Geologically-Constrained Gravity and Magnetic Earth Modelling of the Nechako-Chilcotin Plateau, British Columbia, Canada.
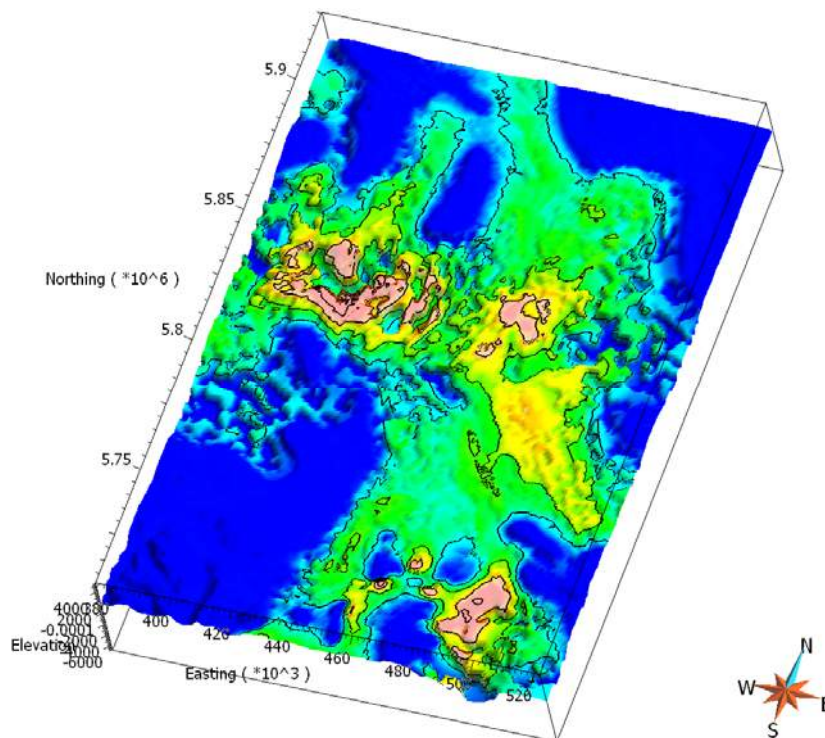
Geoscience BC Report 2014-12

Prepared by Mira Geoscience Ltd. for Geoscience BC

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Executive Summary

Mira Geoscience has completed geologically-constrained 3D Earth modelling and interpretation of gravity and magnetic data for the Nechako-Chilcotin plateau, British Columbia. This work has been conducted for Geoscience BC to aid in the geologic understanding of the extents of existing sedimentary basins, or remnants of former basins, that are only partly recognized beneath the volcanic and glacial cover. Understanding of this basin system, as well as basin-bounding faults, and lithological variability in volcanic units and basement rocks, can help economic prioritization of mineral, oil and gas, and geothermal exploration targets.

The 3D Earth modelling effort undertaken for this project has been employed to reconcile the constraining data (geologic mapping, wells, physical property data, magnetotelluric and seismic interpretations) with gravity and magnetic data. The aim is to better understand and refine the structural interpretation of the area, specifically attempting to resolve basin lithology and geometry. The 3D integrated Earth modelling and data reconciliation process involves iterative interpretation as the model evolves and brings together in a geologically reasonable and consistent manner all available geoscientific constraints.

The GOCAD Mining Suite 3D geologic modelling and interpretation software platform was used for data compilation, geological modelling, property modelling, and for dynamic linking to the VPmg (Vertical Prism magnetics and gravity) geophysical modelling software from Fullagar Geophysics (Fullagar et al., 2000, 2004, 2008, and Fullagar and Pears, 2007).

The VPmg 3D forward modelling and inversion software was used for the constrained potential field modelling. VPmg allows a wide variety of inversion styles and model options. In this case, the geology was simplified to a number of layers representing the primary stratigraphic units within the Nechako-Chilcotin plateau. The VPmg geometry inversion methods were applied to adjust the shape of the contacts between the stratigraphic units subject to geologic mapping and drill-hole constraints, as well as seismic and magnetotelluric interpretations. VPmg physical property inversion methods then introduced physical property (density and magnetic

susceptibility) variations within the stratigraphic units in order to improve the fit to the survey data and to define areas where the geometry needs further study.

The result of this effort is a 3D Common Earth Model that is both lithological and petrophysical in nature, and honors all available observed and interpreted data where possible. The model results are presented both as 3D surfaces representing stratigraphy, and as geological and physical property block models that provide guidance for delineation of geologic units, basins and structures, deep intrusive bodies, and, ultimately, resource exploration targets of interest.

To fully assess the results, we recommend that the accompanying digital results be reviewed in a 3D GIS environment in conjunction with this report.

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1. Introduction

Geophysical methods provide information about geology within the Earth's subsurface, helping geoscientists to image the Earth below cover and at depth, improving mapping and modelling where they are unable to physically map or sample. Inversion of geophysical data is a process of calculating a physical property model of the Earth that is able to predict an observed set of geophysical data. Since physical rock properties relate directly to intrinsic characteristics of rocks - their mineral content and texture - physical property models can be interpreted in terms of lithology and/or geological processes, providing information on rock type, overprinting alteration, structure, and possibly mineralization.

Geophysical inversion of potential fields data applied at regional scales is an effective tool for mapping 3D geologic (volcanic or sedimentary) stratigraphy, the extents and geometry of intrusive domains, and crustal-scale basement structures. Regional 3D modelling will help to identify geologic and structural settings that are conducive to the formation of mineral, and oil and gas resources. Ultimately, the goal of such a modelling campaign is to focus attention on locations for subsequent follow-up with detailed mapping, sampling, and geophysics.

Mira Geoscience has constructed a 3D geologic model for the Nechako-Chilcotin plateau project area. This is a component of a Geoscience BC initiative to investigate the mineral and oil and gas potential of this region. The geophysical data blocks covering this region are shown in Figure 1. Mira Geoscience's Nechako-Chilcotin plateau 3D model was created using constrained magnetic and gravity inversion methods which iteratively refined a starting geologic model, until a model of the Earth was achieved that was consistent with observed geophysical data collected over the Nechako-Chilcotin plateau. The starting geologic model was built from existing mapping and drilling data, from interpretations of seismic and magnetotelluric (MT) data, and from the physical properties of samples and outcrop within the study area.
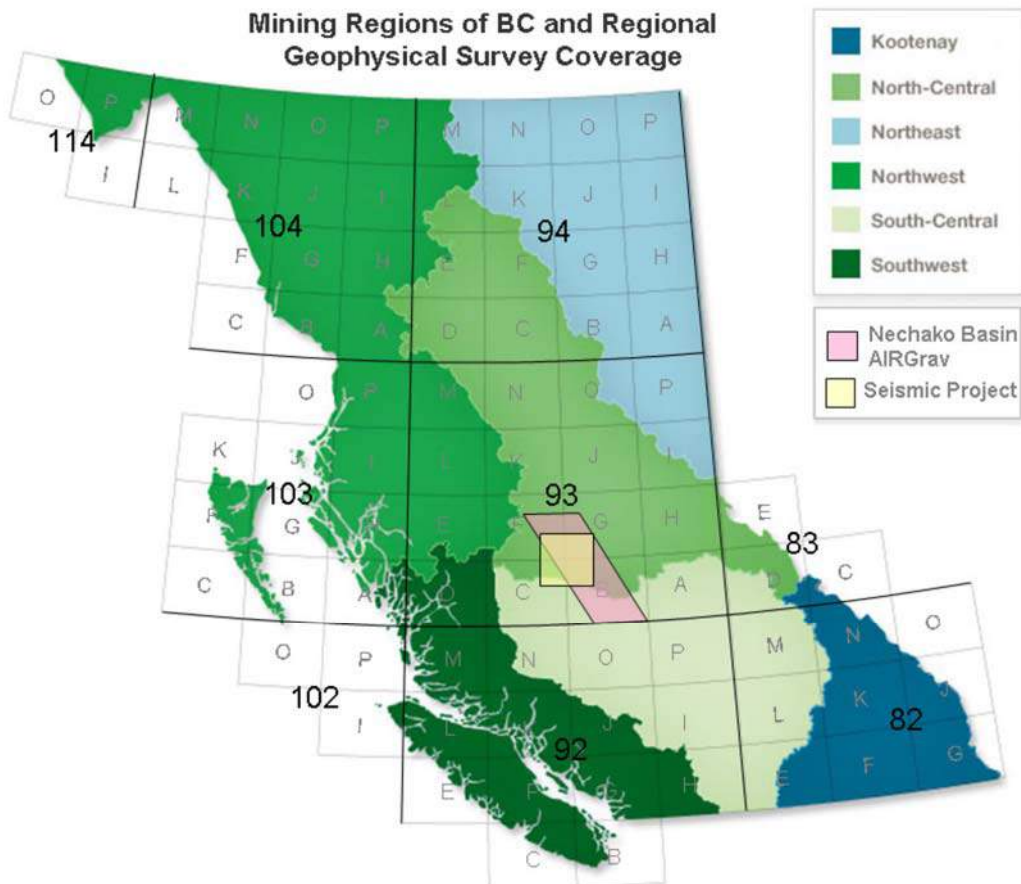
Figure 1. Location map showing BC mining regions with Nechako-Chilcotin plateau geophysical data areas. NTS sheets shown.

The VPmg (Vertical Prism magnetics and gravity) software from Fullagar Geophysics (Fullagar et al., 2000, 2004, 2008, and Fullagar and Pears, 2007) was used for 3D inversion modelling. VPmg is designed to co-operatively invert gravity and magnetic data with geologic and physical property constraints. It is well-suited for this work as the model structure in the program matches the layered type geology found within the Nechako-Chilcotin plateau, and geologic domains have relatively unique geophysical responses. The GOCAD Mining Suite software was used for geologic modelling, preparation of data and constraints, inversion management, data and model integration, visualisation, and interpretation.

This report describes the data used, data processing, methodology, and results of the 3D Earth modelling effort for the study area. Mira Geoscience project participants included: Thomas Campagne (potential field modeller), Shannon Frey (geologic modeller), Diane Hanano (geologic modeller – now at UBC Earth and Ocean Sciences), Dianne Mitchinson (physical property analyst and geological consultant), Peter Kowalczyk (principal geophysicist), and Nigel Phillips (project manager).

1.1. **Objective**

The objective of this study is to construct and refine a 3D geologic model for the Nechako-Chilcotin plateau project area using relevant geological and physical property information with geophysical data available for the area. This will help define present sedimentary basins, or remnants of former basins, that are only partly recognised beneath the volcanic and glacial cover.

The resulting 3D "Common Earth Model" is both geologic and petrophysical in nature, and can be queried and interpreted for specific geological and exploration objectives. The Common Earth Model presented here is a single representation of the Earth generated based on available geoscientific data and interpretations, using a specific suite of geologic and geophysical modelling algorithms. It is not meant to be a complete and final model, but rather is meant to be tested through drilling and mapping, and should be updated and refined by subsequent work done at different scales.

1.2. **Approach**

1.2.1. *Scope of Work*

The scope of work included the following major steps:

- Review and analysis of physical property data

- Preparation and processing of other constraining information

- Construction of a starting geologic model from geologic maps, well data, and seismic and MT interpretations

- Preparation and processing of gravity and magnetic data

- Constrained geophysical inversion modelling using VPmg methodology

- Analysis of results

1.2.2. 3D Modelling Process

The 3D modelling process begins with an analysis of the physical property characteristics of the principal geologic units to be modelled. This analysis, using various existing physical property databases, is conducted to determine whether geologic units will have sufficient physical property contrast to distinguish them from neighboring geologic units using magnetic data or gravity data or both. Focusing on those regional geologic units with relative petrophysical contrasts, a modelling stratigraphy was chosen. Some thinner or localized geologic units, or units with little to no petrophysical contrast with neighboring units were grouped with similar units above or below in the stratigraphy. A simplified 3D geologic model is then constructed from provided geologic maps, geologic well logs, and seismic and MT interpretations. Each lithology in this model is assigned physical property values (density and magnetic susceptibility) based on the previous physical property analyses. These initial 3D physical property models are used in forward modelling exercises as a starting point for constrained inversion modelling. Forward modelling of the initial starting models reveals locations within the model where updates to either geometry of geologic domains, or physical properties, must be made. Geophysical inversion modelling using VPmg codes is applied to update the geologic and physical property models to arrive at a model which is able to predict the observed magnetic and gravity data. The inversion work is iterative in that it shifts between refinement of physical properties per geologic domain, and refinement of geometry, but also switches between gravity inversion and magnetic inversion calculations, to ensure that a single model can effectively predict both sets of geophysical data. The constraining data submitted to the inversion is honored throughout the modelling process, fixing geometry and

physical property values in specified locations, while the other model components have the flexibility to be changed and updated during the geophysical inversion process. All changes are subject, however, to being able to predict the observed geophysical data.

Several assumptions have been made in order allow the modelling to be conducted in a practical manner, and to make the modelling effort a tractable problem to solve. These assumptions include:

- The simplified stratigraphic section is appropriate over a large area.

- The physical property summary statistics are appropriate over a large area.

- The starting geologic model is reasonably continuous laterally away from constraints and at depth.

While these assumptions are thought to be reasonable considering the scope and scale of the project, the results should be considered within the context of these assumptions. It should also be recognized that, for some local areas within the model volume, these assumptions will not be valid.

1.2.3.   *Inversion Methodology*

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, 2008, and Fullagar and Pears, 2007).

In VPmg, each volume of the subsurface is assigned to a rock unit. The shape and petrophysical properties (density or susceptibility) of each unit can change during inversion, but its geological identity is preserved. Geological contacts can be fixed (where pierced by a drill hole for example), bounded, or free to move during inversion. Upper and lower bounds can be imposed on each unit's physical properties, and observed 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 (Figure 2). 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 discretization. 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 with physical properties varying in all directions.
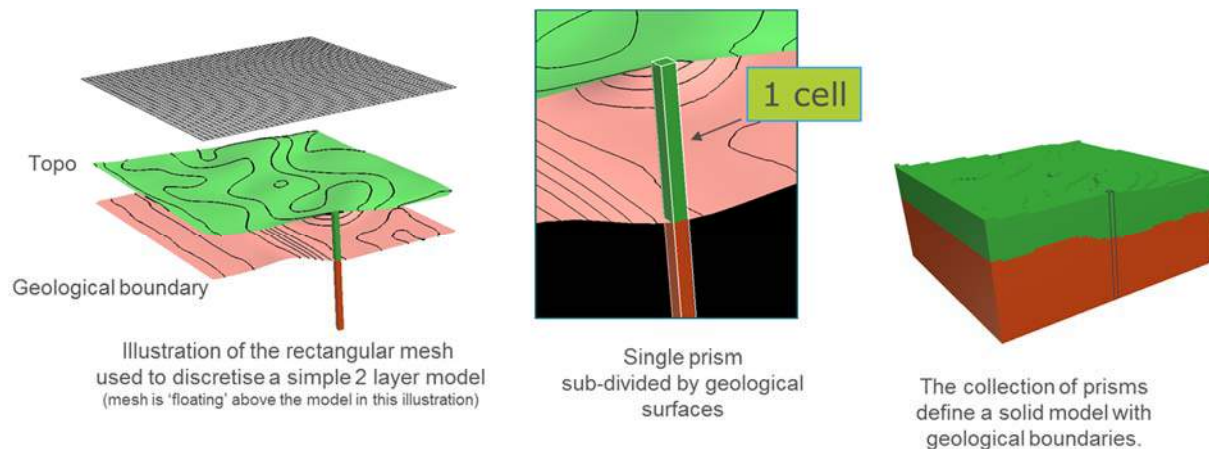
Figure 2. Illustration of VPmg model parameterisation for a simple two layer model comprising cover and basement.

The local model parameters can be adjusted by inversion until the gravity, gravity gradient, magnetic, 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 (Figure 3). During property inversion, model contacts (geometry) are fixed, and homogeneous or heterogeneous physical property values are calculated. 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.

The root mean square (RMS) misfit characterizing the difference between the observed data and data calculated from the model result is used to assess how well the inverted model explains the observed data. The succession of inversion types used is not standard for each model and varies to best fit the geologic setting, modelling objectives, and data for each area. Results improve through incorporation of additional relevant geological and physical property constraints.

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.
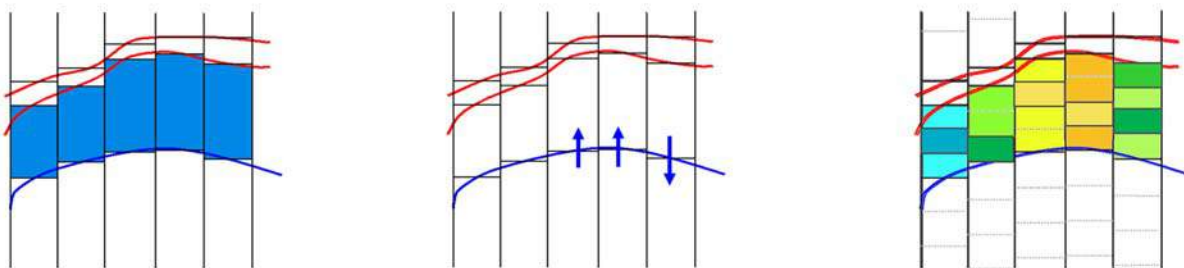
Figure 3. Schematic illustrations of VPmg inversion styles; homogeneous unit inversion (left), geometry inversion (centre) and heterogeneous property inversion (right).

