YGS Open File 2024-3

Analysis of geoscience data for geothermal exploration in the Dakwäkäda (Haines Junction) area, Yukon

J.B. Witter

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Yukon Geological Survey
102-300 Main Street
Box 2703 (K-102)
Whitehorse, Yukon, Canada Y1A 2C6
email geology@gov.yk.ca
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Cover photo: Looking west at the Dezadeash River, the Village of Haines Junction and the Kluane Ranges in the background.

Yukon

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Analysis of geoscience data for geothermal exploration in the Dakwäkäda (Haines Junction) area, Yukon

J.B. Witter
Innovate Geothermal Ltd.

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Abstract

In collaboration with the Yukon Geological Survey, the Geological Survey of Canada, and other project partners, Innovate Geothermal Ltd. performed an analysis of geoscience data in southwestern 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. The study area for this project is located in the vicinity of the Village of Haines Junction (Dakwäkäda) and lies between the Denali and Shakwak fault zones. 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 where 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 audio-magnetotelluric survey data. At a regional scale, multiple lines of evidence suggest that subsurface temperatures are above the crustal average. More importantly, a municipal water well drilled in 2002 in the Village of Haines Junction produce warm (~20 °C) water from a depth of ~350 m. This water well proves that at least one permeable sediment-hosted geothermal aquifer is present under Haines Junction. Additional geothermal aquifers within the pile of young sediment that sits atop the bedrock are likely present. However, due to a lack of deep drilling in the area, the exact location, temperature, thickness and permeability of such aquifers remains unknown. In this study, a depth-to-bedrock model has been generated to aid with the identification of favourable target areas for exploratory drilling of geothermal wells. The four areas where the top-of-bedrock is deepest have estimated depths in the range 650 to 1225 m below ground surface. Temperature data from two wells in the Haines Junction area suggests the temperature gradient is ~60 °C/km. Thus, geothermal aquifers located near the top-of-bedrock in the four areas identified could have temperatures in the range of 39–74 °C. Production of geothermal fluids from these areas requires permeability in the sediments that sit above the bedrock. Deeper drilling is needed to measure actual subsurface temperatures beneath the village and to identify permeable intervals. Geologic structures and faults that may control permeability in the bedrock remain poorly constrained.

Plain language summary

Geothermal energy is a type of renewable energy that involves pulling heat out of the Earth's interior to directly heat homes and businesses. A warm (20 °C) geothermal energy resource was discovered at a shallow depth beneath Haines Junction when a municipal water well was drilled in 2002. The purpose of this study is to analyze a variety of geoscience data from the Haines Junction area to try and identify the location, temperature and depth of additional geothermal energy resources that could be used to provide heat to the village and thereby decrease dependence on fossil fuels. This study concluded that additional geothermal resources under Haines Junction are most likely to be found in a thick (~1 km) layer of geologically young sediment that rests on top of bedrock. Within that thick sediment layer, warm geothermal aquifers would be found in the portion that consists of coarse material (e.g., sand and gravel) and would not be found in the parts that consist of fine material (e.g., clay). In addition, the warmest geothermal aquifers would be found where the coarse sediment layers are deepest underground. Geoscience data analysis in this study has identified four areas at the bottom of the thick sediment layer and on top of the bedrock where geothermal aquifers, if present, would be expected to have temperatures

of 39–74 °C and occur at depths of 650 m to 1225 m below ground surface. Drilling a well is required to confirm the presence of a geothermal aquifer. Geothermal fluids at these temperatures could be utilized for a wide variety of heating applications to benefit the village. The drilling of exploratory wells to find and develop these geothermal resources is recommended.

Introduction

Dakwäkäda (Haines Junction) is a village in southwest Yukon (Fig. 1) which obtains energy from a 25 kV electric transmission line connected to Whitehorse and a 1.5 MW diesel generating station (Government of Yukon, 2018). Energy derived from subterranean geothermal reservoirs in the Haines Junction area could be beneficial in two important ways: 1) hot water from higher temperature (e.g., ~60 °C) geothermal reservoirs could be utilized to directly heat buildings; and 2) warm water from lower temperature geothermal reservoirs (e.g., ~20 °C) could be fed into heat pumps to reduce the amount of externally-derived fossil or electrical energy needed for space heating. In addition, warm geothermal fluids can be utilized for a variety of other applications such as greenhouses, snow-melting, and food drying.

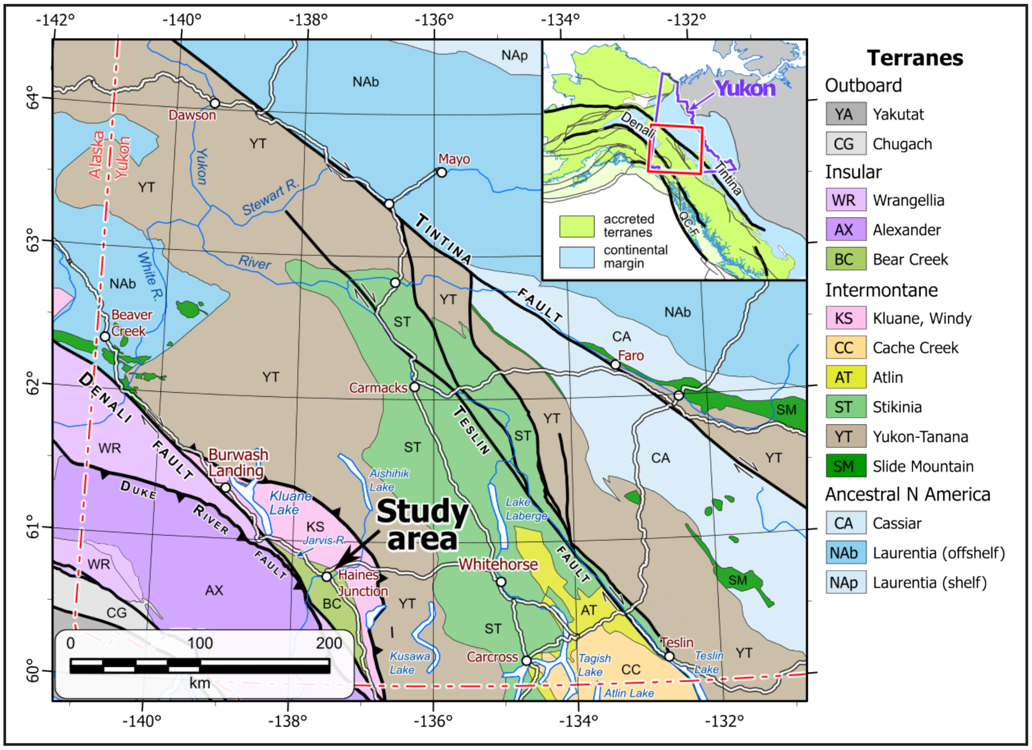

Figure 1. *Map of southwest Yukon illustrating the location of the study area described in this report. Geologic terrane basemap from Yukon Geological Survey (2023a). Black lines depict major faults. Red dashed lines show provincial/territorial borders.*

Successful development of a natural geothermal system requires two factors in the subsurface: an elevated temperature, and permeability in the rock. Existing geoscience data suggests that there are above average subsurface temperatures in the Haines Junction region. The evidence comes from Curie point depth mapping (Li et al., 2017; Witter et al., 2018; Gaudreau et al., 2019), a temperature gradient well drilled in 1979 (Burgess et al., 1982), and, importantly, a 385 m deep water supply well (Well #5) drilled in 2002 in the village itself.

Permeability in the subsurface (i.e., fractures and/or pore space in rock) allows the geothermal fluids to flow through the units into the wellbore of a geothermal production well. Two possible types of permeable rock beneath Haines Junction are: 1) porous sedimentary layers (e.g., sand/gravel); and 2) faulted and fractured bedrock. The geology log from Well #5 reports permeable sand and gravel at a depth of ~350 m, and the well produced ~25 L/sec of warm water from this interval. Thus, Well #5 proved the existence of a permeable sediment layer beneath the village. This discovery warrants further investigation to find more warm aquifers near Haines Junction. However, the location, depth, and thickness of additional permeable sediment layers in the area are currently not known. Likewise, little is known about fault structures in the area, that may or may not act as permeable conduits to allow warm geothermal fluids to ascend from greater depths.

The goals of this study are to obtain and interpret baseline geoscience data in the Haines Junction area in order to:

- better constrain the thickness of the sedimentary overburden (i.e., depth to bedrock);
- develop a 3D geologic framework for the Haines Junction subsurface to infer the locations of fault structures; and
- better understand the geometry of major rock units that may or may not host geothermal reservoirs.

The study area for this project is ~10 km wide and ~12.5 km long around the Village of Haines Junction (Fig. 2). Existing, public domain geoscience data were compiled for the study area which included topography, heat flow data, regional gravity data, aeromagnetic data, Curie point depth data, radiogenic heat production data, warm springs data, bedrock geology and faults, surficial geology, earthquake data, rock property data, and water well data. New geoscience datasets were also collected as part of this project including: 1) a gravity survey; 2) bathymetry data at Pine Lake (Tsi Män); 3) audio-magnetotelluric (AMT) data; and 4) passive seismic data. All of these datasets are described in this report.

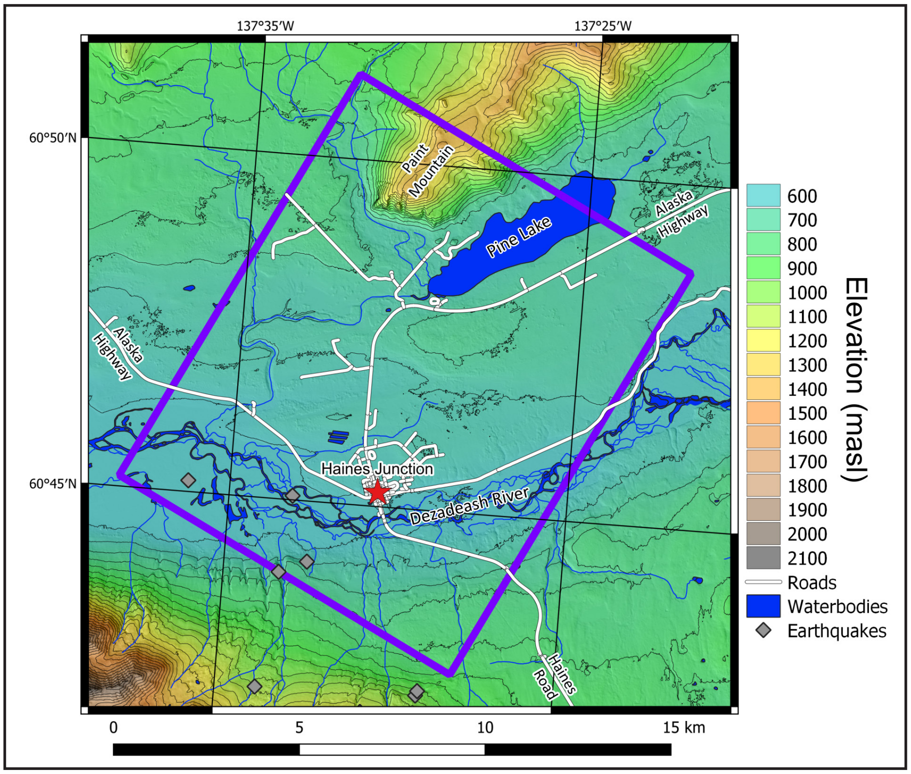

Figure 2. *Location map showing the ~10 km by ~12.5 km study area (purple box). Historic earthquake epicentres are also shown (grey diamonds). Contour interval is 50 m.*

Background

Typical indicators of high temperature geothermal resources (e.g., hot springs and active volcanism) are absent within the study area. However, there is a variety of geoscience evidence which is relevant to the question of the favourability of geothermal resources near Haines Junction. This background information 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; Gaudreau et al., 2019). The CPD mapping is a geophysical method, 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. Two different Curie point depth values have been estimated for the Haines Junction area in two separate studies: ~12.5 km (Li et al., 2017) and ~18 km (Gaudreau et al., 2019). These values translate into an average, crustal-scale temperature gradient of ~32–46 °C/km. Such a thermal gradient is higher than the average thermal gradient for continental crust (~25 °C/km).

Bedrock and surficial geology

Bedrock geology in the Haines Junction area (Fig. 3) can be summarized as follows (from Yukon Geological Survey, 2023b; Israel et al., 2015; Israel and Kim, 2014):

- Bear Creek assemblage: strongly deformed, Upper Triassic metasedimentary and metavolcanic rocks whose geologic origin is enigmatic.
- Dezadeash Formation: Upper Jurassic to Lower Cretaceous siliciclastic sedimentary rocks that unconformably overlie the Bear Creek assemblage.
- Pyroxenite Creek suite: Early Cretaceous gabbro and diorite plutonic rocks (dated at 125–113 Ma).
- Kluane Schist: Cretaceous biotite and muscovite schist.
- Paint Mountain pluton: Eocene felsic to intermediate plutonic rocks (diorite, granodiorite; part of the Hayden Lake suite; dated at 55–45 Ma).

Surficial geological mapping (Yukon Geological Survey, 2020; Rampton and Paradis, 1981) shows that the lowlands in the Haines Junction area are blanketed by significant thicknesses of glacial lake sediments. For example, at the end of the McConnell glaciation, Glacial Lake Champagne formed in the Dezadeash River valley where the town of Haines Junction is now located. Pre-McConnell sediments that may lie below the glacial lake sediments and above bedrock are not exposed. Bedrock is also not exposed across most of the study area but is found in upland regions that have been scoured by glaciers, such as the Paint Mountain area.

Shakwak fault and other geologic structures

Major faults in southwest Yukon include:

a. Denali fault — a crustal-scale, northwest-trending, dextral strike-slip fault with as much as 400 km of movement since the Late Cretaceous.

b. Duke River fault — a northeast-directed thrust fault that places Alexander terrane rocks on top of Wrangellia terrane rocks and has been active from the Late Cretaceous to the present.

c. Shakwak fault — an inferred fault structure that juxtaposes rocks of the Bear Creek assemblage against the Kluane schist.

The Denali and Duke River faults lie ~20 km southwest of the study area while the Shakwak fault strikes northwest-southeast, running through the northern portion of the study area (Fig. 3). Little is known about the Shakwak fault and the lack of recent seismicity along this fault suggests it is currently inactive. However, recent surficial geological mapping in the Kathleen River fan area (~2 km east of the study area) found linear features that cut modern fluvial fan sediments in the vicinity of the trace of the Shakwak fault (P. Lipovsky, 2024, personal communication). Although these features need further investigation, they may indicate Holocene movement on the Shakwak fault.

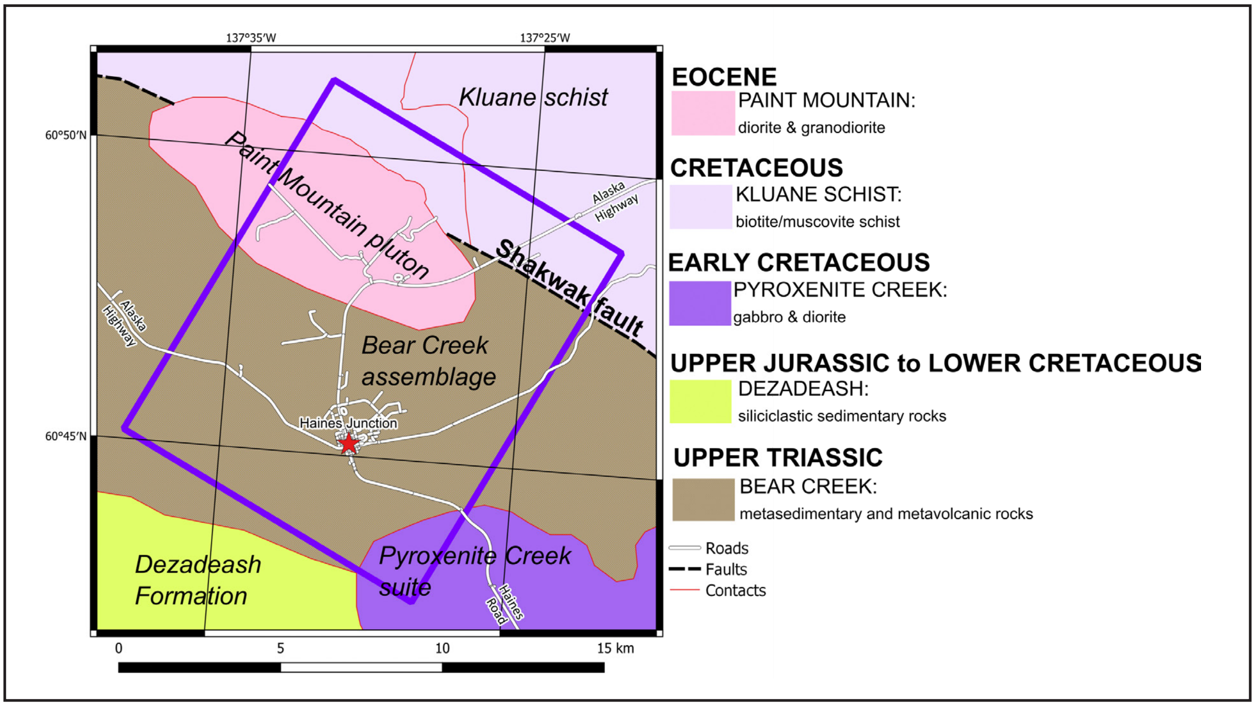

Figure 3. *Bedrock geology in the Haines Junction area, Yukon (adapted from Colpron, 2022 and Yukon Geological Survey, 2023b). The study area is delineated by purple rectangle.*

Volcanism and warm springs

About 20 km west of the study area, extensive outcrops of the Wrangell volcanic group can be found. These are Miocene, felsic to mafic volcanic rocks of the Alsek volcanic field which formed due to leaky strike-slip volcanism along the Duke River fault, dated at 16.4–15.4 Ma (Trop et al., 2012). Although there may have been geothermal systems associated with the Alsek volcanic field during the Miocene, these rocks are likely too old to serve as a heat source for a modern-day geothermal system.

