Natural Resources Canada / Ressources naturelles Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8939

Evaluation of geothermal resource potential of hot sedimentary aquifers in the Horn River Basin, northeast British Columbia, Canada

P. Akto, Z. Chen, and K. Hu

2023

Canada

ISSN 2816-7155
ISBN 978-0-660-46783-2
Catalogue No. M183-2/8939E-PDF

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8939

Evaluation of geothermal resource potential of hot sedimentary aquifers in the Horn River Basin, northeast British Columbia, Canada

P. Akto[1], Z. Chen[2], and K. Hu[2]

[1]Geothermal Consulting Services, 2527 1 Avenue N.W., Unit 306, Calgary, Alberta
[2]Geological Survey of Canada, 3303-33rd Street N.W., Calgary, Alberta

2023

Permanent link: https://doi.org/10.4095/331225

This publication is available for free download through GEOSCAN (https://geoscan.nrcan.gc.ca/).
Recommended citation

Akto, P., Chen Z., and Hu, K., 2023. Evaluation of geothermal resource potential of hot sedimentary aquifers in the Horn River Basin, northeast British Columbia, Canada; Geological Survey of Canada, Open File 8939, 38 p. https://doi.org/10.4095/331225

Publications in this series have not been edited; they are released as submitted by the author.

TABLE OF CONTENTS

Abbreviations

Abbreviation	Full
%	Percent
Av.	Average
BHT	Borehole Temperature
CE	Cordova Embayment
Cum.	Cumulative
CWP	Cumulative Water Production
e6, e9	$*10^6$,$*10^9$
F	Formation
HRB	Horn River Basin
HRG	Horn River Group
Hrs.	Hours
HSB	Hot sedimentary basin
ID	Identification
Km	Kilometer
m	Meter (s)
m^3	Cubic meters
masl	Meters above sea level
min.	Minutes
NTS	National Topographic System
ºC	Degrees centigrade
Perm.	Permeability
Prod.	Production
Sub-HRG	Sub-Horn River Group
T	Temperature
UWI	Unique well identifier

ABSTRACT

This study assesses the geothermal potential of Hot Sedimentary Aquifers underlying the Horn River Basin (HRB) based on analyses of borehole temperatures, geological and production data, core porosity and permeability measurements, and geophysical well logs. The proposed criteria are applied to evaluate the geothermal potential of the Horn River Group (HRG) and sub-HRG formations. Favourable spots are identified and ranked by applying temperature, thickness, porosity, permeability and flow rate mapping.

The results show that the HRG and its underlying strata have a good potential of geothermal energy resource. Among the HRG formations with an average temperature of 110°C, the Otter Park Formation is the hottest and relatively thick with high water production rate. The Muskwa Formation is the second favourable for geothermal resource potential. Within the sub-HRGs, the Slave Point Formation is the most advantageous because of the high flow rate and high temperature, while the Keg River Formation is the hottest and thickest, and is considered as the second favorable stratigraphic unit.

Combining the geological and geographical characteristics, four favourable hot zones have been identified, further indicating that the northwest Zone 1 and the southeast Zone 4 are the hottest areas with thicker reservoirs (>300m) and higher temperatures >130°C (at depth >3 km).

1. INTRODUCTION

The Western Canada Sedimentary Basin (WCSB) is a vast wedge-shaped depositional basin containing deposits that host Canada's hydrocarbon wealth. Within the hydrocarbon-rich sedimentary layers, there are abundant aquifers that contain large amounts of stored warm water, representing a potential geothermal resource. Such an undeveloped resource is called as Hot Sedimentary Aquifers (HSA) that can be characterized using exploratory drilling and production data collected by hydrocarbon producers.

The HSA-type geothermal system, with a temperature of <190°C, has been classified as a "Low-Temperature" resource (Sanyal, 2005). Albeit the inherently low temperature, the high water content of these HSA reservoirs, coupled with the average geothermal gradient (>30°C/km), makes them attractive for the extraction of geothermal energy. The heat in the WCSB's HSAs is produced by the radioactive decay of instable chemical elements in metamorphic and igneous rocks that lie beneath the WCSB, as well as in the fine-grained sedimentary rocks of the basin. The geothermal gradient and heat flow through the sedimentary strata in the WCSB are highly variable, ranging from approximately 20 to >50°C/km and 40 to >90 mW/m^2, respectively (Majorowicz, 2018).

The HRB of the WCSB is located in NEBC (North East British Columbia) and contains substantial resources of energy. It predominantly encompasses unconventional gas reservoirs, which have been explored for decades. Currently, there are more than 1,200 wells drilled within the HRB. After the Montney unconventional play, the HRB is the second-largest productive play in BC (BC MEM-NEB, 2011). By the end of 2016, it accounted for 5% of the province's total gas production

($38,782\ 10^6 m^3$ - 1,370 Bcf). In the overall production of the HRB, oil is a relatively negligible (BC Oil and Gas Commission, 2017).

The average geothermal gradient and heat flow in NEBC are approximately 40-50°C/km and 70-90 mW/m^2, respectively, featuring a hot area called the northern hot spot in the WCSB (Majorowicz, 2018). In addition to oil and gas production, many of the wells drilled in the HRB co-produce warm water from deep aquifers. This warm water can be utilized directly or indirectly as a source of thermal energy. The direct use of geothermal waters includes heating the commercial-scale buildings, greenhouses, district heating, providing waters for spas and swimming pools, lumber drying, etc. Power generation is the indirect utilization of these types of fluids.

Several approaches can be adapted to access geothermal waters of HSAs, such as co-produced fluids alongside oil and gas, drilling to reach hotter formations, or re-using abandoned or inactive wells to extract hot waters from cased formations or hidden geo-pressured reservoirs. It is highly potential to make use of the geothermal energy available in the deep and hot sedimentary aquifers, and sustainably produce heat and power energy for industries and local communities in remote areas. The geothermal energy generated in the HSAs situated in NEBC could also be used as a secure, base-load energy source for many domestic, commercial, and industrial applications. Additionally, it will help reduce carbon emissions by offsetting the use of fossil fuels to generate heat or electricity.

The Geological Survey of Canada-Calgary (GSCC) was interested in using the available data collected from various sources through petroleum exploration and production wells to assess the geothermal potential of HSA resources in the HRB. The GSCC specifically requested a geothermal resource assessment of the HRG shale formations. In addition to the HRG, the current study also investigates the geothermal potential of sub-HRG formations to obtain a broader picture of the reservoir volume that stores the heat energy and formation water for geothermal energy production in the HRB.

The initial target of this project is the HRG shales that have been hydraulically fractured for gas production, under the hybrid geothermal project of the GNES program. Those shales are intrinsically tight and not suitable for the sustainable production of geothermal fluids. New ideas and unconventional techniques are required to tap the geothermal resource from the unconventional reservoir. Recent studies (e.g., Palmer-Wilson, et al., 2018) suggest that the underlying and associated carbonates, particularly reefal carbonates and hydrothermal dolomites, have high geothermal potential. Therefore, the target strata of this study are expanded to the sub-HRG to attain a better understanding of the Devonian section sandwiched between the Fort Simpson Formation (top) and the Lower Keg River Formation (bottom).

