Yukon

YGS Open File 2022-8

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J.B. Witter Innovate Geothermal Ltd.

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Front cover: View to the south over Second Wye Lake in the Town of Watson Lake. Part of the Alaska Highway is visible in the background. Photo credit: Panya Lipovsky, YGS.

Preface

In 2010, the Kaska Nation undertook an inventory of clean energy resources and identified geothermal energy as a key opportunity for providing renewable energy to its communities. This project, carried out through a partnership between Yukon Geological Survey (YGS) and Liard First Nation (LFN), set out to advance LFN's interest in geothermal energy in the Watson Lake – Upper Liard areas.

This report presents the results of the YGS-LFN collaborative study. The project specifically examined the Tintina fault zone where it crosses the Alaska Highway, to assess whether there are one or more sites where fault geometry locally created extensional conditions resulting in enhanced permeability, and by association, potential for a geothermal reservoir.

The Tintina fault zone in this area is overlain by Cenozoic sedimentary rocks deposited in a pull-apart basin formed during faulting. The author has integrated existing geological and geophysical data with newly collected gravity and magnetotelluric data to model the fault below the basin, and has identified a target location to drill a well to measure geothermal gradient and physical rock properties.

Funding for this project was provided by YGS (Yukon government's Our Clean Future Strategy), LFN (through a grant from Crown-Indigenous Relations and Northern Affairs Canada's Northern REACHE Program), and NRCan (via an Emerging Renewable Power Program to YGS). In-kind contributions were made by the following organizations: Liard First Nation (project co-management), Barkley Project Group (project co-management), University of Alberta (magnetotelluric data collection and processing), and the Geological Survey of Canada (technical advice).

This study is one of a series of studies underway to assess the geothermal energy potential of crustal-scale fault systems in Yukon.

Carolyn Relf
Director, Yukon Geological Survey

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Abstract

In collaboration with the Yukon Geological Survey, Liard First Nation and other project partners, Innovate Geothermal Ltd. performed an analysis of geoscience data in southeastern Yukon as part of an effort to better understand the potential for geothermal energy resources that, if present, could be utilized to help reduce fossil fuel use in off-grid communities. The study area for this project is located near the Town of Watson Lake and straddles the crustal-scale Tintina fault zone. The main aim of this project is to analyze and interpret a variety of pre-existing and newly-acquired geological and geophysical datasets to evaluate whether geothermal reservoirs may be present within the study area. A secondary aim is to propose favourable drilling locations, if warranted, for exploratory wells to collect information on subsurface temperature and permeability. The geoscience work accomplished here includes both 2D map interpretation as well as construction of a 3D geologic model that was guided by geophysical inversion modelling of gravity, magnetic and magnetotelluric survey data. In the study area, the distribution of temperature in the subsurface remains a significant unknown; however, limited evidence suggests subsurface temperatures are modest. Regional-scale, Curie point depth estimates suggest an average geothermal gradient of only ~31°C/km. In contrast, two oil and gas exploration wells from the 1960s located 15–35 km outside the study area give a geothermal gradient range of ~38–50°C/km. Drilling is required to measure actual subsurface temperature gradients in the vicinity of Watson Lake. Evidence for substantial subsurface permeability is generally lacking in the study area. Analysis of the geoscience data did not reveal any specific locations along the Tintina fault that suggest a structural environment favourable for subsurface fracture permeability. Furthermore, the Tintina fault presents little evidence of active tectonism. Active tectonism helps maintain open fractures in the fault zone which could facilitate deep circulation of fluids to form a natural geothermal system. A lack of active tectonism could limit permeability in the fault zone. In addition, geophysical modelling suggests that large portions of the Watson Lake study area are likely underlain by shale-rich bedrock. This type of rock has very low permeability and is not favourable for maintaining open fractures. The only evidence for subsurface permeability found in this study is sand layers in the Cenozoic sedimentary rock of the Tintina trough. These sand layers could be permeable but are interbedded with low permeability layers such as silt and clay; the thickness and lateral extent of the sand layers is unknown. The 3D geologic model developed in this study suggests that the Cenozoic sedimentary rock of the Tintina trough is limited to less than ~1 km thick. This implies that fluids residing in sand layers in this rock unit would have a maximum temperature of between ~38 and 50°C. Geothermal fluids at these temperatures could potentially be utilized to help heat buildings in the community of Upper Liard. Many unknowns regarding the temperature and permeability of the subsurface still exist in the Watson Lake study area. The location of a 1 km deep scientific research well is proposed to help answer many of the remaining questions. However, considering the lack of evidence for bedrock permeability in the study area, other approaches to utilizing the Earth's heat, such as Borehole Thermal Energy Storage (BTES) systems, could be considered to help the community of Watson Lake reduce dependence on fossil fuels for residential heating.

Introduction

Watson Lake is a town of ~1000 people in southeastern Yukon which obtains 100% of its electric power from fossil fuels (Government of Yukon, 2018). Replacing the fossil fuel power generation with clean, renewable power would significantly reduce greenhouse gas emissions from Watson Lake and free the community from the uncertainty associated with the cost of hydrocarbons. Energy derived from subterranean geothermal reservoirs in the Watson Lake area could be beneficial in two different ways: (1) warm water from lower temperature geothermal reservoirs could be tapped to directly heat homes, thereby reducing the amount of fossil fuel needed for residential heating; and (2) hot water from higher temperature geothermal reservoirs could be utilized to generate electricity to directly replace fossil fuel power generation.

Existing geoscience data (although limited) suggest that there are above average subsurface temperatures in the Watson Lake region. However, for a natural subsurface geothermal reservoir to be tapped, there also needs to be permeability (e.g., fractures) in the subsurface that allow the geothermal fluids to flow through the rock into the wellbore of a geothermal production well. One possible location of fractured rock and permeability is the Tintina fault, a major, crustal-scale structure that runs NW–SE near the Town of Watson Lake (Fig. 1). Unfortunately, our geologic understanding of the Tintina fault is incomplete, due to a lack of detailed geoscience investigations in the Watson Lake area coupled with an absence of deep drilling anywhere near the Tintina fault. Therefore, the purpose of this study is to obtain and interpret baseline geoscience data in the Watson Lake area in order to:

1. better constrain the location, strike, dip and width of the Tintina fault and associated fault structures;
2. develop a 3D geologic framework for the Watson Lake subsurface to infer the locations of potentially permeable fault structures; and
3. better understand the geometry and composition of major rock units that may or may not host geothermal reservoirs

The specific study area for this project is ~5 km wide and ~23 km long, straddles the Alaska Highway, and extends from the Town of Watson Lake in the east to Junction 37 in the west. Three-dimensional geoscience modelling was performed to try to extend our understanding of the study area to a depth of ~3.5 km below the ground surface. Such an exercise can be useful because the presence or absence of geothermal fluid reservoirs can be dependent on both rock type and geologic structures. Thus, having some idea for what rock types are where, as well as the location of faults in the subsurface, is valuable in the search for geothermal resources. To achieve these aims, existing geoscience data from the study area were compiled and interpreted alongside new geoscience data which were acquired as part of this project. All of these data are described in this report.

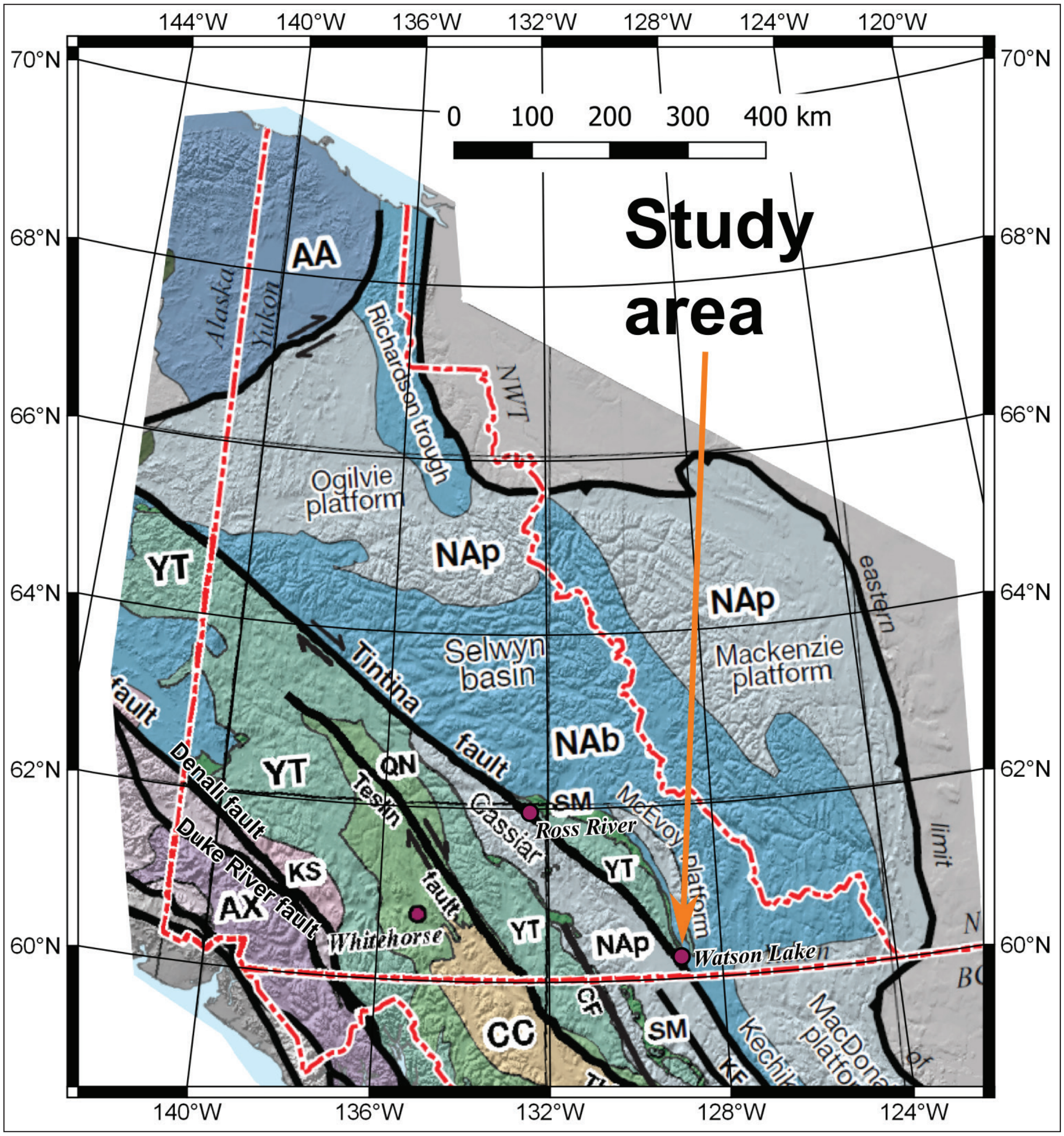

Figure 1. Map of Yukon illustrating the location of the study area described in this report. Geologic terrane basemap from Nelson et al. (2013). Black lines depict major faults (Colpron and Nelson, 2011). Red dashed lines show provincial/territorial borders.

Background

Typical indicators of geothermal resources (*e.g.*, hot springs and active volcanism) are absent in the Watson Lake study area. However, there is evidence for above average subsurface temperatures at a regional scale. Furthermore, volcanic eruptions have occurred in the area in the geologically-recent past and a major, crustal-scale fault zone cuts through the study area suggesting the possible presence of fractured, permeable rock in the subsurface. Background information on these topics is summarized here.

Curie point depth estimate

Curie point depth (CPD) mapping has been used as an initial exploration tool in Yukon to help identify warm *vs.* cool crustal temperatures in the territory (Witter *et al.*, 2018). CPD mapping is a method, originally developed in the 1970s, which uses regional-scale magnetic survey data to map the depth to the Curie point temperature (~580°C) where magnetization in rocks disappears. Regions found to have shallow CPD values are expected to have higher heat flow, higher average thermal gradient, and therefore, a higher likelihood of geothermal energy resources that are accessible via drilling. Curie point depth values calculated for the Watson Lake area are estimated to be ~19 km (Li *et al.*, 2017; Witter *et al.*, 2018) which translates into an average, crustal-scale temperature gradient of ~31°C/km. Such a thermal gradient is only modestly higher than the average thermal gradient of the Earth's crust (~25–30°C/km). If these estimates are correct, a 2 km borehole in the Watson Lake area could be expected to reach ~62°C.

Historic oil and gas wells

Public records describe two oil and gas exploration wells drilled within ~35 km of Watson Lake. First, the Scurry NV East Watson Lake YT G-79 well was drilled from December 1967 to January 1968 at a location ~15 km NE of Watson Lake (Fig. 2). Drilling and logging records for this well are available on the GeoYukon website (https://yukon.ca/en/doing-business/licensing/find-oil-and-gas-maps-and-data). This well had a total depth of 1143 m and was plugged and abandoned the day after drilling finished. Drill stem tests were not performed on the well, oil and gas were not encountered, and the well was characterized as a dry hole. Three wireline geophysical logs recorded bottom hole temperatures (BHT) of 51.1, 53.3 and 54.4°C. These measurements occurred over a 6 hour time period revealing that the well was in the process of heating back up after cooling caused by circulation of drilling mud in the wellbore. An estimate of the equilibrium BHT for this well was not reported, but 54.4°C is a minimum BHT value. A geology log from this well describes the stratigraphy downhole as dominated by grey-to-dark grey shale with subordinate intervals of sandstone.

Second, the CNRL Lower Post D- 032-D/104-P-16 well was drilled in 1967 at a location ~18 km SE of the community of Lower Post, BC (~35 km SE of Watson Lake). Information on this well was obtained from the BC Oil & Gas Commission (https://www.bcogc.ca/). This well had a total depth of 1411 m and was plugged and abandoned two days after drilling finished. There are no records of drill stem tests being performed on the well and no showings of oil and gas were reported. Wireline geophysical logs recorded bottom hole temperatures between 47.7 and 50.5°C. An estimate of the equilibrium BHT was also not reported for this well, but 50.5°C is considered a minimum BHT value. Downhole geology is not reported for this well; however, it is located in an area mapped as shale and slate of the Road River and Earn groups of Laurentia (Cui *et al.*, 2017).

If we do not employ any bottom hole temperature corrections and use a mean annual temperature of -3°C for the Watson Lake area (http://climate.weather.gc.ca/ climate_normals), the thermal gradients for the two oil and gas wells are ~38°C/km and ~50°C/km for the CNRL Lower Post and YT G-79 wells, respectively. If these estimates are correct, a 2 km borehole in the Watson Lake area could be expected to reach 76–100°C. These two oil and gas wells show temperature gradient values that are higher than the average thermal gradient of the Earth's crust (~25–30°C/km) and higher than the estimates derived from Curie point depth calculations in SE Yukon (~31°C/km).

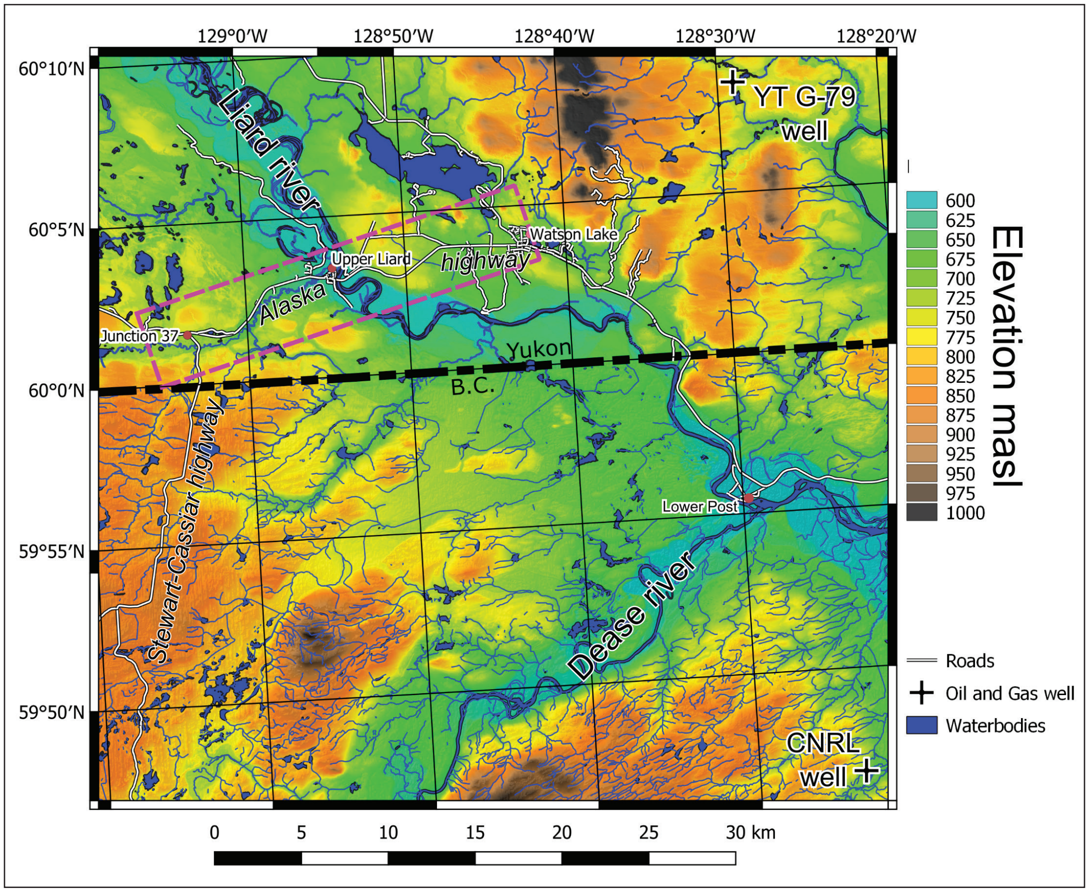

Figure 2. *Topography in the Watson Lake area from Arctic DEM and CDED data with the study area outlined in pink. The crosses show the location of the YT G-79 well drilled in 1967–68 (~15 km NE of Watson Lake) and the CNRL well drilled in 1967 near Lower Post, British Columbia (~35 km SE of Watson Lake).*

Bedrock and surficial geology

Bedrock geology in the Watson Lake area (Fig. 3) is summarized here (from Colpron et *al.*, 2016; Mortensen and Murphy, 2005; Gabrielse, 1967):

- Cambrian-Ordovician clastic and carbonate rocks of the Cassiar terrane lie to the west of the Tintina fault;
- Cenozoic, coal-bearing, clastic sedimentary rocks lie in the Tintina trough, between the Tintina fault and a northwest-striking normal fault adjacent to the Town of Watson Lake;
- Paleozoic clastic sedimentary rocks of the Yukon-Tanana and Slide Mountain terranes are found north and northwest of the Town of Watson Lake;
- Paleozoic clastic and carbonate sedimentary rocks of Laurentia lie on the eastern side of the Inconnu thrust fault to the east of Watson Lake; and
- two occurrences of Quaternary mafic volcanic rocks are on the bedrock geology map of Yukon, one just west of Watson Lake and another south of Upper Liard (Fig. 3). Lipovsky and McKenna (2005) also flew over an unmapped occurrence of (likely) Quaternary columnar basalt exposed on the east side of the Liard River, ~3 km north of Upper Liard. A fourth occurrence of young volcanic rock outcrops along the Alaska Highway ~3½ km east of Upper Liard.

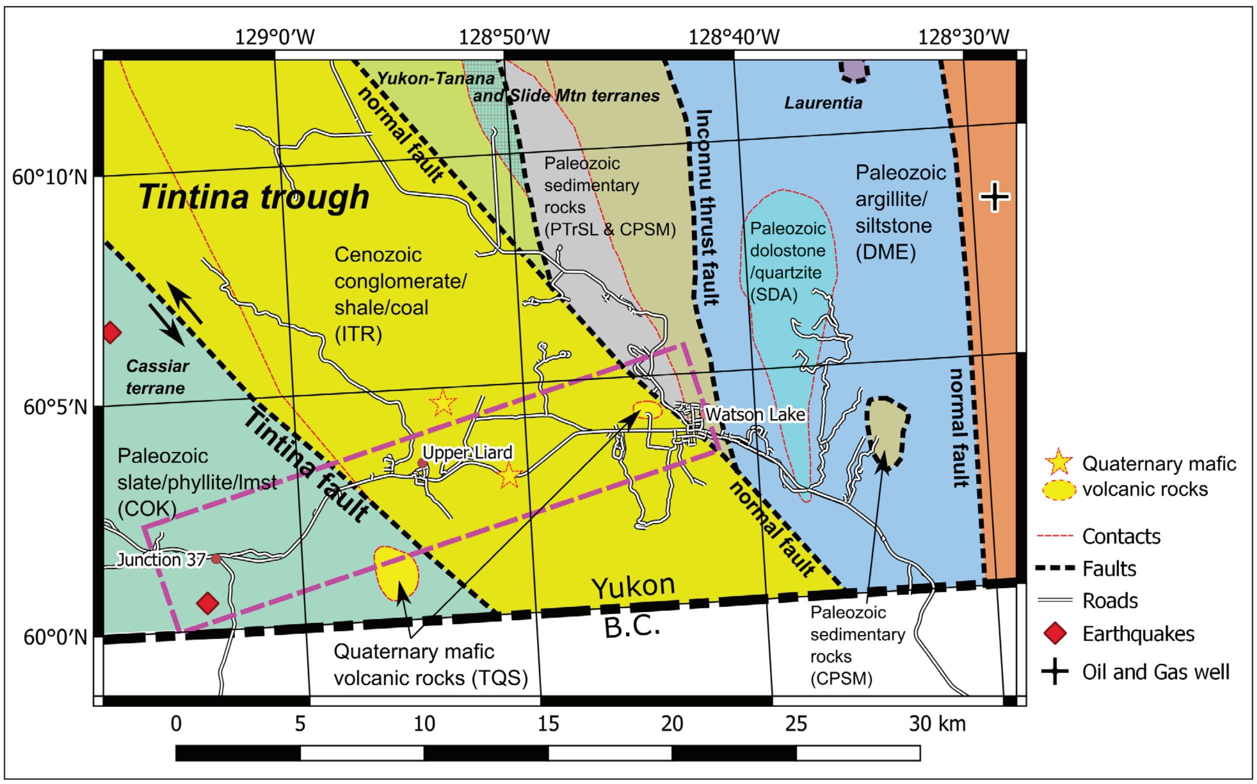

Figure 3. *Bedrock geology in the area of Watson Lake, Yukon (adapted from Colpron et al., 2016). Yellow stars represent two additional occurrences of Quaternary mafic volcanic rocks, one along the Alaska Highway and the other reported by Lipovsky and McKenna (2005). Approximated epicentres of historic earthquakes are shown as red diamonds (source: GeoYukon website* https://mapservices.gov.yk.ca/GeoYukon/*). The study area is shown by the pink dash rectangle.*

Surficial geological mapping by Lipovsky *et al.* (2005) reveals that the Watson Lake area is blanketed by significant thicknesses of glacial deposits (up to ~40 m). Bedrock is exposed only in restricted localities, such as at the bottom of meltwater channels or on high ridges that have been scoured by glaciers. Lipovsky *et al.* (2005) do not report surficial evidence for the Tintina fault or other faults in the area. These observations suggest that there is little, if any, recent movement of the Tintina fault and other major geologic structures in the area.

