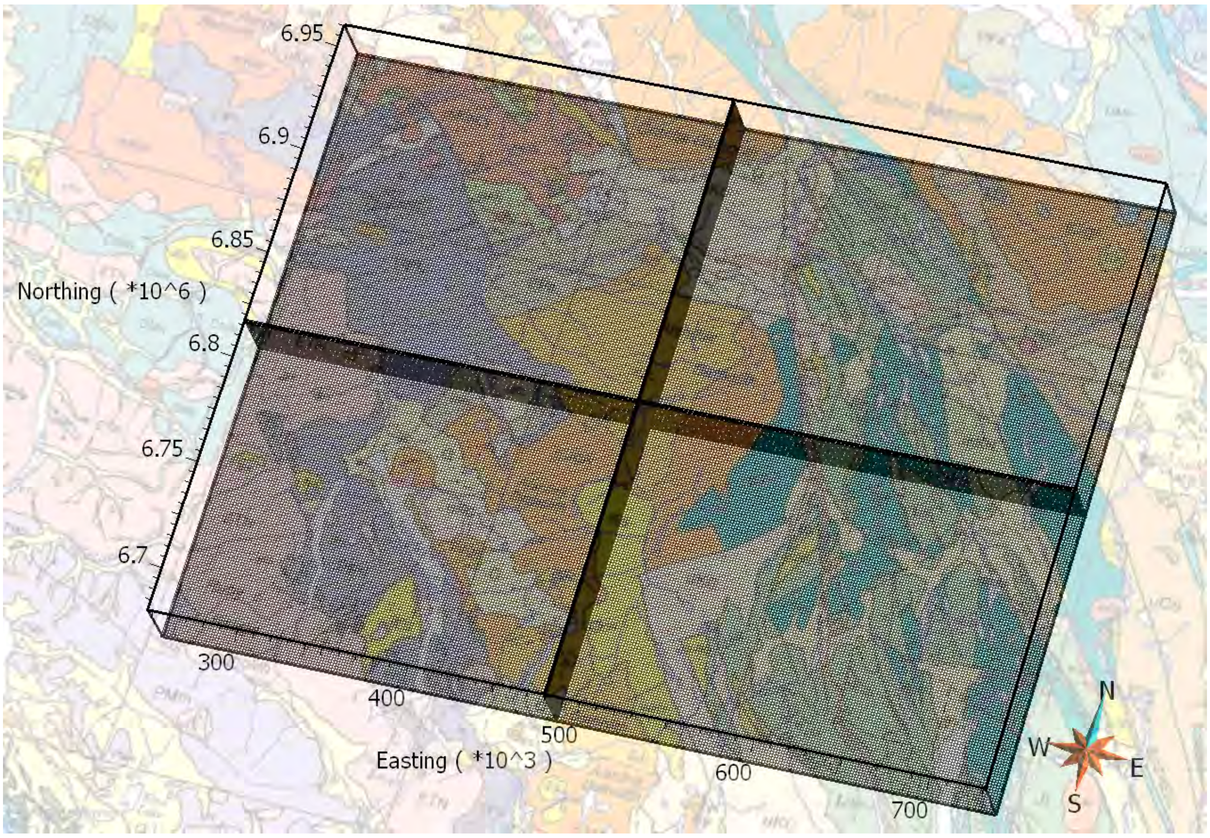

Figure 9. Volume of interest voxet with regional bedrock geology map indicating location within the southwestern Yukon Territory. Cell size is 500 m x 500 m x 500m.

3.3. Interpretation of deep geology from geophysical data

3.3.1. Apparent density and susceptibility models

For this project, apparent density and apparent susceptibility inversions were completed to produce 2D apparent density and susceptibility models to facilitate interpretation of geology within the project area. The inversion process calculates a single density or susceptibility value for each grid cell, such that the observed data are explained. The models vary laterally but not vertically. The resultant apparent density and susceptibility models provide an efficient means for explaining the regional scale potential field response. The modelling was completed using VPmg software, the same software that is at later stages used to perform 3D geologically-constrained inversions. The inversions reveal the locations of dense and susceptible bodies, and are useful for preliminary interpretation of geological and structural features.

Apparent susceptibility and density inversions were completed for the regional GSC gravity data, the higher resolution Aurora gravity survey data, and the regional Yukon Plateau magnetic data.

The regional unconstrained apparent density model was calculated from GSC Complete Bouguer gravity data which were positioned on topography. The model has a resolution of 2860 m x 2860 m, matching the resolution of the GSC gridded data, and the model extents match those of the 3D geologic model voxet (Figure 10). The apparent density model calculated using the Aurora Complete Bouguer gravity data extends over the Aurora survey area, and has a resolution of 500 m x 500 m (Figure 11). The starting density for both gravity inversions was $2.67 g/cm^3$ (representing the residual density). The apparent susceptibility starting model was calculated from the Yukon Plateau magnetic data using data points positioned at 100 m above the topographic surface. The model covers the extent of the project area, and has a 250 m x 250 m resolution (Figure 12). The starting susceptibility was 0 SI. Magnetic susceptibility positivity was enforced during regional apparent susceptibility inversion. Only induced magnetic fields were assumed for regional modelling, magnetic remanence was ignored.

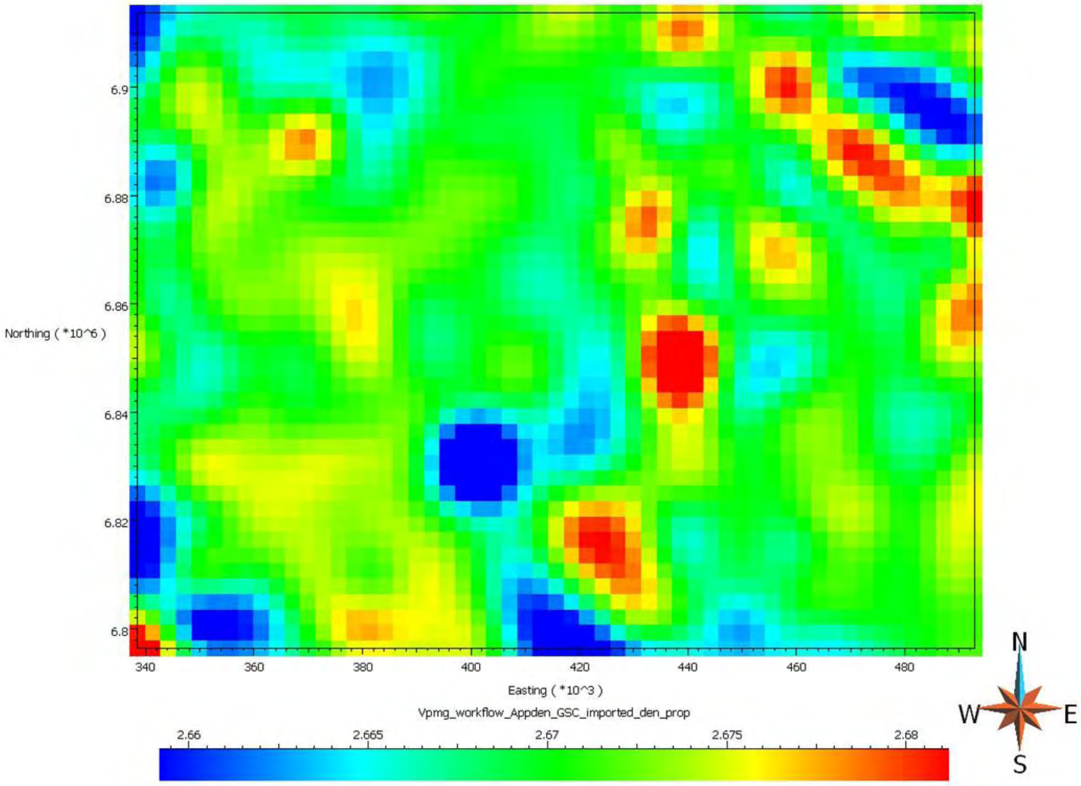

Figure 10. Plan view image of 2D apparent density model calculated from regional GSC gravity data. Resolution of 2860 m × 2860 m.

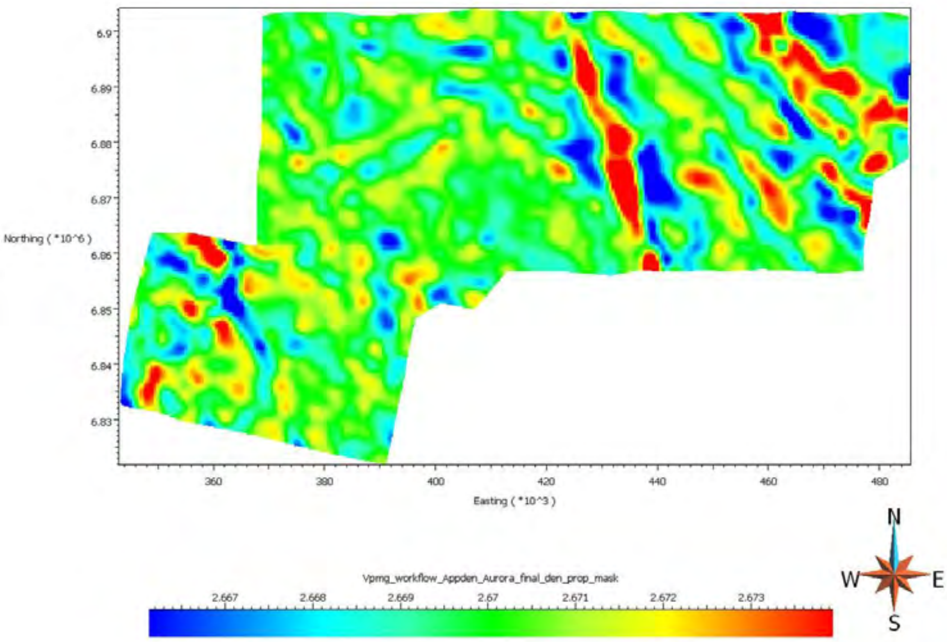

Figure 11. Plan view image of 2D apparent density model calculated from Aurora gravity data. Resolution of 500 m × 500 m.

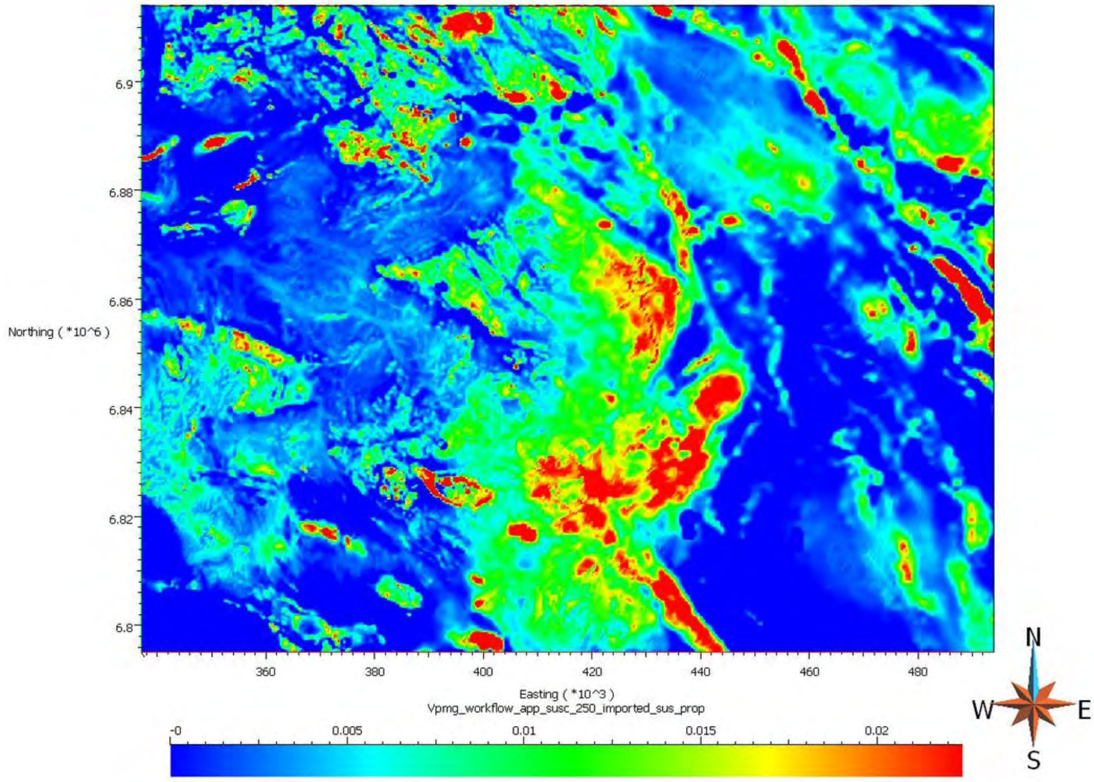

Figure 12. Plan view image of 2D apparent susceptibility data calculated from regional Yukon Plateau magnetic data. Resolution of 250 m × 250 m.

3.3.2. Geological interpretations from magnetic and gravity data

Apparent susceptibility and density models were used to investigate correlations between mapped geology and geophysics, and to update geology where the interpreted geology and geophysical data were found to be conflicting.

The main objectives of carrying out geologic interpretations from geophysical data are to:

- build knowledge of rock property characteristics of major mapped geologic units in the Whitehorse trough – Yukon-Tanana terrane area of interest,
- develop an understanding of geology at depth (especially below thin volcanic cover sequences),
- gather information to develop a strategy for constrained inversion modelling,
- to build a starting geologic reference model wherein geological and geophysical information agrees

Data used for interpretations include:

- 1: 1,000,000 bedrock geology map of Yukon (Gordey and Makepeace, 2001, 1:250,000 Whitehorse trough maps (Colpron, 2011), and NW Aishihik map (Israel and Westberg, 2012)
- Magnetic susceptibility and density data from Tempelman-Kluit and Currie (1978)
- Apparent magnetic susceptibility model calculated from the Yukon Plateau merged magnetic data set
- Apparent density model calculated from the regional GSC gravity data
- Apparent density model calculated from the Aurora gravity survey data

The interpretation process involved first digitizing contacts associated with relevant geologic units and plotting the contacts onto the apparent density and susceptibility models. One or two units were analyzed at a time, inspecting apparent susceptibility and apparent density models, as well as rock property data, and identifying areas where geology and geophysics deviate. Digitized contacts were modified accordingly and were used to update geologic cross-sections, and as input for 3D model building. The following sections summarize updates made to geologic maps by unit.

Stikine volcanic units/Stikine sedimentary units/Whitehorse trough (Laberge Group)

The volcanic Stikine stratigraphy (Lewes River Group) underlying the Whitehorse trough is indicated to be generally high density (Figure 13). Geologic contacts were modified to encompass nearby high density material (Figure 14). 'Upper' Stikine sedimentary units may not be as high density as volcanic Stikine stratigraphy, but they are difficult to separate out since they directly overlie the deeper Stikine volcanic rocks. Laberge Group stratigraphy is indicated to be low density, as is typical for sedimentary rocks.

Updates to Stikine geologic contacts were almost all made in locations where Carmacks Group volcanic rocks were mapped at surface. The high density values in these areas suggest Stikine rocks exist below these relatively thin volcanic rocks (Figure 15).

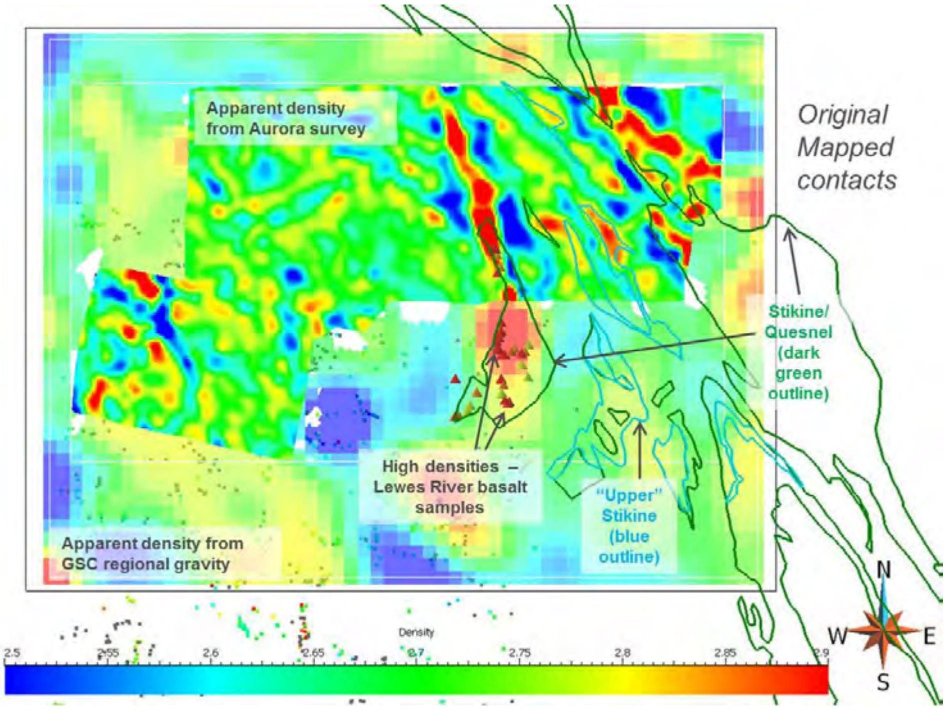

Figure 13. Mapped Stikine contacts overlain on GSC apparent density and Aurora apparent density models. Densities recorded for Lewes River basalts and density values modelled within the mapped Stikine contacts suggest that the Stikine volcanic rocks are generally high density.

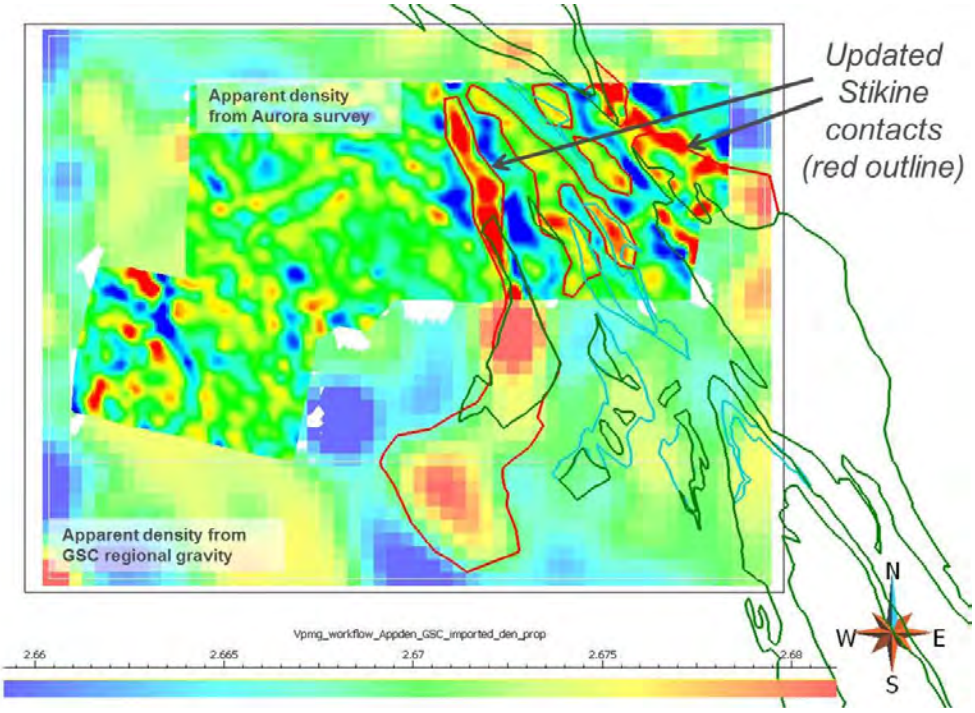

Figure 14. Stikine contacts updated based on modelled distribution of high density material. Updates to Stikine contacts in red outline.

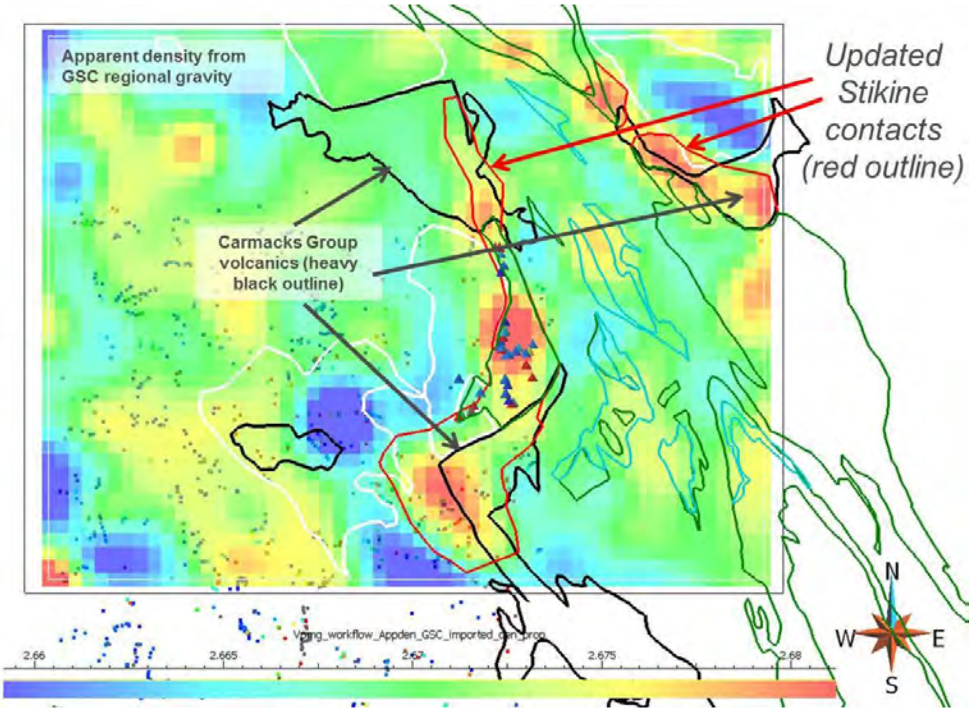

Figure 15. Stikine contacts updated predominantly where overlying Carmacks Group volcanic rocks have been mapped. Modelled densities indicate Stikine rocks lie at depth.

Stikine volcanic rocks appear to be generally high susceptibility, although striping within the bounds of mapped contacts indicates some stratigraphic layers are non-magnetic (Figure 16). Where overlying mafic material-dominated volcanics, such as Carmacks Group, are overlying Stikine rocks, their magnetic responses are superimposed and it is difficult to separate deeper versus shallower units.

