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Geoscience BC

Geoscience BC Peace Project:

FINAL REPORT

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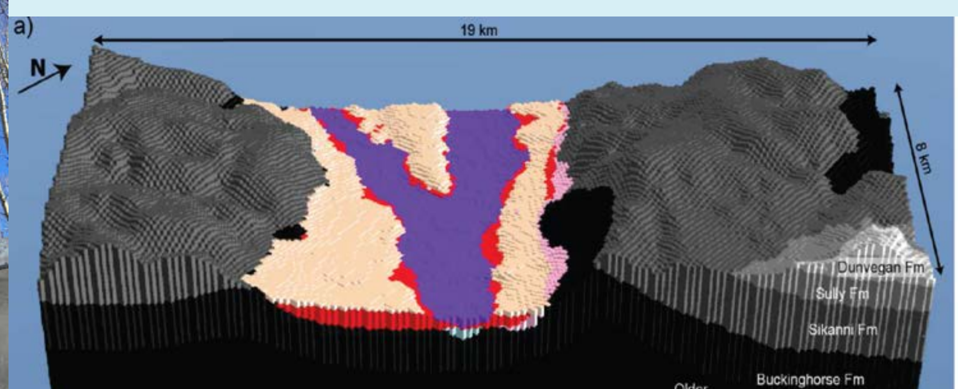

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Executive Summary

The Peace Project was initiated in 2015 by Geoscience BC to improve the understanding of groundwater resources in the Peace Region of Northeast British Columbia. Knowledge of groundwater resources and the distribution of aquifers in the Peace Region is critical for water management, especially given ongoing natural gas development in the area. Such knowledge will enable more informed decision making surrounding responsible groundwater use by the Province, the regulator, energy companies, First Nations and local communities.

The main purpose of the Peace Project was to provide a regional overview of the Quaternary sediments and shallow bedrock geology of the region, and to locate potential aquifers, particularly within buried valleys delineated in the study area. The overall project goals were to: (1) acquire and interpret geophysical data to learn more about groundwater in the Peace region; (2) generate baseline information to guide the use and protection of groundwater in the region; and, (3) freely provide baseline information to First Nations, communities, government and industry to help make informed groundwater management decisions. To meet these objectives, several studies were conducted within the Peace Region, specifically in a study area north of the Peace River. These studies ranged from local to regional scale investigations of the geology, hydrogeology, or combination of the two. The results and interpretations of these studies were then used to provide new insights into the Quaternary geology and an improved understanding of the distribution of aquifers within the Peace Project study area.

The Quaternary sediments of the Peace Region are interpreted to be lithologically heterogeneous across all scales of investigation, and the thickness of the Quaternary sediments is variable; however, the Quaternary fill is generally thick within the outlines of the mapped buried valleys. Permeable deposits are interpreted to exist within the buried valleys, although they were not found to be regionally continuous throughout the whole buried valley network. Nevertheless, locally extensive permeable deposits within the buried valleys appear to exist at smaller scales. Therefore these localized buried valley aquifers may offer a viable groundwater source for low demand users.

A number of factors, in addition to geology, were found to be important when evaluating the resource potential of buried valley aquifers, in particular, connection to recharge sources and hydraulic connections to surface water bodies. The potential

water quantity needs of the aquifer, such as for industrial or private use, should also be considered when evaluating the resource potential.

Additional geophysical surveys, hydrogeological investigations, and extension studies are recommended when there is a need to further improve local Quaternary aquifer knowledge of the study area, and the recommendations may be applicable for improving bedrock aquifer knowledge as well. These recommendations include seismic refraction and ground-based electrical surveys, additional drilling, and further airborne electromagnetic surveys south of the Peace River.

The Peace Project was supported by a number of partners from government, industry, and academia. Results and data collected from this project are freely available as part of Geoscience BC's directive, and provide critical baseline information for future groundwater research.

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1. Introduction

1.1. Background

The Peace Project was initiated by Geoscience BC (GBC) in 2015 to acquire, interpret, and share new baseline scientific information about groundwater resources in the Peace Region of Northeast British Columbia (NEBC) (Figure 1). Knowledge of groundwater resources across NEBC is limited, particularly at a regional scale. While some regional scale groundwater studies have been completed (e.g. Lowen, 2011; Baye et al., 2016), information on regional groundwater resources, particularly north of the Peace River, is lacking.

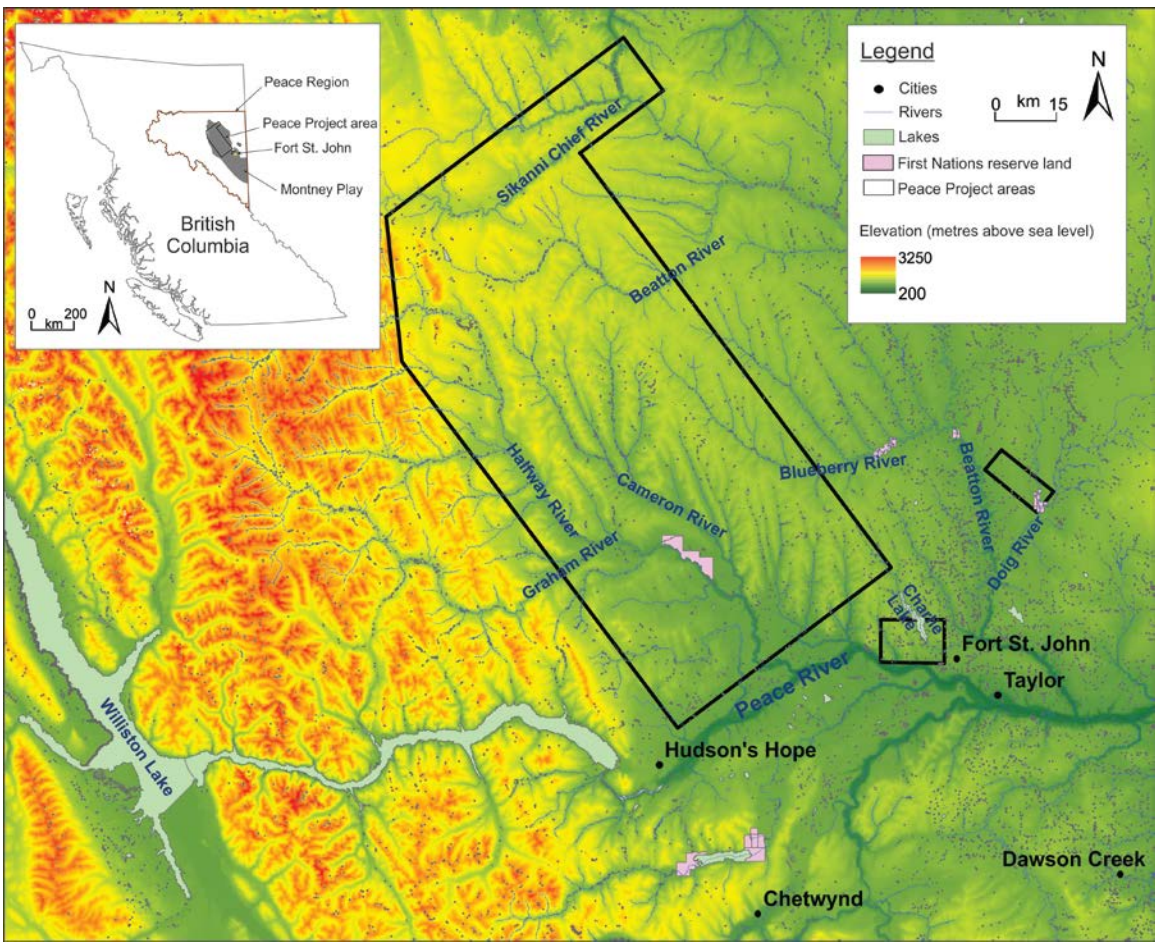

Figure 1. Regional map of the Peace Project area. The major cities, rivers, lakes, and First Nations reserve lands in the Project area are shown. Inset map shows the location of the Peace Project area in relation to the Peace Region of Northeast BC, as well as to the Montney Play trend (grey shaded area).

Knowledge of the groundwater resources in the Peace Region is critical for water management in relation to the use and protection of groundwater. Such knowledge is particularly important given the extensive shale gas development in the region, which is currently focused on the Montney play (Figure 1), an area of enormous natural gas potential[1]. Given ongoing natural gas development, furthering our understanding of shallow groundwater resources will enable more informed decision making surrounding responsible groundwater use by the Province, the regulator, energy companies, First Nations and local communities.

1.2. Study Area

The Peace Project study area covers an area of approximately 9,600 km^2, and is located north of the Peace River (Figure 1). Within the broader Peace Region, the terrain is generally low-relief with thick deposits of glacial drift and extensive forest cover (Levson, 2008). The major river is the Peace, which drains an area of approximately 122,000 km^2 within British Columbia (BC). The headwaters of the Peace River are located in the Rocky Mountains, and the river flows to the east into Alberta. Other major river systems within the Peace Project study area include the Sikanni Chief, Beatton, Blueberry, Halfway, Cameron, and Graham rivers (Figure 1).

1.2.1. Bedrock and Surficial Geology

The shallow bedrock geology of the Peace Project study area comprises Cretaceous sedimentary rocks that outcrop at surface or directly underlie surficial sediments in the study area. The uppermost bedrock unit is the Upper Cretaceous age Dunvegan Formation sandstones and shales. Underlying the Dunvegan Formation are the Lower Cretaceous Sully shales, Sikanni sandstones and Buckinghorse shales, which comprise the Fort Saint John Group. Because the bedrock regionally dips slightly to the southwest and underwent differential erosion, the uppermost bedrock unit varies across the study area. A simplified cross-section of the bedrock stratigraphy is shown in Figure 2.

[1] The National Energy Board (NEB) estimates that "the thick and geographically extensive siltstones of the Montney Formation are expected to contain 12,719 billion m^3 (449 Tcf) of marketable natural gas, 2,308 million m^3 (14,521 million barrels) of marketable natural gas liquids (NGLs), and 179 million m^3 (1,125 million barrels) of marketable oil."

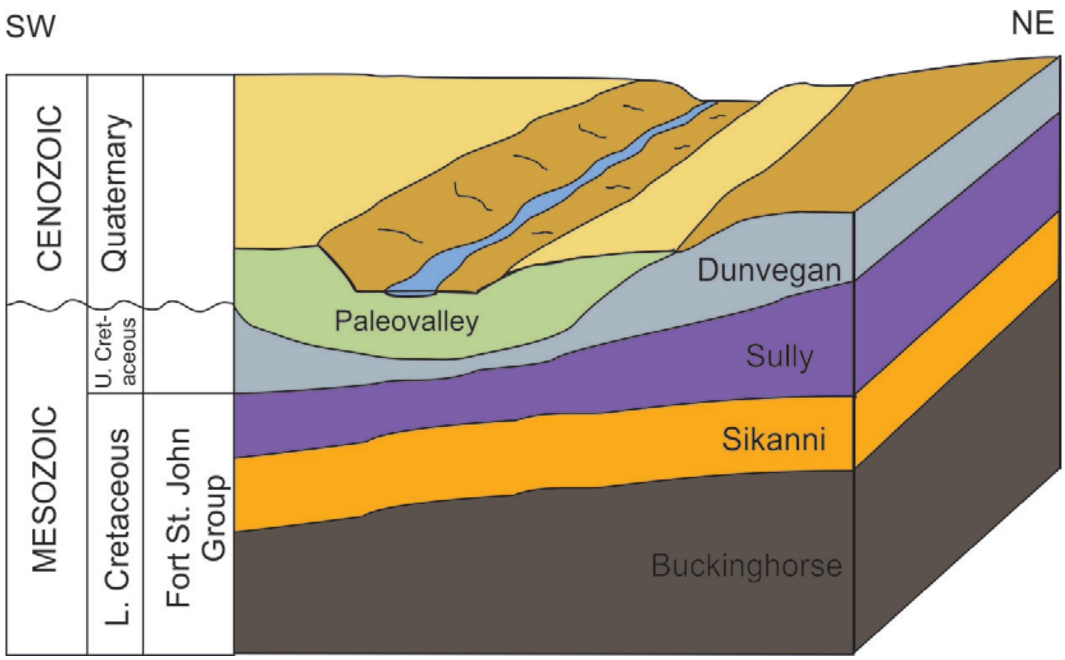

Figure 2. **Simplified cross-section of the shallow Cretaceous bedrock formations in the Peace Project study area. A hypothetical paleovalley eroded into the Dunvegan Formation is also shown.**

Overlying the bedrock are Quaternary age sediments comprising glaciolacustrine silts and clays, glaciofluvial sands and gravels, and till. Paleovalleys formed during both pre-glacial and glacial times were subsequently filled with these sediments (Figure 2). As this fill is more easily erodible than bedrock, the valley-fill deposits may have also been further eroded, and ultimately further filled and then buried during the Late Quaternary by processes such as aggradation. As a result, in many areas, these valleys have little to no surface expression due to thick accumulations of Quaternary sediments.

1.2.2. Groundwater Resources in the Peace Region

The Peace Region is comprised of both deep and shallow aquifers. Deep aquifers are considered to be permeable bedrock formations typically located at depths greater than 600 metres[2]. Deep aquifers contain non-potable water and are used primarily for wastewater disposal[3]. Shallow aquifers are those permeable units located at depths

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[2] Deep aquifers may be located at depths greater than 300 m if the aquifer lies below the "Base of Fish Scales" marker bed (BCOGC, 2016). This marker bed is "an identifiable stratus that demarcates the boundary between the sedimentary rocks of the Lower Cretaceous Age from sedimentary rocks of the Upper Cretaceous Age" (BCOGC, 2016)

[3] Recently, deep aquifers have been used for water sourcing by industry (BCOGC, 2017).

generally less than 600 m. These aquifers can be comprised of either unconsolidated sediments or bedrock, and generally yield potable groundwater.

There have been very few regional hydrogeological investigations in the Peace Region; however, two notable studies include Lowen (2011) and Baye et al. (2016). Lowen (2011) identified, classified, and delineated developed aquifers in the Peace Region, mapping a total of 55 aquifers; 23 bedrock aquifers and 32 comprised of unconsolidated sediments. The highest yielding bedrock wells are those completed in the Dunvegan Formation. Aquifers comprised of unconsolidated sediments are located primarily along modern river valleys, with the most productive water wells completed in glaciofluvial deposits. Baye et al. (2016) undertook a collaborative study with the objective of gaining a better understanding of groundwater in the Dawson Creek-Groundbirch area. Various datasets were integrated to characterize aquifers in the area (south of the Peace River), including available water well information, private well survey data, core drilling data, water chemistry, drilling, pumping test analyses, and monitoring data from observation wells.

Several studies have documented the existence of buried valleys (or paleovalleys) in the Peace Region (e.g. Mathews, 1978; Levson et al., 2006; Hartman and Clague, 2008; Hickin et al., 2016), and it has been suggested that sand and gravel deposits within these paleovalleys, such as basal deposits in the valley thalwegs, could potentially represent significant sources of groundwater (Cowen, 1998). However, their sedimentological architecture, role in regional groundwater flow, and potential connection with surface water bodies, were largely unknown.

With the limited groundwater data in NEBC, the BC Government is currently focusing on mapping aquifers where large numbers of water wells exist (e.g. in and around towns/cities). Although aquifers can be delineated through drilling, this is time consuming and cost prohibitive from a regional mapping perspective. Additionally, with the structural complexity of buried valleys, it becomes impractical to rely solely on point data. Therefore, a more cost effective approach is to carry out regional geophysical surveys, supported by existing surface and subsurface data, to delineate buried valleys and shallow aquifers.

1.3. Project Goals and Scope of Work

The main purpose of the Peace Project was to provide a regional overview of the Quaternary and shallow bedrock geology of the study area, and to locate potential aquifers within NEBC's northern Montney Gas Fairway. The overall project goals were to: (1) acquire and interpret geophysical data to learn more about groundwater in the Peace region; (2) generate baseline information to guide the use and protection of groundwater in the region; and, (3) freely provide baseline information to First Nations, communities, government and industry to help make informed groundwater management decisions. In order to accomplish these goals and objectives, the following scope of work was completed:

1. Fly an airborne electromagnetic (AEM) geophysical survey over a 9,600 km^2 section of the Peace region between Hudson's Hope, Charlie Lake, and Pink Mountain to gather information on the resistivity of the shallow subsurface.

2. Gather geological and geophysical data from the shallow intervals of petroleum wells in the region, and correct (normalize) the available gamma-ray logs that were collected through the cased interval near surface.

3. Drill shallow wells at eight locations throughout the Peace project area to calibrate the geophysical data, with the primary objective of verifying the geological interpretation of the AEM and gamma-ray data.

4. Use the collected data to interpret the Quaternary sediments and depth to bedrock, determine the petrophysical characteristics, and construct 2D and 3D geological and hydrogeological models.

5. Use the collected data to identify potential aquifers that may provide groundwater supplies for First Nation areas.

The purpose of the present report is to summarize the key findings of the Peace Project. The scope of work described above was completed through a number of studies carried out under the auspices of the Peace Project, which are referenced in this report. Table 1 shows a list of the various reports, all of which can be accessed from the Peace Project website: http://www.geosciencebc.com/s/PeaceProject.asp.