To achieve this goal, geology and production data namely: temperature, depth, gross thickness, porosity, permeability, and water production rate were collected, filtered, analyzed, and interpreted. Potential aquifers were ranked based on reservoir temperature and data quality, and water flows in both HRG and sub-HRG.

2. LITERATURE REVIEW

Since 1962, studies have been conducted to map and assess Canada's geothermal resources. The "Geothermal Research Program" is one of the studies initiated by the Canadian Government in 1976, in response to the global oil crisis (Jessop et al., 1991). This research program accelerated the studies carried out by the Geological Survey of Canada (GSC) in two areas: the Mount Meager Volcanic Complex of the Garibaldi Volcanic Belt in British Columbia, and the Regina volcano group on the north flank of the Williston Basin in Saskatchewan. This program was terminated in 1986 due to the drop in oil prices and in an attempt to mitigate public fear caused by supply shortages (Jessop et al., 1991).

The study of the potential geothermal energy resource in Canada by Grasby et al. (2012) suggested that there are substantial resources in a wide variety of geological settings. While high-temperature geothermal resources for power generation are associated with the active plate tectonic boundaries in western, such as in the Garibaldi Volcanic Belt; the direct use potential is broadly distributed in the sedimentary basins from coast to coast in Canada, particularly in the warmer western half of the WCSB, with the highest potential regions for the binary power generation being located in British Columbia, Yukon, NWT, and northern Alberta. The potential for binary system electrical generation, associated with warm sedimentary basins, also occurs in the vast areas of western and northern Canada. For decades, however, the geothermal exploration efforts in Canada have focused on high-temperature and conventional hydrothermal systems associated with volcanic belts in the west. In the past two decades, with the increase in data volume and accuracy from the petroleum industry, in addition to the improvement in reservoir enhancement technology and the innovation of the high-efficiency binary power generation technology, the attention of geothermal geoscientists and developers have shifted to include "low-temperature and low permeable geothermal systems". This type of geothermal potential consists of HSA and Enhanced/Engineered Geothermal Systems (EGS) in the WCSB. If the EGS technology is applied to the crystalline basement of the WCSB, more geothermal resources could be added to the assumed resources (Majorowicz and Moore, 2008). More recently, Majorowicz and Moore (2014), and Majorowicz (2018) mapped the heat flow and investigated the geothermal gradient of the WCSB based on an extensive thermal database, and showed that the deep formations (3-5 km) could provide hot fluids (100-210°C) at a flow rate of 5-50 l/s if the EGS technology could be applied.

Their studies suggested that thermal gradients appear to be low (20°C/km) in the southwestern part of the WCSB, and moderate in southern Alberta (30-45°C/km) and the central-western section of the basin (>35°C/km). The geothermal gradients in southeastern Saskatchewan and the northwestern part of the basin, where Fort Nelson and Fort Liard communities are located, are 40°C/km and 40-50°C/km, respectively (Majorowicz, 2018). Compared to other sedimentary basins in the world, the geothermal gradient of 35-50°C/km in most areas of the WCSB is considered high (Jessop, 1992). Paleozoic carbonate formations appear to have the highest potential from HSA and are suitable for geothermal development (e.g., Weides et al., 2012, 2013; Ardakani et al., 2016).

In some areas of the basin, such as northern Alberta, northeastern British Columbia, and southern Northwest Territories, thick overburden coupled with high heat flow (>80 mW/m^2) shows high thermal resource potential (Majorowicz and Grasby, 2010). Whereas in other areas such as in northeastern Alberta beneath the Athabasca oil sands, where the sedimentary wedge thins out, the temperature from the crystalline Precambrian basement can reach 60°C, becoming the target for spacing heating (Majorowicz et al., 2012). In areas such as Hinton in Alberta, Estevan in Saskatchewan, and near Fort Liard in NWT where temperatures exceed 120°C and fluid production rate is >80 kg/s, resource potentials for binary electricity generation exist (Majorowicz and Grasby, 2021).

In 2013, Canadian Geothermal Energy Association (CanGEA) conducted a geothermal favourability study in Alberta and estimated that the power generation potential at a depth of 5.5 km can reach 175,000 MWe with a recovery rate of 14% (CanGEA, 2013). Banks et al. (2017) performed a detailed feasibility study in Alberta and identified 22 hydrocarbon pools with temperatures over 100°C, and introduced four potential mid-Devonian formations, including Leduc, Swan Hills, Giltwood, and Granite Wash. They also suggested that these formations include over 6,100 MWt of thermal power capacity and over 1,150 MWe of technically recoverable power generation potential for a production period of 30-years. To tap those resources, it is recommended to increase the productivity by hydraulic fracturing stimulation coupled with horizontal or inclined wells treatments (Hoffman, 2015). However, commercializing geothermal resource production in the WCSB is challenging because the viable temperature (>120°C) is inconsistent with the permeable formation at economic drilling depth (Hickson et al., 2020).

Majorowicz and Grasby (2021) conducted a geothermal feasibility analysis for municipalities, indicating that geothermal energy can be obtained from several geological formations such as Lower to Middle Cambrian basal sandstone and Deadwood Formation, and Devonian Winnipegosis Formation, the Beaver Hill Lake, Winterburn and Wabamun groups. They also suggested that municipalities located in the WCSB above sediment with a thickness in excess of 2-3 km can be directly heated by geothermal energy.

Most studies within the WCSB focused on the identification of HSA and EGS resources with low and moderate temperatures, evaluating the resource potential by examining thermal gradient and temperature mapping along with geological features, such as thickness, porosity and permeability. A few mathematical models have also been used to map the relationship between the heat flux and water flow in the deep sedimentary formations of Alberta and suggested that as the heat flux increases, the water density decreases, leading to the upwelling of hot water and increasing the economic geothermal potential (Graf, 2009). However, it is worth noting that most studies on the geothermal potential of the WCSB are based on subsurface temperature data obtained from industrial sources, which is subject to biases due to the overall quality of the data (Gray et al., 2012) and the viewpoint of resource from thermal conductivity without considering regionally and locally focused convective heat flow.

Most of NEBC's geothermal studies have focused on the Middle Devonian aquifers and showed that the porous carbonate reservoir in the Clarke Lake Gas Field with a geothermal gradient greater than 50°C/km and formation water temperature higher than 110°C, may provide sustainable geothermal energy capability of 12 to 74 MW (Renaud et al., 2018), supplying most of the energy needs of local communities and oil and gas facilities (Walsh and Tu, 2014).