Tintina fault and other geologic structures

The Tintina fault is a crustal scale, strike-slip fault that has undergone ~430 km of dextral displacement during the Cenozoic (Gabrielse *et al.*, 2006). The fault is an extension of the Northern Rocky Mountain Trench in British Columbia and generally separates Laurentian rocks of ancient North America to the east from allochthonous terranes on the west that were accreted to the margin of North America during the late Paleozoic and Mesozoic eras (Colpron *et al.*, 2007).

The Tintina fault as well as a NW-trending normal fault (that lies adjacent to the Town of Watson Lake) are thought to form the boundaries of the Tintina trough (Fig. 3), which is occupied by the Liard River lowland and is filled with Cenozoic, coal-bearing sedimentary rock. These characteristics suggest that crustal extension and down-faulting may have occurred to accommodate the accumulation of geologically-young sediments in this area. The north-trending Inconnu thrust fault that extends to the north of Watson Lake is a Jurassic-Cretaceous structure which separates the Slide Mountain terrane on the west from rocks of Laurentia on the east.

The study area was purposefully selected to cross the Tintina fault zone, as well as the entire Tintina trough. Such a zone of extension could provide the vertical pathways within the Earth's crust that would allow for deep circulation and heating of groundwater. Active movement of the Earth's crust along a fault zone is key for creating the cracks and permeability that can facilitate deep geothermal fluid circulation. Although data are sparse, the estimated deformation rate along the Tintina fault zone is only ~0.5 mm/year (Leonard *et al.*, 2008). This compares with ~3 cm/year relative plate motion along the San Andreas fault in California. The Tintina fault zone, therefore, is relatively inactive.

Past volcanism

The Watson Lake area lies within the Northern Cordilleran Volcanic Belt (NCVP; Edwards and Russell, 2000), an enigmatic zone of recent volcanism that extends from west-central British Columbia to the border between central Yukon and Alaska. The portion of the NCVP near Watson Lake is an area characterized by a small number of widely dispersed, small-volume mafic volcanic centres. Farther afield, additional Quaternary mafic volcanic outcrops have been identified following a NE-trend that crosses the Tintina trough, along the Rancheria River about 25 km northwest of Watson Lake (Klassen, 1987). These young volcanic rocks mostly range in age from ~230 ka to ~750 ka (Fig. 3; Edwards and Russell, 2000). Residual heat from the specific magma bodies that fed these small-volume volcanic centres has certainly dissipated in the long period of time since emplacement. However, if mafic magma intrusion is still occurring today in this part of the NCVP, it could provide a heat source to warm subterranean geothermal fluid reservoirs. In addition, the margins of magmatic intrusions can be a zone of weakness to potentially provide a permeable pathway for the ascent of geothermal fluids. Additional mapping and dating of young volcanic rocks in the Watson Lake area would help clarify any connection between recent volcanism and possible geothermal resources.

Heat flow data

Only three heat flow data points obtained from mineral exploration boreholes (Lewis *et al.*, 2003) are available within ~100 km of Watson Lake:

- Sa Dena Hess mine (~50 km N of Watson Lake): 105 mW/m^2
- Logan mine (~100 km NW of Watson Lake): 95 mW/m^2
- Midway mine (~80 km WSW of Watson Lake): 126 mW/m^2

Thus, regional heat flow for the Watson Lake region is rather elevated with an average value in excess of 100 mW/m^2. This compares to a mean heat flow of 65 mW/m^2 over continental crust.

Radiogenic heat production data

Due to a lack of outcrop, we do not have direct estimates of radiogenic heat production from plutons that may lie beneath the Watson Lake area. The nearest heat production data point lies ~41 km to the NW of Watson Lake and it is from a Mississippian age, quartz-feldspar metaporphyry with a radiogenic heat production value of only 1.5 $\mu W/m^3$ (Colpron, 2019). The global average for heat production in granites is 2.5–2.8 $\mu W/m^3$ (Hasterok and Webb, 2017). Farther afield, approximately 90 km to the WNW of Watson Lake, is the Cretaceous, Meister Lake pluton with a radiogenic heat production value of 4.0 $\mu W/m^3$ (Colpron, 2019). The only other heat production data nearby comes from the Thunder Mountain batholith ~55 km north of Watson Lake. However, the heat production estimate from this rock unit is only 1.8 $\mu W/m^3$ (Colpron, 2019). Thus, there is scant evidence from surface outcrops for anomalous radiogenic heat production in the Watson Lake area. If radiogenic plutons actually are a significant heat source, they must be either unrecognized or entirely buried. One possible candidate for plutonic rocks that could potentially be buried in the Tintina trough near Watson Lake would be rocks analogous to the Eocene Black River suite. Located ~160 km NW of Watson Lake, these rocks lie along strike of the Tintina fault, are coeval with the extension that formed the Tintina trough, and yield radiogenic heat production values of 6.0–8.2 $\mu W/m^3$ (Colpron, 2019). Note that radiogenic heat production from plutons south of Watson Lake (in British Columbia) is not known due to a lack of data; however, bedrock geological mapping suggests an absence of plutonic rocks in this part of BC (Cui *et al.*, 2017).

Earthquake data

Data on earthquake epicenters for the Watson Lake area were obtained from the GeoYukon website (https://mapservices.gov.yk.ca/GeoYukon/). Only two, small magnitude, historic earthquakes within ~30 km of Watson Lake are present in the catalogue (Fig. 3). One quake with a magnitude of 2.6 occurred ~25 km WNW of Watson Lake in 2005. The epicenter of another quake is located ~21 km WSW of Watson Lake; this magnitude 2.7 event occurred in 1979. Both quakes are located west of the mapped location of the Tintina fault within rocks of the Cassiar terrane. However, due to sparse seismic instrumentation in the Watson Lake area, combined with the low magnitude of the events, the estimated location of these earthquakes is imprecise. The paucity of historic earthquakes in the Watson Lake region is consistent with many geologic observations which suggest a lack of recent fault movement. However, the proximity of these two historic quakes to the Tintina fault suggests that any fault movement in the present-day would likely be associated with the Tintina fault.

Favourable structural environments

For geothermal fluids to flow in the subsurface, faults and fractures need to be open, not shut. Studies from southern Yukon show that the tectonic regime in the area is under compression in a direction oriented approximately NE–SW (Hyndman *et al.*, 2005). Compressional conditions in the crust tend to close fractures and inhibit subsurface fluid flow.

In contrast, extensional tectonic conditions are more conducive for the formation of geothermal reservoirs. For example, as the crust pulls apart and extends, faults pull open to allow for geothermal fluid flow. Crustal extension that runs parallel to the Tintina fault zone has occurred in the past near Ross River, Yukon developing into narrow pull-apart basins that filled with Tertiary age volcanic rocks and an epithermal gold-silver deposit at Grew Creek (Christie *et al.*, 1992). Such pull-apart basins are good indicators of the tectonic conditions that would help facilitate subsurface geothermal fluid flow. Indeed, Faulds and Hinz (2015) analyzed 250 geothermal fields in the Great Basin of western USA in which they identified 8 characteristic structural settings that are favourable for the formation of geothermal systems. One of these settings is a transtensional pull-apart in a major strike-slip fault zone (Fig. 4).

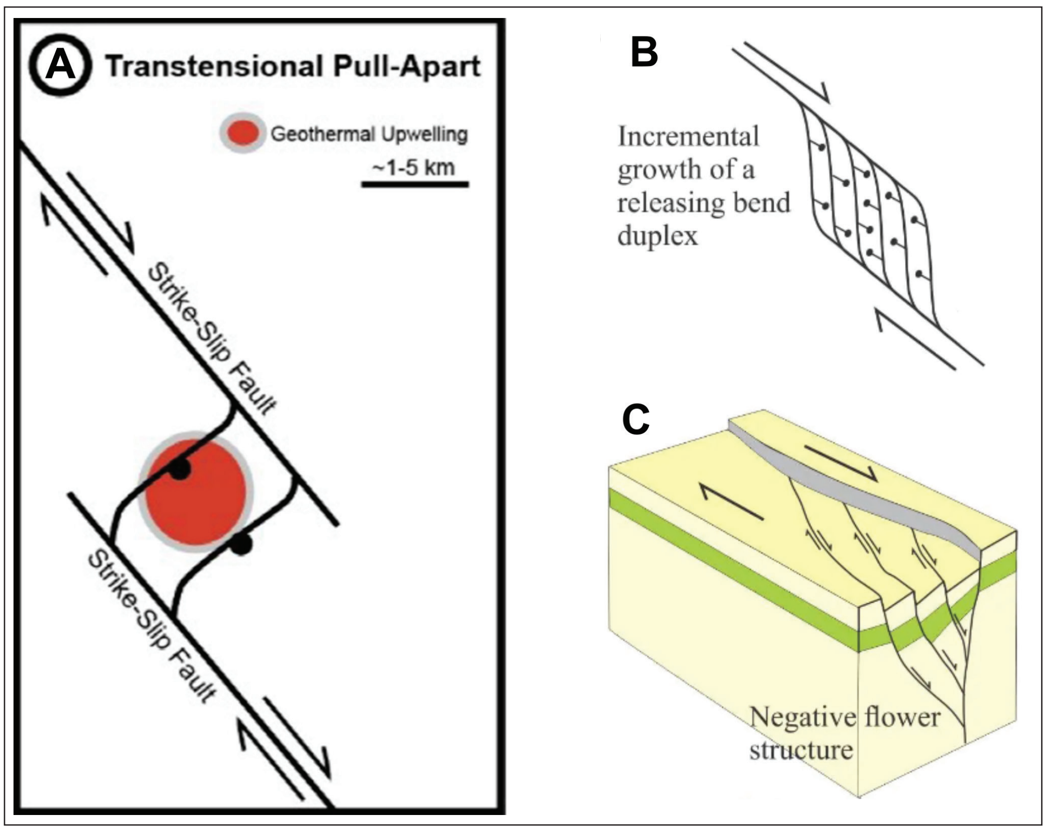

Figure 4. (A) *Schematic diagram of a transtensional pull-apart structural setting which can be a favourable geological environment for geothermal fluid upwelling (from Faulds and Hinz, 2015).* ***(B)*** *Significant movement along a transtensional structure can generate a releasing bend duplex that consists of numerous normal faults that creates an elongated, down-dropped, pull-apart basin.* ***(C)*** *3D perspective view of a transtensional pull-apart basin with normal faults in the form of a negative flower structure. These schematic diagrams represent transtensional pull-apart structures that may exist in association with the Tintina fault zone. For example, similar to the diagrams, the Tintina fault zone has a northwest strike, and dextral motion. A right step-over in the fault would create a zone of extension and, possibly, geothermal fluid upwelling. Note: images from (B) and (C) are from geological-digressions.com.*

Fault-parallel extension in a transtensional pull-apart is an example of a favourable structural environment which could explain the presence of the sediment-filled Tintina trough that lies adjacent to Watson Lake. In addition, ~100 km northwest of Watson Lake, the Tintina fault undergoes a 15° bend associated with a 20 km wide displacement transfer zone that lies at the northern end of the Tintina trough. This fault bend and transfer zone is likely related to the formation of the Tintina trough. Although, such a structural environment can favour the formation of geothermal reservoirs, the low deformation rate for the Tintina fault zone, mentioned previously, suggests that such fault-parallel extension does not appear to be highly active in the present day in the study area.

Geothermal exploration summary and strategy

What do we know?

Existing geoscientific information in the project area, outlined in the previous section, suggests:

a. a slightly elevated average crustal thermal gradient of ~31°C/km is present in the Watson Lake area, based upon Curie point depth mapping;

b. bottom hole temperature data from two historic oil and gas exploration wells (Fig. 2) provide evidence for an even higher thermal gradient in the Watson Lake area of ~38–50°C/km reaching depths of ~1.1–1.4 km. Neither exploration well reported permeable oil and gas horizons in the subsurface;

c. a handful of data points show that regional heat flow is high in the Watson Lake area, on the order of ~100 mW/m^2;

d. fault-parallel, transtensional tectonics likely occurred to create the sediment-filled Tintina trough;

e. four localities of young volcanic rocks of Quaternary age have been identified in the Watson Lake area which may represent zones of weakness in the Earth's crust. However, this volcanism is likely too old to contribute significant amounts of modern geothermal heat;

f. the tectonic regime along the Tintina fault is a transpressive environment which exhibits right-lateral strike-slip fault motion;

g. deformation rates along the Tintina fault are only ~0.5 mm/year, which is low compared to other crustal scale fault zones;

h. earthquake activity is quite low along the Tintina fault and, thus, may contribute little to the current production and maintenance of open fractures (*i.e.*, permeability) in the subsurface in the Watson Lake area; and

i. one possible structural environment that would be favourable for geothermal fluid upwelling (if present) along the Tintina fault near Watson Lake is a trans-tensional pull-apart; indeed, such a structural environment appears to have occurred along the Tintina fault at the Grew Creek epithermal deposit near Ross River, Yukon ~50 million years ago (Christie et *al.*, 1992). In addition, the Tintina fault hosts a large displacement transfer zone and 15° bend at the north end of the Tintina trough.

What do we want to know?

In any geothermal exploration program, the two key requirements for a viable geothermal resource are elevated temperature and adequate rock permeability. Subsurface temperatures in the uppermost few kilometres of the Earth's crust can only be known accurately via downhole measurements in wells. At the present time, the absence of deep wells within the study area prevents us from knowing more about subsurface temperatures close to Watson Lake than what can be inferred from the Curie point depth map and the pair of oil and gas wells that lie >15 km away. The task at hand, then, is to attempt to identify where the fractured and permeable rocks may exist in the subsurface in the study area. By doing so, we can infer where geothermal fluid upwelling might be possible. The exact type of permeability we are in search of is crustal scale fracture permeability along faults that would promote deep (*i.e.*, several kilometres) meteoric water circulation that transports the heat at depth to the surface. For this study, there are several important questions to address.

1. Since the Tintina fault does not have good exposure in the Watson Lake area, what evidence do we have to support the location and orientation of the Tintina fault zone?
2. For the Tintina fault zone, how wide is the system of faults? In other words, how big is the fault damage zone?
3. Is there a trans-tensional pull-apart structural environment associated with the Tintina fault zone within the project area? If so, where?
4. Exactly where in the subsurface are the rock types that are more prone to sustain open fractures and what is their spatial distribution?

In order to begin to address such questions, a more thorough understanding of the 3D geological and structural framework of the subsurface is required. Thus, a significant amount of the effort in this study is aimed at building a 3D geoscience model of the lithology and faults within the project area. The overall goal is that the 3D geoscience model, generated for this project, can serve as a guide for selecting drilling targets that would give direct characterization of the bedrock and measurements of subsurface temperature and permeability. The next sections describe the data and methods used in our attempt to create a 3D geoscience model that is consistent with all the various geoscience datasets available.

Data used in this project

Existing geoscience data

Topographic data

Topographic data compiled in the Watson Lake region include Arctic DEM data in Yukon (as good as 2 m resolution) and CDED data (25 m resolution) on the British Columbia side of the border. In general, elevation ranges from ~600 masl in the Liard River valley to ~1000 masl in the hills to the NE of Watson Lake (Fig. 2). During this study, we found significant elevation discrepancies between the Arctic DEM data and the CDED data (up to 100 m) in the Watson Lake area. We also found discrepancies between these two topographic datasets and new high resolution GNSS elevation measurements obtained during the 2021 gravity survey. As a result, we chose to use the Arctic DEM and CDED data primarily for visualization purposes and limited its use in the quantitative modelling aspect of this study.

Gravity survey data

Regional-scale gravity data were obtained from the NRCAN Geoscience Data Repository for Geophysical Data (https://geophysical-data.canada.ca/). In the Watson Lake area, gravity measurements are generally quite sparse (~10 km station spacing). However, gravity data with a much tighter average spacing of ~750 m have also been collected along the Alaska Highway, a short section of the Robert Campbell Highway and the Stewart-Cassiar Highway. When these gravity data points are gridded (Fig. 5), it reveals a significant, NW-trending gravity low that exists in the Liard River lowland. Such a gravity low would be consistent with a basin, filled with low-density sedimentary rock. Curiously, the gravity low does not lie in the centre of the Tintina trough; rather, the low gravity readings extend out westward, across the inferred location of the Tintina fault. Since major faults often occur on the boundaries between gravity highs and lows, the regional-scale gravity map shown in Figure 5 hints that the actual location of the Tintina fault likely lies farther to the west, near Junction 37.

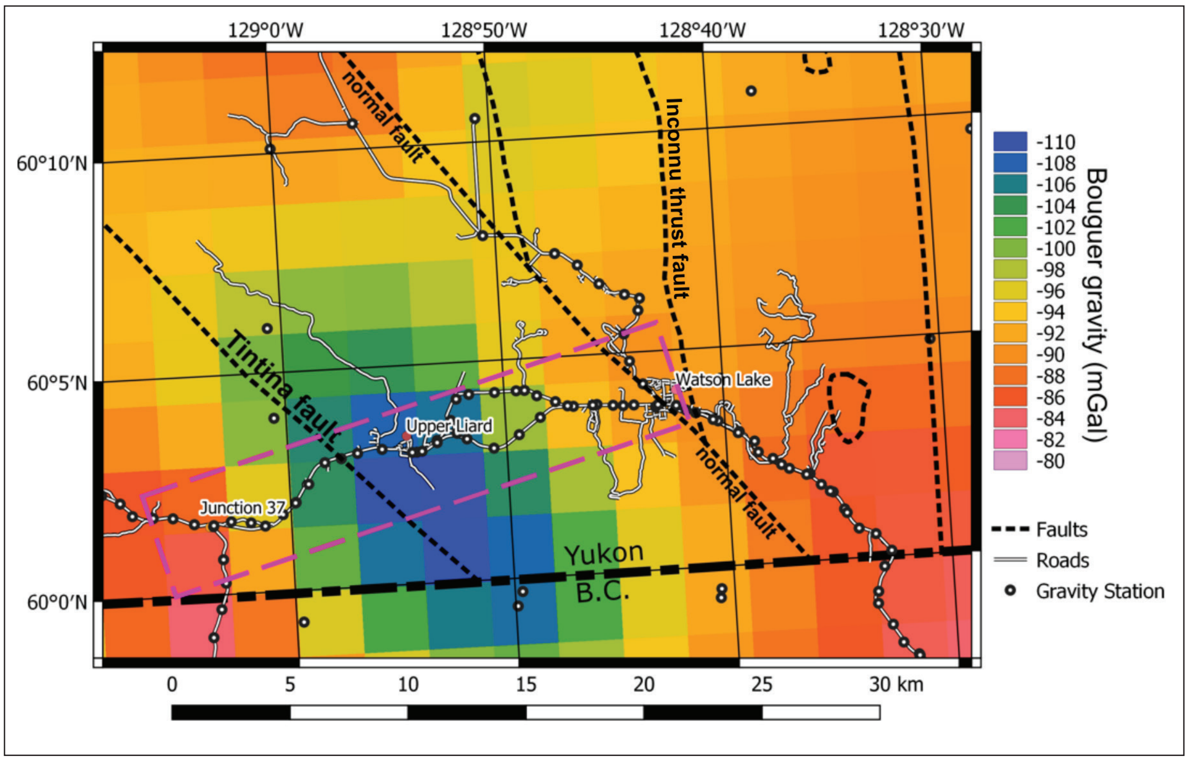

Figure 5. *Regional scale Bouguer gravity map for the Watson Lake area. Gridded gravity data are shown as the coloured background with the locations of gravity measurement points overlain. The region of low gravity (green and blue squares) is likely the location of the Tintina trough that is filled with low-density sedimentary rock. If this interpretation is correct, the NW-trending Tintina fault is most likely located further west than shown above (i.e., near Junction 37). The study area is shown by the pink dash rectangle.*

Airborne magnetic survey data

Magnetic survey data were obtained for the Watson Lake area from both the NRCAN Geoscience Data Repository for Geophysical Data and the Yukon Geological Survey (YGS). The YGS magnetic survey data were reprocessed in 2017 and were gridded with a ~100 m cell size. As a result, higher resolution YGS magnetic data were used for the map-based interpretation, while the NRCAN magnetic survey data were used in the 3D magnetic inversion modelling in order to utilize a large footprint of magnetic survey data extending across both sides of the Yukon–BC border.

Coal borehole data

Paleocene to Lower Eocene sediments in the Tintina trough, west of Watson Lake, host coal deposits (Borovic, 1977; Jenkins, 1979, 1980). These deposits have been found in outcrop near the Liard River as well as in exploratory boreholes. From 1977 to 1980, a coal exploration program resulted in the drilling of 10 boreholes located to the west, southwest and northwest of the community of Upper Liard (Fig. 6). The boreholes were drilled to depths of 98 to 167 m, coal was encountered in every borehole, and the base of the Paleocene sediments was not encountered in any of the holes. Other than coal, clay, sand and silt were encountered in these holes. It is interesting to note that three of the coal exploration holes were drilled on the southwest side of the mapped trace of the Tintina fault. Since Paleocene, coal-bearing sediments were encountered in these three holes (as opposed to bedrock), this suggests that the actual location of the Tintina fault likely lies to the west of these boreholes.