'Upper' Stikine units, representing sedimentary stratigraphy are consistently low susceptibility with the exception of the volcanic Nordenskiold formation, which is identified in the apparent susceptibility model as thin linear high susceptibility features. Several isolated small magnetic features within the Whitehorse trough may represent intrusive rock. For example, three susceptible bodies are imaged in the northern Whitehorse trough. The magnetic highs here are correlated both with mapped Carmacks Group volcanics (Gordey and Makepeace, 2001), and Carmacks Group gabbroic intrusives (White et al., 2012).

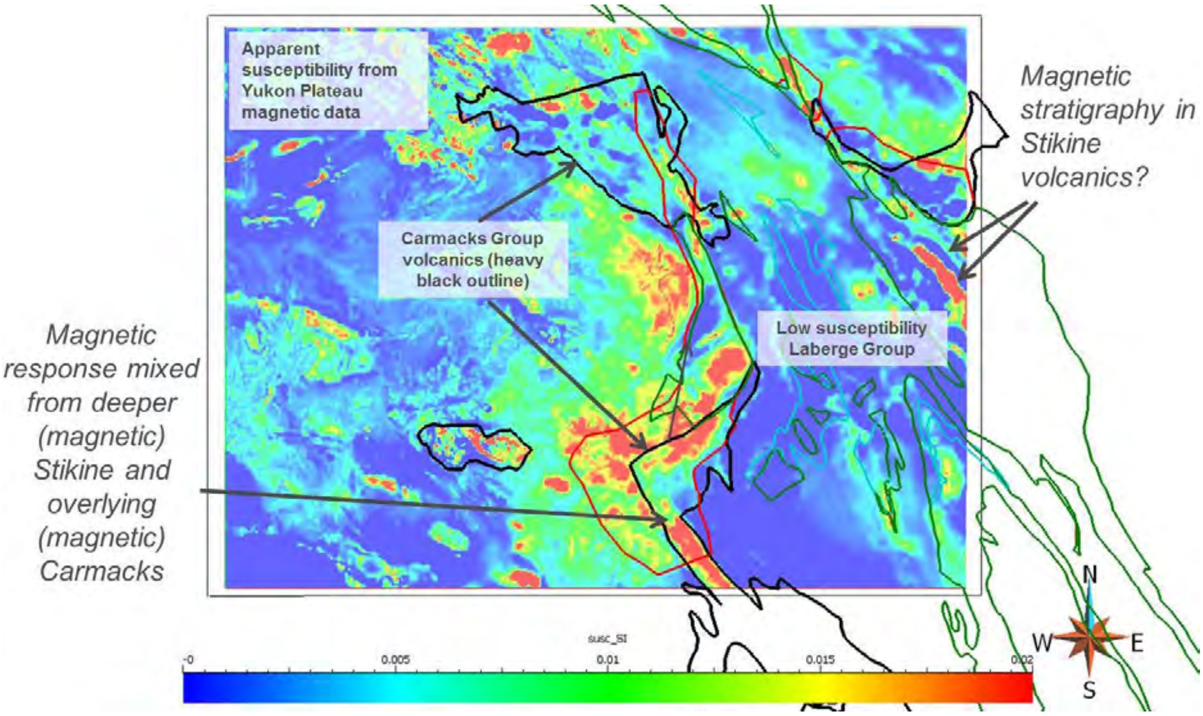

Figure 16. Mapped Stikine contacts overlain on Yukon Plateau apparent magnetic susceptibility grid. Susceptibilities modelled within the mapped Stikine contacts suggest that the Stikine volcanic rocks are generally high susceptibility. Whitehorse trough Laberge Group stratigraphy is low susceptibility.

Aishihik Batholith, Long Lake Batholith, and Whitehorse Suite

Intrusive rocks within the project area tend to be low density and they have generally high, but very heterogeneous susceptibilities. Areas of anomalously low density areas might signify deep roots to the intrusive rocks. There are several areas where high density material occurs within the boundaries of the mapped intrusive rocks, and this was taken to indicate that the intrusives are 'overlapping', or emplaced above denser material. The modelled density and susceptibility patterns suggest that the western contacts of the Aishihik and Long Lake batholiths dip eastward (Figures 17 and 18). Limited modifications were made to the original interpreted geological contacts at the surface. Low densities extending north off the central mapped Long Lake Batholith indicates the batholith continues beneath Carmacks Group volcanic rocks.

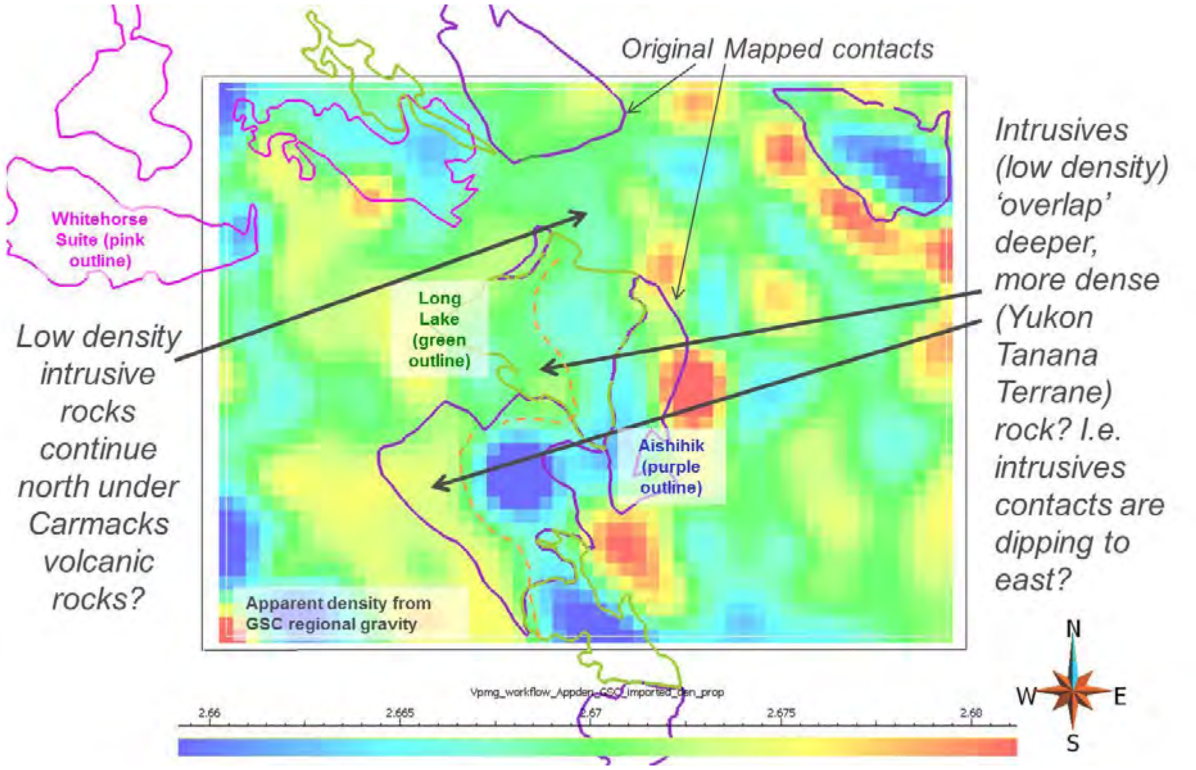

Figure 17. Mapped intrusive contacts (for Whitehorse Suite, Aishihik, Long Lake, and similar age batholiths) overlain on GSC apparent density model. Densities modelled within the mapped batholiths suggest that these intrusive rocks are generally low density. High densities encroaching on the western margin of the Aishihik and Long Lake batholiths suggest Yukon-Tanana terrane is underlying. Low densities extending north off the central mapped Long Lake Batholith indicates the batholith continues beneath Carmacks Group volcanic rocks.

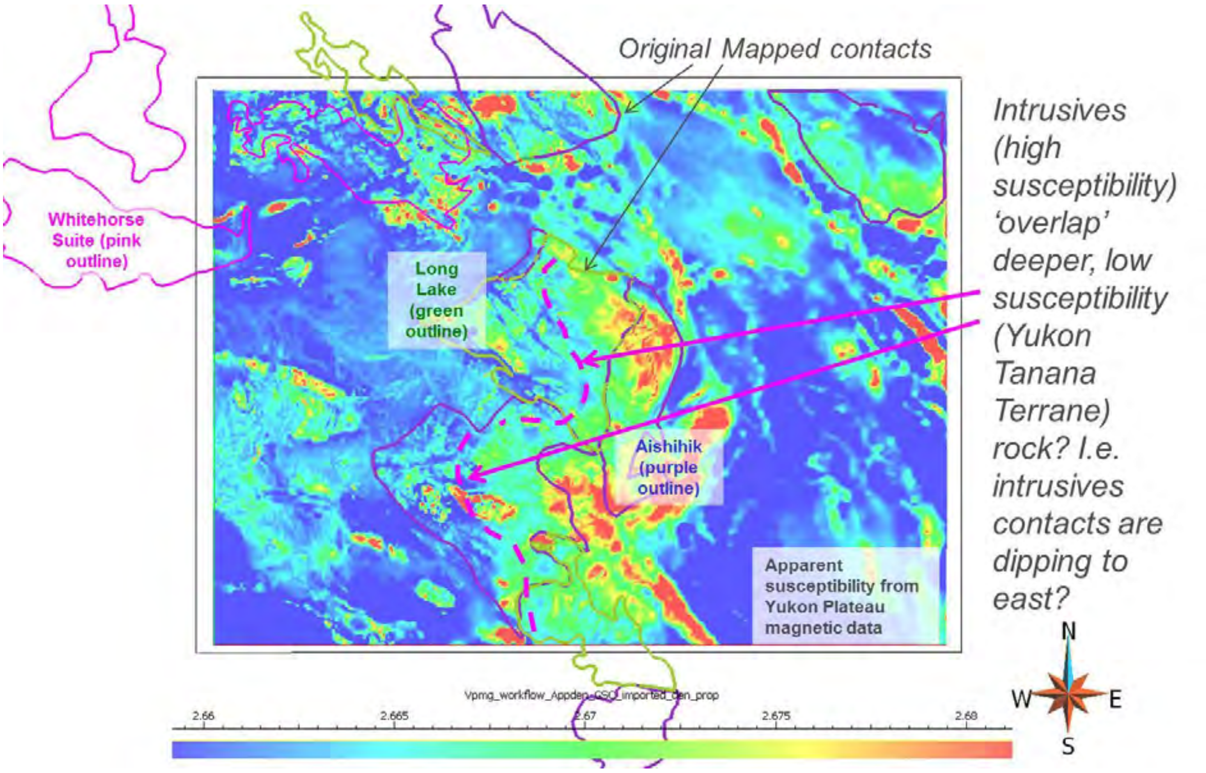

Figure 18. Mapped intrusive contacts (for Whitehorse Suite, Aishihik, Long Lake, and similar age batholiths) overlain on Yukon Plateau apparent susceptibility model. Susceptibilities modelled within the mapped batholiths suggest that these rocks are generally high susceptibility, but very heterogeneous magnetically. Lower susceptibilities modelled at the western margin of the Aishihik and Long Lake batholiths may support the interpretation from the density model that the Yukon-Tanana terrane is underlying.

Yukon Tanana terrane and Ruby Range Batholith

Rocks composing the Yukon-Tanana terrane appear to be consistently low susceptibility, and consistently high density, making the Yukon-Tanana terrane quite distinguishable from the low density, high susceptibility intrusive rocks that are in contact with it. Based on the apparent susceptibility and density models, the subsurface extents of the Yukon-Tanana terrane are interpreted to be greater than its mapped extent, and the geological contacts were updated to reflect this (Figures 19 and 20).

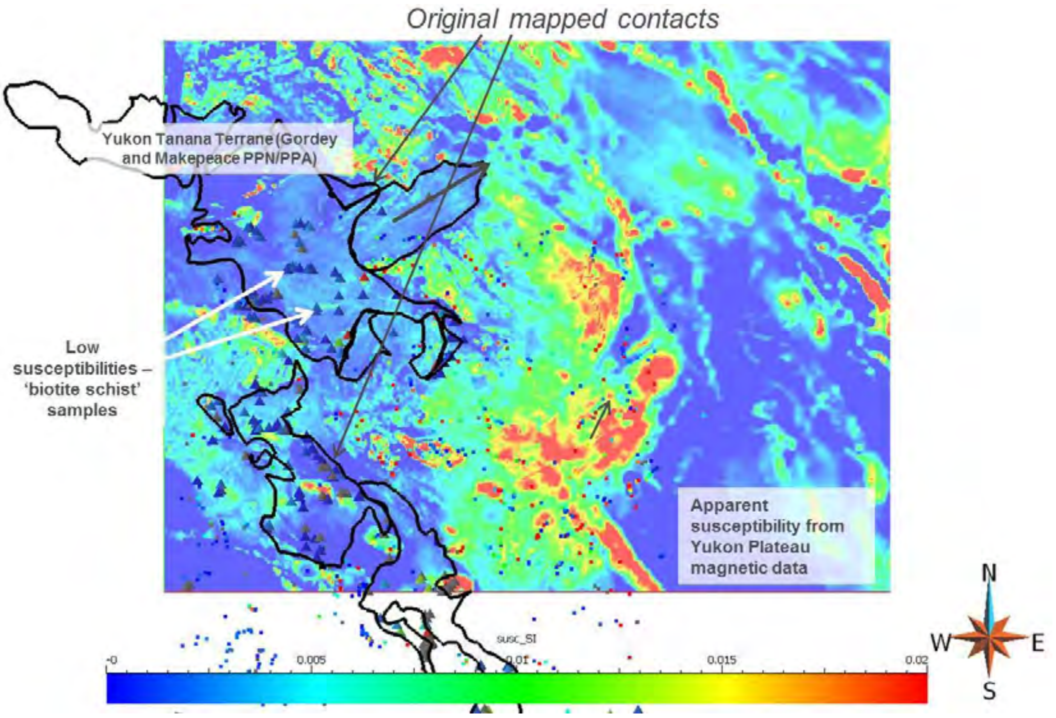

Figure 19. Mapped Yukon-Tanana terrane contacts overlain on Yukon Plateau apparent susceptibility model. Yukon-Tanana terrane rocks are consistently low susceptibility.

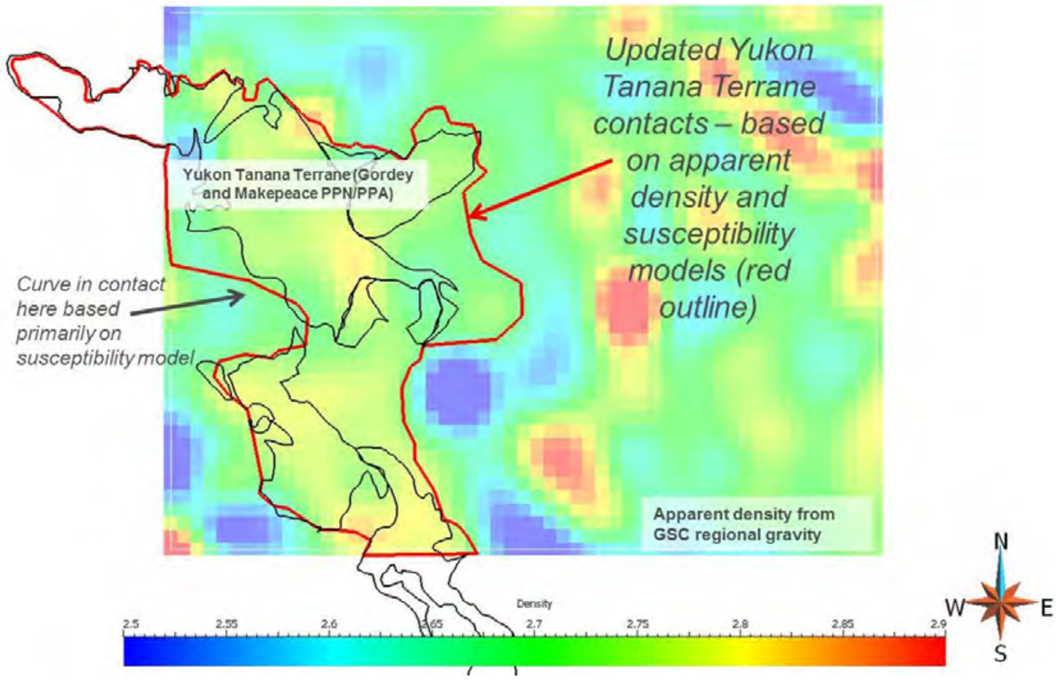

Figure 20. Mapped Yukon-Tanana terrane contacts overlain on GSC apparent density model. Modelling suggests that these rocks are generally high density. Geology contacts are updated based on similar patterns in density and susceptibility models.

Like other intrusive rocks mapped within the project area, those of the Ruby Range Batholith appear to be characterized by low densities and high (but variable) susceptibilities. An interesting conflict occurs between the magnetic susceptibility model and the mapped geology. A northwest trending boundary is indicated by a sharp contrast between high and low susceptibility regions in the west-central magnetic susceptibility model. Ruby Range plutonic rocks are observed in the field to extend northward, cross-cutting this boundary. Although the rocks change quickly from magnetic to non-magnetic, no macroscopic change is apparent in the intrusive rocks mapped at the surface. An interpretation of the conflicting information provided by the apparent susceptibility models and the mapped geology is that these intrusive rocks exist as a very thin sheet above low susceptibility, high density Yukon-Tanana terrane rocks. Apart from these discrepancies, the mapped contact between the Ruby Range and the Yukon-Tanana terrane generally correlates well with density and susceptibility models, and minimal updates were made to the interpretations (Figure 21).

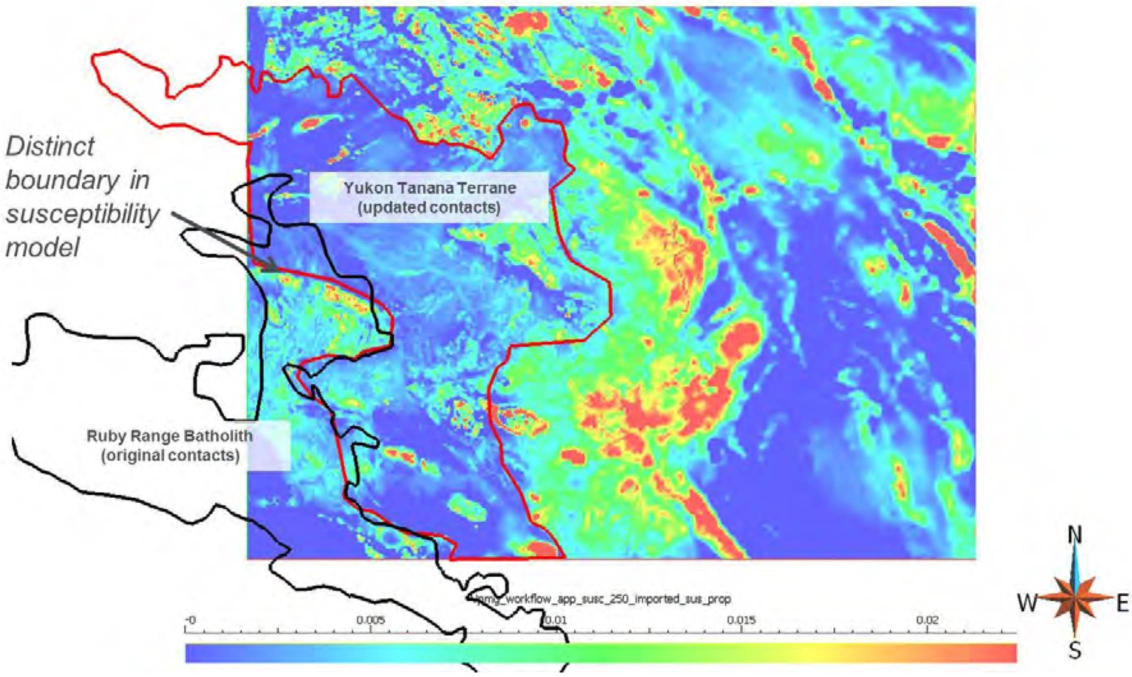

Figure 21. Mapped Ruby Range Batholith contacts with updated Yukon-Tanana terrane contacts overlain on Yukon Plateau apparent susceptibility model. Modelling suggests that these rocks are characterized by low densities and variable susceptibilities. Although it appears that low susceptibility Yukon-Tanana terrane exists where Ruby Range rocks have been mapped in the west-central area of interest, Ruby Range rocks are confirmed to occur there. Ruby Range contacts are otherwise generally kept as mapped.

3.3.1. Updates to geologic cross-sections

The geologic cross sections were updated to reflect the new interpretation of the geology at depth inferred from analysis of gravity and magnetic data. Most of the re-interpretations of geology occur in the western project area where geology has been mapped in less detail (compared to the Whitehorse trough). In general, where lows exist in the density models, intrusive bodies (Aishihik Batholith, Ruby Range Batholith, and Whitehorse Plutonic Suite) were interpreted to exist. Where densities were calculated to be high, and accompanied by low susceptibilities, Yukon-Tanana terrane, or Stikine volcanic rocks were interpreted at depth. After updating the three deep cross-sections which span the project area, three additional cross-sections were built. These simple cross-sections fill gaps in the model volume so that the deep geology can be more easily correlated (Figure 22).

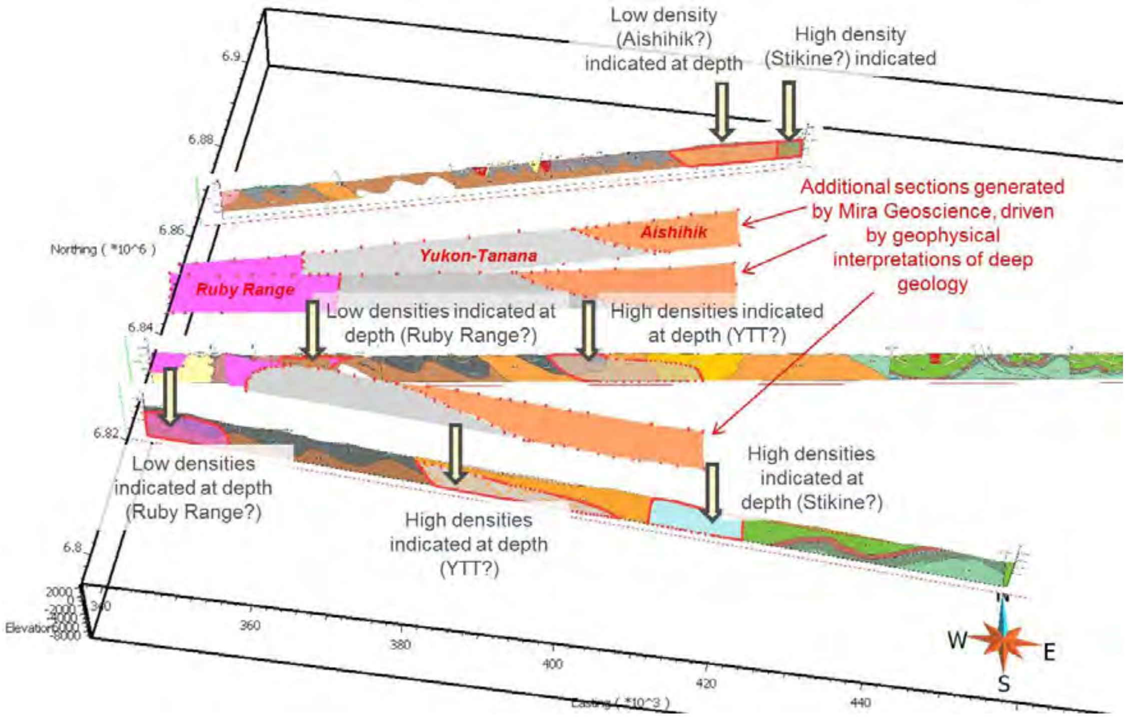

Figure 22. Updates to geological sections based on geophysical interpretations, and three additional cross-sections with interpreted deep distribution of Ruby Range Batholith, Yukon-Tanana terrane, and Aishihik Batholith rocks.