Palmer-Wilson, et al. (2018) evaluated the technical and economic potential of geothermal energy resources in NEBC, and highlighted favourable areas. They quantified the available electricity production at four locations within the study area, namely Horn River, Clarke Lake, Prophet River, and Jedney. In their approach, they used temperature and water flow rate from Devonian aquifers as the geothermal reservoir criteria, and the access to electrical transmission grids, the potential for industry activities, and proximity to community centers as "economic measures". Their geothermal resource assessment suggested that the Clark Lake gas field has the largest resource potential and the gross power generation capacity is 71.3 MW at 50% probability. Whereas the Horn River Basin is the least with an estimated gross power generation capacity of 5.2 MWe (P50).

The BC government has recently granted a license and provided financial support to the indigenous communities of the Fort Nelson to advance the Geothermal Project in Clark Lake and use geothermal energy to replace power generated from fossil fuels (https://www.cbc.ca/news/canada/british-columbia/fort-nelson-first-nation-clarke-lake-geothermal-project-funding-shortfall-1.5821432).

3. GEOLOGY OF THE STUDY AREA

The HRB, a sub-basin of the WCSB is located between 58-60°N and 121-124°W in the northeast British Columbia. It covers an area of over 1.1 million hectares, 3,000 square miles, underling the north of Fort Nelson and south of the Northwest Territories border (Figure 1).

The HRB is bounded by Devonian-aged carbonate rocks of the Cordova Embayment (CE) in the east, and the Bovie Lake Structure in the west, which also separates the HRB from the Liard Basin (Figure 2). The Devonian is one of the major oil and gas producers in the WCSB (Field et. al., 1970; Mossop and Shetsen, 1994) and becomes the target for geothermal resource development in recent years (e.g., Gray et al., 2012; Weides et al., 2014; Banks, 2017; Palmer-Wilson, et al., 2018). Although various studies have been conducted on geothermal resource potential in northwest BC, the HRG shales are excluded from geothermal energy studies because of their low natural permeability, which usually requires artificial fracturing to enhance hydraulic conductivity. The current study aims to evaluate the geothermal potential of the HRG shales within the HRB as a part of feasibility study of converting shale gas production horizontal well network to geothermal production facility to support Canadian government's goal of achieving net-zero CO_2 emission in 2050.

3.1. Horn River Group

The Middle and Upper Devonian HRG shale were deposited within a *ca.* 8 M.a. time interval (late Eifelian to early Frasnian stages) and consists of Evie/Klua and Otter Park formations and Muskwa Formation (Oldale and Munday, 1994; Reynolds et al., 2010; Hulsey, 2011). These units are predominantly composed of shale and are lateral basinal equivalents of reefal carbonates of the Cordova Embayment (CE): the Upper Keg River, Sulphur Point (Elk Point Group), and Slave Point (Beaverhill Lake Group) (Oldale and Munday, 1994; Meijer Drees: 1994) (Figure 2).

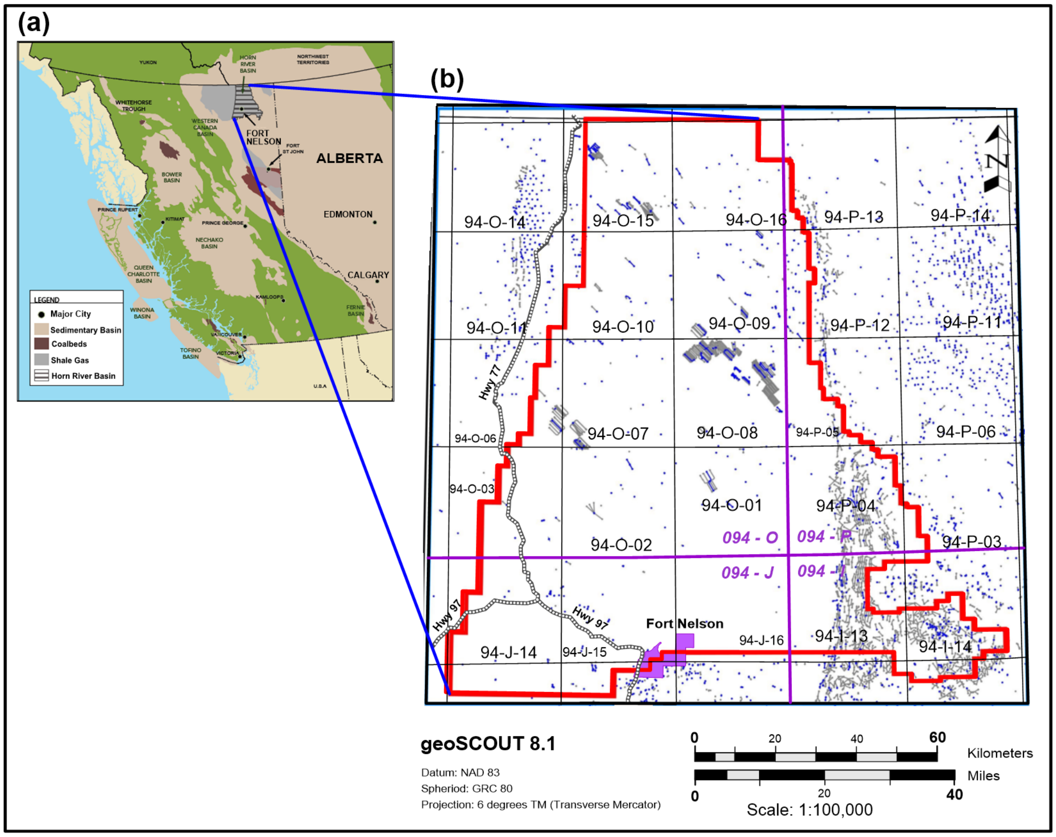
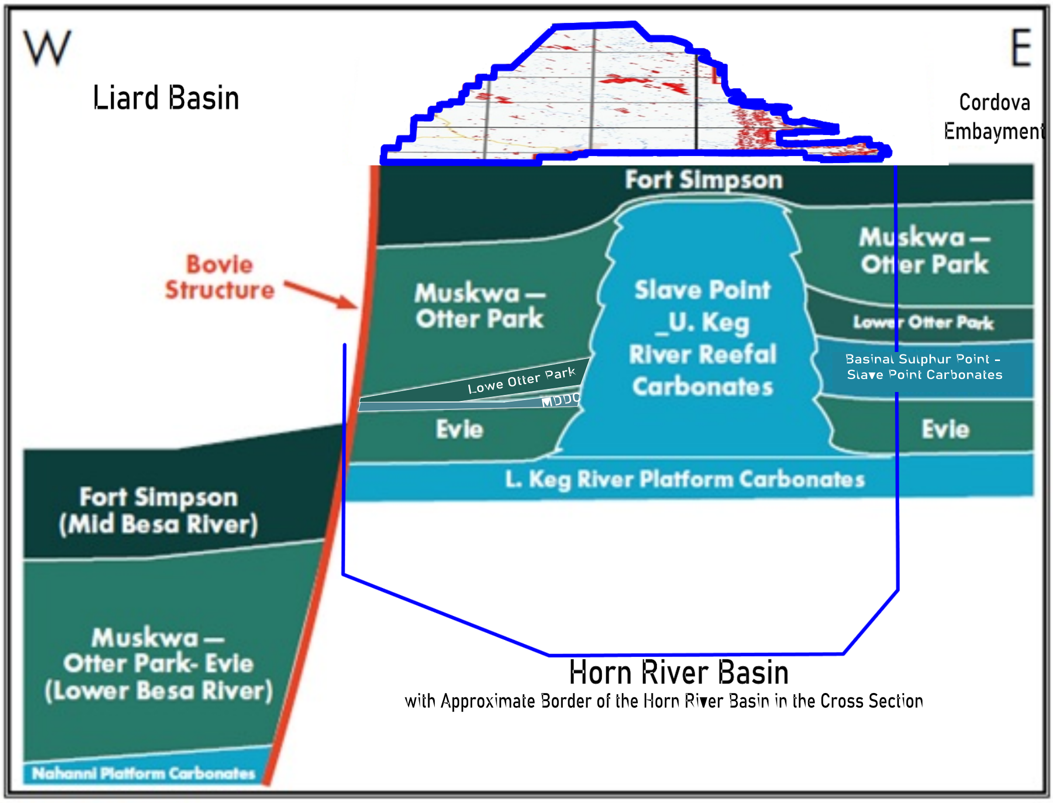