Table 1. **List of reports from studies conducted under the auspices of the Peace Project. All reports can be accessed from the Peace Project website: http://www.geosciencebc.com/s/PeaceProject.asp.**

Author & Date	**Report**
SkyTEM Surveys ApS (2015)	SkyTEM survey: British Columbia, Canada, Data report. Geoscience BC, Report 2016-03, 62 pp.
Petrel Robertson Consulting Ltd. (2015)	Interpretation of Quaternary sediments and depth to bedrock through data compilation and correction of gamma logs. Geoscience BC, Report 2015-04, 24 pp.
Aarhus Geophysics ApS (2016)	a. Processing and inversion of SkyTEM data. Charlie Lake Area- Phase 1. Geoscience BC, Report 2016-09b, 28 pp.
	b. Processing and inversion of SkyTEM data. DOIG Area- Phase 1. Geoscience BC, Report 2016-09c, 27 pp.
	c. Processing and inversion of SkyTEM data. Peace River “Conoco” Area- Phase 2. Geoscience BC, Report 2016-09d, 33 pp.
	d. Processing and inversion of SkyTEM data. Peace River Main Area- Phase 1. Geoscience BC, Report 2016-09a, 28 pp.
	e. Processing and inversion of SkyTEM data. Peace River “Sikanni” Area- Phase 2. Geoscience BC, Report 2016-09e, 27 pp.
Bemex Consulting International and Quaternary Geosciences Inc. (2016)	Peace area project – well selection for testing geological model based on gamma and airborne electromagnetic (AEM) studies. Geoscience BC, Report 2016-18, 42 pp.
Jørgensen et al. (2016)	Structural geology of folded terrain in the Rocky Mountains’ foothills interpreted from SkyTEM, Geological Survey of Denmark and Greenland Report 2016/34, 21 pp.
Levson and Best (2017)	a. North-east BC sonic drilling project physical log descriptions and interpretations. Geoscience BC, Report 2017-16, 35 pp.
	b. Summary report on proposed water well locations for Halfway River First Nation area. Geoscience BC, Report 2017-17, 21 pp.
Best and Levson (2017)	Peace area project- comparison of resistivity, gamma, and geological logs with airborne EM inversions. Geoscience BC, Report 2018-08, 27 pp.
Mykula (2017)	Petrophysical interpretation on six shallow wells in the Peace Region of BC. Geoscience BC, Report 2017-18, 7 pp.
Aarhus Geophysics ApS and GEUS (2017)	Processing and inversion of SkyTEM data. Peace River North-Western Area, Geoscience BC, Report 2018-06, 40 pp.
Hall et al. (2017)	Peace Region Project Doig block and Charlie Lake Cross Sections. Simon Fraser University, unpublished report, 10 pp.
Morgan (2018)	Investigating the role of buried valley aquifer systems in the regional hydrogeology of the Central Peace Region in Northeast British Columbia. (MSc Thesis). Simon Fraser University, Burnaby, Canada, 191 pp.

1.4. Partnerships

The Peace Project was supported by a number of partners including the Ministry of Forests, Lands and Natural Resource Operations and Rural Development, the Ministry of Environment & Climate Change Strategy, the BC Oil & Gas Commission, the Ministry of Energy, Mines, & Petroleum Resources, Progress Energy Canada Ltd., ConocoPhillips Canada, Northern Development Initiative Trust, and the BC Oil & Gas Research and Innovation Society. The Project had additional support from the Peace River Regional District and the Canadian Association of Petroleum Producers, and was one of the projects supported by the Northeast Water Strategy[4]. The Project also involved collaboration with Simon Fraser University, the University of British Columbia, Quaternary Geosciences Inc., Bemex Consulting International, Aarhus Geophysics ApS, Petrel Robertson Consulting Ltd., SkyTEM Surveys ApS, and the Geological Survey of Denmark and Greenland.

2. Project Data Collection Overview and Produced Data

This section provides an overview of the methodology for the collection of data that were produced as part of the scope of work outlined in section 1.3. Figure 3 shows the outline of the Peace Project area, and identifies the different blocks in which data were collected. Figure 4 is a flow chart illustrating the various project tasks and data surveys that were carried out, and acts as an outline for the following subsections.

[4] Information on the Northeast Water Strategy can be found on the website: https://www2.gov.bc.ca/gov/content/environment/air-land-water/water/water-planning-strategies/northeast-water-strategy

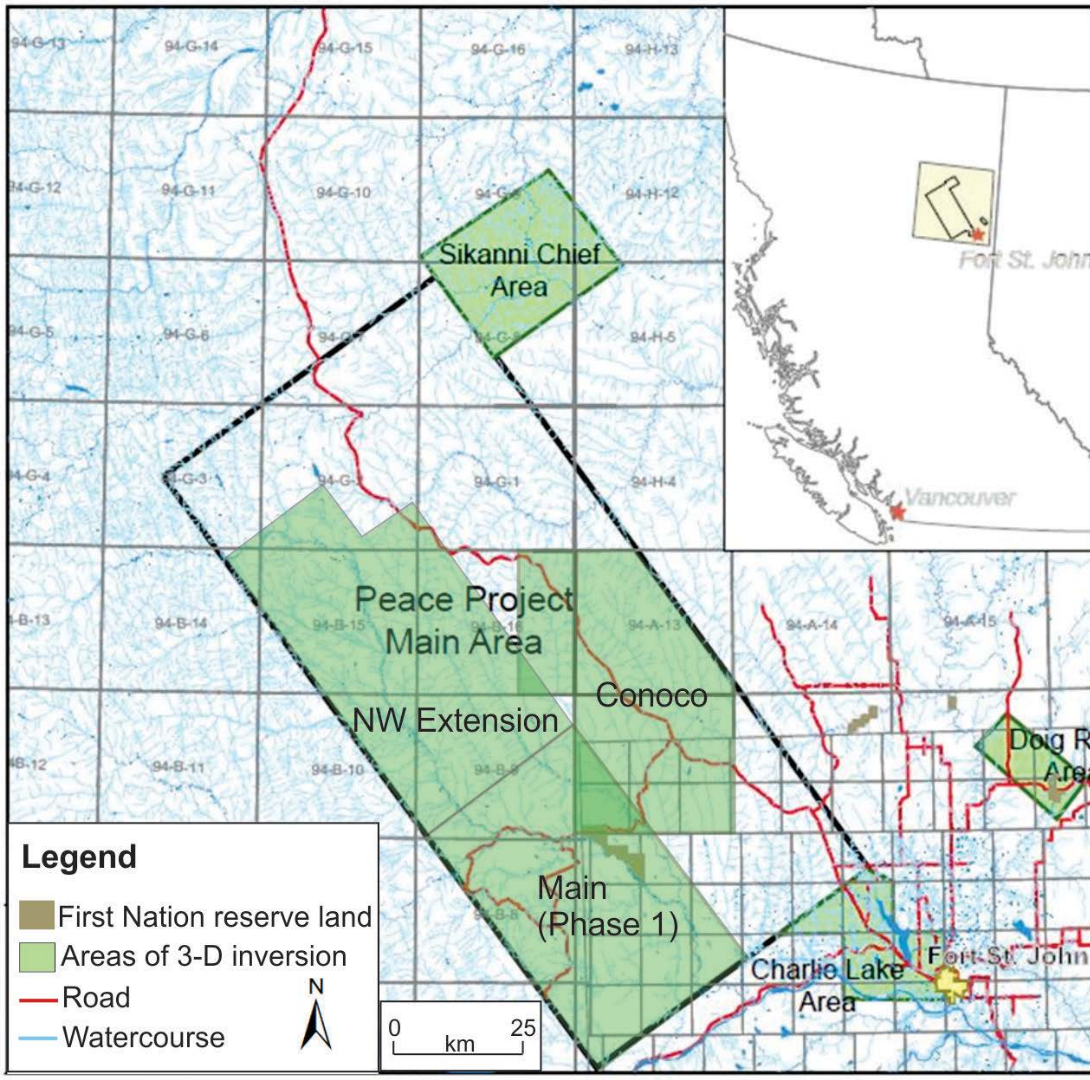

Figure 3. **Peace Project area outline identifying the six sub-areas (blocks). These blocks also correspond to the areas where Aarhus Geophysics ApS (2016a-e) and Aarhus Geophysics ApS and GEUS (2017) performed 3D inversion (see section 2.1 below). Modified from Petrel Robertson Consulting Ltd. (2015).**

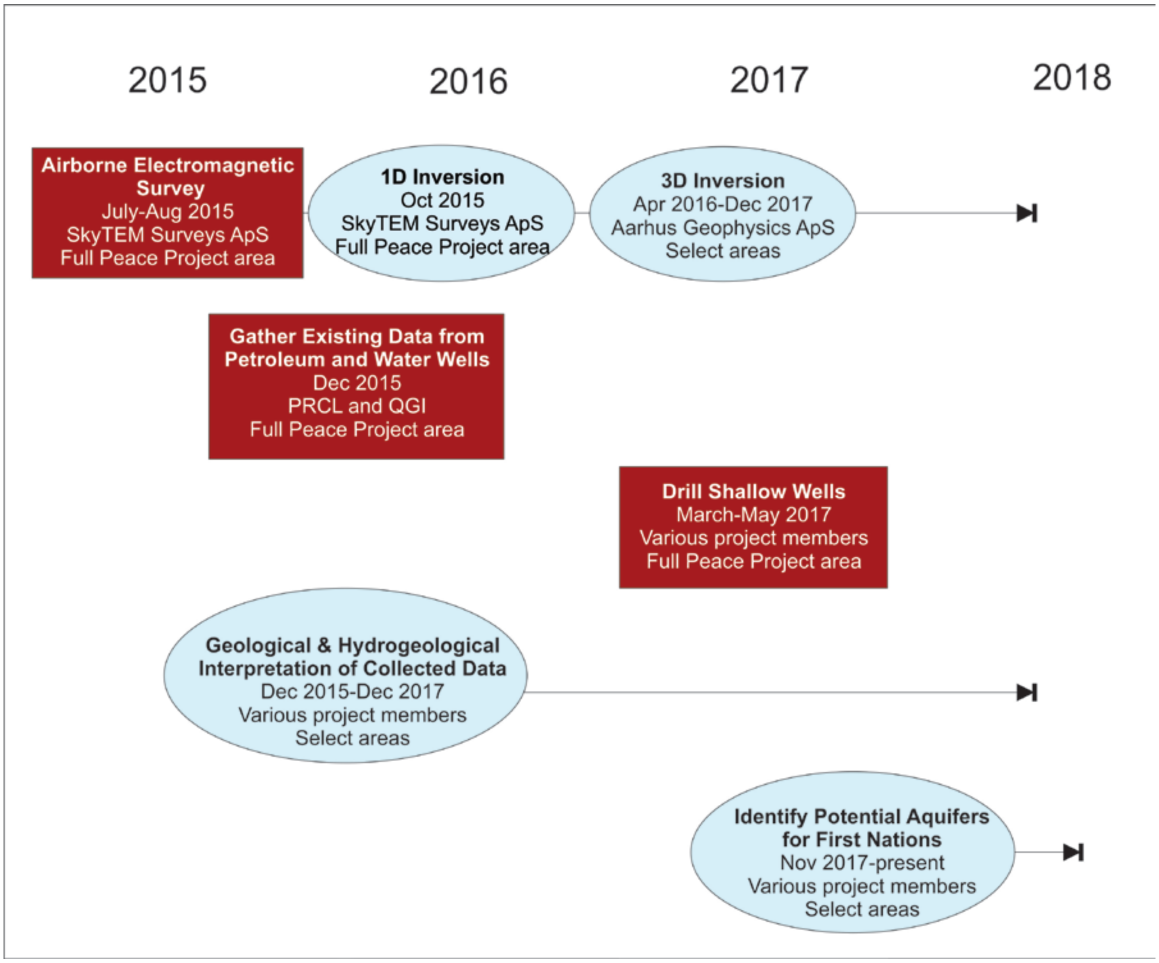

Figure 4. **Timeline and flow chart identifying the various project tasks/data surveys. Items in red rectangles are data surveys and items in blue ellipses are further interpretation studies on the collected data.**

2.1. SkyTEM Survey

During July and August 2015, a helicopter completed a large airborne electromagnetic (AEM) geophysical survey, known as a SkyTEM survey, over a 9,600 km^2 section of the Peace Region between Hudson's Hope, Charlie Lake, and Pink Mountain. In SkyTEM surveys, a large transmitter loop is suspended below the helicopter and, using a car battery, the loop induces an electric current into the ground. A receiver loop then detects the induced current, which will vary depending on how well the rocks, sediment, and water below the Earth's surface conduct electricity. AEM techniques can detect variations in the conductivity of the ground to a depth of several hundred metres.

The SkyTEM survey for the Peace Project was performed by SkyTEM Surveys ApS, and consisted of a total 20,999 line kilometres: 20,337 km in the Main Peace block, 425 km in the Doig block, and 237 km in the Charlie Lake block (Figure 2). Figure 5 shows the flight lines (approximately 600 m spacing) for the SkyTEM survey.

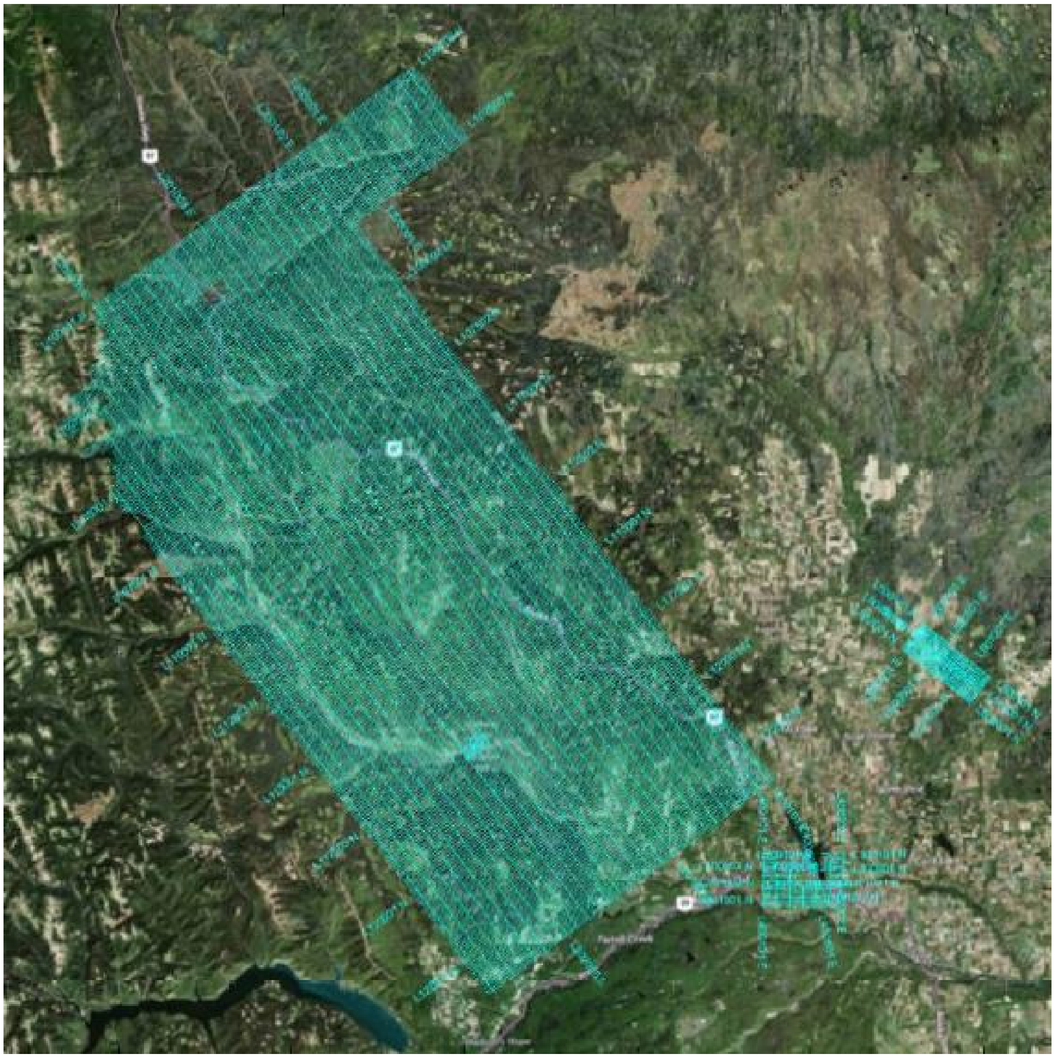

Figure 5. Flight lines for SkyTEM survey (blue lines). From SkyTEM Surveys ApS (2015).

The raw AEM data collected from the SkyTEM survey had to be converted to be used in geological interpretation. This conversion process is known as geophysical inversion, which essentially estimates the physical properties of the subsurface (here, resistivity, which is the inverse of electrical conductivity) based on the raw data obtained from the survey. This process has associated uncertainties, as various inversion schemes can be used, leading to different interpretations of the resistivity distribution. Notwithstanding these uncertainties, the resultant dataset is very useful for regional geological studies due to its large spatial coverage.

Geophysical inversion can be performed in 1-dimension (1D), 2-dimensions (2D), or 3-dimensions (3D). For 1D inversion, the simplest form of inversion, the subsurface sediments are considered to be layered; therefore, there are variations with depth, but no variation in the horizontal directions. In 2D inversion, the subsurface sediments are considered to vary with depth and in one of the horizontal directions, and in 3D inversion, the subsurface sediments are considered to vary in all directions. In glaciated terrain where Quaternary lithology is likely heterogeneous, an inversion scheme which considers the sediments to vary in all directions (i.e. 3D) is preferable.

1D inversion was performed on the data collected by SkyTEM Surveys ApS for the entire project area (see Figure 3), and 3D inversion was performed by Aarhus Geophysics ApS for specific areas within the Peace Project area (see Figure 3). The depth of investigation for the 1D and 3D resistivity inversions ranges from 200 – 300 m. For more details on the geophysical inversion and data processing, refer to SkyTEM Surveys ApS (2015), Aarhus Geophysics ApS (2016a-e), and Aarhus Geophysics ApS and GEUS (2017).

2.1.1. Produced Data

The interpretations produced from the SkyTEM survey are presented as either 1D (SkyTEM Surveys ApS) or 3D (Aarhus Geophysics ApS) horizontal depth slices of resistivity distribution, and vertical resistivity sections. Figure 6 shows examples of the 1D data, and Figure 7 shows examples of the 3D data. The full suite of all available resistivity slices and sections from SkyTEM Surveys ApS (2015), Aarhus Geophysics ApS (2016a-e), and Aarhus Geophysics ApS and GEUS (2017) are available on GBC's Peace Project website (http://www.geosciencebc.com/s/PeaceProject.asp).