A notable geothermal feature outside the study area is the Jarvis River Warm Springs, located ~30 km northwest of the Village of Haines Junction. They consist of several pools and springs ~100 m north of the Jarvis River and reach temperatures up to 18 °C. Extensive work by EBA Engineering in 2009 (EBA Engineering, 2010a and references therein), did not identify other warm springs in the area with temperatures higher than the Jarvis River Warm Springs.

As part of the 2009 studies summarized in EBA Engineering (2010a), chemical analysis of water samples collected from the Jarvis River Warm Springs yielded the following information.

- The spring waters are classified as sodium bicarbonate-type and they have elevated chloride and elevated electrical conductivity, which is consistent with deep fluid circulation and water-rock reactions.
- Water isotopes fall on the “meteoric line” for the region, which suggests a meteoric (i.e., not magmatic) source for the spring water.
- Radiocarbon dating of the spring water suggests an age of ~30,000 years BP; this suggests that the Jarvis River Warm Spring waters were last in contact with the atmosphere during the Pleistocene.
- ^{3}He/^{4}He ratios suggest mantle helium is penetrating through the crust and arriving at the surface in the waters of Jarvis River Warm Springs.
- Geothermometry analysis of several samples from Jarvis River Warm Springs gave equilibrium deep aquifer temperatures of 60–111 °C.

These results suggest that the source of the Jarvis River Warm Springs is relatively old meteoric water heated by deep circulation in warm crustal rocks.

In 2009, EBA Engineering attempted a geothermal drilling program at Jarvis River Warm Springs to obtain information on subsurface geology and temperature (EBA Engineering, 2010b). While drilling through glacial sediments at a depth of 46 m, they encountered a pressurized aquifer which caused uncontrolled artesian flow from the well. Through subsequent efforts, the flow from the well was eventually stopped; however, the drill program had to be abandoned.

Shallow well data

Records from 24 water wells are available for the Haines Junction area (Yukon Water Well Registry website; https://yukon.ca/en/get-information-about-yukon-groundwater-and-wells). These data provide information on subsurface geology, depth to bedrock, and subsurface temperature. Most of the water wells are located within a few kilometres of the Village of Haines Junction (Fig. 4). The water wells range in depth from 11 m to 385 m deep. Nineteen of the water wells have a geologic log, all of which describe gravel, sand, silt and clay as the materials encountered downhole. Only one of the wells is reported to have hit bedrock. This well is the Pine Lake campground well (5 km north of Haines Junction) and it hit an unidentified rock type (possibly Eocene Paint Mountain pluton) at a depth of 44 m. The deepest well in the area is

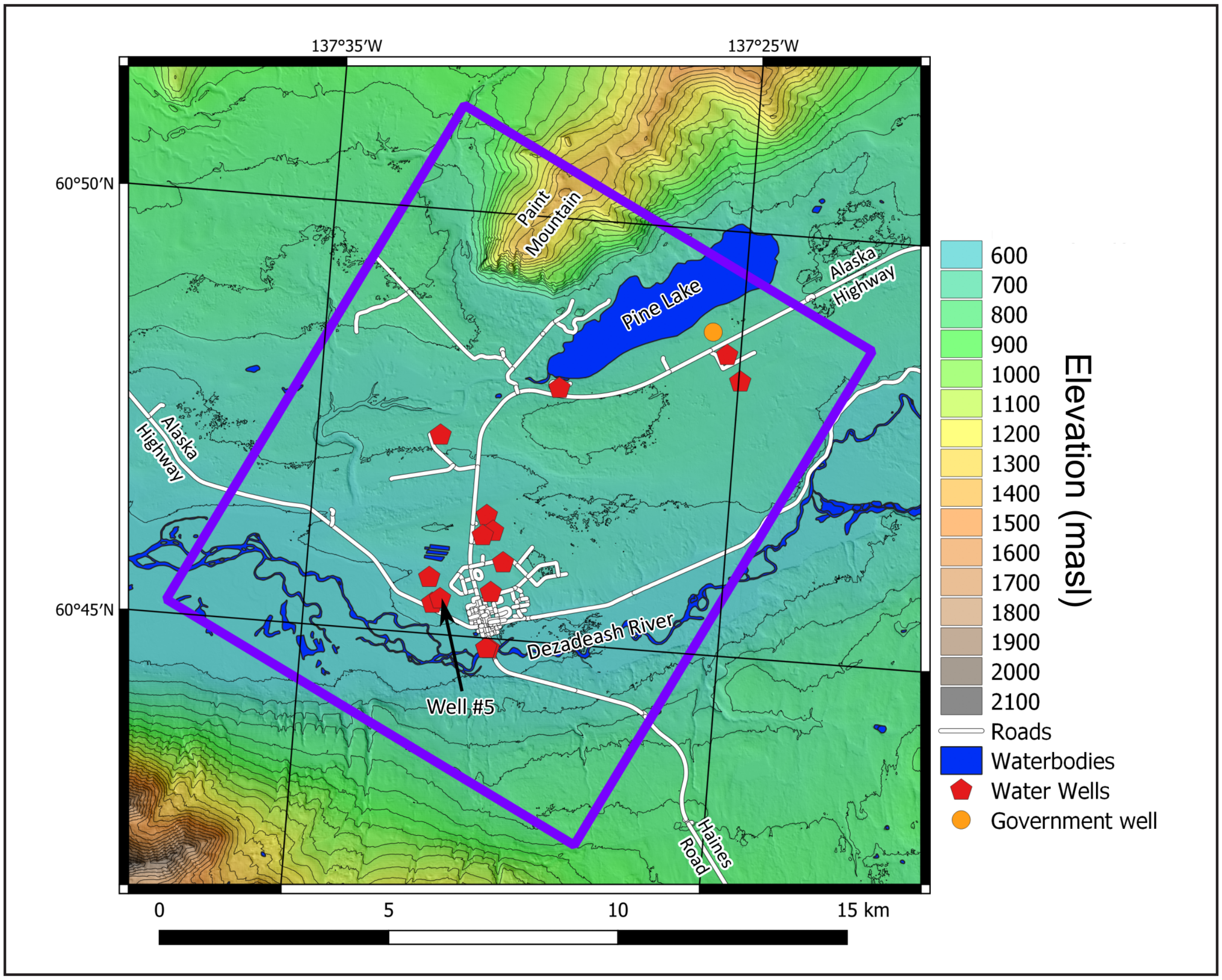

Figure 4. *Detailed topography of the study area based upon merged lidar and Arctic digital elevation model (DEM) data. Topographic contours are 50 m. Locations of water wells are also plotted (red pentagons). The orange dot shows the location of a temperature gradient well (Foothills CS-1) drilled in 1979 as part of the government of Canada's geothermal program.*

Well #5 (385 m deep) and it is located on the west side of the Village of Haines Junction and encountered clay-rich till and lake sediments as well as sand and gravel units. The lack of bedrock encountered in the Haines Junction area wells combined with the noteworthy depth of Well #5 suggests that a significantly thick (i.e., >385 m) package of near surface sediments underlies the Haines Junction area.

Subsurface temperature measurements are available from Well #5. This well was drilled as a water supply well for the village in 2002. The drilling program encountered a flowing, sand/gravel aquifer at a depth of 329 to 369 m and the well produced ~25 L/sec of 17 °C water under artesian conditions. Downhole temperature measurements registered 19.75 °C at the level of the flowing aquifer. If we assume an average annual temperature of -1 °C at the land surface in Haines Junction (Environment Canada, http://climate.weather.gc.ca/) then we can use these data from Well #5 to infer a temperature gradient of 56–63 °C/km beneath the village. This estimate is higher than the crustal thermal gradient estimated from Curie point depth mapping (32–46 °C/km).

The temperature gradient estimated from Well #5 is similar to that measured from the 30 m deep Foothills CS-1 well drilled near Pine Lake as part of the government of Canada's geothermal research program (Burgess et al., 1982). The temperature gradient measured on four occasions in the Foothills CS-1 well in 1979 and 1980 had the range of 66–68 °C/km.

Deep well data

According to public records, no deep wells (i.e., > 500 m) have been drilled in this part of Yukon.

Heat flow data

There are no heat flow datapoints available within an ~80 km by ~80 km area around the Village of Haines Junction. The nearest heat flow datapoints are:

- Casino mine (~230 km NNW of Haines Junction): 86 mW/m^2;
- Clear Lake mine (~260 km NE of Haines Junction): 118 mW/m^2; and
- Whitehorse (~130 km E of Haines Junction): 60 mW/m^2.

Considering these regional heat flow measurements for southern Yukon (Lewis et al., 2003) heat flow in the Haines Junction area is estimated to be on the order of ~80 to 100 mW/m^2. This is higher than the mean heat flow of 65 mW/m^2 over continental crust.

Radiogenic heat production data

There are many direct estimates of radiogenic heat production from plutons located in the region around Haines Junction (Colpron, 2019). Most of these estimates, however, are similar to or less than the global average value for heat production in granites (2.5–2.8 μW/m^3; Hasterok and Webb, 2017).

For example, the early Tertiary Ruby Range batholith that is mapped north and east of the study area yield rather modest heat production values in the range 0.6–2.9 μW/m^3. Two samples from the Eocene Shakwak pluton (part of the Hayden Lake suite, ~30 km northwest of the study area) returned modest values (1.6–2.0 μW/m^3). Similarly, Permian plutonic rocks of the Donjek Glacier suite (~20 to 25 km west and southwest of the study area) returned heat production values of only 0.7 μW/m^3. Mafic rocks in the Kluane Ranges, such as those of Pyroxenite Creek and the Kluane Ultramafic suites yield low heat production values in the range of 0.1–1.4 μW/m^3. Based upon these data, radiogenic heat production is not expected to be a significant heat source for geothermal reservoirs in the Haines Junction area.

Earthquake data

Data on earthquake epicentres for the Haines Junction area were obtained from the U.S. Geological Survey Earthquake Catalog website (https://earthquake.usgs.gov/earthquakes/search/) by searching for all earthquakes from 1900 to present. Only four historic earthquakes are reported within the Haines Junction study area (Fig. 2). These quakes occurred between 2016 and 2023 with magnitudes ranging from 0.8 to 2.2 and depths between 3.9 and

10.5 km. An additional 3 earthquake epicentres lie just outside of the study area and have a similar depth range and magnitude. There are no mapped fault structures associated with these recent earthquakes on the south side of the study area. Furthermore, no earthquakes are reported on the north side of the study area which suggests a lack of recent movement along the Shakwak fault.

Favourable geothermal environments

For geothermal fluids to flow underground, there needs to be permeability in the rocks either in the form of faults and fractures or pore space. Studies from southern Yukon show that the tectonic regime in the area is under compression in a direction oriented approximately northeast-southwest (Hyndman et al., 2005). Such conditions in the crust tend to close geologic structures, such as the Shakwak fault, that are oriented perpendicular to the compression direction. As a result, we would expect low permeability and an unfavourable geothermal environment along the Shakwak fault and other structures that run parallel to it. A favourable geothermal environment in the Haines Junction study area is more likely to exist in the porous and permeable young sediments that lie above the bedrock.

Geothermal exploration summary and strategy

What do we know?

Existing geoscience information in the study area, outlined in the previous section, may suggest geothermal potential and is listed below.

a. An above average crustal thermal gradient of ~32–46 °C/km is present in the Haines Junction region, based upon Curie point depth mapping.
b. Well #5 confirmed the presence of a warm, permeable sand/gravel aquifer at a depth of ~350 m in the sediments below Haines Junction.
c. Downhole temperature data from Well #5 suggest a temperature gradient of ~60 °C/km in the glacial sediments.
d. Downhole temperature data from the Foothills CS-1 well suggest a temperature gradient of ~67 °C/km in the near surface sediments.
e. Geological mapping suggests that the area is blanketed by a thick accumulation of glacial sediments deposited during the McConnell glaciation.
f. The Shakwak fault is the only mapped fault in the study area, it has an orientation that is unfavourable for geothermal fluid flow, and any recent movement on this fault is poorly understood.
g. Except for a small number of events in the south, earthquake activity in the study area is absent and our understanding of fault-related fracture permeability in bedrock in the study area remains very limited.
h. The most favourable geothermal targets in the Haines Junction area are coarse and permeable sedimentary layers within the thick accumulation of near surface sediments that fill the Dezadeash River valley.

What do we want to know?

The two key requirements for a viable geothermal resource are elevated temperature and adequate rock permeability. Fortunately, Well #5 has shown that warm (~20 °C) geothermal aquifers are present in sand/gravel layers beneath the village. However, the locations of even hotter geothermal aquifers in the subsurface of the Haines Junction area remain unknown. It is reasonable to assume that the temperature gradient measured in Well #5 (~60 °C/km) remains fairly constant down through the entire thickness of near surface sediments. Using this line of reasoning, the location of the hottest geothermal aquifer under the Haines Junction area would be in the deepest portions of the sediment pile, at or near the contact with the top of bedrock. Therefore, a depth-to-bedrock map is needed to estimate the variations in sediment thickness across the study area to identify the locations where depth-to-bedrock is greatest and temperatures will be highest.

It is also reasonable to assume that there are more sedimentary layers (in addition to the one found in Well #5) that are coarse grained and permeable. Thus, one important item to know is whether the sediments that rest on top of the bedrock (where we expect the subsurface temperature to be the highest) are indeed permeable. This question is best answered by drilling a test well.

In order to build an accurate depth-to-bedrock map, we constructed a 3D geoscience model of the lithology and faults within the study area. The next sections describe the data and methods used 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 Haines Junction region include Arctic Digital Elevation Model (DEM) data (as good as 2 m resolution) and lidar data (made available by the Yukon Geological Survey). To create the best possible topographic dataset for the study area, the lidar data was given first priority and then supplemented by Arctic DEM data, as needed, to fill in gaps to create a new DEM. This topographic stitchwork was performed by Aurora Geosciences as part of their gravity survey effort (Appendix 1). Elevation in the Haines Junction study area ranges from ~600 m above sea level (asl) in the Dezadeash River bottom to ~1400 masl on top of Paint Mountain (Fig. 4).

Airborne magnetic survey data

Magnetic survey data were also obtained from Yukon Geological Survey for the Haines Junction area. These data were part of a Yukon compilation of many airborne surveys, re-processed and re-gridded with a ~100 m cell size (Aurora Geosciences and Bruce, 2020).