1.3. **Geologic Setting**

1.3.1.   *The Nechako-Chilcotin plateau*

The Nechako-Chilcotin plateau lying within the south-central Intermontane Belt of British Columbia, is the setting of a series of Jurassic-Cretaceous to Paleocene sedimentary basins which have potential for hosting hydrocarbons (Riddell, 2011, and references therein). These basins formed as a result of uplift, deformation, and erosion of North American continental rocks and amalgamated terranes. The basins of greatest interest are those hosting large volumes of coarse clastic sedimentary successions that were deposited at the end of the Early Cretaceous. Structure development, as well as magmatism and burial related to compression tectonics in the middle to Late Cretaceous and transtensional regimes in the Eocene led to optimal conditions for hydrocarbon development and maturation (Riddell, 2010).

An incomplete picture of the extent, depth, and volume of these sedimentary basins exists due to deformation and dismemberment occurring during Cretaceous to Eocene time. Additionally, due to overlying Eocene and Miocene age volcanic sequences, and presence of significant glacial till coverage, there is minimal surface exposure of the Cretaceous and Eocene sedimentary basins of interest.

1.3.2.   *General Nechako-Chilcotin Plateau Stratigraphy*

Devonian to Jurassic Hazelton group volcanic and sedimentary stratigraphy of the Stikine volcanic arc terrane underlies much of the project area.

Early and Middle Jurassic strata consist primarily of basaltic and andesitic lava flows, sedimentary rocks, lapilli tuff and rhyolite ash flows generally prescribed to the Hazelton Group. Middle to Upper Jurassic strata are composed of sandstone, conglomerate, shale and minor calcareous sediments, andesitic, rhyolitic, and basaltic flows associated with tuff, breccias and volcaniclastic sandstone and conglomerate (Riddell, 2006).

Thick sedimentary sequences of marine to non-marine clastic material formed in syn-orogenic basins during compressional-transpressional tectonic regimes active during the Cretaceous. Prospective Cretaceous sedimentary rocks are generally poorly exposed, documented locally primarily in the northwest Nechako-Chilcotin plateau, in the Nazko Valley, and near the Chilcotin Mountains, south of the study area (Riddell, 2011). Sequences are additionally logged in several oil and gas wells drilled in the area (Riddell et al., 2007, and references therein), but the full extent of these sequences is unknown.

Over 25,000 km^2 of Eocene volcanic rocks have been mapped in the Nechako-Chilcotin plateau (Bordet et al., 2014). A change from transpressional to transtensional deformation in the Eocene was accompanied by volcanism, and deposition of thick volcanic sequences in association with development of extensional fault systems and pull-apart basins.

Eocene volcanic rocks have been traditionally divided into the Ootsa Lake Group and the Endako Group. The Ootsa Lake Group comprises flow-banded rhyolite, dacite, amygdaloidal basalt flows and minor andesite flows and tuff units locally interbedded with alternating sandstone and coarse pebble-to-cobble conglomerate beds. The Endako group consists of andesitic basalts and basalt flows.

Unconformably overlying the Eocene volcanic sequences are the Neogene Chilcotin group flood basalts. These are generally flat-lying to shallow dipping basalt lavas with minor pillow basalts and hyaloclastite. They cover an area of greater than 30,000 km^2 in central BC (Andrews and Russell, 2007).

A simplified stratigraphic log representing geology within the project area is shown in Figure 4. For a more detailed stratigraphy of the Nechako study area, please refer to Bordet et al. (2011).
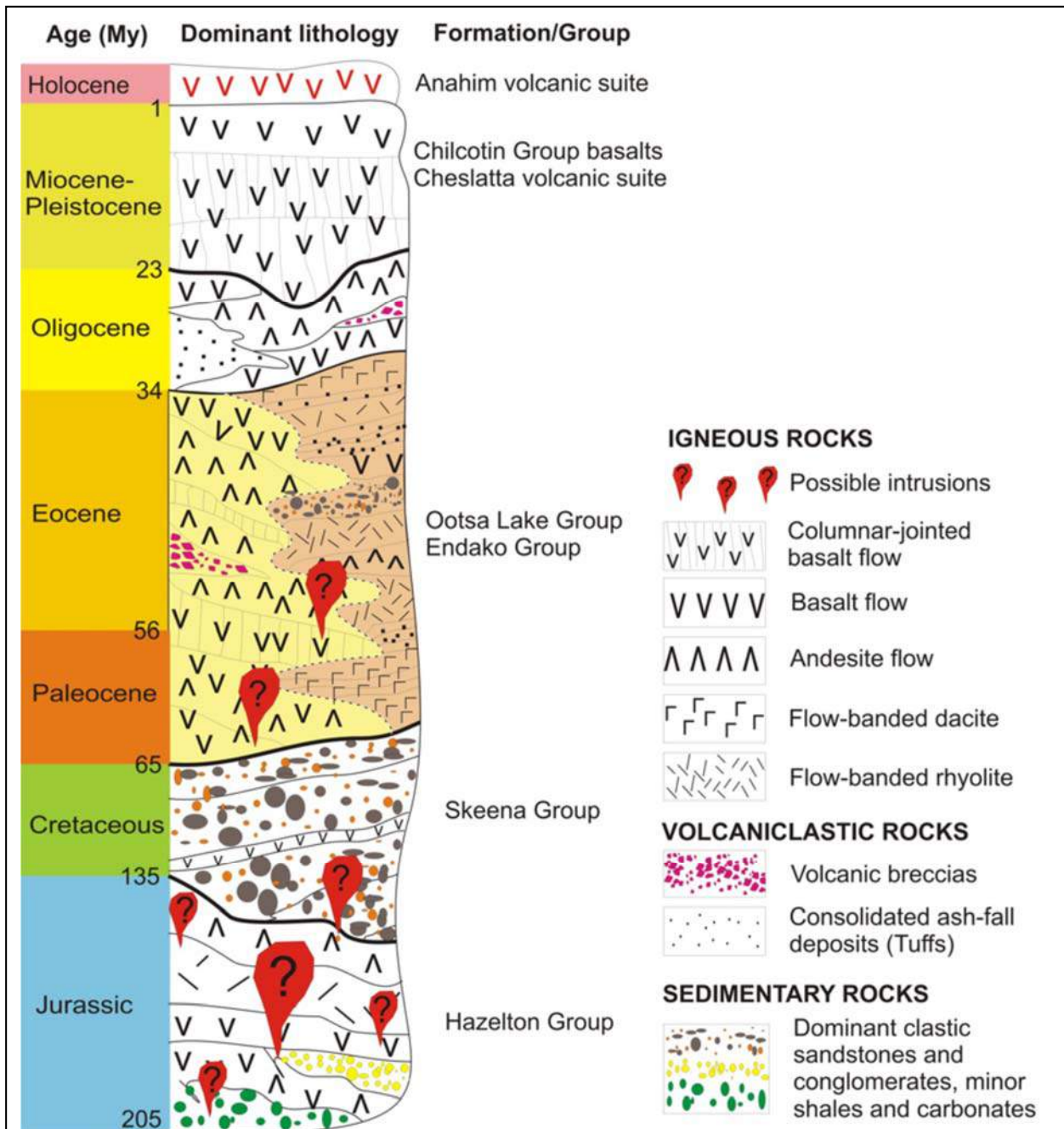
Figure 4. Simplified regional stratigraphy for the Nechako-Chilcotin plateau study region, central British Columbia. From Bordet et al., 2011.

2. Data

2.1. Coordinate System and Datum

The data and models for the Nechako-Chilcotin plateau project were compiled in the NAD 83 UTM zone 10 datum and projection.

2.1. Geological Observations

2.1.1. Maps

A geologic map of the Nechako-Chilcotin plateau area was obtained from Riddell (2006; **Error! Reference source not found.**) and covers NTS zones 92N, 92O, 93B, 93C, 93F, and 93G. Riddell (2006) completed this map as a geologic compilation of the Nechako area.

2.1.2. Wells

Oil and gas exploration in south-central British Columbia began in 1931. Between 1931 and 1986 twelve exploratory wells were drilled in the Nechako-Chilcotin plateau basins. The data obtained from the wells has been revisited in an effort to extract new data from old wells, using old drill cuttings and core, radiometric age dating, fission track analysis, and petrophysical analysis from log data. Well logs and reports are available from the Ministry of Energy and Mines website (http://www.empr.gov.bc.ca). Lithology data for eight of the wells were obtained (**Error! Reference source not found.**).
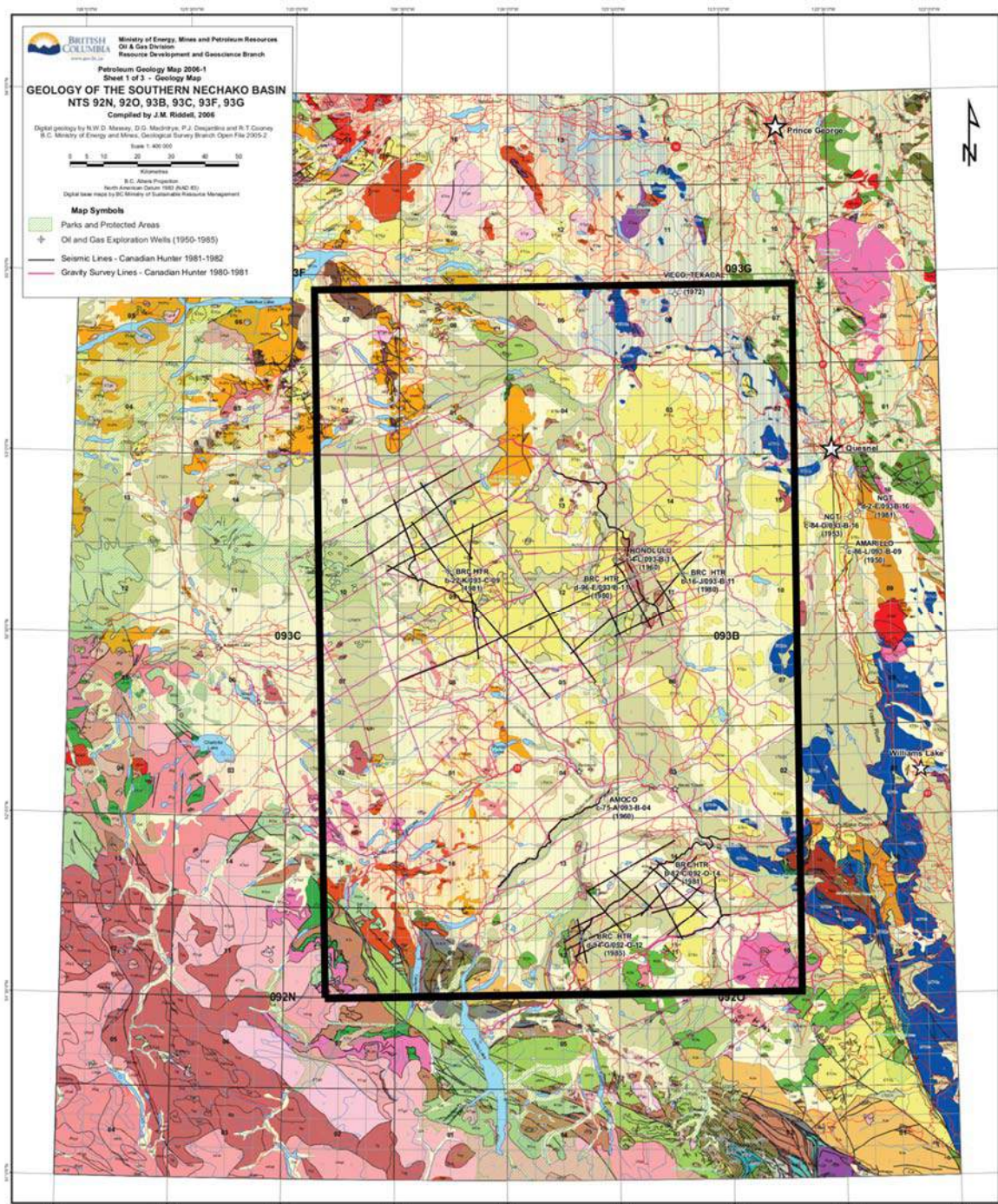
Figure 5. Geologic map of the Nechako-Chilcotin plateau area compiled by Riddell (2006). Project area outlined by black rectangle. Note the cities of Prince George, Quesnel, and Williams Lake are shown as stars on the right side of the map as points of reference.
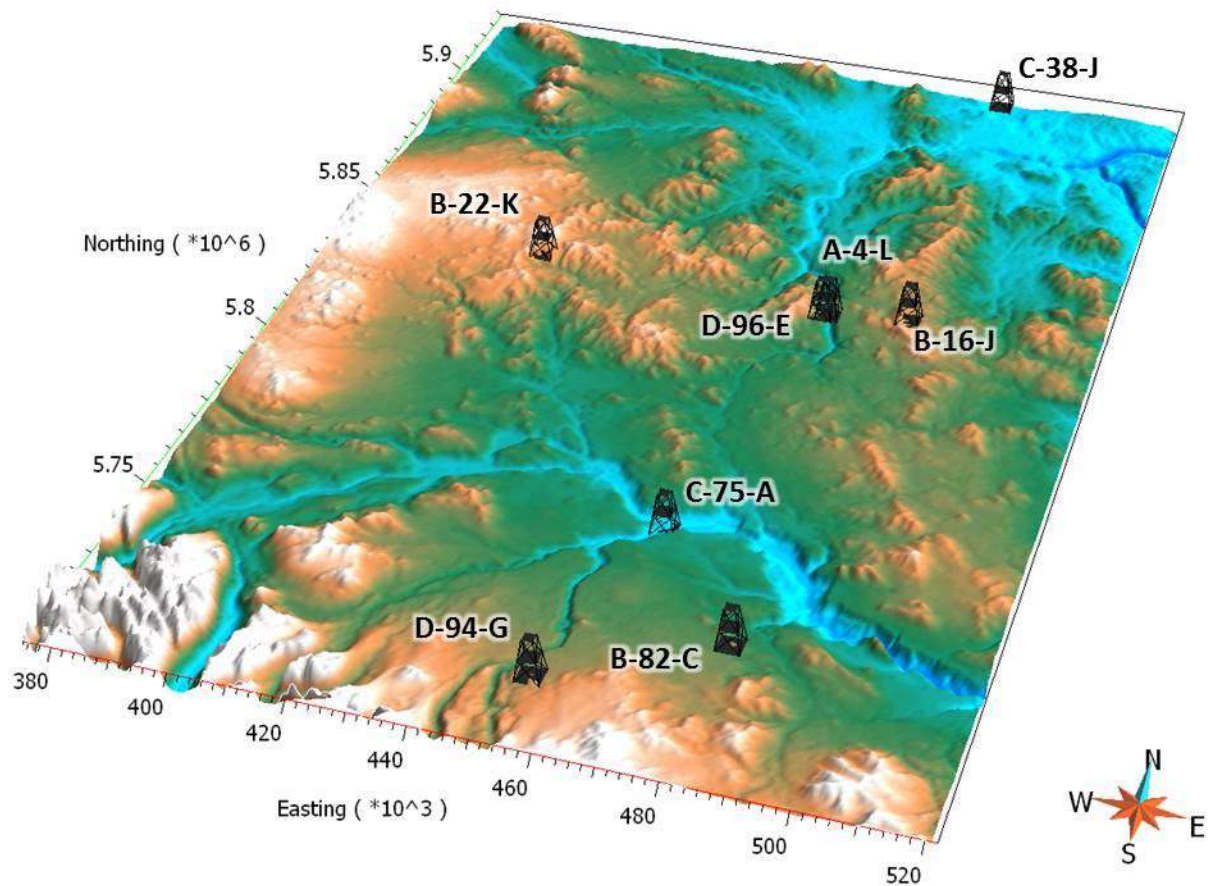
Figure 6. Locations of eight wells with geologic information within the project area. Topography is also shown with a vertical exaggeration x5.