3.3.2. Summary of geologic interpretations and implications for constrained inversion modelling

A comparison between geology and the geophysical data used in this study shows that regional gravity (and apparent density) is the best dataset for identification of geologic units at depth: intrusive rocks are generally consistently low density, Yukon Tanana terrane rocks are high density, and Stikine volcanic stratigraphy is high density. This understanding has informed the geophysical workflow used to interpret the gravity and magnetic data. Gravity inversions have been focused on to define the distribution, and to model contacts of density-distinct units at depth, specifically identifying relationships between intrusive rocks and Yukon-Tanana terrane, and intrusive rocks and volcanic Stikine rocks.

Although some units have characteristic magnetic susceptibilities which may allow identification (for example Stikine volcanics are thought to be generally high susceptibility, while Yukon-Tanana terrane and Laberge sedimentary rocks are low susceptibility), density distinctions can already identify these units. Additionally, intrusives and onlapping young volcanic rocks are very heterogeneous magnetically, making these units challenging to model as coherent bodies based on magnetics. The majority of magnetic inversion modelling is therefore saved until a later stage to add heterogeneity to these units once gravity modelling has defined their 3D extents.

From an assessment of the physical property contrasts and the initial geophysical interpretations, it was concluded that sixteen geologic units would be modelled. Figure 23 is a schematic diagram showing the distinguishing geophysical contrasts that will allow modelling of the 15 units plus a ‘ghost’ basement (required for inversion). Table 2 summarizes generalized rock property characteristics for each geologic unit.

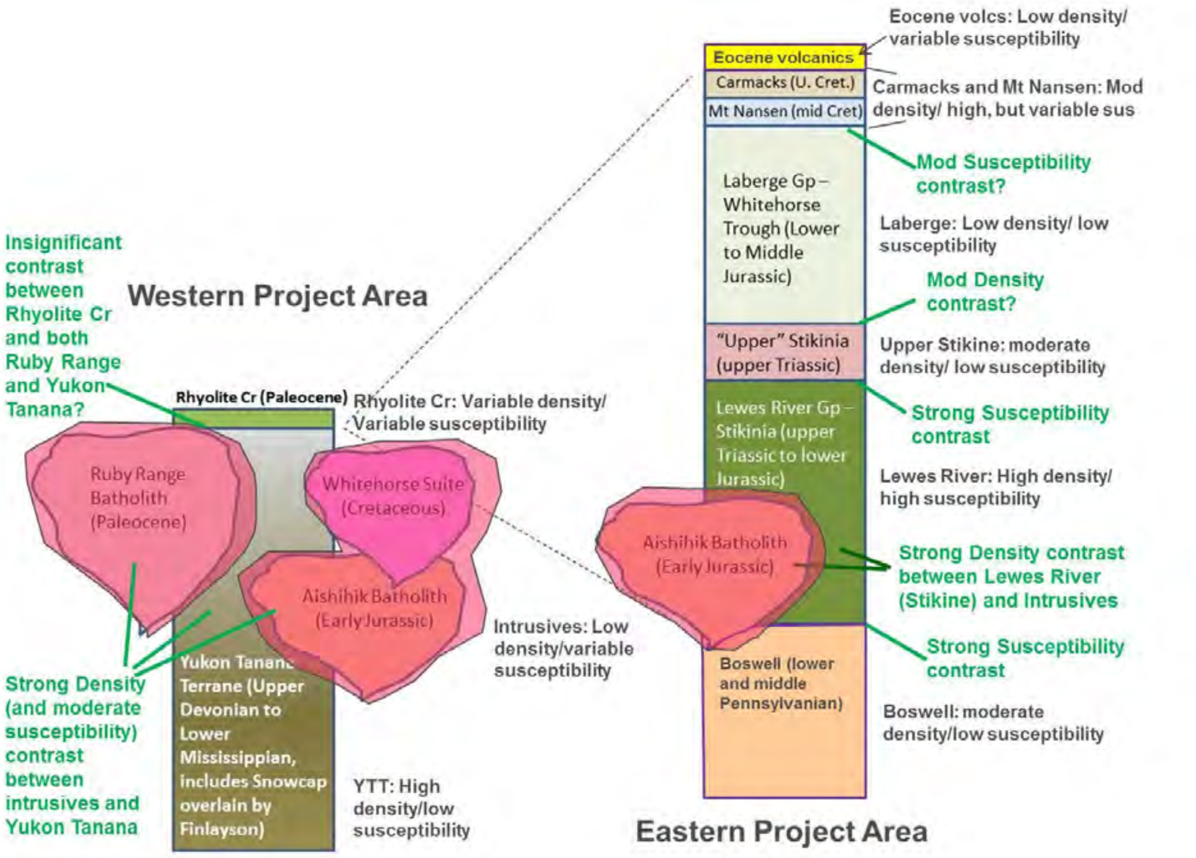

Figure 23. Updates to geological sections based on geophysical interpretations, and three additional cross-sections with interpreted deep distribution of Ruby Range Batholith, Yukon Tanana terrane, and Aishihik Batholith rocks.

Table 2. Summary of generalized rock property characteristics for each geologic unit.

3D Model Geologic Domain Name	Density	Susceptibility
Rhyolite Creek Volcanics	low	low
Eocene Volcanics	low	high/variable
Carmacks Volcanics	moderate	high/variable
Gabbro (Carmacks age)	moderate	high/variable
Mt. Nansen Volcanics	moderate	high/variable
Laberge	low	low
Upper Stikine	low to moderate	low
Stikine	high	high/variable
Boswell	moderate	low
Whitehorse Suite	low to moderate	high/variable
Aishihik (+Long Lake) Batholith	low	high/variable
McGregor Pluton	low	high/variable
Tatchun Batholith	low	high/variable
Ruby Range Batholith	low	high/variable
Yukon-Tanana terrane	high	low

3.4. 3D modelling using SKUA and Sparse in GOCAD

3D model construction for the Whitehorse trough – Yukon-Tanana terrane project area was approached using two different 3D modelling methods. For quick and geometrically accurate modelling of the Whitehorse trough, SKUA, an implicit modelling application for GOCAD, was used. SKUA is optimally used where stratigraphy is well-defined and generally conformable, and is well-suited to modelling the stratigraphic layers within the Whitehorse trough.

The remaining model volume is quickly built up using GOCAD's Sparse parametric modelling application. Sparse uses structural and geological data from surface maps and cross-sections, and extends this information into the surrounding volume to build 3D geological bodies that are consistent with this information. Structural measurements collected at geological contacts will also be honored if incorporated. The Sparse modelling tool was used effectively to model the various batholiths and plutons within the relatively coherent Yukon-Tanana terrane, and the Stikine and Boswell volcanic assemblages. It was also used to model the younger, thin volcanic units overlying the older volcanic and metamorphic terranes in the project area.

3.4.1. SKUA modelling of the Whitehorse trough

SKUA software was used to build the 3D geologic surfaces representing the stratigraphy of the Whitehorse trough. Three geologic domains were focused on at this stage: the deep Stikine volcanic rocks, the upper sedimentary rocks of the Stikine (referred to here as ‘upper Stikine’), and the overlying Laberge Group sedimentary rocks.

The first stage of SKUA modelling involves establishing a stratigraphy. Contacts must be defined as conformable, unconformable, or intrusive. The stratigraphic rules are adhered to during the modelling process. To encourage underlying Stikine stratigraphy to mimic the overlying Triassic and Jurassic sedimentary units, it was considered to be a conformable unit.

The second step in the SKUA modelling process is to develop the structural framework which will contain the stratigraphy to be modelled. A structural framework, or network, was built based on the distribution of major mapped faults at surface and in cross-section. The Tatchun fault marks the eastern boundary of the Whitehorse trough SKUA model, and the Braeburn fault, plus two unnamed faults bounding Carmacks Group volcanic rocks at the western margin of the trough, mark the western boundary (Figure 24).

Next, geologic contacts were digitized from surface maps and cross-sections. Two contacts were required to model the three stratigraphic units of interest in the trough: the contact between the Laberge Group and the upper Stikine (base of Laberge Group) and the contact between the upper Stikine and the Stikine (base of the upper Stikine). Additional parallel sections, or grip frames, were built to guide the modelling (Figure 25). The implicit modelling attempts to best fit all of the supplied constraints with abrupt discontinuities permitted at faults (Figure 26). Some iteration was required during construction of the Whitehorse trough model, with additional interpolated constraints added to encourage in places tighter folding, or thinning or thickening of units. Stratigraphic surfaces are often modelled to extend above topography and beyond the bounding faults, however the extraneous surface parts are eventually cut back against these boundaries.

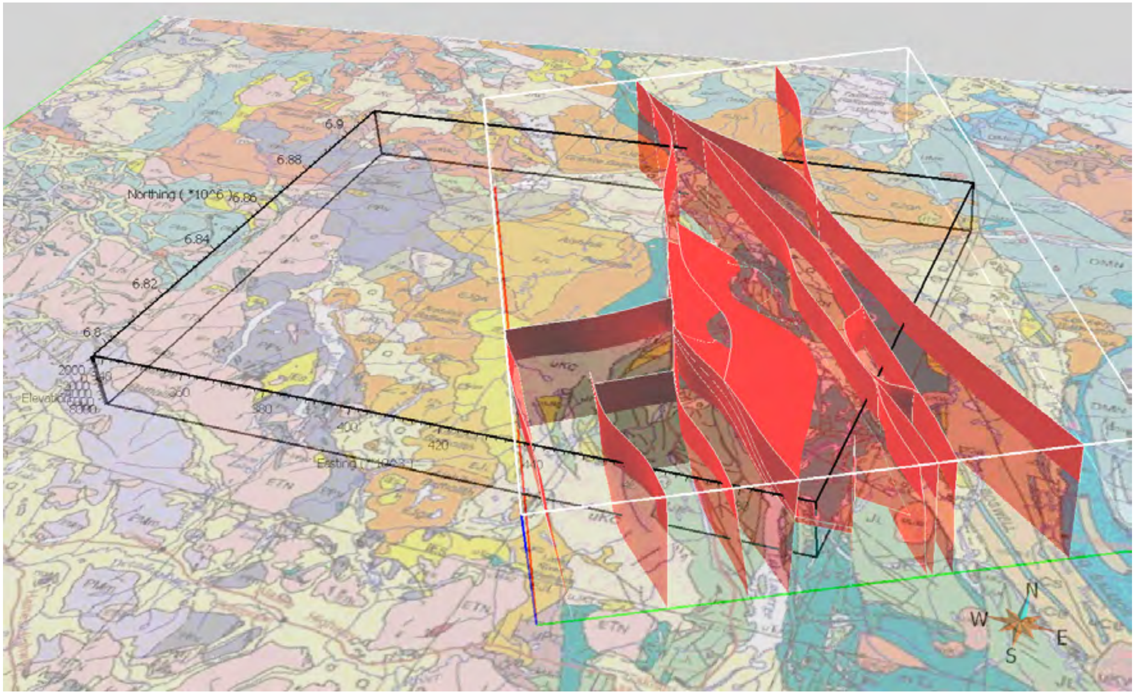

Figure 24. Volume, and fault network used for SKUA implicit modelling within the Whitehorse trough.

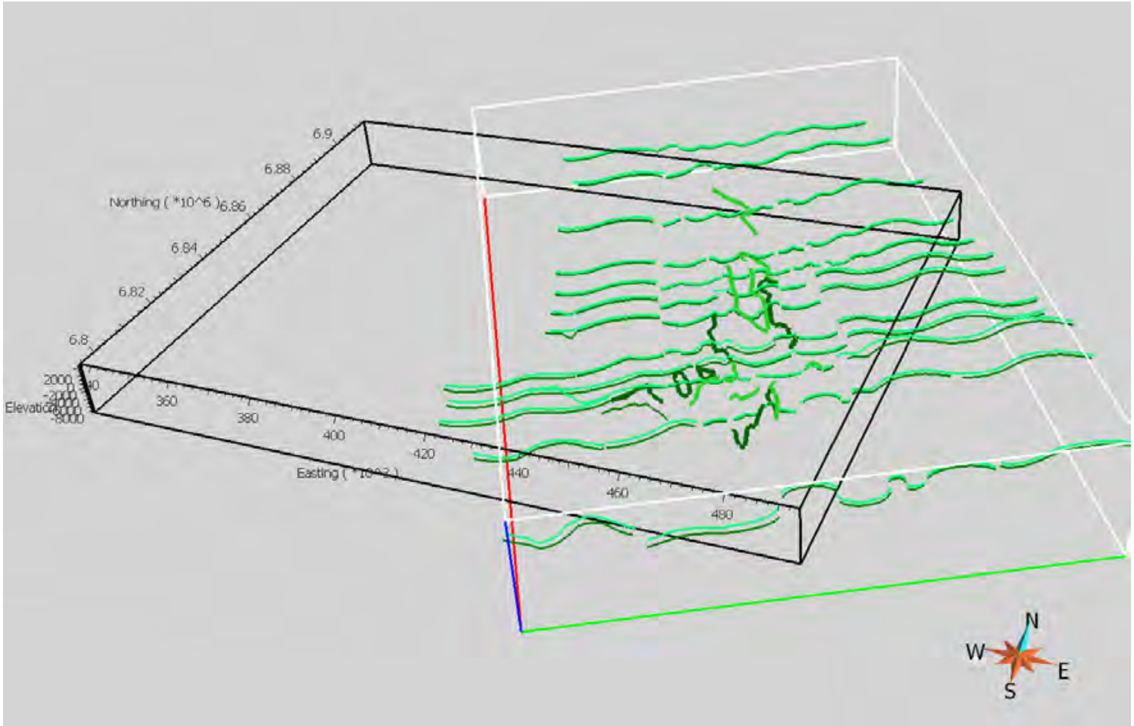

Figure 25. Curves digitized from cross sections and maps tracing the top of Stikine stratigraphy (dark green) and top of upper Stikine stratigraphy/bottom of Laberge Group (light green).

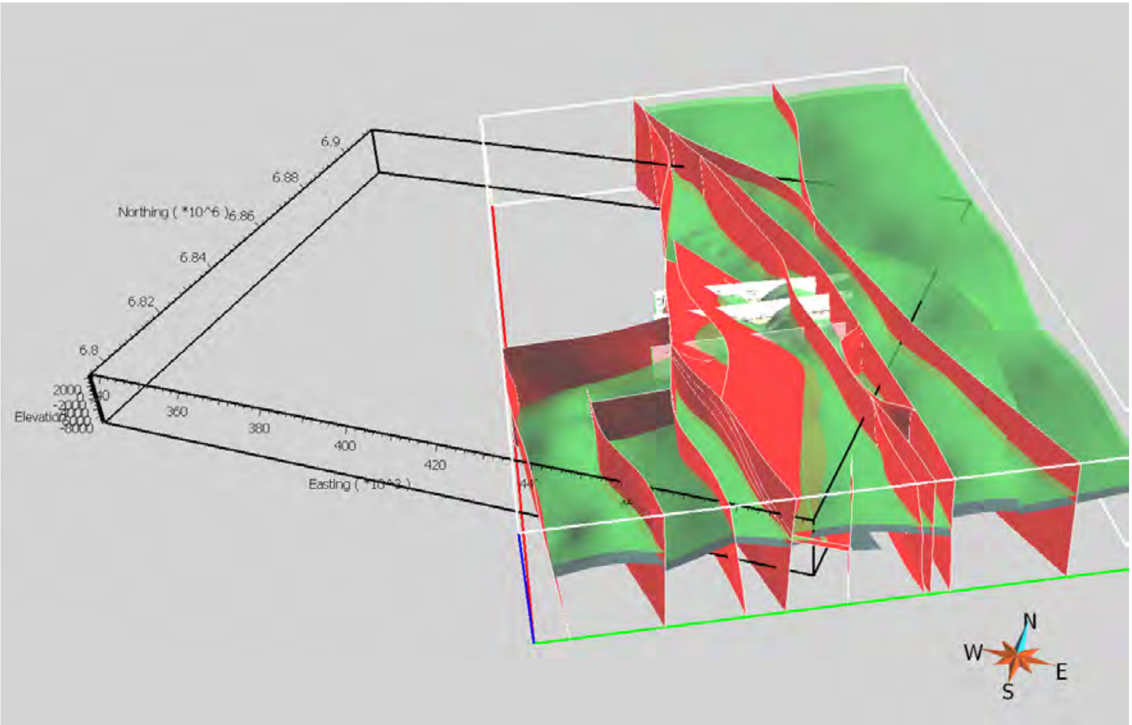

Figure 26. Surfaces derived from SKUA implicit modelling constrained by fault network and digitized curves. Surfaces are later cut by any overprinting geology.

3.4.2. Sparse modelling of batholiths and surficial volcanic units

The remaining parts of the 3D model are quickly and easily built using GOCAD's Sparse Workflow, which allows construction via parametric modelling of geologic bodies within more massive blocks. This tool is ideal for modelling intrusive bodies. Sparse allows various types of structural data to be incorporated, and surfaces can be required to honor these data. All of the plutons and batholiths within the project area were modelled using Sparse. Geologic map contacts were digitized, and strikes and dips entered where known or inferred to direct the trajectory of the surfaces.

The Aishihik Batholith, Whitehorse Suite Intrusions and Ruby Range Batholith were all modelled as geobodies sitting within the Yukon-Tanana terrane (Figure 27). The Aishihik Batholith was interpreted to be shallower at its Western edge and deeper to the east, based on interpretations from gravity data. The Ruby Range Batholith was extended vertically downward to the base of the geologic model. The McGregor pluton was modelled to sit within Stikine volcanic rocks, and modelled vertically to depth since no depth information was available. The Tatchun Batholith was modeled to sit within the Boswell volcanic and sedimentary assemblage. A depth was estimated based on previously interpreted seismic data.

More recent, surficial volcanic rocks, overlying parts of the project area, were also modelled using Sparse. These units include the Carmacks, Mount Nansen, Eocene Skukum, and Rhyolite Creek volcanics (Figure 28).

Once all geologic surfaces were generated, a geologic block model could be created (Figure 29).

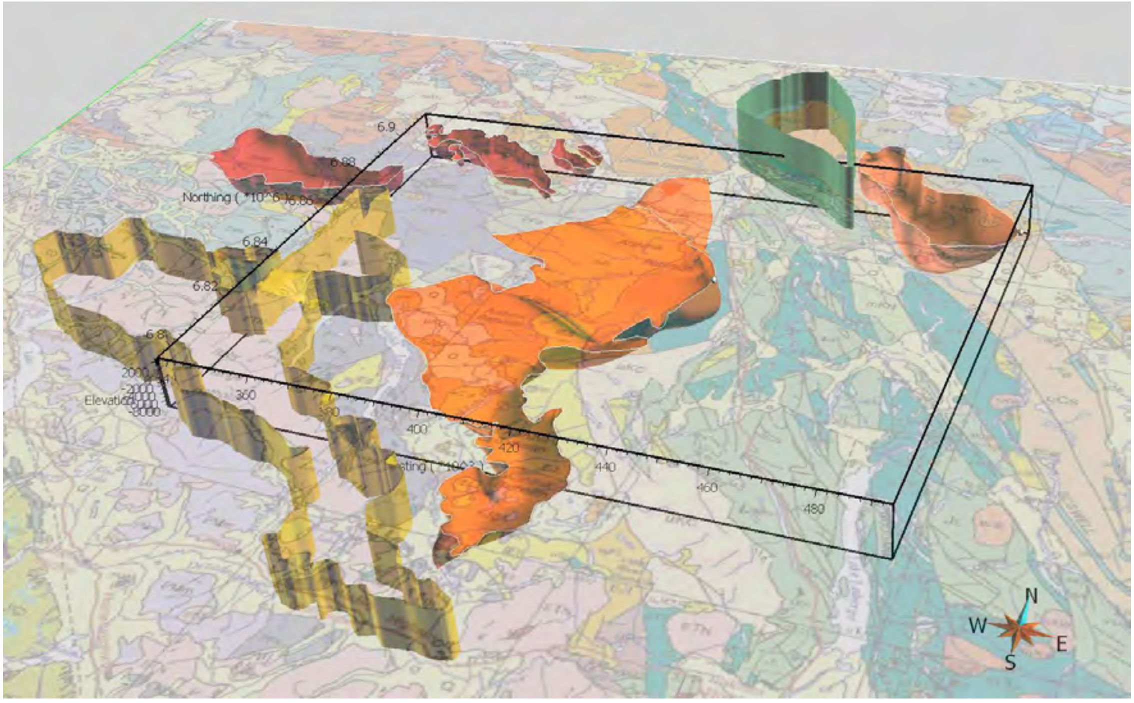

Figure 27. Intrusive surfaces generated using GOCAD's Sparse tools. Whitehorse Suite (red), Aishihik Batholith (orange), and Tatchun Batholith (pink) are modelled with given depth extents, whereas Ruby Range Batholith (yellow), and McGregor Pluton (blue) are extended vertically to depth below the model volume.