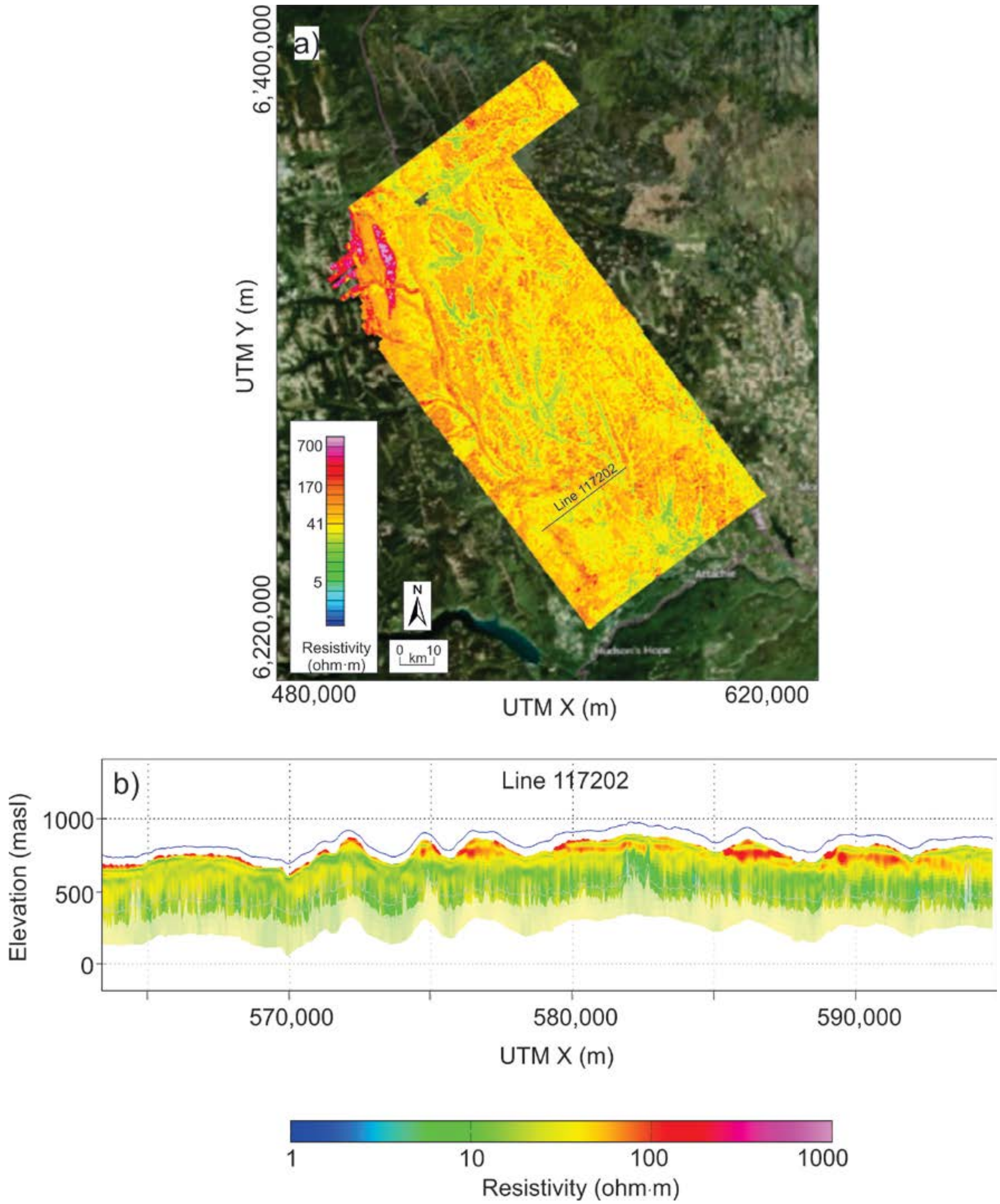

Figure 6. **Interpretation results of the 1D inversion of AEM data collected from the SkyTEM survey for the Peace Project Main Area derived from laterally constrained inversion. a) Example of a horizontal subsurface resistivity slice showing the resistivity distribution from 6.8 to 9.7 m below ground surface at approximately 1:850,000 scale. b) Example of a vertical resistivity section showing the resistivity distribution along flight line 117202. Modified from SkyTEM Surveys ApS (2015).**

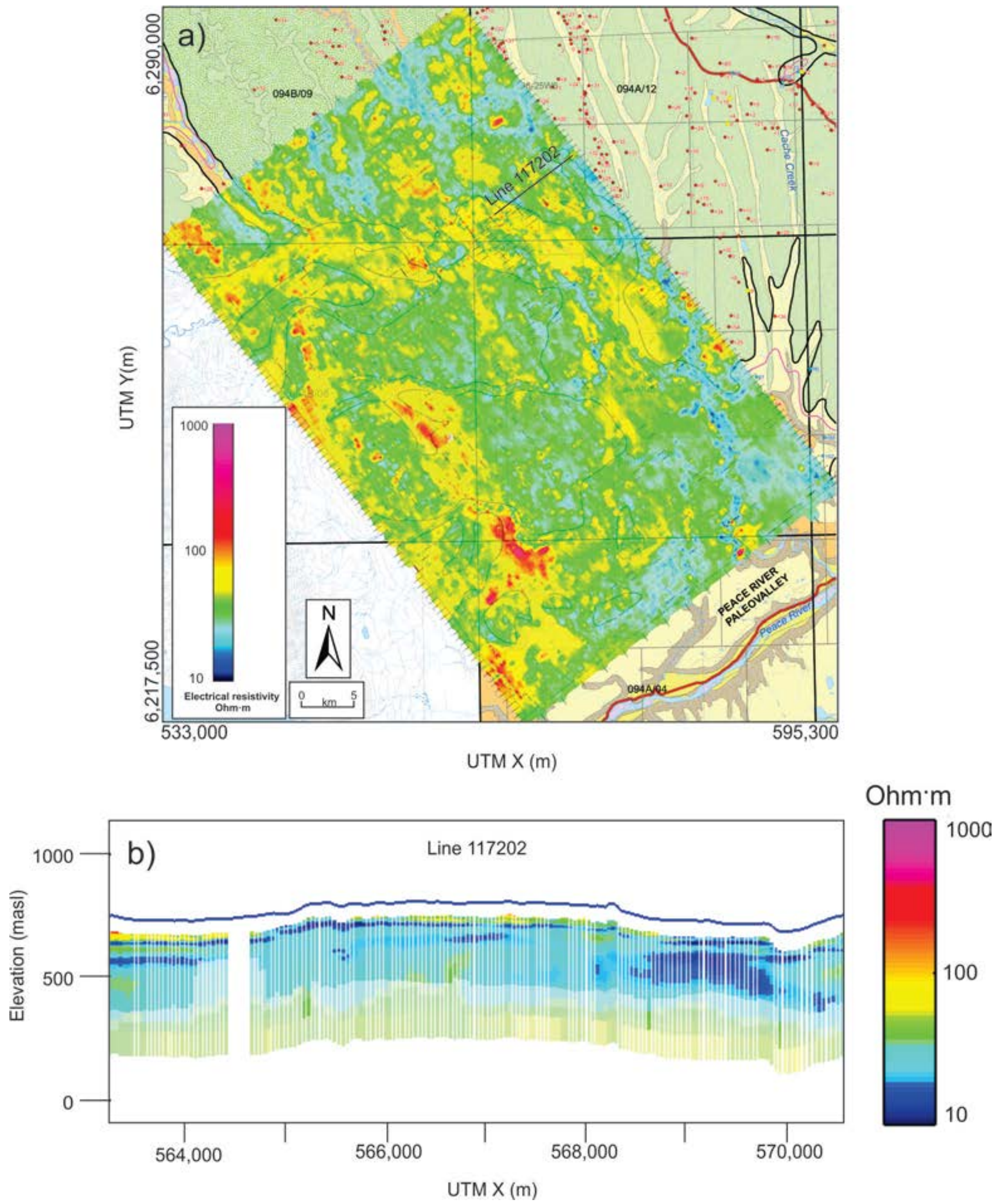

Figure 7. **Interpretation results of the 3D inversion of AEM data collected from the SkyTEM survey for the Peace Main Phase 1 sub-area of Geoscience BC's Peace Project derived from spatially constrained inversion. For the results in other areas of the Peace Project, refer to Aarhus Geophysics ApS (2016a-e) and Aarhus Geophysics ApS and GEUS (2017). a) Example of a horizontal subsurface resistivity slice showing the resistivity distribution from 5 to 10 m below ground surface at approximately 1:50,000 scale. Section line for b) is shown. b) Example of a vertical resistivity section showing resistivity distribution along flight line 117202. Modified from Aarhus Geophysics ApS (2016d).**

2.2. Geological and Geophysical Data Gathered from Shallow Intervals of Petroleum and Water Wells

In support of the airborne electromagnetic (AEM) survey, Petrel Robertson Consulting Ltd. (PRCL) and Quaternary Geosciences Inc. (QGI) used a combination of existing data, including geological maps, hydrogeological reports, and well data from petroleum and water wells, to conduct a geological characterization of the Quaternary and shallow bedrock formations in the Peace Project area.

Cased-hole gamma-ray logs from the petroleum wells in the study area were gathered and used in the geological characterization. Gamma-ray logs record the natural radioactivity of the sediments. High gamma values generally imply clays, and result from higher concentrations of radioactive elements found in clay minerals, such as uranium, potassium and thorium (Quartero et al., 2014). Low gamma values generally imply sands and other coarse-grained sediments. Gamma-ray logs are commonly used to determine the subsurface lithology and for stratigraphic correlation.

The steel surface casing surrounding petroleum wells provides wellbore stability; however, it mutes the gamma-ray response from the formation, which is problematic for geological interpretation (Quartero et al., 2014). To enable the use of gamma-ray logs from cased petroleum wells, Quartero et al. (2014) developed a gamma-ray normalization procedure that corrects for the casing effect by adjusting the statistical distribution of the gamma values from the cased portion so that the high and low percentiles are equal to those of the gamma values from the non-cased portion. This normalization method allows the cased and non-cased log intervals to be merged into one continuous gamma-ray curve for stratigraphic correlation (Quartero et al., 2014).

Within the Peace Project area, the gamma-ray logs from approximately 1200 wells were corrected using the Quartero et al. (2014) technique (Petrel Robertson Consulting Ltd., 2015). Using the corrected gamma-ray logs, PRCL and QGI identified the top of bedrock depth (i.e. the Quaternary-bedrock surface) and subsequent thickness of Quaternary cover for each well, and additionally identified intervals of potential sands within the Quaternary sediments. An example of a corrected gamma-ray log is shown in Figure 8.

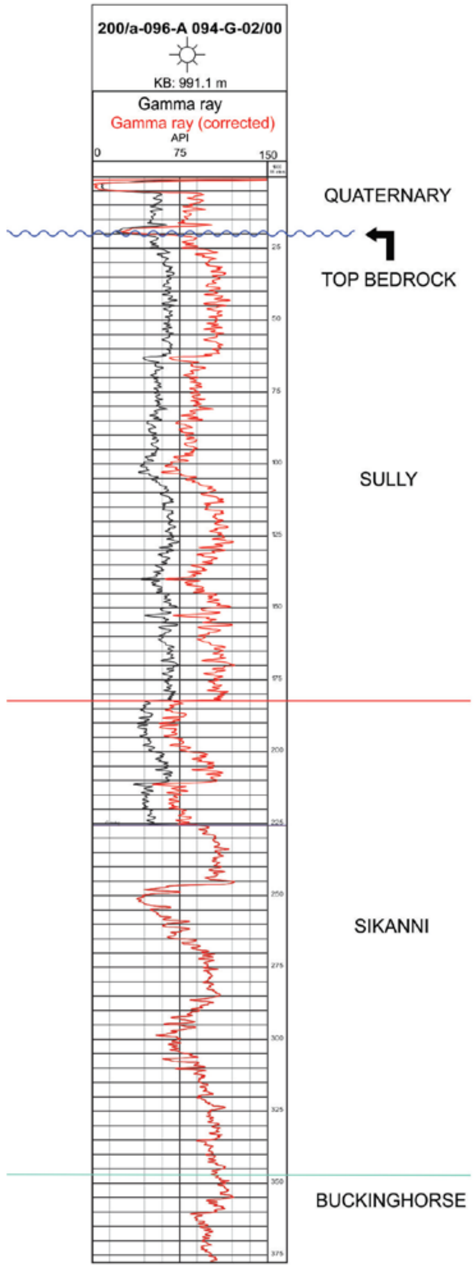

Figure 8. Example of a gamma-ray log from the Peace Project area corrected using the Quartero et al. (2014) method. The gamma-ray curve from the cased-hole interval is shown in black and the corrected gamma-ray curve is shown in red. Stratigraphic picks for the Quaternary-bedrock contact and other bedrock contacts are also shown. The Quaternary-bedrock contact is identified for all wells; however, deeper bedrock contacts were not identified and are only included in this figure for demonstrating the use of the corrected curve in making stratigraphic picks. From Petrel Robertson Consulting Ltd. (2015).

PRCL and QGI also gathered existing water well driller's logs in the Peace Project area from the BC WELLS database (BC Ministry of Environment, 2018). These logs provided additional depth to bedrock values as well as the location of sand intervals within the Quaternary sediments.

Using the combined dataset from the petroleum and water wells, as well as maps of the surficial and bedrock geology, QGI interpreted the outlines of potential paleovalleys throughout the Peace Project area, and identified locations where thick Quaternary fill may be present.

2.2.1. Produced Data

The final deliverables from this study included: a stratigraphic database summarizing interpretations from all petroleum boreholes including all associated corrected gamma-ray logs (available in LAS and PDF format); a database tabulating depth to bedrock for water wells; and detailed surficial geology maps for the full Peace Project Main area, Sikanni Chief area, Doig River area, and Charlie Lake area, along with the interpreted outlines of paleovalley systems and areas of thick Quaternary fill. These deliverables from Petrel Robertson Consulting Ltd. (2015) are available on GBC's Peace Project website (http://www.geosciencebc.com/s/PeaceProject.asp).

2.3. Peace Project Drilling Program

To test the validity of the geological interpretation of the AEM data and gamma-ray logs, locations were selected throughout the Peace Project area to drill calibration wells. Ten wells were drilled at eight different locations (Table 2) throughout the Peace Project area. The locations of the calibration wells were selected based on surficial geology (Petrel Robertson Consulting Ltd., 2015), the 3D resistivity depth slices and sections (Aarhus Geophysics ApS, 2016a-e), and road accessibility. Bemex Consulting International and Quaternary Geosciences Inc. (2016) provide the detailed rationale for the selection of each well's location. It should be noted that the objective of the drilling program was to test the validity of the geological model derived from the surficial geology and resistivity data; not to locate shallow Quaternary and/or bedrock aquifers. Figure 9 shows a map of the locations of the 10 drilled wells.

Table 2. **UTM coordinates of the wells drilled for the Peace Project drilling program.**

Well #	UTM Easting (m)	UTM Northing (m)
3	532800	6337068
6a & 6a-MW	546650	6262600
7	570761	6262059
10b	564653	6220724
10x & 10x-2	570720	6225047
11	628484	6237717
12	627050	6234063
13	579293	6234812

Figure 9. **Well locations (black stars) for the Peace Project drilling program overlain on the surficial geology map created by Levson in Petrel Robertson Consulting Ltd. (2015).**

The wells were drilled with a sonic rig (Figure 10), which vibrates the drill bit up and down in addition to pushing it downwards. Sonic drilling allows for excellent core recovery compared to conventional rotary drilling. Core was collected and logged along the entire length of the hole. Figure 11 shows an example of core collected at hole 6a-MW (see Figure 9 for location). Following drilling, the boreholes were completed with solid PVC pipe and backfilled with cement grout to enable geophysical logging.

At two drilling locations (6a and 10x; see Figure 9 for locations), a water-bearing unit was intersected. The water-bearing units had sufficiently high permeability to warrant the installation of a monitoring well. Therefore, the drill rig was moved less than 5 m away, and a new borehole was drilled to the particular depth associated with the water-bearing unit. The borehole was then cased with solid PVC pipe, with slotted PVC pipe serving as a screen across the water-bearing unit. Following installation, water samples were collected from each well for chemical analysis.

Figure 10. Sonic drill rig used during the Peace Project drilling program.

Figure 11. **Core retrieved from hole 6a-MW identifying the Quaternary-bedrock contact at approximately 22 ft depth. See Figure 9 for the well location. Photo from Vic Levson.**

Sediment samples were collected from the cores of holes 10b and 10x (see Figure 9 for locations) from the depth interval corresponding to the screened interval, and from other locations of coarse-grained units (i.e. sand), for grain size analysis (described in Morgan, 2018).

With the exception of the monitoring wells, all calibration wells were logged using various geophysical logging tools, including resistivity, neutron-porosity, density-porosity, gamma-ray and dipole sonic.

Holes 10x and 10x-2 (see Figure 9 for locations) were drilled at locations suitable for a field investigation currently being conducted by the University of British Columbia on methane migration in the shallow subsurface.

2.3.1. Produced Data

The final deliverables from the drilling campaign include detailed lithology logs from all ten wells, geophysical logs for eight wells (i.e. those completed with solid PVC; see Figure 12 for example), and two monitoring wells with water chemistry data. These data are available on the GBC Peace Project website (http://www.geosciencebc.com/s/PeaceProject.asp), along with the accompanying reports: Levson and Best (2017a), Mykula (2017), and Best and Levson (2017).

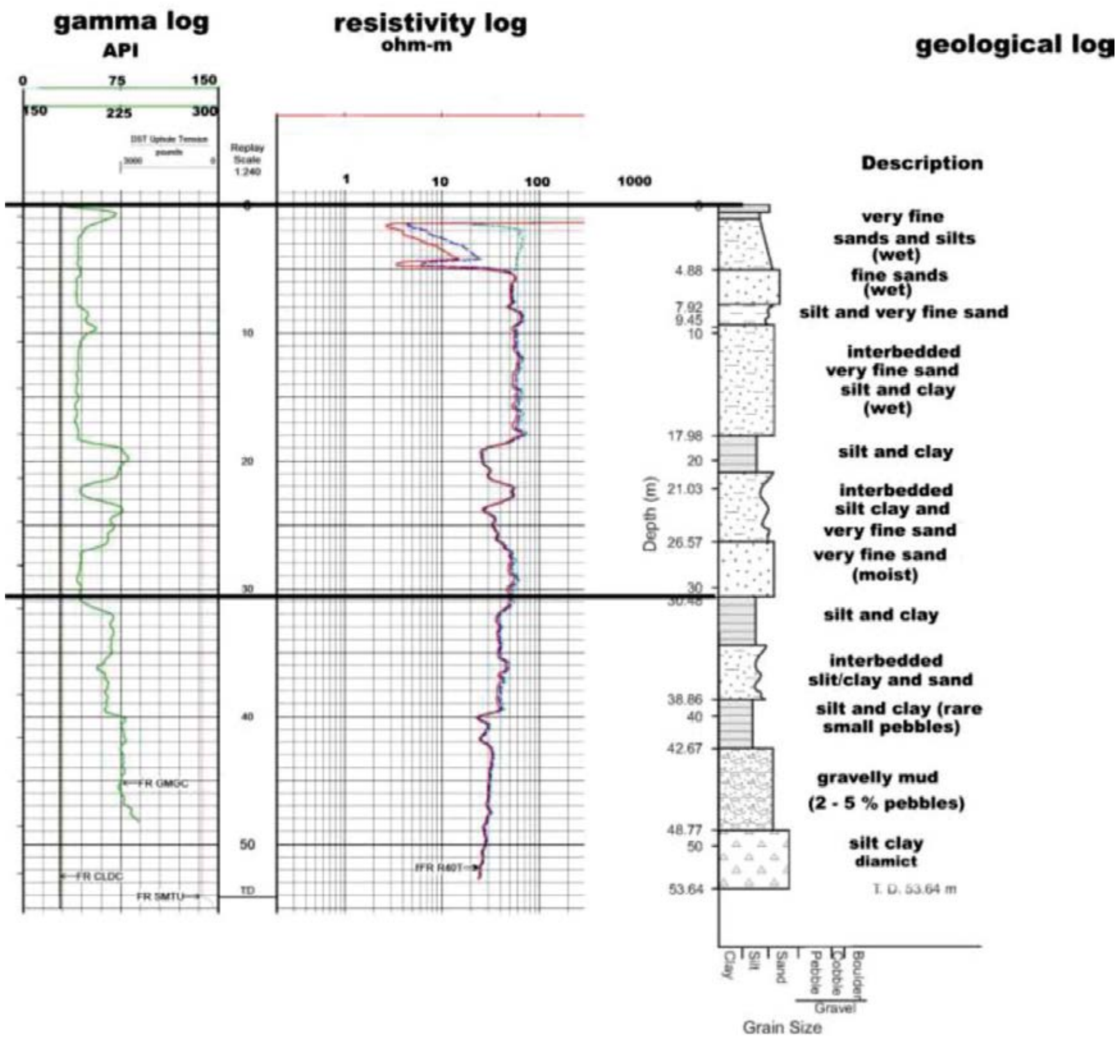

Figure 12. **Well 7 resistivity, gamma, and geological logs. See Figure 9 for the well location. From Best and Levson (2017).**

3. Applications of the Project Data

Various studies have been conducted utilizing the data collected and produced from the Peace Project. This section of the report summarizes each study and identifies the main outcomes.