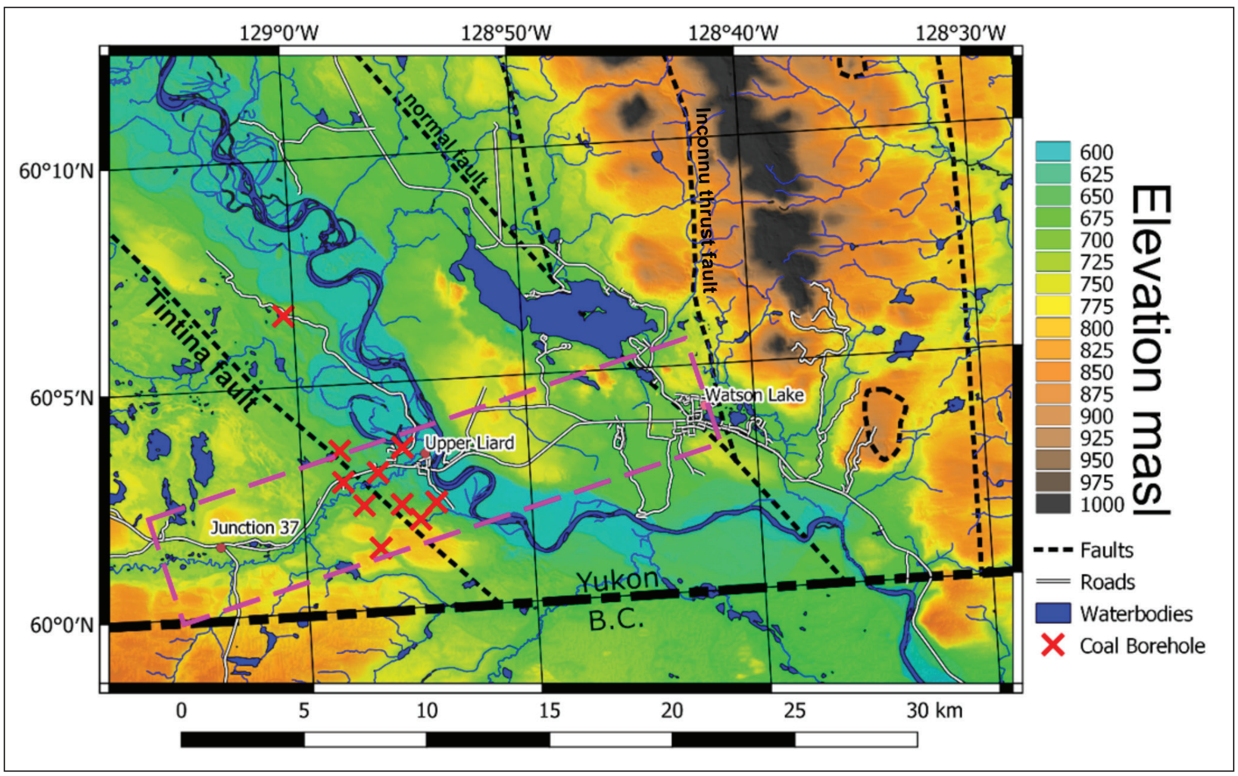

Figure 6. *Topographic map showing the location of ten boreholes (red Xs) drilled in a coal exploration program in 1977–80. The study area is shown by the pink dash rectangle.*

Water well data

Subsurface information on water wells in the Watson Lake area is available on the Yukon Water Well Registry website (https://yukon.ca/en/get-information-about-yukon-groundwater-and-wells). Water wells can provide important data on subsurface geology, depth to bedrock and subsurface temperatures. In total, the Yukon Water Well Registry contained information on 133 water wells in the Watson Lake area (Fig. 7). Of these, 64 water wells had a geologic log. Eight of the water wells reported hitting bedrock at depths ranging from 4 to 90 m. The two deepest wells in the Watson Lake area are the "Lot 18, Block 20" well (a 98 m deep well located on the north side of the Town of Watson Lake) and the Watson Lake Campground well (a 91 m deep well located on the south side of the Watson Lake water body). Both wells hit bedrock (rock type unspecified). In addition, six water wells, in the area of the Watson Lake landfill, drilled through intervals of basalt that varied in thickness from a few to several metres. All other geology logs reported sand, silt and clay as the materials encountered downhole.

Unfortunately, most of the water wells (and the only ones that hit bedrock) lie either outside of, or on the far eastern edge of the study area. The small number of water wells that lie in the rest of the project area are shallow (*i.e.*, <30 m deep) and do not hit bedrock (Fig. 7).

Groundwater temperatures measured in select Watson Lake area water wells have been reported in a document titled "Yukon Observation Well Network" (Government of Yukon, 2019). These data show that in a few wells in the Watson Lake area, groundwater at depths of 6–40 m remains ~3–7°C above freezing throughout the year.

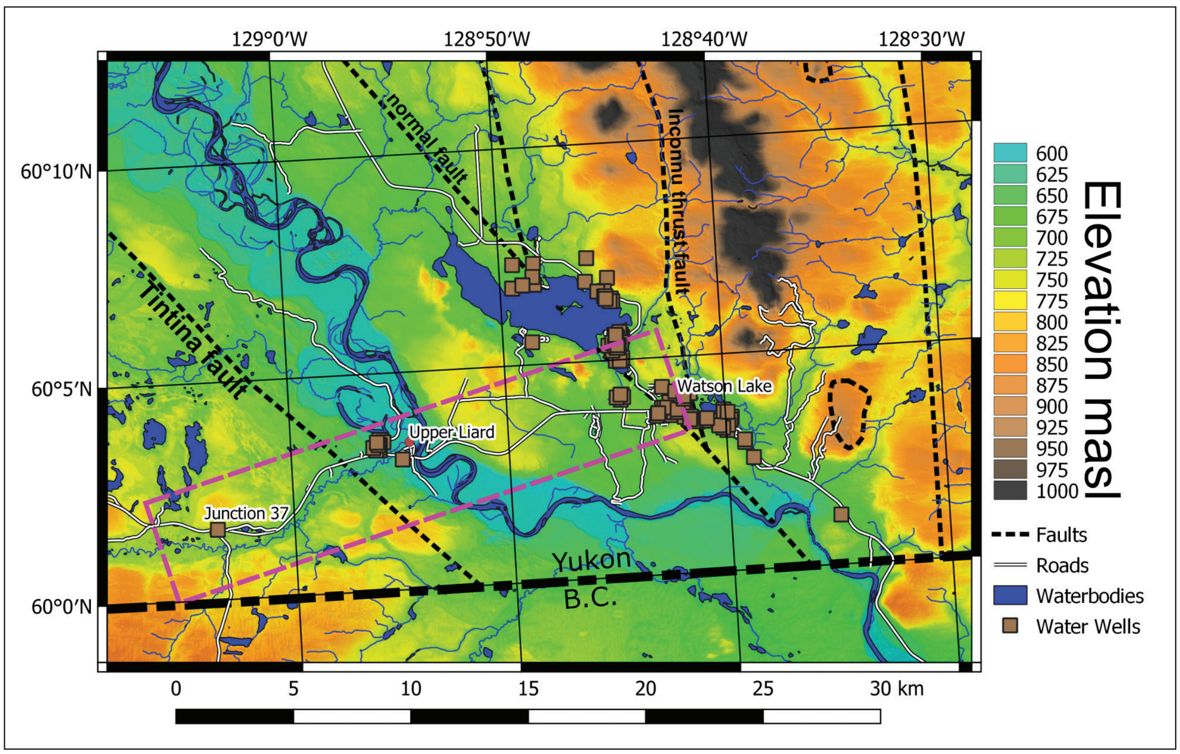

Figure 7. *Topographic map showing the location of water wells (brown squares) in the Watson Lake area. The study area is shown by the pink dashed rectangle.*

Other existing geoscience data

SNORCLE 2D seismic data

As part of the Lithoprobe SNORCLE project, 2D seismic profiles 2a and 2b both passed through the study area, specifically, along the portion of the Alaska Highway between Watson Lake and Junction 37 (Cook *et al.*, 2004; Calvert, 2016). Unfortunately, the published seismic profiles do not provide sufficient detail in the uppermost 1–2 km to discern the Tintina trough basin boundary. Reprocessing of the SNORCLE seismic data using modern methods would be a worthwhile effort to try and resolve a top-of-bedrock reflector in the study area.

SNORCLE magnetotelluric data and 2D resistivity model

As part of the Lithoprobe SNORCLE project, magnetotelluric soundings were also made in the vicinity of Watson Lake, along the Alaska and Stewart-Cassiar highways, with an average spacing of ~15 km. These data were modelled as a 2D resistivity profile by Ledo *et al.* (2002) and reveal the Tintina fault as a region of electrically resistive rock (Fig. 8). Although the SNORCLE MT data are important for regional scale interpretations, the wide spacing and sparse number of MT stations are of limited use for the purposes of this project and will not be discussed further.

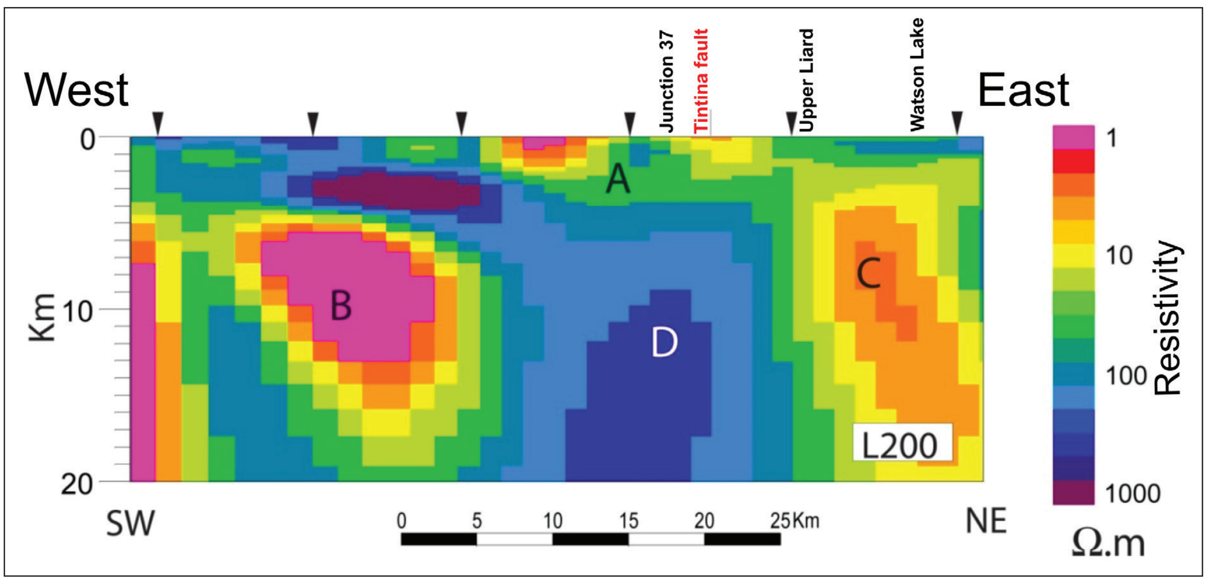

Figure 8. *2D resistivity profile of Ledo et al. (2002) marked with the locations of the SNORCLE MT stations (tall, black triangles). The positions of the communities in the Watson Lake area are also shown. The crustal-scale Tintina fault is thought to lie between Upper Liard and Junction 37. The SNORCLE MT data are very sparse as there are only 3 measurements in the Junction 37 to Watson Lake region.*

Resource exploration assessment reports

Assessment reports from mineral exploration activity in the Watson Lake region were also reviewed for this study. Overall, information in the assessment reports provided limited assistance to improve understanding of the regional geological framework.

Several assessment reports describe the geology and the 1979–2013 exploration efforts at a Paleozoic Sedex Pb-Zn-Ag play located ~6 km SE of Watson Lake straddling the Yukon-BC border. Any hydrothermal activity associated with the formation of this mineral deposit is far too old to be of any relevance to present-day geothermal exploration. Various geophysical surveys were performed on this property; however, the geophysical data/maps presented in the assessment reports are incomplete.

A second set of assessment reports describe exploration work searching for carbonate-hosted Pb-Zn mineralization from 1982 to 1996 at a site ~25 km NW of Watson Lake. A gravity survey conducted along the Campbell Highway near Tom Creek identified what is interpreted as a significant, buried, NW-trending normal fault scarp with offset down to the SW. This normal fault likely connects to normal faults with similar trend in the study area to the south. Other geophysical data/maps presented in these assessment reports are unhelpful to the current geothermal exploration effort.

Newly collected geoscience data

Gravity survey data

In 2020, a ground-based gravity survey was proposed as the next step in a geothermal exploration program for the Watson Lake area. Gravity data would be helpful to improve understanding of the geologic structures that bound the Tintina trough. If found, such structures could potentially serve as permeable pathways for the ascent of warm geothermal fluids.

A 4.5 km × 23 km gravity survey area containing a uniform grid of 470 gravity stations spaced 500 m apart was proposed. The gravity survey area extends from Watson Lake to a few kilometres west of Junction 37 (Fig. 9). It is also co-located with the region that has the best road access (e.g., Alaska Highway, side roads and trails). Geologically, the proposed survey area crosses the Tintina fault, the Tintina trough and a mapped normal fault adjacent to the Town of Watson Lake.

In 2021, Aurora Geosciences collected new measurements from 404 of the proposed gravity stations (Fig. 9; Appendix 2). High-resolution GNSS (Global Navigation Satellite System) elevation measurements were made at each gravity station. The GNSS data were quite valuable to confirm the accuracy of lidar topographic data (discussed below). Gravity and GNSS data were not collected in an area along the SE side of the survey area due to access difficulties as well as limitations on time and budget. The overall, average measurement error for the 2021 gravity survey is 0.063 mGal.

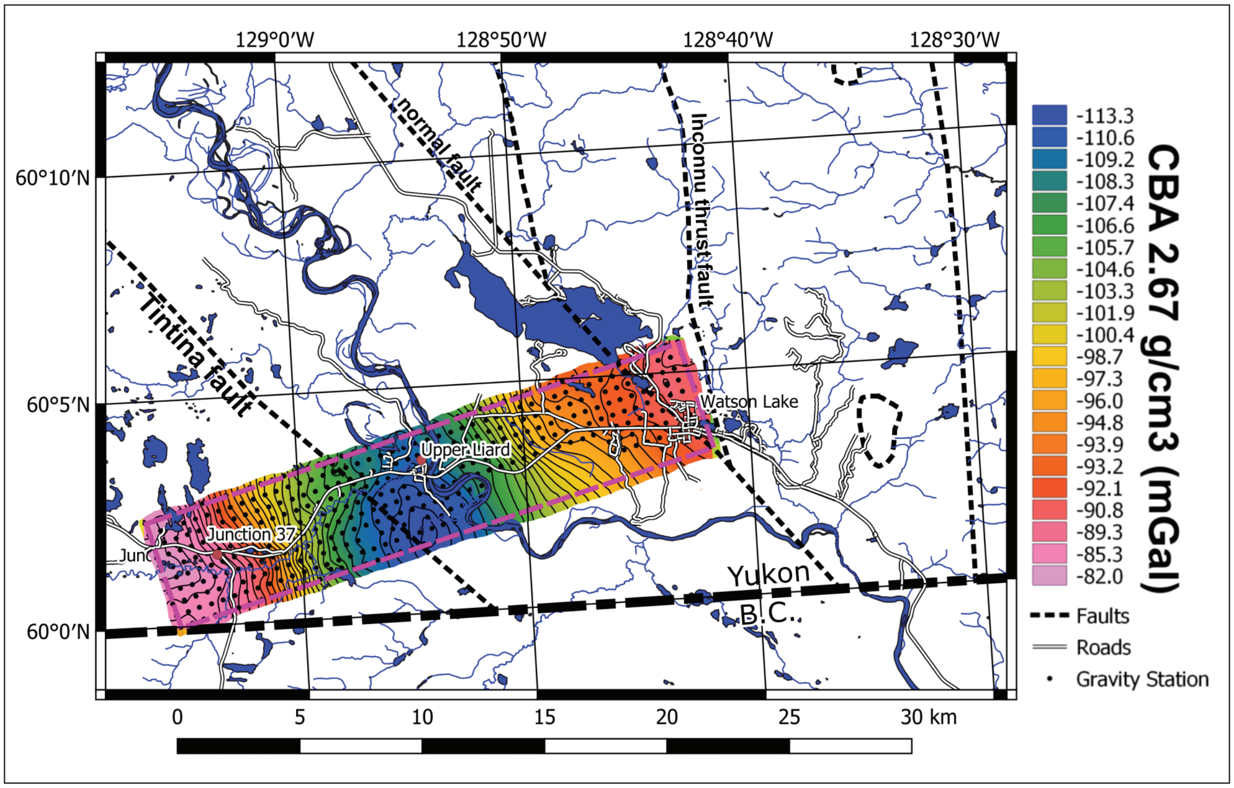

Figure 9. *New gravity data collected within the 4.5 km × 23 km survey area (pink dashed rectangle). Gravity stations occupied in 2021 are shown as black dots. The Complete Bouguer Anomaly data gridded with a 2.67 g/cm^3 terrain correction density is plotted according to the colour ramp at right (cool/warm colours represent gravity lows/highs). The background image shows water bodies and faults as in Figure 7.*

Magnetotelluric survey data

As part of this project, Liard First Nation (LFN) and YGS engaged researchers from the University of Alberta to conduct a magnetotelluric survey in the study area to better understand subsurface electrical resistivity variations at a much higher resolution than was obtained in the Lithoprobe SNORCLE project. A total of 36 MT stations were occupied extending along the entire length of the study area from east to west (Fig. 10). MT station coverage to the north and south of the Alaska Highway was possible in the eastern half of the study area, but in the western half of the study area, MT data was only collected along the Alaska and Stewart-Cassiar highways.

Lidar data

Liard First Nation provided airborne lidar data for this project which significantly improved the quality of the topographic data needed for geophysical data analysis. The lidar data were obtained by Eagle Mapping in 2021, covered the majority of the study area and enabled construction of a 0.5 m resolution digital elevation model (DEM).

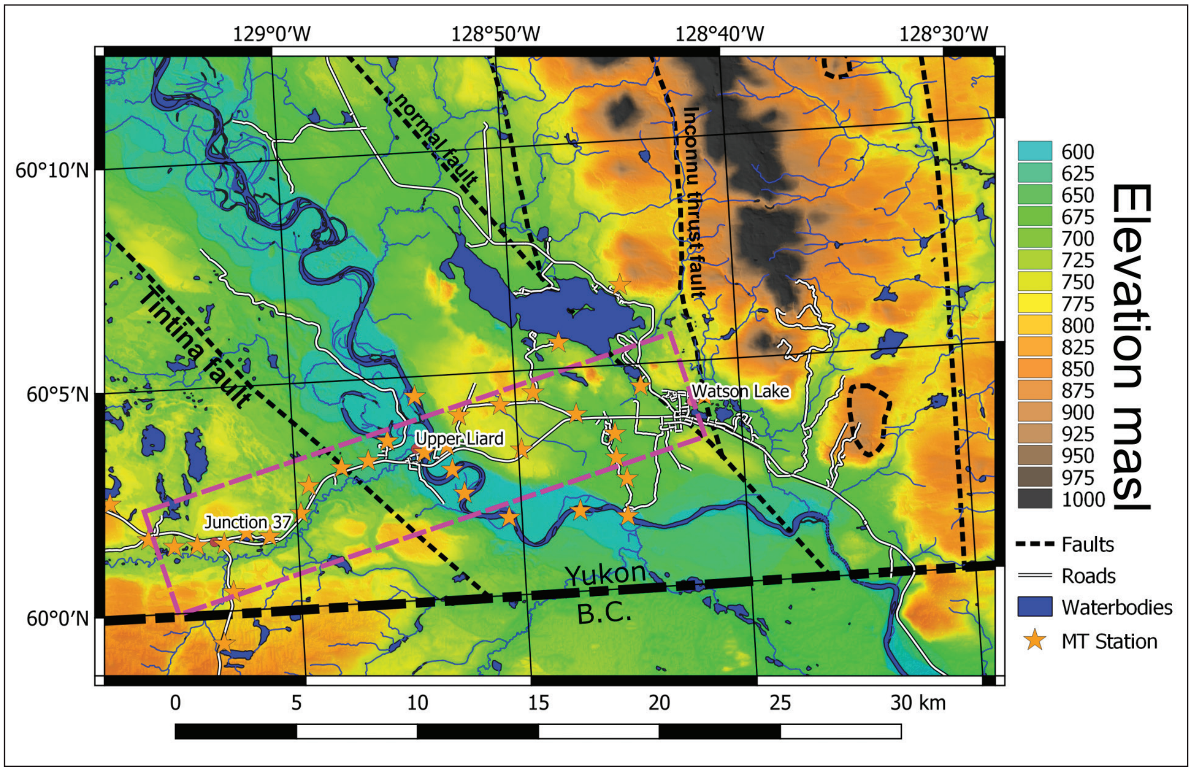

Figure 10. *Topographic map showing the location of MT stations (orange stars) occupied in 2021 by University of Alberta researchers. The study area is shown by the pink dashed rectangle.*

A QC analysis of the lidar data found that lidar-measured elevations were within ~3 cm of GNSS elevations measured at gravity stations during the 2021 gravity survey. Such a small discrepancy between these two datasets lent confidence that the lidar-measured elevations were accurate. In contrast, large elevation discrepancies, on the order of metres to tens-of-metres, exist in some areas between the aforementioned GNSS-measured elevations and two public domain elevation datasets (*i.e.*, Arctic DEM and CDED). Thus, the lidar data proved to be a highly accurate and valuable dataset for the project for the purposes of building a topographic surface for the 3D geology model as well as for gravity data terrain-correction calculations.

In addition, detailed analysis of the lidar data by T. Finley (written communication, 2022) identified a potential northwest-trending, Quaternary fault scarp located ~5 km south of Upper Liard (Fig. 11). Unfortunately, this fault scarp lies ~1 km outside of the footprint of the project area and, therefore, does not have the advantage of multiple, overlapping geoscience datasets to enable a more thorough evaluation.