Figure 1: a) Location map (modified from BC MEM-NEB, 2011), and
b) Regional base map of the Horn River Basin (solid red boundary).

3.1.1. Evie/Klua Formations

The Evie Formation is composed of a dark grey to black, organic- and pyrite-rich calcareous siliceous shale (Dong, 2016), which unconformably overlies the lower Keg River Platform carbonates. It constitutes the lower part of the most radioactive shales with the highest total organic content in the Horn River Shale (McPhail et al., 2008; Dong et al., 2015). The Evie Formation is correlative to the Keg River and Sulphur Point reefal carbonates (Elk Point Group) (Meijer Drees, 1994; Ness et al, 2010) (Figure 2). The uppermost part of the Evie Formation becomes more silty and argillaceous (clay-rich) (Dong, 2016) and has a thickness of over 70 m from the west of the Upper Keg River to the Slave Point platform margin. Near the Bovie Lake Structure, the thickness of the Evie Formation thins to less than 40 m (McPhail et al., 2008).

The bituminous shales of the Klua Formation of the CE, known as "a tongue of Otter Park shale in the carbonate barrier" (Williams, 1983), are proposed to be an equivalent to the Evie Formation in the HRB. The Klua and Evie Formations are combined and referred to as Evie/Klua Formations in this report. The difference between these two formations is only associated with the direct and indirect transition of the Klua and Evie Formations towards the Otter Park Formation, respectively (Morrow et al., 2002).



Source: AAPG Explorer

Figure 2: Cross-section showing the stratigraphy of the Horn River Basin (schematic solid blue boundary and lines), Cordova Embayment, Liard Basin (modified from Ross and Bustin, 2008).

3.1.2. Otter Park Formation

The Otter Park Formation consists of grey to dark grey, pyritic, non-calcareous to calcareous, and siliceous shale with less radioactivity and total organic content than the underlying Evie Formation and the overlying Muskwa Formation (McPhail et al., 2008; Dong et al., 2015), and becomes less calcareous and more siliceous upwards (Dong, 2016). It is correlative to the Middle Devonian carbonates of the Slave Point, and Swan Hills formations (Beaver Hills Lake Group) (Oldale and Munday, 1994; Ness et al., 2010) (Figure 2). The Otter Park Formation has a maximum thickness of over 270 m in the southeast corner of the HRB, and thins northwards and westwards, where it contains more radioactive siliceous black shale beds (McPhail et al., 2008).

The Otter Park Formation comprises three units (lower, middle, and upper) based on its relative organic and clay content (Ness et al., 2010). The lower Otter Park is an organic-rich unit, which is correlative with the Slave Point and possibly the initial reef developments of the Swan Hills Formation. In comparison to the lower Otter Park unit, the middle and upper Otter Park units show distinctive depositional styles (clinoform geometries) and more clay-rich. The lower and middle Otter Park units are linked to the intraformational unconformity in the Swan Hills Formation and the upper part of the Swan Hills, respectively, and the Upper Otter Park unit is proposed to be equivalent to the Waterways Formation (Ness et al., 2010).

3.1.3. Muskwa Formation

The Muskwa Formation is dominantly composed of grey to black, organic-rich, generally siliceous shales, which represents the upper package of highly radioactive shales in the Horn River Formation (McPhail et al., 2008; Zahrani, 2011; Dong et al., 2015). It underlies the silt-rich shales of the Fort Simpson Formation (Ross and Bustin, 2008) and is mainly equivalent to the Slave Point Formation (Beaver Hills Lake Group) (Oldale and Munday, 1994).

The Muskwa Formation in the HRB is 30 m thick from the vicinity of the Upper Keg River to the Slave Point platform margin, and 60 m thick near the Bovie Lake Structure on the western side of the basin. Its thickness decreases significantly at the southeast corner of the HRB, where the Otter Park Formation reaches the maximum thickness (over 270 m). In the CE, the thickness varies from 50 to 70 m. The Muskwa Formation extends over the Slave Point Formation in the adjacent reefal carbonates and the entire northeastern BC, distinguishing it from the underlying Evie and Otter Park shales that are restricted only to the CE and HRB (McPhail et al., 2008).

3.2. Middle to Upper Devonian Shallow Marine Carbonate Platform Formations

3.2.1. Keg River Formation

The Keg River Formation of the Elk Point Group was deposited in the intracratonic Elk Point Basin and is divided into the lower and upper formations of the Keg River. They are composed of fossiliferous shallow marine carbonates (predominantly limestone and dolostone), which were deposited during a period of sea transgression. Subsequent sea-level falls along with the development of the Presqu'ile Barrier Reef led to the restriction of the Elk Point Basin, resulting in the formation of the Prairie Evaporite. Most of the Keg River strata are characterized by porous dolomites, which are converted from the original limestone during the Prairie evaporitic phase (Meijer Drees, 1994; Rogers, 2017). The Evie/Klua formations of the HRB conformably overlie the Keg River Formation in northeastern BC and are considered as the basinal equivalent of these reefal carbonates (Meijer Drees, 1994; Ness et al, 2010) (Figure 2).