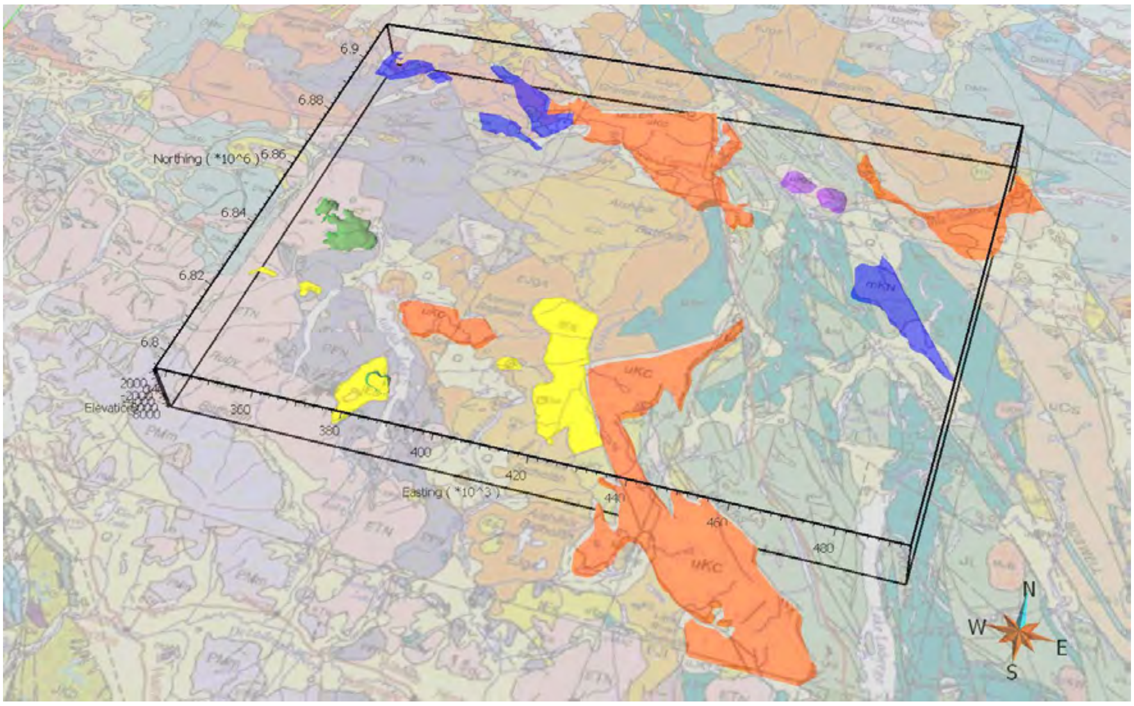

Figure 28. Thin, surficial volcanic units generated using GOCAD's Sparse tools. Surfaces are built from mapped contacts and cross-section information.

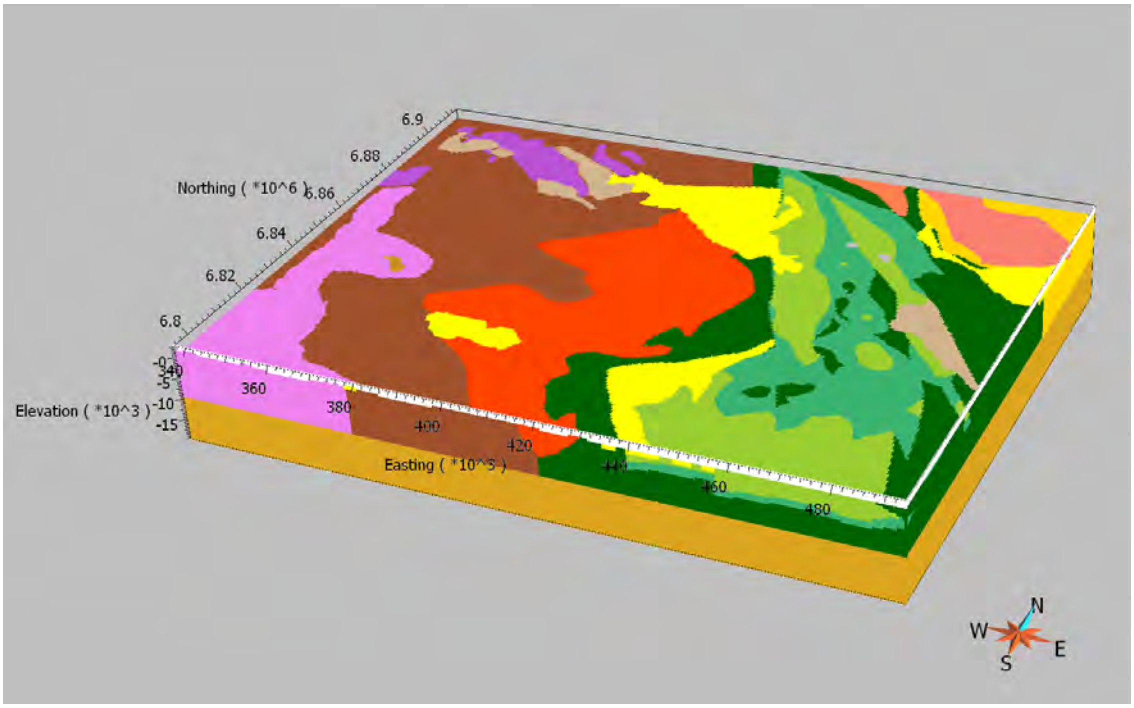

Figure 29. Rasterized starting geologic model built from SKUA and Sparse surfaces. Top view is at 250 m elevation.

4. Potential fields inversion and modelling methodology

4.1. Introduction

A key goal of this project is to test current understanding of geology against available geophysical data, and to update the existing geologic model so that it is consistent with observed and modelled geophysical data. Areas where geology and geophysical data cannot be reconciled suggest there are unaccounted for or buried geologic bodies, that locations and orientations of geologic contacts should be reinterpreted, or that the physical property values for geologic domains may not be fully understood. Geological domains exhibiting anomalous inverted density and susceptibility relative to the expected rock property values may have implications for mineral exploration, signifying overprinting metamorphism or alteration. Completing integrated 3D geologic and geophysical modelling helps to quickly identify inconsistencies between geologic and geophysical information and evaluate the specific updates to geology that would be required to fit the geophysics. Modelling helps improve our broad understanding of stratigraphy and tectonics in the project area, and directs us to anomalous areas of interest.

In this project, the VPmg 3D potential fields forward modelling and inversion software (Fullagar et al., 2000, 2004, 2007, 2008) was used for both gravity and magnetic modelling (see Appendix D for additional software details). Typically inversion is an iterative process: a starting 3D geologic model is adjusted, during each iteration, to improve the fit to the observed data. Geophysical interpretation and inversion is ambiguous, and is best completed in tight integration with geological constraints.

In this project, each domain of the initial 3D geologic model was attributed with best estimate density and susceptibility to create a starting model for potential field modelling and inversion. VPmg permits a variety of inversion styles to update the geometry of geologic domains as well as to update the density or susceptibility values within the domains. Both geometry and physical property (homogeneous and heterogeneous) inversion methods were applied to refine the 3D geologic model for the northern Whitehorse trough and neighbouring Yukon-Tanana terrane.

VPmg inversion modelling of Yukon potential field data revealed that elements of the initial intepreted 3D geological model were not consistent with observed geophysics, and that either the geometry of the model, or the density or susceptibility reference values needed to be changed. UBC-GIF potential field inversion codes were used to generate an alternate 3D magnetic susceptibility model which can act as a guide for re-interpreting subsurface geology and physical properties. The UBC-GIF models here are less strictly constrained than VPmg models, primarily using surface geology as a guide.

4.2. VPmg potential field inversion modelling

This section describes the VPmg geologically constrained modelling done in this project, detailing model preparation, model updates, forward modelling and inversion as applied to the Whitehorse trough – Yukon-Tanana terrane model.

4.2.1. Strategy

This project focused on the geological framework and explaining the potential field responses initially in terms of homogeneous density and susceptibility assigned to the geological domains. This approach tests the existing understanding of rock properties assigned to the geological domains and then provides an opportunity to refine that understanding in accordance with the potential field survey data. The strategy of adjusting the model domain properties first using homogeneous physical property values typically provides a better starting model for follow-on domain geometry adjustment and heterogeneous property inversion.

Once the bulk properties of the geological domains are optimized, geologically constrained geometry inversion is applied to update geological boundaries, while heterogeneous property inversion solves for 3D density and susceptibility variations within the geological domains.

VPmg homogeneous property, heterogeneous property, and geometry inversions are described in Appendix E.

The regional gravity data was the primary dataset inverted to update geologic geometries during the iterative VPmg modelling process. Magnetic inversions used gravity-updated models as constraints, and were primarily run to identify susceptibility heterogeneities within the various geologic domains.

The GOCAD Mining Suite served as a data repository, and platform for running the inversions (including data and model preparation, imposition of constraints, and assessment of inversion results).

4.2.1. Data

The data used for VPmg inversion are the same that were used for previous apparent density and apparent susceptibility modelling.

Regional Geological Survey of Canada Complete Bouguer gravity data, and the higher resolution Aurora Geosciences Complete Bouguer gravity data were gridded at 500 m, and draped 1 m above the topographic surface for use in the inversion process.

Geological Survey of Canada data were used in initial VPmg inversion stages, with Aurora survey gravity data merged and used at later stages to extract additional detail.

Yukon Plateau magnetic data, gridded at 500 m, and draped 100 m above topography were used for VPmg magnetic inversions.

4.2.2. Processing

The inversion stages are numbered and can be cross-referenced to steps portrayed in Figures 30 and 32.

VPmg inversion preparation

Step 1. *VPmg starting geologic model*. The 3D Yukon Tanana terrane - Whitehorse trough geology model was used as the basis for geologically constrained inversions. A starting block model of 500 x 500 x 500 m cells was generated from SKUA and Sparse geologic surfaces (Figure 31a). For input into VPmg applications, the block model is converted into a prism model, where geological contacts define cell boundaries within the vertical prisms (see Appendix E). Later, the geological domains within the model can be subdivided vertically to invert for full 3D property variation. Model cells constituting the geological domains of the starting model were assigned density and susceptibility values based on statistical assessment of the Geological Survey of Canada physical property measurements from the southern Yukon and are summarised in Table 1. The starting 3D density model is shown in Figure 31b.

Step 2. *Forward modelling*, using constant (homogeneous) gravity and magnetic susceptibility values within each modelled geologic domain (values from Table 1), is completed to assess the integrity of the Yukon Tanana terrane – Whitehorse trough geological starting model. The correspondence between the observed field response, and that computed from the starting 3D geologic model was reasonable, but there was scope to further reduce the misfit by updating geologic surfaces and reference density and susceptibility values, and by allowing intra-domain density and susceptibility variations. The subsequent modelling steps are outlined below.

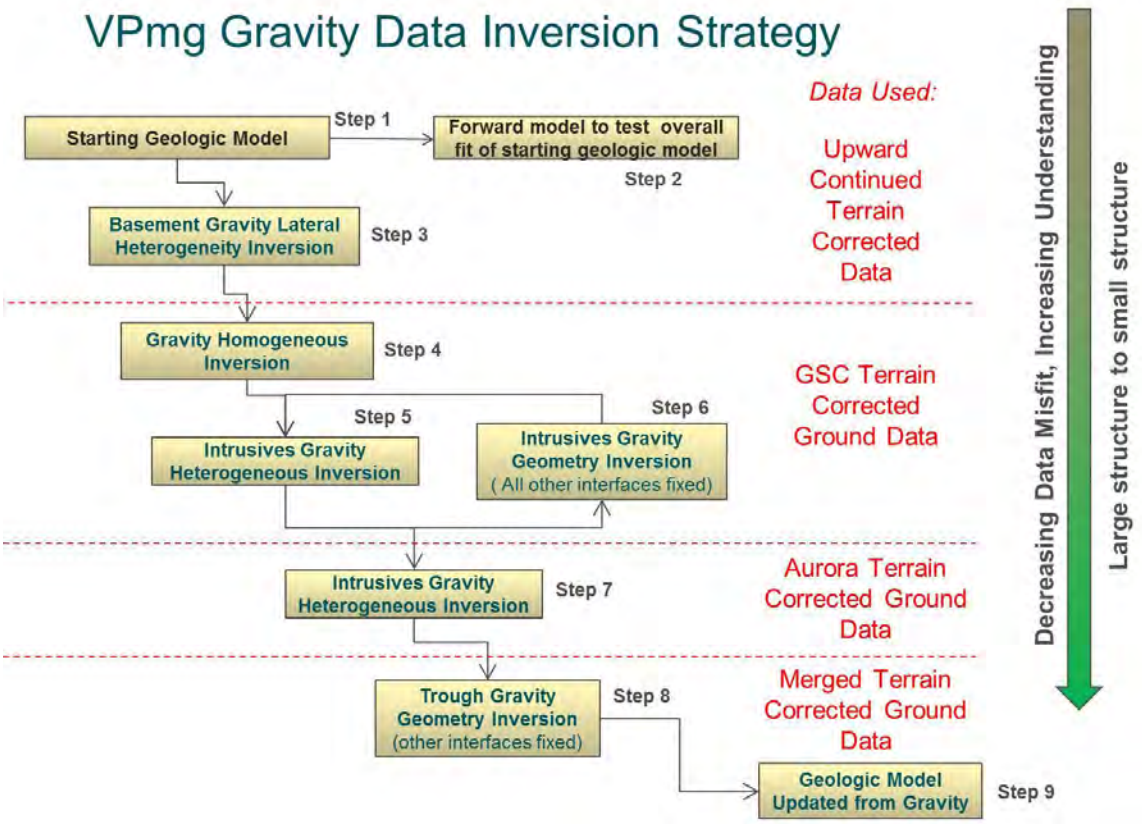

Figure 30. Workflow for geologically constrained gravity inversion modelling. Iterative steps are shown as loops. Data used in each modelling step is depicted in red.

Gravity inversions

Step 3. *Laterally heterogeneous gravity inversion* of upward continued regional gravity data was completed to generate first pass density models to account for regional-scale gradients. Lateral (apparent) density variations beneath the extent of the geological model were modelled to account for the regional gravity response. This deep 'basement' density model exhibits densities which vary laterally, but not vertically (Figure 31c).

Step 4. *Homogeneous gravity inversion* takes into consideration the previous deep basement density variations, and finds a best fitting constant density value for each geologic domain in the 3D geologic model, subject to respecting a reference density value and density bounds that were set for each domain. The goal is to optimize the starting density values for ensuing stages of inversion that then modify the geometry of geologic features and add heterogeneity (Figure 31d).

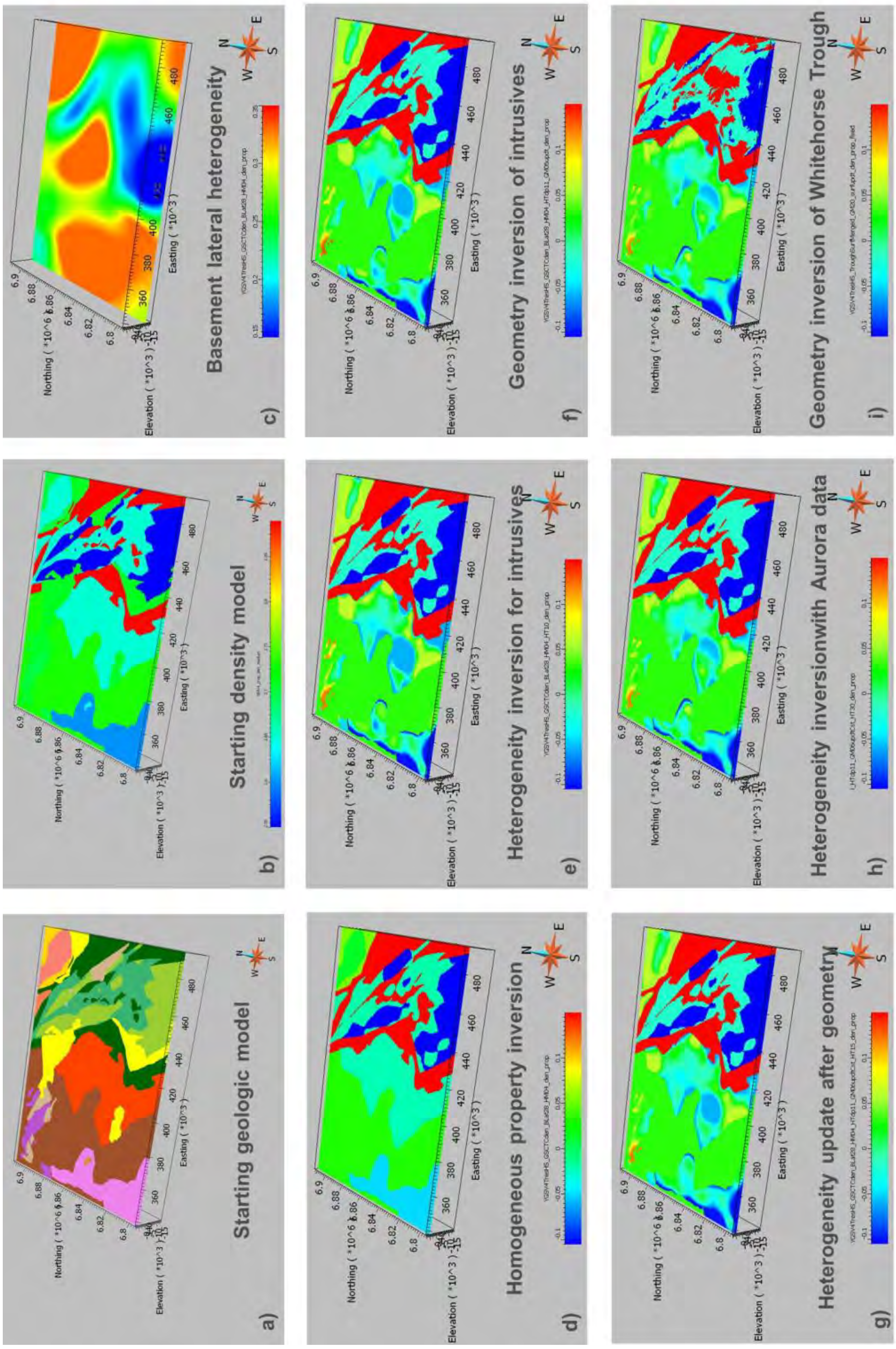

Figure 31. Horizontal slices through VPmg gravity inversion models. Images a) to i) show the various modelling stages associated with iterative VPmg inversion modelling of GSC and Aurora gravity data.

Step 5. *Heterogeneous gravity inversion* was completed using regional GSC gravity data to model heterogeneity within intrusive units (Figure 31e). Updated homogeneous densities from Step 4 were used as starting reference values for this stage of modelling. In a petrophysical sense, intrusive units are thought to be the most heterogeneous units within the project area, and heterogeneity inversion was applied to account for additional variability in the gravity data associated with these geologic domains.

Step 6. *Geometry gravity inversions* are performed on regional GSC gravity data to automatically update geologic domains representing intrusive units situated within the Yukon-Tanana terrane, and Stikine and Boswell stratigraphy (Figure 31f). Significant density contrasts are required between intrusive units and host rocks for geometric inversion to be most effective. Two types of geometry inversions were employed. The first type of geometry inversion works with a starting 'zero thickness' layer which is assigned a density range, and expands to form a 'geo-body' that is consistent with observed gravity data. The second geometry inversion involved unlocking existing geologic contacts between geologic domains and allowing these surfaces to move in 3D in order to improve the fit of the model to the observed gravity data. Several iterations were completed whereby geometry was updated, followed by heterogeneous inversion to update the distribution of density within intrusive domains (Figure 31g).

Step 7. *An additional heterogeneous inversion* was completed using higher resolution Aurora gravity data merged with GSC data (Figure 31h). This was performed to resolve in more detail density variability within intrusive units.

Step 8. *Geometry inversions* were done using merged regional GSC gravity data and Aurora data to update Whitehorse trough stratigraphy (Figure 31i). The 'bottom of Laberge' and 'bottom of upper Stikine' surfaces were unlocked and allowed to move to improve fitting of observed gravity data, while all other surfaces within the 3D model remained locked and stationary.

Magnetic inversions

Step 9. The *starting model for the magnetic inversions* is the 3D geologic model with geologic contacts updated from gravity inversion modelling (Figure 33a). The various geologic domains are populated with magnetic susceptibility reference values and are assigned allowable ranges derived from physical property statistics calculated or estimated for each of the geologic units present (Figure 33b).

Step 10. *Laterally heterogeneous magnetic inversion* of upward continued regional magnetic data was completed to generate first pass magnetic susceptibility models to account for regional-scale gradients. Lateral (apparent) susceptibility variations beneath the extent of the geological model were modelled to account for the regional magnetic response. This deep 'basement' susceptibility model exhibits susceptibilities which vary laterally, but not vertically (Figure 31c).

Step 11. *Homogeneous magnetic inversion* takes into consideration the previous deep basement magnetic susceptibility variations, and finds a best fitting constant susceptibility value for each geologic domain, subject to respecting a reference susceptibility value and susceptibility bounds that were set for each domain. The goal is to optimize the starting susceptibility values for ensuing stages of inversion that will modify geometry of geologic features and add heterogeneity (Figure 33d).

Step 12. *Heterogeneous magnetic inversion* was completed using Yukon Plateau magnetic data to model heterogeneity within intrusive units (Figure 33e). Updated homogeneous susceptibilities from Step 11 were used as starting reference values for this stage of modelling. Geologic surfaces updated from gravity modelling remain unmodified, and only physical property values vary. Magnetic data has indicated that many of the modelled units, while having generally consistent densities, are very magnetically heterogeneous. Heterogeneity inversion was applied to account for variability in the magnetic data associated with each of the geologic domains.

Step 13. *Geometry and heterogeneous magnetic inversions* were done to update the geometry of thin surficial volcanic units, which are magnetically heterogeneous, but generally high susceptibility, providing a relatively good contrast with most underlying units.

Step 14. *Heterogeneous magnetic inversion* was completed for remaining geologic units in a step by step fashion (Figure 33f-i) to provide additional geological control on how the inversion reconciles the unexplained magnetic response. Geologic surfaces updated from previous gravity inversions remain unmodified, and only physical property values were allowed to vary. In turn, the Yukon-Tanana terrane, Stikine stratigraphy, Boswell formation, and Whitehorse trough stratigraphy were modelled for heterogeneity. A final step inverts all units at once for heterogeneity with combined results from previous step-wise heterogeneity inversions being used as a reference model.