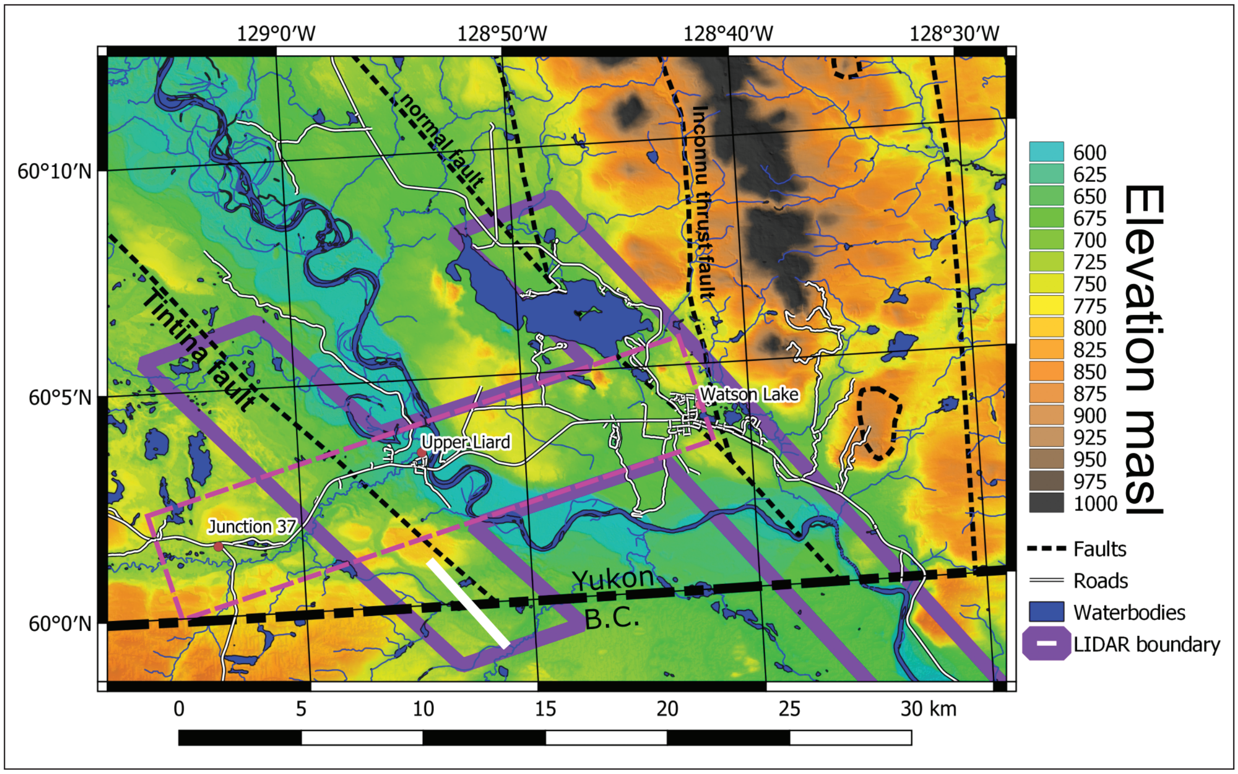

Figure 11. *Topographic map showing the lidar survey boundary (purple). The study area is shown by the pink dashed rectangle. A potential Quaternary fault scarp inferred from the lidar by T. Finley (written communication, 2022) is shown by the white line.*

Rock property data

There are few opportunities to sample bedrock for rock property analysis (e.g., rock density and magnetic susceptibility) given very limited outcrops in the Watson Lake area. Nonetheless, YGS personnel visited the Watson Lake area in 2022 and collected 12 hand samples for rock property analysis from the following rock units: Quaternary mafic volcanics (n = 3), Slide Mountain terrane (n = 1), Yukon-Tanana terrane (n = 7) and Laurentia (n = 1). Magnetic susceptibility was measured on outcrop and hand samples in the field while density was measured on hand samples in the Yukon Geological Survey laboratory in Whitehorse. YGS archives were also searched to obtain additional, representative rock property data for geologic terranes present in the Watson Lake area.

Methodology

Map-based interpretation

In an effort to better characterize the structural and geological framework within the project area, the following datasets were interpreted using a map-based approach: topography, gravity, magnetics and geology. All map-based interpretation was performed with the software QGIS (qgis.org).

Various filters were applied to the gravity and magnetic survey data to aid map-based interpretation of the spatial extent of dense and magnetic rock units as well as the orientation of fault structures that lie under Quaternary cover. These filters include first vertical derivative, total horizontal gradient and tilt derivative, as well as analytic signal (magnetics only). Geophysical filtering was performed using GeoToolkit software from the UBC Mineral Deposit Research Unit (https://geotoolkit.readthedocs.io/). The gravity and magnetic geophysical data were interpreted in conjunction with the mapped geology (*e.g.*, Colpron *et al.*, 2016) and rock properties to better understand structures and lithologic contacts in the project area.

3D gravity and geology modelling

3D geologic models were constructed for the study area to aid in interpretation and to serve as an important constraint for 3D gravity inversion modelling. Rhinoceros software (www.rhino3d.com) was used to build the 3D geologic model as surfaces that represent geologic horizons and faults. The 3D geologic model was built to honour the bedrock geology map of Colpron *et al.* (2016) with one exception: the Tintina fault was moved west based upon the locations of coal boreholes and interpretation of gravity data from this study. In addition, the thickness variations of the Cenozoic sedimentary rocks of the Tintina trough were inferred from a preliminary 3D MT resistivity inversion model generated by the University of Alberta for this project (discussed below).

3D geophysical inversion modelling of gravity data was performed as part of the effort to iteratively build and improve the 3D geologic framework of the project area. Gravity data are sensitive to changes in subsurface rock density and rock density can be used as a proxy for rock type, provided sufficient density contrasts between rock units are present. The 3D inversion modelling of gravity data pursued here was guided by both the 3D geological model described above as well as average rock density values for each geologic unit. The inversion algorithm employed for the modelling is the open source SimPEG code (Cockett *et al.*, 2015). We used both rock property and geologically-constrained inversion strategies as described by Fullagar and Pears (2007) and Fullagar *et al.* (2008). In addition, we used spatially variable mixed Lp norms for the model regularization as described in Fournier and Oldenburg (2019).

The 3D gravity model volume was 4 km thick and we assumed a background density value of 2.67 g/cm^3. The 3D model mesh consists of 80 m cells in the X and Y directions with model cell thicknesses of 40 m (from 0–160 m depth) and 80 m (from 160–4000 m depth). Two kilometres of padding cells were added to the model volume on the sides and bottom to minimize edge effects. The topographic surface of the 3D geophysical model volume was created from a 0.5 m resolution DEM derived from the 2021 lidar dataset with a small portion on the west side (with no lidar data) using Artic DEM topographic data. A total of 404 gravity data points, with an average measurement error of 0.063 mGal, were used in the inversion modelling. The gravity data consisted of Complete Bouguer Anomaly gravity values with a terrain correction density of 2.67 g/cm^3. The gravity data were upward continued by 500 m prior to inversion modelling to minimize near surface effects and model artifacts.

3D magnetic modelling

Magnetic data are sensitive to variations in the magnetic susceptibility of rocks in the subsurface. Due to the presence of a large, NW-trending magnetic high anomaly observed in the TMI magnetic map, 3D geophysical inversion modelling of magnetic data was performed to help better estimate the depth and geometry of the inferred plutonic body that lies below.

Unlike the gravity modelling described above, the 3D inversion modelling of magnetic data was not guided by a 3D geological model because of a lack of adequate geologic constraints on the magnetic rock bodies in the Watson Lake area. As a result, geologically-*unconstrained* magnetic inversion modelling was performed. The magnetic inversion modelling used the open source SimPEG code (Cockett *et al.*, 2015) and spatially variable mixed Lp norms for the regularization (Fournier and Oldenburg, 2019). The 3D magnetic model volume was made quite large (50 km E–W × 35 km N–S × 8.2 km thick) to encompass the entire region. As a result, the model mesh was coarser than the gravity model mesh to ease the computational requirements of the inversion. Thus, for the 3D magnetic modelling, the mesh consists of 200 m cells in the X and Y directions with model cell thicknesses of 100 m (surface layer), 200 m (from 100–1900 m depth), 400 m (from 1900–6700 m depth) and 800 m (from 6700–8200 m depth). Two kilometres of padding cells were added to the model volume on the sides and bottom to minimize edge effects.

A total of 21,680 magnetic survey data points were used in the inversion modelling, derived from gridded TMI magnetic survey data from the NRCAN Geoscience Data Repository for Geophysical Data (http://gdr.agg.nrcan.gc.ca/). Magnetic field parameters used for the inversion modelling include declination (32.075°), inclination (77.623°) and total field strength (58 823 nT). Lastly, for simplicity, we assumed that remanent magnetization of rocks is not present in the project area.

Limitations and uncertainty of 3D geophysical inversion modelling

For all geophysical models, non-uniqueness is a problem such that even if a geophysical model is mathematically correct and matches the surface geophysical measurements quite well, it may not necessarily be geologically correct. In this study, we try to reduce this uncertainty by simultaneously matching the geophysical measurements, rock property data and a geologically-reasonable 3D geology model that honours bedrock geology mapping.

Results

Map-based interpretation

Gravity survey data

Complete Bouguer Anomaly (CBA) gravity data collected for this study, with a terrain correction density of 2.67 g/cm^3, has a range from -112 to -82 mGal (Fig. 12). The key feature in the gravity map is a gravity low in the centre of the study area with gravity highs to the NE and SW. The gravity low is inferred to represent the extent of the Tintina trough, a basin filled with low-density, coal-bearing sedimentary rock. Indeed, the gravity low encompasses the footprint of the coal boreholes drilled in the 1970s. The gravity highs are inferred to represent regions of bedrock near the surface with a relatively thin covering of glacial sediments.

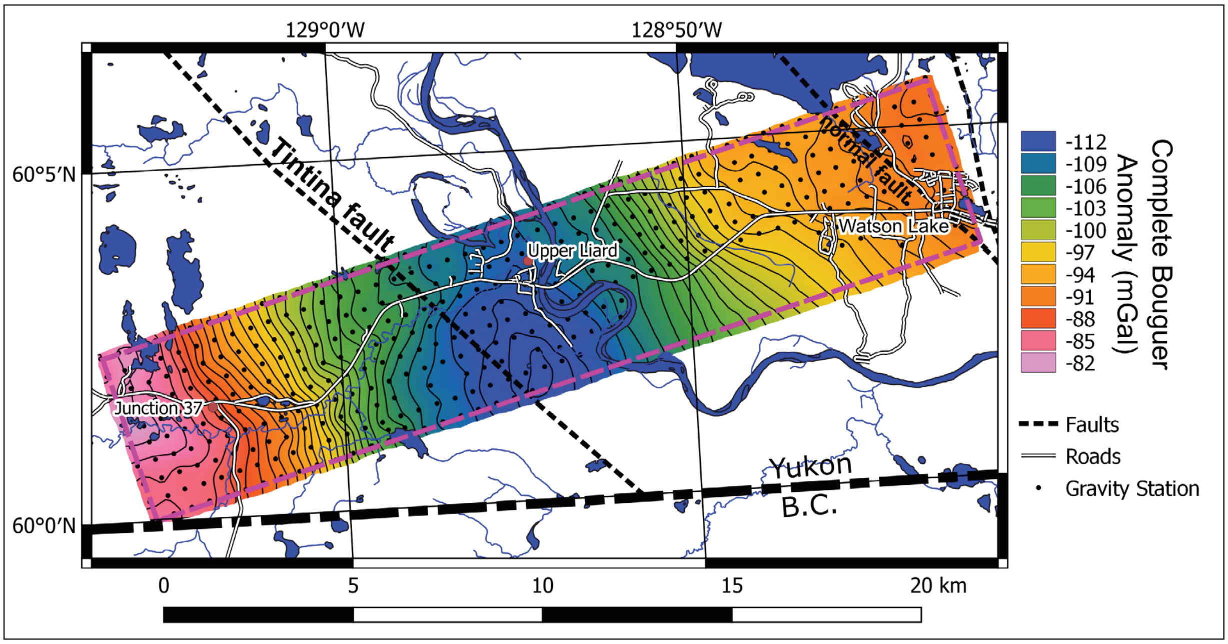

Figure. 12. *Complete Bouguer Anomaly (CBA) gravity data gridded with a 125 m cell size. Black dots represent gravity survey stations. Gravity contour lines are shown at 1 mGal (black lines) intervals. The background image shows water bodies and faults as in Figure 7. The study area boundary is the pink dashed rectangle. Black dashed lines are faults inferred from bedrock mapping (Colpron et al., 2016) Proposed new location of Tintina fault shown in Figure 13. Note: CBA gravity map is speculative in the southeastern portion of the study area where there are no gravity data points.*

A second newly recognized feature in the gravity map is a subtle, NE-trending zone of elevated gravity that parallels the Alaska Highway between Junction 37 and Upper Liard. This gravity high also coincides with Albert Creek. It is inferred that this elevated gravity response is due to the deposition of sediments in the Albert Creek valley (likely derived from Cassiar terrane rocks to the west) that have a higher density than the coal-bearing sediments in the Tintina trough that lie underneath.

Unfortunately, most of the outcrops of mafic volcanic rocks lie outside of the gravity survey area. This means that the gravity response of these Quaternary volcanic bodies cannot be assessed. The single occurrence of mafic volcanic rock that lies within the gravity survey area consists of thin (4–7 m) basalt layers reported in five boreholes drilled at the Watson Lake landfill just west of town. These likely represent a single, thin basalt flow unit derived from a volcanic vent that lies "uphill" somewhere towards the east. There is no obvious gravity response from the basalt reported from the boreholes which is likely due to the thin, layer-cake geometry of the volcanic rocks.

A total horizontal gradient (THG) filter was applied to the gravity data to highlight the zone of greatest horizontal change in the gravity (Fig. 13). THG maps are commonly used in gravity interpretation to infer fault contacts since THG high anomalies represent zones of strong density contrast. The THG map generated for the study area reveals two zones with high horizontal gradient response. The THG high anomalies are ~800 m and ~2500 m across and are interpreted

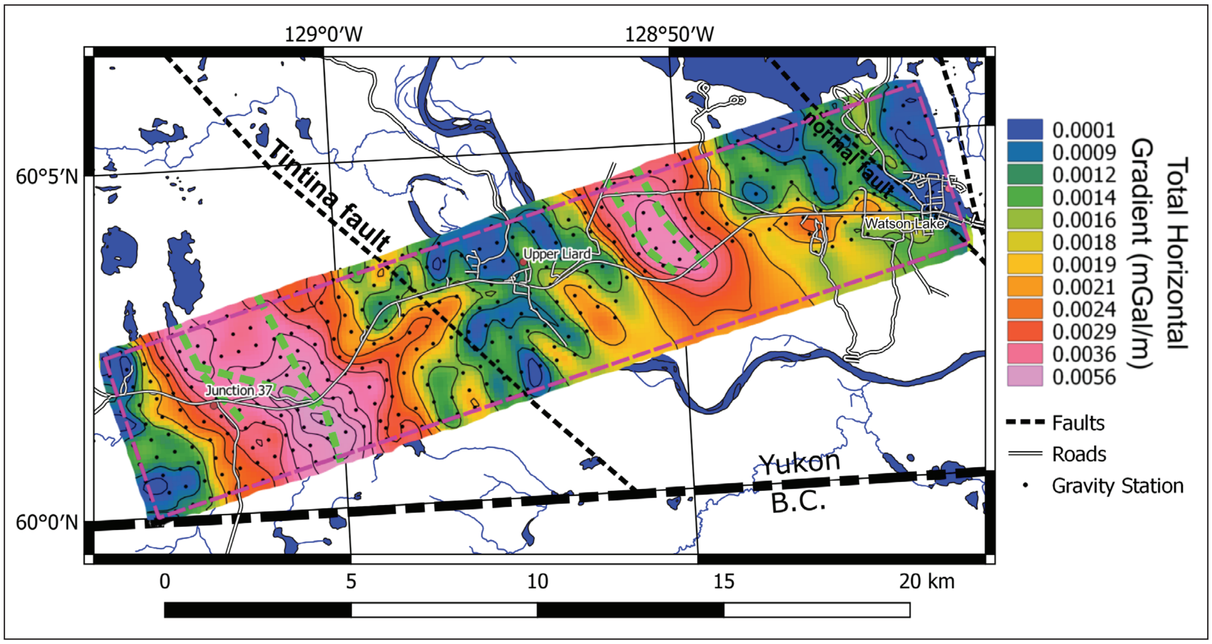

Figure. 13. *Complete Bouguer Anomaly gravity data upward continued by 500 m and with the total horizontal gradient (THG) filter applied. Black dots represent gravity survey stations. The background image shows water bodies and faults as in Figure 7. The study area boundary is the pink dashed rectangle. Black dashed lines are faults inferred from bedrock mapping (Colpron et al., 2016). Thick green dashed lines are faults interpreted from the new gravity data. This new gravity interpretation places the Tintina fault zone ~5 km southwest of the previous location. Note: THG gravity map is speculative in the southeastern portion of the study area where there are no gravity data points.*

to represent NW–SE trending fault zones that are characterized by a relatively wide zone of deformation. We further conclude that these fault zones, inferred from the gravity, form the boundaries of the Tintina trough. One of these new fault zones lies ~3.5 km east of Upper Liard; the other lies immediately east of Junction 37. The coal-bearing boreholes from the 1970s lie between these two fault zones in the Tintina trough. Here, we propose that the fault zone adjacent to Junction 37 is the main strand of the Tintina fault; this would require moving the currently mapped location of the Tintina fault ~5 km to the SW (Fig. 13).

Magnetic survey data

Within the study area, the YGS Total Magnetic Intensity (TMI) data with Reduction to Pole (RTP) have a range from -15 nT to +250 nT. The magnetic response in the study area is dominated by a broad, smooth, NW-trending, magnetic high situated between Junction 37 and Upper Liard (Fig. 14). The geologic origin of this magnetic high is unclear since the Cassiar terrane bedrock on the west of the study area is dominantly slate, phyllite and limestone (rocks with low magnetic susceptibility) with only minor amounts of mafic volcanic rocks. However, these types of large, smooth, magnetic high anomalies are commonly interpreted as deeply buried, magnetic plutons (Dentith and Mudge, 2014). Indeed, Snyder et *al.* (2005) interpreted this NW-trending magnetic high to be a plutonic rock body, the top of which lay at ~6 km below the ground surface. The NW-orientation of the magnetic anomaly suggests that pluton emplacement and displacement along the Tintina fault is related. Other NW-trending plutons in Yukon emplaced along the Tintina

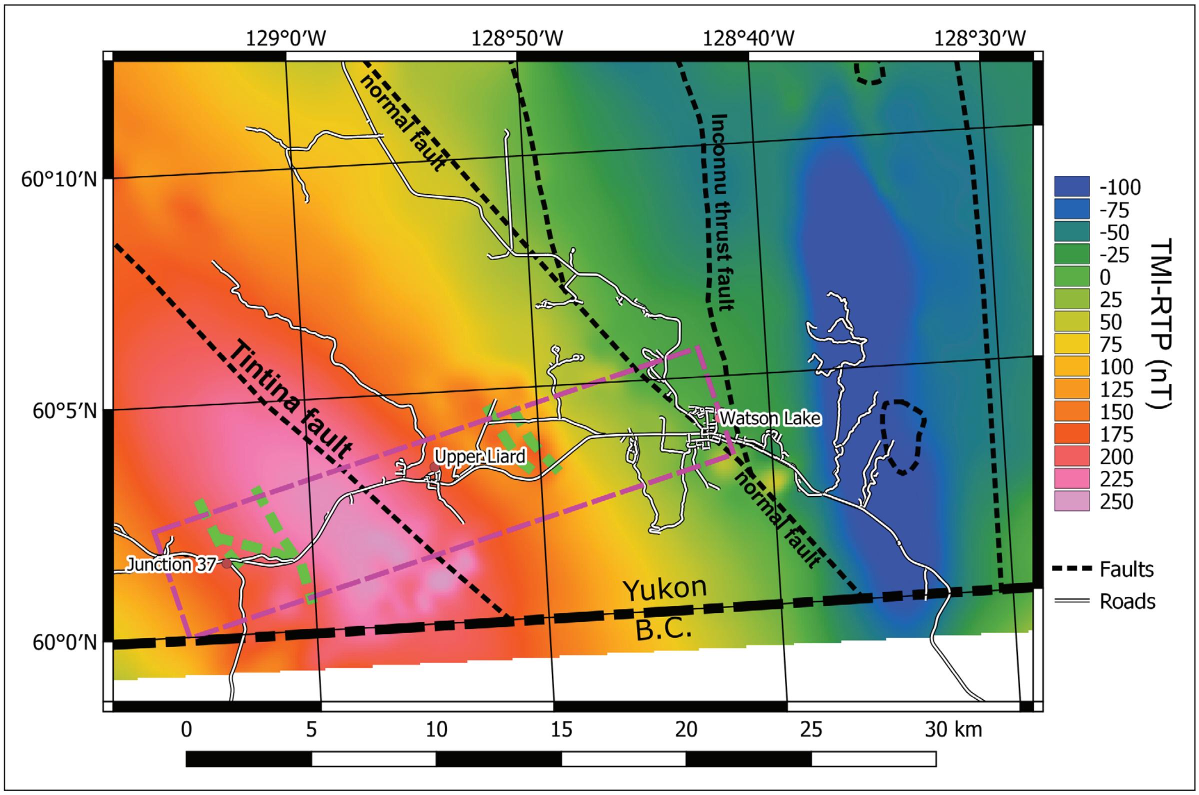

Figure 14. *Reprocessed aeromagnetic survey data (Aurora Geosciences and Bruce, 2017) gridded with a 100 m cell size. Total Magnetic Intensity with Reduction to Pole applied (TMI-RTP) is shown here. Black dashed lines are faults inferred from bedrock mapping (Colpron et al., 2016). Thick green dashed lines are faults interpreted from the new gravity data. Project area boundary is the pink dashed rectangle.*

fault, as mentioned previously, include the Eocene age Black River suite which has a measured radiogenic heat production of 6.0–8.2 μW/m^3 (Colpron, 2019). The radiogenic heat production (if any) of the pluton that lies beneath Junction 37 is not known. On the eastern side of the study area, the magnetic response is characterized by decreasing magnetic intensity which broadly corresponds to the area mapped as the Paleozoic rocks of Yukon-Tanana terrane, Slide Mountain terrane and Laurentia (*i.e.*, low magnetic susceptibility rocks).

Additional details hidden in the magnetic survey data can be obtained by applying filters to the TMI-RTP data. The TMI-RTP data with the tilt angle filter applied (Fig. 15) reveal what appear to be strongly magnetic, NE–SW features that crosscut the Tintina fault just to the south of Upper Liard. Additional, strongly-magnetic, lozenge-shaped features, 1–3 km in size, can be seen between Upper Liard and Watson Lake. The four known occurrences of young mafic volcanic rocks in the study area coincide with the zones of dipolar magnetic anomalies and thus, we infer that these zones have strongly magnetic rocks present at the surface and/or in the shallow subsurface. This interpretation would imply that Quaternary mafic volcanic rocks may be much more abundant in the study area than what the four recognized occurrences would indicate. Although mafic igneous rocks like these most likely cooled long ago, the margins of such intrusions could potentially provide permeable pathways for the ascent of geothermal fluids.