3.2.2. Pine Point, Sulphur Point, and Slave Point Formation

The reefal carbonates of the Pine Point and Sulphur Point formations (Elk Point group) and Slave Point Formation (Beaverhill Lake Group) constitute the lower and upper part of the Presqu'ile Barrier reef, respectively (Meijer Drees, 1994). Skall (1975) classified the fossiliferous dolostone of the Pine Point Formation into the group consisting of the Keg River and Sulphur Point formations. The Sulphur Point Formation is comprised of fossiliferous limestone and the Slave Point Formation consists of limestone with minor dolomite (Oldale and Munday, 1994; Meijer Drees, 1994). They are best developed in the CE and up to 60 m thick. In the HRB, the basinal equivalents of these reefal facies are composed of argillaceous limestone and interbedded shale (Morrow et al., 2002), which are regionally traceable and thins westwards from 15 m to 5 m in the vicinity of the Bovie Lake Structure (McPhail et al., 2008).

3.3. Middle Devonian Carbonates (MDDC)

The Middle Devonian Carbonate (MDDC) is a thin regionally widespread basinal carbonate beds, consisting of argillaceous buff-colored marlstone. It is correlated with the carbonates located directly above the sub-Watt Mountain unconformity (base of the Slave Point Formation) in the CE (McPhail et al., 2008; Ness et al., 2010) (Figure 2).

3.4. Basinal Detrital Formation

3.4.1. Watt Mountain and Granite Wash Formations

The Watt Mountain Formation includes siltstone and shale at the top of the Elk Point Group, representing the period of sea-level fall (mid-Givetian regression) in the Elk Point Embayment. It lies unconformably above the Sulphur Point Formation in the CE (sub-Watt Mountain unconformity) (Meijer Drees, 1994). It is the basinal equivalent of the MDDC in the HRB (Hulsey, 2011). The Granite Wash Formation is another basinal detrital formation in the HRB that is composed of interbedded sandstone, dolostone, and shale (Meijer Drees, 1994).

4. DATA AND METHODS

4.1. Data Analysis

The original data consists of the basic well information (depth, elevation, formation at depth, etc.), geology (stratigraphy column of the wells), borehole temperatures, DST (drill stem test), porosity, and permeability (core measurements), and production data (water and hydrocarbon production and injection data). We reviewed geological and wellbore factors and their effects on wells' fluid production and carried out data quality screening prior to data analysis.

A total number of 1,252 wells were collected in this study. Figure 3 presents the distribution of 612 active wells (blue points and tracks) and 640 inactive wells (grey points and tracks) in the HRB. The active wells include the wells with the latest reported status of operation from pumping and flow testing, and the inactive wells include wells that are abandoned, closed, canceled, and/or junked.

All the graphical maps such as isopach or isotherm maps were created using the "Golden Software Grapher 8" that employs the inverse distance algorithm for gridding. The acquired and interpreted multi-feature criteria used to evaluate the geothermal potential of the HSA in the HRB include subsurface temperature, depth and thickness, porosity and permeability, and flow rate.

4.2. Borehole Temperature (BHT)

Temperature data are a critical input for geothermal energy source investigation. In this study, subsurface temperature data have been compiled from petroleum exploration wells drilled in the HRB. The collected borehole temperature data includes the maximum temperatures of the drill stem tests (DSTs) from two resources (geoSCOUT database and BC Government database), and the maximum bottom-hole temperature measured from well log runs. BHTs are compiled from 200 wells in the HRB.

Well tests are designed to extract formation fluids from a limited depth interval within a borehole in order to evaluate the nature of the pore fluid and the hydraulic properties of the formation containing the fluid. Commonly, the temperature is measured during the fluid flow and pressure build-up phases of a DST. After drilling stops, the mud circulation is usually continued for a period of time, which results in the measured temperature being generally lower than the true formation temperature because of the circulation of cooler drilling mud (exceptions occur when the drilling mud is hotter than the surrounding rock formations, usually in shallow depth).

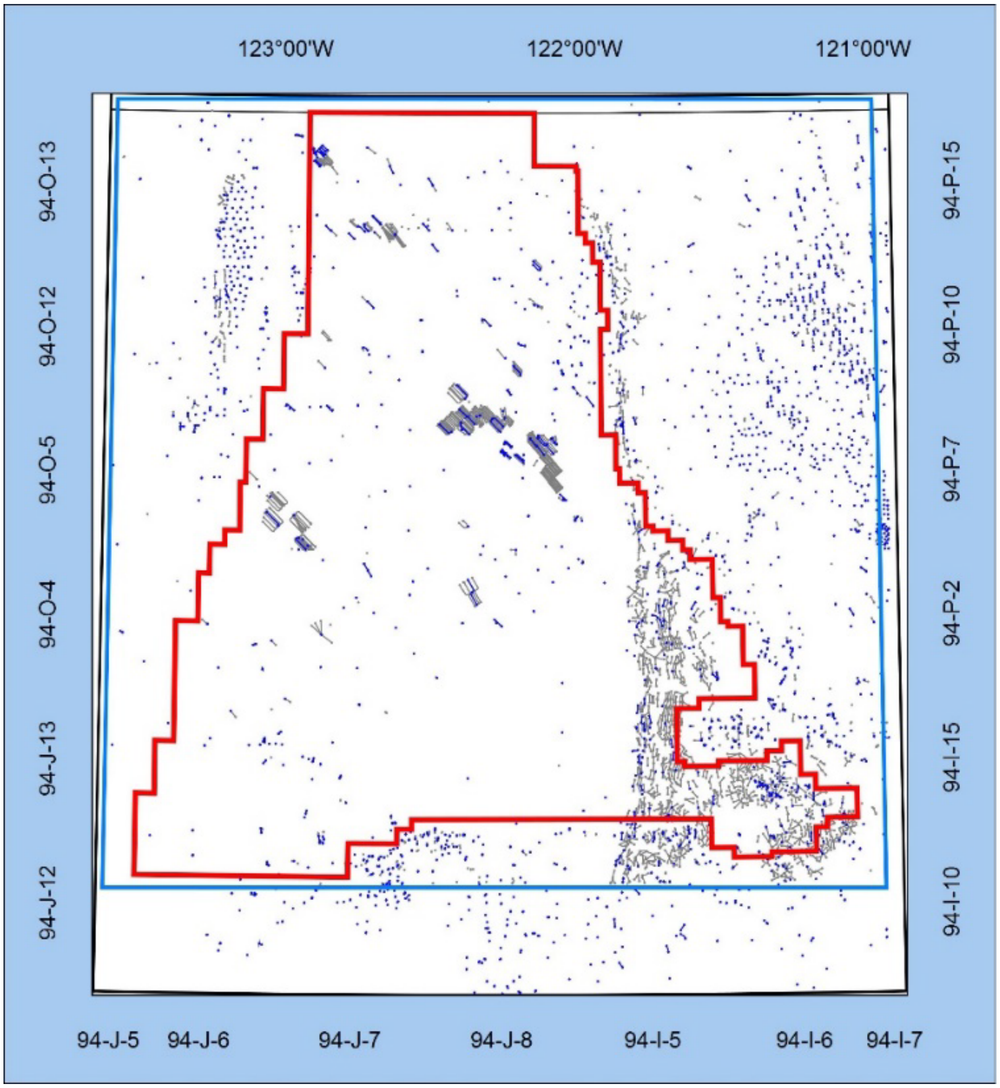


Figure 3: Distribution map of wells in the HRB. Active wells and well tracks are in blue and inactive wells and well tracks are in grey.