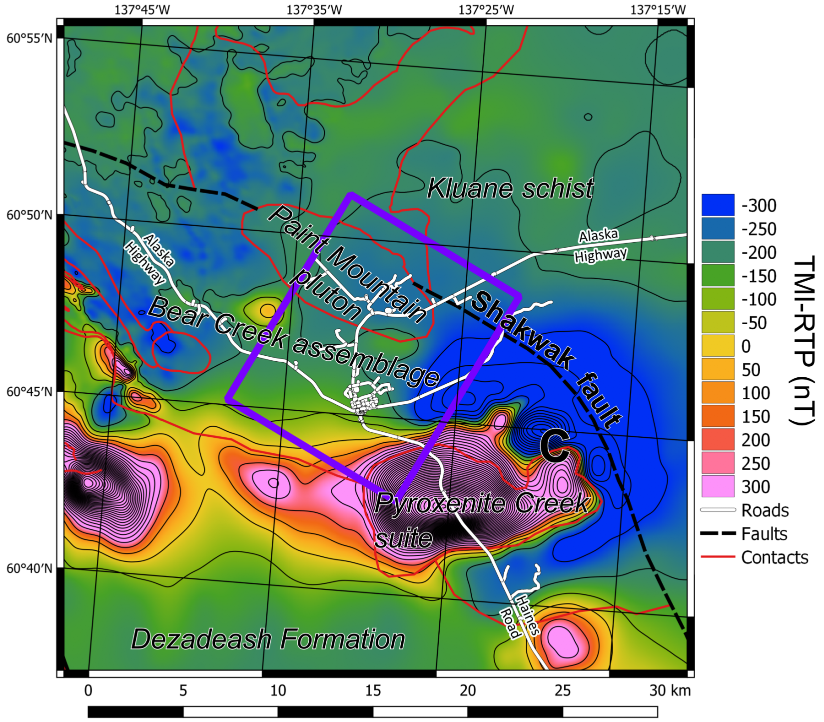

Figure 5. *Magnetic survey data for the greater Haines Junction area plotted as Total Magnetic Intensity-Reduced to Pole (TMI-RTP). The data are gridded with a 100 m cell size and coloured with cool/warm colours representing magnetic lows/highs. See text for discussion.*

These data were used for both the map-based interpretation and the 3D magnetic inversion modelling. Overall, the Total Magnetic Intensity-Reduced to Pole (TMI-RTP) data generally correspond to the mapped geology (Fig. 5). For example, the mafic intrusive rocks of the Pyroxenite Creek suite correspond to strong magnetic highs. The Bear Creek assemblage, Paint Mountain pluton, and Kluane Schist are characterized by relatively low magnetic response. Most of the Dezadeash Formation in the Auriol Range (south of Haines Junction, just outside of the study area) is magnetically featureless with low magnetic intensity values. Lastly, there are no characteristic magnetic features co-located with the Shakwak fault.

Newly collected geoscience data

Gravity survey data

Gravity data is useful to improve understanding of the geometry of rock units and depth to bedrock. In 2022 and 2023, Aurora Geosciences collected new gravity measurements at 512 stations over a ~10 km by ~12.5 km survey area using 500 m station spacing (Fig. 6). The gravity survey area was co-located with the best road access (e.g., Alaska Highway and side roads) and was roughly centred over the Village of Haines Junction. Geologically, the gravity survey area extended from the highlands of Paint Mountain in the north to the magnetic anomaly of the Pyroxenite Creek suite in the south. High-resolution Global Navigation Satellite System (GNSS) elevation measurements were also made at each gravity station. About 20 gravity stations were collected on the surface of Pine Lake when the lake was frozen. In order to properly correct for the presence of the low-density body of lake water, Aurora Geosciences also conducted a boat-based bathymetric survey of Pine Lake within the study area along survey lines spaced ~250 m apart. The overall measurement error for the gravity survey is estimated at 0.05 mGal. A full description of the gravity and bathymetry data acquisition by Aurora Geosciences is in Appendix 1.

Audio-magnetotelluric survey data

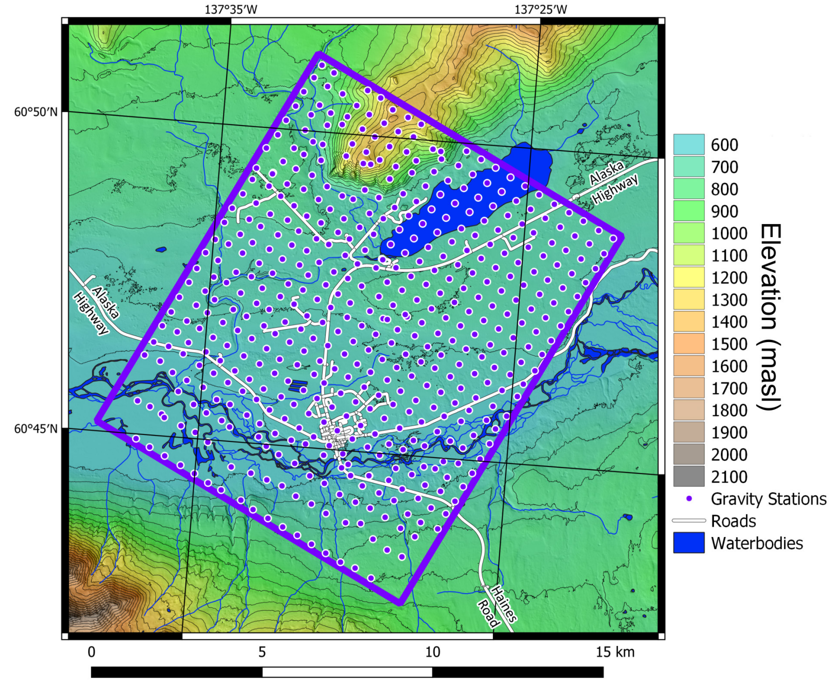

Figure 6. *Map showing gravity stations (purple dots) from the 2022/2023 gravity survey by Aurora Geosciences. The survey area is ~10 km by ~12.5 km (purple rectangle). The background image shows topography, waterbodies and roads.*

As part of this project, YGS and the Geological Survey of Canada (GSC) contracted Quantec Geoscience in 2023 to conduct an audio-magnetotelluric survey in the study area to better understand electrical resistivity variations in the subsurface. A total of 20 AMT stations were installed across the study area (Fig. 7). The AMT survey employed a frequency range of 10 kHz to 3 Hz and had a nominal station spacing of 2 km. The AMT survey data complemented regional scale magnetotelluric (MT) survey data collected in 2021 by Quantec (under contract to YGS and GSC) along the Alaska Highway through Haines Junction. In 2024, the GSC generated a 3D resistivity model of the Haines Junction area for the benefit of this geothermal study utilizing all the AMT data as well as two MT stations (C. Hanneson, 2024, personal communication).

Passive seismic data

Passive seismic data were collected in 2023 at 14 locations across the Haines Junction study area by researchers from the University of Calgary (Leishman et al., 2024). Passive seismic data can be useful to estimate the thickness of the sedimentary overburden. Preliminary results of the passive seismic research program were made available for this study (J. Dettmer, 2024, personal communication).

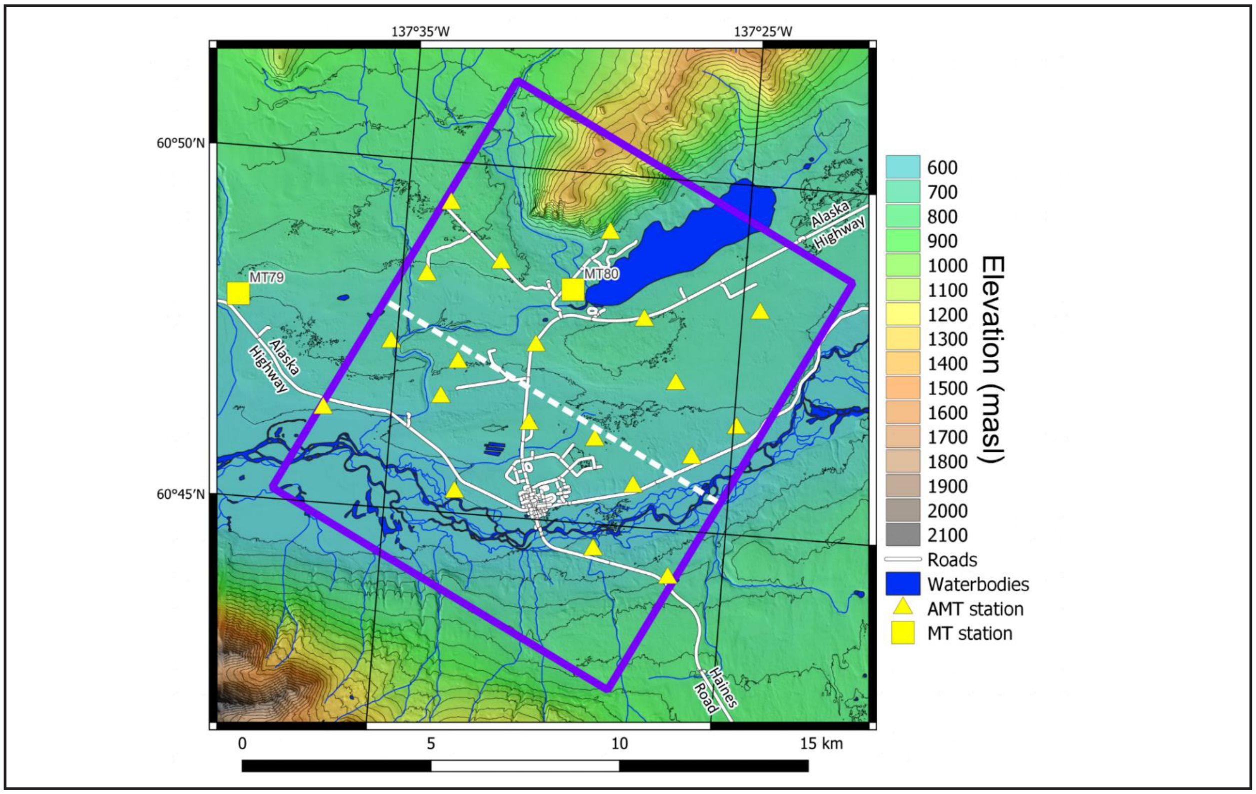

Figure 7. *Map showing locations of AMT (yellow triangles) and MT (yellow squares) stations used by Geological Survey of Canada to generate the 3D resistivity inversion model. Location of resistivity cross-section (Fig. 14) is shown by the white dashed line.*

Methodology

Map-based interpretation

To better characterize the structural and geological framework within the study area, the following data sets were interpreted using a map-based approach: topography, gravity, magnetics and geology. All map-based interpretation was performed with the software QGIS (www.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 inferred fault structures that lie under sedimentary 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 Geoscience Analyst Pro software (https://mirageoscience.com/). The gravity and magnetic geophysical data were interpreted in conjunction with the mapped geology (e.g., Yukon Geological Survey, 2023b) and rock properties to better understand the geophysical response of the major rock units in the study area (Appendix 2).

3D geology modelling

Three-dimensional geologic models were constructed for the study area to aid in interpretation and to serve as an important guide for 3D gravity and magnetic 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 as much as possible.

3D gravity modelling

Three-dimensional geophysical inversion modelling of gravity data was performed as part of the effort to iteratively build a 3D geologic framework for 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 geologic 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 has the following dimensions 10.4 km northwest-southeast by 12.6 km northeast-southwest by 4 km thick. We assumed a background rock density value of 2.67 g/cm^3. The 3D model mesh consists of cubic cells of the following sizes: 10 m cells from 0 to 30 m depth, 40 m cells from 30 to 2030 m depth, and 80 m cells below 2030 m. The purpose of the 10 m model cells down to 30 m depth is to provide detail of the topographic surface and to capture Pine Lake in the 3D model (the depth of Pine Lake is < 30 m). Two kilometres of padding cells were added to the model volume to minimize edge effects. The topographic surface utilized for the 3D geophysical model volume was stitched together from lidar and Arctic DEM data (Appendix 1). A total of 512 gravity data points 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 200 m prior to inversion modelling to minimize near-surface effects and model artifacts. The 3D density model derived from the gravity inversion modelling is available in Appendix 2.

3D magnetic modelling

Magnetic data are sensitive to variations in the magnetic susceptibility of rocks in the subsurface. Due to the presence of the magnetic high anomaly spatially associated with the Pyroxenite Creek suite, 3D geophysical inversion modelling of magnetic data was primarily performed to help better estimate the depth and geometry of that rock unit.

Like the 3D gravity modelling, the 3D inversion modelling of magnetic data was also guided by a 3D geologic model and average magnetic susceptibility values for each rock unit. The magnetic inversion modelling also used the open source SimPEG code (Cockett et al., 2015) and spatially variable mixed Lp norms for the regularization (Fournier and Oldenburg, 2019). To account for magnetic remanence, we employed the magnetic vector inversion algorithm of Fournier et al. (2020). The 3D magnetic model volume is the same size as the one used for the 3D gravity modelling. However, the model mesh consists of 50 m cubic cells. Two kilometres of padding cells were added to the model volume to minimize edge effects.

A total of 13 106 magnetic survey data points were used in the inversion modelling, derived from gridded TMI magnetic survey data from the Yukon Geological Survey (Aurora Geosciences and Bruce, 2020). Magnetic field parameters used for the inversion modelling include declination (26°), inclination (76°), and total field strength (57 191 nT). We used a nominal height of 100 m above topography for modelling the reprocessed aeromagnetic data. The 3D magnetic susceptibility model derived from the magnetic inversion modelling is available in Appendix 2.

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 attempting to simultaneously match the geophysical measurements, rock property data, and a geologically reasonable 3D geology model that honours bedrock geology mapping.

Results

Rock property data analysis

As part of this project, rock property data were compiled from over 200 hand samples in the YGS archives. The samples do not all come from within the boundary of the study area but instead are from rock units that represent all of the four major rock types present within the study area (Kluane Schist, Pyroxenite Creek suite, Paint Mountain pluton, Bear Creek assemblage) as well as another rock unit that crops out immediately south of the study area (Dezadeash Formation). The Bear Creek assemblage has been divided into two separate facies — volcanic and sedimentary rocks. Rock property data for the Paint Mountain pluton was derived from samples collected in the Hayden Lake suite, to which the Paint Mountain pluton belongs. The rock property data were compiled from samples collected during fieldwork described in Israel and Kim (2014) and Israel et al. (2015) as well as by other YGS personnel. In this study, all young sediments (i.e., above bedrock) are assumed to be Quaternary. Rock property data for these sediments are not available so representative values have been estimated.

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 the data distribution (Figs. 8 and 9). 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 8, average rock density is broadly similar for most of the rock units (~2.75 g/cm^3). The volcanic facies of the Bear Creek assemblage appears to have a slightly higher density. However, the range in density values for this unit overlaps with several other units such that it would be difficult to distinguish them based upon density alone. In contrast, the Pyroxenite Creek suite of rocks clearly has a higher density (~3.18 g/cm^3) than all the other rocks in the Haines Junction area.

As shown in Figure 9, a very low magnetic susceptibility is characteristic of most of the rock units in the study area (~$10^{-3.6}$ SI). These rock units are essentially magnetically indistinguishable from one another. In contrast, the Pyroxenite Creek rocks are strongly magnetic (average ~$10^{-1.8}$ SI) and have a rather wide range of magnetic susceptibility. Rock property data for Quaternary sediments were not available for this study and, thus, we use assumed values (Table 1).