3.1. Geological and Petrophysical Interpretations of the Drilling Data

3.1.1. Drilling Descriptions and Interpretations - Levson and Best, 2017a (Geoscience BC Report 2017-16)

As described in section 2.3, the drilling program was carried out to confirm the geological interpretations of the resistivity data and corrected gamma-ray logs. The report by Levson and Best (2017a) provides the lithological core descriptions and preliminary geological interpretations for each of the eight well locations. Photographs of the core at each location are also included. An example of a lithology log and geological interpretation for well 3 (see Figure 9 for location) is shown in Figure 13.

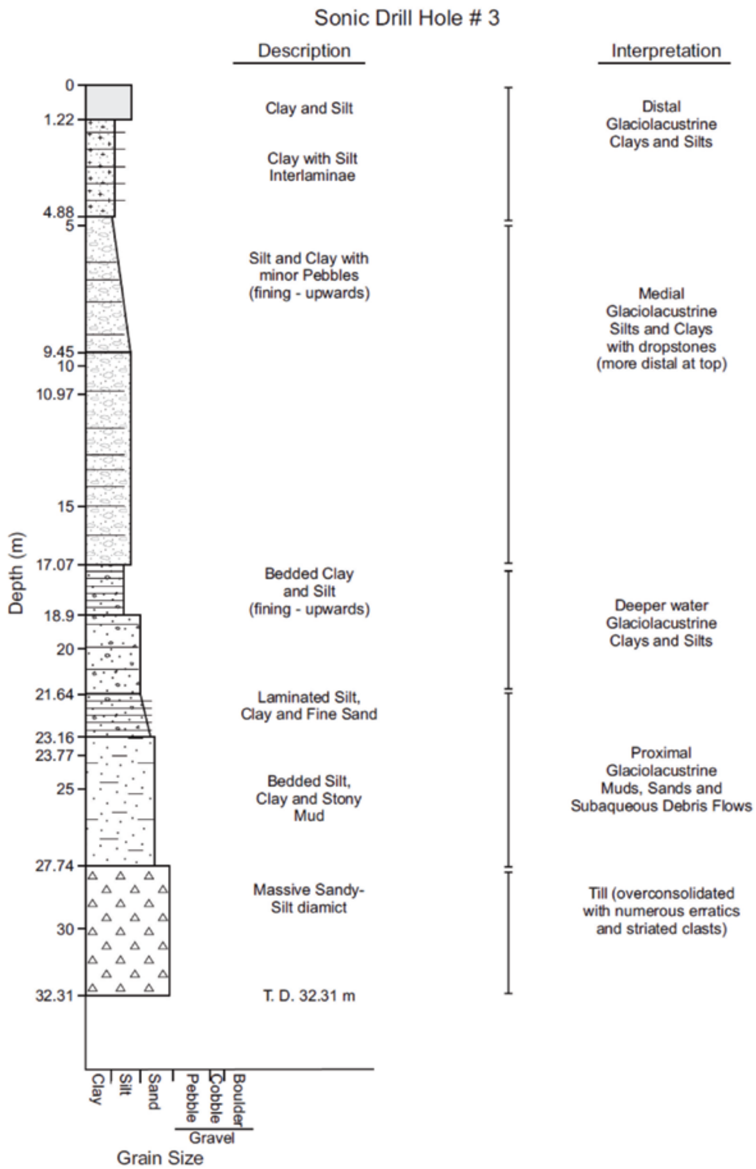

Figure 13. Well 3 lithology log and geological interpretation. From Levson and Best (2017a).

The drilling program confirmed the presence of deep paleovalleys filled with heterogeneous Quaternary sediments in the Peace Project area, some even deeper than originally estimated (Bemex Consulting International and Quaternary Geosciences Inc., 2016). Bedrock was only encountered at one site (6a); therefore it was not possible to quantify the underestimation of paleovalley depths. The Quaternary stratigraphy encountered at the drill sites was generally consistent with the preliminary predictions (Bemex Consulting International and Quaternary Geosciences Inc., 2016), with the exception of small-scale variations due in part to the large distances from the drill sites to the nearest interpreted petroleum well log, and the coarse resolution of the AEM survey data not detecting thin stratigraphic sequences, especially at greater depths.

Sand and/or gravel units, as potential aquifers within finer glacial sediments, were encountered at all holes except 3 and 11, where they were expected at greater depths than were drilled. The granular sediments encountered in most wells were water-bearing to some degree; however, they were too thin, or too fine-grained, to warrant the installation of groundwater monitoring wells (except for sites 6a and 10x where monitoring wells were installed).

3.1.2. Petrophysical Interpretations on Six Shallow Wells – Mykula, 2017 (Geoscience BC Report 2017-18)

The study conducted by Mykula (2017) included petrophysical interpretations of the geophysical well logs collected from six of the wells from the drilling program (6a, 7, 10b, 10x, 12, and 13). The following geophysical well logs were used in the interpretation: gamma-ray spectral, caliper, resistivity, neutron, density, PE, density correction, and sonic.

The various geophysical logs were analyzed with the HDS 2008™ software to generate V_{SH} (shale volume), PhiE (effective porosity), and S_w (water saturation) curves, as well as calculate average values of each petrophysical characteristic (i.e. V_{SH}, PhiE, and S_w) of the pore zones (sandy intervals) for each well. Additionally, detailed petrophysical descriptions using the calculated characteristics were provided for each well, including a comparison of the petrophysical interpretation to the lithology log for each well.

Each well contained a number of sandy intervals that were analyzed. Four of the six wells (6a, 7, 10b and 10x) contained water within some of the zones, while the remaining two (12 and 13) were dry. Average V_{SH} values ranged from 0.067 to 0.338, with higher values indicative of a larger amount of fine-grained sediments (i.e. silt) within the interval. Average PhiE values ranged from 22.5 to 33.5%.

3.1.3. Comparison of Borehole Geophysical Logs with AEM Data – Best and Levson, 2017 (Geoscience BC Report 2018-08)

Using the borehole lithology logs, geophysical logs, and AEM data from the SkyTEM survey, Best and Levson (2017) provide a comparison of the various data at each completed well location, and relate the wells in the context of the regional Quaternary geology of the area. The primary objective of this study was to compare the results of the 3D inversions carried out by Aarhus Geophysics ApS to the collected borehole geological logs and resistivity and gamma-ray logs at each well. An example of a comparison of the AEM data and borehole logs for Well 7 is shown in Figure 14.

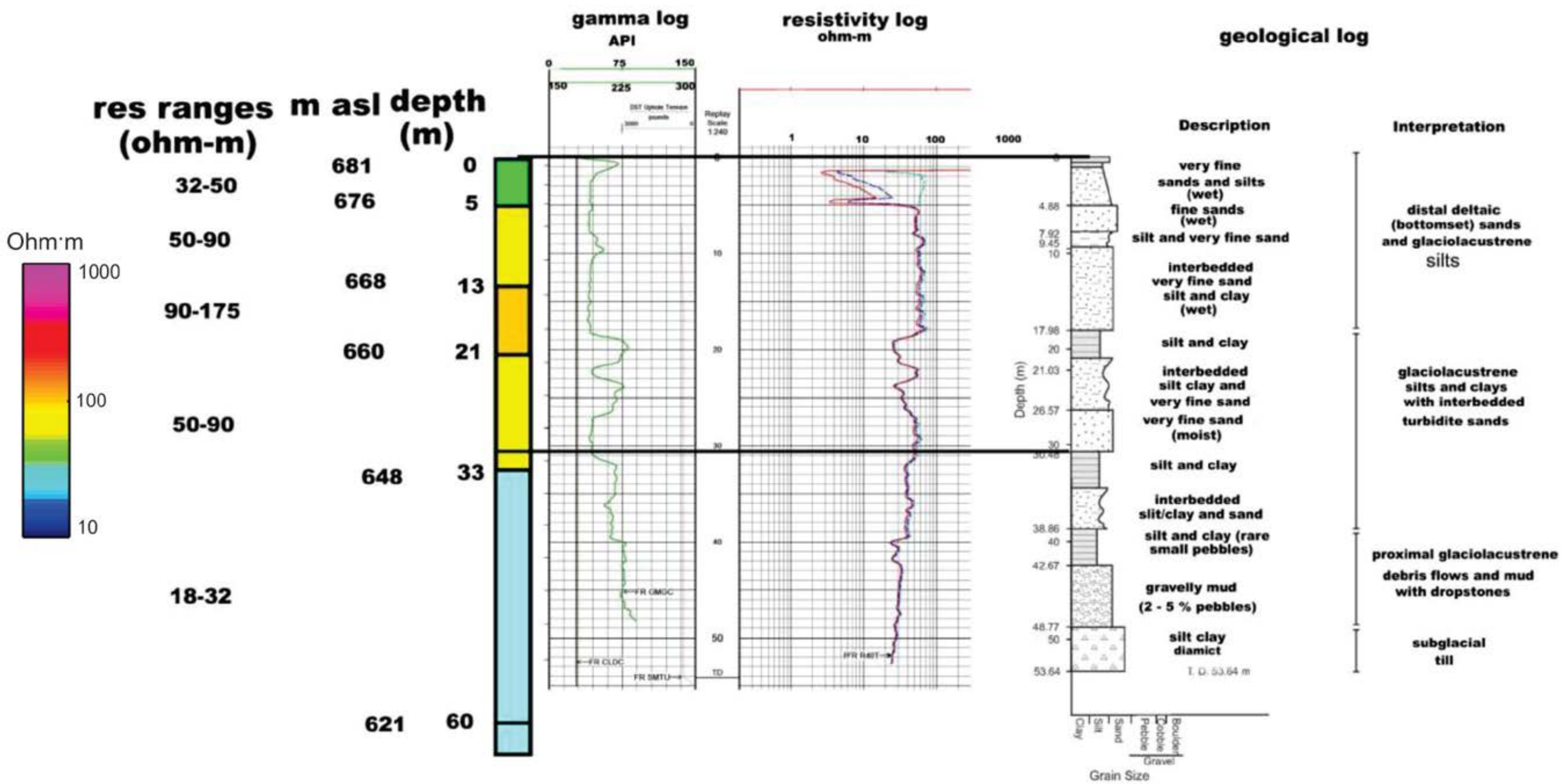

Figure 14. Comparison for well 7 of resistivity range from the 3D AEM inversions (resistivity values and colour bar shown) on the left side, and the downhole resistivity, gamma, and lithologic description and interpretation from core on the right side. The depth scales are approximate (within 1-2 m of each other). Modified from Best and Levson (2017).

The lithologic logs for each well are significantly more detailed than the results from the AEM inversions (Figure 14), which is to be expected given that the core was logged at fine scale. The resistivity values interpreted from the AEM data tend to agree with the overall geological properties (i.e. fine and coarse-grained); however, in some instances the contacts between different materials that have similar resistivity values (e.g. sands/gravels versus sandstone) are not as apparent in the AEM data (e.g. well 6a, not shown). This is because AEM surveys average the properties of subsurface materials over large volumes, and thus, the resistivity response from an AEM survey is smoothed and decreases in resolution with depth. The inversion process itself also has inherent uncertainties that lead to uncertainties in the interpreted lithology.

The downhole resistivity tool targets a zone proximal to each well, and therefore, the resistivity values more strongly correlate with the lithologic units. In particular, poorly sorted gravels and/or diamicts with coarse clasts are associated with high resistivity values, but the finer-grained matrix of these materials resulted in high gamma counts. Finally, as stated in section 3.1.1, predicted bedrock depths were shallower than what was encountered during drilling - only one well intersected the Quaternary-bedrock contact. This is likely a result of the limitations of AEM surveys listed above.

Overall, the results from the SkyTEM survey provide a good regional evaluation of resistivity distribution, and the AEM data correlate reasonably well with the borehole resistivity logs. The resistivity logs provided a better correlation with the lithology logs. Inconsistencies are a result of the different scale/resolution to which the data are best suited (i.e. regional versus fine-detailed local scale).

3.2. Proposed Well Locations for Halfway River First Nations Area – Levson and Best, 2017b (Geoscience BC Report 2017-17)

Levson and Best (2017b) conducted a study that aimed to identify potential sites for groundwater development in the vicinity of the Halfway River First Nations (HRFN) lands. The data used in this analysis included the geological and geophysical data (i.e. lithology logs, surficial geology maps, AEM resistivity data, and borehole geophysical logs) acquired as part of the Peace Project, as well as pre-existing lithology records from the provincial WELLS database for water wells within and around the HRFN area, information on the Halfway River aquifer as mapped by the BC Ministry of Environment, and bedrock geology maps.

Levson and Best (2017b) present an overview of the surficial and bedrock geology of the HRFN area and use this information, in combination with the datasets listed above, as a basis for inferring the groundwater potential. They identified seven potential target locations in the HRFN area for drilling water wells, and discuss each target location in terms of advantages and disadvantages regarding proximity to the community, the likely permeability of the target aquifer, the potential recharge areas, and land access. The seven target well locations are shown in Figure 15.

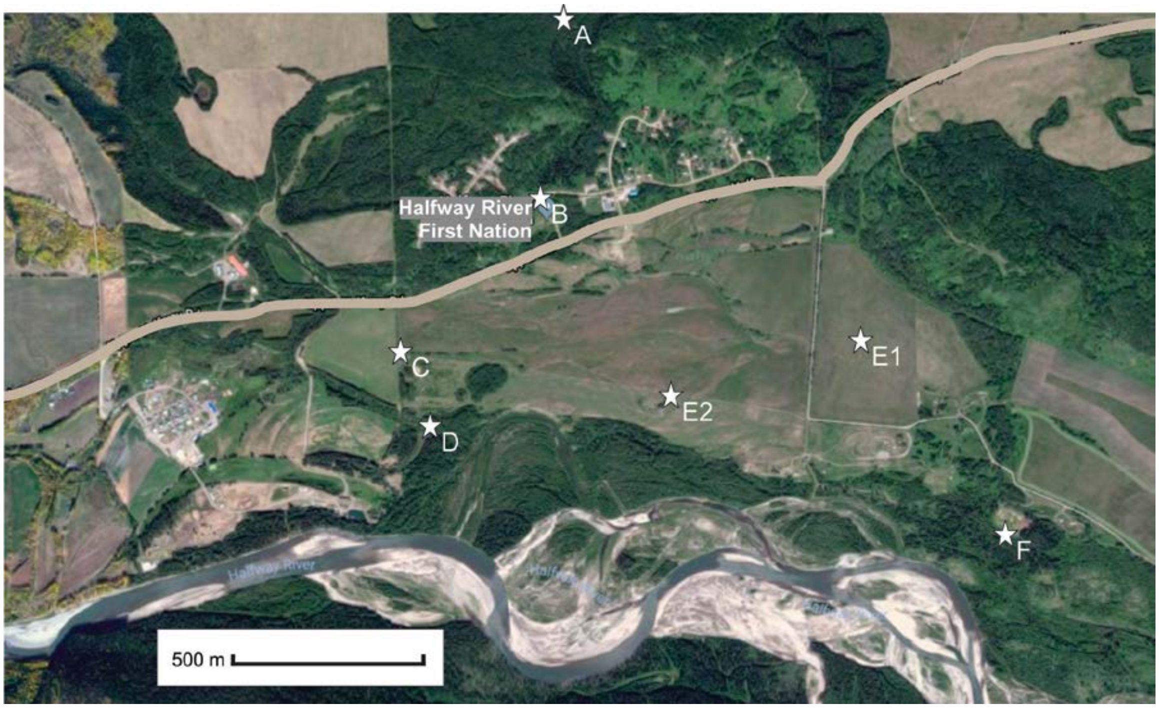

Figure 15. **Map of target locations for potential water wells in the Halfway River First Nations area. Locations from Levson and Best (2017b).**

3.3. 3D Geological and Hydrogeological Modelling of the Peace Main Phase 1 sub-area – Morgan, 2018 (M.Sc. thesis)

Morgan (2018) explored the role of a large buried valley network in the regional hydrogeology of the central Peace Region. The study area coincided with the Peace Main Phase 1 sub-area (see Figure 3), where the largest network of paleovalleys had been delineated by Levson in Petrel Robertson Consulting Ltd. (2015). In this study, a geological model of this buried valley network was created using a facies modelling approach and the reservoir software, Petrel (Schlumberger, 2016). The primary data used in the geological modelling were the 3D inversion results from Aarhus Geophysics (2016d).

High resistivity values were interpreted to represent sands and gravels, and low resistivity values were interpreted to represent clays, silts, and till. The resistivity data were supplemented by the corrected gamma-ray logs, and the borehole geophysical and lithology logs from the Peace Project drilling campaign. Figure 16 compares the inverted resistivity data and the geological interpretation for one cross-section through the paleovalley network.