In the pre-feasibility study stage of the HSA resources (desktop study) which principally aims to identify potential formations or well sites, it appears that BHTs corrections do not change the result drastically. Therefore, no correction was applied to the measured BHT data in this study, but some anomaly BHTs (zero and negative temperatures) were removed from the thermal plots and maps. However, in the next stage of feasibility studies, the accuracy and precision of the data are critical for more meticulous evaluation of the reservoir's techno-economic models, and project viability assessment. Temperature data should be then corrected.

4.3. Geology (Depth and Thickness)

During drilling operation, cutting and core samples are collected by on-site geologists and interpreted for their lithology and stratigraphic units. Porosity and permeability of the rock samples are generally measured in the laboratories, which also assist the geologists to characterize different stratigraphic units. These characteristics, as well as production data (e.g. hydrocarbons or water), drilling data (rate of penetration and hardness of unit being drilled), and other parameters provide a series of unique features that help identify a stratigraphic unit bounding surfaces. Analyzing cores and cuttings and comparing them with other datasets, allow geological and reservoir models to be created.

By subsurface mapping, the depth of the top and bottom of each stratigraphic unit, a contour map of the unit is built. The depth map can be a good proxy for subsurface structure depicting various trends and boundaries because the surface relief does not seem to vary substantially in the study area.

The thickness of each stratigraphic unit was mapped in this study to show the volume of the sedimentary package as the holder of the heat resources.

4.4. Porosity and Permeability

Porosity and permeability are the most important physical properties of a reservoir rock. Porosity is the volume percentage of pore space of the rock, which is a measure of reservoir storage capacity. Permeability is a measure of the ease of flow of a fluid or gas passing through a porous solid. In this study, porosity and permeability data obtained from core measurements are compiled from 47 wells.

4.5. Flow Rate

A challenge in producing geothermal energy from the hydrocarbon-rich sedimentary basins is the lack of flow tests of the targeted formations. However, since most of oil and gas pools contain water discharged together with hydrocarbon production, the produced water can also be a good indicator of the mass flow intensity of the wells. Mass flow or flow rate is equally important as the formation temperature in the production of geothermal energy. The co-produced water volume in an oil/gas well can also indicate the permeability of the aquifer, the water storage capacity, and the mass flow potential of the formation.

In a recent study of geothermal energy potential in British Columbia's portion of the WCSB, Palmer-Wilson et al. (2018) suggested a flow rate of 0.0371 l/s to be the minimal required for power generation, which is consistent with the conclusions of a flow rate of 30 kg/s per well in Alberta portion of the same basin from other studies (Majorowicz and Moore 2014; Majorowicz and Grasby, 2014).

5. TEMPERATURE GRADIENT IN THE HRB

A total of 299 borehole temperature data points are used to create a thermal gradient and isotherm contour map of targeted formations in the HRB. Figure 4 shows the distribution of wells used for temperature gradient and mapping. Although the overall distribution of wells is uneven, the data are suitable for estimating thermal gradients (Figs. 5, 6a, and 6b), and their spatial variation presented as isothermal maps in Figs. 7-10.

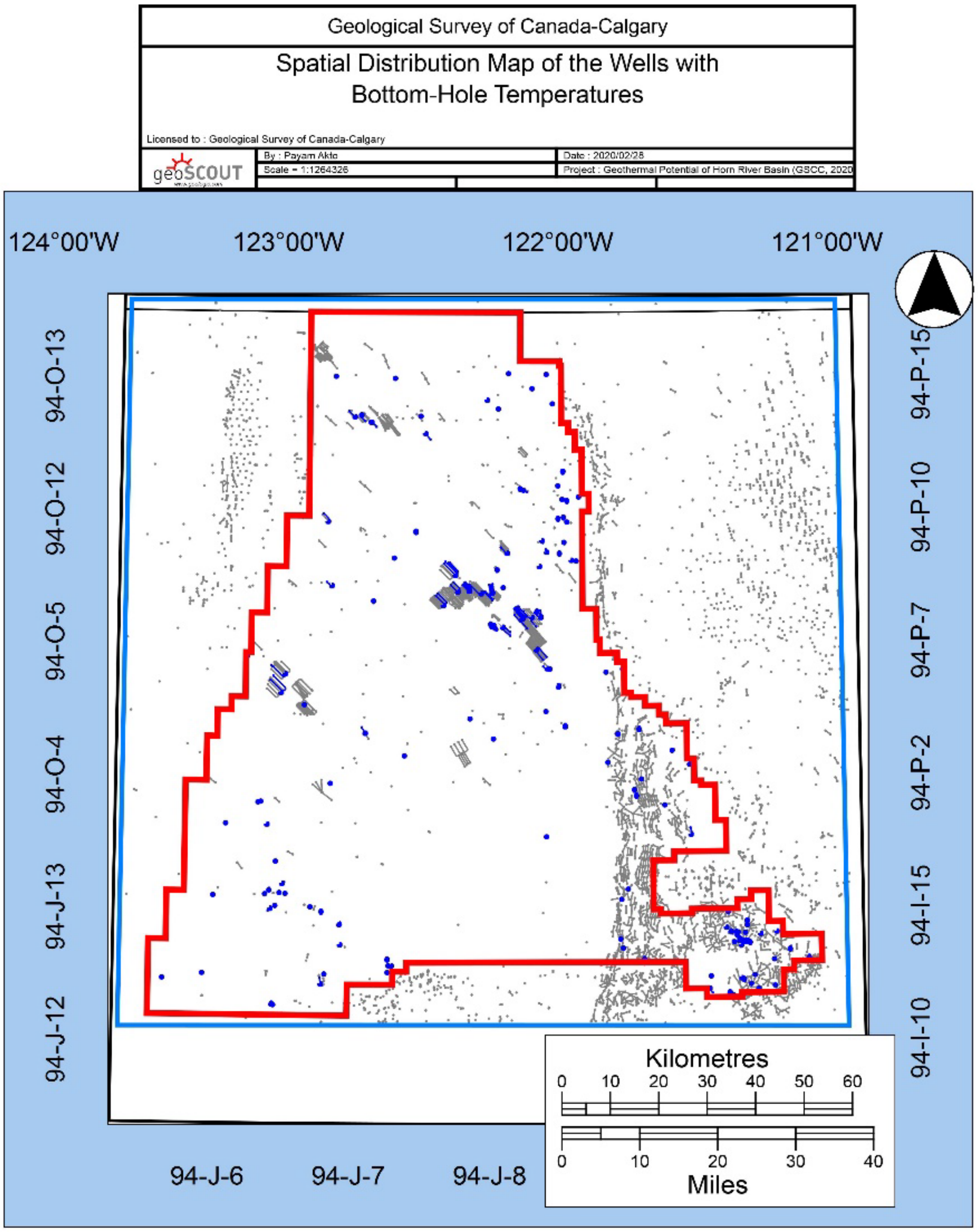


Figure 4: Spatial distribution of wells with BHTs used in the gradient plots and isothermal maps.