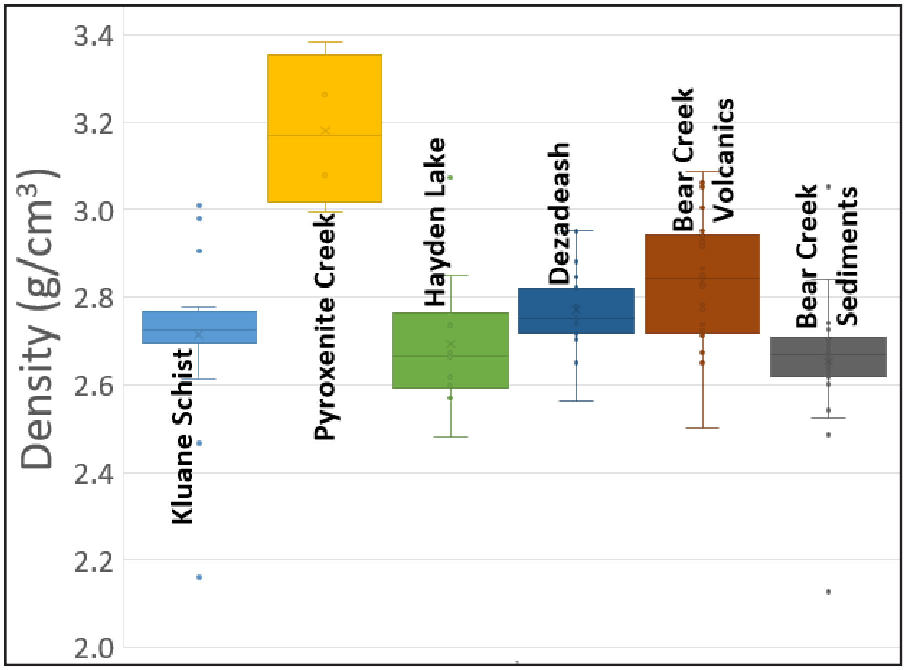

Figure 8. *Rock density data compiled from 103 hand samples that are representative of rock units in the Haines Junction area. Paint Mountain pluton rocks belong to the Hayden Lake suite.*

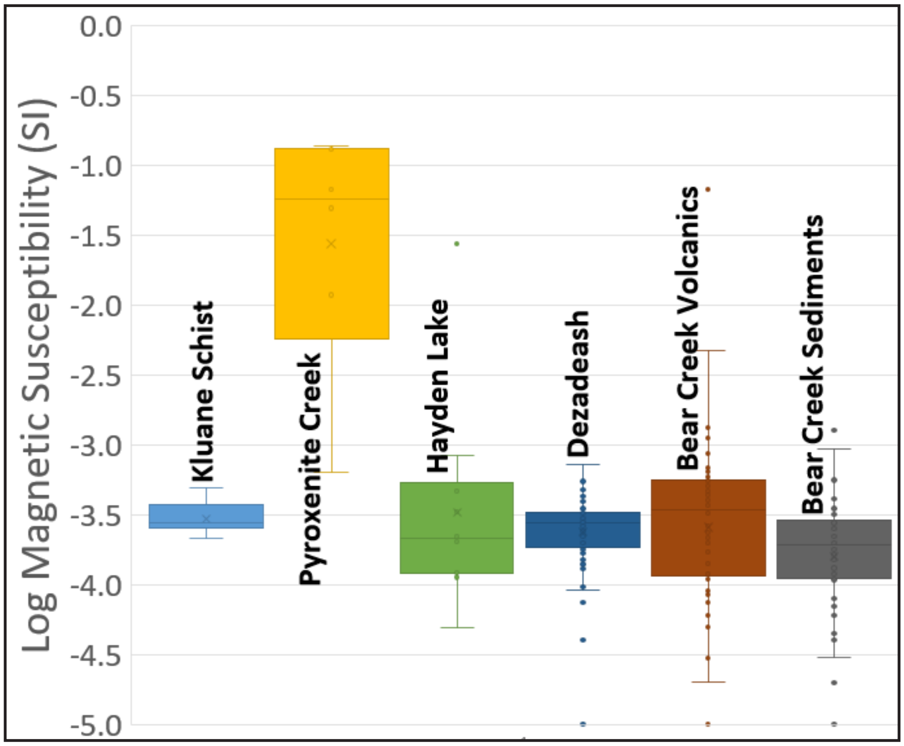

Figure 9. *Rock magnetic susceptibility data compiled from 234 hand samples that are representative of rock units in the Haines Junction area. Paint Mountain pluton rocks belong to the Hayden Lake suite. Variations in magnetic susceptibility are shown on a log scale such that log magnetic susceptibility = -3 is equivalent to a magnetic susceptibility value of 10^{-3} or 0.001 SI units.*

Table 1. *Simple statistics of the a) density data and b) magnetic susceptibility data categorized according to rock type; n = number of measurements. Rock property data for Quaternary sediments are representative values from the literature.*

a) Rock density data:

Rock unit	Minimum	Maximum	Average	1σ Std. Dev.	n
	(g/cm^3)	(g/cm^3)	(g/cm^3)	(g/cm^3)	
Quaternary sediments	2.1	2.4	2.25	n/a	0
Kluane Schist	2.16	3.01	2.72	0.17	22
Paint Mountain pluton	2.48	3.07	2.69	0.17	10
Bear Creek (volcanic)	2.50	3.09	2.84	0.15	24
Bear Creek (sedimentary)	2.13	3.05	2.65	0.16	24
Bear Creek (volcanic & sedimentary)	2.13	3.09	2.75	0.18	48
Dezadeash Formation	2.56	2.95	2.77	0.09	19
Pyroxenite Creek	3.00	3.38	3.18	0.18	4

b) Rock magnetic susceptibility data:

Rock unit	Minimum	Maximum	Average	1σ Std. Dev.	n
	(Log SI units)	(Log SI units)	(Log SI units)	(Log SI units)	
Quaternary sediments	-4.0	-4.0	-4.0	n/a	0
Kluane schist	-3.7	-3.3	-3.5	0.1	22
Paint Mountain pluton	-4.3	-1.6	-3.5	0.8	10
Bear Creek (volcanic)	-5.0	-1.2	-3.6	0.6	69
Bear Creek (sedimentary)	-5.0	-2.9	-3.8	0.4	50
Bear Creek (volcanic & sedimentary)	-5.0	-1.2	-3.7	0.5	119
Dezadeash Formation	-5.0	-3.1	-3.6	0.3	77
Pyroxenite Creek	-3.2	-0.9	-1.6	0.9	6

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 the range -124 to -97 mGal (Fig. 10). The key features of the gravity map include:

- a strong gravity high in the south corner that coincides with the Pyroxenite Creek intrusion;
- a moderate gravity high in the west corner of the study area;
- a region of intermediate gravity response in the northern part of the study area that correlates with the area around Paint Mountain; and
- gravity lows in the east and central portions of the study area with a north-northeast trending ridge of moderate gravity separating the two.

The high density of Pyroxenite Creek rocks provides a good explanation for the very strong gravity response observed in the southern corner of the study area. Unfortunately, the measured densities of the other bedrock units in the study area are quite similar to one another (Fig. 8). As a result, differentiating these other bedrock lithologies and mapping their geologic contacts with gravity alone is difficult. The most likely explanation for the observed variations in the gravity response across most of the Haines Junction study area is the varying thickness of low-density sediments resting on top of higher density bedrock. The areas with the greatest thickness of sediment likely correspond to the strongest gravity lows. Similarly, regions of elevated gravity represent places where bedrock is close to the surface and sediment cover is thin.

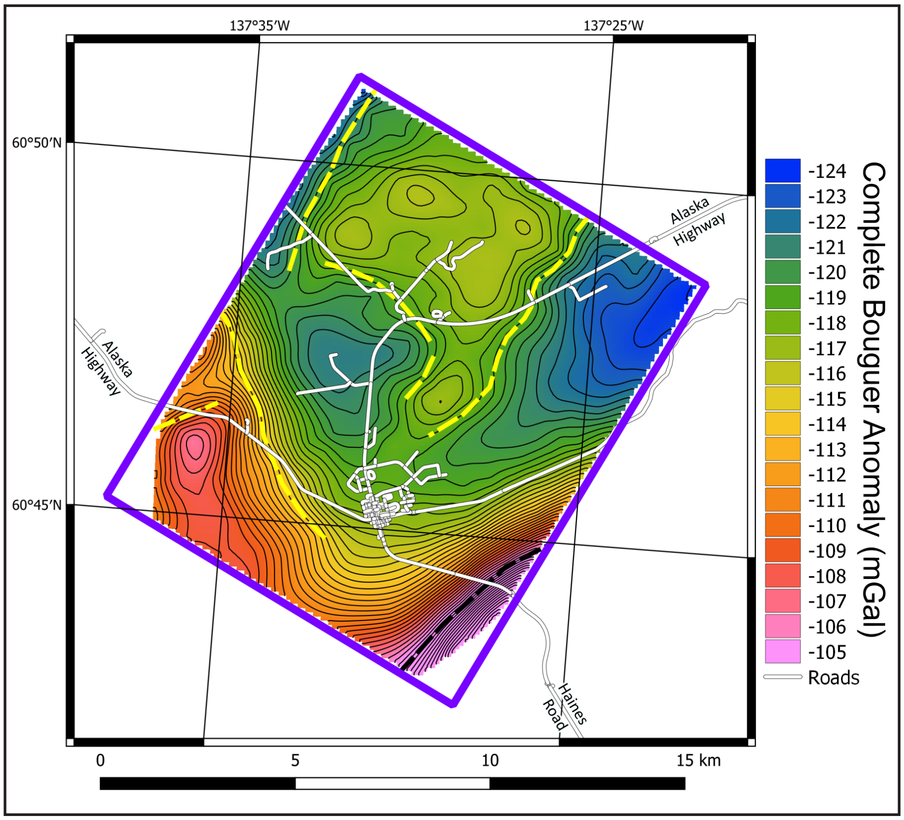

Figure. 10. *Complete Bouguer Anomaly (CBA) gravity data gridded with a 100 m cell size. Gravity contours (black solid lines) are shown at 0.5 mGal intervals. Cool/warm colours represent gravity lows/highs. The inferred contact between the high density Pyroxenite Creek rocks and the lower density Bear Creek assemblage (black dashed line) as well as the edges of bedrock highs (yellow dashed lines) are also shown. These interpretation lines were inferred from another gravity map (not shown) with THG filter applied.*

A total horizontal gradient (THG) filter was applied to the gravity data to highlight the zones of greatest horizontal change in the gravity. The total horizontal gradient is commonly used in gravity interpretation to infer fault or rock unit contacts. Using this method, the location of the geologic contact between high density Pyroxenite Creek rocks and the lower density Bear Creek assemblage has been inferred (interpretation lines shown in Fig. 10). It is assumed that the mafic plutonic rocks of the Pyroxenite Creek suite form an intrusive contact, as opposed to a fault contact, with the adjacent Bear Creek assemblage. Using a similar gravity interpretation technique, the edges of bedrock highs have also been identified. Unfortunately, it is not possible to determine if the inferred bedrock highs are present due to glacial erosional processes, faulting, or both.

Magnetic survey data

Within the study area, the Total magnetic intensity (TMI) map with reduction to pole (RTP) applied has the range -600 nT to +2600 nT (Fig. 11). The key features of the magnetic map include:

- a strong magnetic high in the southern corner of the study area that coincides with the Pyroxenite Creek intrusion;
- a strong magnetic low located immediately north of the aforementioned magnetic high;
- a west-northwest-trending ridge of elevated magnetic response located southwest of the study area; and
- generally low and largely featureless magnetic response elsewhere.

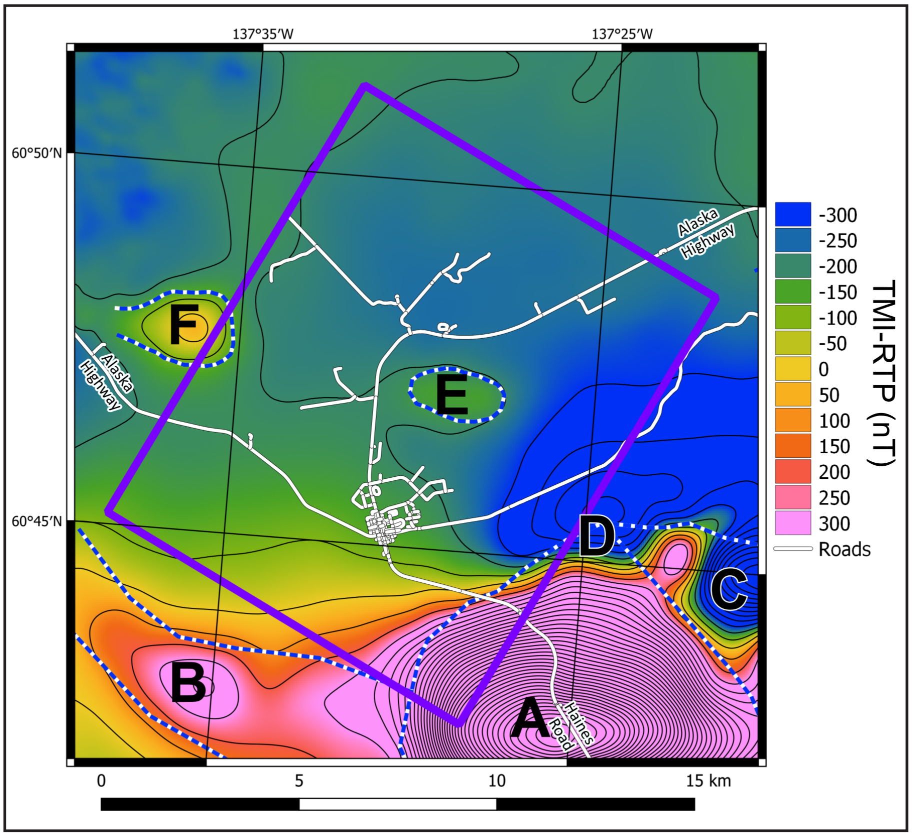

Figure 11. *Magnetic survey data gridded with a 100 m cell size. Total Magnetic Intensity with Reduction to Pole applied (TMI-RTP) is shown. Blue and white dashed lines are interpretation lines that mark the edges of magnetic bodies. See text for explanation of the labels.*

Hand samples of Pyroxenite Creek rocks yield high values for magnetic susceptibility and provide an adequate geologic explanation for the very strong magnetic response observed in the southern corner of the study area. Unfortunately, the measured magnetic susceptibility values for other bedrock units in the study area are essentially indistinguishable (Fig. 9). As a result, mapping the boundaries of the other bedrock lithologies using the TMI-RTP magnetic survey data alone is not possible. A curious feature of the TMI-RTP map is two strong magnetic lows, just outside the eastern boundary of the study area, situated immediately north of the strong magnetic high associated with Pyroxenite Creek rocks. Such dipolar anomalies sometimes indicate the presence of magnetic remanence (i.e., reversely magnetized rocks). Further analysis of the TMI-RTP data was needed to investigate this possibility.

One approach for conducting map-based interpretation of magnetic survey data, in the presence of reversely magnetized rocks, is to use the analytic signal of the magnetic field (Roest et al., 1992). Analytic signal is a method which assists in the determination of the geometry of magnetic source bodies regardless of the presence or absence of magnetic remanence. Specifically, reversely magnetized rocks may be present where the analytic signal map shows a magnetic high but the TMI-RTP map shows a magnetic low. This occurs because the magnetism in reversely magnetized rocks essentially cancels out the ambient magnetic field leaving a strong magnetic low on a TMI-RTP map. But since reversely magnetized rocks are actually magnetic, they appear as a high on an analytic signal map.

In the analytic signal map for the Haines Junction area (Fig. 12), there are two magnetic highs at the same location as the two aforementioned strong magnetic lows seen on the TMI-RTP map. These are interpreted as two portions of the Pyroxenite Creek intrusive rocks that are reversely magnetized. Further, the reversely magnetized rocks are separated from normally magnetized Pyroxenite Creek rocks located to the south by a northwest-trending trough of low magnetism. This trough is interpreted as a northwest-trending fault (or possibly an intrusive contact) that separates the different bodies of Pyroxenite Creek rocks.

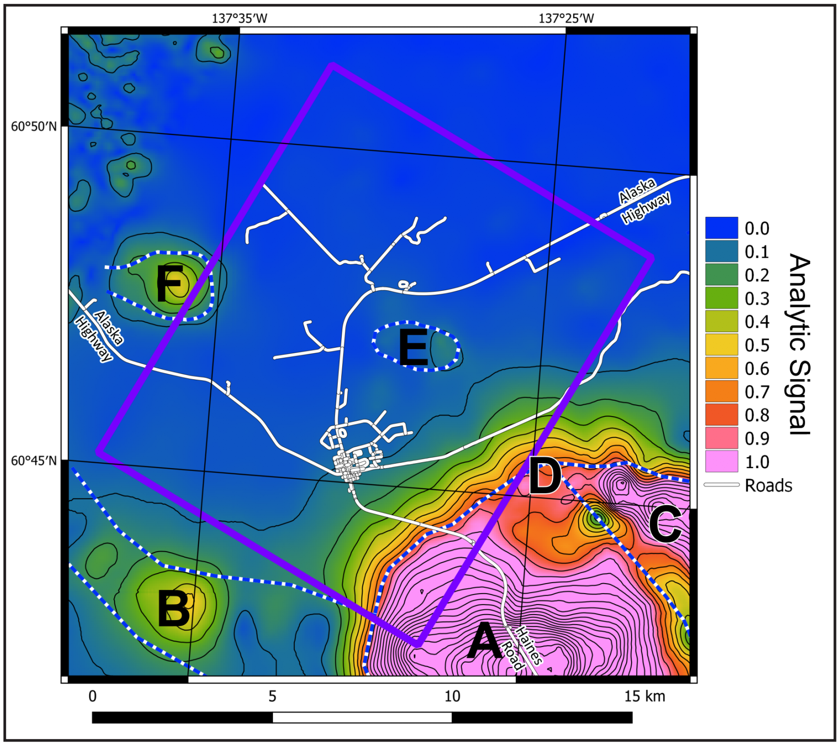

Figure 12. *Magnetic survey data gridded with a 100 m cell size. Total Magnetic Intensity with Reduction to Pole and Analytic Signal filter applied is shown. Blue and white dashed lines are interpretation lines that mark the edges of magnetic bodies. See text for explanation of the labels.*

In summary, specific magnetic features shown in Figures 11 and 12 are interpreted as follows: (A) Pyroxenite Creek rocks that are likely buried at a shallow depth to give a very strong magnetic response; (B) a westward extension of the strongly magnetic Pyroxenite Creek suite rocks that is more deeply buried than (A) to yield the moderately high magnetic response; (C) and (D) reversely magnetized Pyroxenite Creek suite rocks; (E) a very subtle magnetic feature that may be due to a deeply buried cupola of Pyroxenite Creek rocks, a magnetic contact aureole associated with the Paint Mountain pluton, or natural variability in the magnetic susceptibility of rocks in the Bear Creek assemblage; and (F) likely a small, buried cupola of Pyroxenite Creek rocks similar to (B).