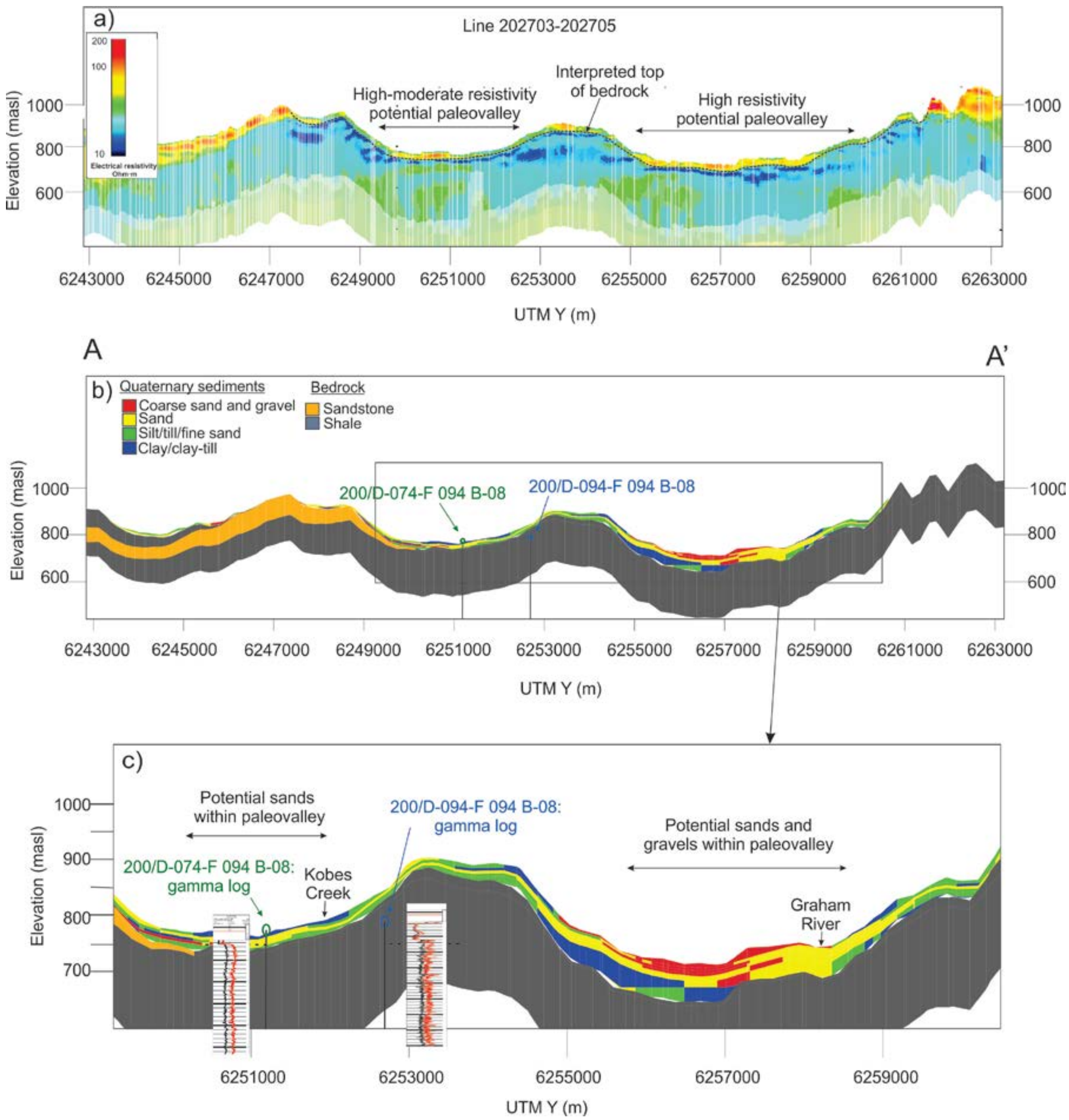

Figure 16. **Example of the resistivity data (a) from Aarhus Geophysics ApS (2016d) compared to the geological modelling results from Petrel (b and c) (Morgan, 2018).**

Morgan (2018) discusses the limitations associated with the geological modelling in terms of geophysical uncertainty (i.e. resistivity is a function of multiple variables besides grain size, such as water saturation and salinity of pore waters) and generalizing Quaternary lithology type over large grid cells; however, this was necessary due to the regional scale of the investigation.

Morgan (2018) used the geological model as a basis for developing numerical models of the regional groundwater flow system. Due to the sparsity of hydrogeological data in NEBC, these numerical models were interpretive in nature; however, interpretive models are still valuable tools in conceptualizing flow systems and investigating parameters and groundwater processes.

The results of Morgan's (2018) study suggest that permeable deposits exist within the buried valleys, but they are not regionally connected throughout the whole network (Figure 17), and thus do not play a significant role in the regional groundwater flow regime. This conclusion was based on the geological modelling, the water balance and hydraulic head distributions from the numerical groundwater flow models, and practical applications of the numerical models that included pathline mapping and travel time estimation, and pumping simulations. Despite not being regionally connected, extensive permeable deposits within the buried valleys exist at smaller, more local scales, and thus they may offer a viable groundwater source in the area.

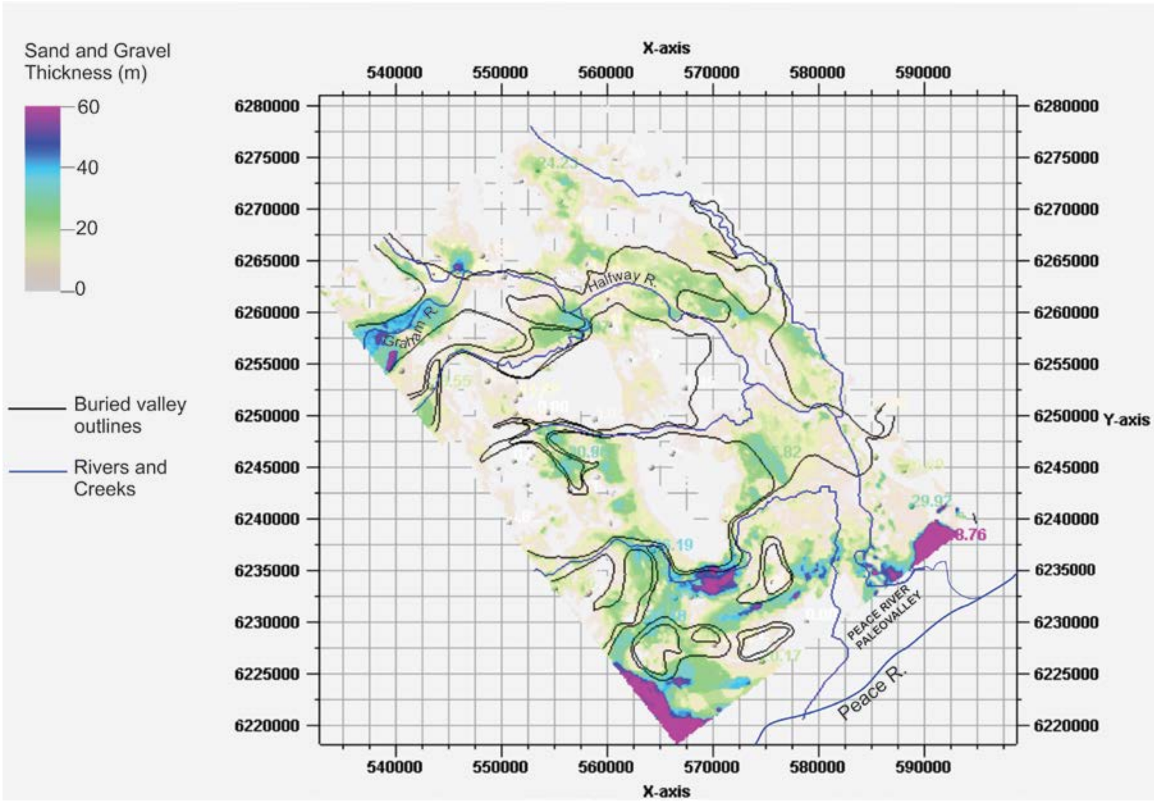

Figure 17. **Map showing the modelled thickness of the sand and gravel facies within the Peace Main Phase 1 sub-area in Petrel (Morgan, 2018).**

3.4. Geological and Hydrogeological Interpretation of the Charlie Lake and Doig sub-areas – Hall et al., 2017 (unpublished report)

This sub-component of the Peace Project aimed to develop a three-dimensional geological (facies) model for two small sub-regions: the Doig block and the Charlie Lake block (Figure 18) using available resistivity data and borehole logs. The purpose of this modeling was to examine the potential for deep Quaternary aquifers within the paleovalley network.

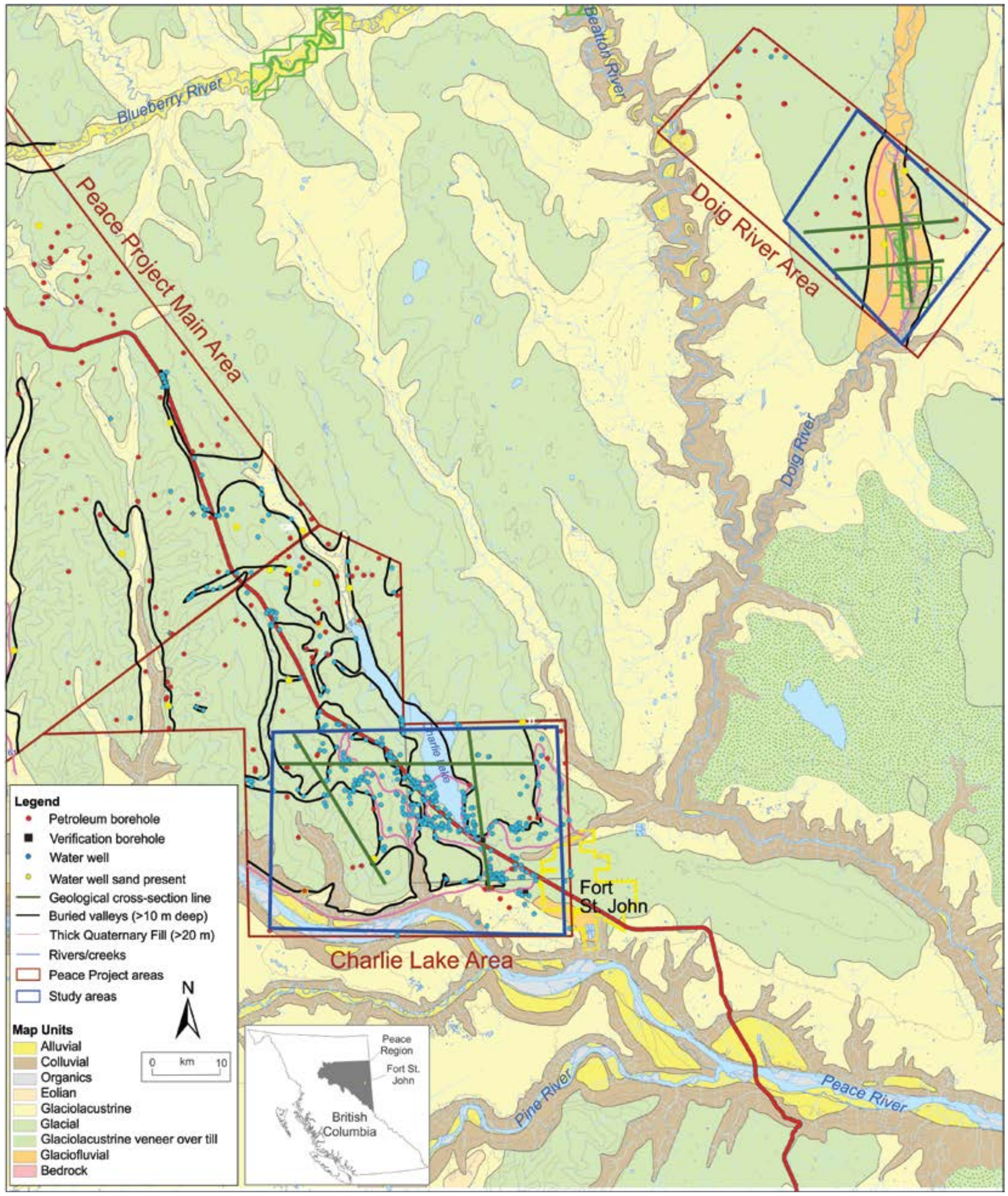

Figure 18. **Surficial geology and locations of the Doig and Charlie Lake blocks. Petroleum wells, water wells, and wells from the Peace Project drilling are shown. Blue outlines indicate areas where 3D inversions of the resistivity data were performed (Aarhus Geophysics ApS, 2016a and b). Surficial geology map from Levson in Petrel Robertson Consulting Ltd. (2015).**

The first attempt at constructing a facies model from resistivity data followed the methodology outlined by Morgan (2018). Unfortunately, due to the small scale of these regions, this approach produced significant artifacts (bullseyes) and did not adequately reproduce the resistivity distributions (Figure 19).

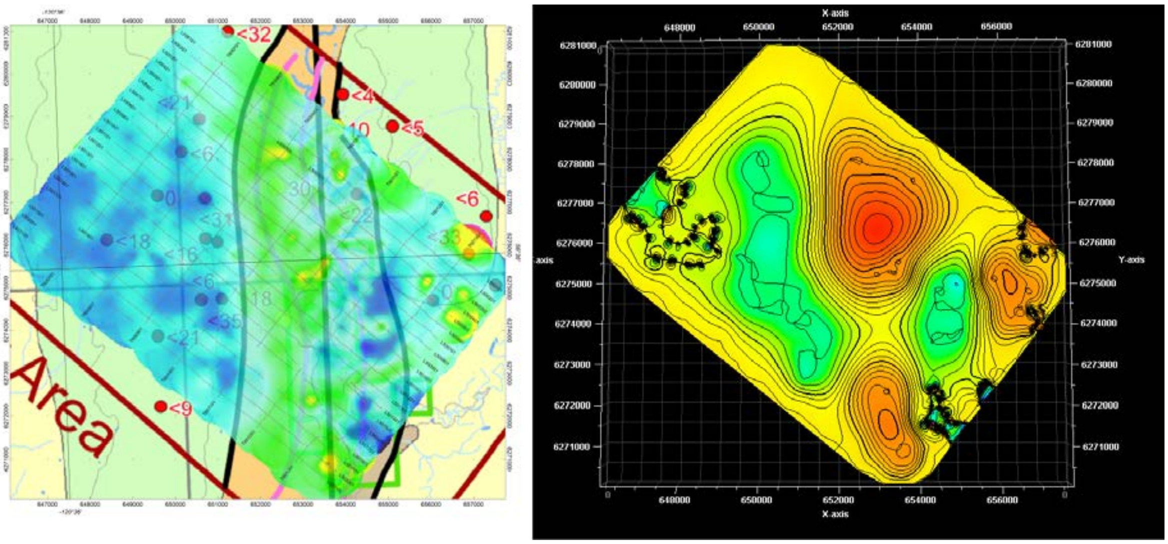

Figure 19. **Resistivity slices for the 0 to 5m depth slice for the Doig block (Aarhus Geophysics ApS, 2016b) (left), and the reconstruction in Petrel (right). Colour scales are not the same between the two models. Note the strong "Bullseye" effect apparent in the Petrel reconstruction.**

An alternative approach was thus used to construct the geological models, whereby cross-sections through each region, based on the resistivity data, were constructed in graphics software. Screenshots of the resistivity slices along the chosen cross-section lines were aligned in CorelDraw (graphics software) with their corresponding topographic profile. The resistivity values for each depth slice were then annotated manually on the cross-section. Facies interpretation was made according to the resistivity-facies relationships established by Morgan (2018) after Bemex Consulting International and Quaternary Geosciences Inc. (2016).

3.4.1. Charlie Lake Cross-Sections

The Charlie Lake cross-sections were oriented to capture as much as possible of the extent of the high resistivity units. Line 1 extends east-west, while lines 2 and 3 extend roughly north-south (Figure 20). The modern valley in the southwest quadrant was not chosen for a cross-section location because the resistivity data indicated no large continuous zone of high resistivity in the upper 50 m in the valley.

Since the resistivity values interpreted to represent sand (50-90 Ohm·m) are the same as the resistivity values interpreted to represent sandstone (here the Dunvegan Formation), identifying the bedrock contact in locations where sand overlies sandstone was nearly impossible using the resistivity data alone. Bedrock depths are highly variable throughout the Charlie Lake area, and so while borehole data were used to constrain the interpretation of bedrock depth, the bedrock surface indicated on the cross-sections, especially in areas where sand directly overlies sandstone, is uncertain. Depth to bedrock was based on the Charlie Lake surficial geology depth-to-bedrock map produced by Levson in Petrel Robertson Consulting Ltd. (2015).

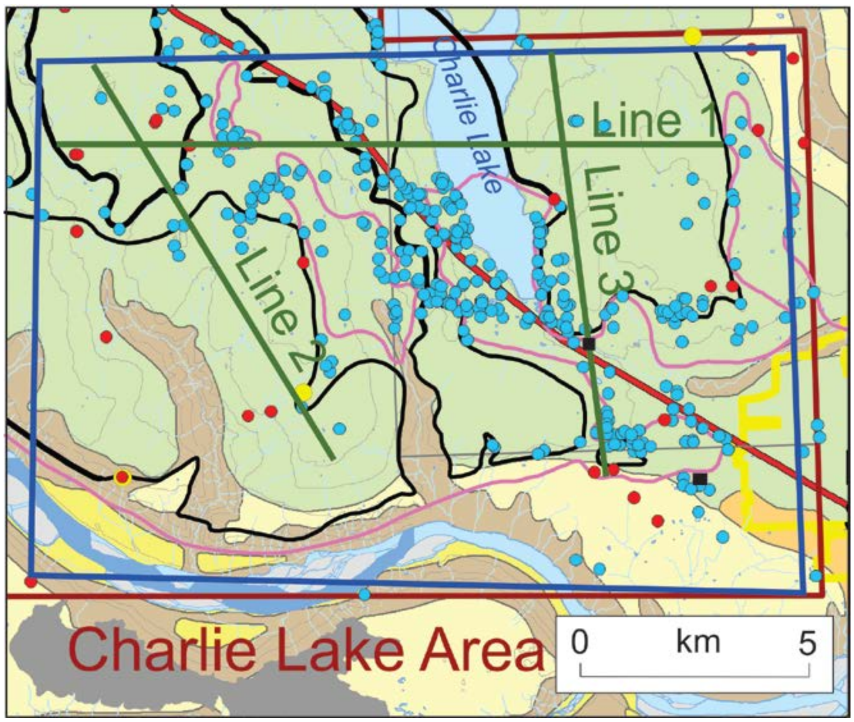

Figure 20. **Charlie Lake cross-section locations. Lines were chosen so as to maximize coverage of high resistivity areas. Map from Levson in Petrel Robertson Consulting Ltd. (2015).**

The Charlie Lake cross-sections (Figure 21) suggest that bedrock depths throughout the region are shallow (generally mimicking topography), and that Quaternary cover ranges in thickness from 5 to 35 m (Figure 20). The Quaternary sediments are interpreted to be interlayered sand, silt, clay, and till. The topographic lows in this region are dominantly in-filled with low resistivity material, which is interpreted to be clay and till. Sand deposits in this region are interpreted to be extremely thin and discontinuous, and well logs in the area indicate that these sand units are interbedded with clay and silt at a finer resolution than can be shown on these cross-sections. This interpretation is supported by lithology logs of water wells from the provincial WELLS database. All existing wells in this region appear to be developed almost exclusively in underlying bedrock, rather than in the Quaternary deposits. Thus, the sand units are unlikely to be potential aquifer units.