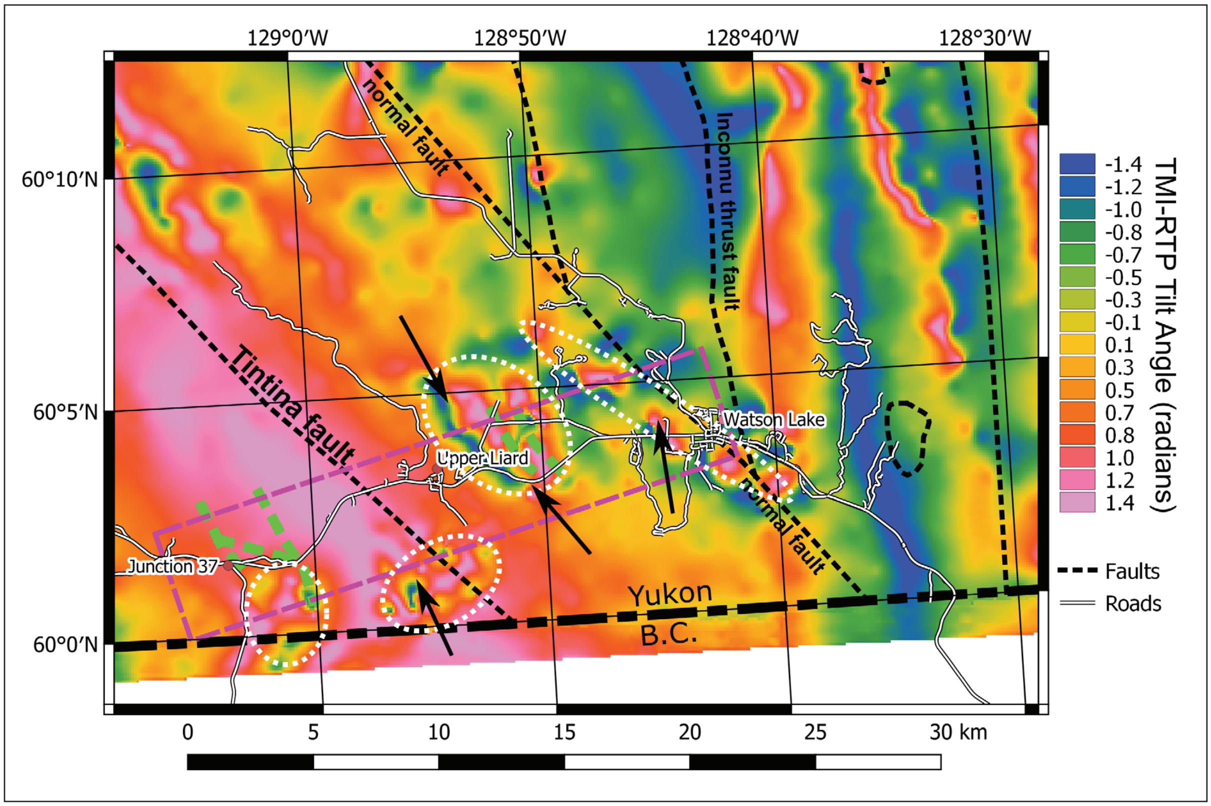

Figure 15. *Reprocessed aeromagnetic survey data (Aurora Geosciences and Bruce, 2017) with the tilt derivative applied to enhance the magnetic features. Black arrows point to known occurrences of Quaternary mafic volcanic rocks. White-dotted ovals surround areas of small, discrete, dipolar magnetic anomalies that are inferred to represent strongly magnetic rocks present at the surface and/or shallow subsurface. Black dashed lines are faults inferred from bedrock mapping (Colpron et al., 2016). Thick green dashed lines are faults interpreted from the new gravity data. Project area boundary is the pink dash rectangle.*

Rock property data analysis

As part of this project, 12 rock samples were collected for rock property measurements. These samples were collected from outcrops within 8 km of Watson Lake; they represent four out of the six major rock types present within the study area (Quaternary mafic volcanic rocks, and rocks of the Yukon-Tanana, Slide Mountain and Laurentia terranes).

Additional rock property data for the Slide Mountain (n = 48) terrane and Laurentia (n = 25) were obtained from YGS archives to supplement the limited number of field measurements. These additional rock property data are from the Finlayson Lake area, just north of the Watson Lake area, and are most likely broadly representative for the rocks of Laurentia.

The lithology of the Slide Mountain terrane, however, can be variable which complicates the geoscience interpretation effort. For example, in the Finlayson Lake area, Slide Mountain terrane rocks are represented by the Campbell River Formation which is dominated by mafic volcanic rocks with minor chert/argillite. In the Watson Lake area, by contrast, the Slide Mountain terrane is represented by the Fortin Creek Group which is composed primarily of chert, phyllite and argillite. Based upon their lithology, we would expect the Campbell River Formation rocks to have a higher average density than the Fortin Creek Group rocks. As expected, analysis of the rock density data show that the Campbell River Formation rocks have a high average density (2.81 g/cm^3) with a high degree of variability reflecting the mixture of higher density mafic volcanic rocks and lower density chert/argillite rocks. Surprisingly, the density of the single sample from the Fortin Creek Group also has a high density (2.96 g/cm^3). This suggests that the Campbell River Formation and Fortin Creek Group portions of the Slide Mountain terrane may not have substantially different rock densities. Considering that we only have a single rock density measurement from the Fortin Creek Group (which may or may not be representative) we choose to use the overall average density of all Slide Mountain terrane rock samples for the modelling purposes of this study.

Density and magnetic susceptibility measurements for the Cenozoic sedimentary rocks in the Tintina trough were also obtained for this study from the original core extracted during the 1977 to 1980 coal exploration program. The core had been stored in the YGS archives for the last ~45 years. YGS personnel were able to obtain rock property measurements for numerous portions of the core from all 10 boreholes.

All the rock property data were categorized according to the major rock unit to which they belong and were graphed as box and whisker plots for better visualization of their distribution (Fig. 16). Simple statistics (*i.e.*, maximum, minimum, mean and 1σ standard deviation) were calculated to assess the variation in the results (Table 1). The average rock property values shown in Table 1 are assumed to be representative of each rock unit and, therefore, were used as starting and reference values in the 3D geophysical inversion modelling.

As shown in Figure 16, average rock density is highly variable yet elevated for the Slide Mountain terrane samples (2.82 g/cm^3), and also elevated for the Quaternary mafic volcanic rocks (2.79 g/cm^3). The rock densities are lower for the Yukon-Tanana terrane (2.71 g/cm^3) and Laurentia (2.62 g/cm^3), while the average density for the near surface Cenozoic sedimentary rock is substantially lower (1.75 g/cm^3).

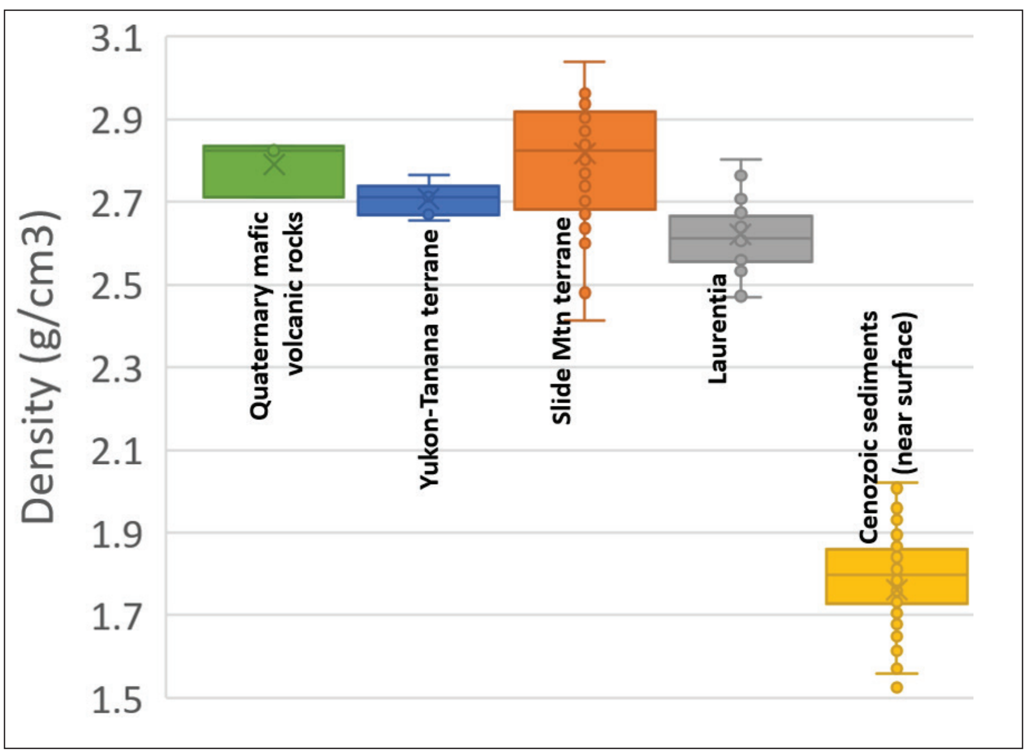

Figure 16. *Rock density data compiled from 12 hand samples collected from the study area in 2022, rock property data in the YGS archives, and core from 1970s era coal boreholes.*

Table 1. *Simple statistics of the* **(A)** *density data and* **(B)** *magnetic susceptibility data categorized according to rock type. n = number of measurements. Note: a median value (*) is reported for Slide Mountain terrane magnetic susceptibility instead of an average value to avoid the dominating influence from outlier data points.*

(A)

Rock unit	Minimum (g/cm^3)	Maximum (g/cm^3)	Average (g/cm^3)	1σ Std. Dev. (g/cm^3)	n
Cenozoic sedimentary rocks	1.01	2.02	1.76	0.17	142
Quaternary mafic volcanics	2.71	2.83	2.79	0.07	3
Yukon-Tanana terrane	2.66	2.77	2.71	0.04	7
Slide Mountain terrane	2.41	3.45	2.82	0.17	49
Laurentia	2.47	2.80	2.62	0.09	26

(B)

Rock unit	Minimum ($SI \times 10^{-3}$)	Maximum ($SI \times 10^{-3}$)	Average ($SI \times 10^{-3}$)	1σ Std. Dev. ($SI \times 10^{-3}$)	n
Cenozoic sedimentary rocks	0.04	1.05	0.16	0.10	145
Quaternary mafic volcanics	6.13	7.56	6.61	0.83	3
Yukon-Tanana terrane	0.15	0.27	0.20	0.04	7
Slide Mountain terrane	0.03	52.6	0.16*	8.28	49
Laurentia	0.01	0.52	0.10	0.11	24

As shown in Figure 17, average magnetic susceptibility is low for the Yukon-Tanana terrane, Slide Mountain terrane, and the near surface Cenozoic sediments (~0.2×10^{-3} SI). These rock units are essentially magnetically indistinguishable from one another. Laurentia has an average magnetic susceptibility value that is even lower (~0.06×10^{-3} SI), yet the range in the measurements overlaps significantly with the other rock units, which would make Laurentia difficult to distinguish using magnetic properties alone. In contrast, the Quaternary mafic volcanic rocks have much higher magnetic susceptibility values (~7×10^{-3} SI).

Rock property data for the sixth rock unit present in the study area, the Cassiar terrane, were not available for this study. However, for the slate/phyllite/limestone rocks of the Cassiar terrane, a rock density of ~2.8 g/cm^3 and magnetic susceptibility of 1×10^{-4} SI would be typical, based upon literature values (Dentith and Mudge, 2014).

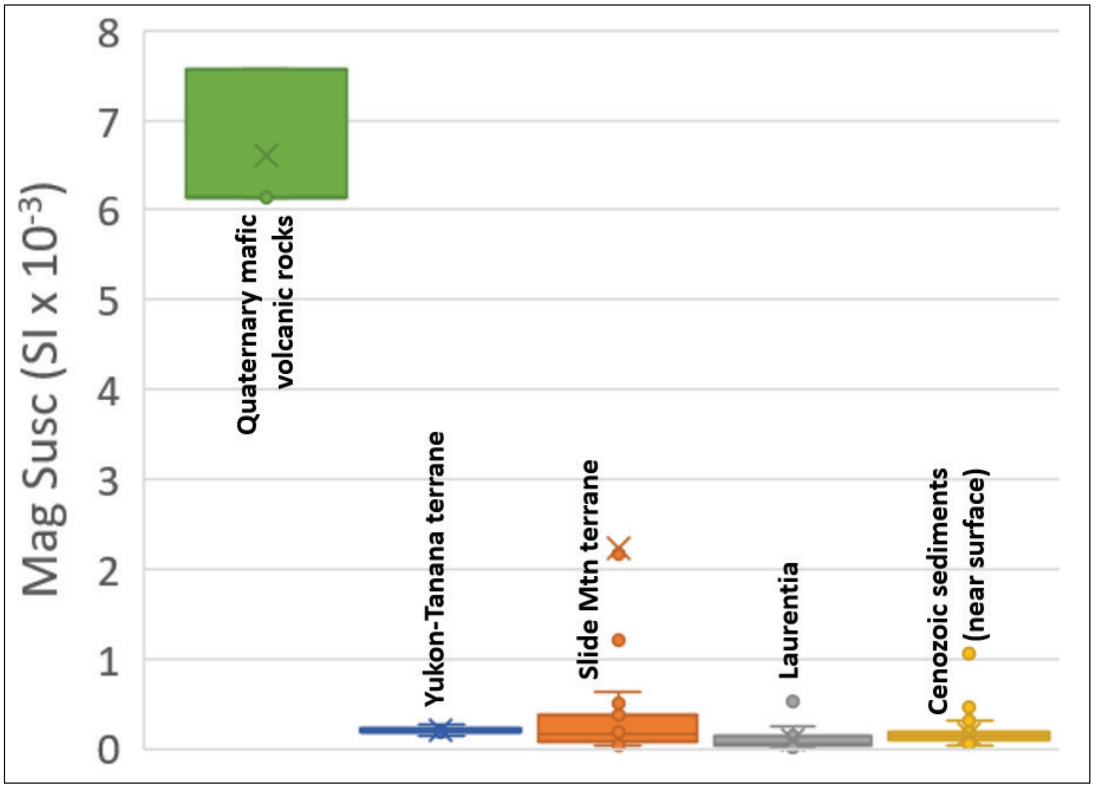

Figure 17. *Rock magnetic susceptibility data compiled from 12 hand samples collected from the study area in 2022, rock property data in the YGS archives, and core from 1970s era coal boreholes.*

Integrated 3D geoscience model interpretation

2D interpretation of the MT resistivity model

A key unknown at the start of this project was the extent and thickness variations of the Cenozoic, coal-bearing sedimentary unit in the Tintina trough. Our plan was to use the gravity data to pursue depth-to-basement modelling of this low-density rock unit to help determine the basin depth and shape. However, geologic constraints such as rock density measurements and basin depth estimates (e.g., from wells or other data/models) would be useful to help guide the depth-to-basement modelling effort towards a geologically reasonable result. Fortunately, rock density measurements from the coal boreholes are available and provide useful constraints for the density of the Cenozoic sedimentary rocks in the Tintina trough. However, the density of the underlying bedrock is unknown. Furthermore, we lack other data that could help indicate what the thickness of the Cenozoic sedimentary unit might be. For example, none of the coal boreholes or water wells in the Tintina trough drilled deep enough to reach bedrock beneath the Cenozoic sedimentary unit. In addition, published SNORCLE 2D seismic profiles that cross the study area do not have sufficient resolution to provide even a rough estimate of the thickness of the Cenozoic sediments.

As a result, to support the depth-to-basement modelling effort, we used a preliminary 3D resistivity model from the Watson Lake MT survey (Fig. 18) to explore possible thicknesses of the Cenozoic sedimentary rock unit. The resistivity model reveals a buried zone of very low resistivity within the confines of the Tintina trough. It is overlain by a thinner zone of variable resistivity that also lies between the faults that form the margins of the Tintina trough. The resistivity model provides at least two possibilities for the stratigraphy and thickness of the Cenozoic sedimentary package. One option (A) is that Cenozoic sediments are thin (~1 km thick) and are represented by the variable resistivity region with the underlying low resistivity body as a separate rock unit. An alternative option (B) is that the Cenozoic sedimentary rock package is quite thick (~3 km) and consists of both the deeper, low resistivity body as well as the overlying variable resistivity region. We ran some test gravity inversion models on both of these options to see which was more geologically reasonable. We found that the thick rock package option (B) would require an unusually high rock density (>3.0 g/cm^3) for the bedrock that underlies the Cenozoic rocks to compensate for the large amount of low-density rock material in the overlying Cenozoic sedimentary package. As a result of these tests, further 3D geologic modelling assumed that the Cenozoic sedimentary rock unit is most likely thinner (~1 km) and can be represented approximately by the region of shallow, variable resistivity.

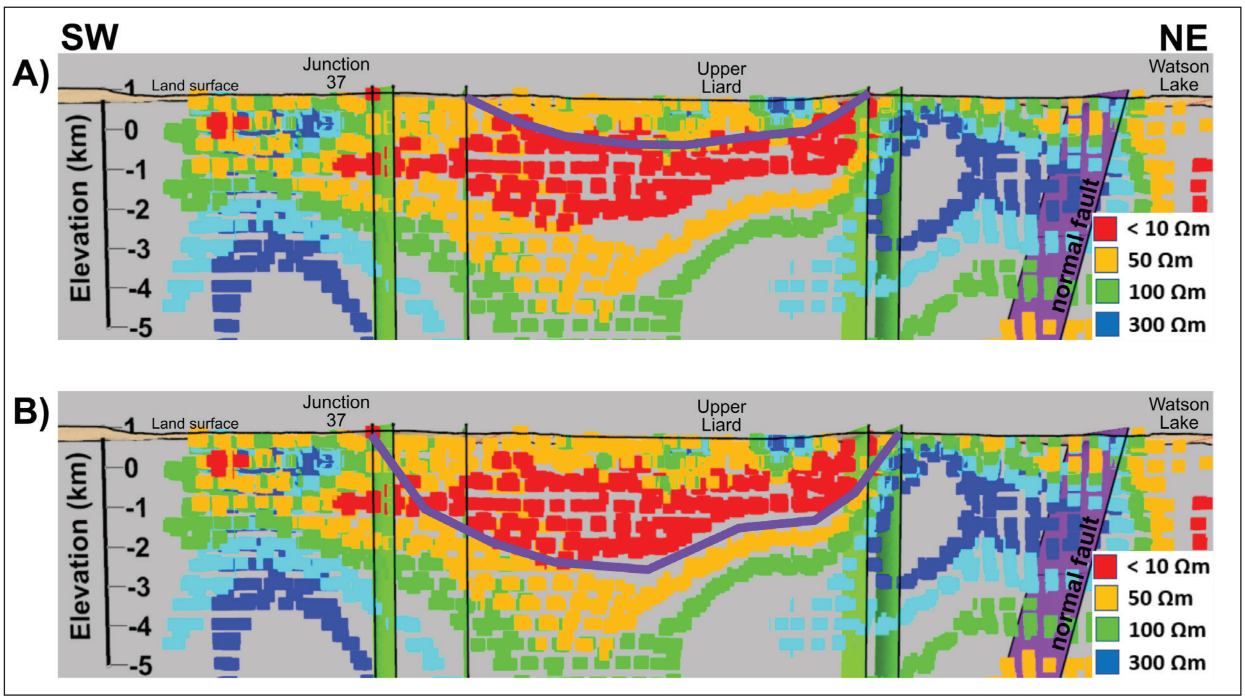

Figure 18. *Simplified 2D profile through the 3D resistivity model generated by University of Alberta researchers that follows a straight NE–SW line passing approximately through the towns of Watson Lake and Upper Liard as well as Junction 37. The figure above depicts two options for the thickness and approximate shape of the Cenozoic sedimentary rock unit in the Watson Lake study area (thick purple lines). In option* ***(A)****, the Cenozoic sedimentary package is characterized by a relatively thin (~1 km) basin with moderately low but variable resistivity. In option* ***(B)****, the Cenozoic sedimentary package is much thicker (~3 km) and is dominated by very low resistivity values in the lowermost* $^2/_3$ *of the stratigraphy. Resistivity variations in the subsurface are shown according to the colour bar on the right in units of ohm-metres; warm colours = low resistivity and cool colours = high resistivity. The green vertical planes represent the fault-bounded margins of the Tintina trough inferred from the map-based gravity interpretation. The normal fault (purple plane) is based upon bedrock mapping (Colpron et al., 2016) with an assumed steep dip. The measured gravity response and various rock density considerations favour the thinner sediment package in option (A).*

3D geology + gravity modelling

For this project, a 3D geologic model was constructed to provide a 3D lithologic framework within which to interpret the geothermal resource potential of the Watson Lake area. A key aim of the 3D geologic model building exercise was to build a geologic volume (of fault planes and discrete blocks of rock) that is consistent with all the available geoscience data. To do this, the model was built in a multi-step manner, beginning with a very simple geologic model that consisted of only two rock units (low density sediments and high density bedrock). Geologic details were added, then 3D gravity inversion modelling was performed at each successive step to test whether geologic modifications honoured the gravity data.

For each 3D gravity inversion, different rock units in the 3D geologic model were assigned starting density values based upon rock density measurements (Table 1). Two rock units in the 3D geology model are unknown because they have no surface outcrops and are completely covered by glacial sediments or other rock units; these were assigned a starting density value of 2.67 g/cm^3 (average crustal density). For each gravity inversion step, the inversion algorithm adjusted the rock density values in the model cells until a match was achieved with the measured gravity survey data. A match was achieved when the root-mean-squared (RMS) misfit, calculated for the 3D density model, reached the average measurement error of the gravity survey data (*i.e.*, 0.063 mGal). The actual calculated RMS misfit obtained for the final 3D density model is 0.052 mGal.

The final 3D geologic model contains eight different rock units (Table 2) and largely honours the bedrock and fault mapping of Colpron *et al.* (2016). One key difference is the location of the Tintina fault. As described in previous sections of this report, various pieces of evidence suggest that the surface trace of the Tintina fault lies near Junction 37, a few kilometres west of where it is currently mapped. This new location of the Tintina fault has been incorporated into the 3D geology model presented here. Unfortunately, the dip angle of Tintina fault is still highly uncertain with very little information available to guide us. As a result, the final 3D geology model is presented as two end-member scenarios: one with the Tintina fault dipping down to the east (Fig. 19) and another with the Tintina fault vertical (Fig. 20).