Figure 5 shows all the BHTs (DSTs and log-based temperatures) measured within the HRB. The average thermal gradient of the HRB is 46.4°C/km, which is higher than the global average thermal gradient (25-30°C/km; Fridleifsson et al., 2008) in the sedimentary basin, and the temperature measurements range from 12°C to 178°C.

Temperature Gradient of the Horn River Basin
(for all BHTs with no age-filter)

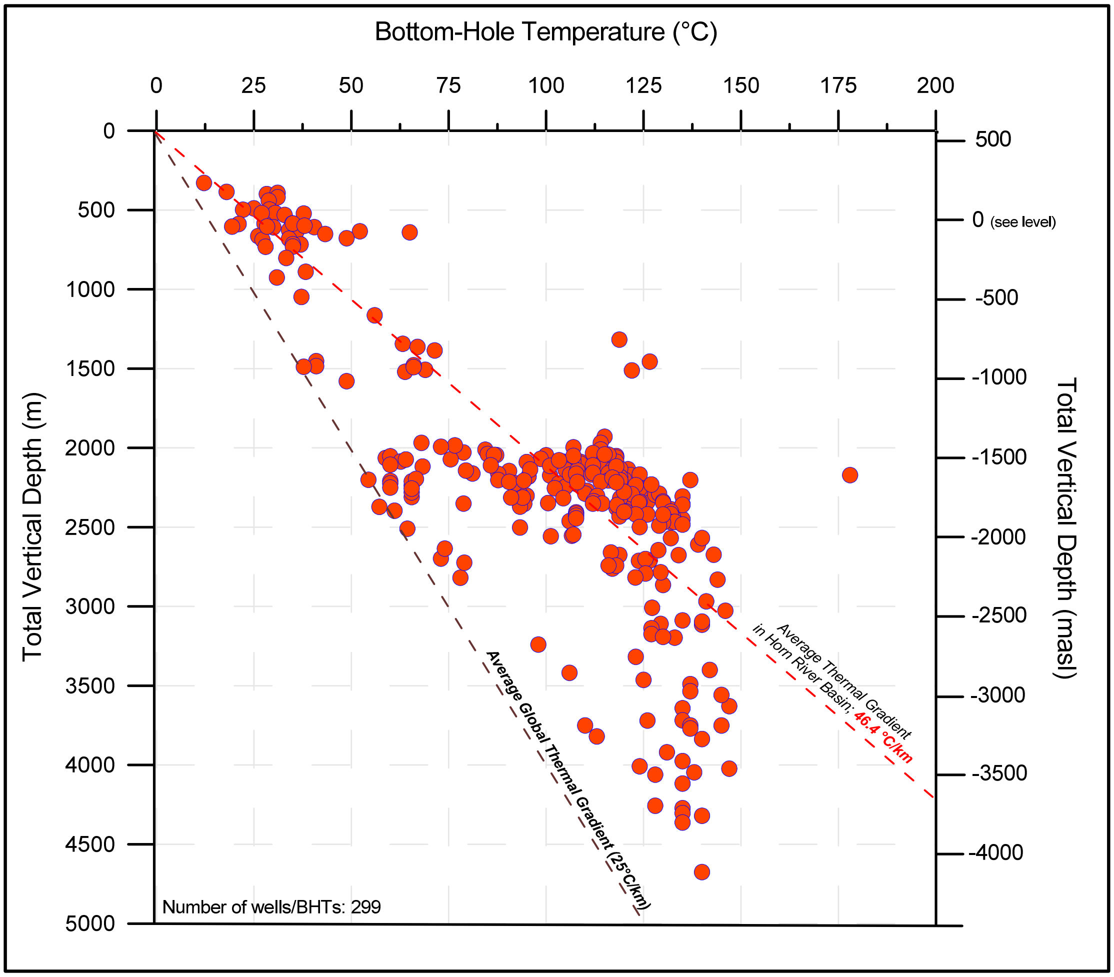
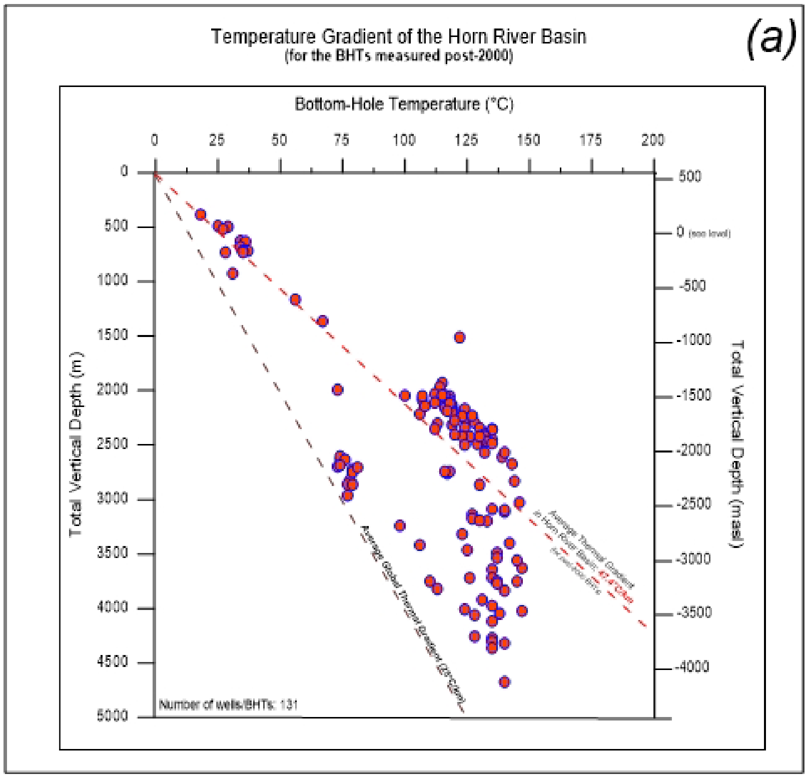


Figure 5: Temperature gradients of the Horn River Basin.

To test the data quality, BHTs of the wells are plotted separately by drilling year (Fig. 6). Figs. 6a and 6b present the BHT vs depth profile from the wells drilled after 2000 (2000-2018) and before 2000 (1955-1999), respectively. The BHT measurements recorded post-2000 at depths greater than 2 km show a relatively uniform increase with depth, which confirms that the accuracy of the recorded BHTs is satisfactory. As the post-2000 BHTs is used, the average thermal gradient is determined to be 47.4°C/km (Fig. 6a), which is comparable to the average thermal gradient of the HRB is 47.0 °C/km from the pre-2000 BHTs (Fig. 6b).