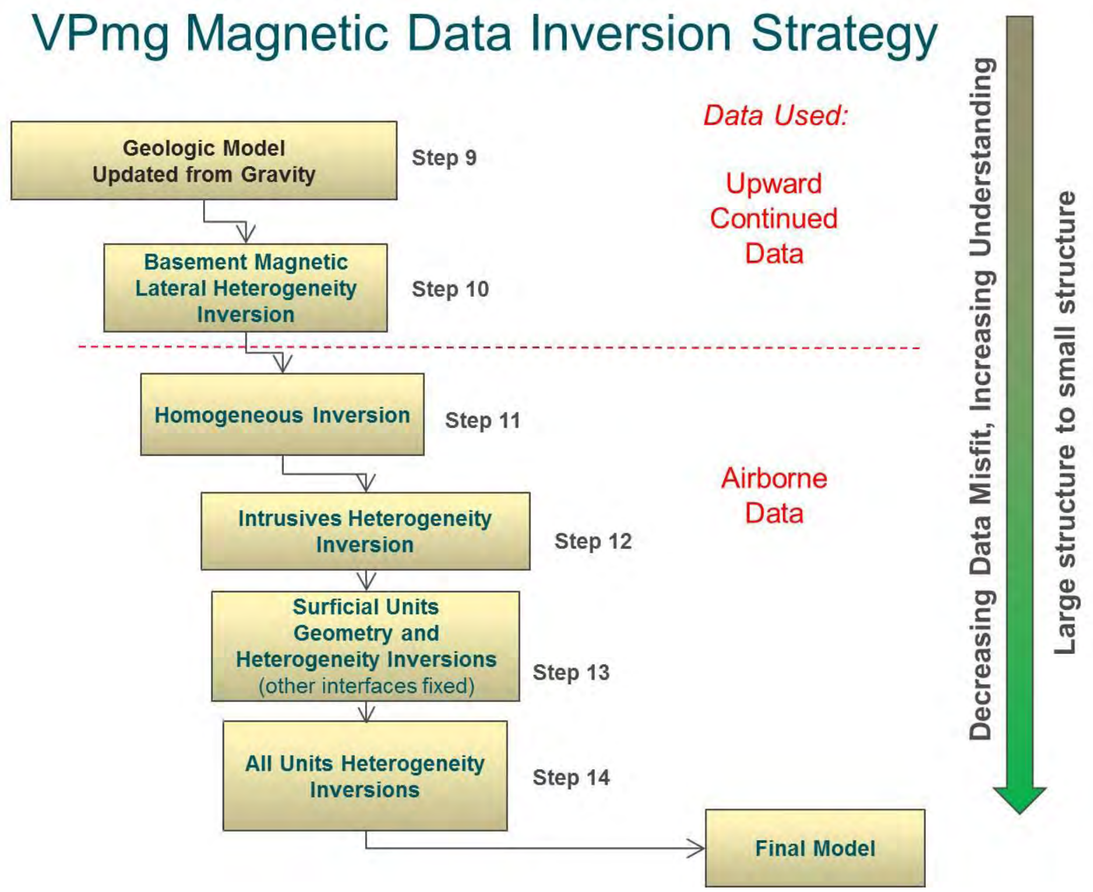

Figure 32. Workflow for geologically constrained magnetic inversion modelling. Data used in each modelling step is depicted in red.

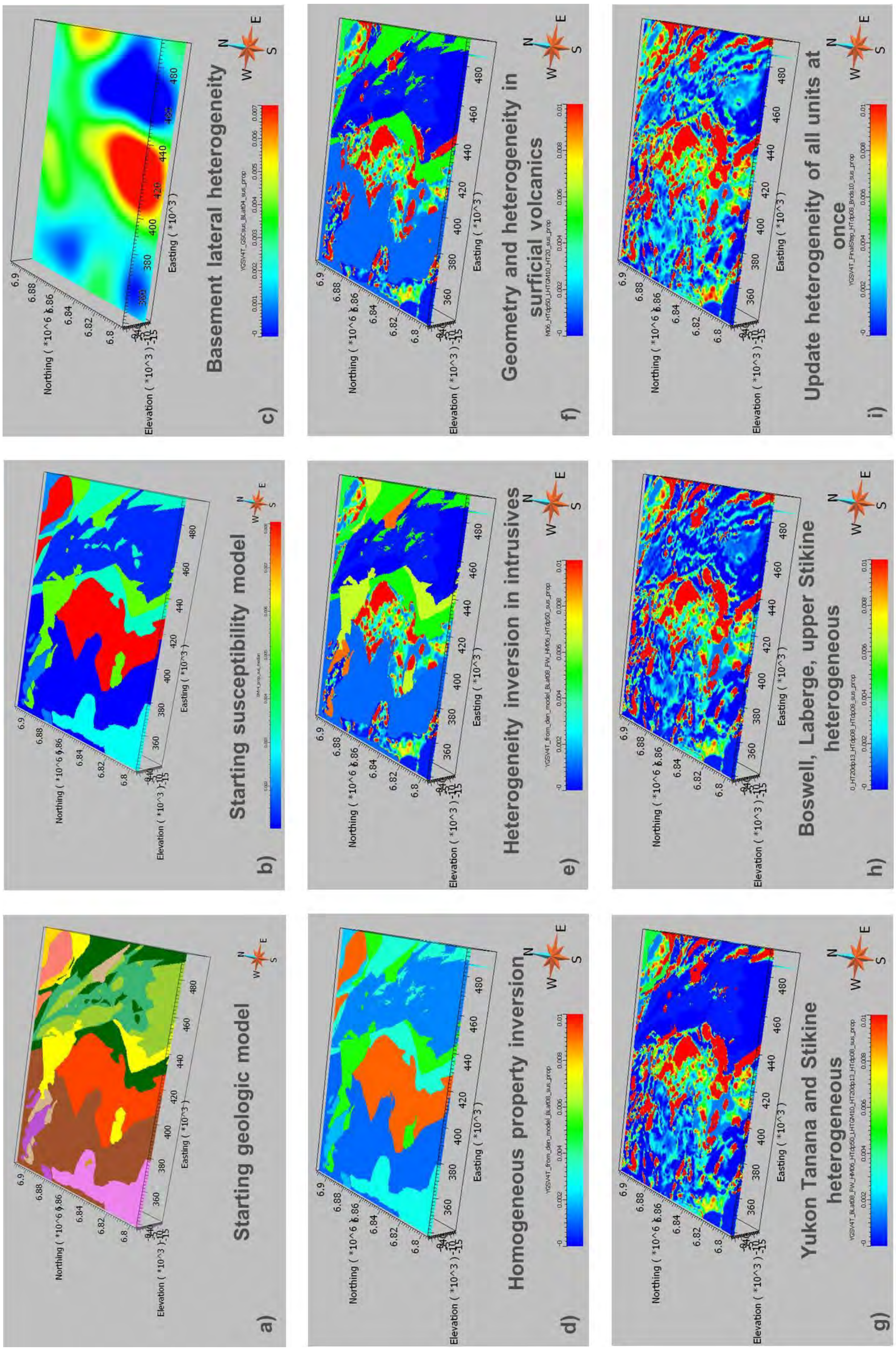

Figure 33. Horizontal slices through VPmg magnetic inversion models. Images a) to i) show the various modelling stages associated with iterative VPmg magnetic modelling of Yukon Plateau magnetic data.

Observed and predicted gravity data are shown in Figure 34, and observed and predicted magnetic data are shown in Figure 35.

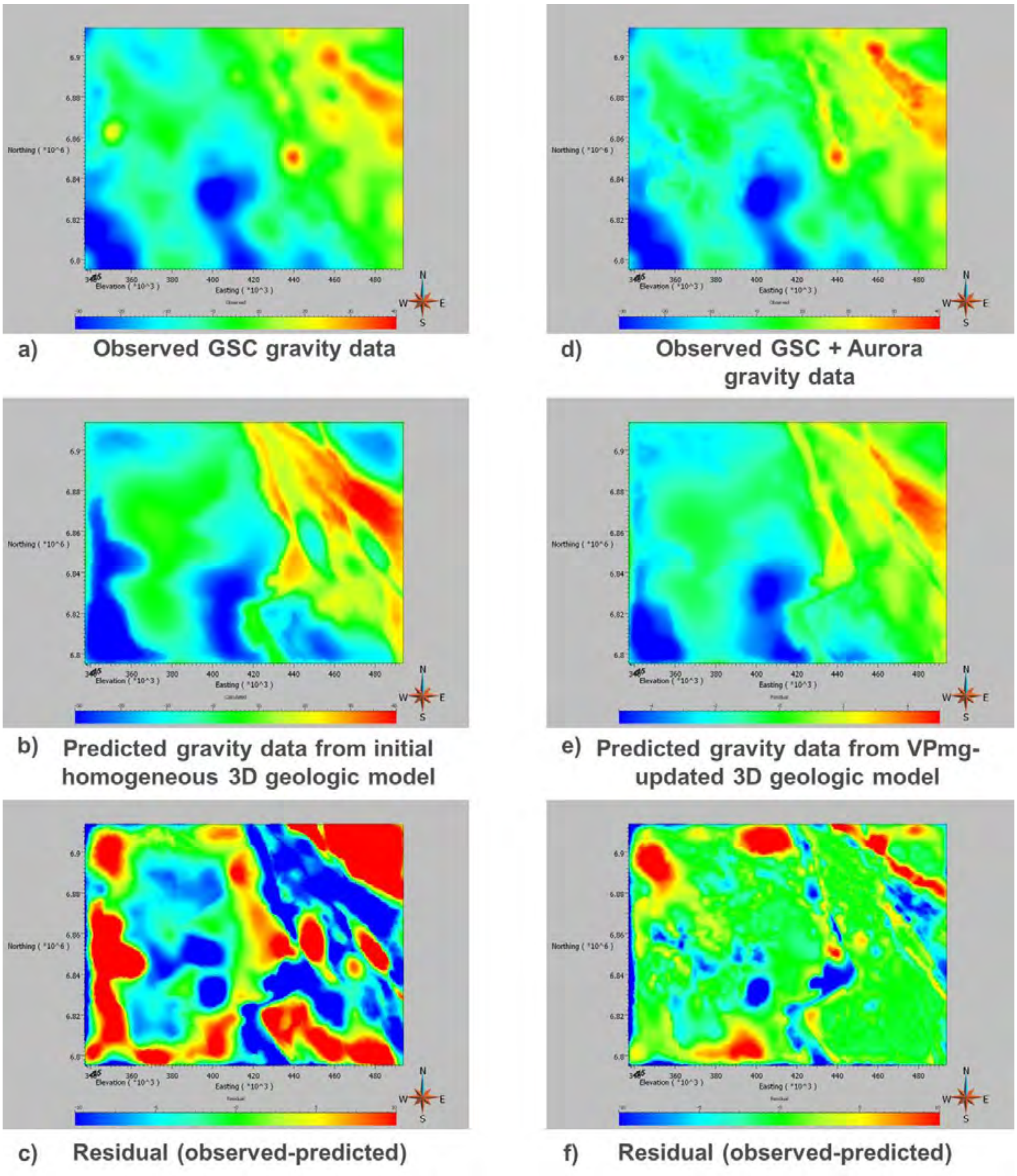

Figure 34. Observed and predicted gravity data based on homogeneous 3D geologic model prior to updates from VPmg inversions (a-c), and after VPmg inversion updates (d-f). Small residuals (~0 mGal, green color) indicate an improved fit of observed gravity data.

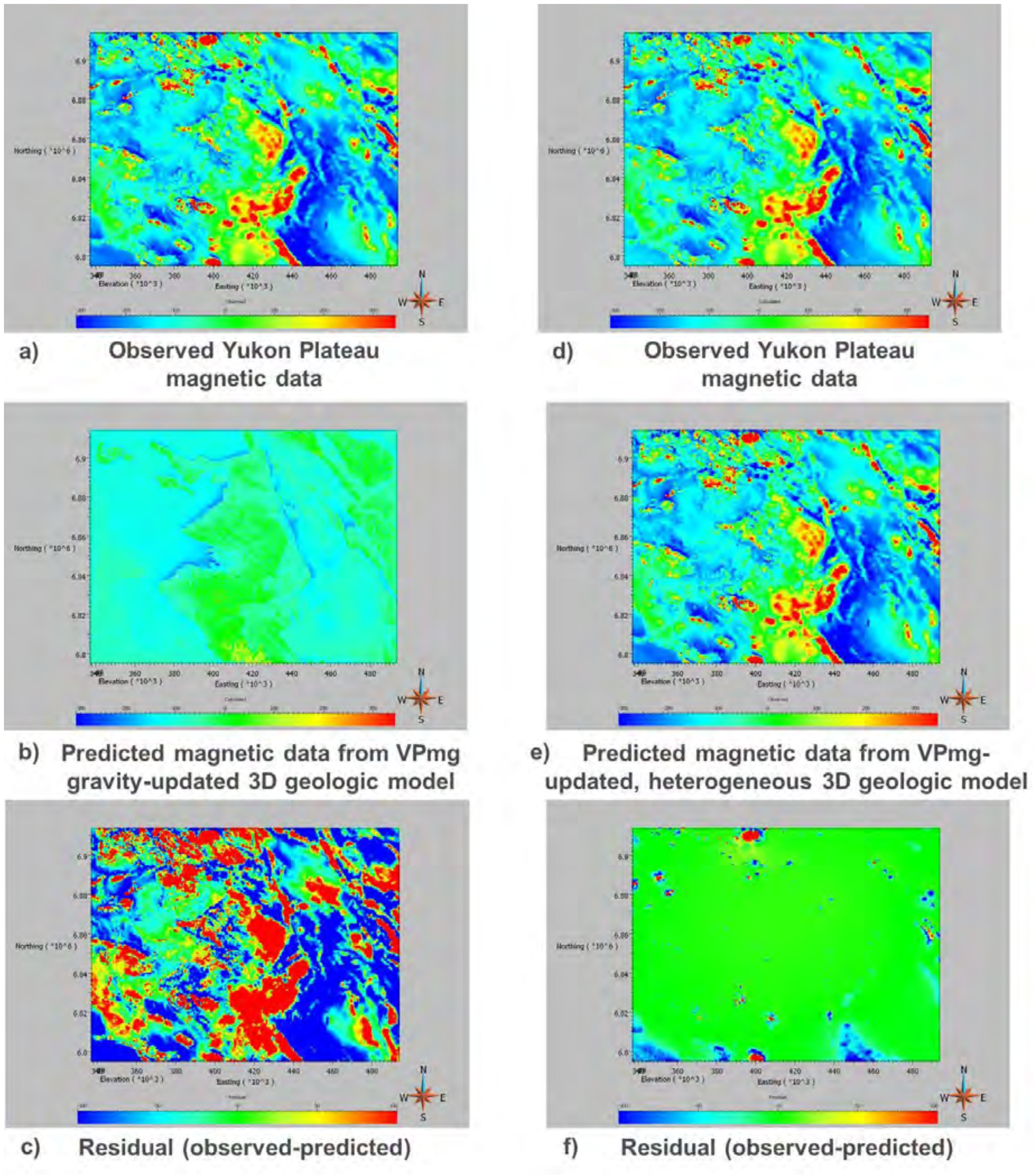

Figure 35. Observed and predicted magnetic data using VPmg gravity-updated 3D geologic model (a-c), and after VPmg magnetic inversion updates (d-f). Small residuals (~0 nT, green color) indicate an improved fit of observed magnetic data.

The product of a VPmg inversion is a geological model that has been updated to improve the fit of the model to the observed geophysical data. Initial and final surfaces representing the various geological units modelled are shown in Figure 36.

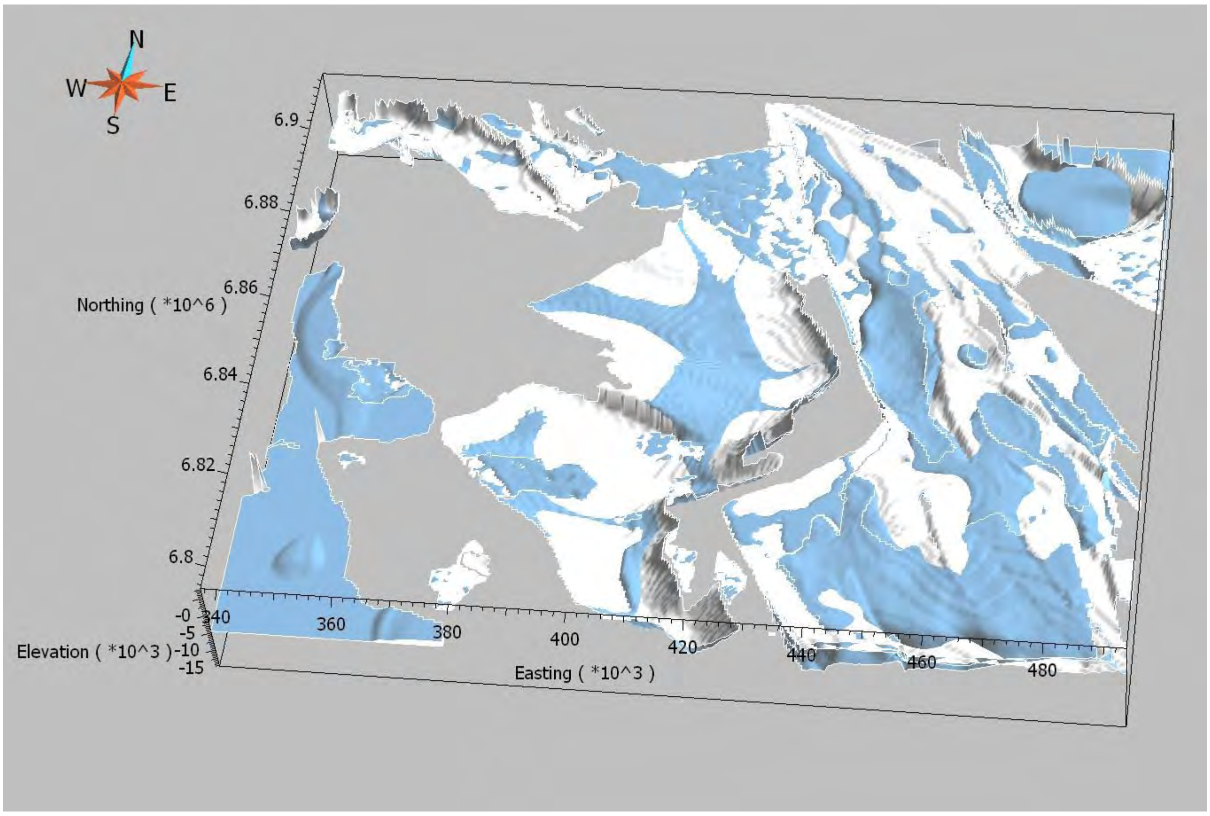

Figure 36. Initial geological surfaces shown in white, and final surfaces from VPmg modelling shown in blue. Final surfaces are exposed where the surface has moved upward relative to initial surfaces. Otherwise final surfaces remained stationary or moved downward relative to the initial surfaces. The lower contacts of the Yukon-Tanana and Stikine geologic domains are not shown since they lie at the base of the model volume. Note that irregular, spiny surface edges are artefacts of inversion grid discretization.

4.1. UBC-GIF potential field inversion modelling

VPmg inversion modelling updates an initial 3D geological model, within given physical property constraints, to make it consistent with various observed potential field data. Results of VPmg inversion also direct the geologist to areas where the geologic model is not consistent with observed geophysics, and thus indicates aspects of the model which require re-evaluation. In the case of the geologically complicated and heterogeneous Yukon-Tanana terrane – Whitehorse trough model, it was not possible within the time-frame of the project to carefully model and refine all features to fully explain the geophysical response. Certain geological units were chosen to be focused on, and their associated contacts and physical property values were updated automatically during the VPmg process. While some of the geometric and physical property updates improved the model's fit to the observed geophysical data, discrepancies remained between the geological model and the observed geophysical data. More intensive manual remodeling of various parts of the model would be required to account for the more significant discrepancies. Aishihik Batholith intrusive bodies, in particular, require an improved initial model, as they appear to extend much deeper beneath the subsurface than originally expected.

To gain a relatively quick alternate perspective of the subsurface which might guide re-interpretation of geology at depth within the project area, and focusing on magnetic bodies such as the Aishihik Batholith, UBC-GIF inversion codes (software summary in Appendix F) were used to generate a magnetic susceptibility model. This smoother, and less tightly constrained alternate magnetic susceptibility model, sheds light on general depths, shapes and physical property ranges of large scale magnetic features (primarily intrusive units). The UBC-GIF magnetic susceptibility model can be used in future work to manually update the depths and distributions of intrusive units that were modelled too shallowly in the original 3D geologic model.

This section describes UBC-GIF constrained inversion modelling, detailing model preparation, and inversion.

Inversion preparation

The UBC-GIF MAG3D (MAG3D, Li and Oldenburg, 1996) algorithm was used to invert the Yukon Plateau magnetic data. The Yukon Plateau magnetic data is the same data used in previous VPmg magnetic inversions, with data gridded at 500 m, but with a DC shift of 200 nT applied.

The original 3D magnetic susceptibility reference model, unmodified by VPmg inversion, and with 3D upper and lower susceptibility bounds used as constraints, was used as input to the MAG3D algorithm. Susceptibility values used to populate the reference and bounds models are the median, minimum and maximum susceptibility values recorded for each of the modelled geologic units, which are summarized in Table 1. The inversion algorithm will attempt to remain close to the reference value (as long as the model continues to predict the observed magnetic data) and values are forced to stay within the defined upper and lower bounds.

It was decided to apply a weighting scheme to these constraints which set stronger weights within the uppermost layer of model cells, and gradually decreasing weights with depth relative to topography. The weights were scaled from 10 near the topographic surface to 1 at depth, the weights decreasing as a function of inverse distance. This means that the reference values near surface, where there is more confidence in the mapped and interpreted geology, are more strongly adhered to while the deeper reference model has less influence on the final inversion result. Inversion parameters are summarized in Table 3.

Table 3. UBC-GIF magnetic inversion parameters.

Constraints	Reference 3D susceptibility model acts as initial and reference model
Weights	10 near topographic surface, decreasing as a factor of depth down to 1
Convergence Criteria	Fixed Chi Factor = 0.1
3D Mesh	Core 500 m x 500 m horizontal cells with variable depth thicknesses comprised of near surface 500 m cells, then slowly expanding with depth.
Number of Cells in Mesh	4,274,820
Length Scales	1000, 1000,1000 (Le, Ln, Lz)
Number of Data Inverted	74,729
Achieved Misfit	9.081433E+04

Figure 37 shows slices through the reference magnetic susceptibility model, the weighting model, and the upper and lower bounds models. A comparison between observed and predicted magnetic data following inversion is shown in Figure 38. The magnetic inversion result is shown in Figures 39 and 40.