Structural interpretation

As mentioned previously, the Pyroxenite Creek suite is the only bedrock unit that has strong rock property contrasts that enable it to be clearly distinguished from other bedrock units. Thus, using gravity and magnetic data to infer bedrock structures that might influence the flow of geothermal fluids in the study area is problematic due to insufficient rock property contrasts in most of the bedrock units. Despite this, co-interpretation of the gravity, magnetic and bedrock geology yields a possible structural interpretation of the Haines Junction area (Fig. 13). The Shakwak fault is a significant northwest-trending structure that separates Kluane Schist on the north from the Bear Creek assemblage on the south. Northwest-trending features observed in the gravity and magnetic survey datasets suggest that there may be geologic structures in the bedrock that run sub parallel to the Shakwak fault across the study area and intersect the Shakwak fault in the Paint Mountain pluton. The dip angle of these proposed fault structures is not discernible from the present analysis. Unfortunately, these interpreted fault structures are perpendicular to the regional tectonic compression direction and, therefore, do not have a favourable orientation that would facilitate geothermal fluid flow.

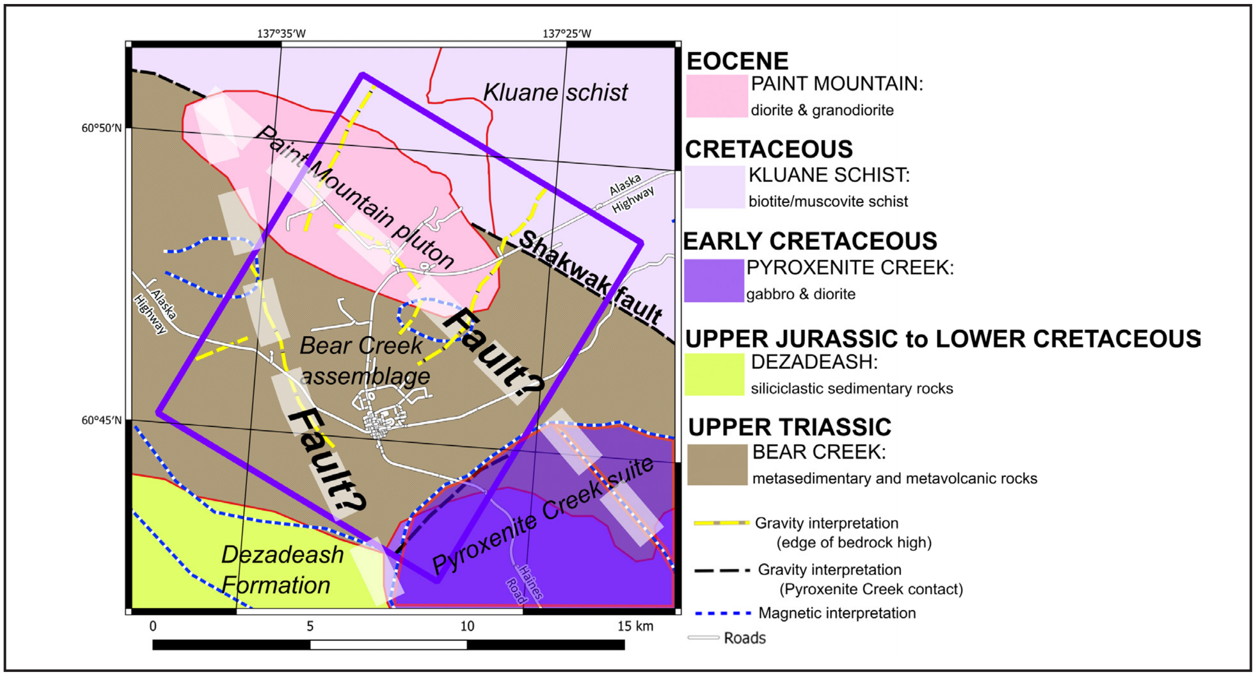

Figure 13. *Map-based structural interpretation for the Haines Junction area derived from co-interpretation of gravity, magnetic and bedrock geology data. Large dashed white lines are proposed fault structures that are interpreted as splays of the Shakwak fault. See text for discussion.*

Integrated 3D geoscience model interpretation

Interpretation of the AMT resistivity model

A key unknown at the start of this project was the variation in thickness of the Quaternary sediments in the Haines Junction area. This is important because variations in sediment thickness can have a strong influence on the gravity and magnetic model results. Sparse, existing data suggests that the sediment thickness has a minimum range of 0 m (bedrock exposed at the surface) to more than 385 m (measured in the deepest water well in the Village of Haines Junction). For most of the study area, however, there is little information on the depth-to-bedrock. Thus, an AMT resistivity model would help us identify regions of the study area where thick sections of sediments are more likely and other areas where sediment cover is thin or absent. We assume that Quaternary sediments in the study area are characterized by lower resistivity (i.e., < 50 ohm.m) due to their clay content, which contrasts with more resistive bedrock units.

A preliminary 3D resistivity model of the AMT data, generated by the Geological Survey of Canada, (C. Hanneson, 2024, personal communication) was made available for this study. The 3D resistivity model is interpreted here as follows. In the southern corner of the study area, the Pyroxenite Creek suite is characterized by a buried and resistive (500–700 ohm.m) body. Similarly, the other bedrock units (e.g., Paint Mountain pluton, Kluane Schist and Bear Creek assemblage) are generally characterized by slightly more resistive rock material (500–1000 ohm.m). The AMT model is preliminary and because these contrasts are minor, the location of bedrock contrasts may be poorly resolved, and as such they may shift in subsequent AMT models (J. Craven, 2024, personal communication). Thus, utilizing the 3D resistivity model alone to map out the geometry and structural relations of the bedrock units has not been attempted here. There is, however, a strong resistivity contrast between the bedrock units and the overlying sediments. The 3D resistivity model suggests that the entire study area, apart from Paint Mountain itself, is covered by lower resistivity (< 50 ohm.m) sediments that vary in thickness from a few metres to ~1 km thick (Fig. 14). There is no AMT station coverage in the northeast and southwest sides of the study area (Fig. 7), thus resistivity model results for rock units in these areas are less reliable. Nonetheless, the sediment thickness estimates provided by the 3D AMT resistivity model provide a key input to help guide the 3D potential field modelling discussed in the next section.

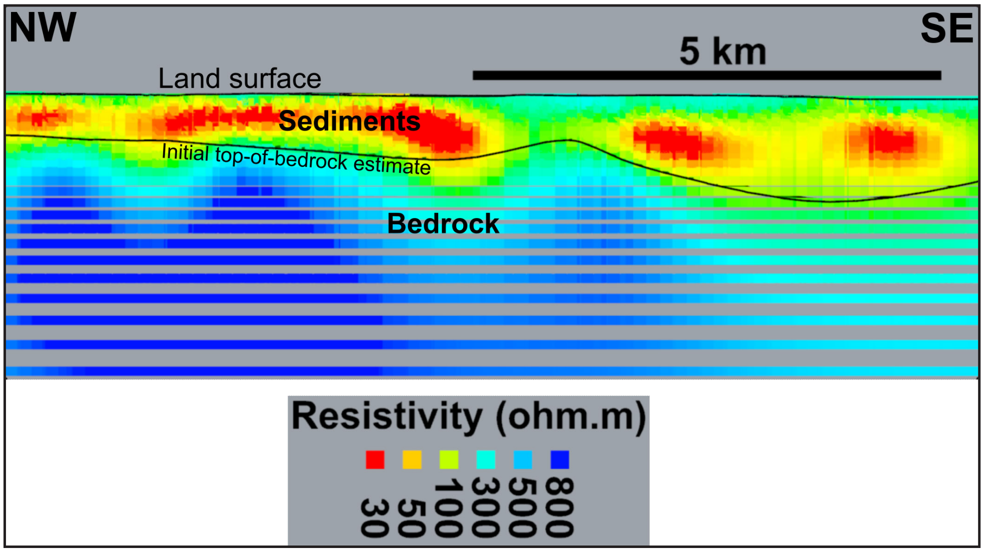

Figure 14. *Northwest-southeast cross-section across the Haines Junction project area showing a vertical profile through the 3D AMT resistivity model. Vertical and horizontal scales are equal. Location of cross-section is shown in Fig. 7.*

3D geology + gravity + magnetic modelling

A 3D geologic model was constructed to provide a framework to help better interpret regions of potential geothermal favourability in the Haines Junction area (Fig. 15). A key aim of the 3D geologic model building exercise is to build a geologic volume consisting of fault planes and discrete blocks of rock that is, as much as possible, consistent with all the available geoscience data. To do this, the model was built in a multi-step manner. The first step was to build a simple 3D geologic model that honours the bedrock geology map and utilizes the 3D AMT resistivity model as an initial model for the thickness of the overlying sediments. In subsequent steps, the Pyroxenite Creek and top-of-bedrock boundaries were adjusted, then 3D gravity and magnetic inversion modelling was performed multiple times to test which geologic modifications best honour the geophysical datasets.

For each 3D gravity inversion, different rock units in the 3D geologic model were assigned reference density values based upon rock density measurements. Similarly, for each 3D magnetic inversion, the rock units in the 3D geologic model were assigned reference magnetic susceptibility values based upon rock property measurements (Table 1). In the inversion calculations, the inversion algorithm adjusted the rock property values (either density or magnetic susceptibility) in the model cells until a match was achieved with the measured geophysical data. For the gravity modelling, a match was achieved when the root-mean-squared (RMS) misfit, calculated for the 3D density model, reached a nominal value of 0.1 mGal (slightly higher than the average measurement error of the gravity survey data of 0.05 mGal). The actual calculated RMS misfit obtained for the final 3D density model is 0.097 mGal. Similarly, 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 4.6 nT. Thus, both the gravity and magnetic inversion modelling exercises reached the target misfit values and the model outputs are considered consistent with the geophysical survey data.

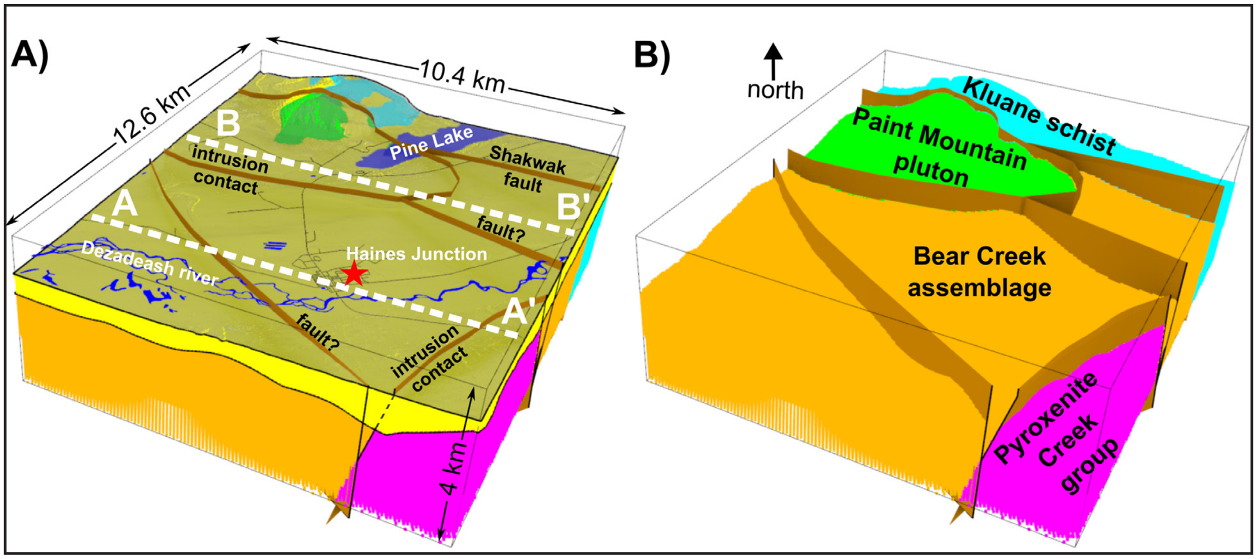

Figure 15. Perspective view of the 3D geologic model for the Haines Junction area: ***a)*** *3D geologic model that highlights Quaternary sediments (yellow), lake (blue), topography (translucent grey), and roads (black lines);* ***b)*** *3D geologic model with sediments and lake removed to show bedrock units. Faults and intrusion contacts are shown in brown and extend above topography to aid visualization. Dashed white lines in (a) show the locations of 2D cross-sections A-A' and B-B' extracted from the 3D model shown in Figures 16–21.*

The final 3D geologic model (Fig. 15) contains five different rock units (Table 2) and largely honours the bedrock and fault mapping of Yukon Geological Survey (2023b). Two hypothesized northwest-trending faults have been added that were inferred from the potential field interpretation.

Table 2. List of rock units in the Haines Junction 3D geologic model.

Rock unit name	Age	Rock type
Quaternary sediments	Quaternary	Lake sediments and glacial sediments
Paint Mountain pluton	Eocene	Diorite and granodiorite
Kluane Schist	Cretaceous	Biotite/muscovite schist
Pyroxenite Creek suite	Early Cretaceous	Gabbro and diorite
Bear Creek assemblage	Upper Triassic	Meta-sedimentary and meta-volcanic

Many assumptions went into the creation of the 3D geologic model. For example, we assume that the magnetic susceptibility of the Quaternary sediment is, on average, 10^{-4} SI. Furthermore, we assume that the density of the Quaternary sediment increases linearly with depth (due to compaction) from 2.1 g/cm^3 to a maximum of 2.4 g/cm^3. These values are likely not correct since we would expect lake sediments and glacial sediments (which are lumped together here) to have different rock properties. However, in the absence of rock property measurements for the Quaternary sediments, these estimates suffice for the geophysical modelling performed here. We also assume that other rock units have a generally uniform density and magnetic susceptibility (i.e., no significant variations laterally or vertically within a single rock unit). Faults are assumed to be steeply dipping or vertical. Similarly, due to an absence of information, the intrusive contact for the Paint Mountain pluton is assumed to be vertical. 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 close to reality as possible—an initial 3D geologic framework which can be subsequently tested and improved with additional geophysical data and/or drilling.

The overall outcome of the 3D geology + gravity + magnetic inversion modelling effort includes new 3D rock density and 3D magnetic susceptibility models with faulted and stratigraphic geologic boundaries. Two cross-sections have been extracted from the 3D rock property models that run along nothwest-southeast profiles (Figs. 16–21). Although the rock property models are in three dimensions, the 2D cross-sections presented here highlight some of the key elements of the rock property models.

The 2D cross-sections showing density model results (Figs. 16–17 and 19–20) contain the following elements: a reference geologic model (showing rock types), a reference density model (showing the values and geometry of the geologic constraints), and a geologically constrained density inversion model output (our best attempt to reconcile geology, gravity data, and rock property measurements). The density model results are presented using two colour scales (1.9–2.5 g/cm^3 and 2.6–3.1 g/cm^3) to help better visualize the lower density and higher density rock distribution in the density models. The 2D cross-sections showing magnetic susceptibility model results (Figs. 18 and 21) contain similar elements. However, the susceptibility model results are visualized using a log colour scale with the range 0.0001–0.05 SI units.

By comparing the density and magnetic susceptibility model results with their reference rock property and geology models we can gain insight into how good the match is between our conceptual understanding of the subsurface geology and reality. In some areas, the agreement between the reference and inversion rock property models is good. In other areas, regions of mismatch are clear and represent areas where the geologic understanding is reduced and more information is needed to help better understand the subsurface.

Explanation of cross-Section A-A': through the Village of Haines Junction

The northwest-southeast cross-section through the Village of Haines Junction contains three of the five rock units found in the study area and also passes through Well #5, the deepest well in the area (Fig. 16A). Key features of the geology model in this section include: a layer of Quaternary sediments that is thickest on the southeast side, a fault inferred from the gravity and magnetic interpretation, and an intrusive contact between the Pyroxenite Creek suite and the Bear Creek assemblage. It is also notable that the depth to the top of the bedrock under Well #5 is about twice the depth of the well.