2.2. **Topographic Data**

Public-domain topographic data that covers the project area were utilized in the modelling effort. Shuttle Radar Topography Mission (SRTM) elevation data were obtained from the NASA Jet Propulsion Laboratory website to create a digital elevation model (DEM) for the project area (Figure 7).
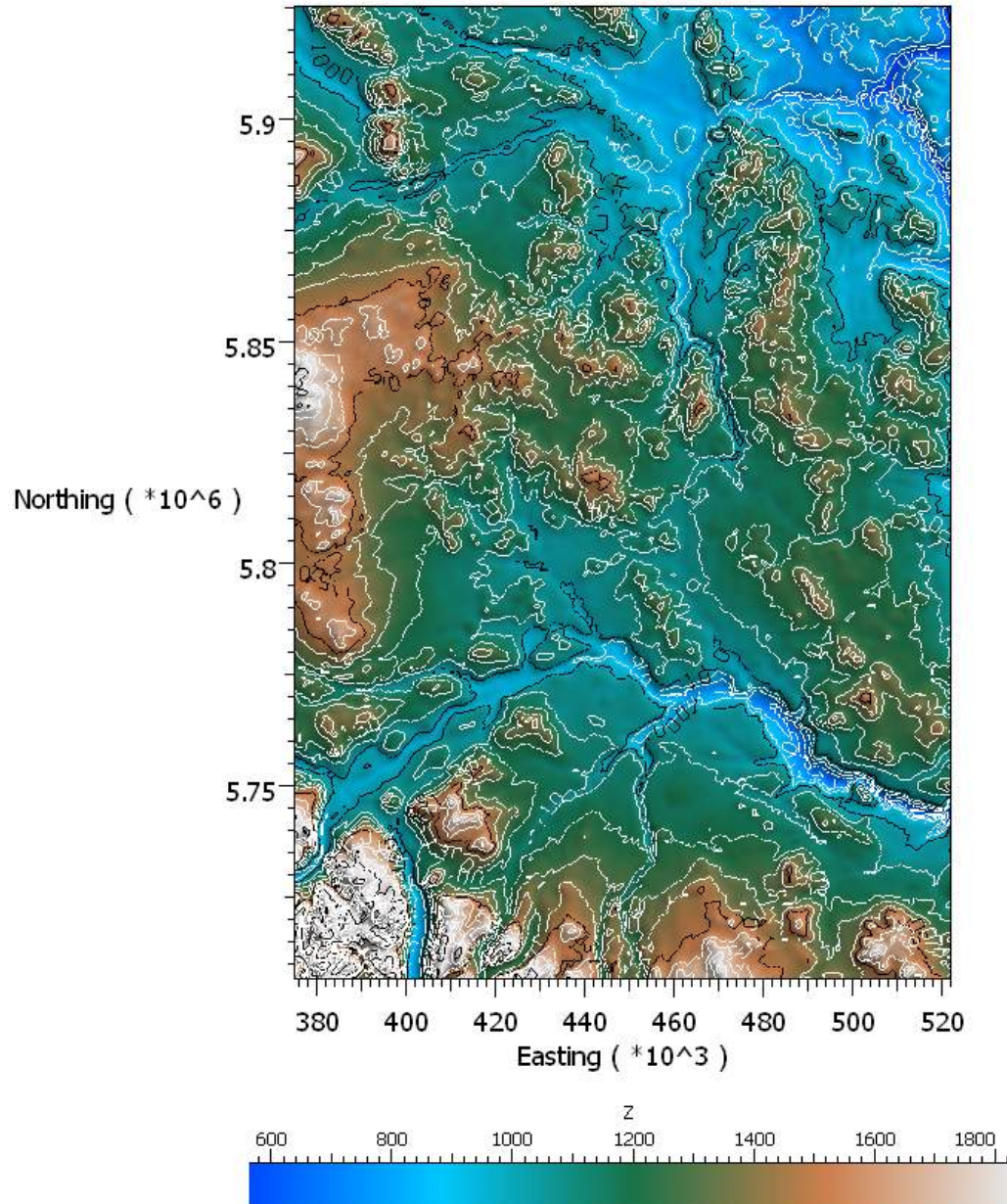
Figure 7. Topographic data covering the project area. Map shows 100 m contours.

2.3. **Geological Interpretations**

2.3.1.   Seismic Interpretations

In the early 1980's, Canadian Hunter Exploration completed several integrated gravity and seismic surveys (**Error! Reference source not found.**). These data were reprocessed by Arcis Corporation in 2006. Stratigraphic control was provided from drill hole data and the bedrock geological compilation was completed by Riddell (2006). A structural and stratigraphic interpretation of the seismic lines was completed by Hayward and Calvert (2011).

Additional seismic data was acquired in 2008 through a project funded by Geoscience BC and the Northern Development Initiative Trust Pine Beetle Recovery Account (Calvert et al., 2009). These data and subsequent interpretations were also used for building the initial geologic model and for constraining the inversions.
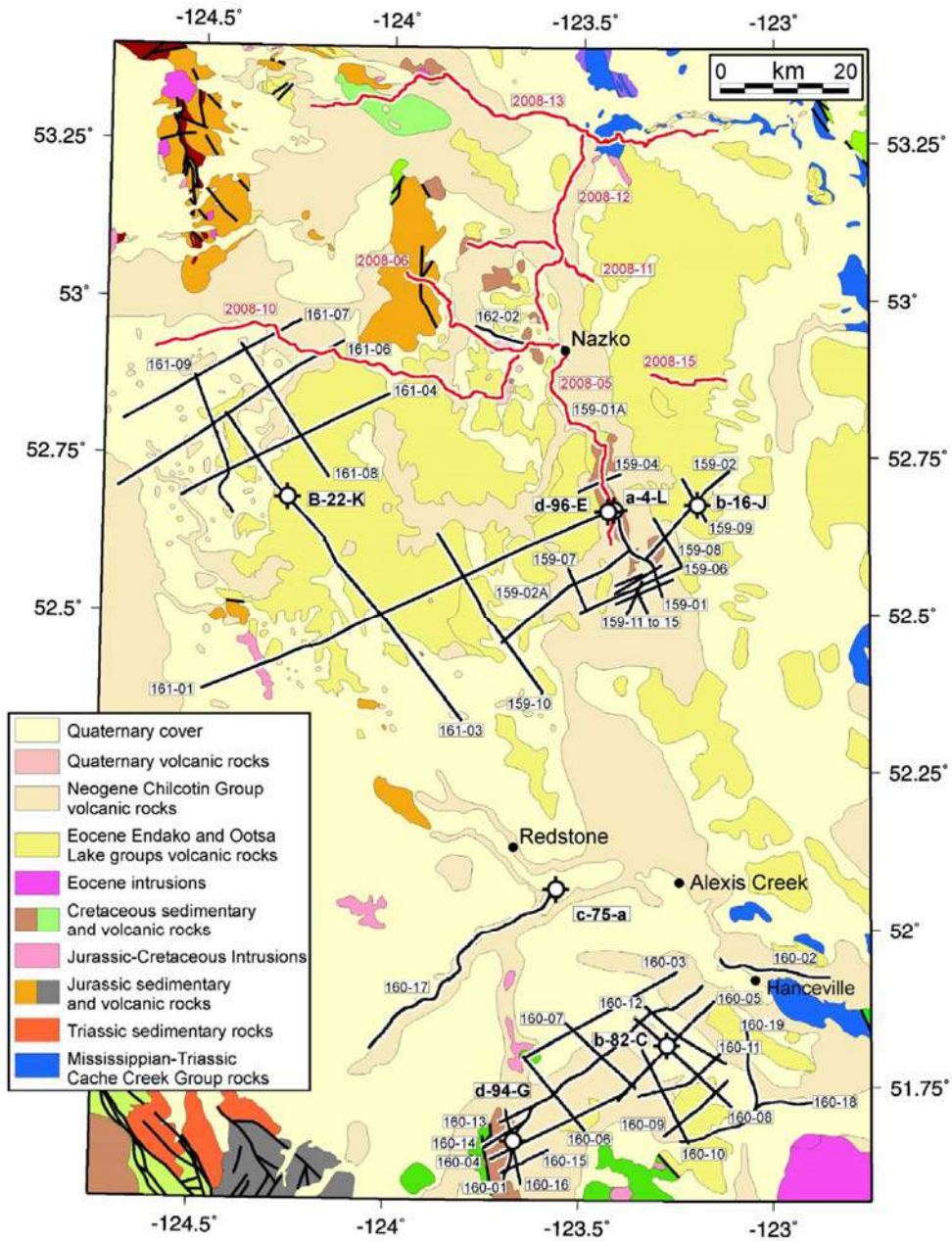
Figure 8. Geologic map of the Nechako-Chilcotin plateau area with the locations of Canadian Hunter Ltd. seismic lines (black), and seismic lines from the 2008 Geoscience BC survey (red) (from Calvert et al., 2009).

2.3.2. Magnetotelluric Interpretations

In the fall of 2007, 734 combined broadband and high frequency magnetotelluric (MT) sites were deployed throughout the Nechako-Chilcotin plateau to help evaluate the hydrocarbon potential of the area. Data from sites concentrated along roads and along seismic lines were inverted to generate 2D conductivity sections. The 2D conductivity sections were interpreted for lithology by Spratt and Craven (2011). Eight MT sections were imported into the study dataset (**Error! Reference source not found.**), and the interpretations of Spratt and Craven (2011) were re-digitized to represent lithological boundaries.
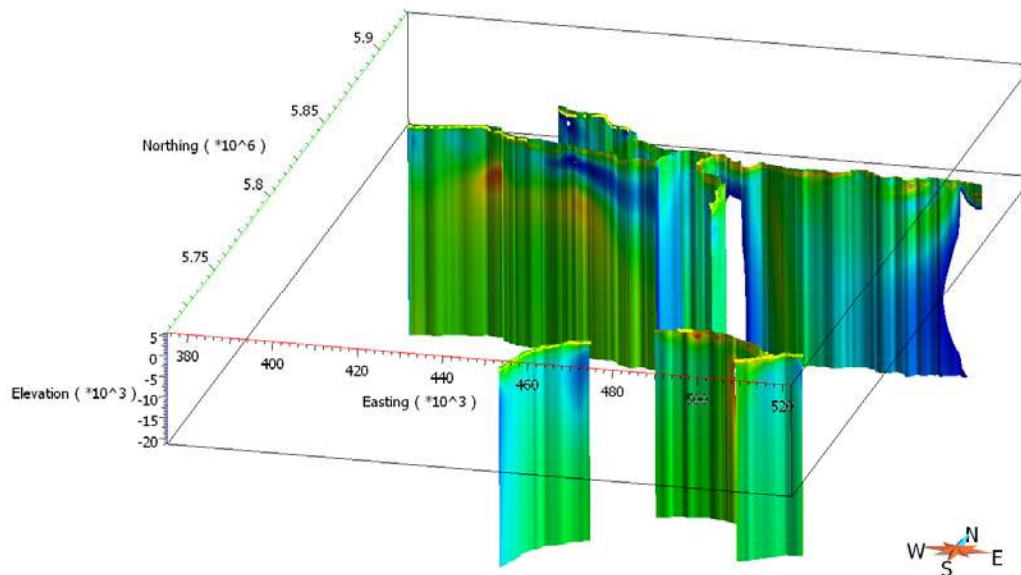
Figure 9. 3D perspective view looking to the NNW showing 2D magnetotelluric conductivity models. Warm colours represent high conductivity and cool colours represent low conductivity. Vertical exaggeration x3.

A 3D MT model of conductivity was also provided to Mira Geoscience for this project from research conducted at the Memorial University of Newfoundland (M.Sc. thesis, Drew, 2012). This 3D conductivity model (Figure 10) provided an additional constraint on the thickness of Miocene Chilcotin and underlying Eocene volcanic units. This model was preliminary, and final model results were not available for reference at the time of geological model building.
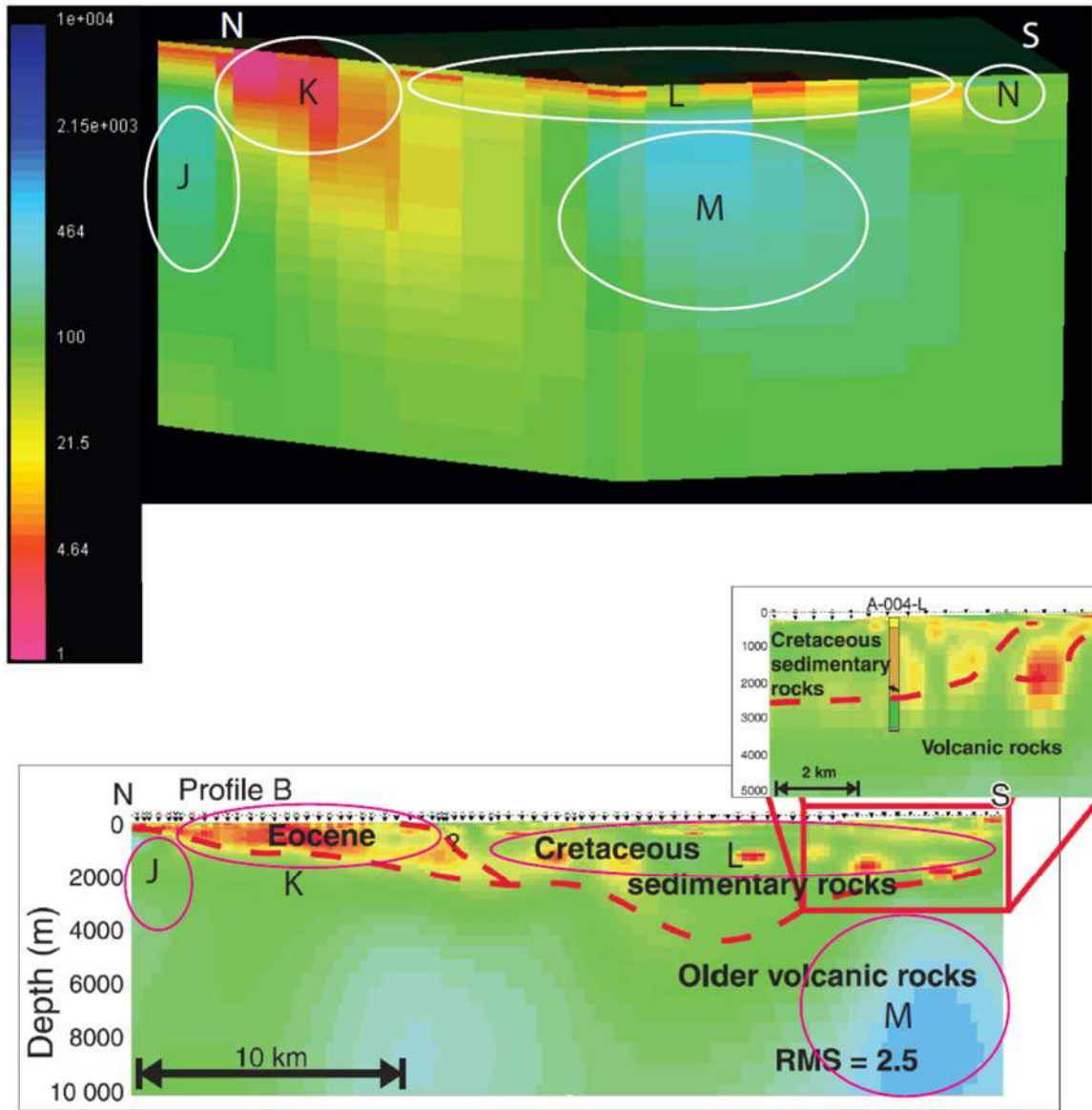
Figure 10. A comparison of a slice through 3D MT inversion model from Drew (2012) (top) to a 2D MT inversion section from Spratt and Craven (2010) (bottom). Colour bar shows units in Ohm-m for both models.

2.4. **Physical property Data**

Several sources of physical property data exist with coverage over the study area. Geoscience BC funded an investigation of the physical rock properties to aid in the interpretation of the extensive geophysical data collected over the area (Andrews et al., 2011). Enkin et al. (2008) provides a compilation of physical properties and paleomagnetic data for South-Central British Columbia. Compiled physical property data include bulk density, connected porosity, magnetic susceptibility, magnetic remanence, electrical resistivity, chargeability, and seismic velocity. Mira Geoscience has focused on the bulk density and magnetic susceptibility properties as they provide direct input for magnetic and gravity inversion modelling. Samples collected by E. Bordet in the 2010 and 2011 field seasons were a principal source of physical property data. The bulk densities of all samples from the E. Bordet sample suite were measured using the hydrostatic method (Johnson and Olhoeft, 1984). Magnetic susceptibilities were measured at each outcrop using a hand-held magnetic susceptibility meter, and minimum, maximum, and average susceptibilities per outcrop were compiled. These data were compared with the Enkin et al. (2008) physical property database to ensure consistency and to modify ranges as necessary.

2.5. **Geophysical Data**

2.5.1. *Airborne Gravity Data*

Airborne gravity data was collected by Sander Geophysics and made available through Geoscience BC (Sander Geophysics Limited, 2008). These data were acquired during a helicopter-borne gravity survey carried out between March 1st and March 23rd, 2008. The data were acquired using an AIRGrav gravimeter installed in an Astar helicopter. The traverse line spacing was 2000 m (E-W) with a control line spacing of 10 km, and the average aircraft altitude was 150 m above ground. The data were provided as free-air corrected gravity, intersection adjusted, with a 100 s full wavelength line filter applied.

2.5.2. *Ground Gravity Data*

Land-based, regional ground gravity data were acquired by Canadian Hunter Exploration as part of their integrated seismic and gravity surveys in the 1980's. For the areas surrounding the Nechako-Chilcotin plateau, regional land-based free-air gravity data were acquired from Natural Resources Canada.

2.5.3. *Magnetic Data*

Regional magnetic data were downloaded from the Natural Resources Canada Geoscience Data Repository (http://gdr.agg.nrcan.gc.ca/gdrdap/dap/search-eng.php). The regional magnetic data was collected from 1947 to present and consists of 500 surveys generally with a line spacing of 800 m and an altitude of 305 m above ground. The data were supplied already levelled, and gridded at 200 m.