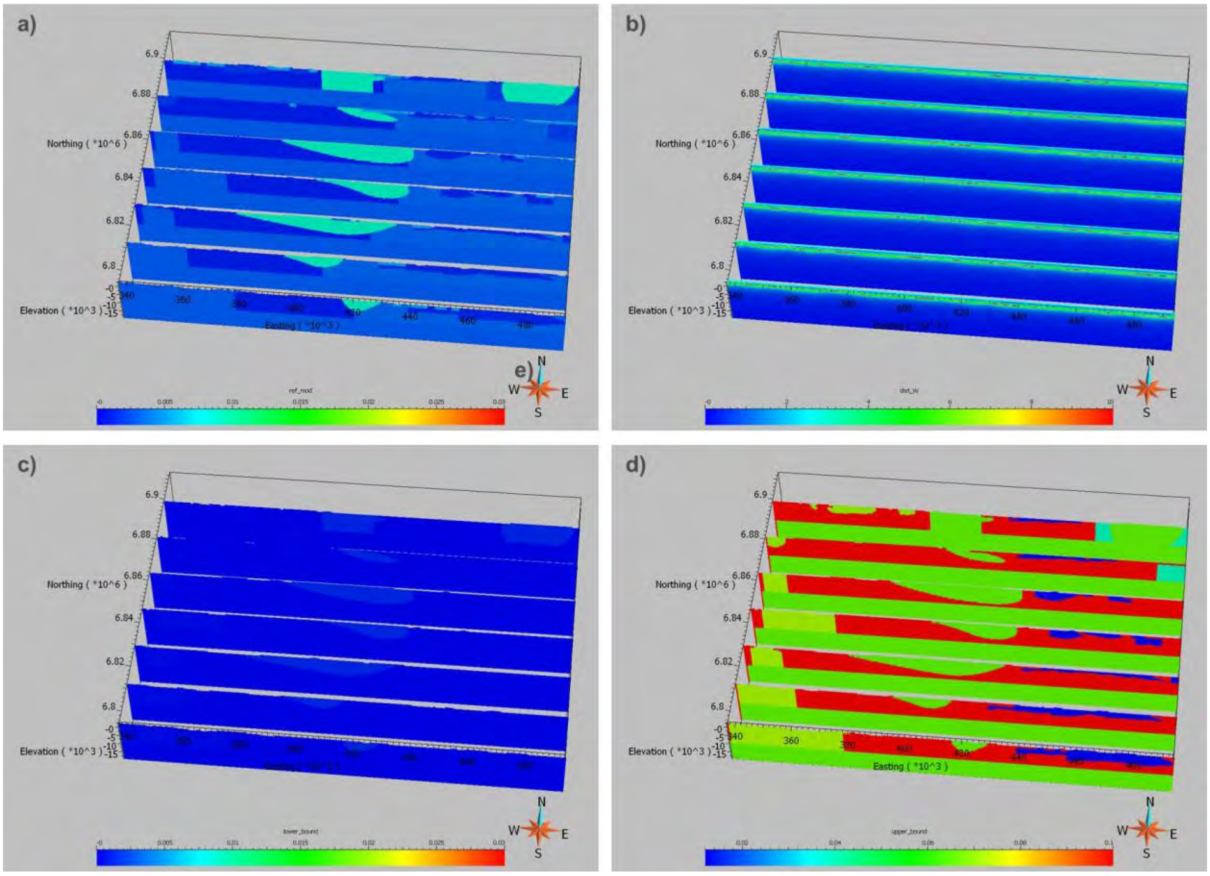

Figure 37. Vertical slices through a) the reference model, b) the weighting model (with highest weights closest to surface), c) the lower bounds model, and d) the upper bounds model.

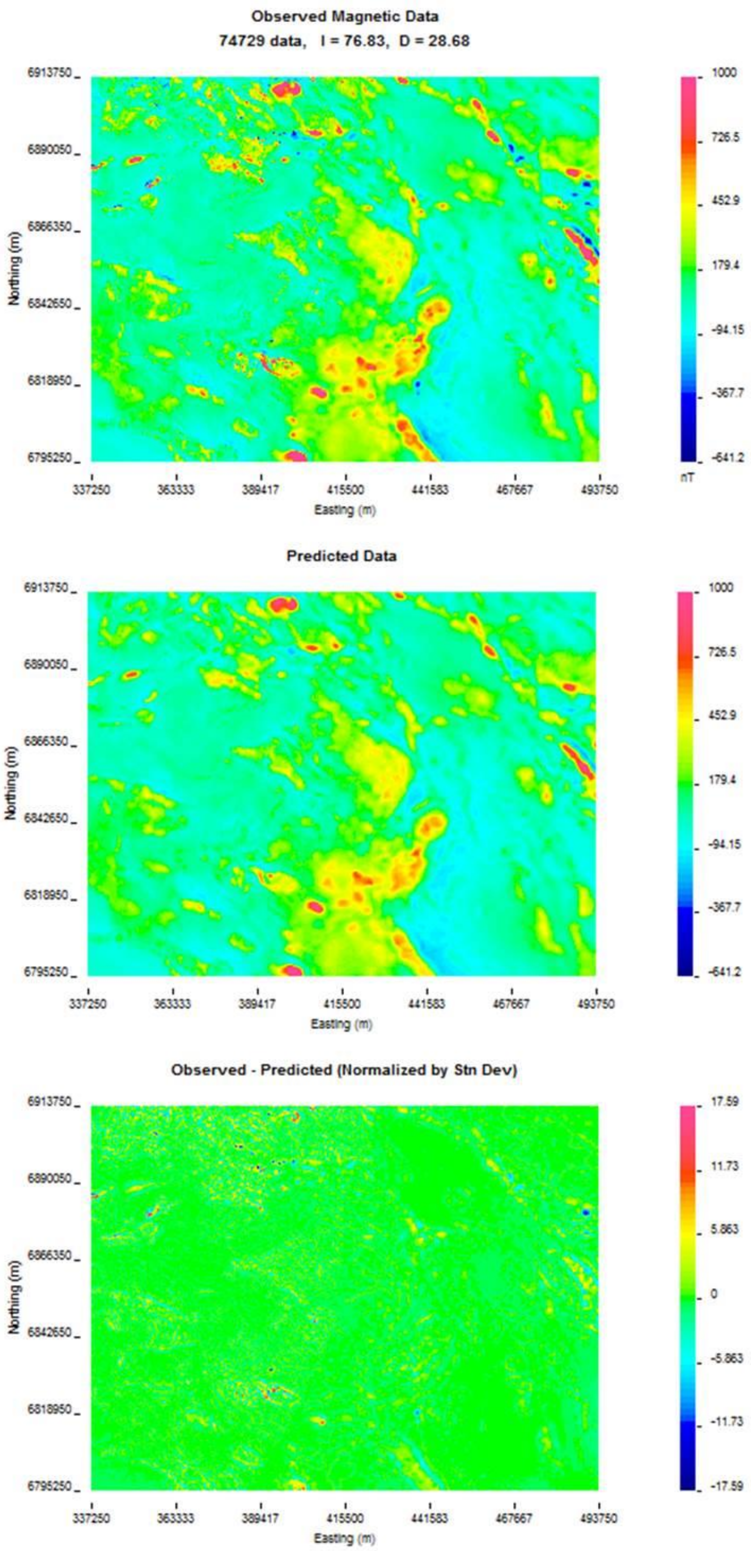

Figure 38. Observed and predicted data for the UBC-GIF inversion of Yukon Plateau magnetic data. Upper image shows observed magnetic data, middle image is data predicted by the inversion result and the lower image shows the difference between observed and predicted data.

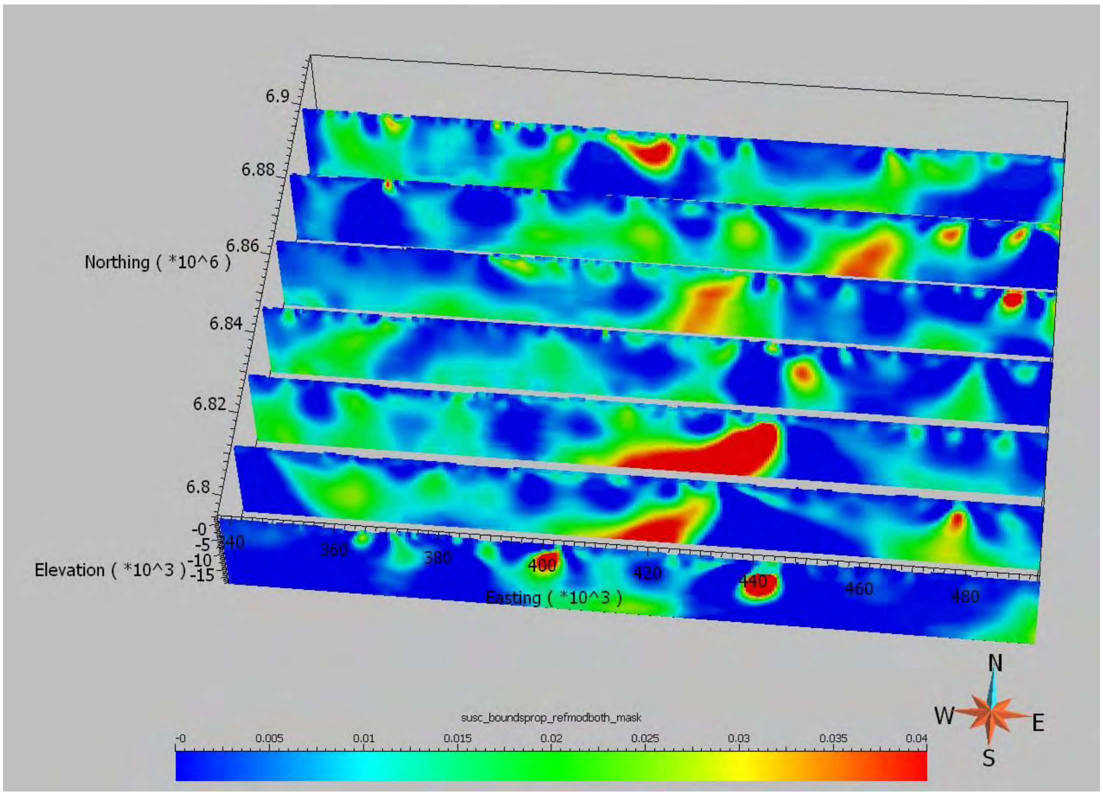

Figure 39. East-west slices through the UBC-GIF 3D magnetic inversion model.

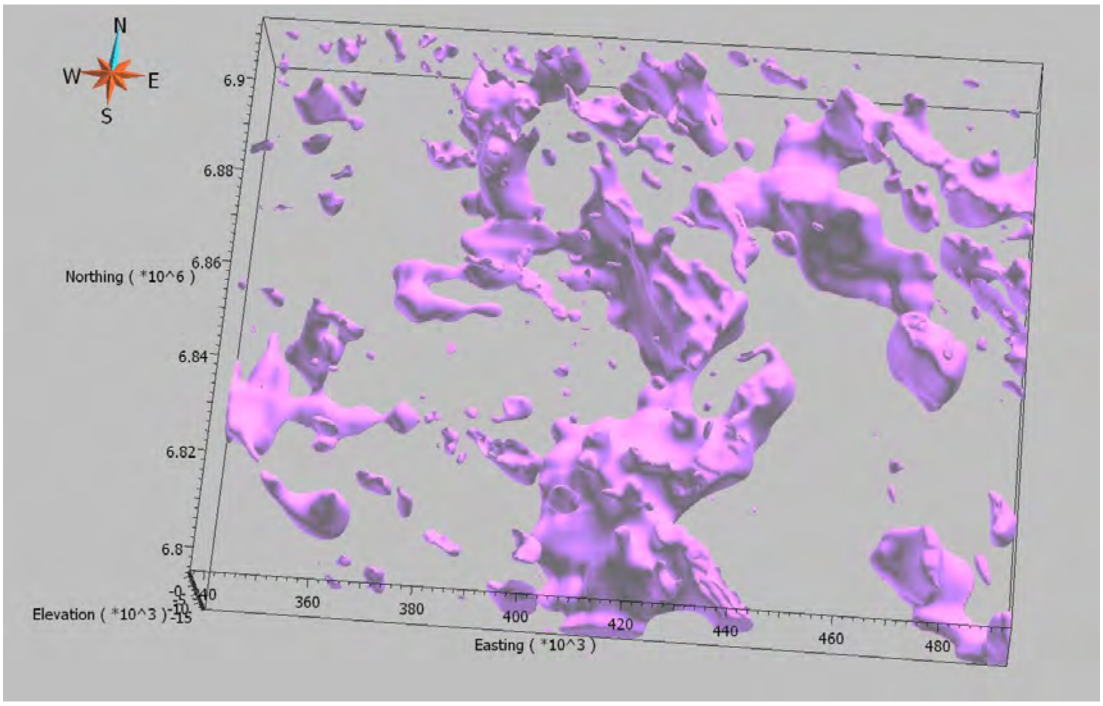

Figure 40. Isosurface generated from UBC-GIF magnetic susceptibility model. Cut-off at 0.015 SI units.

5. Interpretations

This section presents an overview of the key features of interest resulting from constrained VPmg and UBC-GIF inversion modelling.

5.1. VPmg results and interpretations

The gravity inversions played a more prominent role in refining the original 3D geologic model than magnetic inversions did, due to the distinct and consistent density contrasts between important geological domains. The results of the VPmg gravity inversions are described in this section.

A key result for this project is a 3D geologic model that has been updated using constrained geophysical inversion. Updated 3D geologic surfaces can be compared with starting surfaces to identify specific localities where the model required revisions in order to better explain observed gravity data.

Gravity inversion was used to refine the geometry of the surfaces defining the Whitehorse trough stratigraphy. A distinct density contrast between deep, predominantly mafic Stikine stratigraphy, and overlying Whitehorse trough sedimentary stratigraphy, made it possible to link the geologic model directly to gravity data, and to update geology based on observed variations in gravity. Figure 41 (a and b) shows the initial SKUA-modelled surface representing the bottom of the 'upper' Stikine (or, top of the Stikine), and the final surface revised through VPmg inversion modelling (Figure 41c). It is possible to gain some insight into the surface refinement process by looking at GSC gravity data as a property on the starting geologic surface (Figure 41b). It is apparent that in order to explain the gravity highs in some regions it was necessary to lift the upper Stikine surface, bringing the underlying high density Stikine rocks closer to the topographic surface.

Figure 42 shows the starting and final 'base of upper Stikine' surfaces relative to interpreted cross-sections. Regions where the final surface has moved up relative to the starting surface are correlative with higher measured gravity.

Because of consistent density contrasts between low density intrusive units within the project area, and high density Yukon-Tanana terrane and Stikine rocks, it was also possible to use gravity inversion to update intrusive boundaries. Figure 43 shows updates made to the surface representing the extent of the Aishihik Batholith. Some very low gravity values have forced the bottom of the Aishihik Batholith to move further to depth. VPmg magnetic inversion results further indicate that Aishihik intrusive phases (specifically phases composing the magnetic eastern portion of the Aishihik Batholith) extend significantly deeper than what was originally modelled. Constraints set on the model as a whole likely restricted the surface from extending deeper during geometry gravity inversions.

Following each inversion, the resulting 3D physical property model is forward modelled so that the calculated response can be compared to the observed geophysical data. The residual represents the 'predicted data' subtracted from the observed data. Residual gravity maps show areas where the initial 3D geologic model is unable to explain the observed geophysical data. There may have been an incorrect interpretation of geology at depth, an incorrect estimate of physical properties, or a combination of the two. Through VPmg gravity inversion modelling, it was possible to update the geologic model to improve the misfit between its calculated response and the observed gravity data, lowering the residuals over much of the project area (Figure 44). Nonetheless, several areas show persevering residuals (Figure 45). These areas should be focused on with the goal to update the geologic model in a way which allows the geophysical data to be explained.

The 3D geologic model developed during this project for the Whitehorse trough and adjacent Yukon-Tanana terrane represents a single interpretation of the subsurface which combines information from mapping and geophysics. The model can and should be updated based on insight from alternate or more focused geophysical models, new or refined geological mapping, drilling, and physical rock property measurements.

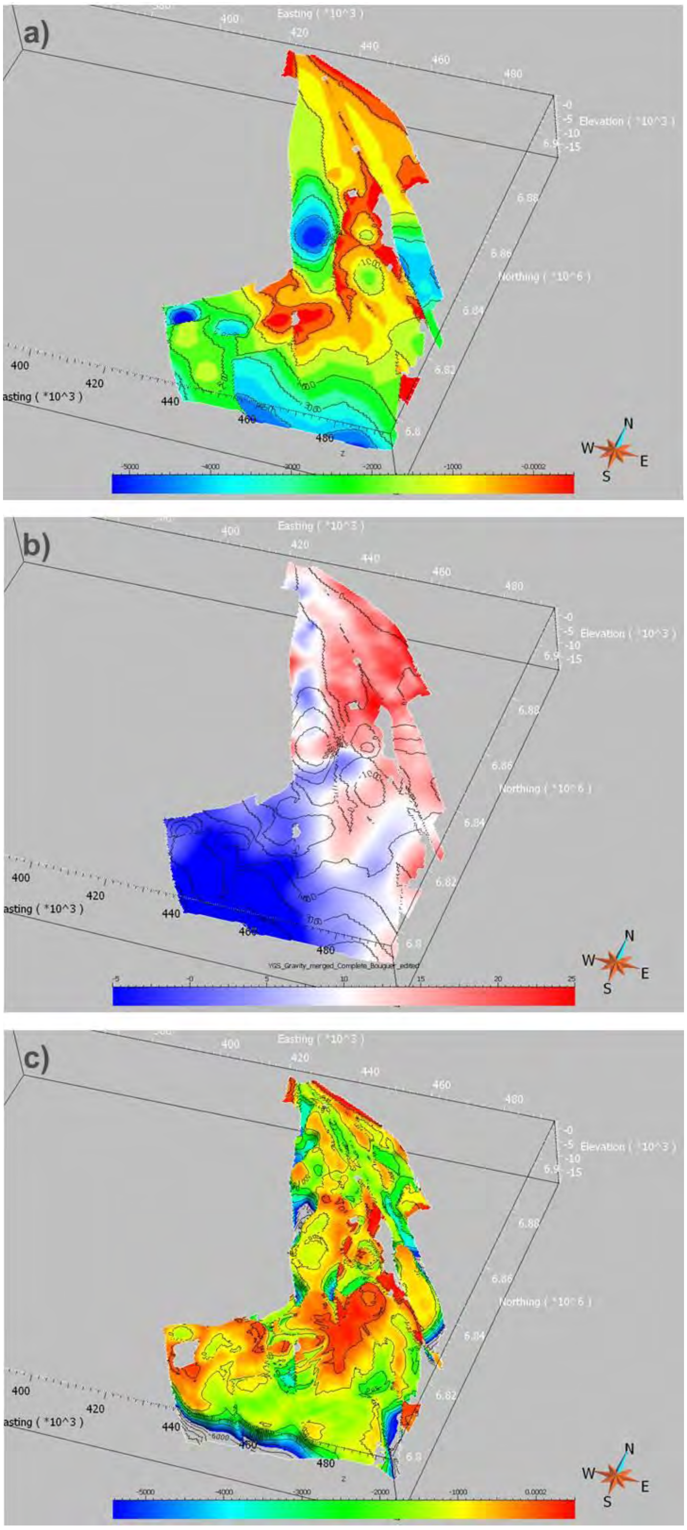

Figure 41. Image a) shows initial base of upper Stikine surface from implicit SKUA modelling colored and contoured by elevation, b) shows GSC gravity mapped onto the initial surface (with starting surface elevation contours), and c) shows the final base of upper Stikine surface colored and contoured by elevation.

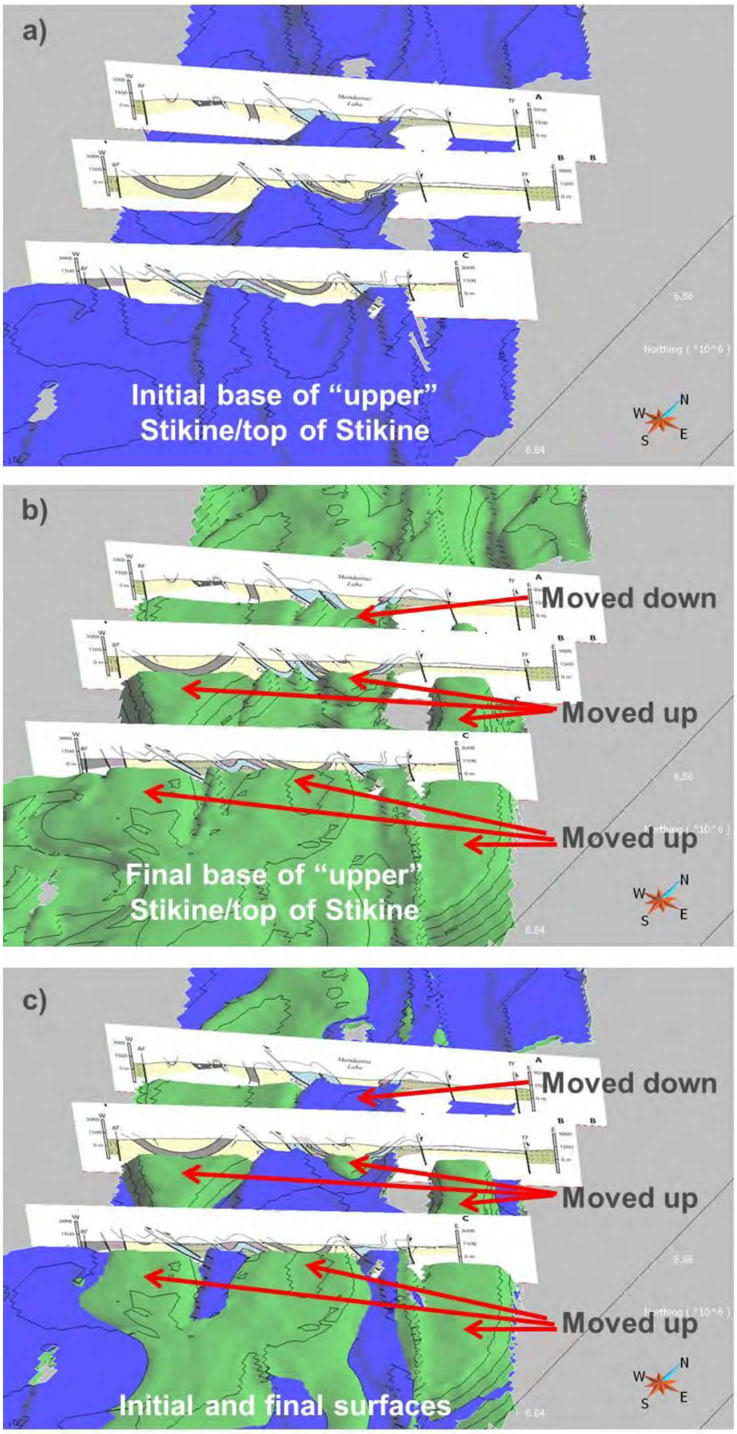

Figure 42. Upper image a) shows the SKUA-modelled surface representing the base of the upper Stikine relative to interpreted cross sections from White et al. (2012). Image b) shows the revised surface and indicates general changes relative to the initial surface. Image c) shows both initial and final surfaces together.