Table 2. *List of rock units in the Watson Lake 3D geologic model. Note: a layer of glacial sediments (a few to tens of metres thick) that covers the bedrock as well as Quaternary volcanic rocks were not included as distinct rock units in this study as they are too thin and too small, respectively, to be resolved in the geophysical modelling performed here.*

Rock unit name	Age	Rock type	Location in study area
Cassiar terrane	Paleozoic	Limestone, slate, phyllite	West side
Coal-bearing sedimentary rock	Cenozoic	Claystone, shale, coal, conglomerate	Centre
Albert Creek sediments	Cenozoic	Fluvial sediments	Centre
Unknown rock type #1	Paleozoic?	Unknown (Earn/Road River Group?)	Centre
Unknown rock type #2	Paleozoic?	Unknown (Earn/Road River Group?)	East side
Yukon-Tanana terrane	Paleozoic	Sandstone, siltstone conglomerate	East side
Slide Mountain terrane	Paleozoic	Phyllite, chert, argillite, basalt?	East side
Laurentia	Paleozoic	Argillite, siltstone, sandstone	East side

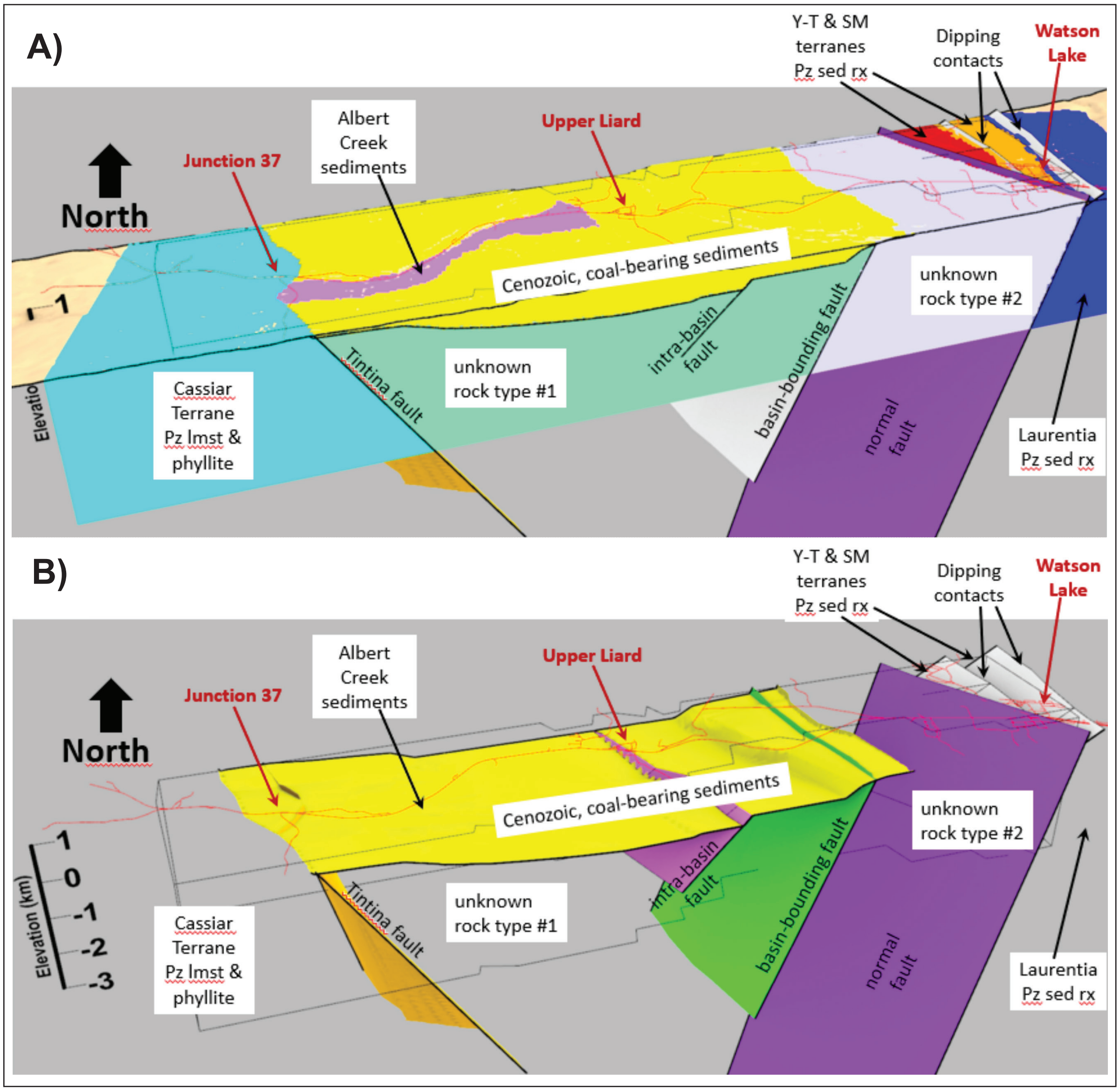

Figure 19. *Perspective view of the "Dipping fault" 3D geology model end-member scenario.* ***(A)*** *3D geology block model with the Tintina fault dipping down to the east and different rock units shown as different random colours.* ***(B)*** *Same as in (A) but with the blocks of rock and topography removed to show the faults, geologic contacts, and elevation scale bar. In both (A) and (B), roads are shown as red lines and the 3D gravity inversion model volume is marked by the thin black line. Pz = Paleozoic, Y-T = Yukon-Tanana, SM = Slide Mountain.*

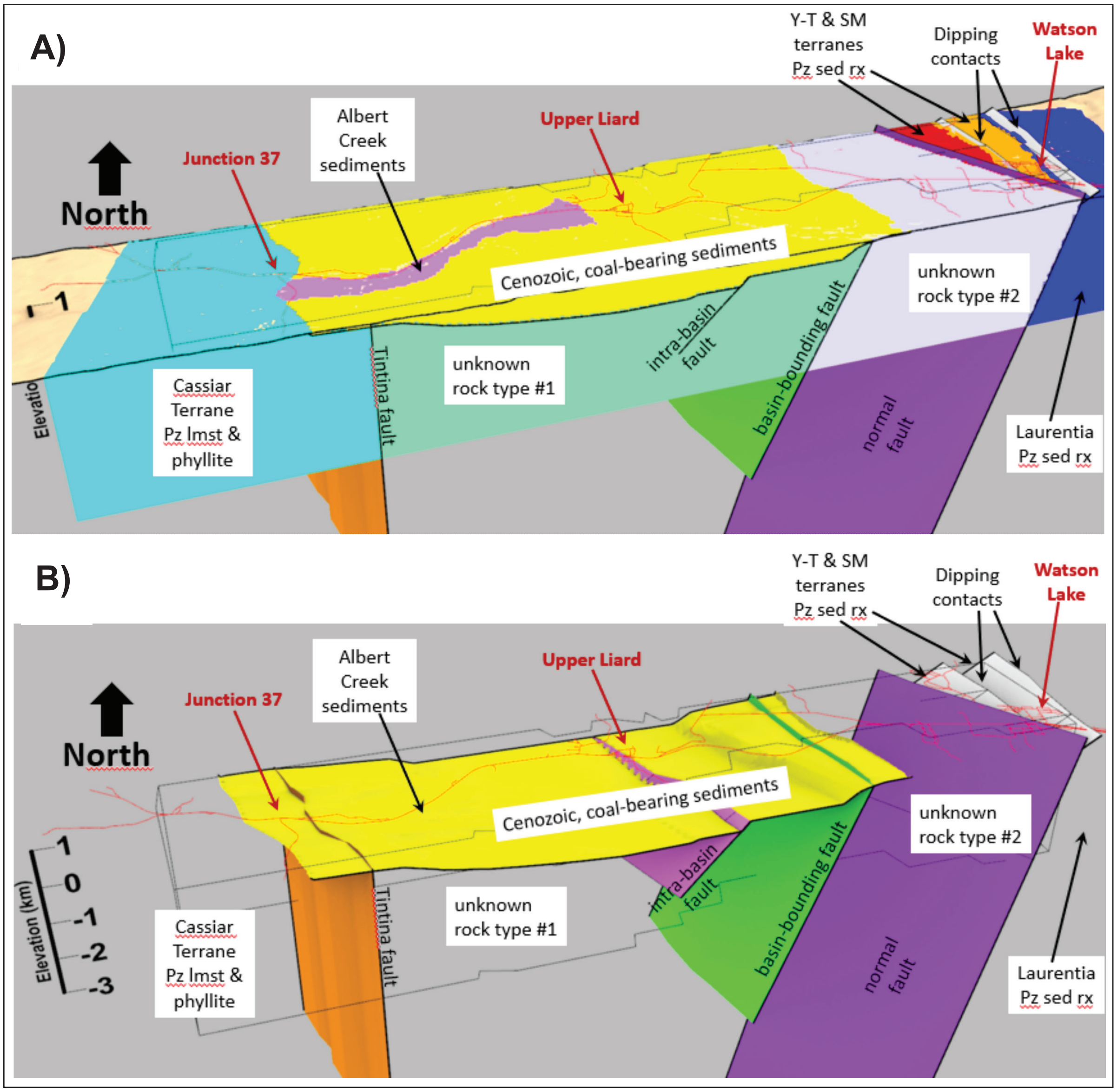

Figure 20. *Perspective view of the "Vertical fault" 3D geology model end-member scenario.* ***(A)*** *3D geology block model with a vertical Tintina fault and different rock units shown as different random colours.* ***(B)*** *Same as in (A) but with the blocks of rock and topography removed to show the faults, geologic contacts, and elevation scale bar. In both (A) and (B), roads are shown as red lines and the 3D gravity inversion model volume is marked by the thin black line. Pz = Paleozoic, Y-T = Yukon-Tanana, SM = Slide Mountain.*

Aside from those mentioned above, additional assumptions went into the creation of the 3D geologic model. For example, we assume that all rock density in the Cenozoic sedimentary unit increases linearly (due to compaction) to a maximum of ~2.4 g/cm^3. We also assume that other rock units have a generally uniform density (*i.e.*, no significant variations laterally or vertically). Faults that are inferred within the Tintina trough are assumed to have typical, normal fault dip angles of ~60–70 degrees. Furthermore, the geologic contacts between the Yukon-Tanana terrane, Slide Mountain terrane and Laurentia are assumed to dip at ~30 degrees to the west. Due to these many assumptions and the uncertainty associated with them, the 3D geologic model is not intended to be a 100% accurate depiction of the subsurface. Rather, the 3D geologic model is meant to be as realistic as possible; an initial 3D geologic framework which can be subsequently tested and improved with additional geophysical data and/or drilling.

In summary, the outcome of the 3D gravity inversion modelling is a new 3D rock density model with faulted and stratigraphic geologic boundaries. Cross sections have been extracted from the 3D rock density models that run along a NE–SW profile that roughly parallels the Alaska Highway and lies approximately in the middle of the gravity survey area (Fig. 21). Although the rock density model is in three dimensions, the 2D cross sections shown in Figures 22 to 25 do present the main structural and stratigraphic elements of the rock density model. Cross sections for both the "Dipping fault" model and the "Vertical fault" model are presented. For each case, a reference geology model is presented (with starting rock density values), followed by two depictions of the 2D cross section that use two separate colour scales to help visualize the lower density and higher density rock distribution in the density models. The starting models can be compared with the rock density inversion model outputs to show how good the match is between the starting rock densities and the density model calculated by the inversion modelling. For both the "Dipping fault" and the "Vertical fault" model scenarios the agreement between the starting and output density models is fairly good. Regions of mismatch can be clearly identified and represent areas

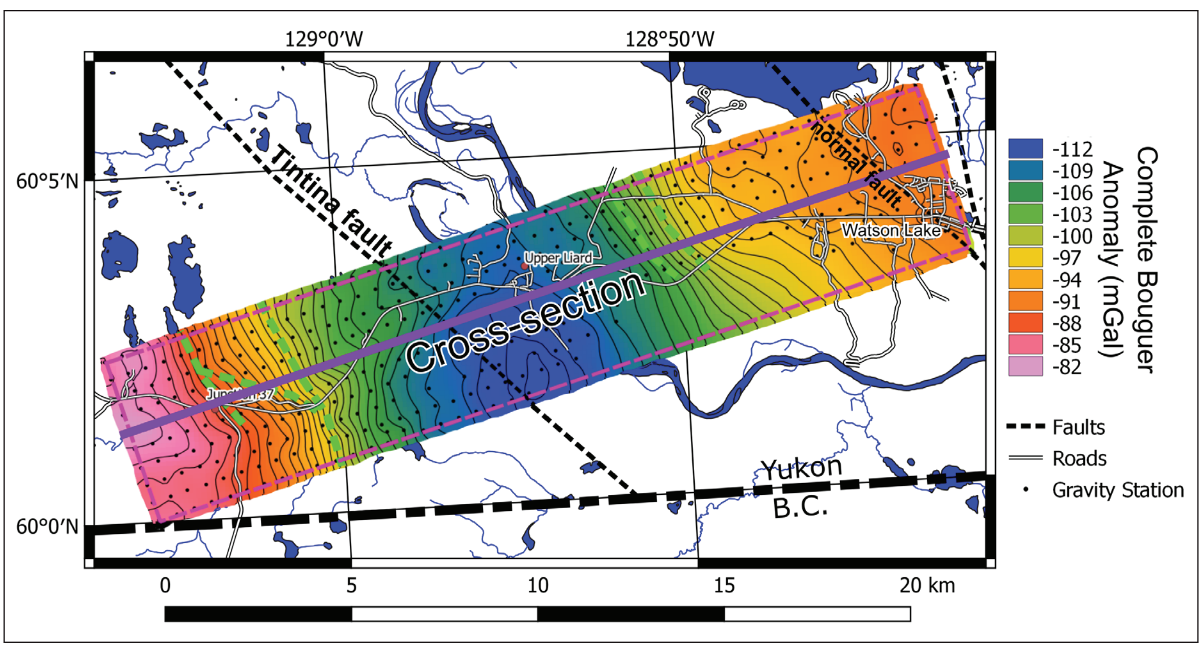

Figure 21. *Location of 2D cross section shown in Figures 22 to 25. Features in the map above are the same as those in Figure 12.*

where more information is likely needed to help better understand the subsurface. Based upon the interpretation presented in the 2D cross sections, the existing data do not strongly favour one end-member scenario over the other (*i.e.*, dipping vs. vertical Tintina fault). One of the overall conclusions of the 3D geology modelling exercise is that the bedrock underneath the Tintina trough sedimentary unit is most likely moderate density rock (*e.g.*, 2.65–2.75 g/cm^3). Based upon rock density alone, candidate rock types would include the Yukon-Tanana terrane and Laurentia. Slide Mountain terrane may be too dense and Quaternary mafic volcanic rocks are too dense and too magnetic and are, therefore, unlikely possibilities.

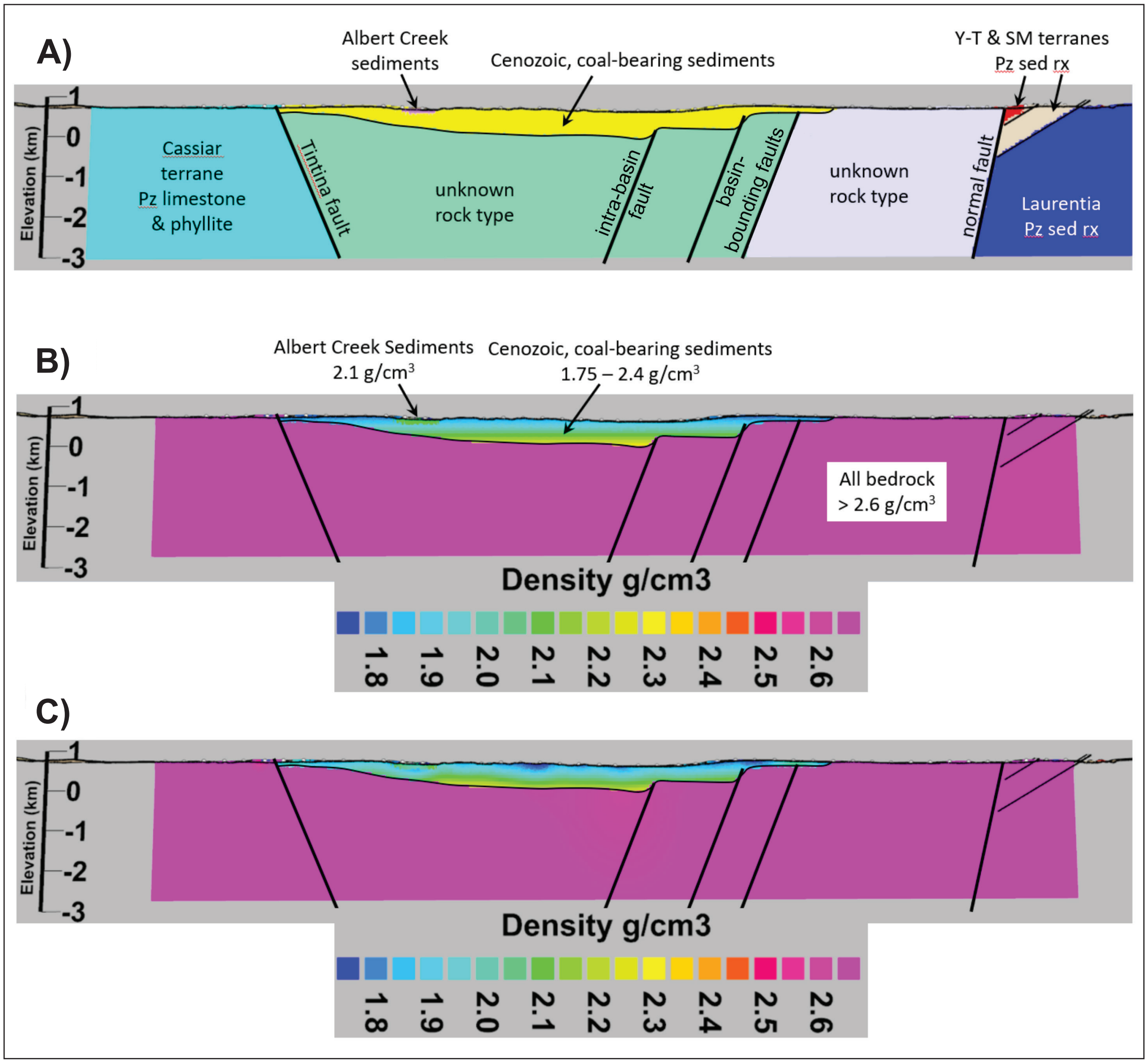

Figure 22. *2D cross section through the 3D geologic and rock density model for the "Dipping fault" scenario in the lower density range (1.75–2.65 g/cm^3).* ***(A)*** *Reference geology model with rock units labeled and with different random colours.* ***(B)*** *Starting rock density model.* ***(C)*** *Rock density model returned by the 3D gravity inversion modelling that honours the gravity data. The colour scale for (B) and (C) is at the lower end of the density range (1.75–2.65 g/cm^3) to visualize the lower density sedimentary rocks in the area. It is clear that the match between the starting rock density model (B) and the inverted rock density model (C) is good showing the gradual increase in density with depth in the Cenozoic sedimentary rock section. This means that the geologic model in (A) with the rock densities in (B) are quantitatively consistent with the gravity measurements. Y-T = Yukon-Tanana, SM = Slide Mountain, and Pz = Paleozoic. See text for further explanation.*

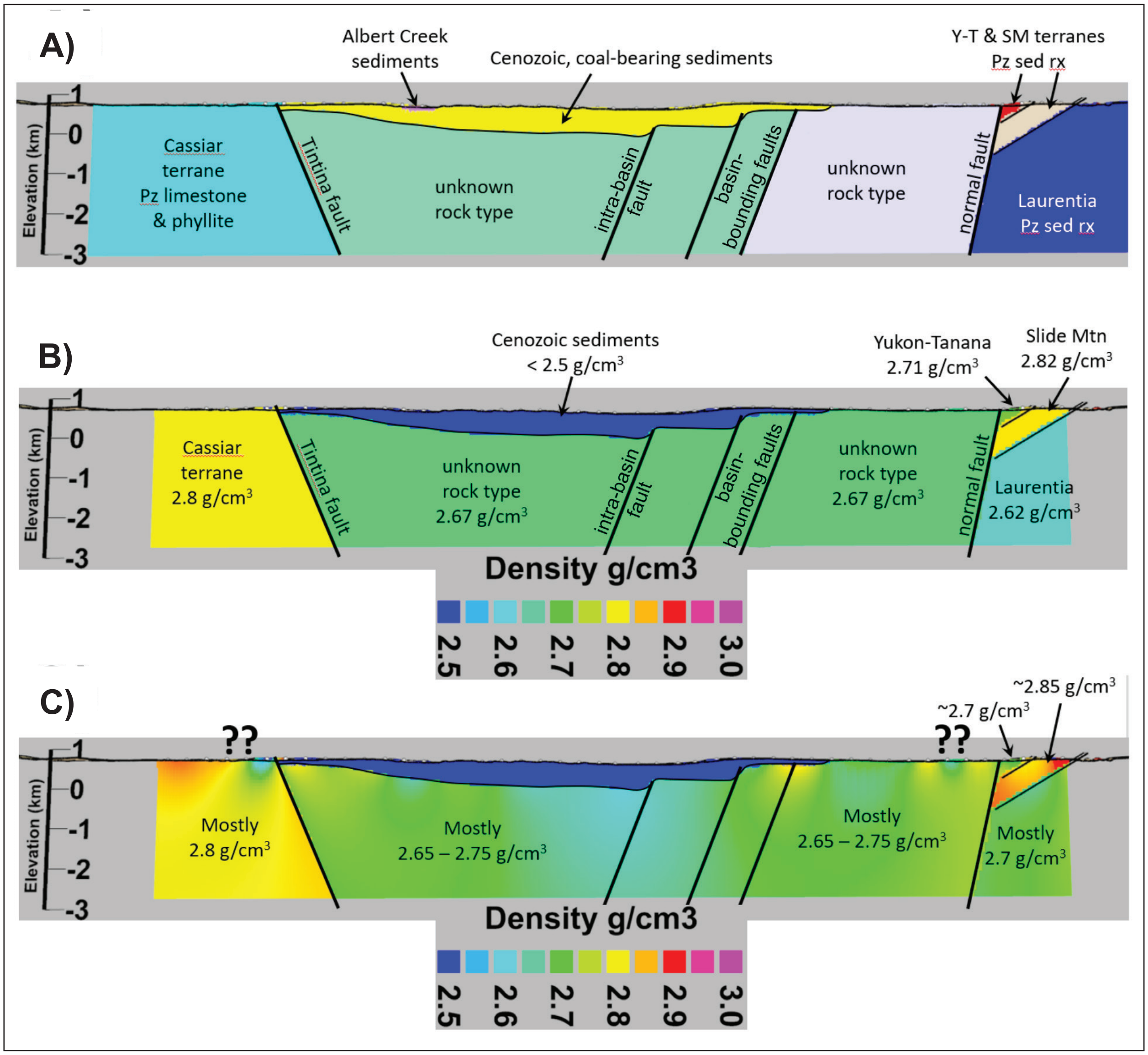

Figure 23. *2D cross section through the 3D geologic and rock density model for the "Dipping fault" scenario in the higher density range (2.5–3.0 g/cm³).* ***(A)*** *Reference geology model with rock units labeled and with different random colours.* ***(B)*** *Starting rock density model.* ***(C)*** *Rock density model returned by the 3D gravity inversion modelling that honours the gravity data. The colour scale for (B) and (C) is at the higher end of the density range (2.5–3.0 g/cm³) to visualize the higher density bedrock units in the area. The match between the starting rock densities (B) and the inverted rock density model (C) is fair-to-good in most areas. This means that the geologic model in (A) with the rock densities in (B) are mostly consistent with the gravity measurements. Locations where mismatches occur (marked by ??) need more information to help better understand the subsurface. Y-T = Yukon-Tanana, SM = Slide Mountain and Pz = Paleozoic. See text for further explanation.*