These data sources were combined to provide Total Magnetic Intensity data coverage over the entire study area. All supplied data were checked for quality and consistency, processed and edited if necessary, re-sampled, and converted to a format suitable for 3D magnetic inversions.

3. Data Preparation and Processing

All of the input data were carefully prepared and processed to provide a consistent high quality data set ready for the geological and geophysical inversion modelling stages. This ensured all data being used are clean, well-suited for the modelling objectives, and non-contradictory in nature.

3.1. Physical Property Analysis

Physical property data analysis was completed on data from Bordet et al. (2011) in order to define typical values and ranges of magnetic susceptibility and density for the key geological domains to be modelled using inversion. Physical property statistics were calculated for each lithologic age group based on sample measurements from Bordet et al. (2011): Miocene (Chilcotin basaltic rocks), Eocene (primarily volcanic rocks), Cretaceous (primarily sedimentary rocks), and Jurassic (volcanic and intrusive basement rocks). The mean, minimum, 20th percentile, 80th percentile, and maximum magnetic susceptibility and density values were calculated. These statistical results are used to constrain the physical property distributions, and subsequently the contact surfaces, of the related geologic domains during VPmg inversion modelling.

Magnetic and density data for Miocene Chilcotin basalt samples and the Cretaceous sedimentary rock samples were generally homogeneous, occurring over limited ranges with some outliers.

Bordet et al. (2011) data revealed significant compositional and textural heterogeneity within Eocene age formations. This leads to highly variable physical properties within the Eocene sample suite. Physical property statistics were calculated separately for each of four compositional rock groups, andesite, dacite, rhyolite, and volcaniclastic rocks, to develop an understanding of more fine-scale physical property distributions within Eocene rocks. The data indicated important differences between the different lithologies, however, the scale at which geophysical data were to be inverted for this project would not allow detailed modelling of Eocene physical property variations. As such, physical property statistics representing the full suite of Eocene samples were applied, meaning that a large range of susceptibilities and densities would be allowed during modelling of geologic domains assigned as Eocene. Future work involving modelling of Eocene

stratigraphy may attempt to further subdivide geology using physical property statistics generated from the different Eocene lithologic groups.

Bordet et al. (2011) Jurassic samples were restricted to Hazelton Group volcanic rocks, which have a narrow range of densities, but a wide range of susceptibilities.

Comparison to other datasets was necessary to gather additional rock property information for under-sampled formations of Cretaceous and Jurassic age. Data from Enkin et al. (2008), Andrews et al. (2011), and Quane et al. (2010) indicate generally consistent magnetic susceptibility and density values for Cretaceous sedimentary rocks compared to those from Bordet et al. (2011).

The lowermost geologic domain within the geologic model constructed for this study is generalized as 'basement'. For modelling, basement was considered to be composed of Jurassic volcanic and plutonic rocks as well as overlying Cretaceous volcanic rocks. Jurassic-age samples from the various physical property studies exhibit a large range of densities and susceptibilities reflecting highly variable volcanic and sedimentary Jurassic stratigraphy as well as the presence of plutonic rocks. As a result of these observations, the magnetic susceptibility and density ranges for Jurassic rocks defined by the Bordet et al. (2011) samples were modified to allow for a larger range of physical property values to be modelled in the basement.

The physical property values used for the VPmg modelling are summarized in Table 1 and Table 2. An important density contrast occurs between the 'basement' and overlying units, and an important magnetic susceptibility constrast occurs between the Cretaceous sediments and other units.

Table 1. Density properties used for VPmg modelling.

Simplified stratigraphic unit for VPmg modelling	Median density (g/cm³)	20th percentile Density (g/cm³)	80th percentile Density (g/cm³)	*Notes*
Chilcotin	2.63	2.54	2.77	
Eocene volcanics	2.47	1.89	2.61	*Median for dacites used, range is for all Eocene samples*
Cretaceous sediments	2.47	2.42	2.55	
"Basement" (Cret. volcanics + Jurassic volcanic + plutonic rocks)	2.75	2.5	2.9	*E. Bordet data used, but with ranges chosen to account for plutonic rocks*

Table 2. Magnetic susceptibility properties used for VPmg modelling.

Simplified stratigraphic unit for VPmg modelling	Median magnetic susceptibility (x10⁻³ SI units)	20th percentile magnetic susceptibility (x 10⁻³ SI units)	80th percentile magnetic susceptibility (x10⁻³ SI units)	Notes
Chilcotin	9.89	3.524	13.77	
Eocene volcanics	9	2	22.96	*Median for dacites used, range is for all Eocene samples*
Cretaceous sediments	0.19	0	0.295	
"Basement" (Cretaceous volcanics + Jurassic volcanic + plutonic rocks)	3.54	0	15	*E. Bordet data used, but with ranges accounting for plutonic rocks*

3.2. **Stratigraphic Simplification**

Within the Nechako study area there are significant compositional and textural variations within and between the various geologic units. For initial modelling purposes, the first step was to create a simplified stratigraphic column subdivided by key geological and physical property boundaries that could be applied to the entire study area. The simplified stratigraphic column consisted of (from oldest to youngest): Jurassic and older volcanic rocks, Cretaceous volcanic rocks with lesser sedimentary rocks and plutonic rocks (grouped with Jurassic rocks and included as 'basement'), Cretaceous sedimentary rocks, Eocene volcanics and volcanoclastic rocks, and Miocene basaltic rocks (generally referred to in this report as the "Chilcotin" basalts). Two primary physical property distinctions were also used to define these units: 1) an inferred density contrast between the Cretaceous sedimentary rocks and underlying Mesozoic 'basement', and 2) a susceptibility contrast between Eocene volcanic and volcaniclastic rocks and underlying Cretaceous sedimentary rocks. These physical property contrasts existing between different pairs of geologic units in different property space (magnetic and density) allows for the integrated geological and geophysical modelling to be possible; where one contact may not be distinguished using magnetics (or magnetic susceptibility), there is an opportunity for it to be distinguished using gravity (or density).

Although a density contrast does exist between the Miocene basalts and the Eocene volcanic rocks, this contrast did not come into play in the VPmg modelling, primarily due to the relative thinness of the Miocene cover rocks as compared to underlying geologic units.

The stratigraphic simplification and associated physical contrasts are presented in Figure 11**Error! Reference source not found.**

Figure 11. Original Nechako stratigraphy from Bordet et al. (2011) paired with the simplified stratigraphy used in the VPmg modelling.

3.3. **Geological Interpretation**

Given the stratigraphic simplification described above, a geologic outcrop map was prepared to be consistent with the geologic domains to be used for inversion (**Error! Reference source not found.**). A significant amount of Quaternary cover is present in the Nechako-Chilcotin plateau, however, geologic contacts to be used for 3D modelling and inversion work were interpreted assuming no cover as the cover would not be modelled at the scale of the inversion.
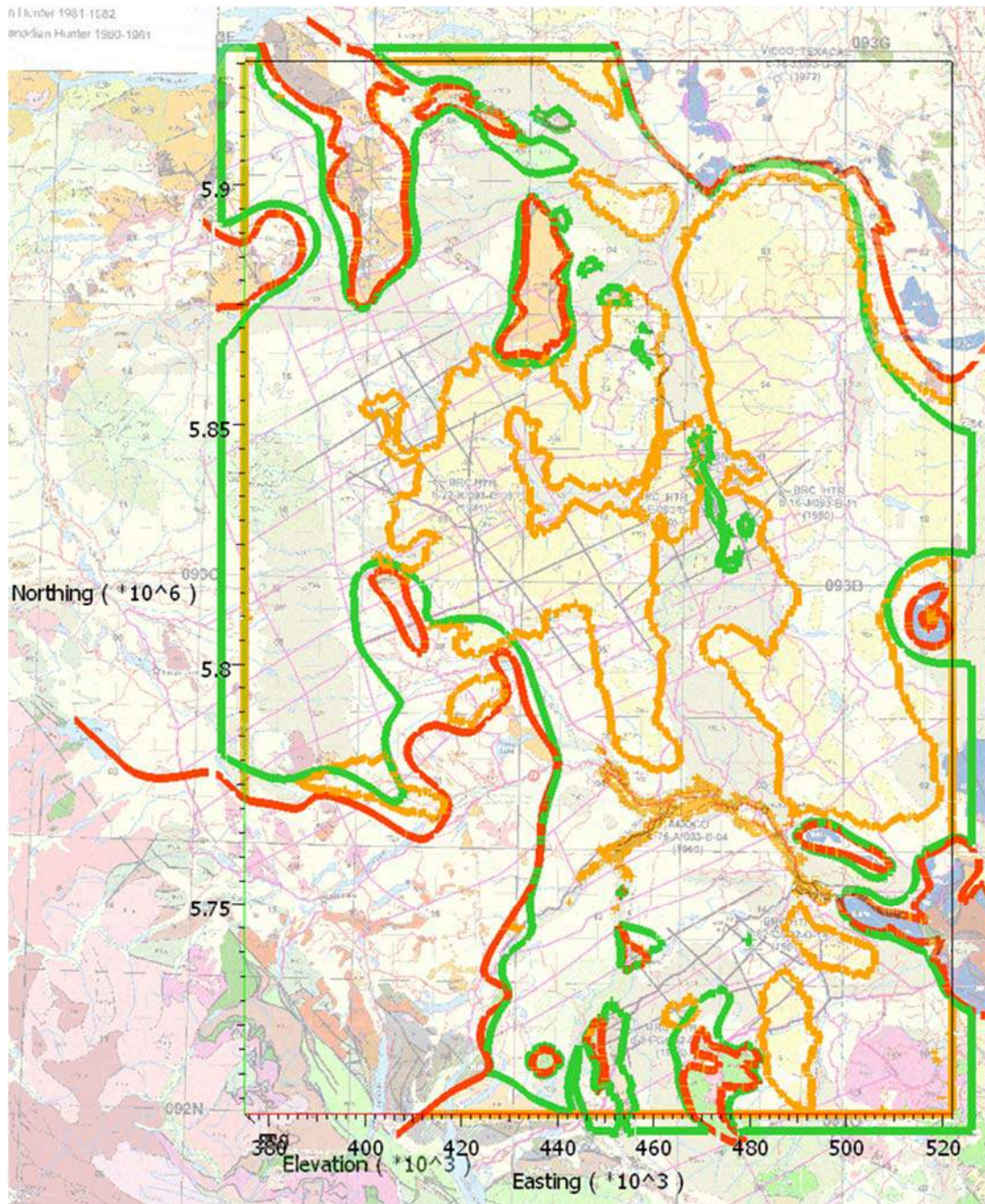
Figure 12. Observed and inferred geologic contacts digitized from geologic map of the southern Nechako-Chilcotin plateau compiled by Riddell (2006). Orange curve indicates geologic contacts representing the top of the Eocene, green indicates contacts representing the top of the Cretaceous, and red indicates contacts representing the top of the basement. Quaternary cover rocks were not included in the modelling, thus were not digitized.

3.4. **Seismic Time-to-Depth Conversion**

Seismic sections used for this study were provided to Mira Geoscience in SEG-Y format with time as the z-axis. For these seismic sections (and interpretations derived from them) to be used in the modelling project, both the sections and the interpretations needed to be converted from the time domain to the depth domain (in the z-axis). Seismic velocity data were provided along with the seismic sections, to aid with the time-to-depth conversion. The velocity data were interpolated into a 3D cube surrounding the survey area (Figure 13) and then smoothed horizontally to minimize any artifacts that may have resulted from the initial interpolation. The data within this 3D velocity cube was transferred to each individual seismic section, creating individual velocity profiles for each section. A time-to-depth conversion was then calculated for each section, shifting both the sections and interpretations into the depth domain ready for geologic modelling (Figure).
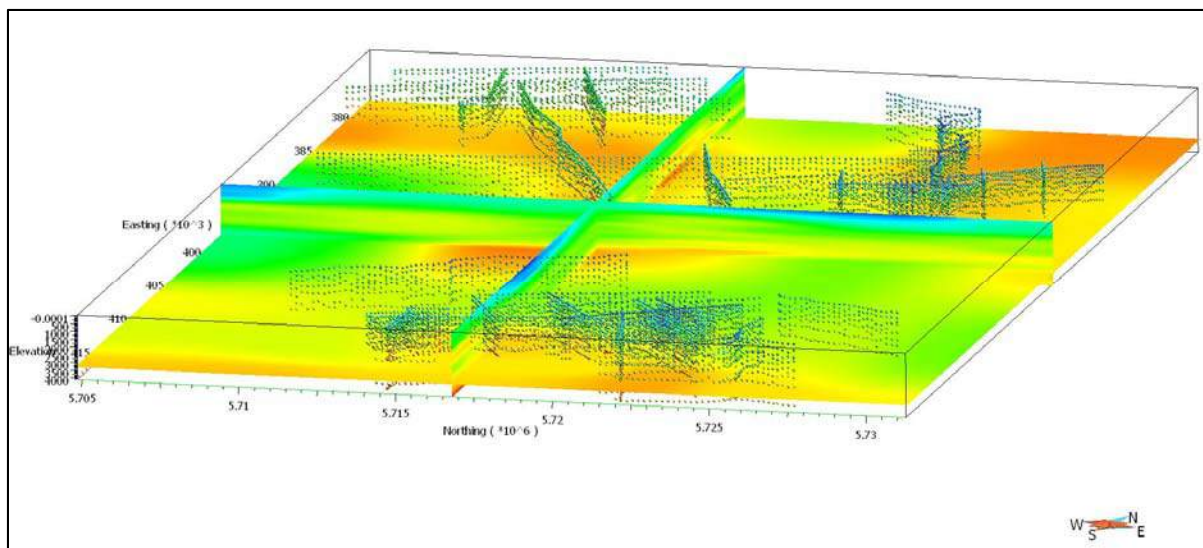
Figure 13. 3D perspective view of the velocity cube interpolated from velocity data on the seismic lines. Vertical exaggeration x3. Points represent velocity data on the seismic lines from which the interpolation is done. Warm colours in the model represent high seismic velocity while cool colours represent low seismic velocity.
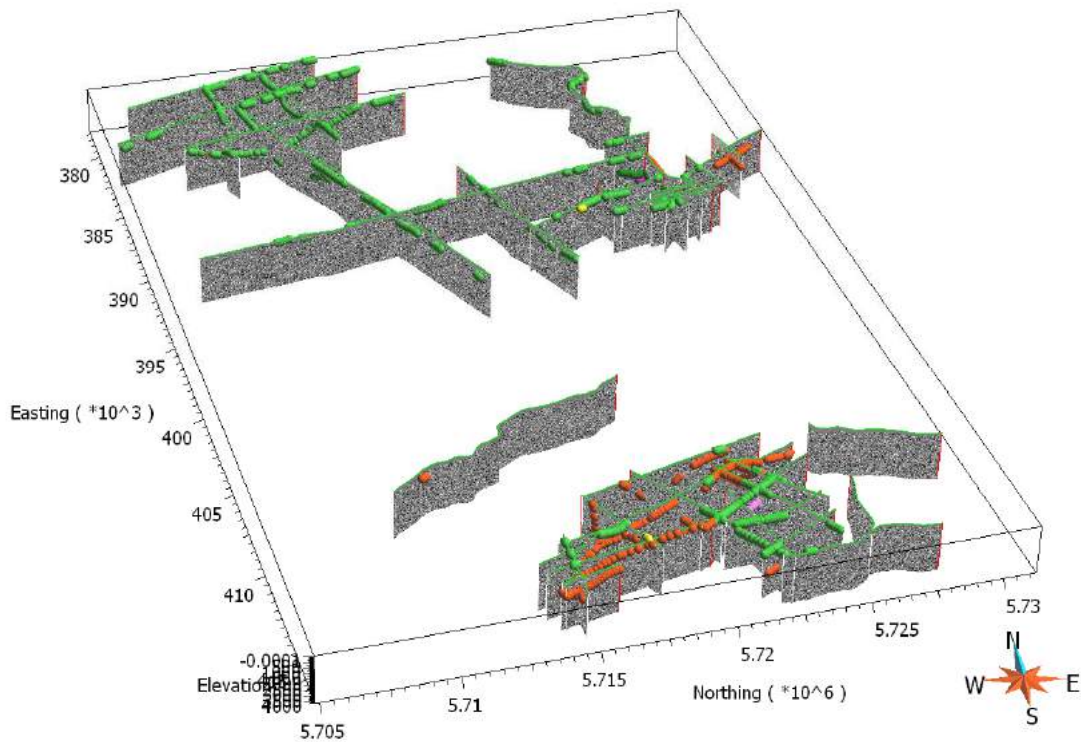
Figure 14. 3D perspective view of the seismic sections and horizon interpretations. Yellow represents the top of Eocene volcanics as interpreted from seismic lines, green represents the top of Cretaceous sedimentary rocks, orange indicates top of basement (Jurassic + Cretaceous volcanics), and dark green is the top of Jurassic basement. Pink and red curves represent tops of intrusive units. Vertical exaggeration x2.