The geologically constrained density inversion model results for cross-section A-A' show mostly a good match between the reference model and inversion results (Fig. 16 b and c). A density mismatch can be seen in the Quaternary sediments on the southeast edge of the profile and could be caused by: a) the top of the modelled Pyroxenite Creek rocks is too shallow; or b) a geophysical model artifact (i.e., an edge effect) due to a lack of gravity data immediately outside of the study area above the dense Pyroxenite Creek rocks. Viewing the density inversion model results with a different colour scheme (Fig. 17 b and c) also shows a good match between the reference and inversion results. The small magnitude variation observed in the model density values for the bedrock units (e.g., 2.7–2.8 g/cm^3 for the Bear Creek assemblage; Fig. 17c) is well within the ranges of the density measurements made on rock samples (see Fig. 8).

The geologically constrained magnetic inversion model results for cross-section A-A' (Fig. 18 b and c) shows agreement for the high magnetic susceptibility Pyroxenite Creek suite rocks in both the reference and inversion results. However, the inversion result suggests there may be more highly magnetic Pyroxenite Creek rocks further to the west of the intrusive contact. The match between the reference and inversion models for the Quaternary sediments and Bear Creek assemblage is generally poor. Both rock bodies are expected to have low magnetic susceptibility and, therefore, it is not surprising that the inversion model is unable to distinguish between these two rock units. Curiously, the inversion results also suggest that there is more magnetic material in the Bear Creek assemblage than implied by existing rock property measurements. This may be a model artifact or maybe caused by magnetic rock units not yet recognized.

Explanation of cross-section B-B': near Pine Lake

Cross-section B-B' was selected to pass through a part of the study area where sediment cover is thinner and also through the only water well reported to have hit bedrock, the Pine Lake campground well. This cross-section contains three of the five rock units found in the study area (Fig. 19a). Key features of the geology model in this area include: a layer of Quaternary sediments that is, again, thickest on the southeast side and an intrusive contact between the Paint Mountain pluton and the Bear Creek assemblage.

The geologically constrained density inversion model for cross-section B-B’ shows a good match between the reference model and inversion results for the Quaternary sediments (Fig. 19 b and c). During construction of the model, the top-of-bedrock was fixed to the depth-to-bedrock reported for the Pine Lake campground well (i.e., 44 m). Unfortunately, the driller’s log for this well does not describe the bedrock type encountered, specifically, whether it is actual bedrock (i.e., Paint Mountain pluton) or unusually hard glacial till (i.e., that could have been mistaken for bedrock).

Viewing the density inversion model results with a different colour scheme (Fig. 20 b and c) also shows a good match between the reference model and inversion results. And, again, the small magnitude variation observed in the model density values for the bedrock units (e.g., 2.65–2.70 g/cm^3 for the Paint Mountain pluton; Fig. 20 c) still fall within the range of the density measurements made on rock samples (see Fig. 8).

The geologically constrained magnetic inversion model results for section B-B’ (Fig. 21 b and c) show a poor match between the reference and inversion results for the Quaternary sediments, Paint Mountain pluton and Bear Creek assemblage. Based upon rock property measurements of hand samples, all three of these rock units are expected to have very low magnetic susceptibility values. As a result, the inversion algorithm is unable to distinguish one rock unit from another. Magnetic inversion modelling in this part of the 3D model volume is unhelpful for resolving the geometry of the 3D geology model.

Overall, this 3D modelling exercise has generated a geologically reasonable understanding of the structure, bedrock distribution, and depth-to-bedrock for the Haines Junction study area. Where there are adequate rock property contrasts, the contacts between the major rock units largely agree with the gravity and magnetic modelling. Similarly, the gravity modelling suggests that the Quaternary sediments are thickest on the southeast side of the study area.

Interpretation of the passive seismic data

The passive seismic data collected by University of Calgary researchers in 2023 enabled estimation of seismic velocities at various depths in the subsurface sediments (Leishman et al., 2024). This research is useful because sudden changes in seismic velocity with depth may represent the transition from lower velocity sediments (< 1200 m/s) to higher velocity bedrock (> 2000 m/s) and help us map the depth-to-bedrock. In areas where we expected the top-of-bedrock to be shallow (i.e., < 200 m) the depth to the change in seismic velocity showed reasonable agreement with the top-of-bedrock estimate inferred from the 3D geoscience modelling (Fig. 22). In areas where the top-of-bedrock is likely deeper (i.e., > 200 m) the data from all but one of the passive seismic stations did not identify a change to high velocity bedrock because the bedrock interface was too deep to be detected. Collection of additional passive seismic data is merited to help improve the detection of the top-of-bedrock using this method.

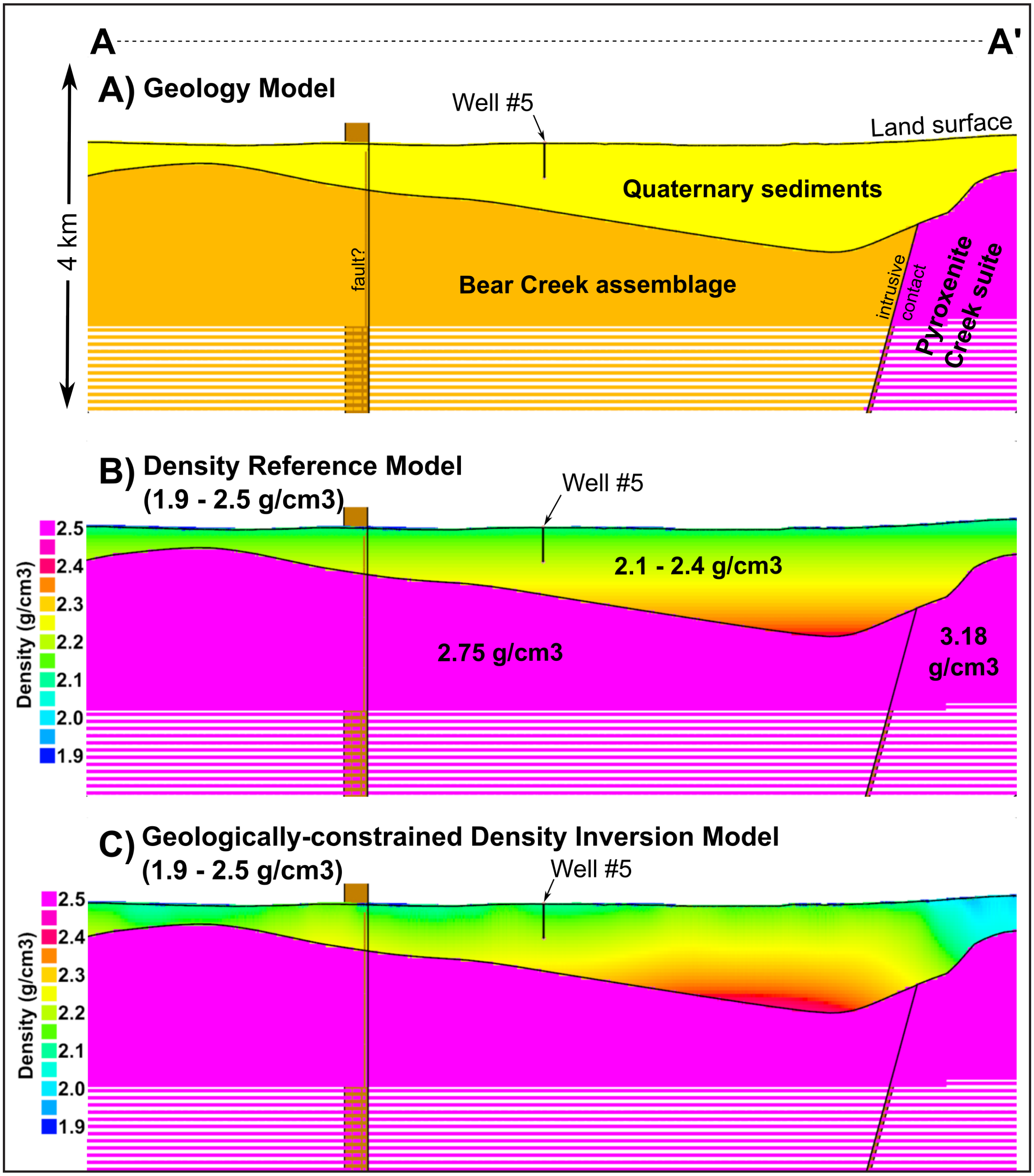

Figure 16. *Geology and density cross-sections along A-A' through the Village of Haines Junction using the lower density colour ramp (1.9–2.5 g/cm^3).* ***a)*** *Reference geology model with rock units labeled.* ***b)*** *Reference rock density model used as a constraint in the modelling.* ***c)*** *Rock density distribution 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 (1.9–2.5 g/cm^3) to visualize the lower-density sedimentary rocks in the area. The match between the reference rock density model (b) and the inverted rock density model (c) is good. See text for further explanation.*

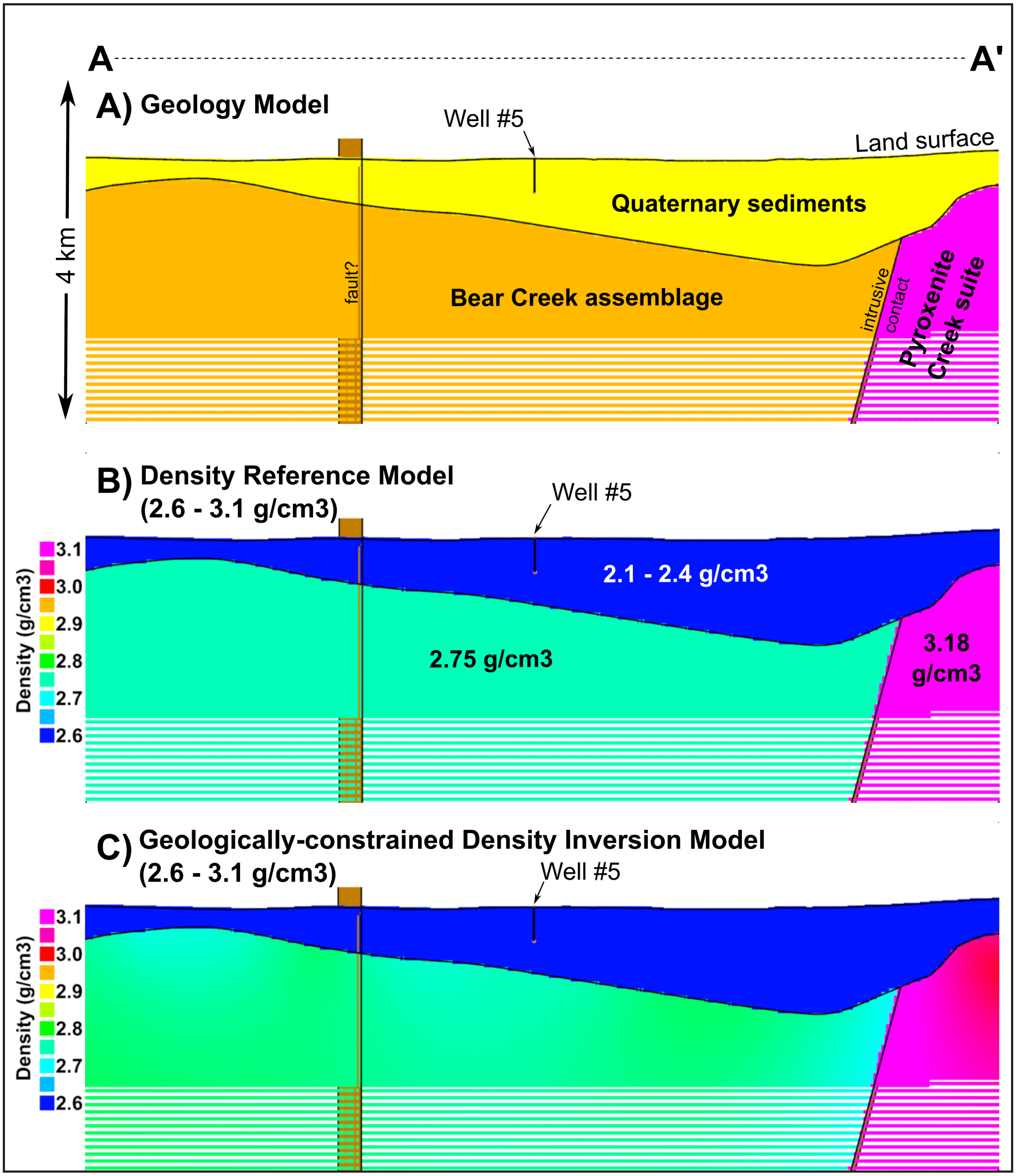

Figure 17. *Geology and density cross-sections along A-A' through the village of Haines Junction using the higher density colour ramp (2.6–3.1 g/cm^3).* **a)** *Reference geology model with rock units labeled.* **b)** *Reference rock density model used as a constraint in the modelling.* **c)** *Rock density distribution 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 (2.6–3.1 g/cm^3) to visualize the higher-density bedrock lithologies in the area. In this view, the match between the reference rock density model (b) and the inverted rock density model (c) is also good. See text for further explanation.*

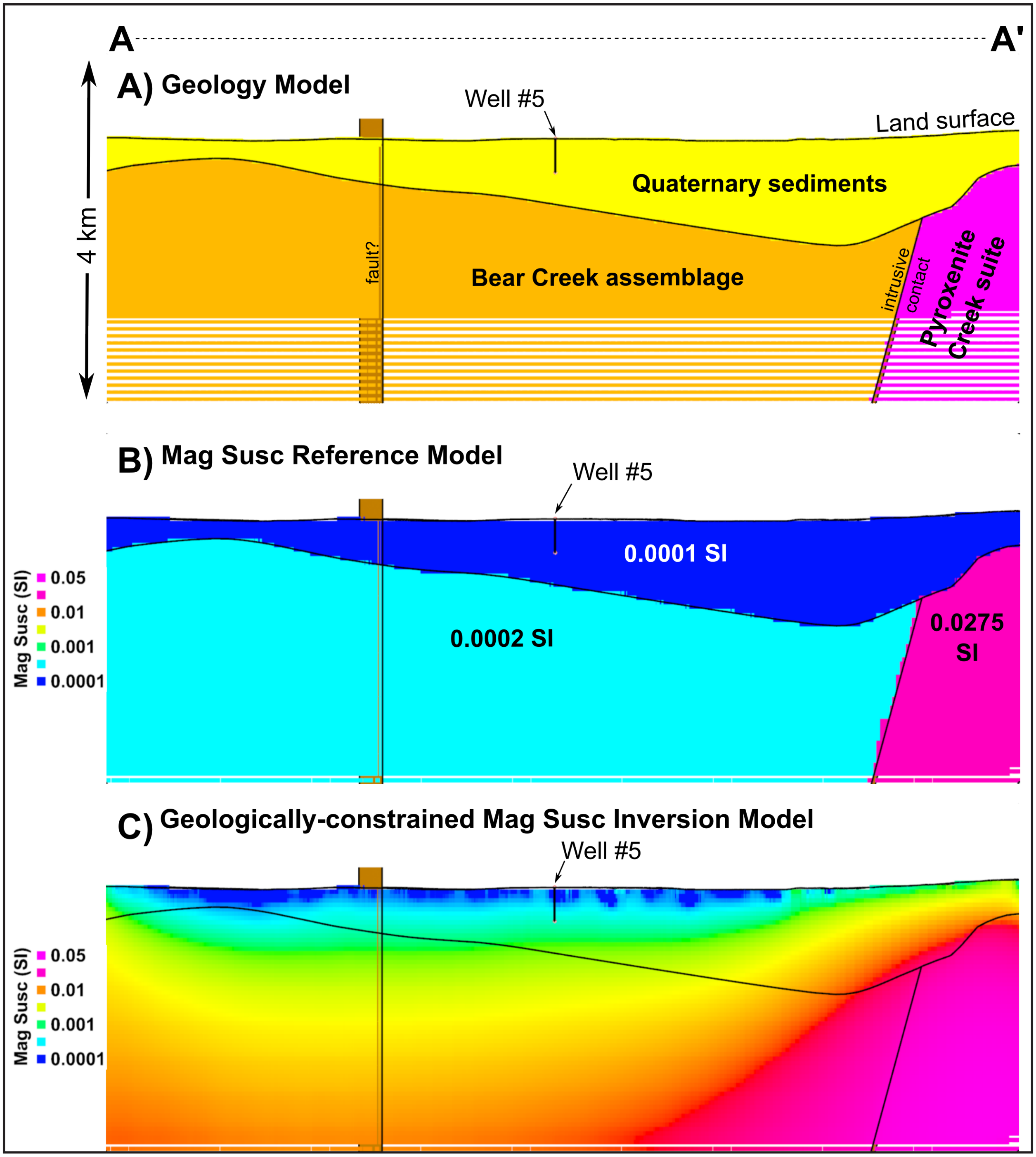

Figure 18. *Geology and magnetic susceptibility cross-sections along A-A' through Haines Junction.* ***a)*** *Reference geology model with rock units labeled.* ***b)*** *Reference rock magnetic susceptibility model used as constraints on the modelling.* ***c)*** *Rock magnetic susceptibility distribution returned by the 3D magnetic inversion modelling that honours the magnetic survey data. A log scale is used for the magnetic susceptibility values to help better visualize the results. The match between the reference rock susceptibility model (c) and the inverted rock susceptibility model (d) is fair near the Pyroxenite Creek suite but it is not good in other parts of the model.*