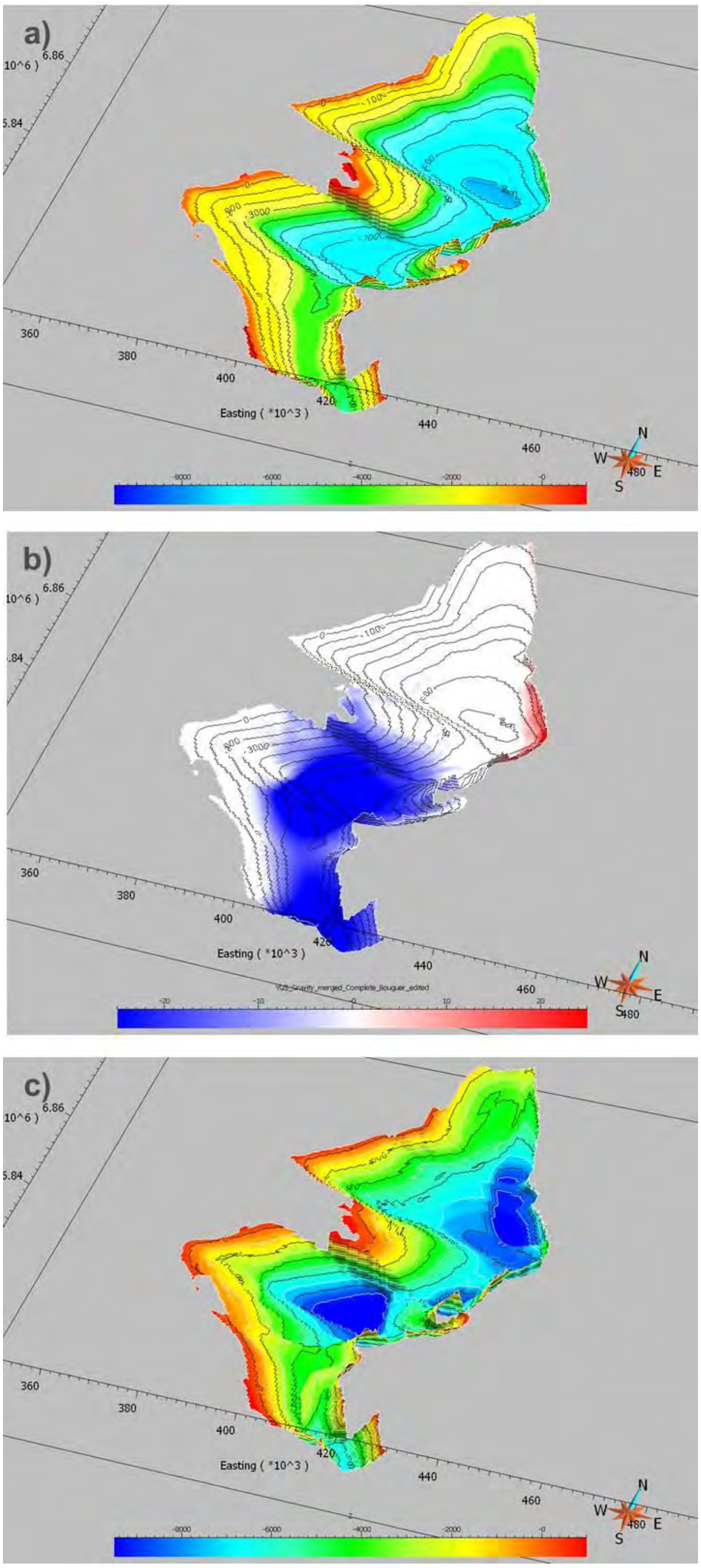

Figure 43. Image a) shows initial Aishihik Batholith surface colored by elevation, b) shows GSC gravity mapped onto the initial surface, and c) shows the final Aishihik Batholith surface colored by elevation.

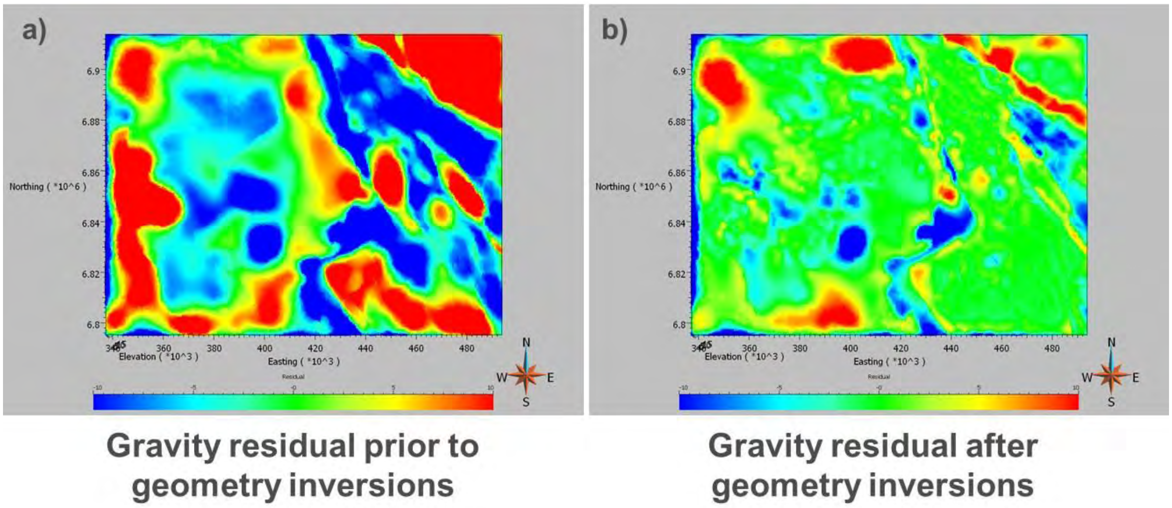

Figure 44. Gravity residuals before updates to 3D geologic model (a), and after updates to the geologic model via geometry and heterogeneity VPmg inversions (b).

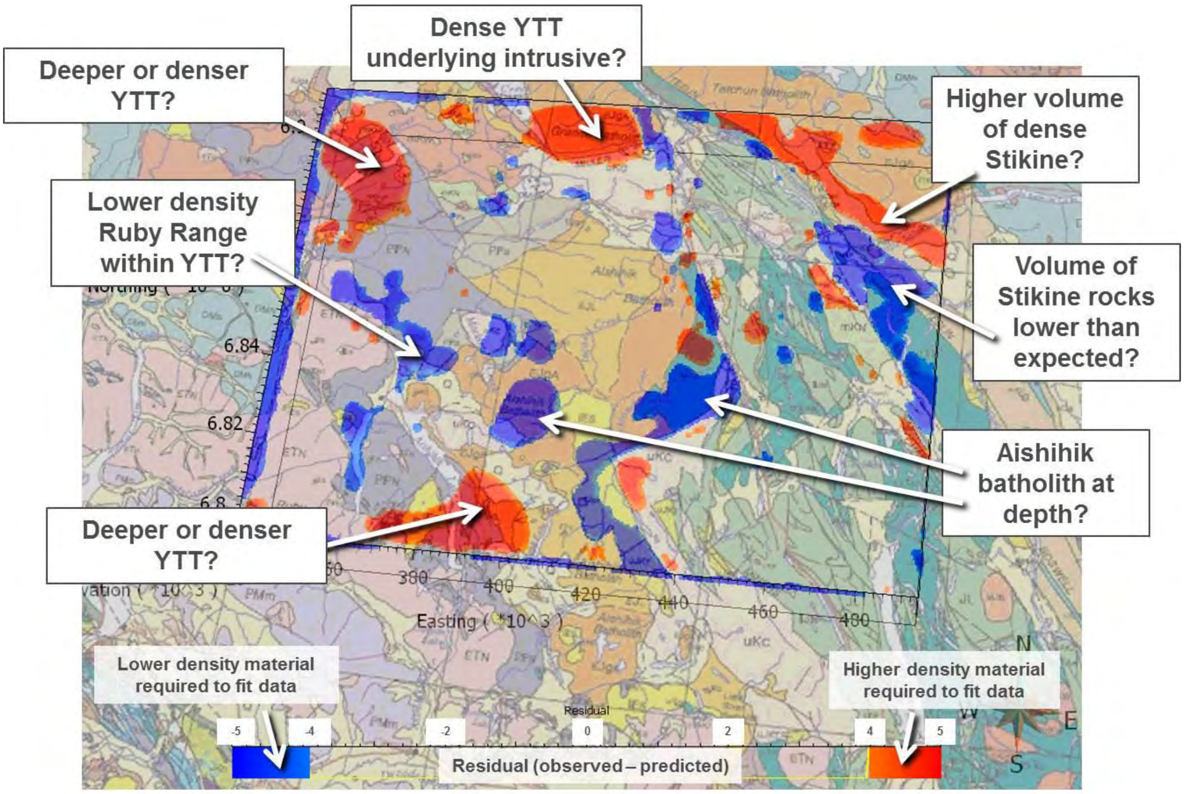

Figure 45. Anomalous high and low gravity residuals, relative to mapped geology, with possible interpretations.

5.2. UBC-GIF magnetic inversion results and interpretations

The unconstrained magnetic inversion models provide information about distributions, size, and depths of magnetic geologic units within the subsurface. Comparison to mapped geology indicates that most of the modelled magnetic bodies represent intrusive rocks, and surficial volcanic units.

Figure 46 shows the 0.015 SI magnetic susceptibility isosurface with intrusive geologic domains superimposed. The high compositional variability of the various intrusive units is observed. The Aishihik Batholith, within the central project area, is composed of magnetite-bearing as well as non-magnetite-bearing intrusive phases. A strongly magnetic phase composes the eastern part of the batholith, which from this modelling effort appears to exist at depth beneath mapped Whitehorse trough and Stikine stratigraphy. The inverted magnetically susceptible body has steeply dipping eastern edges, and extends to depth > 20 km. A non-magnetic intrusive phase apparently sits west of and above the magnetic phase. From earlier geophysical data analysis, the western parts of the batholith are interpreted to be thin, overlying Yukon-Tanana terrane metamorphic rocks, and increasing in thickness to the east. Future 3D geologic modelling must account for both intrusive phases in order to reconcile with geophysical data.

The Ruby Range Batholith is similarly compositionally variable. Within the study area a central zone appears to be dominated by magnetite-bearing intrusive phases, while Ruby Range intrusive rocks to the north and south do not correlate with high magnetic susceptibilities.

The Whitehorse Suite, McGregor Batholith, and Tatchun Batholith all appear to be primarily non-magnetic, with minor magnetic phases.

Figure 47 shows the occurrence of thin surficial volcanic units relative to high magnetic susceptibility regions within the 3D magnetic susceptibility model. Carmacks Group volcanic rocks are magnetically variable, with some volcanic flows apparently containing magnetite, while others lack magnetite. There is a northwest-southeast trend to Carmacks Group volcanic stratigraphy in the north. Mount Nansen Cretaceous volcanic rocks are consistently high susceptibility, some of these mapped units having apparently deep magnetic roots (in the northwest project area, and in the east beneath the Whitehorse trough).

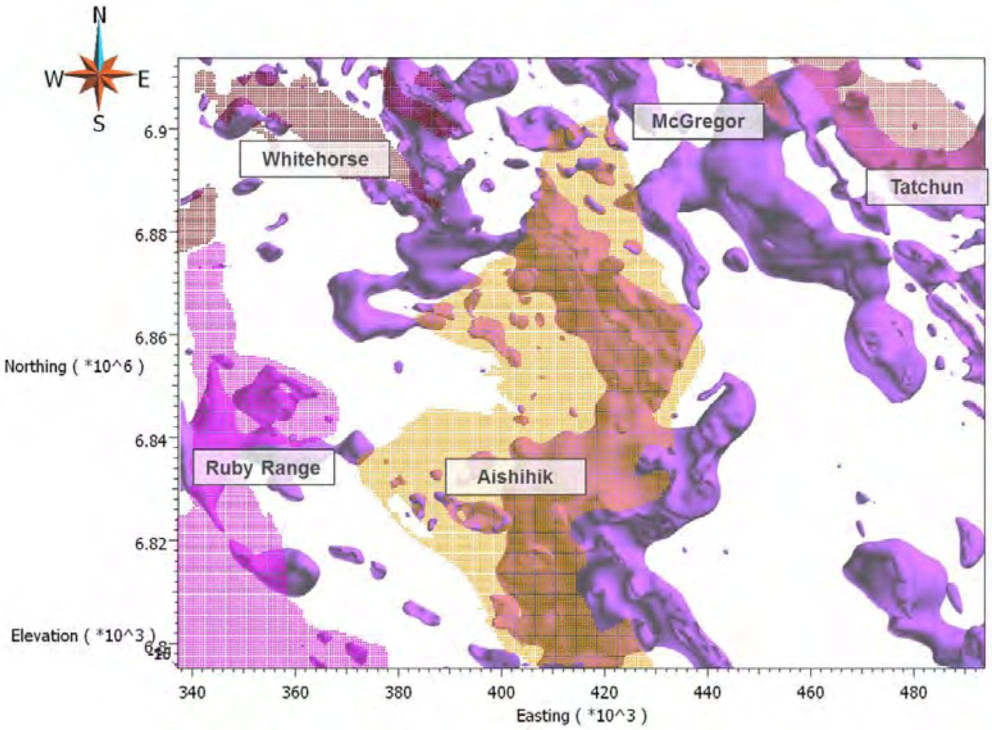

Figure 46. Plan view of magnetic inversion result shown as an isosurface model with intrusive geologic domains superimposed.

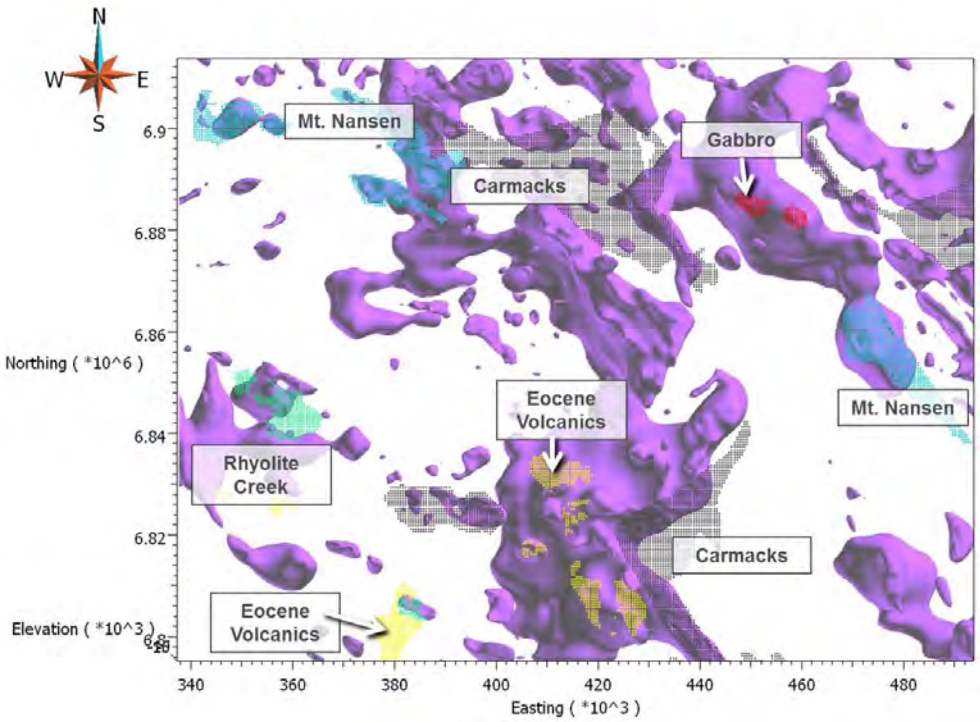

Figure 47. Plan view of magnetic inversion result shown as an isosurface model with surficial volcanic rock domains superimposed.

Further evaluation of the 3D magnetic susceptibility model highlights several interesting features, annotated in Figure 48.

A suite of NW-trending, apparently structurally controlled discrete magnetic features, possibly dikes or small intrusive bodies, are indicated within the 2D magnetic susceptibility model. These features are shallow and generally steeply dipping. Some of the discrete bodies sitting along these linear trends correlate with mineral deposit occurrences documented in the Minfile database.

In the eastern project area, mapped gabbroic rocks are linked at depth to a magnetically susceptible body. This deep magnetic anomaly extends to the southeast where it comes back up to the surface and is correlated to mapped Mt. Nansen volcanic rocks. The 3D model might indicate a genetic relationship between the gabbros and volcanic rocks. Further south a similar shallow magnetic feature occurs, and is also linked to a deeper magnetic body, that may potentially represent a volcanic feeder zone.

The eastern extent of the Aishihik Batholith is characterized by sharp, steep margins, which suggest a steeply-dipping structural contact with deep Stikine stratigraphy to the east.

Although there are some magnetite-bearing units within Stikine stratigraphy (Figure 16) through magnetic modelling, Stikine stratigraphy was shown to be predominantly non-magnetic. Most magnetic features are explained by intrusive rocks and later volcanic deposits. This is contradictory to original thinking that Stikine units were relatively magnetic. Rock property data would require updating to reflect this prior to further or additional geologically-constrained inversion modelling.

The large and small scale features of the 3D magnetic susceptibility model can be fully explored using 3D modelling or viewing software. A range of isosurfaces should be built to more effectively evaluate the distribution of the various magnetic bodies.

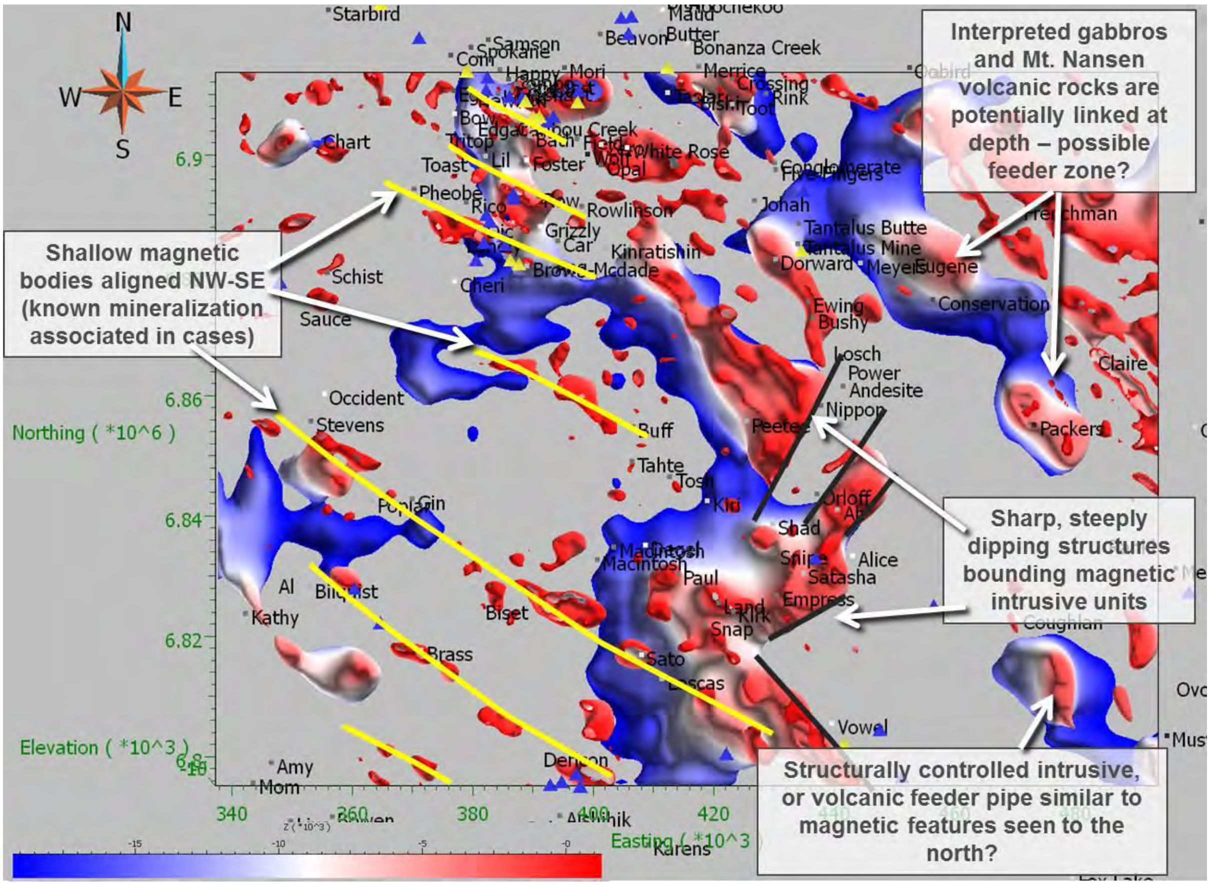

Figure 48. Plan view of magnetic inversion result shown as an isosurface with a cut-off of 0.015 SI units. The isosurface is painted by elevation (Z) to highlight shallow (red) and deep (blue) features.

6. Summary

Geologically constrained potential field inversions were completed to test whether interpreted Yukon geology is consistent with collected geophysical data, and to provide a geophysical framework for updating current geological maps and models. Two different geophysical inversion codes were used to generate alternate 3D models of the subsurface.

VPmg potential field modelling for the Whitehorse trough - Yukon-Tanana terrane project area initially focused on testing a starting 3D geological model by attempting to explain the gravity and magnetic responses in terms of homogeneous density and magnetic susceptibility assigned to the geological domains. This approach serves to validate the existing understanding of physical rock properties in terms of the modelled geological domains, and highlights regions where the 3D geologic model must be updated. Geometry and heterogeneous VPmg inversions are employed to modify geologic contacts and rock property values in order to fit observed geophysical data. Gravity modelling was more effective in updating geologic contacts due to distinct and consistent density contrasts between important geologic units. Magnetic data were very heterogeneous making it difficult to distinguish and model individual geologic domains.

To better evaluate the magnetic heterogeneity within the project area, which may be helpful in indicating different intrusive phases, alteration domains, and structure, UBC-GIF magnetic inversion codes were used to generate a smooth 3D magnetic susceptibility model of the subsurface.

The constrained 3D geological and geophysical models can be used as a basis for ongoing mapping and exploration. Inconsistencies between the geologic model and the inversion models may signify the presence of unmapped, buried, or unaccounted for geologic domains, or may represent altered or metamorphosed domains which may have significance for mineral exploration.

Geologically constrained inversion is most successful when the geologic domains of interest have distinct and consistent physical rock property characteristics. In this case, geologically constrained inversion highlighted some of the shortcomings of the geological framework assumed for potential fields modelling (e.g. appreciable heterogeneity within domains).