It should be noted that topographic effects on AEM conductivity data are most significant at the higher frequencies used to investigate the shallow subsurface. While the data were treated to remove significant topographic effects (Aarhus Geophysics ApS, 2016a and b), there appears to be a correlation between higher resistivity values and areas of higher topographic slope in the Charlie Lake area. This effect may also simply be a result of the Dunvegan being closer to the surface on steep slopes. In addition, the elevation of the contact of the Sully shale Formation was obtained from the Aarhus Geophysics ApS (2016a) shallow resistivity cross-sections. These cross-sections have a coarse vertical resolution; therefore, the Sully contact shown on the cross-section is uncertain.

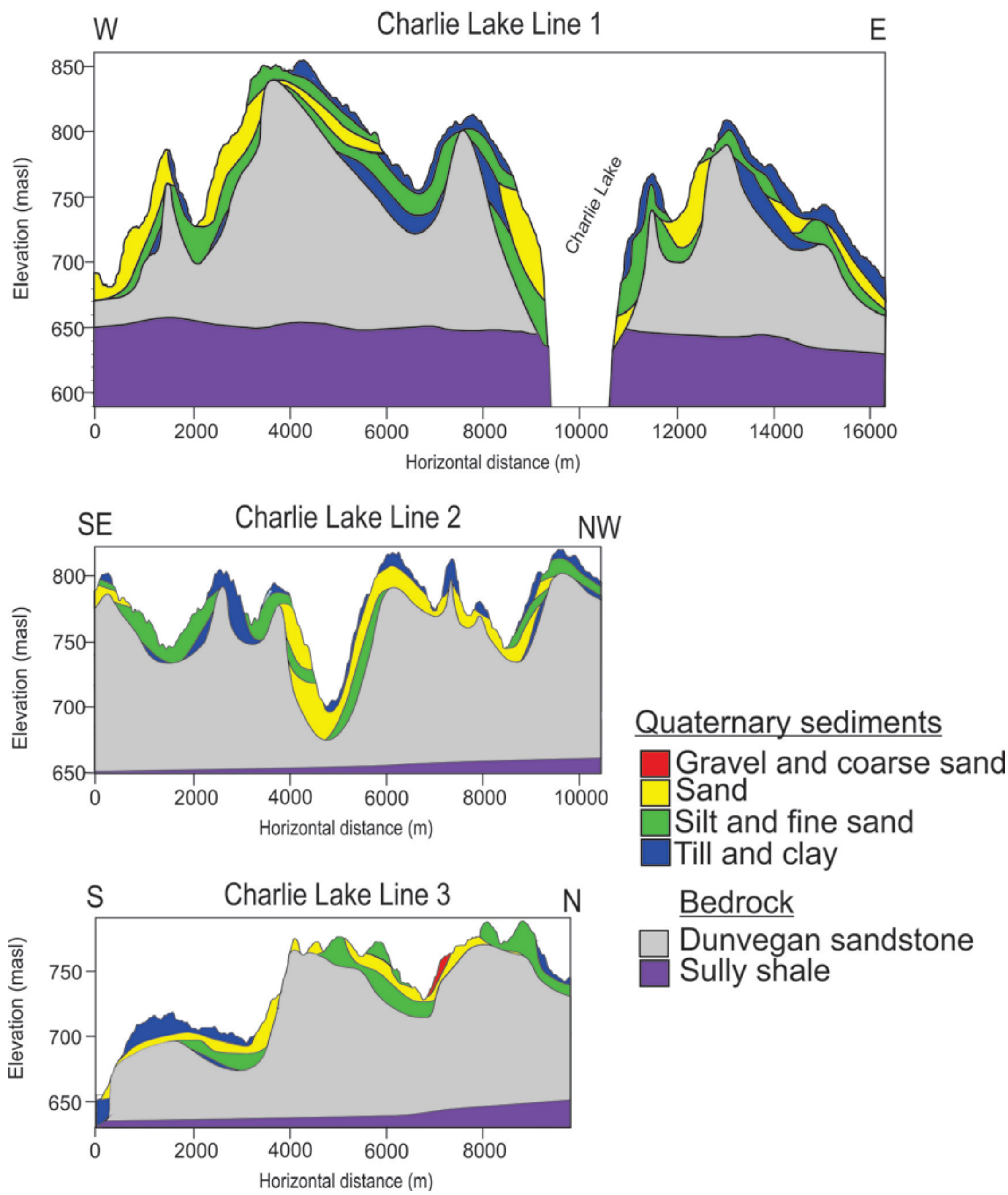

Figure 21. Charlie Lake cross-sections. See Figure 20 for cross-section line locations.

3.4.2. Doig Block Cross Sections

Doig block cross-section lines 1 and 2 are oriented perpendicular to the trend of the modern valley, while line 3 is parallel to the valley thalweg (Figure 22). These orientations were chosen so as to maximize the coverage of the observed high resistivity zone within the valley fill.

The Doig block cross-sections (Figure 23) suggest a buried bedrock valley oriented roughly north-south through the area. Depth to bedrock was constrained using depth-to-bedrock values from nearby water wells, where available (Figure 22). The modern valley is incised into a paleovalley, which is interpreted to be infilled predominantly with silt and fine sand, interspersed with lenses of coarser sand (Figure 23). Till and clay deposits cap these sand and silt deposits along the edges of the valley.

Two sand units are interpreted. The shallower sand unit at approximately 670 masl appears to extend through the middle of the valley (Line 3). The top and bottom elevations of this sand unit vary (i.e. the unit appears to undulate). Due to its continuous nature, this upper sand unit is a potential aquifer. Interpreted lithology information from the corrected gamma-ray logs within the Doig River valley also indicates a potential aquifer in this location. There is also a deeper sand unit at the base of the paleovalley; however, this unit does not appear to be extensive as it only appears in Line 2.

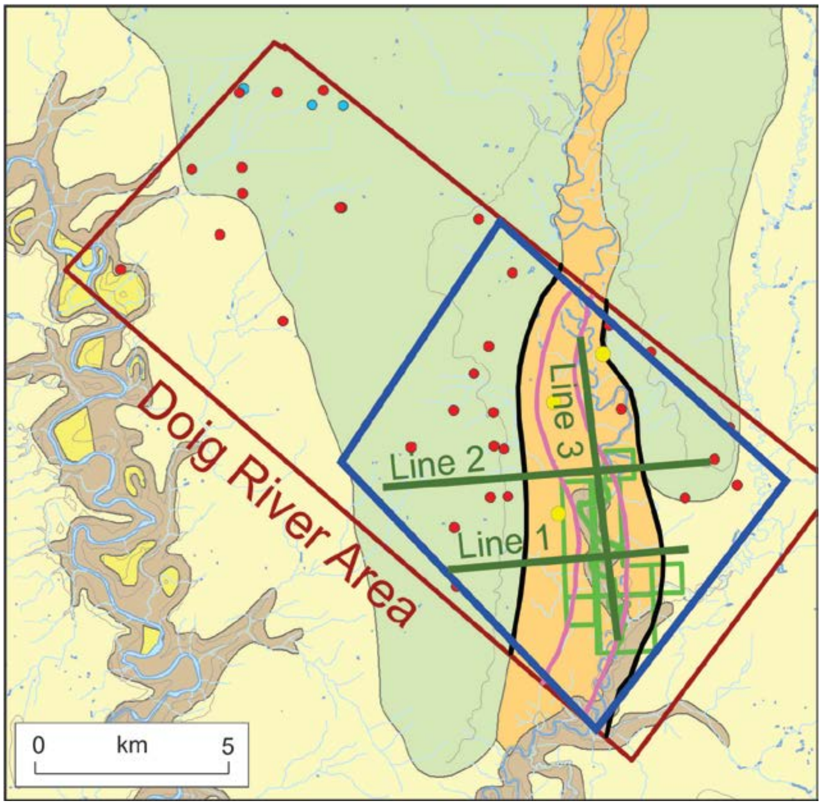

Figure 22. Doig Block cross-section lines. Map from Levson in Petrel Robertson Consulting Ltd. (2015).

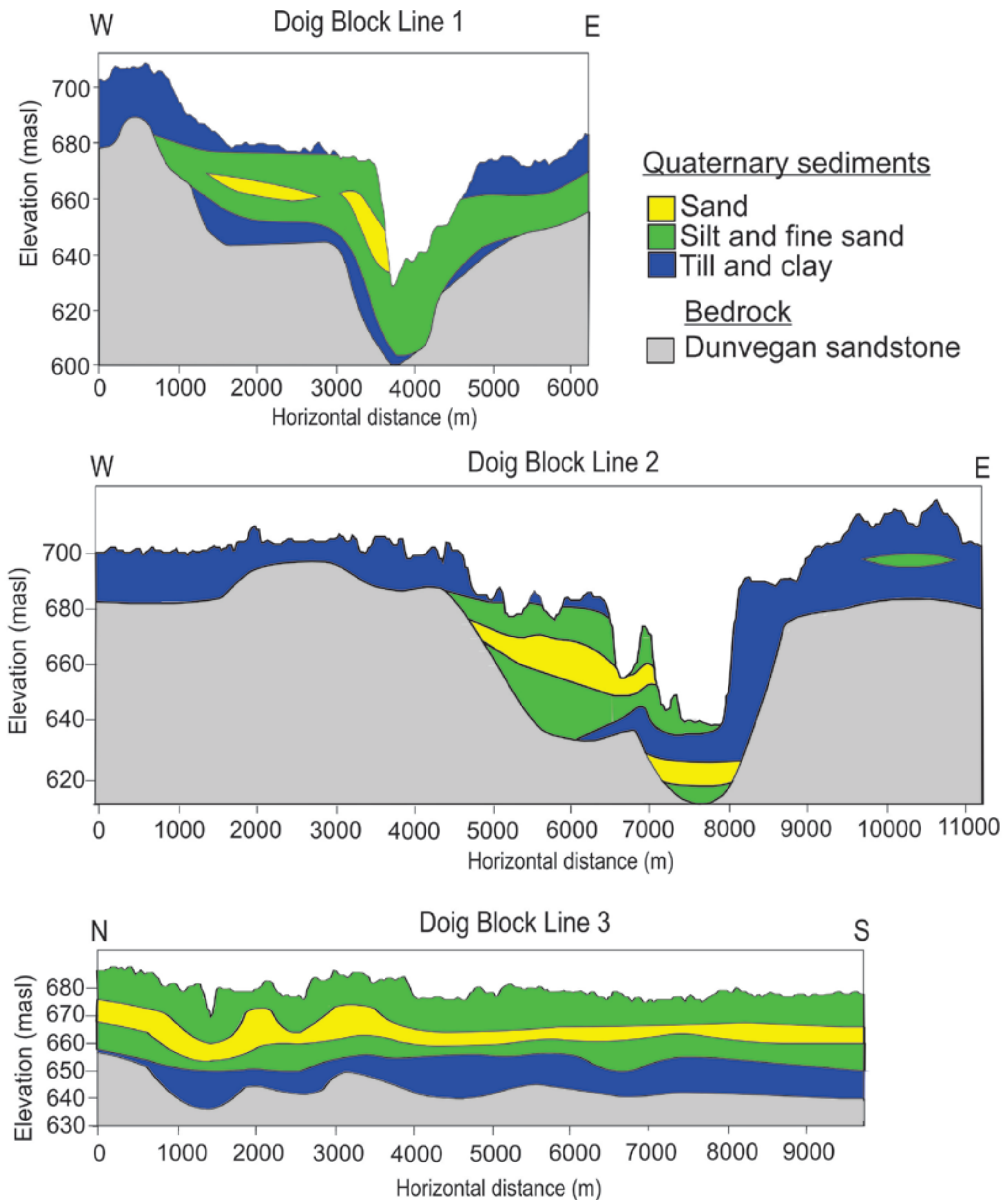

Figure 23. **Doig block cross-sections. See Figure 22 for cross-section locations.**

3.5. 3D Geological and Hydrogeological Modelling of the NW Extension from the Peace Main sub-area – Aarhus Geophysics ApS and GEUS, 2017 (Geoscience BC Report 2018-06)

At the request of GBC, Aarhus Geophysics ApS and GEUS (Geological Survey of Denmark and Greenland) (2017) performed additional processing and 3D inversion of the raw SkyTEM data over the NW extension portion of the survey area (see Figure 3 and Figure 24). This area was added after the initial 3D inversions had been carried out (Aarhus Geophysics ApS, 2016a-e), and involved geological and hydrogeological interpretation of the data as well, which were not done in the original five areas. As stated in section 2.1, details on the data processing and inversion can be found in Aarhus' report (Aarhus Geophysics ApS and GEUS, 2017) on GBC's Peace Project website.

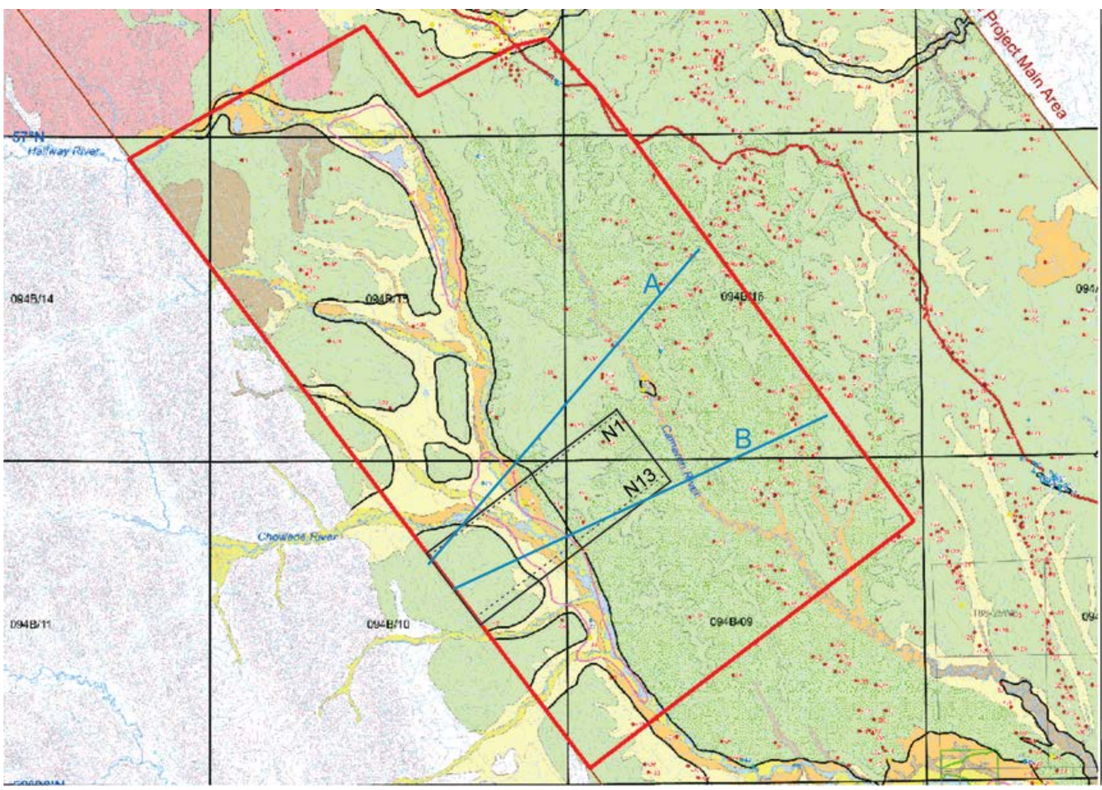

Figure 24. **Surficial geology of the NW extension area for Aarhus Geophysics ApS and GEUS (2017) extension study. Surficial map created by Petrel Robertson Consulting Ltd. (2015). The NW extension is shown in the red polygon. The 3D model area for the NW extension is shown in the black rectangle. The profile lines for Figure 26 are shown in blue. Flight lines N1 and N13 are shown with black dashed lines.**

As part of the geological modelling, different facies were differentiated within the Quaternary cover based on the resistivity data (similar to the facies modelling approach taken by Morgan, 2018). Particular importance was placed on interpreting the Quaternary stratigraphy within the buried valleys, specifically to identify resistive features. The detailed geological model is shown in Figure 25. The bedrock stratigraphy was also interpreted based on the resistivity data (Figure 26). The Sully and Buckinghorse shale formations display a clear conductive response, and the Dunvegan sandstone displays a predominantly resistive response; however, the Sikanni sandstones display an inconsistent response, likely due to heterogeneities within the unit or variable water quality. Aarhus Geophysics ApS and GEUS (2017) also interpreted the formation and genesis (relative age) of the buried valleys, suggesting they were mostly formed as sub-glacial tunnel valleys containing enclosed depressions that in some locations could be filled with coarse-grained material. At least two generations of buried valleys were suggested to be present, separated by a spatially extensive unit comprised of glaciolacustrine and fluvial sediments.