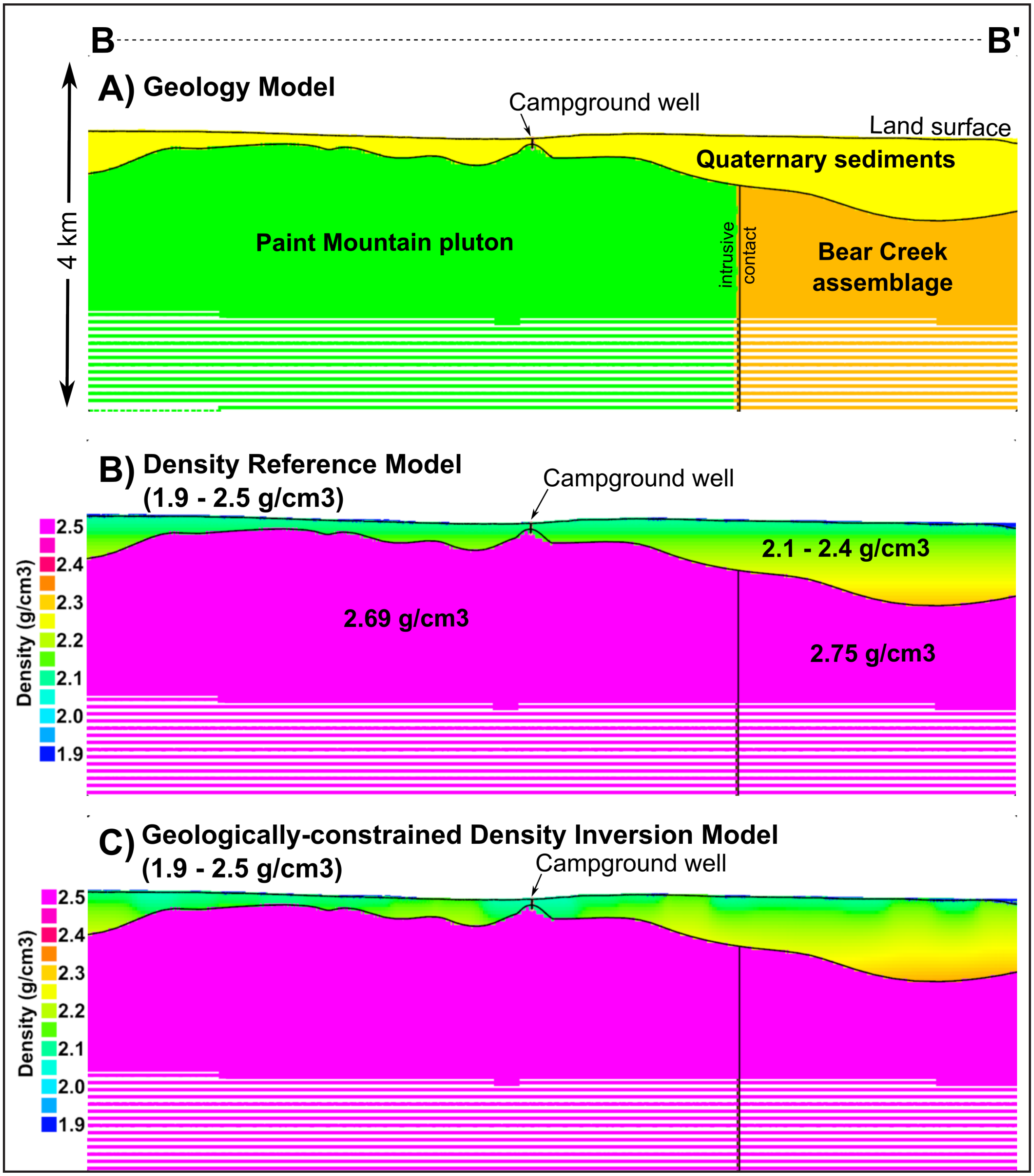

Figure 19. *Geology and density cross-sections along B-B' using the lower density colour ramp (1.9–2.5 g/cm*^{3}*).* ***a)*** *Reference geology model with rock units labeled.* ***b)*** *Reference rock density model used as a constraint in the modelling.* ***c)*** *Rock density distribution returned 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 (1.9 –2.5 g/cm*^{3}*) to visualize the lower density sedimentary rocks in the area. The match between the reference rock density model (b) and the inverted rock density model (c) is good. See text for further explanation.*

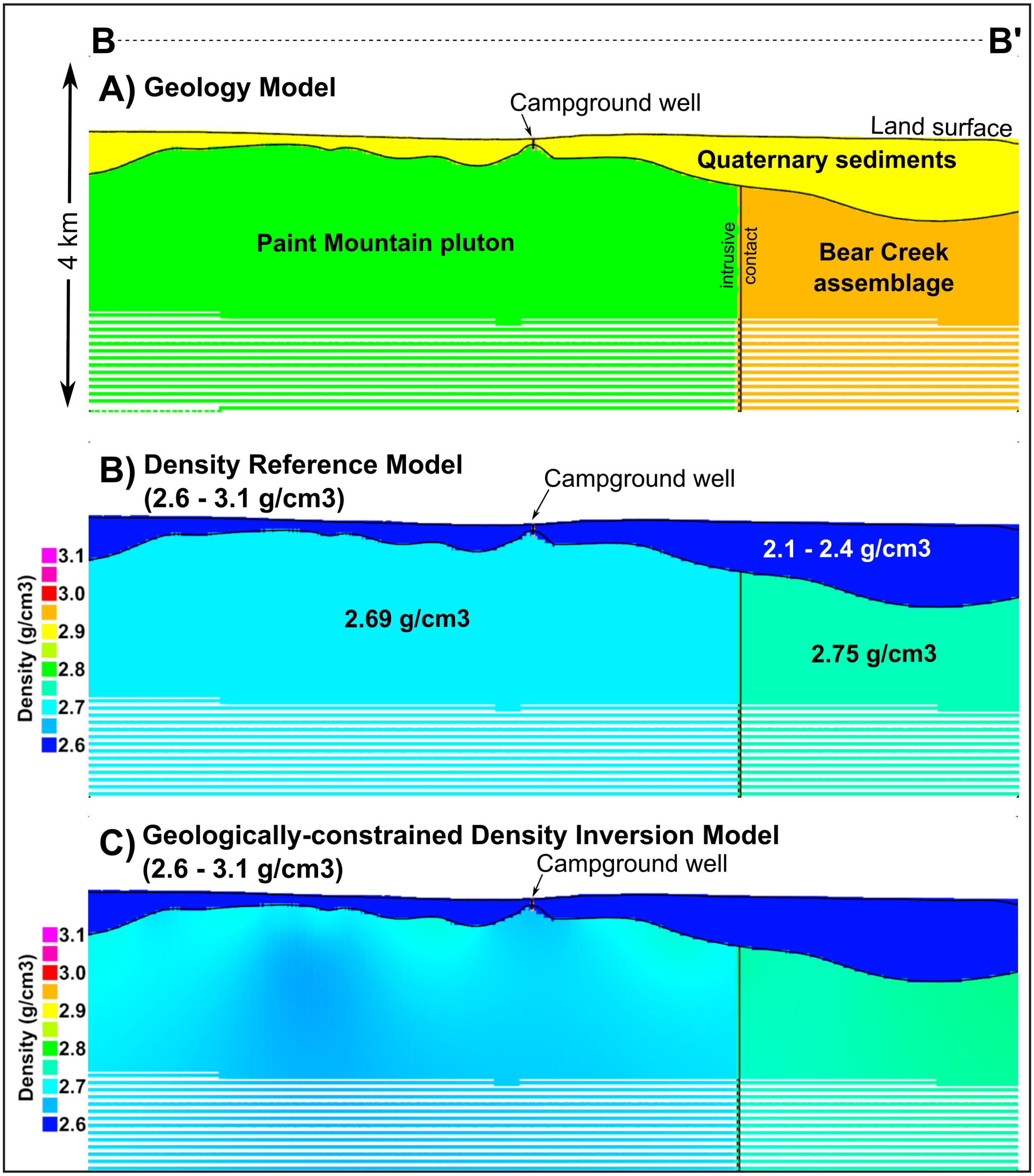

Figure 20. *Geology and density cross-sections along B-B' using the higher density colour ramp (2.6–3.1 g/cm^3).* ***a)*** *Reference geology model with rock units labeled.* ***b)*** *Reference rock density model used as a constraint in the modelling.* ***c)*** *Rock density distribution returned by 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 (2.6–3.1 g/cm^3) to visualize the higher density bedrock lithologies in the area. In this view, the match between the reference rock density model (b) and the inverted rock density model (c) is also good.*

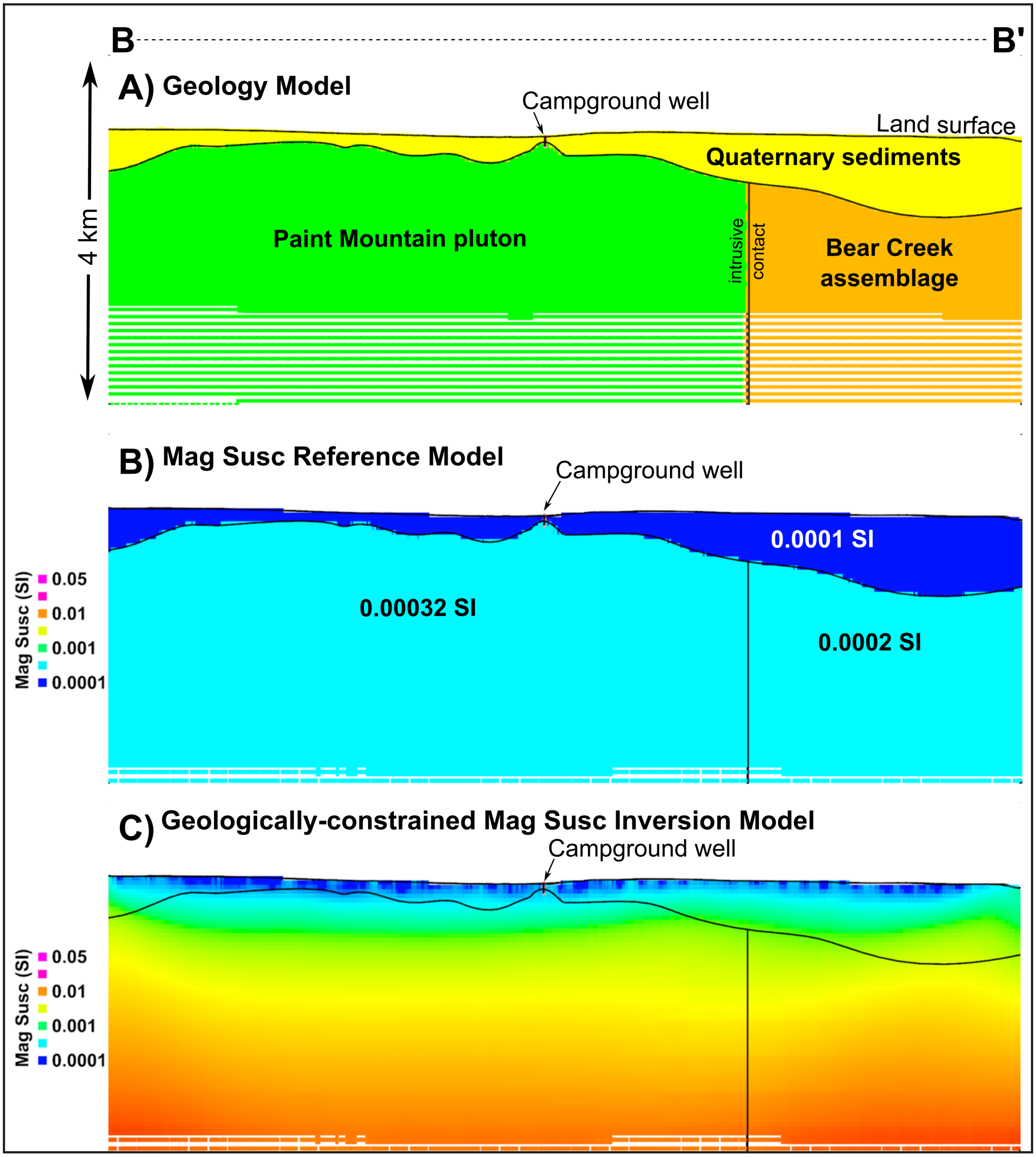

Figure 21. *Geology and magnetic susceptibility cross-sections along B-B'.* ***a)*** *Reference geology model with rock units labeled.* ***b)*** *Reference rock magnetic susceptibility model used as constraints on the modelling.* ***c)*** *Rock magnetic susceptibility distribution returned by the 3D magnetic inversion modelling that honours the magnetic survey data. A log scale is used for the magnetic susceptibility values to help better visualize the results. The match between the reference rock susceptibility model (c) and the inverted rock susceptibility model (d) is generally poor.*

Depth-to-bedrock model

The 3D geologic model results were used to construct a depth-to-bedrock map for the entire study area around the Village of Haines Junction (Fig. 22). This depth-to-bedrock map estimates the thickness of Quaternary sediments on top of the bedrock. Sediment thicknesses less than 10 m are unable to be discerned because that is the thickness of the smallest cell size used in the modelling. It should be noted that surficial geology mapping (Rampton and Paradis, 1981) shows that bedrock is exposed on top of Paint Mountain in an area which broadly correlates with the area identified in this study with a depth-to-bedrock of 0 m. Overall, the greatest thicknesses of sediment cover lies east and southeast of the centre of Haines Junction where the depth to the top of the bedrock reaches ~1200 m. Similarly, a broad area extending northwest of Haines Junction as far as the airport has a depth-to-bedrock of ~700 m. In the western corner of the study area, as well as the region around Paint Mountain and Pine Lake, the depth-to-bedrock is generally less than a few hundred metres. The uncertainties in the depth-to-bedrock calculations are estimated to be ±50 m in the near surface and up to ±200 m in the deepest parts of the Quaternary sediment pile.