In overview, this project has completed a thorough investigation into the potential field response of the Whitehorse trough and adjacent Yukon-Tanana terrane in terms of the existing interpreted and modelled geology. While due care has been taken to generate models consistent with all available information, it is important to recognise that a model satisfying measured geophysical data is not unique, even when an integrated approach is adopted. The delivered models should therefore be regarded as an advancement of the prior understanding and a starting point for future work rather than as a final interpretation. In addition to the models themselves, value is added through the documented investigations that sought to reconcile potential field response in terms of characterized geological domains.

The 3D geological and geophysical models are best assessed and queried in a 3D GIS visualisation package, but representative illustrations of the results are included in this report for completeness. It is recommended that the reader specifically review the accompanying digital deliverables.

7. Recommendations

The outcomes documented in this report should be reviewed in conjunction with the digital deliverables to discern where additional value can be added. In particular, further analysis of the density and susceptibility modelling results by geologists working in the southern Yukon Territory should be undertaken incorporating other geoscientific data and additional geological and petrophysical information.

As a starting point for future work refining 3D geologic models using inversion methods, a strong recommendation is to ensure that the initial 3D geological model represents the best, most current geological interpretation. Any inconsistencies in geological interpretations, and between geological and geophysical data that have been identified should be reconciled early on. In the case of the Whitehorse trough – Yukon-Tanana terrane model, a specific recommendation for future modelling is more rigorous assessment of deep-seated regional structure and geologic domains (importantly, the intrusive units) and explicit representation of the geological domains of the model to greater depth prior to application of geophysical inversion.

The 3D geologic model can be further refined though incorporation of constraints derived from additional seismic interpretations, and drilling.

Future work may also involve focusing on answering more specific geological questions within localized areas of the Whitehorse trough – Yukon-Tanana terrane project area, further refining boundaries and physical properties of geologic units of interest.

Higher resolution geophysical methods, or more local-scale surveys may be applied to areas of interest. Gravity was shown to be a useful method for identifying extents and depths of intrusive units, as well as for detecting stratigraphic variability within the Whitehorse trough. Adding more detailed gravity data within the study area would improve mapping and constrained modelling of geology within it. Magnetic data and models are best used to identify heterogeneity within geologic domains, due to compositional variability, structure, or alteration.

Electromagnetic techniques, depending on the method applied, might be used to identify faults, overburden thickness, or distinguish between more resistive areas (e.g. more coherent intrusive or metamorphosed units) and less resistive areas (e.g. more porous volcaniclastic or sedimentary units).

The present understanding of the physical properties associated with geological domains and changes in physical properties with mineralization and alteration could be improved and thus extending the physical property database may provide more robust constraints for modelling. It is recommended to use observed geophysical data and inversion results to direct collection of samples for density, magnetic susceptibility, and electrical measurements.

Physical property data evaluation, and geophysical data and modelling revealed that intrusive rocks in the project area have strong heterogeneity. Research on relevance of various intrusive phases is of interest, and may have implications for exploration.

Finally, compilation of the existing 3D geologic model and geophysical data and models with other geoscientific data (e.g. geochemical data and interpretations, structural interpretations) would set the stage for quantitative mineral potential targeting, or oil and gas resource targeting. Weights-of-evidence analysis could be applied to test spatial relationships between existing mineral occurrences and geological, structural, geophysical, geochemical variables.

8. References

Canadian Geodetic Information System, 2008. Gravity data - Bouguer anomaly 2 km grid of Canada, Gravity & Geodetic Networks Section, Geodetic Survey Division, Geomatics Canada, Earth Sciences Sector, Natural Resources Canada, http://gdr.agg.nrcan.gc.ca/gdrdap/dap/search-eng.php.

Colpron, M. (compiler) 2011. Geological compilation of Whitehorse trough - Whitehorse (105D), Lake Laberge (105E), and part of Carmacks (115I), Glenlyon (105L), Aishihik Lake (115H), Quiet Lake (105F) and Teslin (105C). Yukon Geological Survey, Geoscience Map 2011-1, 1:250 000.

Colpron, M. and Nelson, J. L., 2011, A digital atlas of terranes for the northern Cordillera: Yukon Geological Survey, www.geology.gov.yk.ca/bedrock_terrane.html, accessed December 2013; also BC Geological Survey, BC GeoFile 2011-11.

Fullagar, P.K., Hughes, N., and Paine, J., 2000. Drilling-constrained 3D gravity interpretation, Exploration Geophysics, v. 31, p. 17-23.

Fullagar, P.K., Pears, G.A., Hutton, D., and Thompson, A, 2004. 3D gravity & aeromagnetic inversion, Pillara region, W.A., Exploration Geophysics, v. 35, p. 142-146.

Fullagar, P.K. and Pears, G.A., 2007. Towards Geologically Realistic Inversion, In Proceeding of Exploration 07: Fifth Decennial International Conference on Mineral Exploration, Toronto.

Fullagar, P.K., Pears, G.A., and McMonnies, B., 2008. Constrained inversion of geological surfaces - pushing the boundaries. The Leading Edge, v. 27, p. 98-105.

Hayes, B. J. R., 2012, Petroleum resource assessment of Whitehorse trough, Yukon, Canada: Yukon Geological Survey, Miscellaneous Report 6, 52 p.

Hayes, B.J.R. and Archibald, H.B., 2012. Scoping study of unconventional oil and gas potential, Yukon. Yukon Geological Survey, Miscellaneous Report 7, 100 p.

Hayward, N., Miles, W., and Oneschuk, D., 2011. Geophysical Series, regional geophysical compilation project, Yukon Plateau, Yukon, parts of NTS 105, 106, 115 and 116. Geological Survey of Canada, Open File 6959.

Gordey, S.P. and Makepeace, A.J. (compilers), 2001, Bedrock geology, Yukon Territory, Geological Survey of Canada, Open File 3754, 1:1 000 000 scale.

Israel, S. and Westberg, E., 2012. Geology and mineral potential of the northwestern Aishihik Lake map area, parts of NTS 115H/12 and 13. In: Yukon Exploration and Geology 2011, K.E. MacFarlane and P.J. Sack (eds.), Yukon Geological Survey, p. 103-113.

Kiss, F., 2010, Residual total magnetic field, and First vertical derivative of the magnetic field, Kluane area aeromagnetic survey Parts of NTS 115A/13, 14 and 115B/16 and 115G/1, 8 and 115H/3, 5, 6, Yukon. Geological Survey of Canada, Open Files 6584 to 6591; Yukon Geological Survey, Open Files 2010-17 to 2010-28, Scale 1:50 000.

Kiss, F., and Coyle, M., 2011, Residual total magnetic field, and First vertical derivative of the magnetic field, Aeromagnetic Survey of the Nisling River Area, Parts of NTS 115G/10, 11, 13, 14, 15, 16, and 115H/6, 7, 10, 11, 13, 14, 15 and 115I/ 4 and 115J/1, 2, 3, 5, 6, 7, Yukon; Geological Survey of Canada, Open Files 6891 to 6912; Yukon Geological Survey, Open Files, 2011-5 to 2011-26, scale 1:50 000.

Li, Y., and Oldenburg, D.W., 1996. 3-D inversion of magnetic data, Geophysics, v. 61, p. 394-408.

Lowe, C., Horner, R. B., Mortensen, J. K., Johnston, S. T., and Roots, C. F., 1994. New geophysical data from the northern Cordillera: preliminary interpretations and implications for the tectonics and deep geology, Canadian Journal or Earth Sciences, v. 31, p. 891-904.

MAG3D. A Program Library for Forward Modelling and Inversion of Magnetic Data over 3D Structures, Developed under the consortium research project Joint/Cooperative Inversion of Geophysical and Geological Data, UBC-Geophysical Inversion Facility, Department of Earth and Ocean Sciences, University of British Columbia, Vancouver, British Columbia.

Tempelman-Kluit, D.J., and Currie, R.G., 1978. Reconnaissance rock geochemistry of Aishihik Lake, Snag, and Stewart River map areas in the Yukon Crystalline Terrane, Geological Survey of Canada, Paper 77-8.

White, D., Colpron, M., and Buffett, G., 2012. Seismic and geological constraints on the structure and hydrocarbon potential of the northern Whitehorse trough, Yukon, Canada, Bulletin of Canadian Petroleum Geology, v. 60, p.1-17.

Yukon Geological Survey, 2011. Bouger gravity anomaly of the northern Aishihik Lake area, Yukon (parts of NTS 115H, I and G). Yukon Geological Survey, Open File 2011-27, 2 maps and data files.

APPENDIX A: Digital deliverables

Folder	File	Description	2D/3D
All data and projects in Nad 83 UTM Zone 8			
3DGOCAD_project	GOCAD project: YGS_MiraGeoscience_WT_YTT_3DGeol_Inversion.gprj	Contains all deliverables objects, requires GOCAD software	3D
3DViewer_project	YGS_MiraGeoscience_Whitehorse_Trough_3DViewer_Project.bin	3D Viewer software download required, please visit: http://www.scicomap.com/downloads.htm	3D
DXF_curves	Mira_interpreted_lineaments_from_magdata.dxf	Lineaments interpreted from magnetic data	2D
	YGS_project_AOI.dxf	Mira Geoscience/YGS Whitehorse trough project area of interest	2D
Geophysical_data_grids_derivatives	Geophysical_data_ASCII	Raw and gridded gravity and magnetic data as ASCII pointsets	2D
	Gravity_data_grids_and_derivatives	Gridded Aurora and GSC gravity data and derivatives	2D
	Magnetic_data_grids_and_derivatives	Gridded magnetic data and derivatives	2D
TIFF_images	Various .tiff images, 1:750000	Includes geological interpretations from geophysical data, as well as geophysical data, and data derivative images	2D
UBC_GIF_magnetic_inversion	ASCII_format	UBC-GIF magnetic inversion result, in ASCII pointset format	3D
	UBC_GIF_format_3D_models	UBC-GIF magnetic inversion result, in UBC 3D model file format	3D
	UBC_mag_inversion_model_slices_grd_files	Slices through UBC-GIF magnetic inversion in .grd file format	2D
	UBC_GIF_inversion_mag_susc_isosurfaces	Suite of isosurfaces generated from UBC-GIF magnetic inversion	3D
VPmg_inversion	VPmg_observed_and_predicted_data_following_inversion	VPmg observed magnetic and gravity data, and data predicted following inversion	2D/3D
	VPmg_starting_and_final_models_in_ascii_format	starting and final (post VPmg) geologic models in ASCII format	3D
	VPmg_starting_and_final_models_in_UBC_file_format_for_viewing	starting and final (post VPmg) geologic models in UBC 3D model file format	3D
	VPmg_starting_and_final_models_slices_grd_files	Slices through final VPmg geologic model in .grd file format	2D
	VPmg_surfaces_geologic_contacts_DXF	Whitehorse trough faults used for geologic modelling, and starting (pre-inversion) and final (post VPmg inversion) 3D geological surfaces	3D
	Geological_Legend.xlsx	Legend matching numerical geologic ID to lithologic units	
XYZ_pointsets	minfile_Z8_YGS_project.xlsx	Minfile Zone 8	2D
	Physical_props_Zone8N_TempelmanKluit_Currie_1978_xyz.txt	Physical property data from Tempelman-Kluit and Currie 1978, ASCII format	2D

APPENDIX B: Glossary of useful terms

See accompanying document:
Mira AGIC Glossary of Useful Terms.pdf

APPENDIX C: Tempelman-Kluit and Currie, 1978, physical property data

See accompanying .xls document:
YukonPlateauPhysProps_TK_C_1978_Mira_edited

APPENDIX D: VPmg software overview

VPmg is a gravity, gravity gradient, magnetic, and magnetic gradient 3D modelling and inversion program developed by Fullagar Geophysics Pty Ltd (Fullagar et al, 2000; 2004; Fullagar & Pears, 2007; Fullagar et al, 2008).

In VPmg, the models are geological (categorical) insofar as each volume of the subsurface is assigned to a rock unit. The shape and property (density or susceptibility) of each unit can change during inversion, but its geological (or topological) identity is preserved. Geological contacts can be fixed (where pierced by a drill hole for example), bounded, or free to move during inversion. Bounds can be imposed on each unit's properties, and density or susceptibility measurements (on drill core samples or from downhole logs) are honoured during property inversion.

VPmg represents the sub-surface as a set of tightly-packed vertical rectangular prisms, which in plan view appear as a regular mesh or grid. Prism tops honour surface topography, and in its simplest form, internal contacts representing geological boundaries divide each prism into (usually elongated) cells. The vertical dimension of cells is arbitrary, implying that the vertical position of the geological boundaries is not "quantised" by vertical discretisation. The internal contacts represent geological boundaries that collectively define the shape of geological units. The geological units can either be homogeneous, i.e. uniform in density or susceptibility, or fully heterogeneous. When considering property inversion, a geological unit can be discretised in different ways. In the first instance, the property of each vertical prism segment of a geological unit can be allowed to vary independently, thereby introducing a lateral property variation within the unit. Full 3D property variation is achieved by introducing vertical sub-celling within the selected units.

VPmg offers considerable flexibility during interpretation. The model complexity ranges from conventional (uniform density) terrain models, to discrete bodies in a uniform background, to layered stratigraphy on basement, to complex 3D models. Regional effects can be handled by constructing a regional model, based on a relatively large rectangular mesh. The regional model is in turn embedded in a uniform half-space. A local model, comprised of smaller prisms, can be embedded in a regional model. The local model parameters can be adjusted by inversion until the gravity, gravity gradient, TMI, or magnetic gradient data within the local model area are satisfied.

VPmg offers a variety of inversion styles: homogeneous unit property, contact geometry, and heterogeneous property. During property inversion, model contacts (geometry) are fixed. During contact geometry inversion, geological boundaries are altered while physical properties remain fixed. The user is able to easily switch from one inversion style to another.

GOCAD Mining Suite utilities developed by Mira Geoscience facilitate communication of model and data information to and from VPmg, and expedite assignment of drill hole constraints.

APPENDIX E: VPmg model parameterisation and inversion styles

In VPmg, the Earth is represented as a close packing of vertical prisms, each of which is divided into cells by horizontal boundaries that coincide with geological contacts (Figure 1). The tops of the prisms coincide with the topography. A rock type and a rock property (density or susceptibility) is assigned to every cell. For rank green fields, the same rock type is assigned to every cell, and the starting model degenerates into a homogeneous half-space for unconstrained inversion.

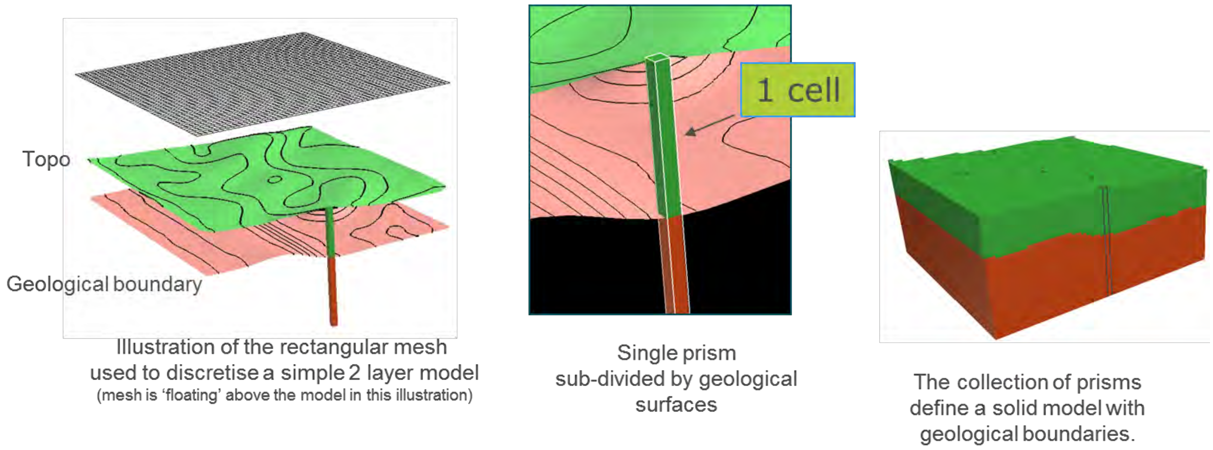

Figure E1: Illustration of VPem1D model parameterisation for a simple 2 layer model comprising cover and basement.

Although a layered model is illustrated in Figure A1, this style of model parameterisation does not enforce a constant stratigraphy in all prisms and therefore supports full 3D geological complexities.

VPmg model parameterisation permits a wide variety of starting model options and 3 general inversion styles: homogeneous unit inversion, geometry inversion and heterogeneous property inversion. These inversion styles are illustrated schematically in Figure 2.

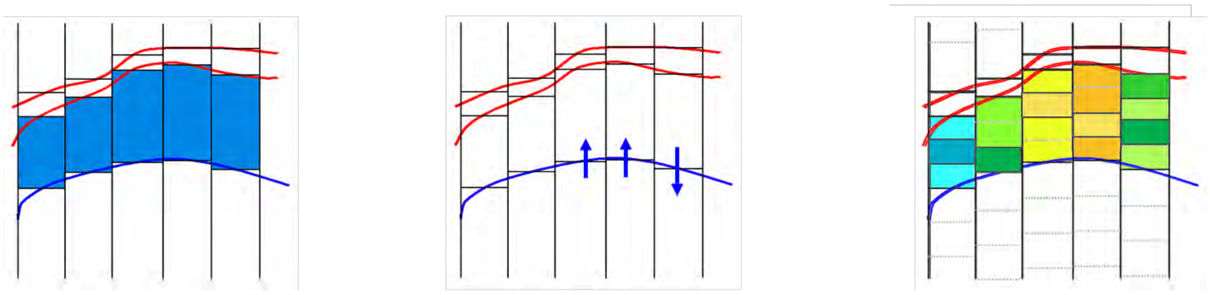

Figure E2: Schematic illustrations of VPmg inversion styles; homogeneous unit inversion (left), geometry inversion (centre) and heterogeneous property inversion (right).

Various inversion options are elaborated upon below.

Homogeneous unit property inversion

For a homogeneous unit property inversion, the starting model is comprised of geological units with uniform density or susceptibility. Inversion optimises the density or susceptibility of one or more units to improve the data fit to the entire data set. Upper and lower property bounds for each unit can be imposed during inversion.

Geometry inversion

Geometry inversion adjusts the elevation of geological boundaries. Geological boundaries can be designated as free or fixed (e.g. pierce by a drill hole), or could be bounded above (e.g. by the end of drill hole). If drill hole information is used to fix a geological boundary, changes to the model in the vicinity of the drill hole are also suppressed (as a measure to preserve consistency with the drill hole away the actual drill hole intersection).

Geometry inversion facilitates a variety of applications such as depth to basement modelling and refining the geological boundaries of a complex geological model. In the absence of a geological model, geometry inversion can assist be implemented during preliminary interpretations by using a simple body (e.g. ellipsoid or rectangular slab) and geometry inversion will adjust the conceptual starting model to fit the data.

Heterogeneous unit property inversion

Geological domains can be discretised internally and heterogeneous unit property inversion can be performed. VPmg domains are intrinsically discretised laterally (by the vertical prism boundaries), and users can specify whether geological domains are also discretised vertically for heterogeneous property inversion. Vertical discretisation is typically specified to be either a constants cell size, or a cell size expanding with depth. The vertical discretistation settings can be different for each geological domain.

Heterogeneous unit inversion adjusts the property (density or susceptibility) variations within one or more geological domains (subject to imposed upper and lower property bounds) to produce a model with an improved fit between the observed and computed gravity and magnetic responses.

During inversion, cells can be designated as fixed if their property has been defined by downhole logging or core measurements. If drill hole physical property measurements are used as hard constraints, changes to the model in the neighbourhood of hard constraints are also suppressed (as for geometry inversion).

Individual weights can also be assigned to individual cells. For example, depth weighting constraints can be set to compensate for heightened sensitivity of model cells closer to the survey measurements.

Geologically unconstrained property inversion

Although VPmg is well-suited to geologically constrained inversion, in the absence of a geological model, unconstrained density or susceptibility inversion can be executed.

VPmg offers two styles of unconstrained property inversion; full 3D density or susceptibility inversion and apparent density or susceptibility inversion (both of which are heterogeneous property inversions). The VPmg apparent density and apparent susceptibility models comprise the 2D grid of tightly packed vertical prisms (elongated cells) with great depth extent (see Figure A1 but with no vertical divisions). A VPmg 3D unconstrained inversion adopts a similar model structure, but each vertical prism is divided into cells. For both these models, the same rock type identifier is simply assigned to every cell.

Apparent density and susceptibility inversions can be executed faster than full 3D unconstrained inversions. In the absence of a regional geological model, apparent density and susceptibility models provide an efficient means for explaining the regional scale potential field response. VPmg can literally incise a local geological model into the regional apparent density or susceptibility model during potential field modelling.

Geologically unconstrained geometry inversion

A style of unconstrained geometry inversion is also permitted using a scheme known as "geobody" inversion. Geobody inversion considers a simple 3 layered starting model. The middle layer is initially set to zero thickness and assigned a starting depth and density or susceptibility (upper and lower layers are generally assumed to be 0 SI or 0 g/cc). VPmg geometry inversion increases the thickness of the geobody to produce a volume of material that provides an improved fit with the observed data.

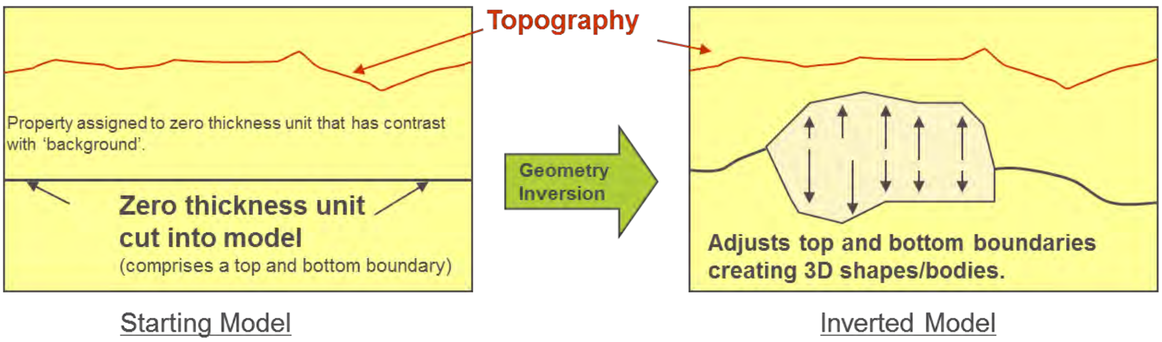

Figure E3: Schematic sections depicting the mechanics of a VPmg geobody style inversion.

APPENDIX F: UBC-GIF MAG3D software overview

MAG3D is a program library (version 4.0 as of January 2014) 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).