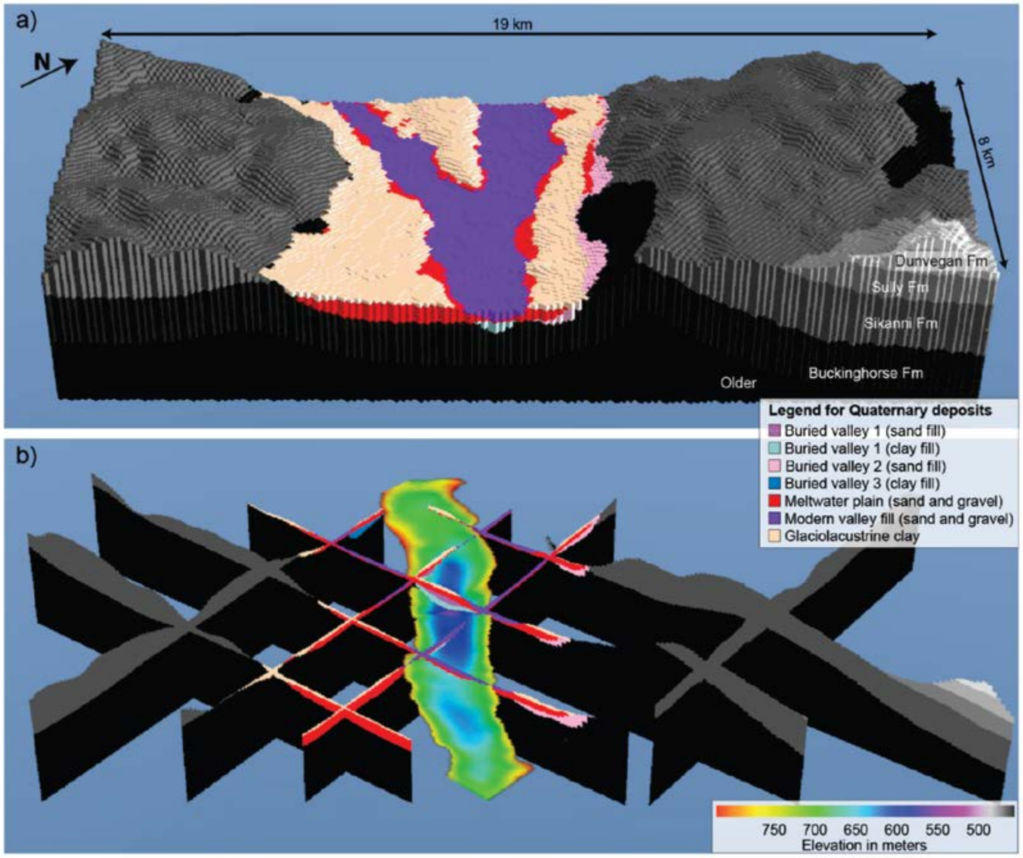

Figure 25. 3D geological model of the NW extension area (see Figure 24 for location). 5x vertical exaggeration. a) 3D view, b) elevation of the buried valley outlined by Levson in Petrel Robertson Consulting Ltd. (2015) shown together with E-W and N-S slices through the model. From Aarhus Geophysics ApS and GEUS (2017).

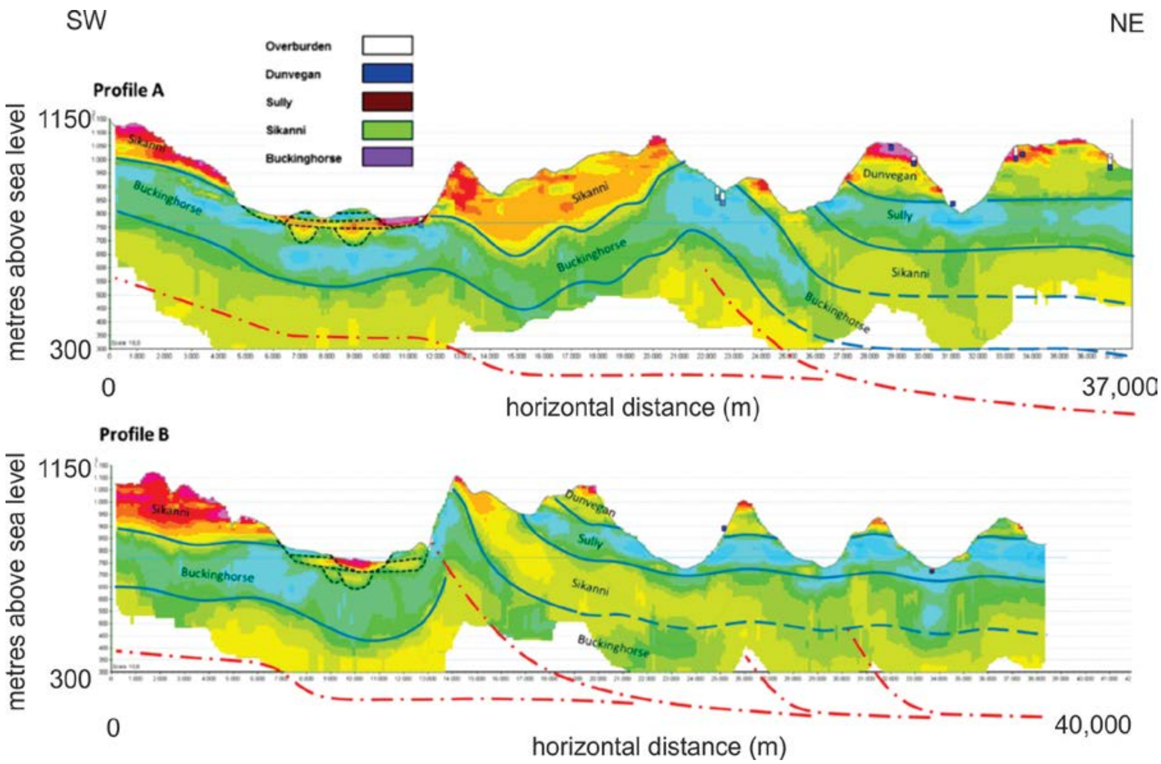

Figure 26. **Resistivity cross-sections from the NW extension area showing geological interpretation (see Figure 24 for locations). Estimated thrust faults, verging in the opposite direction than expected, are delineated with thick red dotted lines and inferred bedrock formation boundaries are delineated by thick blue lines. Interpretations in the drift succession (Quaternary sediments) are delineated by thin black dotted lines. 10x vertical exaggeration. Modified from Aarhus Geophysics ApS and GEUS (2017).**

The hydrogeological interpretation by Aarhus Geophysics ApS and GEUS (2017) is mainly focused on buried paleovalleys, as these represent potential targets for groundwater development, and thus modelling was only conducted within the pre-determined outlines by Levson in Petrel Robertson Consulting Ltd. (2015). The results of the modelling suggest that coarse sediments within the buried valleys and the more recent outwash sediments could represent potential aquifers; however, the Quaternary infills within the buried valleys show varying resistivity values. Even in units of predominantly high-resistivity material, the resistivity can range from 40-100 ohm-m. Therefore, the groundwater potential also likely varies. The highest resistivity deposits are found within the modern riverbed (e.g. Figure 27). Thus, hydraulic connection with the stream is very likely, and extraction could cause river depletion. Therefore, Aarhus Geophysics ApS and GEUS (2017) suggest coarse sediments within the buried valleys that have a hydraulic barrier (i.e. a low resistivity unit such as glaciolacustrine clay) separating them from the riverbed represent the most promising sites for groundwater development.

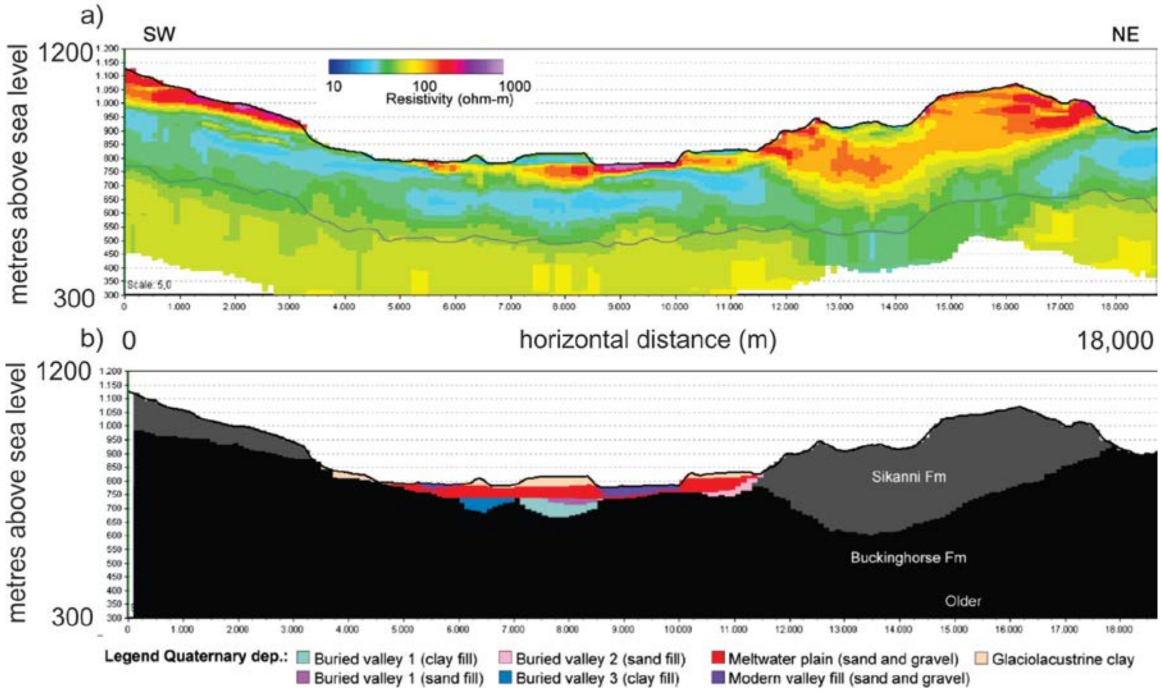

Figure 27. **Resistivity cross-section from flightline N1 (a) compared to geological model results (b) along the same profile for the NW extension area (see Figure 24 for location). 5x vertical exaggeration. Modified from Aarhus Geophysics ApS and GEUS (2017).**

3.6. Interpretation of the Structural Geology of the Peace Project Area Based on SkyTEM Data – Jørgensen et al. (2016)

The Geological Survey of Denmark and Greenland (GEUS; Jørgensen et al., 2016) carried out a study to demonstrate the applicability of the resistivity data from the SkyTEM survey to interpret the 3D structural geology within the Peace Main Phase 1 sub-area of the Peace Project (see Figure 3). The interpretation was done almost solely with the use of the resistivity data, as borehole data were limited and/or of poor quality. The authors also only focused on the bedrock and did not interpret the Quaternary sediments.

Both the vertical resistivity sections and horizontal slices were used in the interpretation of the bedrock stratigraphy. Boundaries were identified on a formation basis as opposed to a lithostratigraphical basis; therefore, the formations may both demonstrate variability, and show similarities, in resistivity values.

The conceptual geological model of the study area represents a sedimentary regime affected by gentle to moderate deformation, and shallow thrust faulting (Figure 28). It should be noted that the eastward-verging thrusts are opposite to the structural style commonly seen in the region, suggesting the presence of triangle zones to the west. Validation of this structural interpretation from seismic is still needed. The deformed sedimentary bedrock is overlain by glacial sediments of varying thicknesses.

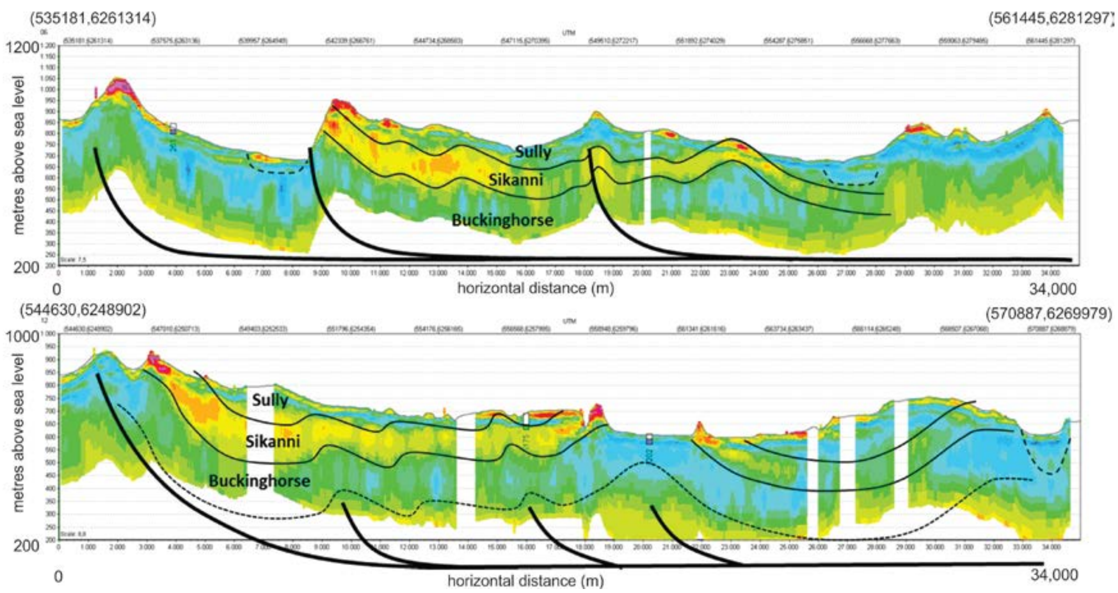

Figure 28. **Geological interpretations of the resistivity cross-sections from the Peace Main Phase 1 sub-area (see Figure 3) identifying main bedrock formations. Left is southwest and right is northeast. Interpreted thrust faults, verging in the opposite direction than expected, are shown as thick black lines. Approximately 8x vertical exaggeration. Modified from Jørgensen et al. (2016).**

4. Discussion

The previous sections summarized the surveys conducted as part of the Peace Project, and presented some of the produced data, as well as highlighted several studies that applied the data to interpret the geology and hydrogeology of the region. This section provides an overview of challenges in interpreting data acquired at different scales, and synthesizes information on the current understanding of the geology, hydrogeology, distribution of aquifers, and understanding of the buried valleys in the region, which have all been enhanced by work conducted for the Peace Project.

4.1. Interpreting Results at Different Scales

Numerous previous studies have been carried out in NEBC to investigate the glacial history and resultant Quaternary stratigraphy of the Peace Region. Mathews (1978) combined the interpretation of glacial ice sheet advance, retreat, and geomorphology, to map the surficial geology and outline paleovalleys in the Charlie Lake area. Since Mathews' (1978) seminal work, the interpretations have been refined and/or modified (e.g. Hartman and Clague, 2008), and have been extended into other areas of NEBC (e.g. Levson et al., 2006; Hickin, 2011; Hickin et al., 2016). A common finding of all of these studies is that the thickness of the Quaternary sediments of the Peace Region varies considerably, from <1 metre to hundreds of metres, and contains numerous successions of advance and retreat phase glacial and interglacial sediments that are heterogeneous at different scales. The geological results and interpretations from the Peace Project are consistent with these findings.

On a regional scale (~100s to 1000s of km^2), studies carried out by Morgan (2018) and Aarhus Geophysics ApS and GEUS (2017) illustrate using a facies modelling approach that the spatial distribution of Quaternary sediment types is quite variable, and that broad facies generalizations had to be made based on the resistivity values when correlating these units. These studies illustrate that within the buried valley outlines, Quaternary fill can reach apparent thicknesses of more than 100 metres; however, in some areas bedrock outcrops at, or near, surface. Aarhus Geophysics ApS and GEUS (2017) suggest that the Quaternary fill within the buried valleys is comprised of glaciolacustrine sediments, modern riverbed sediments, sands, and clays. These lithologies were modelled as homogeneous units based on the resistivity data; however, resistivities were shown to vary within these units, suggesting heterogeneous composition.

On an intermediate scale (~10s of km^2), the geological modelling and hydrogeological interpretations by Hall et al. (2017, unpublished report) also illustrate that the thickness of Quaternary sediments is quite variable, even within the broader paleovalley outlines delineated by Levson in Petrel Robertson Consulting Ltd. (2015), and that the Quaternary sediment is heterogeneous. This study also discussed the challenges of relying on resistivity data to interpret lithology, particularly when Quaternary sediments and bedrock formations have similar lithological compositions (i.e. sand versus sandstone).

On a local scale (well scale), the results of the drilling program allow for accurate geological interpretation. Mykula (2017), Levson and Best (2017a), and Best and Levson (2017) discuss the lithological variability observed in the core, and the latter two studies interpret the glacial stratigraphy based on grain size and lithology, and suggest whether units are likely advance or retreat phase glacial sediments. The AEM resistivity data and borehole log comparisons of Best and Levson (2017) were useful for assessing how reliable the AEM data are in predicting lithology type, and for comparing the various borehole geophysical logs to both each other and to the lithology logs. As mentioned above, the resistivity logs better correlate with the lithology logs compared to the AEM data; however, the AEM interpretations provided a reliable estimate of lithology type, with issues arising from small-scale heterogeneities not being resolvable with AEM. The gamma-ray logs also correlate well with the lithology and resistivity logs, particularly with finer-detail lithological variability.

4.2. New Insights into the Quaternary Geology and Buried Valleys in the Peace Project Study Area

Both the larger-scale modelling, and smaller-scale drilling results, show that within the buried valley outlines delineated by Levson in Petrel Robertson Consulting Ltd. (2015), the Quaternary sediments can be very thick. Permeable sediments were interpreted to exist within the buried valley outlines (modelling and drilling), sometimes as fairly thick deposits. The combined modelling results also suggest that within the buried valley outlines, the most laterally extensive permeable deposits seem to be shallow deposits from the modern riverbed or the meltwater plain. Deep permeable deposits within the buried valleys are suggested to be present at smaller scales; however, from the modelling, they do not appear to be regionally connected throughout the entire buried valley network.

Depth to bedrock in the study area is uncertain and challenging to accurately model. This is due to the following factors: (1) the corrected gamma-ray logs have limitations and associated uncertainty. While the gamma-ray logs were effectively utilized to predict depth to bedrock, in some locations depth to bedrock data are sparse; some logs did not extend to ground surface; and sand and sandstone (and likewise clay and shale) have similar gamma-ray responses; (2) the resolution of the AEM data diminishes with depth, and therefore the reliability of utilizing the resistivity data to interpret the bedrock is questionable when the Quaternary cover is so thick. Similar to the gamma-ray logs, sand and sandstone, and clay and shale, have similar resistivity signatures making it difficult to distinguish one from the other; and, (3) there are very few confirmed depth to bedrock points throughout the study area with which to calibrate the AEM results. Bedrock was expected to be encountered at all locations of the drilling program; however, bedrock was only encountered in one of the holes. Therefore, due to the deeper-than-expected bedrock depths, it is possible that deep, more resistive units interpreted to be sandstones, could in fact be deep sand and gravel units within the buried valleys. However, without physically drilling until bedrock is encountered, this can only be hypothesized.