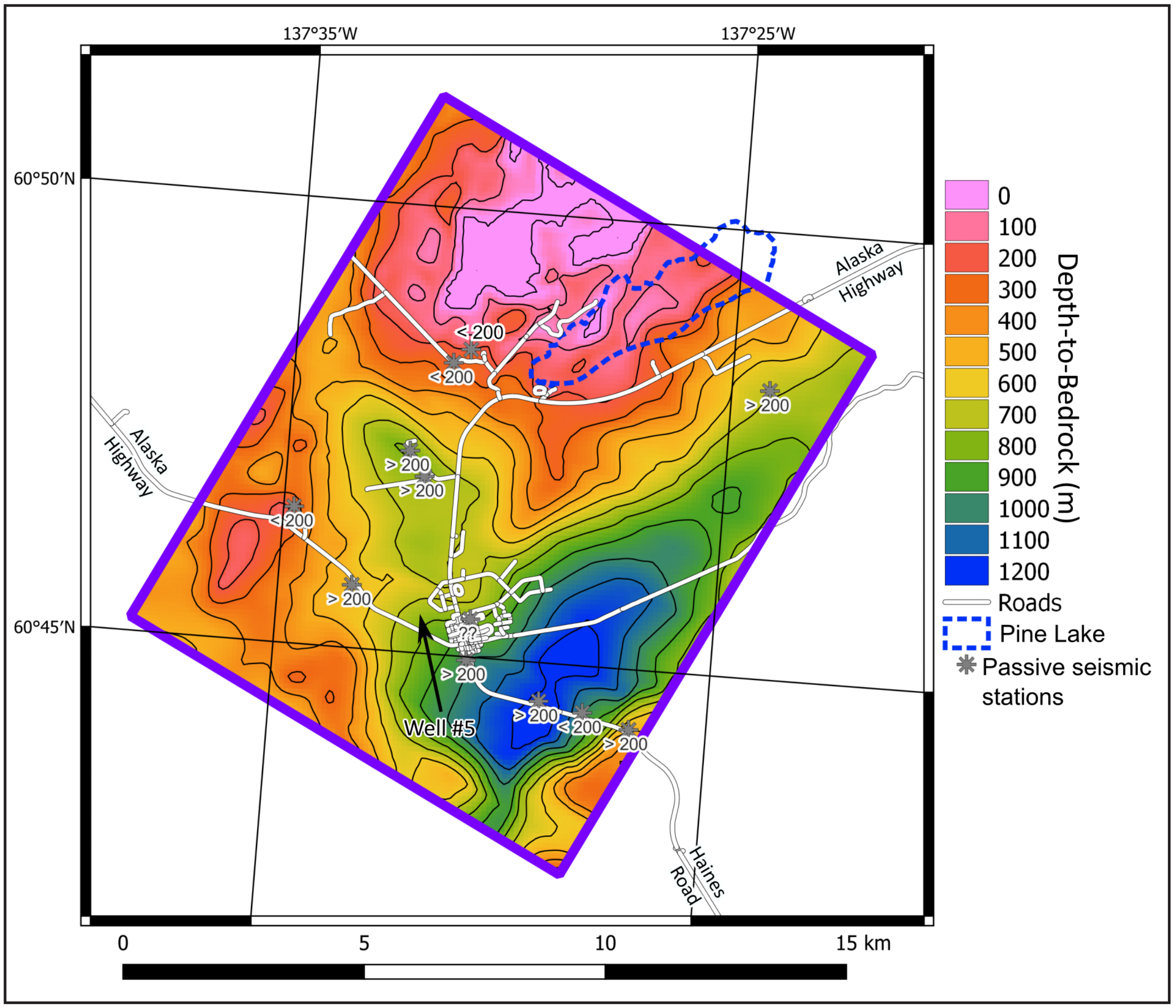

Figure 22. Depth-to-bedrock map for the Haines Junction area. The contour interval is 100 m. The locations of University of Calgary passive seismic stations are marked by grey asterisk symbols. Labels show stations which detected a seismic velocity change at a depth of less than 200 m and stations where a seismic velocity change was not detected suggesting the top-of-bedrock lies at a depth greater than 200 m. Overall, the passive seismic results largely agree with the depth-to-bedrock model.

Discussion – implications for geothermal resources

Temperature

Our understanding of subsurface temperatures in the Haines Junction area comes from multiple sources. Regional-scale heat flow measurements from southern Yukon and Curie point depth mapping both suggest elevated subsurface temperatures across a wide area. Within the study area, downhole temperature profile measurements from Well #5 and the Foothills CS-1 well both document elevated temperature gradients of 60–67 °C/km in the Quaternary sediments. From these results, it is reasonable to expect that the Quaternary sediments in the study area all have a relatively similar temperature gradient from the land surface down to the top of the bedrock. This means that subsurface temperature can be roughly predicted within the Quaternary sediments using the temperature gradient. For example, at a depth of 500 m in the Quaternary sediments, we would expect a temperature of 30–34 °C. Thus, if we can estimate the depth to the bottom of the Quaternary sediments (i.e., the top of the bedrock), then we can estimate the maximum temperature that could be reached in the Quaternary sediments.

Unfortunately, the temperature gradient within the bedrock has not been measured and is, therefore, not known. Thus, predicting the subsurface temperature at greater depths in the bedrock is difficult. The drilling of an exploratory borehole into bedrock would be needed to ascertain the temperature gradient at these depths below the Quaternary sediment pile.

Permeability

Rock permeability, the ability of fluid to flow through the rock, is an additional key requirement for a conventional (i.e., not engineered) geothermal system to be viable. Three types of subsurface permeability, fracture permeability, stratigraphic permeability, and permeability at intrusive contacts, are discussed here.

Fracture permeability

In many cases, geothermal systems are controlled by complex networks of faults and fractures in rock that allow hot geothermal fluids to ascend to shallow areas. Careful mapping of such geologic structures can help pinpoint the location of the geothermal system in the subsurface (e.g., Faulds and Hinz, 2015). Such an approach is difficult in the Haines Junction area, largely because fault structures in the bedrock are obscured by the glacial sediment cover. Similarly, it is difficult to map the fault structures in the study area using geophysical data because of a lack of rock property contrasts between rock units. One significant geologic structure, the Shakwak fault, has been identified in the study area, based upon previous geological mapping. However, this structure is oriented northwest-southeast, which is perpendicular to the direction of the regional compressional stress (northeast-southwest) which would tend to close any fractures in the Shakwak fault. As a result, the Shakwak fault has an orientation which is unfavourable for permeability to form. Lastly, due to the lack of rock property contrasts between the rock units on either side of the Shakwak fault, we were not able to identify any fault step-overs or other variations along strike of the fault which might indicate a zone of potential permeability.

Although we cannot rule out flow of geothermal fluids through fractured bedrock in the study area, we have no data to indicate if or where it might be occurring.

Stratigraphic permeability

An alternative to fracture permeability in geothermal systems is stratigraphic permeability. Stratigraphic permeability involves sub horizontal layers of porous and permeable rock, lying at a certain depth below the surface in which warm geothermal fluids could reside. Good examples of such rock types would be gravel, coarse-grained sandstone, and karstic carbonate rocks (e.g., limestone with portions of it dissolved away).

Well #5 proved stratigraphic permeability in the study area in the form of a 20 °C sand/gravel aquifer in the Quaternary sediment pile at a relatively shallow depth of ~350 m. Additional horizons of stratigraphic permeability are likely to exist within the Quaternary sediments, and the deepest stratigraphic horizons that have permeability would also be the hottest geothermal aquifers since temperature is expected to increase with depth according to the temperature gradient discussed earlier.

It is likely that parts of the Quaternary sediment pile consist of impermeable, fine-grained lake sediment (mud and silt) deposited in glacial lake Champagne that occupied the Dezadeash River valley during the last ice age. Higher permeability stratigraphic targets may exist below the fine-grained glacial lake sediments. For example, it is possible that the best permeability target in the stratigraphy could lie at the bottom of the Quaternary sediments and on top of the bedrock. The reason for this is that the first sediments to be deposited on top of the bedrock may have been coarse-grained material (i.e., sand and gravel) eroded from the nearby mountains. If this is true, then the areas where the top of the bedrock is the deepest are the target areas which could have elevated permeability and the highest temperature.

Permeability at intrusive contacts

Another area of potential subsurface permeability is the geologic contact between igneous intrusions and 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). Two rock units from the study area, the Paint Mountain pluton and the Pyroxenite Creek suite, are bounded by intrusive contacts. This study did not find any evidence for permeability at these intrusive contacts; however, it cannot be ruled out either. Unfortunately, the location of the boundary of the Paint Mountain pluton is imprecisely known because it is buried by glacial sediments and the edges are not sharply imaged by the geophysical data. In contrast, the location and orientation of the intrusive contact of the Pyroxenite Creek unit has been corroborated by both the gravity and magnetic survey data. This contact has an orientation which is parallel to the regional compressional stress (northeast-southwest). In this orientation, existing fractures would not tend to be pressed shut. Therefore, the intrusive contact of the Pyroxenite Creek suite has a favourable orientation for permeability.

Proposed drilling areas

An important outcome of the geoscience data analysis and modelling performed here is that a number of areas have been identified where exploratory geothermal wells could be drilled (Fig. 23). All of the areas proposed target hypothesized porous and permeable layers of coarse sediment (i.e., sand/gravel) within the Quaternary sediment pile that lies above bedrock. None of the areas target faults or fractures in bedrock due to a lack of favourable indicators for such targets. All of the target areas selected have the following characteristics:

- the depth-to-bedrock is > 500 m;
- road access is nearby;
- located outside of the meandering channels of the Dezadeash River; and
- located outside of Kluane National Park.

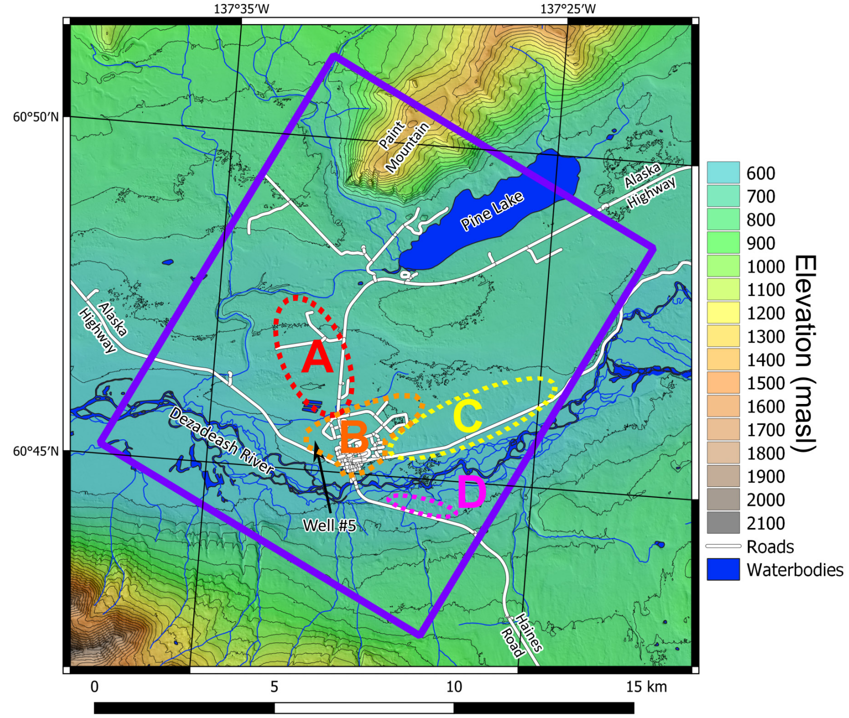

Figure 23. *Map showing the locations of proposed drilling areas. See text for discussion.*

A description of each area is presented here and summarized in Table 3. All geothermal aquifer temperature estimates assume a temperature gradient of ~60 °C/km.

Area A: This area extends from the airport to the north end of the village and is characterized by a depth-to-bedrock of 700 to 800 m. A geothermal aquifer located at the top-of-bedrock would have an expected temperature of 42–48 °C.

Area B: This area covers the Village of Haines Junction proper and is characterized by a depth-to-bedrock of 650 to 1000 m. Geothermal aquifers located at the top-of-bedrock under the village would be expected to have temperatures of 39–60 °C with the higher-temperature aquifers located on the southeast side of the village. The Haines Junction municipal water well #5 is located within Area B.

Area C: This area extends east of Haines Junction along Marshall Creek Road and is characterized by a depth-to-bedrock of 800 to 1200 m. Geothermal aquifers at the top-of-bedrock in this area have expected temperatures of 48–72 °C with the highest temperatures on the south side of Marshall Creek Road.

Area D: This area is located on the north side of Haines Road and on the south side of the Dezadeash River. It is characterized by the greatest values of depth-to-bedrock in the study area which are 1150 to 1225 m. Expected temperatures at the top-of-bedrock in Area D are 69–74 °C.

Table 3. Summary of the depth to top-of-bedrock and temperature at top-of-bedrock for the four proposed drilling areas.

	Expected depth to top-of-bedrock	Expected temperature at top-of-bedrock
Area A	700 – 800 m	42 – 48 °C
Area B	650 – 1000 m	39 – 60 °C
Area C	800 – 1200 m	48 – 72 °C
Area D	1150 – 1225 m	69 – 74 °C

Direct use geothermal applications that could be pursued based upon the expected fluid temperatures listed above include geothermal heat pumps, aquaculture, hot tubs, snow melting and de-icing, greenhousing, building heating, water heating and food drying.

Key questions that may be answered by an exploratory drilling program at any of the proposed target areas include:

a. How thick is the sediment cover at the proposed drill site?

b. What is the temperature at the top of the bedrock?

c. What is the temperature gradient and heat flow?

d. What is the stratigraphy of the sediments in the Quaternary sediment pile?

e. How abundant are the intervals of permeable, coarse sediments within the Quaternary sediment pile?

f. What is the temperature of the aquifers found in the coarse intervals of the Quaternary sediment pile?

g. Do the sediments that lie immediately on top of the bedrock surface consist of coarse material eroded from the nearby ranges or fine-grained, impermeable lake sediments?

h. What type of bedrock underlies the sedimentary materials and is it fractured/permeable?

i. 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)?

Answers to these questions are important to obtain because they will have significant implications for the scale of future development of geothermal resources at Haines Junction.

Conclusions

This study analyzed and interpreted an array of geoscience data near the Village of Haines Junction (Dakwäkäda) in southwestern 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 Haines Junction has arisen due to: a) the previous discovery of a warm geothermal aquifer at municipal Well #5 in the village; b) a desire to reduce the dependence on fossil fuels used for heating purposes by the residents of Haines Junction; and c) multiple lines of evidence supporting above-average temperature gradients in the near-surface sediments of the study area. Key geoscience datasets interpreted in this study include bedrock geology maps, surficial geology maps, fault maps, rock properties, gravity data, magnetic survey data, audiomagnetotelluric data, lidar topographic data, as well as water well data.

A map-based interpretation of these data identified two possible fault structures that run sub parallel to the Shakwak fault. The 3D geologically constrained modelling of gravity and magnetic data helped to define the 3D geometry of two of the major rock units in the study area (i.e., Quaternary sediments and Pyroxenite Creek suite). Unfortunately, many of the other rock units had similar rock property values (i.e., density and magnetic properties) which made it difficult to distinguish one bedrock unit from another using gravity and magnetic survey data.

An important outcome of the 3D geoscience modelling in this study is the characterization of the thickness of the Quaternary sediments (i.e., depth-to-bedrock) across the Haines Junction area. We identified the areas with the greatest depth-to-bedrock to help target the highest temperature areas at the bottom of the Quaternary sediments where coarse, permeable sediments may be found. Four areas around the village have been identified.

The recommended drilling depth to reach bedrock and test the permeability of Quaternary sediments that lie immediately above bedrock varies between 650 m and 1225 m. The expected subsurface temperature at those depths is 39 °C and 74 °C, respectively. If permeable geothermal aquifers are encountered at these depths, there are many ways to directly use the warm geothermal water to benefit the Village of Haines Junction (Dakwäkäda).

Recommendations for future work

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. The drilling of a new well all the way to bedrock in the Haines Junction area would answer many questions about the subsurface. Further geoscience data collection and analysis that would be helpful to better understand the subsurface in the Haines Junction area include:

1. Collection of airborne Z-axis Tipper Electromagnetic (ZTEM) data would provide full data coverage of the Haines Junction study area (including difficult to access areas far from roads). The ZTEM data could be modelled with the existing AMT data to generate a more detailed 3D resistivity model of the study area. Such a resistivity model may be able to help better define the distribution and thickness variations of the Quaternary sediment layer. For example, it may be possible to differentiate glacial till, fine-grained lake sediments, and coarse-grained sand/gravel based upon their resistivity characteristics.
2. Passive seismic studies may be helpful as an additional technique to estimate the depth-to-bedrock and also detect microseismic events along faults in the study area.
3. Additional geologic mapping and rock property data collection at outcrops that lie immediately west of the Haines Junction study area would help to better refine our understanding of bedrock geology.

Acknowledgements

This project benefited greatly from discussions with Maurice Colpron about bedrock geology and structure of southern Yukon; Cedar Hanneson about the Haines Junction AMT survey and resistivity model; and Jan Dettmer about passive seismic studies in the study area. Special thanks to Maurice Colpron for helpful reviews of this report which improved the text. We also thank the Champagne and Aishihik First Nation for this opportunity to work on this interesting project on their Traditional Territories. Special thanks to Parks Canada for giving permission to collect some of the gravity data within Kluane National Park (Research and Collection Permit #KLUNPR-2023-45464).

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Appendix 1: Haines Junction gravity data and report; Aurora Geosciences

This appendix is only available digitally. The files are included in a .zip file that accompanies this report, and are available from https://data.geology.gov.yk.ca

Appendix 2: Additional geoscience data files

This appendix is only available digitally. The files are included in a .zip file that accompanies this report, and are available from https://data.geology.gov.yk.ca

All .shp, .dxf, and .tif files, as well as 3D block models in .txt file format are georeferenced to UTM NAD83 zone 8 (EPSG: 26908).

Appendix 3: 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 nineteen 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.

Dr. J. B. WITTER
36004

Jeffrey B Witter

Dated in Vancouver, British Columbia, Canada this 31st day of March 2024

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

Yukon Geological Survey
Energy, Mines and Resources
Government of Yukon