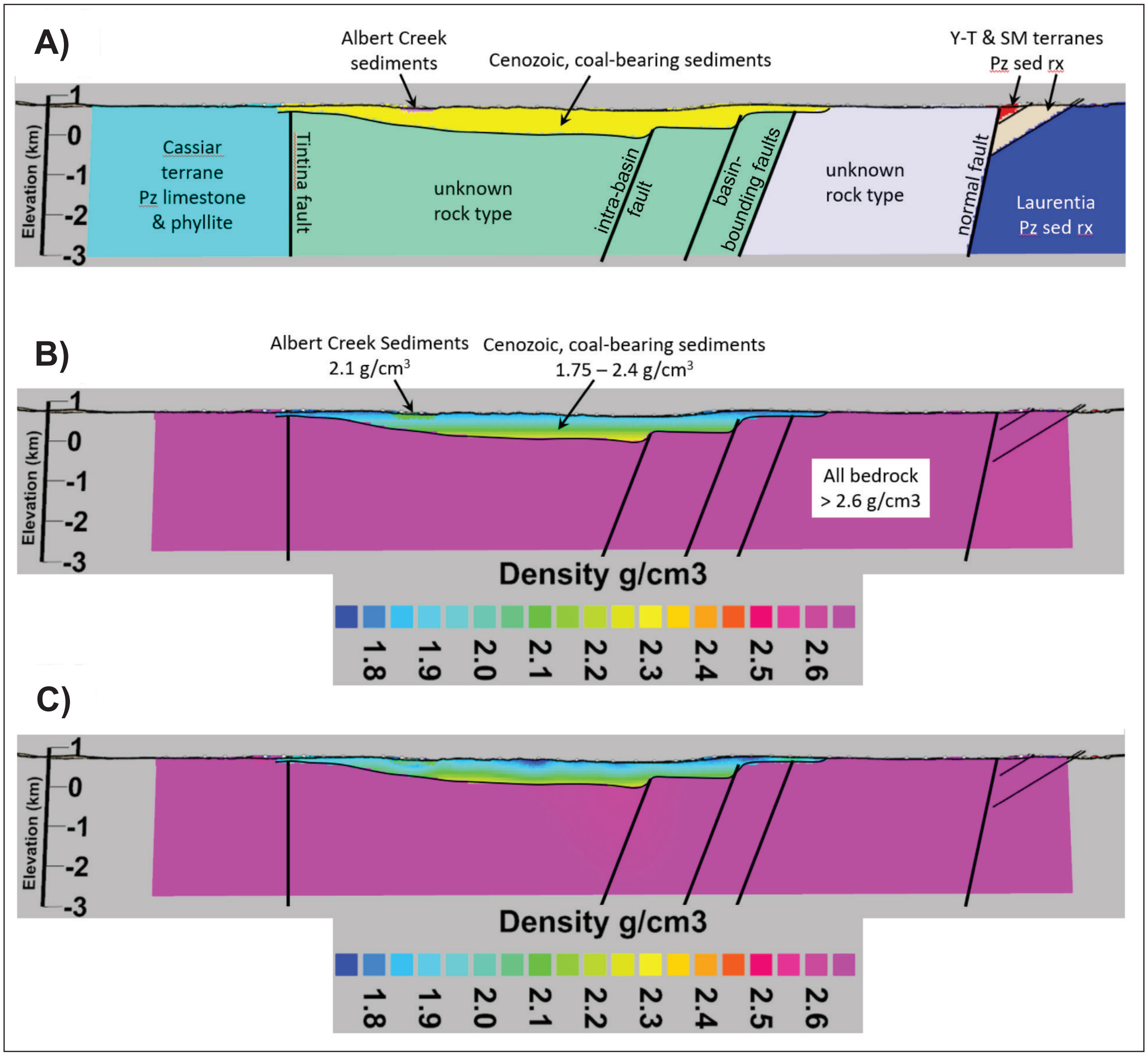

Figure 24. *2D cross section through the 3D geologic and rock density model for the "Vertical fault" scenario in the lower density range (1.75–2.65 g/cm*^{3}*).* **(A)** *Reference geology model with rock units labeled and with different random colours.* **(B)** *Starting rock density model.* **(C)** *Rock density model returned by the 3D gravity inversion modelling that honours the gravity data. The colour scale for (B) and (C) is at the lower end of the density range (1.75–2.65 g/cm*^{3}*) to visualize the lower density sedimentary rocks in the area. It is clear that the match between the starting rock density model (B) and the inverted rock density model (C) is good showing the gradual increase in density with depth in the Cenozoic sedimentary rock section. This means that the geologic model in (A) with the rock densities in (B) are quantitatively consistent with the gravity measurements. Y-T = Yukon-Tanana, SM = Slide Mountain and Pz = Paleozoic. See text for further explanation.*

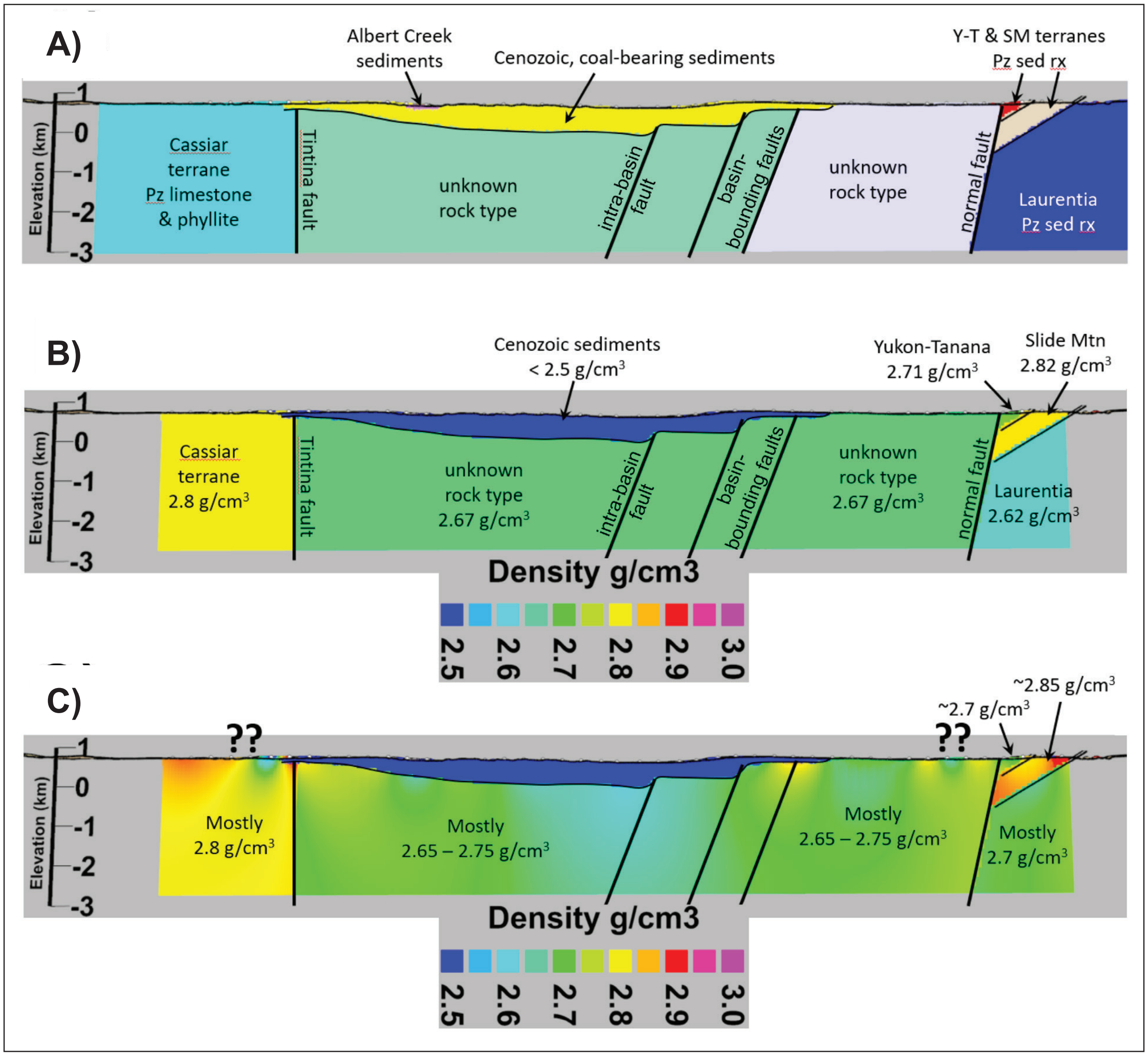

Figure 25. *2D cross section through the 3D geologic and rock density model for the "Vertical fault" scenario in the higher density range (2.5–3.0 g/cm³).* ***(A)*** *Reference geology model with rock units labeled and with different random colours.* ***(B)*** *Starting rock density model.* ***(C)*** *Rock density model returned by the 3D gravity inversion modelling that honours the gravity data. The colour scale for (B) and (C) is at the higher end of the density range (2.5–3.0 g/cm³) to visualize the higher density bedrock units in the area. The match between the starting rock density model (B) and the inverted rock density model (C) is fair-to-good in most areas. This means that the geologic model in (A) with the rock densities in (B) are mostly consistent with the gravity measurements. Locations where mismatches occur (marked by ??) need more information to help better understand the subsurface. Y-T = Yukon-Tanana, SM = Slide Mountain and Pz = Paleozoic. See text for further explanation.*

3D magnetic modelling

3D magnetic inversion modelling was performed separately to help constrain the extent and depth of the inferred NW-trending pluton that lies beneath the Junction 37 area (Fig. 26). Magnetic modelling was performed without any geological constraints for two reasons: (1) apart from the Quaternary mafic volcanic rocks and the inferred NW-trending pluton, all the rocks in the study area have very low magnetic susceptibility and are nearly indistinguishable from one another magnetically (Fig. 17) and (2) we have virtually no subsurface geologic constraints on the magnetic rock units in the area. The purpose of the inversion of the magnetic survey data is to test the hypothesis of Snyder et *al.* (2005) that the top of the geologic body that gives rise to the NW-trending magnetic high is located at ~6 km below the ground surface.

The magnetic susceptibility model output by the inversion algorithm contains a large, NW-trending zone of elevated susceptibility ~10 km wide that lies under the Junction 37–Upper Liard area on both sides of the Tintina fault. Identifying the exact depth of the top of the magnetic body is somewhat subjective since it depends on the magnetic susceptibility value selected to represent the top of the pluton. In this case, we selected 8×10^{-3} SI, which is a typical magnetic susceptibility value for both gabbro and magnetite-bearing granitic rocks (Dentith and Mudge, 2014). At this value, the top of the pluton would lie at depths of about 4–5 km (Fig. 17).

Based upon this analysis, we infer that this deeply buried pluton is less likely to be gabbro because the high density of gabbroic rocks (~3.0 g/cm^3) would have likely generated an elevated gravity response matching the distribution of the magnetic anomaly; evidence for such a co-located gravity and magnetic high anomaly is not present. Similar logic leads one to conclude that the deeply buried pluton is more likely a magnetite-bearing granitic lithology because the density of such rocks (*i.e.*, 2.6–2.7 g/cm^3) is comparable to the rock types thought to be present

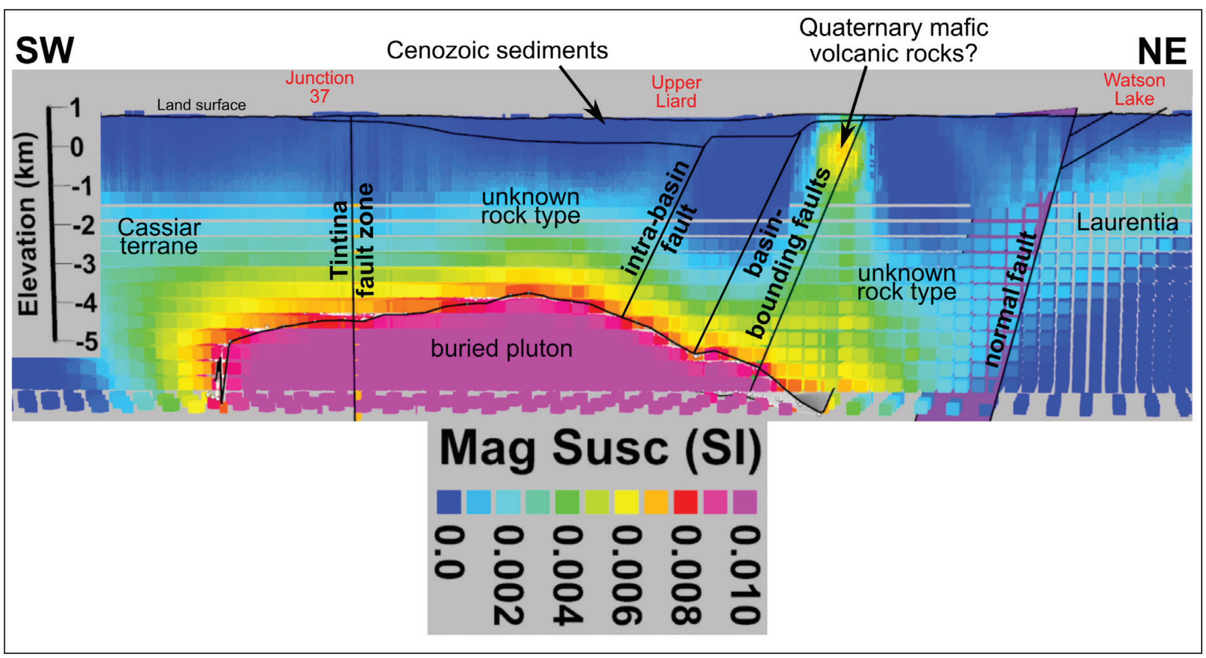

Figure 26. *NE–SW 2D cross section of the 3D magnetic susceptibility model that follows the same path as shown in Figure 21. Magnetic susceptibility variations in the subsurface are shown according to the colour bar in SI units; warm colours = magnetic rocks and cool colours = non-magnetic rocks. The vertical fault 3D geologic model (Fig. 25) has been overlain. The magnetic susceptibility model suggests that the top of a magnetic body (i.e., buried pluton) lies at depths of 4-5 km and has a magnetic susceptibility of >8 × 10^{-3} SI. Rocks that lie above the buried pluton are weakly to non-magnetic. A near surface zone of moderate magnetic susceptibility (i.e., 6 × 10^{-3} SI) is most likely associated with buried Quaternary mafic volcanic rocks.*

in the subsurface above the NW-trending pluton (*e.g.*, 2.65–2.75 g/cm^3). At a depth of 4–5 km and with a weak density contrast between the pluton and the country rock, the gravitational response of the pluton would be very weak and essentially "invisible" in the gravity survey—which is consistent with the lack of a pronounced gravity anomaly to match the magnetic survey data in the area where the pluton is inferred to be located.

Note that the estimated error on the magnetic survey data is ~5 nT; we used this value as the target misfit during the magnetic inversion modelling. The 3D magnetic susceptibility model that was generated during the inversion modelling achieved an actual RMS misfit of 4.2 nT which is better than the target value.

Discussion—implications for geothermal resources

Temperature

This project did not collect any new measurements of subsurface temperature in the Watson Lake area. The only reliable method for determining the temperature in the subsurface to a high degree of accuracy is to drill a well and measure the downhole temperature with a borehole probe. Unfortunately, the only subsurface temperatures available in the Watson Lake study area are individual point measurements at depths of less than 40 m from a few water wells. These data are unhelpful for evaluating the subsurface geothermal potential of the area, especially in cold climate regions where the near surface temperatures are affected by permafrost and post glacial warming.

At a regional scale, only two measurements of subsurface temperature are available. These are from 1.1–1.4 km deep exploration wells drilled in the 1960s that yielded subsurface temperature gradients of 38–50°C/km. These exploration wells were located quite far away (*i.e.*, 15–35 km) from the Town of Watson Lake. One outstanding question then is: are the temperature gradient values measured in these legacy exploration wells representative of the average thermal gradient in this part of Yukon (*i.e.*, including the Watson Lake study area)? Curie point depth mapping (Witter *et al.*, 2018) suggests that a ~170 km (E–W) × 125 km (N–S) area around Watson Lake is characterized by a Curie point depth of 18–20 km with no significant variation. This relatively constant Curie point depth across such a large area would suggest that the subsurface thermal regime at a regional scale also varies little. Thus, subsurface temperature gradients in the vicinity of the exploration wells may not be substantially different from the Watson Lake study area.

For comparison, a geothermal study along a different part of the Tintina fault zone found that the thermal regime in the Tintina trough is the same as the regional thermal regime (Fraser *et al.*, 2018). Near the community of Ross River, Yukon, a 497 m deep temperature gradient well was drilled in the Tintina trough. Curie point depth values in the Ross River area are ~19 km, similar to the Watson Lake study area. Such Curie point depths translate into an average, crustal-scale temperature gradient of ~31°C/km across the Ross River region. The measured temperature gradient in the well drilled near Ross River is essentially the same at 30.6°C/km.

If we assume that the temperature gradient in the Watson Lake study area is 50°C/km (the upper end of the exploration well temperature measurements), that would imply that one would need to drill to at least 1 km depth to reach a temperature of 50°C. According to the 3D geologic model presented above, reaching such a temperature would require drilling into the bedrock almost everywhere in the study area. To reach higher subsurface temperatures would require drilling deep into bedrock. This implies that bedrock properties would largely influence the geothermal production in the area.

Permeability

Rock permeability, in addition to elevated temperature, is a key requirement for a conventional (*i.e.*, not engineered) geothermal system to be commercially viable. Unfortunately, this study did not reveal strong evidence for substantial permeability. Instead, there appears to be weak evidence for mostly subpar permeability.

Fracture permeability

One of the key goals of this project was to try to find permeability (if any) along the fractured rocks of the Tintina fault that could potentially host upwelling geothermal fluids in bedrock. Unfortunately, no such zones were identified and available evidence suggests that such zones are likely not present. For example, the evidence suggests that the Tintina fault is fairly straight and oriented perpendicular to the regional compression direction in the study area. In other words, there is a lack of strong evidence for major structural discontinuities with favourable orientations (*e.g.*, fault step-overs; Faulds and Hinz, 2015) that could facilitate significant amounts of permeability in the subsurface. Furthermore, the rather low level of displacement along the Tintina fault (~0.5 mm/year; Leonard *et al.*, 2008) combined with a general lack of earthquakes in the area serves as corroborating evidence for weak tectonic activity along this section of the Tintina fault. High levels of tectonic activity would be preferred as they can facilitate enhanced fracture permeability.

Active fluid upwelling in fault-controlled geothermal zones in other parts of the world is spatially associated with Holocene earthquake activity that helps keep the fractured fluid flow pathways open over time (Bell and Ramelli, 2009). Analysis of the lidar topographic data collected as part of this study revealed evidence for one Quaternary fault scarp (Finley *et al.*, written comm., 2022). This is certainly encouraging evidence for fault movement in the area in the recent geologic past. However, the location where the Quaternary fault scarp was identified presents some challenges. First, it lies outside of the study area, which means there is no gravity or MT data to help image the subsurface where the purported fault scarp is located. Second, it is located about 2 km from the nearest road and is therefore difficult to access. Third, it is located in the middle of the gravity low (*i.e.*, the middle of the Tintina trough sedimentary basin) which means that it is more likely a small, intra-basinal fault structure, rather than the much larger, crustal-scale Tintina fault. Further studies of the lidar-identified Quaternary fault scarp would be useful, especially trenching to measure the amount of offset as well as the date of the fault rupture that generated the scarp. Additional study may also reveal other, possibly recent faults.

Stratigraphic permeability

An alternative to fracture permeability in geothermal systems is stratigraphic permeability. Stratigraphic permeability involves horizontal layers of porous and permeable rock in which warm geothermal fluids could reside. Good examples of such rock types would be clean, quartz-rich sandstones and karstic carbonate rocks (*e.g.*, limestone with portions of it dissolved away). There is little evidence for an abundance of such rock types in the Watson Lake study area. For example, the Tintina trough sedimentary basin is largely composed of silt, sand, clay and coal; sand is the only lithology known for good permeability. One of the coal boreholes from the 1970s did report artesian flow, which suggests fluid flowing out of a permeable, pressurized local aquifer. How laterally extensive permeable, sandy layers are in the Tintina trough is not known. In the event that laterally extensive sand layers are present in the Cenozoic sedimentary rock section of the Tintina trough, they are interlayered with other low permeability rocks. Furthermore, the regional temperature data combined with the 3D geology model of this study, suggests that any aquifer in the Tintina trough sedimentary rocks would only reach a maximum temperature of ~50°C in the deepest (~1 km) part of the Cenozoic section.

As discussed previously, the bedrock that lies beneath the Tintina trough is most likely Yukon-Tanana terrane or Laurentia rocks based upon geologically-constrained 3D gravity modelling and rock density considerations. However, based upon geologic mapping of bedrock outcrops located 10–20 km southeast of the study area, Ferri *et al.* (1999) identified two localities with Laurentia rocks belonging to the Kechika Group from the Upper Cambrian to Lower Ordovician. These outcrops lie along strike of the unknown bedrock beneath the Tintina trough. Therefore, Laurentia rocks are favoured as the suspect lithology. Note that no outcrops of Yukon-Tanana rocks along strike of the unknown bedrock have been identified in the area.