The results of the geological modelling and interpretations from all studies help further the understanding of buried valleys in the Peace Project study area. The buried valleys in the Peace Region have been largely interpreted as glacially-formed. Therefore, it is to be expected that their fill contains unconsolidated sediments of variable thickness and lithology. However, it is also possible that the paleovalleys were incised within both bedrock and the unconsolidated sediments, and that subglacial meltwater incision may have resulted in these paleovalleys terminating abruptly and not developing regional connections with other units. It is apparent that the buried valley network in the Peace Project area is quite complex. Consequently, the outlines delineated by Levson in Petrel Robertson Consulting Ltd. (2015) may not necessarily reflect the outline of a single buried valley, but rather multiple paleovalleys of various sizes and extents that contain thick Quaternary fill. These may also be different generations (ages) of buried valleys, which was suggested by Aarhus Geophysics ApS and GEUS (2017), but not discussed in the other Peace Project studies. Moreover, the original buried valley outlines by Levson in Petrel Robertson Consulting Ltd. (2015) may not be entirely accurate as they were delineated with the use of the corrected gamma-ray logs, which have associated uncertainties and limitations as discussed above. To more accurately map the extent of buried valleys in the region, further field characterization is necessary. Recommendations for future studies are provided below in Section 5.

4.3. Improved Understanding of the Hydrogeology and Distribution of Quaternary Aquifers in the Peace Project Area, and the Impacts to End-Users

In addition to previous work characterizing the Quaternary sediments of the Peace Region, researchers have also suggested that sand and gravel deposits within the valleys, such as basal deposits in the valley thalwegs, could potentially represent significant sources of groundwater (Cowen 1998). Exposures along tributary valleys of large rivers, such as the Peace River, show large deposits of sands and gravels overlying bedrock (e.g. Hartman and Clague 2008), and thick and permeable deposits are expected at these confluences. If these deposits are connected, they may have an impact on the groundwater flow regime at the local, intermediate, and regional scales. However, the regional geological modelling that has been conducted in the Peace Project study area suggests that these deposits are not regionally continuous, potentially as a result of glacial processes such as ice erosion, or the abrupt nature of meltwater floods. At smaller scales however, buried valley aquifers may play a significant role in conveying local groundwater flow. Nonetheless, to fully assess the potential for groundwater flow within buried valley aquifers (e.g. to provide confidence in sourcing groundwater supplies), detailed hydrogeological investigations are required.

A number of studies carried out as part of the Peace Project focused on the distribution of aquifers and the potential groundwater resource within the buried valley network, at both regional and local scales. Regional hydrogeological modelling conducted by Morgan (2018) showed that due to the lack of regional connectivity of deep permeable deposits within the paleovalley outlines, the buried valley aquifers did not play a significant role in the regional groundwater flow regime, and did not provide a “super highway” for groundwater to flow quickly throughout the region. However, flow within the permeable deposits at a local scale was investigated using the groundwater flow models. Particle pathline mapping, travel time estimation, and pumping simulations suggest that these local-scale buried valley aquifers could represent a potential groundwater source for the area (Morgan, 2018).

The hydrogeological perspectives provided by Aarhus Geophysics ApS and GEUS (2017) on the NW extension suggest that permeable deposits associated with outwash sediments and the buried valleys may be potential groundwater sources. In particular, two buried valley sand deposits, as well as coarse sediments within the meltwater plain, are potential aquifers. However, the varying resistivities within the deposits may reflect varying groundwater yields. Aarhus Geophysics ApS and GEUS (2017) also considered hydraulic connection with the Halfway River, and pointed out that the groundwater potential is dependent on the existence of a hydraulic barrier between aquifers and the modern riverbed to ensure limited impacts to streamflow. In many places, the meltwater plain was interpreted to be connected to the riverbed; therefore, buried valley sand deposits which have a low permeability upper confining bed may have the strongest groundwater potential.

Hall et al. (2017) conducted an intermediate-scale hydrogeological investigation within sub-areas of the Peace Project study area, and identified two sand units as potential aquifers within the Doig River area. Both units are within the paleovalley outlines in the Doig block, and the shallower unit was interpreted to be more laterally extensive than the deeper unit. Sand units in the Charlie Lake area were found to be thin, discontinuous, and interbedded with silts and clays, resulting in low potential for Quaternary aquifers (Hall et al., 2017). On a more local scale, Levson and Best (2017b) identified several Quaternary deposits within the HRFN area with aquifer potential within the paleovalley outlines, potentially near the deeper parts of the valley. These targets were evaluated based on potential for recharge, stream-connectivity, and geomorphology controls.

It is apparent that Quaternary aquifer potential is variable throughout the region. There are localized, moderately extensive deposits with promising geology (i.e. coarse-grained deposits), especially at the confluences of rivers and creeks where these deposits have been observed in the field. However, geology is not the only factor in assessing aquifer potential. Regardless of how coarse-grained an aquifer may be, the long-term sustainability may be limited by recharge, which is difficult to characterize. Morgan (2018) and Levson and Best (2017b) considered recharge in their hydrogeological investigations; however, as recharge is difficult to quantify in the region, their findings have limitations. Assessing the potential connection to streams, and the subsequent impacts to streamflow, must also be considered when assessing the groundwater resource potential. This was considered by most hydrogeological studies from this project.

Finally, the intended use of the aquifer is also a factor in assessing aquifer potential. For example, the groundwater demand for private domestic use is different than for industrial use. Aquifers that are intended for source water for hydraulic fracturing operations or other industrial operations, and those for community supply wells, should be large in extent, connected to a perennial source of recharge, and have limited hydraulic connection with surface water bodies. Therefore, some of the more extensive unconsolidated aquifer units found in the study area, such as shallower deposits within the meltwater plain or those in contact with modern riverbeds, may not be suitable for these uses. The more localized aquifer units at depth within the buried valleys are more ideal targets. However, due to the limitations of the geophysical and geological data discussed in the previous sections, the extent and potential of these deposits is uncertain. Further field work and characterization is needed to fully understand the resource potential and sustainability of these deeper buried valley aquifers at the local water supply level (discussed below in Section 5). In contrast, aquifers that are intended to be used as a private domestic well supply do not necessarily need to be as extensive, as the water demand will be lower than for industrial or community use.

In summary, the studies conducted as part of the Peace Project have provided geological and hydrogeological interpretations that can be used to identify potential source aquifers for various uses. The following section provides specific recommendations for future work, identifying specific areas or locations where in-depth investigations should be carried out to evaluate potential aquifers.

5. Recommendations for Future Work

Hydrogeological characterization in Northeast BC is ongoing, and the studies conducted and data collected as part of the Peace Project provide an excellent basis for prioritizing future studies. The results of this project demonstrate the heterogeneity of Quaternary sediments and the resulting uncertainty related to assessing and locating unconsolidated aquifers. Therefore, future work that improves the characterization of the Quaternary lithology and Quaternary groundwater development may be beneficial for localized studies. However, from a regional perspective, it may be necessary to improve the understanding of the groundwater resource potential of bedrock aquifers. The majority of water wells in NEBC are sourced from bedrock aquifers, and they may provide more regionally consistent aquifer systems compared to the Quaternary units.

This section provides recommendations for future work that have been deduced from the results and discussion provided in the preceding sections. Recommendations are provided to help improve the characterization of the Quaternary geology within the paleovalleys, if there is a need to further improve local Quaternary aquifer knowledge. However, at the regional scale, bedrock may be a more predictable groundwater source in NEBC. Therefore, some of these recommendations may also be applicable to improving bedrock aquifer knowledge.

5.1. Geophysical and Geological Recommendations

The Peace Project studies that involved interpreting lithology relied heavily on the AEM resistivity data. As electrical resistivity does not uniquely define lithology, it is recommended that other geophysical surveys, such as seismic, which has proven very useful in geological modelling of buried valleys (e.g. Jørgensen et al., 2003; Ahmad et al., 2009; Oldenborger et al., 2016), be carried out to more accurately investigate the lithology, top of bedrock surface, and structure of the valley fills. Ground-based electromagnetic and resistivity surveys should also be carried out in order to provide local context for the regional AEM data. Future research should also include different interpretations of the resistivity data, in order to address how variables such as pore fluids, porosity, and texture, might influence resistivity, and analyze how these might alter the geological interpretation. This may be particularly useful in identifying if a conductive response is a result of saline waters in bedrock aquifers, as opposed to fine-grained lithology. Future drilling programs should also aim to acquire borehole geophysical logs to complement the core logs and resistivity data.

Depth to bedrock was challenging to accurately predict and model in the study area. As the top of bedrock surface controls the thickness of Quaternary fill and likely influences whether basal permeable sediments are present within the buried valleys, it is highly recommended that more bedrock contacts, primarily within the buried valley network in the valley thalwegs, be collected to better constrain the top of bedrock surface. While the most accurate method to collect these contacts is drilling boreholes, this is challenging due to the high costs of drilling into deep valley thalwegs. Collecting more bedrock contacts along the perimeter of the buried valley outline can potentially help in confirming whether the buried valleys extend further or are connected to other buried valleys outside of the current interpreted outline. As gas production is likely to increase in this region, new regulations could be developed to require depth to bedrock be recorded in new oil and gas wells and uploaded to a database such as AccuMap (IHS Energy, 2017). Additionally, reporting of depth to bedrock could be required for new water wells and made available in the WELLS database. Not only would depth to bedrock data be beneficial for geological modelling, but such data would also be useful for hydrogeological and geotechnical investigations.

Figure 29 shows the thickness of sand and gravel facies generated by Morgan (2018) (shown previously as Figure 17). This map can be used to identify locations of interest for further Quaternary and bedrock geological characterization (e.g. drilling), geophysical surveys (e.g. seismic), and hydrogeological investigations (e.g. monitoring well installations or pumping tests). For example, in regard to further localized Quaternary investigations, further work has already been conducted on evaluating potential water well locations (e.g. Levson and Best, 2017b) along the Halfway River near the Halfway River First Nations lands, and in the south of the Peace Main Phase 1 sub-area, particularly along Farrell Creek where thick permeable deposits seem to be present. A thick deposit of sand and gravel was also modelled within the Graham River valley; however, it remains uncertain whether in fact the deposit is thick due to the limited, but deep, top of bedrock contacts in the area. Outside of the area shown in Figure 29, additional surveys (geophysical and drilling) should be performed in the Doig River area to supplement the preliminary work done by Hall et al. (2017) in evaluating Quaternary aquifers for a community water supply, as this area offers an ideal location to investigate one large mapped paleovalley, while also benefiting the Doig River First Nations community. As geological characterization of the Quaternary lithology has been accomplished through the Peace Project drilling program, these recommendations for further localized Quaternary investigations should focus on characterizing the water resource potential and investigation of deep paleovalleys.

The thickness of Quaternary sediments (i.e. depth to bedrock) modelled by Morgan (2018; Figure 29) could be also used to identify areas where thin Quaternary cover might allow for a water well to reach a potential bedrock aquifer more readily. However, this would need to be combined with a map of bedrock stratigraphy to target aquifer units (i.e. sandstones). Therefore, potential target locations for further bedrock characterization are not identified in this report.

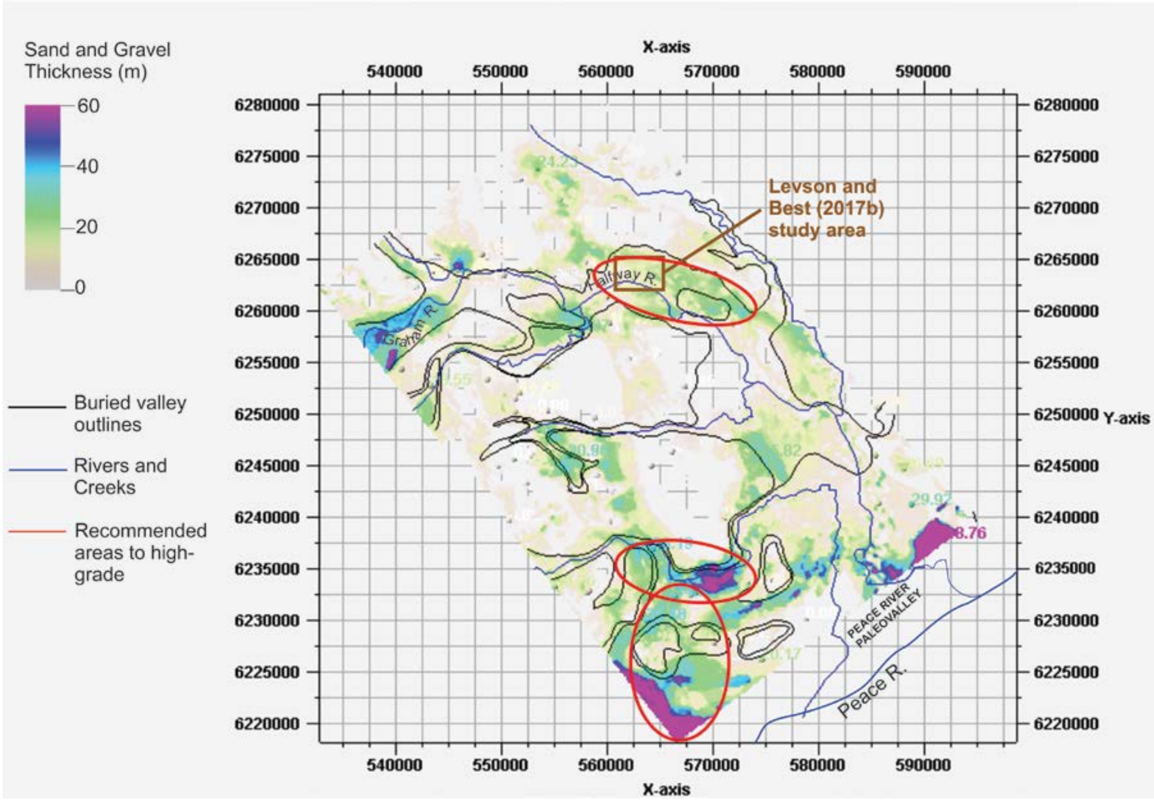

Figure 29. **Map showing the thickness of sand and gravel facies from Morgan (2018) with recommended areas to high-grade for localized improved Quaternary characterization, with future geophysical surveys and hydrogeological investigations shown in red circles.**

5.2. Recommendations for Extension Studies

In addition to conducting further geophysical surveys and field investigations, a few collaborative studies are suggested. Firstly, a study should be carried out which co-interprets the 1D resistivity results for the entire Peace Project area (SkyTEM Surveys ApS, 2015) and the detailed 3D resistivity results (Aarhus Geophysics 2016a-e; Aarhus Geophysics ApS and GEUS, 2017). The 1D results cover a much larger area, and if these data can be reconciled with the 3D results, the regional Quaternary and bedrock geology could be investigated, particularly the full extent of the buried valleys, which were often truncated by the 3D inversion extent. Second, comparison studies should be performed in areas where there is overlap in interpreted results, such as areas where local-scale investigations overlap with regional-scale investigations. For example, if future seismic surveys and detailed geological modelling are conducted in the areas recommended from Figure 29, these results could be compared to the regional geological modelling performed by Morgan (2018). Given the success of the AEM survey, and the wealth of information it provided on the regional geology, it is highly recommended that a similar survey be flown south of the Peace River, ideally encompassing the Groundbirch area where ground-based paleovalley studies have already been completed (e.g. Hickin et al., 2016). There are also many water wells south of the Peace River with lithology logs and water chemistry data, both of which would be useful in constraining the AEM interpretations. It is recommended that this survey have a similar design as the AEM survey from the Peace Project, so that regional correlations can be made. Should future work pursue bedrock characterization, a survey with a greater depth of investigation would be warranted so as to not focus on the shallow subsurface.

Finally, it is recommended that all of the acquired data, geological interpretations, distribution of aquifers, and outlines of paleovalleys, be incorporated into a GIS-based support tool that provides the public with information on aquifers and groundwater in the Peace Region.

6. Conclusions and Main Findings

The Peace Project was initiated by Geoscience BC in 2015 to provide new knowledge on the potential groundwater resources in the Peace Region of NEBC. This goal was achieved through various studies and field campaigns including airborne geophysical surveys, drilling, downhole geophysical logging, collecting and interpreting various geological data, and conducting detailed geological and hydrogeological modelling. The results and combined interpretations from these various studies have led to an enhanced understanding of the distribution of aquifers, buried valleys, and potential groundwater resources in the Peace Region. Future geophysical surveys, hydrogeological investigations, and extension studies are recommended to further improve this knowledge.

The following are the main findings from the Peace Project:

- The results of the SkyTEM survey were successfully used in interpreting the shallow (200 - 300m) lithology of the Peace Project study area. The corrected gamma-ray logs were also effective in identifying the Quaternary-bedrock contact, and Quaternary and bedrock lithologies.
- The Peace Project drilling program allowed for verification and calibration of the AEM and corrected gamma-ray geological interpretations. The AEM data

correlate reasonably well with the borehole logs obtained during drilling, and inconsistencies are likely a result of the different scale/resolution to which the data are best suited (i.e. regional versus fine-detailed local scale).

- The results of the drilling confirmed the presence of deep paleovalleys in the Peace Project study area. All wells were expected to encounter bedrock; however, bedrock was only reached at one well. Therefore, Quaternary fill within the paleovalleys is likely thicker than expected. The Quaternary sediments encountered during drilling are also very heterogeneous.

- Hydrogeological studies identified potential unconsolidated aquifer units within the Doig and Halfway River First Nations areas through geological interpretations of the Project data.

- Hydrogeological modelling results suggest that permeable unconsolidated deposits exist within the paleovalleys at local scales. These may offer a viable water source for low demand users, especially when compared to shallow aquifers that have a higher potential for hydraulic connection with surface water.

- The hydrogeological modelling results indicate that deep permeable deposits do not appear to be regionally continuous throughout the entire paleovalley network. Thus, it is unlikely that they play a significant role in regional groundwater flow. However, bedrock aquifers may offer a more regionally extensive, predictable, and reliable groundwater source for both low and high demand users in NEBC.

- Recommendations for future work include:

    - additional geophysical surveys (e.g. seismic, ground-based EM, a SkyTEM survey flown south of the Peace River),

    - more drilling (to further geological understanding of the area and conduct hydrogeological investigations such as pumping tests),

    - new regulations for oil and gas, and water wells which record depth to bedrock values and make them publicly available,

    - collaborative studies (i.e. co-interpreting the 1D and 3D resistivity results, comparison studies where there is overlap in interpreted results; and,

    - development of a public GIS-based support tool.

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