3.5. **Gravity Data Preparation**

Gravity data sourced from the Geological Survey of Canada (GSC), Canadian Hunter Exploration, and from the Geoscience BC Sander Geophysics airborne gravity survey were merged into a single, consistent data set for modelling. The Canadian Hunter and GSC ground data were prepared through upward continuation to a height of 150 m above the ground, while the airborne data are draped on the flight height surface. The merging process involved a model-based merging sequence (using inversion) so the merged data were still consistent with the gravitational field. A

terrain correction was applied to the data using a density of 2.47 g/cm^3, and a regional signal was removed. The residual gravity data that resulted after the regional removal were gridded at the same resolution as the lateral model cells (1000 m) to provide some regularization in the inversion (Figure 15).
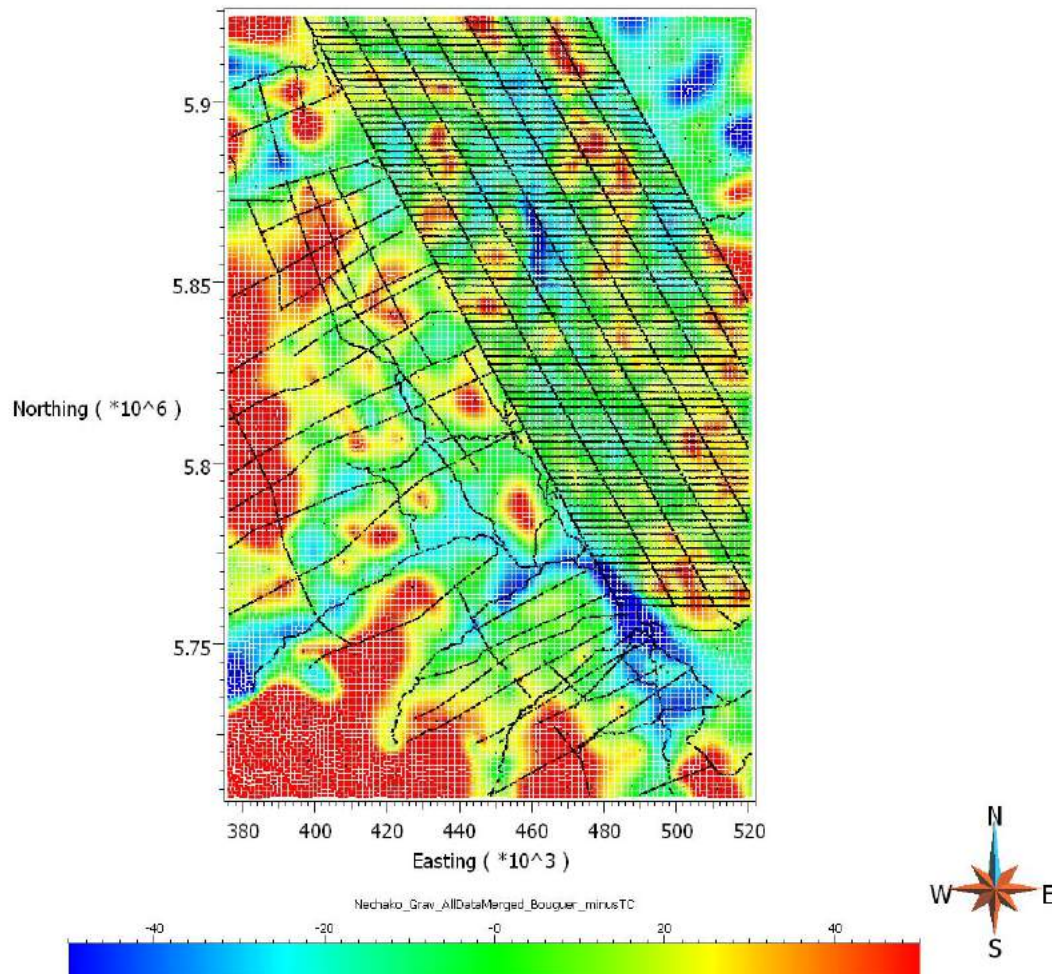
Figure 15. Merged, gridded gravity data from Canadian Hunter, Geological Survey of Canada, and Geoscience BC surveys. Black lines and points represent data along flight lines and from ground gravity surveys.

3.6. **Magnetic Data Preparation**

The magnetic data were extracted from the 200 m GSC magnetic grid to create a 1000 m grid to coincide with the 3D grid cell size used for geological and inversion modelling (Figure 16). The height of 305 m above topography was retained, the height at which the GSC data was originally levelled. No other processing was necessary.
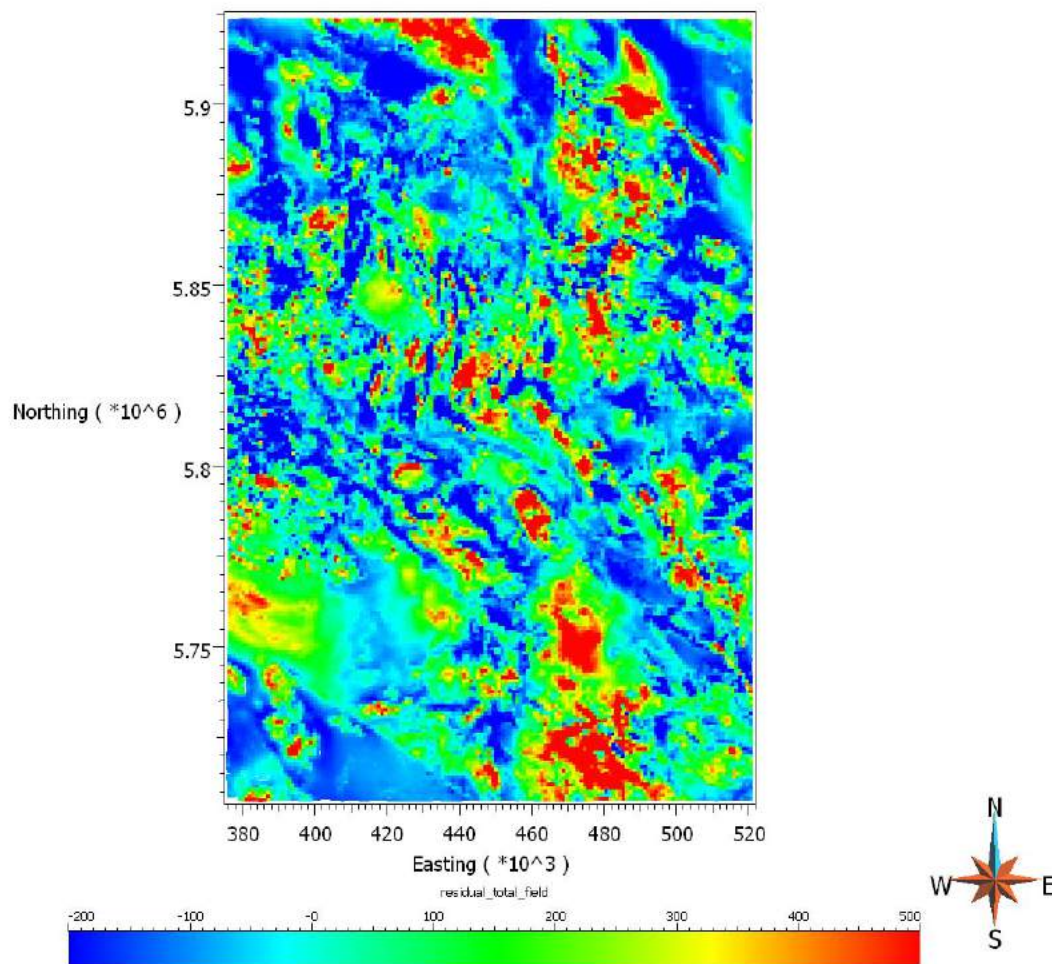
Figure 16. Magnetic data from Natural Resources Canada gridded at 1000 m.

4. Earth Modelling

4.1. Geological Modelling

4.1.1.   Methodology

The first steps in creating a starting geologic model to be submitted for VPmg inversion modelling was to geo-register the geologic map and to drape it on the topography. Five sources of geologic information were used to constrain geologic contact surfaces: outcrop geology, drill hole geology, interpreted geology from seismic lines, gravity data, and interpreted geology from magnetotelluric (MT) inversions. Using the geologic map, the outlines of outcrop (both known and inferred) were digitized onto topography as curves (Figure 17). These curves were used as constraining information for construction of geologic surfaces. Initial surfaces were fit to the outcrop constraints and were warped to fit the available geologic data in drill holes within the study area. These drill hole intersection points were then set as fixed points to be honored throughout the modelling process. Geologic horizons interpreted from the seismic sections (Hayward and Calvert, 2011) were digitized as curves and introduced into the 3D geologic model (Figure 17). Geologic surfaces were warped to fit these interpreted contacts to within a tolerance of 100 m. The Bouguer gravity map from Hayward and Calvert (2010) was used as a general guideline to create basins in the Jurassic (plus Cretaceous volcanics) 'basement' surface. Where significant gravity lows were apparent, it was assumed that there would be a larger volume of low density Cretaceous sedimentary rocks. Cretaceous (and Eocene) basins cutting into the underlying basement were approximated at these locations using the shapes of the gravity lows as guides, while respecting the previous constraints applied to the geologic surfaces (Figure 18). Finally, geologic interpretations from MT models were incorporated as geologic surface modelling constraints. Spratt and Craven (2011) identified the top of the Eocene (bottom of Chilcotin basalts) as the boundary between a thin, near-surface resistive layer and deeper more conductive regions on 2D MT inversion sections (Figure 17). This interpretation was used to separate the Eocene rocks from the Chilcotin basalts in the 3D geologic model. In areas distal from constraining information, the surface representing the top of the Eocene was placed at an elevation of ¼ of the distance between

the topography and top of Cretaceous contact surface. Without additional constraints, this seemed acceptable as a starting point for the initial geologic model.