Apart from the Kechika Group, there are other rocks, higher in the Laurentia stratigraphy that could also be present in the bedrock beneath the Tintina trough. Two notable rock units are the Lower Ordovician to Middle Devonian Road River Group and the Middle Devonian to Lower Mississippian Earn Group. Regardless of which specific Laurentia rock package is present beneath the Tintina trough, all of them (Earn Group, Road River Group and Kechika Group) are characterized by large quantities of argillite, siltstone and slate (Ferri *et al.*, 1999). Similarly, the Fortin Creek group of the Slide Mountain terrane, which has been mapped on the eastern edge of the study area, is predominantly chert and argillite. None of these rock types are favourable for stratigraphic permeability. In fact, the abundance of such rocks that are rich in clay and silt are a disservice to geothermal development because the fine-grained material can clog fractures that may be present. Ferri *et al.* (1999) do report the presence of limestone and quartz sandstones in the Laurentia stratigraphy; however, they are described as thinly-bedded, minor in quantity and commonly silty, which does not favour good permeability. Karstic carbonate rocks were not reported by Ferri *et al.* (1999) in the Earn, Road River and Kechika Groups. It is important to note that the two exploratory wells from the 1960s were drilled into Laurentia rocks and both wells encountered no permeable oil and gas horizons in the subsurface.

Permeability at intrusive contacts

Another possible area of subsurface permeability in the Watson Lake area could be at the geologic contact between igneous intrusions and the country rock. This can happen because igneous intrusions are emplaced at elevated temperatures and upon cooling, thermal contraction can create permeability along the margins of the igneous intrusion (Gilbert *et al.*, 2018). Commonly, however, such enhanced permeability along these igneous margins gets resealed during post-emplacement hydrothermal fluid circulation and mineral precipitation. Permeability at intrusive contacts is, therefore, possible but may not be likely.

Four occurrences of Quaternary mafic volcanic rocks are documented in the study area based upon geologic mapping and water well drilling. These volcanic rocks were emplaced onto the land surface after mafic magma was transported upwards through the Earth's crust in an igneous dike. Furthermore, the magnetic survey data presented previously, suggest that there are likely additional areas with mafic rocks intruded into the subsurface as dikes or other subvolcanic bodies. It is possible that the margins of mafic dikes in the study area may exhibit slightly higher permeability than the country rock that they intrude. For this to be the case, there would need to have been little to no precipitation of hydrothermal minerals along the dike margins. Furthermore, to maintain permeability the dike margins would need to be oriented perpendicular to the least horizontal stress direction to prevent tectonic forces from pressing shut any permeability at the dike margins. The maximum horizontal stress direction in the study area is approximately NE–SW (Leonard et *al.*, 2008). Unfortunately, the exact subsurface locations of the dike margins as well as their orientations are not known. Thus, mafic dike margins with the correct orientation could be challenging to target in a geothermal exploration drilling program.

Explanation of the subsurface low resistivity anomaly

One of the intriguing outcomes of this Watson Lake geothermal study is the discovery by University of Alberta researchers of a body with very low electrical resistivity beneath the Tintina trough. In this section, we attempt to place this geophysical anomaly within the geologic context developed here and provide possible geologic explanations. As shown in Figures 18 and 27, inversion modelling of the MT data revealed a geophysical anomaly with very low electrical resistivity values (e.g., <5 ohm.m) over a distance of several kilometres. Subsurface low resistivity anomalies of this kind are commonly explained due to the presence of one or more of the following: (1) clay, (2) salty brine, or (3) graphite-bearing rock.

Clay is certainly a geologically-plausible explanation for the low resistivity anomaly because argillite (a clay-dominant rock type) is a major component of Laurentia rocks that are inferred to be present at depth in the Tintina trough. A caveat to this clay hypothesis, however, is that there are many types of clay minerals and not all of them have the same low level of electrical resistivity (e.g., <5 ohm.m) that is observed beneath the Tintina trough. An analysis of the clay minerals present in the Laurentia rocks that are inferred to lie beneath the Tintina trough would be helpful to evaluate this hypothesis.

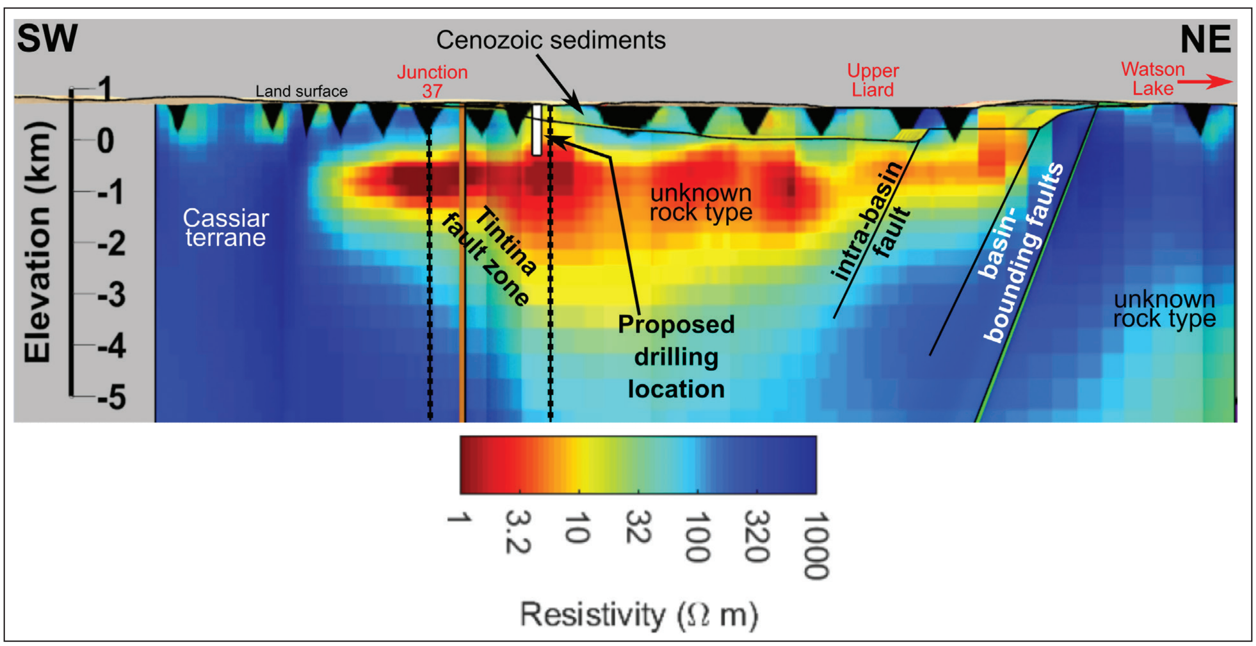

Figure 27. *Cross section through the 3D resistivity model, generated by University of Alberta, that approximately follows the curves of the Alaska Highway. Electrical resistivity variations in the subsurface are shown according to the colour bar in units of ohm-m; warm colours = low resistivity rocks and cool colours = high resistivity rocks. Locations of the MT stations are marked by the inverted black triangles. The vertical fault 3D geologic model (Fig. 25) has been overlain. The proposed location of a scientific research well also lies along the Alaska Highway and is shown by the thick white line. According to the resistivity model, the proposed 1 km deep research borehole should intercept the top of the electrically conductive anomaly in the subsurface identified in the MT model. Black hachures bound the Tintina fault zone inferred from interpretation of gravity data.*

Salty-brine is an alternate explanation for the low resistivity anomaly; however, at present there is no evidence to corroborate the hypothesis that salty-brines are (a) present in the subsurface and (b) the causative factor behind the low resistivity anomaly. Drilling into the low resistivity anomaly and collecting a sample would be the simplest (but most expensive) way to determine if the anomaly is caused by salty brines.

Lastly, graphite-bearing rocks may be the most likely explanation for the low resistivity anomaly that is observed beneath the Tintina trough. Geologic descriptions of both Earn and Road River groups of Laurentia include black argillite and black shale as abundant rock types. These types of clay-rich rocks are black in colour because they are carbon-rich and are deposited under reducing conditions, which is the type of environment in which graphite forms. Furthermore, graphite is a mineral which is highly conductive (e.g., 0.1–10 ohm-m) and, if present, could easily explain the low resistivity anomaly seen in the 3D resistivity model. In summary, thick sections of black shale/argillite in Earn Group and Road River Group rocks positioned beneath the Tintina trough is a geologically-reasonable explanation, broadly consistent with both the geoscience data and geophysical modelling considered in this study.

Proposed drilling target

There are still many unknowns about the subsurface in the Watson Lake study area. Despite the new geoscience data and modelling performed for this study, the actual subsurface temperature gradient and the precise locations (if any) of subsurface permeability are highly uncertain. In light of this, a drill site has been selected for a scientific research well that aims to answer the greatest number of questions about the subsurface at a single location (Figs. 27–29). There are key questions that may be answered with this single well.

a. Is the main strand of the Tintina fault zone located ~4–5 km west of where it has been inferred on current Yukon Geological Survey geology maps?
b. How thick is the Cenozoic, coal-bearing sedimentary rock unit at the proposed drill site in the Tintina trough and does it have stratigraphically permeable intervals?
c. What type of bedrock underlies the Cenozoic sedimentary rocks in the Tintina trough and are they fractured/permeable?
d. Does the bedrock contain clay, graphite or salty brine?
e. Is the 3D geoscience model developed in this study a reasonable depiction of the subsurface?
f. What is the temperature gradient and heat flow near Junction 37?
g. Is there geothermal fluid upflow along the Tintina fault zone?
h. If water is encountered in the well, what does the subsurface water chemistry tell us about the temperature of potential geothermal source aquifers? (*i.e.*, geothermometry)

The location of the proposed drill site is ~2.5 km east of Junction 37 (latitude 60.025827 N, longitude 129.013923 W, 694 m elevation; WGS84 datum). It lies on the north side of Albert Creek at the intersection of a spur road and the Alaska Highway. The proposed depth of the research well is 1 km. There are some advantages of this proposed drill site.

1. There is unimpeded road access to the proposed drill location.
2. Although the drill site has not been visited by the author, according to satellite images, the proposed drill site has been cleared of large trees and appears to have a gentle slope.
3. The location lies above the Tintina fault zone as inferred from the new gravity data.

4. The location sits near the margin of a magnetic anomaly that may represent a relatively shallow, mafic igneous intrusion.
5. A drilling depth of 1 km would most likely penetrate through the Cenozoic coal-bearing sedimentary unit and into the underlying bedrock. According to the 3D geologic model presented in this study, a borehole at the proposed location would drill through ~300 m of Cenozoic sedimentary rock and ~700 m of bedrock.
6. A drilling depth of 1 km would most likely intercept the top of the electrically conductive anomaly in the subsurface that was discovered with the MT modelling effort by the University of Alberta.
7. A depth of 1 km would be sufficient to measure the subsurface temperature gradient with a high degree of accuracy, avoiding any near-surface or paleoclimate/permafrost effects.

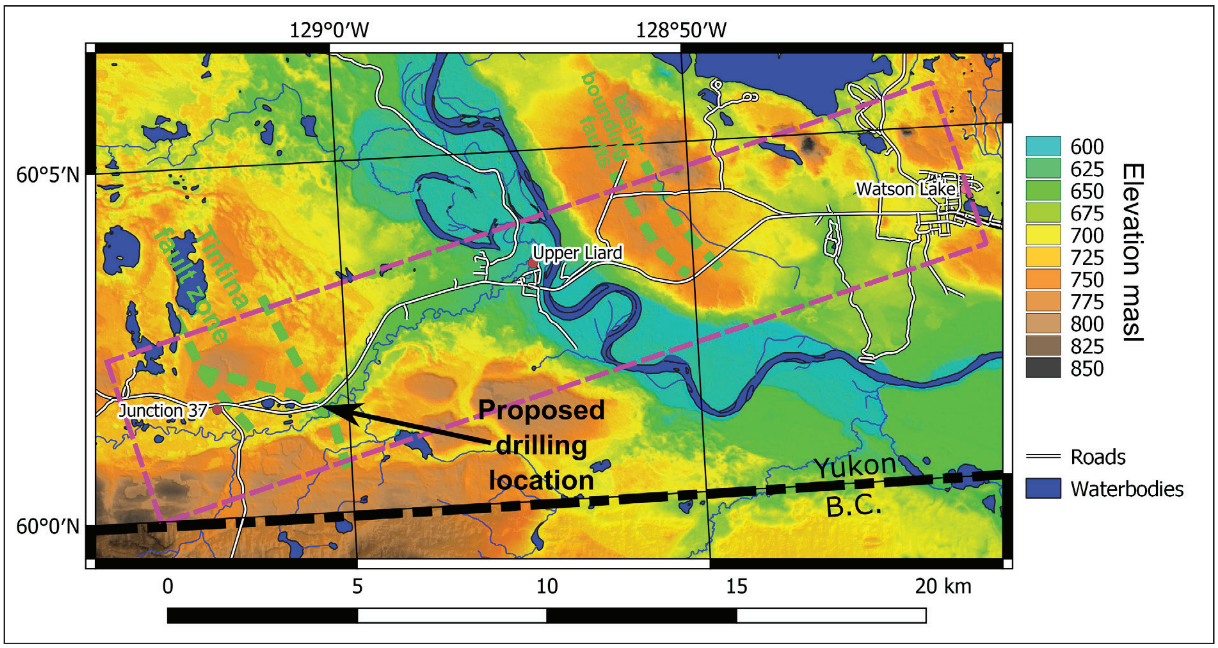

__Figure 28.__ Map showing the proposed location of the scientific research well for the Watson Lake study area. Thick green dashed lines are faults interpreted from the new gravity data. The study area boundary is the pink dashed rectangle.

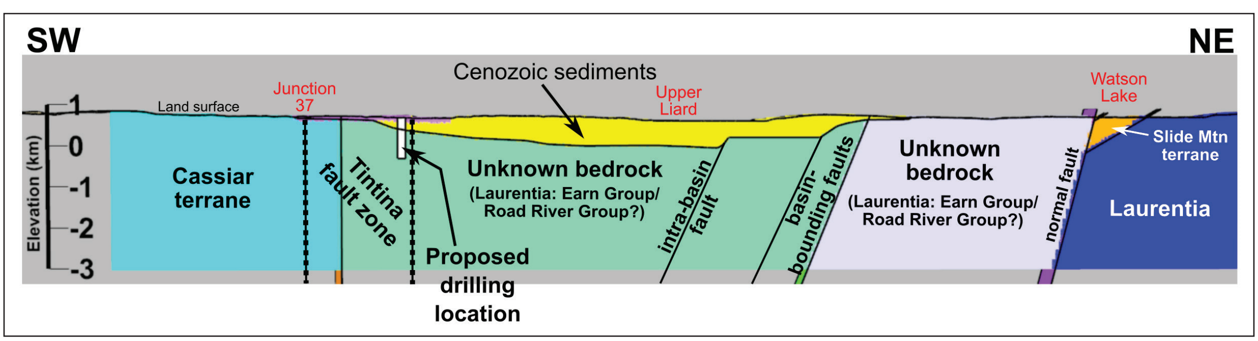

__Figure 29.__ Cross section through the vertical fault 3D geology model generated in this study showing the proposed location of the scientific research well (thick white line) for the Watson Lake study area. According to the geology model, a borehole at the proposed location would drill through ~300 m of Cenozoic sedimentary rock and ~700 m of bedrock within the Tintina fault zone, which is shown as a broad area of deformation about 2 km wide, bonded by black hachures.

Conclusions

This study analyzed and interpreted an array of geoscience data that straddles the Tintina fault zone near the Town of Watson Lake in southeastern Yukon. The primary aim of the study was to better understand the potential for geothermal energy resources in the area in the context of subsurface temperature and permeability. Interest in the geothermal potential near Watson Lake has arisen due to (a) a need to reduce the dependence on fossil fuels used for heat and power by the residents of Watson Lake, (b) the presence of the crustal-scale Tintina fault zone (which suggests the possibility of fractured rock and permeability in the subsurface) and (c) elevated temperature gradients measured in regional exploration wells from the 1960s. Geoscience datasets included in this study include bedrock geology maps, surficial geology maps, fault maps, rock properties, gravity data, magnetic survey data, magnetotelluric data, lidar topographic data, as well as coal borehole and water well data.

A map-based investigation of these data revealed the boundaries of the Tintina trough, a basin that is filled with low-density, Cenozoic, coal-bearing sedimentary rock. Largely coinciding with the boundaries of the Tintina trough is an anomaly of low electrical resistivity, which has been interpreted here as graphite-bearing, black shale bedrock of the Earn or Road River Groups of Laurentia. The measured density of typical Laurentia rock is consistent with 3D geologically-constrained modelling of the gravity data in the Watson Lake area and provides supporting evidence for this interpretation. 3D magnetic modelling showed the region of low electrical resistivity is largely non-magnetic, which is consistent with the measured magnetic susceptibility values for Laurentia rock samples.

There is a lack of evidence pointing toward the location of a favourable structural environment with fractured, permeable rocks that could facilitate deep circulation and heating of geothermal fluids. In addition, the majority of rock types inferred to be present as bedrock (e.g., argillite, shale, siltstone, slate) are clay-rich rocks which are most likely impermeable and not conducive to the formation of sustained open fractures and high permeability. Considering the modest temperature gradients expected in the region (~38–50°C/km; based upon two exploration wells from the 1960s), poor subsurface permeability in the bedrock would greatly hinder any conventional geothermal resource development effort in the Watson Lake area aiming to tap fluids greater than 50°C. The most likely location of subsurface permeability is in relatively shallow, sand-rich intervals in the Cenozoic sedimentary rock in the Tintina trough. However, the thickness, lateral extent and volume of such permeable intervals is unknown.

One of the outcomes of this study is the identification of a drilling location meant to answer several of the key questions about the subsurface in the Watson Lake area that remain unanswered. The most important of these questions are:

1. What is the actual temperature gradient in the Watson Lake area?
2. What type of rock is the bedrock?
3. Is the bedrock in the vicinity of the Tintina fault zone fractured and permeable?
4. Are there stratigraphically permeable intervals in the Cenozoic sedimentary rocks of the Tintina trough?

The recommended drilling depth of the proposed scientific research well is ~1 km. The key datasets extracted from the research well should be downhole geology, water samples and an equilibrated static temperature profile.

Recommendations

This geothermal study has been able to leverage large amounts of pre-existing, high quality geoscientific data thanks to years of effort by the Yukon Geological Survey as well as valuable, complementary data acquired by Liard First Nation. Additional data collection and analysis would be helpful to better understand the subsurface in the Watson Lake area. The drilling of a scientific research well, as mentioned here, would answer many questions about the subsurface in the region. There are additional geoscientific studies which would also be helpful.

1. Collection of more MT data and possibly ZTEM data to give more 3D coverage in difficult to access areas to better define the subsurface extent and geometry of the low resistivity body discovered by the University of Alberta researchers. These data could also help map the 3D thickness variations of the Cenozoic, coal-bearing sedimentary rock unit.
2. Reprocessing and re-interpretation of the SNORCLE 2D seismic profiles that extend between Watson Lake and Junction 37 could help map the top of bedrock along that transect.
3. Detailed 3D modelling of the public domain magnetic survey data could better define the location and shape of subsurface magnetic rock bodies that are likely Quaternary mafic intrusions.
4. Additional effort at mapping and age dating of the Quaternary mafic volcanic rocks exposed at the surface would be helpful to discover new exposures of geologically young volcanic rocks and determine if any eruptions occurred more recently than 230 ka in the Watson Lake area.
5. Collect additional lidar data over Junction 37 and the western part of the study area to find out if there has been any Quaternary faulting along the newly interpreted location of the Tintina fault zone.
6. Trenching and fault rupture age dating at the Holocene fault discovered by T. Finley (written comm., 2022) using the recently collected lidar survey data.

Considering the high likelihood that the bedrock in the Watson Lake study area is largely impermeable, alternate opportunities should be explored to reduce dependence on fossil fuel energy needs for the communities in the Watson Lake area. For example, attempting to exploit low temperature (*e.g.*, 20–50°C?) fluids from sandy intervals in the Cenozoic sedimentary rocks of the Tintina trough might be the best option for the community of Upper Liard, considering its location in the centre of the trough. Produced fluids could potentially be used to heat buildings directly, or the fluids could be fed into a heat pump system, thereby reducing the quantity of fossil fuel energy required for heating.

Alternatively, for the Town of Watson Lake, where bedrock is covered by a relatively thin layer of glacial sediments, a field of boreholes drilled into bedrock for a Borehole Thermal Energy Storage (BTES) system could be an effective approach to reduce dependence on fossil fuels (Giordano and Raymond, 2019; Skarphagen *et al.*, 2019; Kitz, 2021; Catolico *et al.*, 2016). BTES systems do not require large-scale permeability in subsurface rock formations like conventional geothermal systems do. Thus, a BTES system implemented at Watson Lake could avoid the uncertainty, high risk and cost of an ongoing geothermal exploration and drilling program that searches for permeability in the bedrock.

Acknowledgements

This project benefited greatly from discussions with Maurice Colpron about bedrock geology and structure of southern Yukon, Martyn Unsworth and Erich Slobodian about the Watson Lake MT survey and resistivity modelling, and Theron Finley about the structural interpretation of the lidar data. Special thanks to Maurice Colpron and Steve Grasby for helpful reviews of this report which improved the text.

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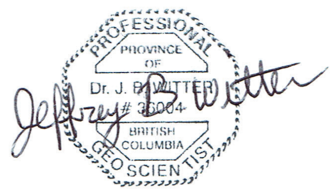
Appendix 1. Statement of qualifications.

This report has been prepared by Jeffrey B. Witter, Principal Geoscientist at Innovate Geothermal Ltd. Dr. Witter holds an undergraduate degree in geophysics as well as Master's and Ph.D. degrees in geology. He has seventeen years of experience as an exploration geologist/geophysicist in the natural resource industry with more than half of that time committed specifically to geothermal exploration and resource evaluation. He is a registered professional geoscientist in the province of British Columbia (Canada) and is a member of Engineers and Geoscientists of British Columbia (EGBC). EGBC has a defined and enforceable Code of Ethics which Dr. Witter agrees to abide by. Dr. Witter has been engaged as a Consultant by the Yukon Geological Survey but holds no financial interest in any geothermal energy project in Yukon.

Dated in Vancouver, British Columbia, Canada this 11th day of November 2022



Jeffrey B. Witter Ph.D., PGeo (Province of British Columbia, No. 36004)

The following appendix is only available digitally:

Appendix 2. Watson Lake gravity data and report; Aurora Geosciences.