Figure 19, Figure 20, Figure 21, and Figure 22 show the starting geologic surfaces built from the various geological and geophysical constraints discussed above. Figure 23 shows the starting model depicted as a geologic block model where each cell contains a lithological ID representing its geologic domain.
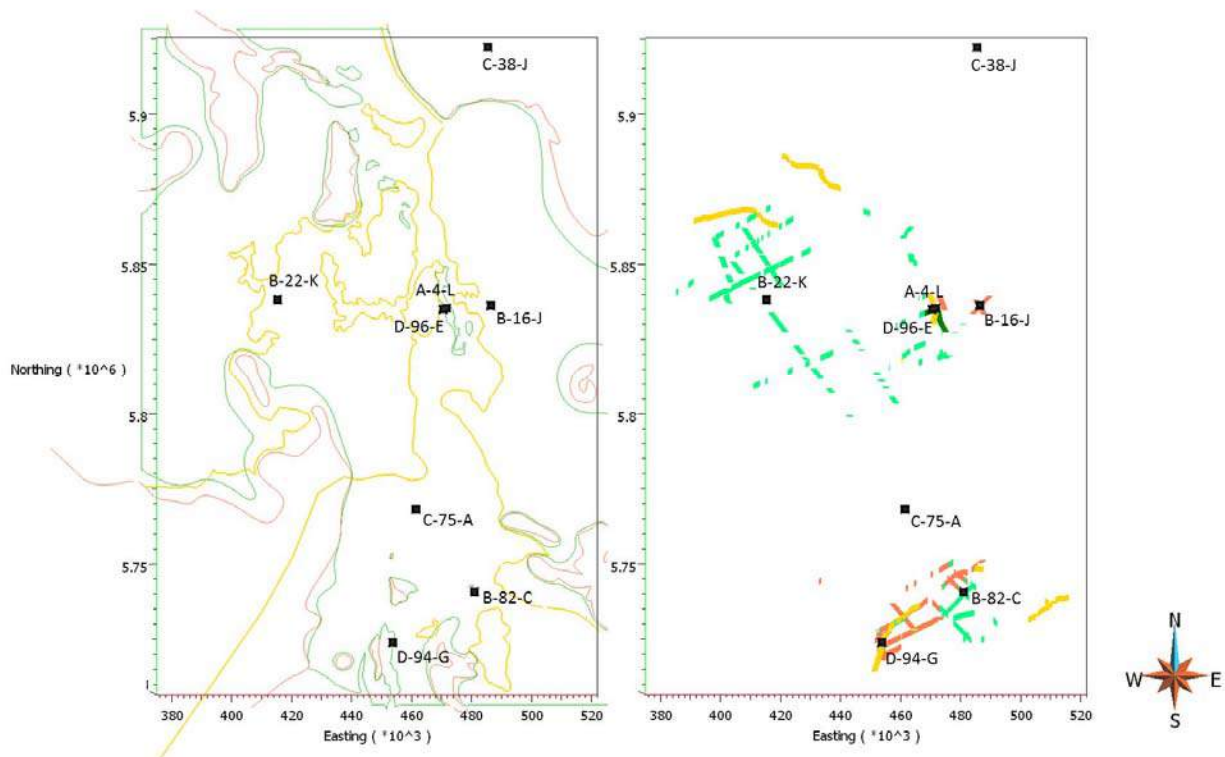
Figure 17. Constraints used for modelling of geologic contact surfaces. Left image is a plan view of location of wells used for constraints, and shows mapped and inferred outcrop traces, where yellow indicates contacts representing the top of the Eocene, green contacts represent the top of the Cretaceous, and orange/red indicates contacts represent the top of the basement. The right image shows wells and locations of geologic horizons interpreted from seismic and MT lines. Yellow represents the top of the Eocene as interpreted from MT lines, green represents the top of the Cretaceous sediments as interpreted from seismic lines, orange indicates top of basement (Jurassic + Cretaceous volcanic rocks), and dark green is the top of Jurassic basement.
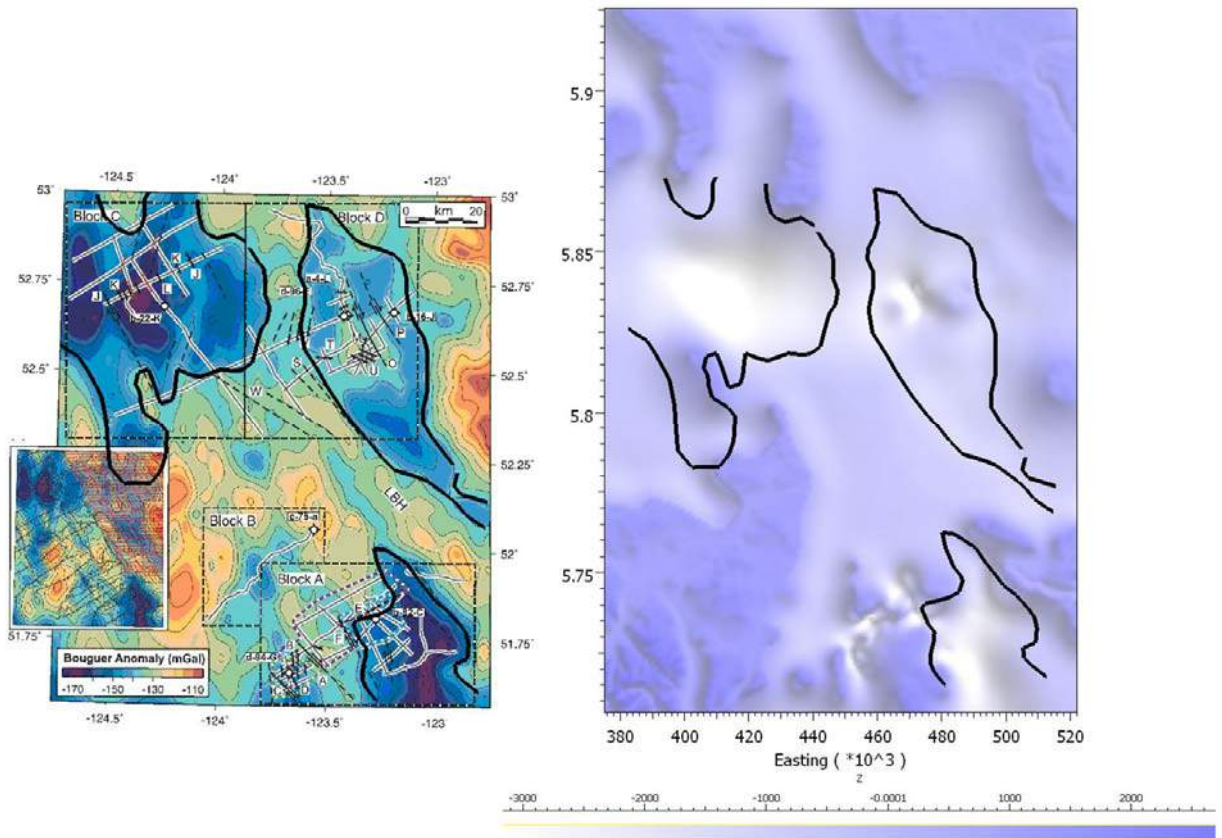
Figure 18. Jurassic basement surface warped to match low density basins as indicated by gravity data lows on Bouguer gravity map from Hayward and Calvert (2010, 2011). Black lines approximate extents of gravity lows.
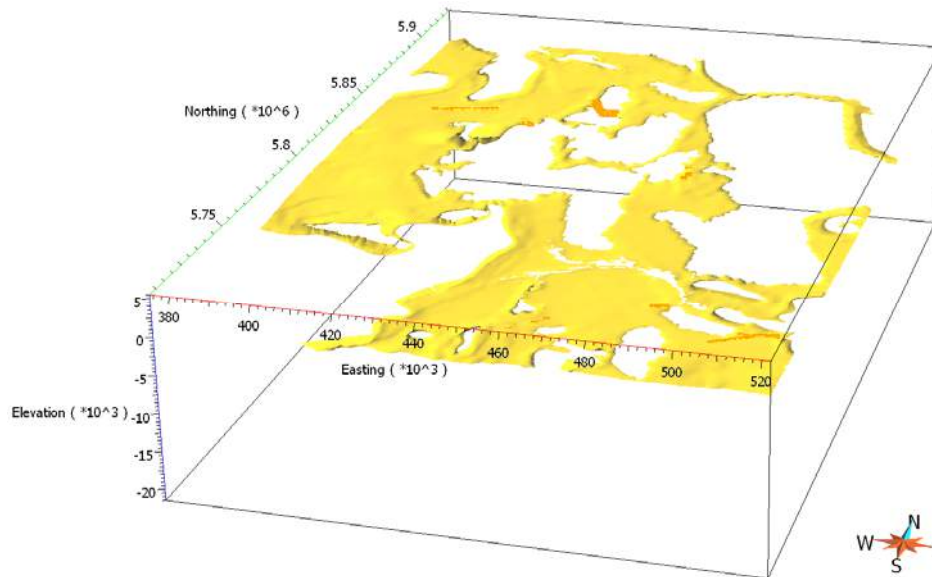
Figure 19. Top of Eocene surface constructed from: geologic outcrop map interpretation, well logs, seismic interpretations, and MT interpretations (seen as dark yellow/orange lines). Vertical exaggeration x5.
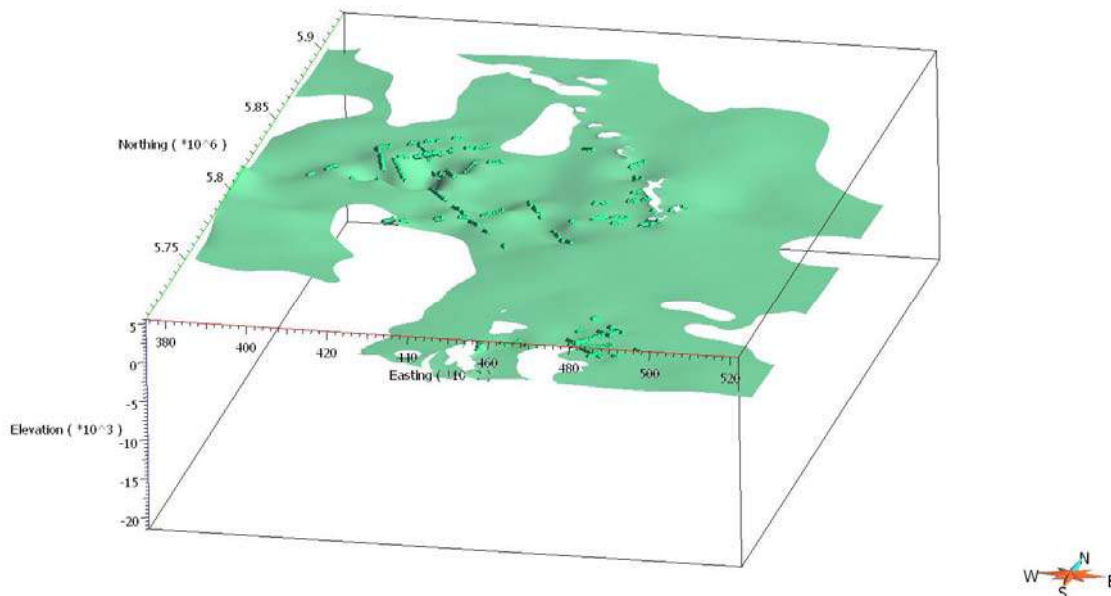
Figure 20. Top of Cretaceous surface constructed from: geologic outcrop map interpretation, well logs, and seismic interpretations (shown as dark green lines). Vertical exaggeration x5.
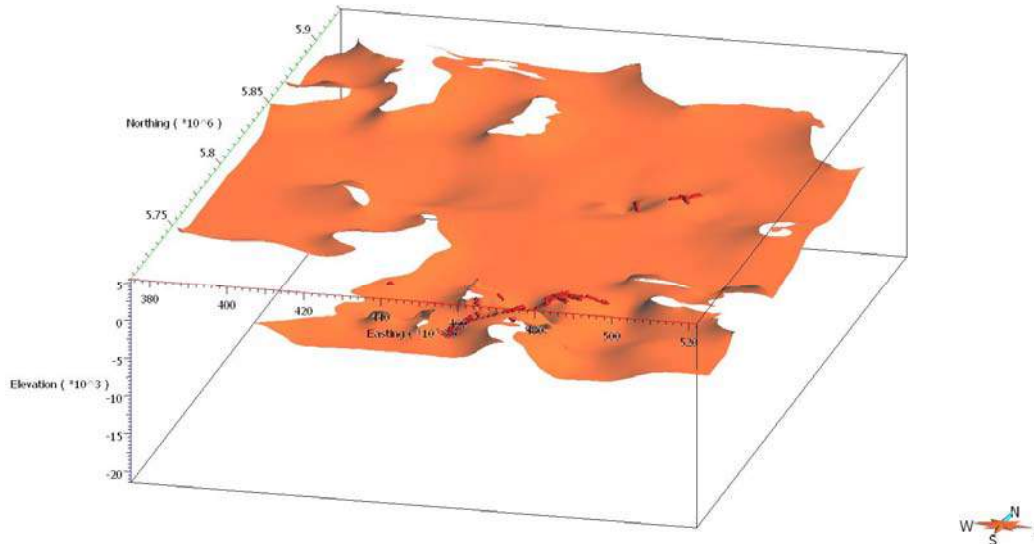
Figure 21. Top of "basement" surface constructed from: geologic outcrop map interpretation, well logs, and seismic interpretations (shown as dark orange/red lines), and warped to indicated basins from gravity lows. Vertical exaggeration x5.
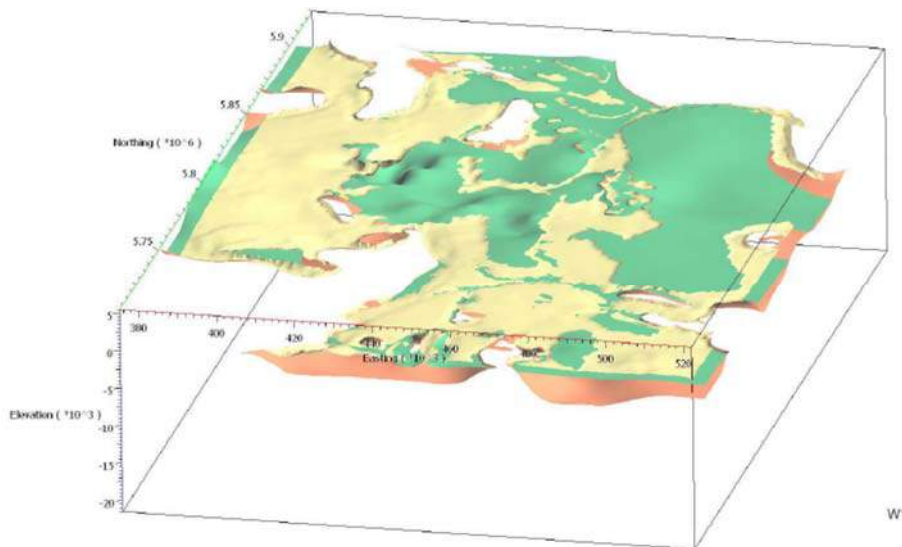
Figure 22. The starting geologic model for VPmg. Orange: top of Jurassic/basement; green: top of Cretaceous, yellow: top of Eocene. Surfaces are cut by topography - top of Miocene Chilcotin (not shown). Vertical exaggeration x5.
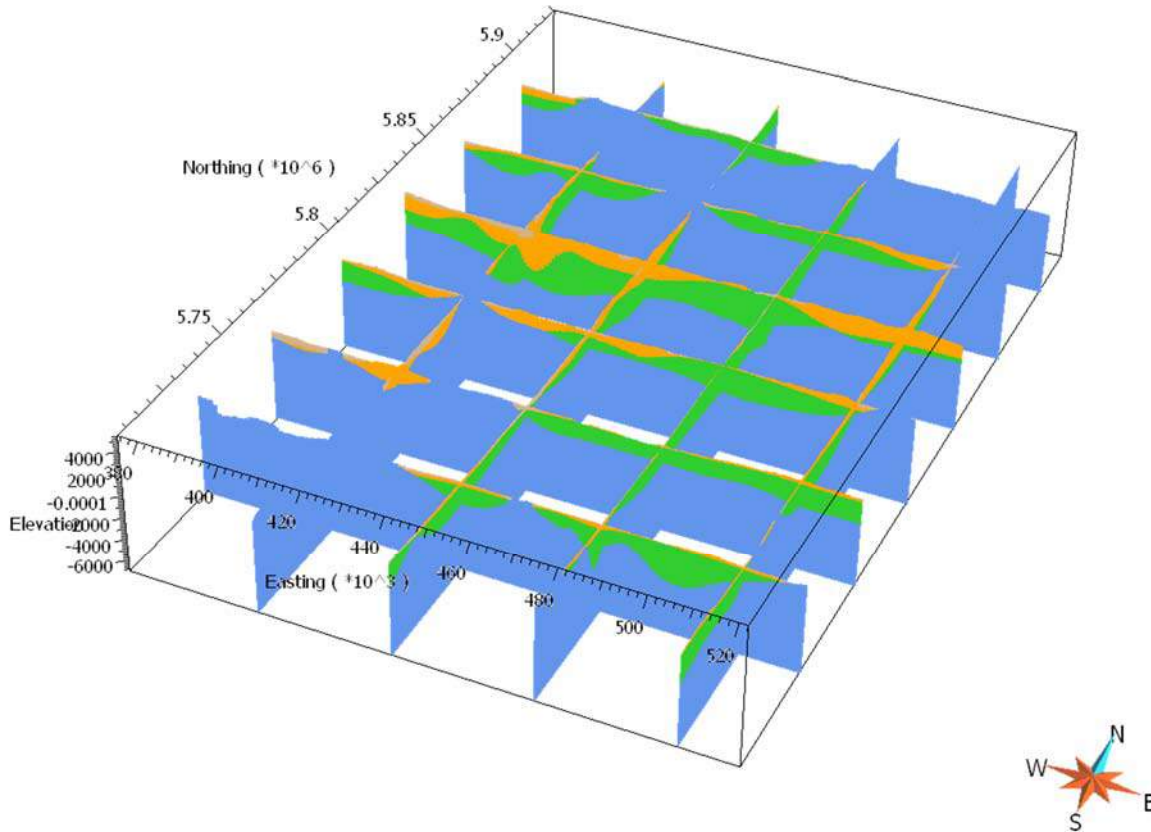
Figure 23. East-west and north-south vertical sections through the starting geologic block model rendered from initial geologic contact surfaces. Blue is basement, green is Cretaceous sedimentary rocks, orange is Eocene volcanic rocks, and brown (thin surficial layer) is Chilcotin basalt. Vertical exaggeration x3.

4.1.2.   *South Basin Structural Update*

Discussions taking place during a Nechako Working Group meeting held in June 2012 lead to an update to the geometry of a basin in the south of the study area to depict a greater thickness of Eocene rocks. This basin was updated in the starting geological model by moving the top of the Cretaceous surface down in elevation closer to the top of basement as shown in **Error! Reference source not found.**. This update to the basin structure was based on the gravity data. Two

constraints from seismic interpretations, two curves representing the top of the Cretaceous sediments, were removed from the modelling process as they were inconsistent with this update.

Other basins in the Nechako study area may be addressed in this way but no other updates were applied due to lack of data warranting such changes.
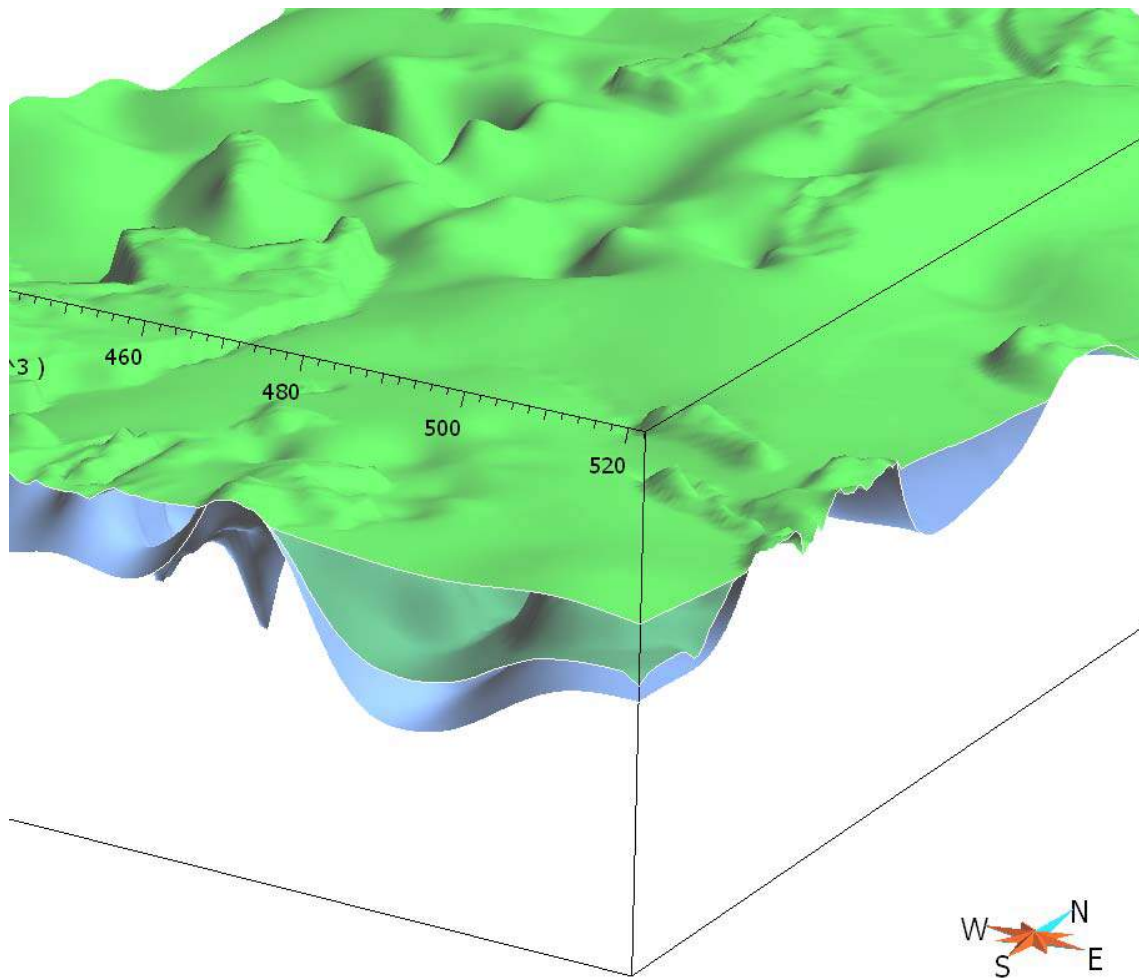
Figure 24. Structural update of the starting geologic model for the south basin. The original top of Cretaceous surface (light green) is replaced by the new top of Cretaceous surface (dark green), which is rendered deeper such that the overlying Eocene will have a greater thickness. The initial top of basement surface is shown in blue. Vertical exaggeration x5.

4.2. Geophysical Modelling

4.2.1. Methodology

VPmg inversion software was used to perform constrained inversion modelling of gravity and magnetic data over the Nechako-Chilcotin plateau study area. Modelling was completed on a 3D grid with cell sizes 1000 m x 1000 m x 50 m. The completed 3D geologic model, consisting of four lithological domains, was used as a starting model. This model is updated through the inversion process, arriving at a final model which can effectively predict observed magnetic and gravity data once forward modelled.

The first step in the inversion process involves assignment of physical properties to the four different geological domains: basement (Jurassic rocks plus Cretaceous volcanic rocks), Cretaceous sedimentary rocks, Eocene volcanic rocks, and Miocene Chilcotin volcanic rocks. Initially, each geologic domain is given a homogeneous density and magnetic susceptibility value based on statistical assessment of physical property data. Each domain is also provided with an upper and lower bound value which will limit the range of magnetic susceptibility and densities allowed (section 3.1, tables 1 and 2).

Inversion is an iterative process that starts by testing the validity of an initial model, and then applying updates to the model to gradually improve fit to observed geophysical data. The workflow for inversion for this project is outlined in Figure 25. In general the model was refined from the bottom upwards, starting with adjustments to the basement units, and ending with refinements to the shallow volcanic units. Gravity is worked with initially to establish geometry of the contact surface representing the top of the basement, across which there is a significant density contrast.
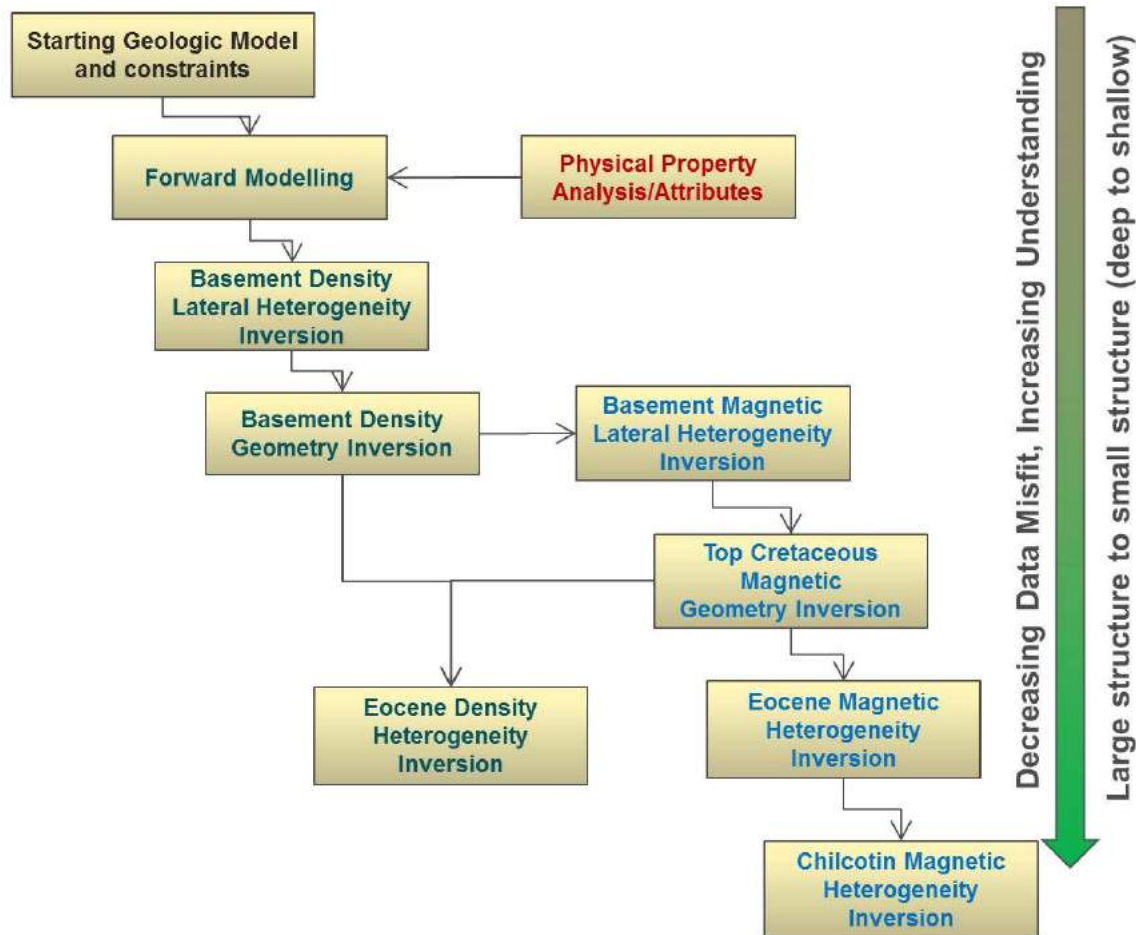
Figure 25. VPmg modelling approach, presented as a workflow with inversion addressing first physical properties and geology at depth, and continuing to improve fit to observed geophysical data as shallower geological units are refined.

Inversion modelling began by testing the starting geologic model and the assigned homogeneous density values. The first update to the model is an adjustment to these homogeneous starting values to find values that best reproduce the broad gravity responses observed. Following this, an inversion which develops lateral heterogeneity of density in the basement in applied. This models the sources responsible for deep gravity responses within the project area. Once appropriate densities within the basement were established, the surface representing the top of the basement

was allowed to move and warp to improve the fit of the model to the observed gravity data. With the geometry of the top of the basement set, magnetic susceptibilities within the basement were addressed. A laterally-varying magnetic susceptibility model was calculated, which adhered to the established geometry from gravity modelling. The next surface focused on was the surface representing the top of the Cretaceous, across which there is an expected susceptibility contrast. With the Cretaceous assigned a homogeneous susceptibility, the top of the Cretaceous was allowed to be modified by applying geometric inversion. The geologic domain representing Eocene rocks was modelled as having heterogeneous susceptibilities and densities, to account for the known compositional variation within these rocks. The Chilcotin basalts retained a homogeneous density value, but were modelled as having a heterogeneous magnetic susceptibility distribution. The geometry of the base of Chilcotin basalts was not updated using inversion.

4.2.2.   Results

Observed gravity and magnetic data is compared to predicted gravity and magnetic data before and after refinement of the 3D geological model in Figure 26 andFigure 27.

The initial geological model yields two strong gravity anomalies which broadly mimic the higher gravity areas seen in the observed gravity data (Figure 26). Refinement to the geologic model helped to reduce the strong gravity anomalies initially being predicted in the north-central and southwestern parts of the model by modifying the thicknesses of lithological units, and refining density values.

The starting geologic model yields a very homogeneous magnetic response due to the weaker contrasts between susceptibilities of the adjacent modelled geologic domains (Figure 27). Iterative refinement of geometry of geologic contacts and of internal physical property variations through VPmg inversion leads to improved prediction of the observed magnetic data. Some areas of high magnetic residual apparent when predicted data is subtracted from observed data may indicate magnetic remanence in Chilcotin basalts.

Figure 26. Observed gravity data (upper left image), gravity data predicted from the starting geologic model (upper right), gravity data predicted from the refined geologic model (lower left), and observed minus final predicted (residual) gravity data (lower right). Green colors in the residual map indicate a good fit to observed data.
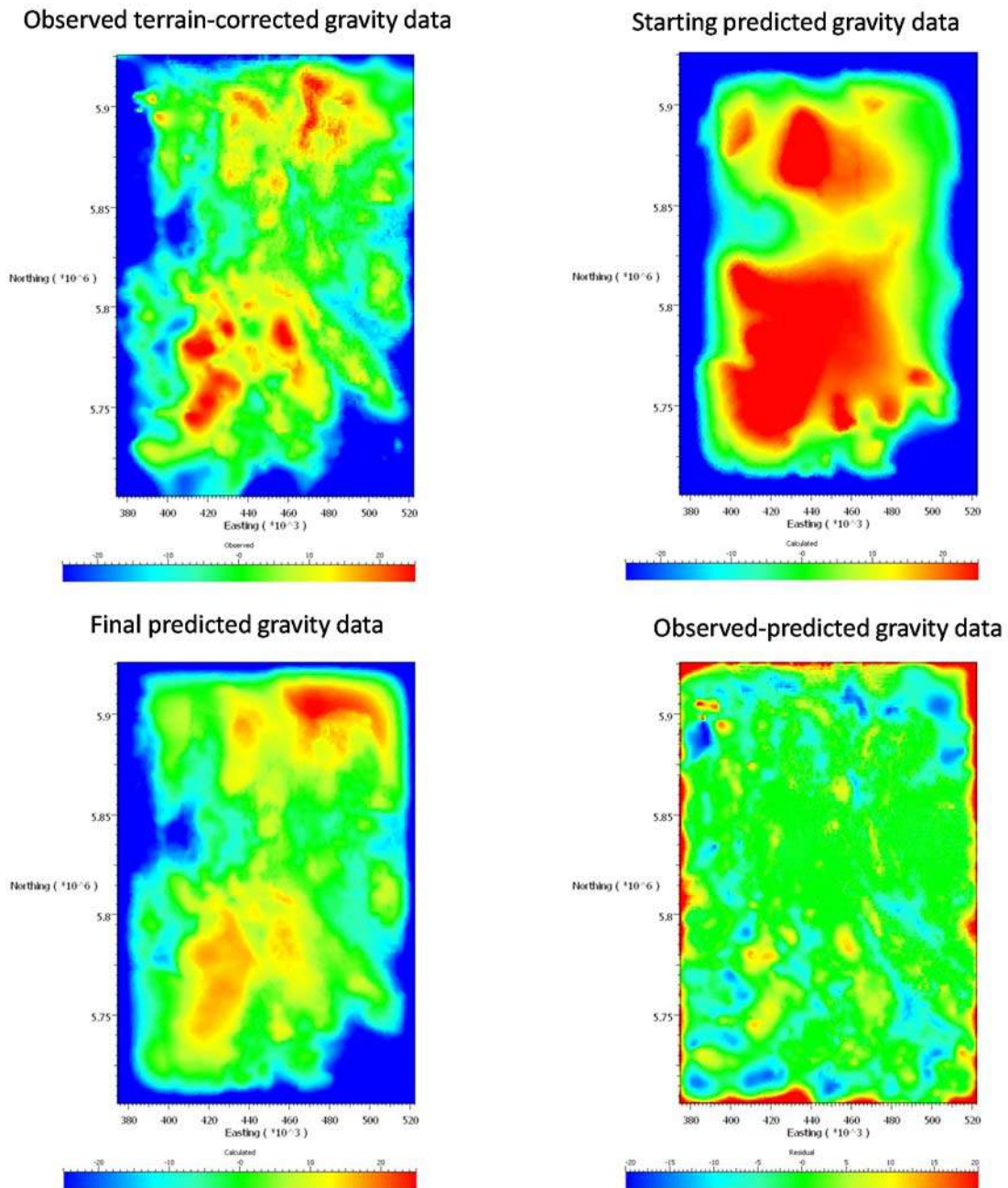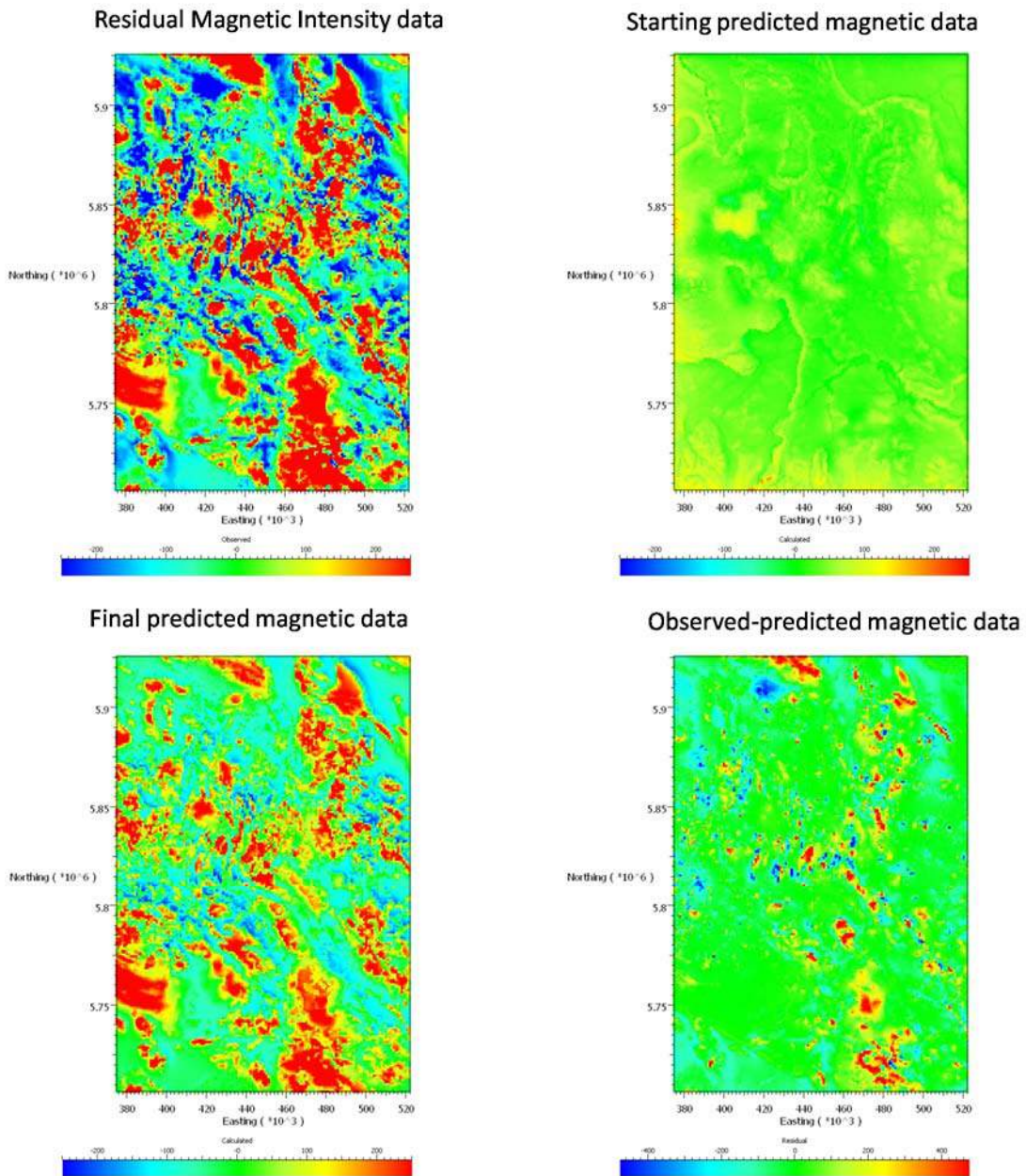
Figure 27. Observed magnetic data (upper left image), magnetic data predicted from the starting geologic model (upper right), magnetic data predicted from the refined geologic model (lower left), and observed minus final predicted (residual) magnetic data (lower right). Green colors in the residual map indicate a good fit to observed data.

The final magnetic susceptibility and density models are shown in Figure 28. The Jurassic basement was modelled via lateral heterogeneity inversion and it is possible to see the laterally varying, but vertically continuous densities and susceptibilities within the deeper levels of the models. The overlying Cretaceous sedimentary domain is modelled as being homogeneous in both density and susceptibility. Above this, within the Eocene domain, densities and susceptibilities were allowed to vary laterally and vertically in three dimensions to try to compensate for the high compositional variability within the volcanic rocks of the Eocene.

The geologic contacts that were modified through inversion represent the final geologic model. From these surfaces and the topography, a 3D geologic block model was built. The initial and final geologic block models are shown in Figure 29.

The contact between the Cretaceous (green) and the overlying Eocene (orange) in the final geologic model (Figure 29) has significantly more structure compared to the starting geologic model, the variations required to improve fit to observed gravity and magnetic data. The contact moves down where higher magnetic susceptibilities and higher densities are required (higher volume of Eocene volcanic rocks versus Cretaceous sediments), and up where lower susceptibilities and lower densities are required (higher volume of sediments, and lower volume of volcanic rocks). Changes to the basement geometry are more subtle. A comparison of the initial versus final basement surfaces show where the basement surface became shallower or deeper following inversion (Figure 30). The difference between the final and starting elevations of the basement can be viewed to identify regions of greatest change in elevation. Of note, the basement surface in the area of the known northwest basin has been elevated within the central part of the basin, while the edges of this basin have been shifted to greater depths. Northeast and southeast basins have also become deeper in places.

By subtracting the final elevation of the basement surface from the final elevation of the top of Cretaceous surface, an isopach map is generated indicating thickness of Cretaceous sedimentary rocks (Figure 31). Basins in the northwest, northeast, and southeast are modelled to have thicknesses of greater than 3000 m.
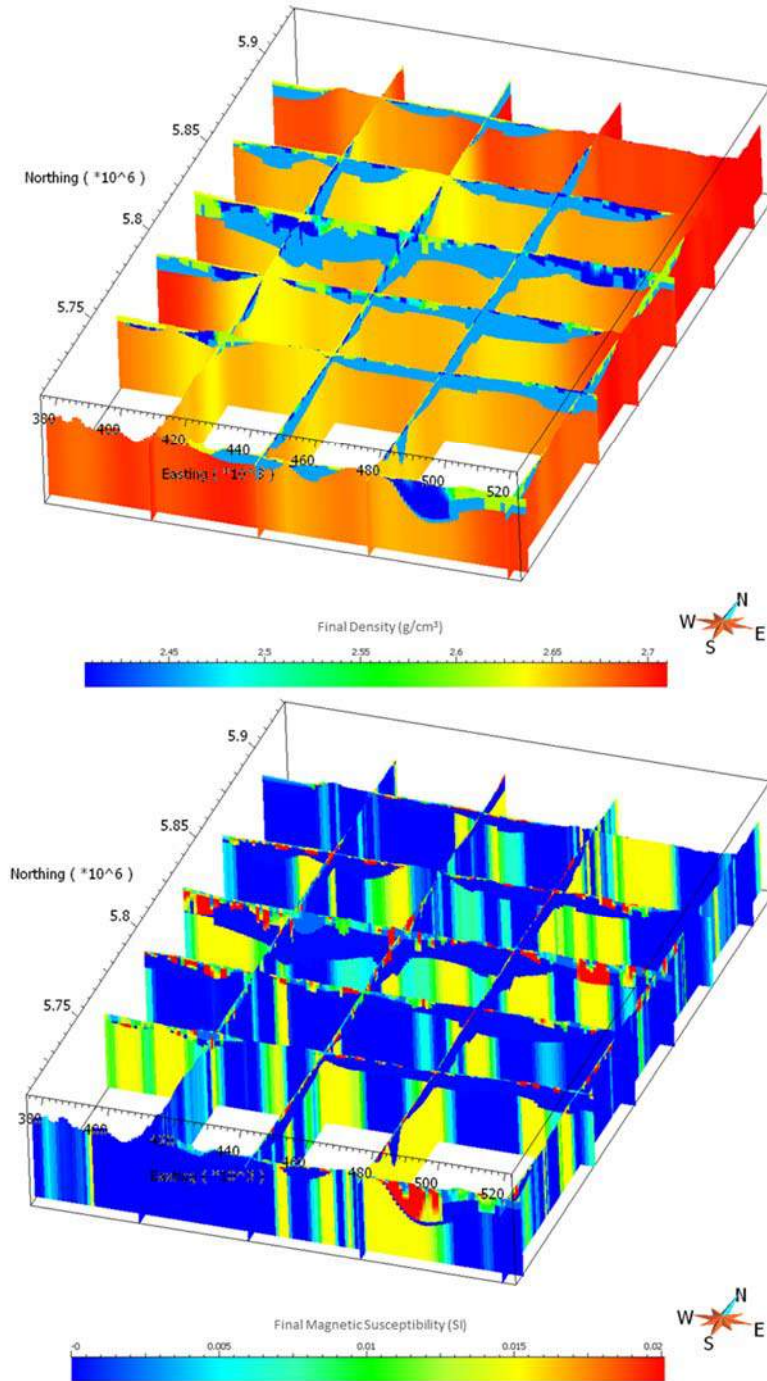
Figure 28. Final density and magnetic susceptibility models from iterative VPmg inversion. Vertical exaggeration x3.
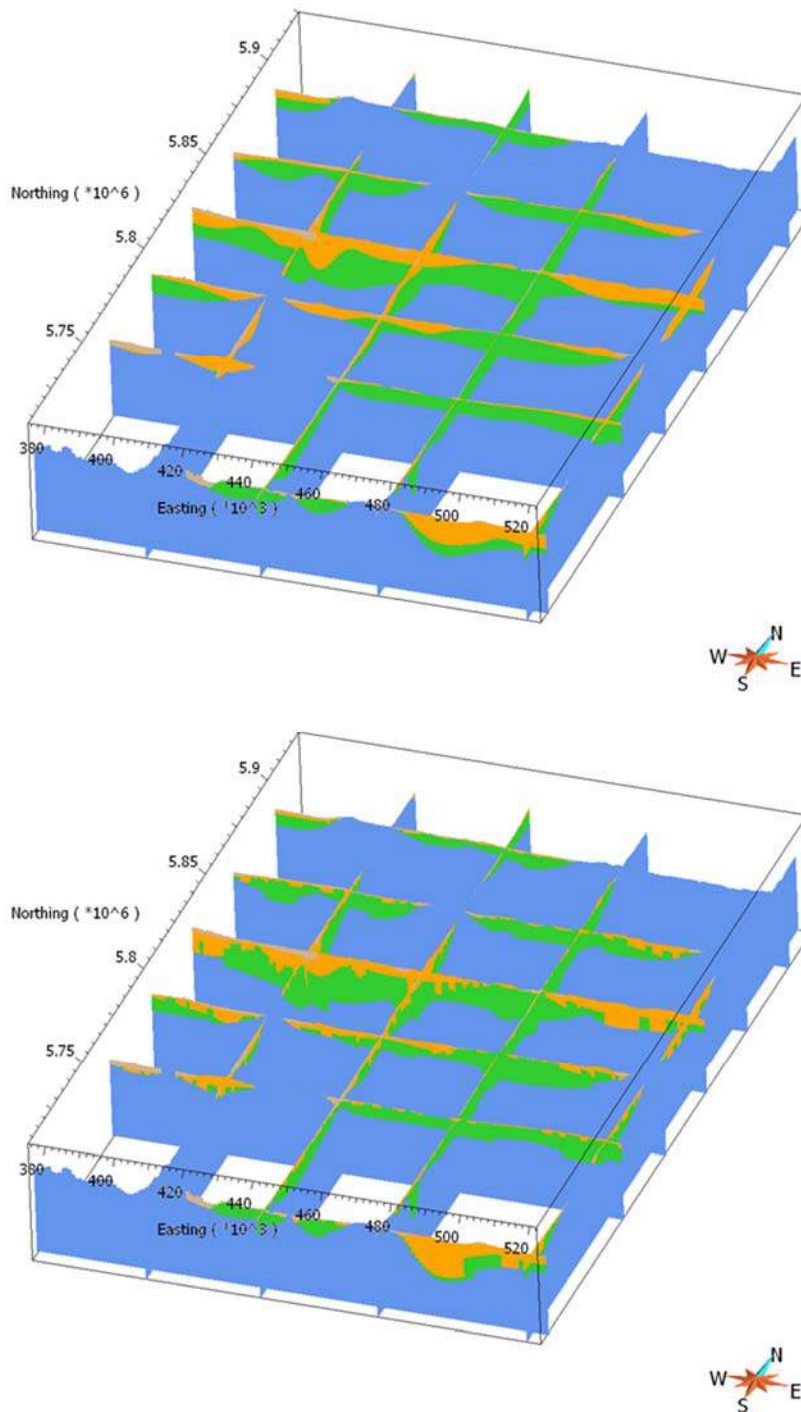
Figure 29. Initial geologic model (upper image) and final geologic block model following VPmg constrained inversion (lower image). Blue is Jurassic basement, green is Cretaceous sedimentary rocks, orange is Eocene volcanic rocks, and brown (thin surficial layer) is Chilcotin basalt. Vertical exaggeration x3.
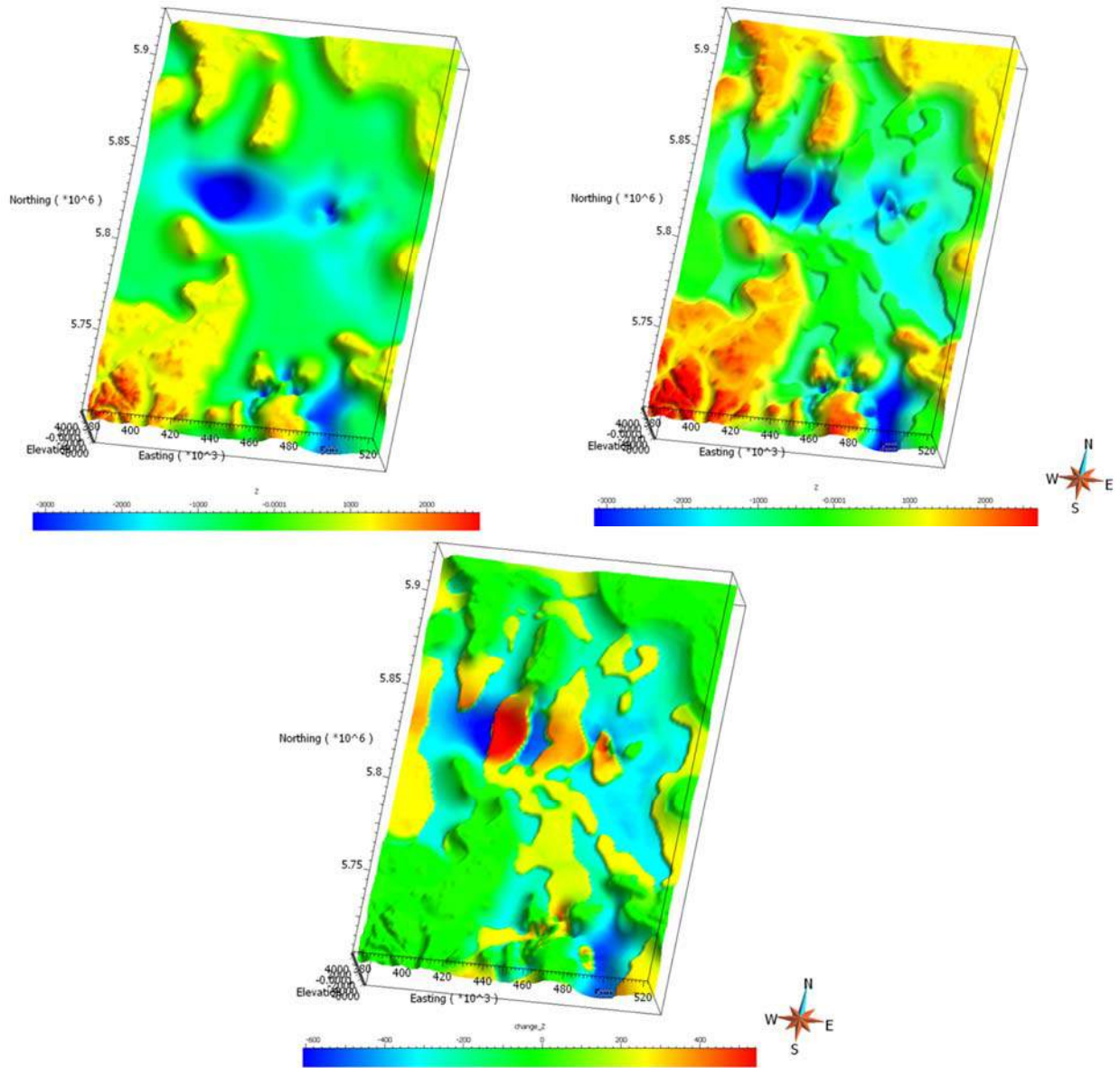
Figure 30. Initial top of basement surface colored by elevation (upper left image), and final top of basement surface colored by elevation (upper right image). Lower image shows the elevation difference between final and initial surfaces (painted on the final basement surface), where yellow to red colors indicate areas where the surface has moved upward, and blues indicate areas where the surface has shifted downward. Vertical exaggeration x3.
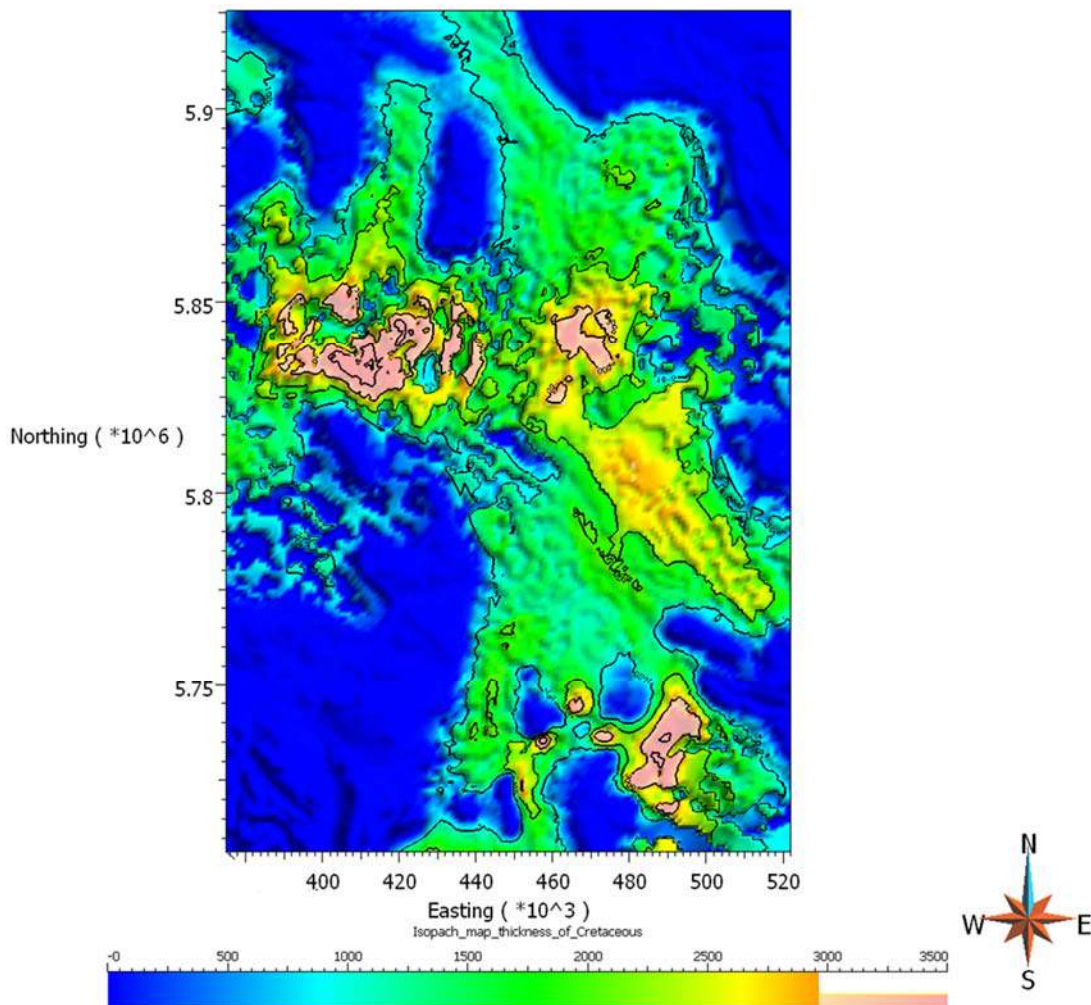
Figure 31. Isopach map painted onto the final top of Cretaceous surface, showing the thickness of the Cretaceous unit calculated from subtracting the final elevation of the basement from the elevation of the top of the Cretaceous. Pink regions are areas where Cretaceous unit thickness has been modelled as being > 3000 m.

Whereas the geologic model output (both the geologic contacts and the block model) from VPmg inversion provides refined locations and depths of geological boundaries within the subsurface indicating shapes and extents of Cretaceous (+/- Eocene) basins, the geophysical inversion models provide details on the heterogeneity of susceptibilities and densities within the modelled units. From the inversion results it may be possible to identify compositional differences within the Eocene that can be related to the occurrence of mafic versus more felsic material. This may have

implications on geologic mapping, volcanic stratigraphy reconstruction, and mineral exploration. The source of broad compositional variations within the basement should also be further investigated. High susceptibility/low density regions may signify buried intrusive rocks which are known to play important roles in the generation and localization of porphyry and epithermal mineral deposits.

5. Conclusions and recommendations

Using constrained geophysical inversion techniques, Mira Geoscience has refined 3D geologic and geophysical models of the Nechako-Chilcotin plateau. The expected density and magnetic susceptibility contrasts between Cretaceous sedimentary rocks and bounding volcanic rocks means that gravity and magnetic data can be modelled to effectively resolve and refine these geologic boundaries in 3D. Through iterative inversion using VPmg software, a suite of geologic, density, and susceptibility models were generated which are collectively able to predict observed gravity and magnetic data collected over the plateau. Constraining Nechako-Chilcotin plateau basin inversions in well-studied areas, using geological information derived from maps, well logs, and seismic data, improves the magnetic susceptibility and density models in poorly sampled and poorly exposed areas.

From constrained inversion results depths of Cretaceous (+/- Eocene) sedimentary basins are derived, which can be reviewed against other existing geological and geophysical models from the Nechako-Chilcotin plateau to assess oil and gas potential. Compositional variations within basement and Eocene stratigraphy indicated by magnetic susceptibility and density heterogeneity within these lithologic domains may be interpreted in terms of structure or rock type (mafic versus felsic, intrusive versus volcanic), that may represent favorable hosts for mineralization.

In order to make the modelling of this large area tractable, several assumptions were made; the stratigraphy was simplified based on a grouping of litho-types and physical property values. The physical property analysis is, itself, based on spatially sparse and clustered data. This simplification is reasonable for application to a broad area, but locally the assumptions are not always sufficient and the data will not all be reconciled in the modelling.

The models generated represent one set of possible solutions, given a particular set of constraints. Geophysical inversion is non-unique and many solutions are possible. Constraining inversions is important as it acts to narrow the range of solutions. The current models should be used to test interpretations and hypotheses. The results should be compared to other models and geological interpretations existing, or in development for this region.

The 3D geological and geophysical models generated are dynamic in nature, representing a current understanding of the geology of the Nechako-Chilcotin plateau. Modifications of the model can occur through additional constraints, e.g., seismic tomography sections, further MT interpretation, updated maps, geologic cross sections, fault interpretation, and additional physical property information.

Typically, regional-scale 3D Earth modelling progresses to more local-scale modelling. Inversion can be applied to further develop models within local areas of interest by inverting to reduce the data misfit for specific features in the data (potential basins, structures, or intrusive bodies). This can be done by adding more local constraining information, developing more geological units, and combining the different VPmg modes for more iterations of heterogeneous and geometry inversions. This would be the recommended course of action for working with specific anomalies in the study area, especially if more comprehensive models are required for the planning of focused geophysical surveys or drilling.

Acknowledgements

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Appendix 1. Project Deliverables

1. Nechako 3D Magnetic Inversion

    ASCII Format

    GOCAD Grid Object

    GRD Model Sections

    TIFF Inversion Slices

    UBC-GIF Format

2. Nechako 3D Gravity Inversion

    ASCII Format

    GOCAD Grid Object

    GRD Model Sections

    TIFF Inversion Slices

    UBC-GIF Format

3. Nechako 3D Geological Model

    ASCII Format

    DXF Geological Surfaces

    GOCAD Grid Object

    GRD Model Sections

    TIFF Isopach Maps

    UBC-GIF Format

4. Nechako 3D GOCAD project

5. Nechako_3D_Integrated_Modelling_Project_28Sept_2014.pdf (this document)