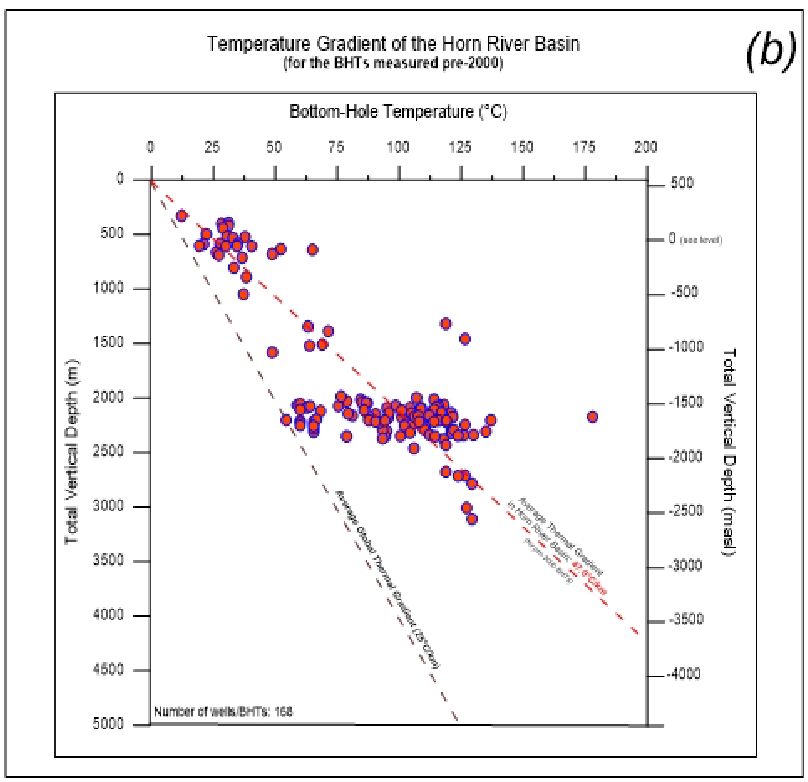


Figure 6: a) Temperature gradients calculated from post-2000 BHTs (2000–2018), b) Temperature gradients calculated from pre-2000 BHTs (1955–1999).

6. MAPPING

6.1. Isothermal Contour Maps

The isothermal contour maps are generated for different formations at various depths to highlight the temperature variation in space. For comparison, thermal maps are generated for two series of formations: (1) Basinal shale formations of the HRG namely the Muskwa formation, Otter Park Formation, and Evie/Klua Formations, as well as thin Middle Devonian Carbonates (Fig. 7), and (2) Platform carbonate formations underlying the HRG, namely the Sulphur Point, Slave Lake, Keg River, and Pine Point formations (Fig. 8).

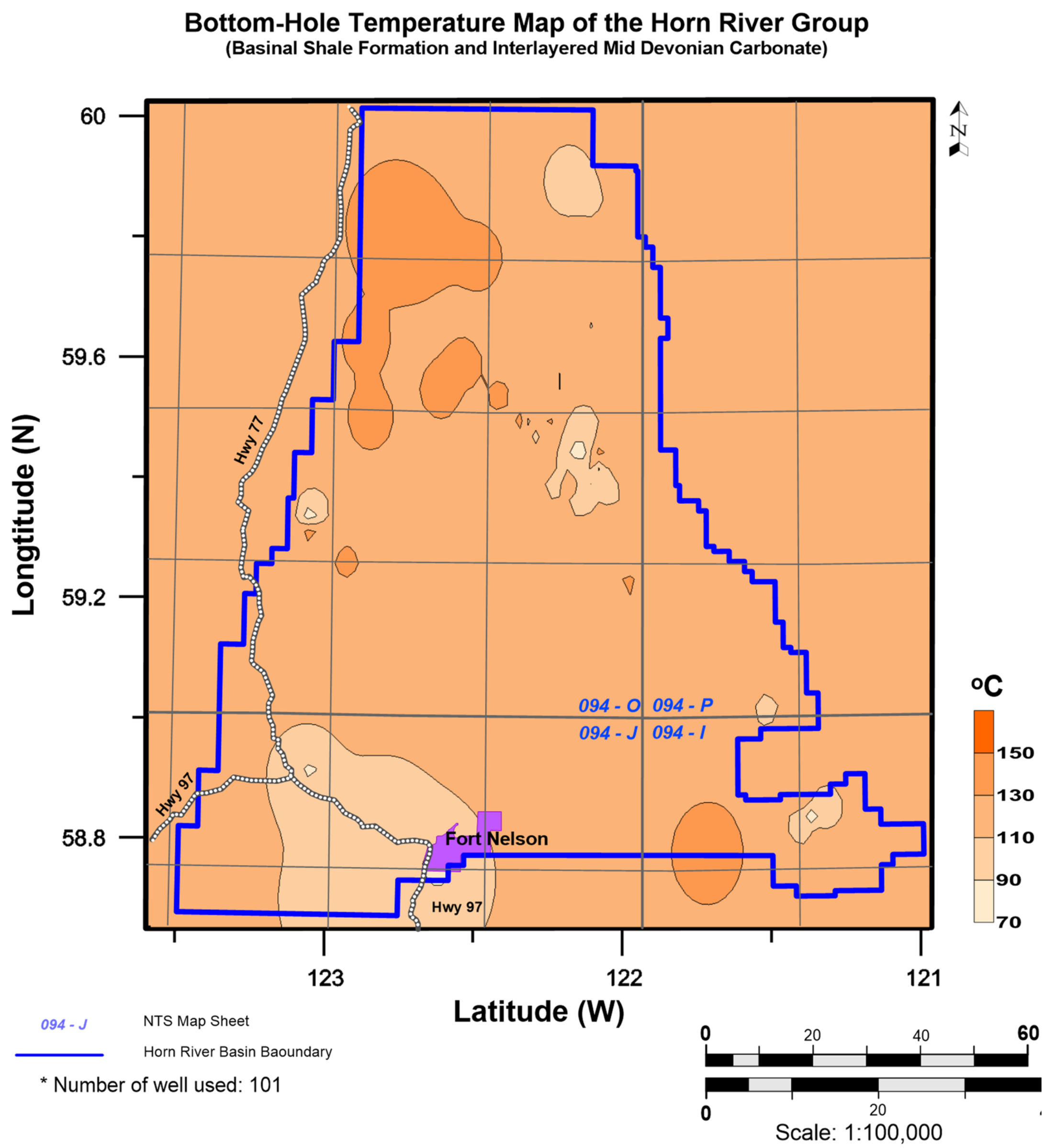


Figure 7: Isothermal contour map of the HRG basinal shales, Horn River Basin.

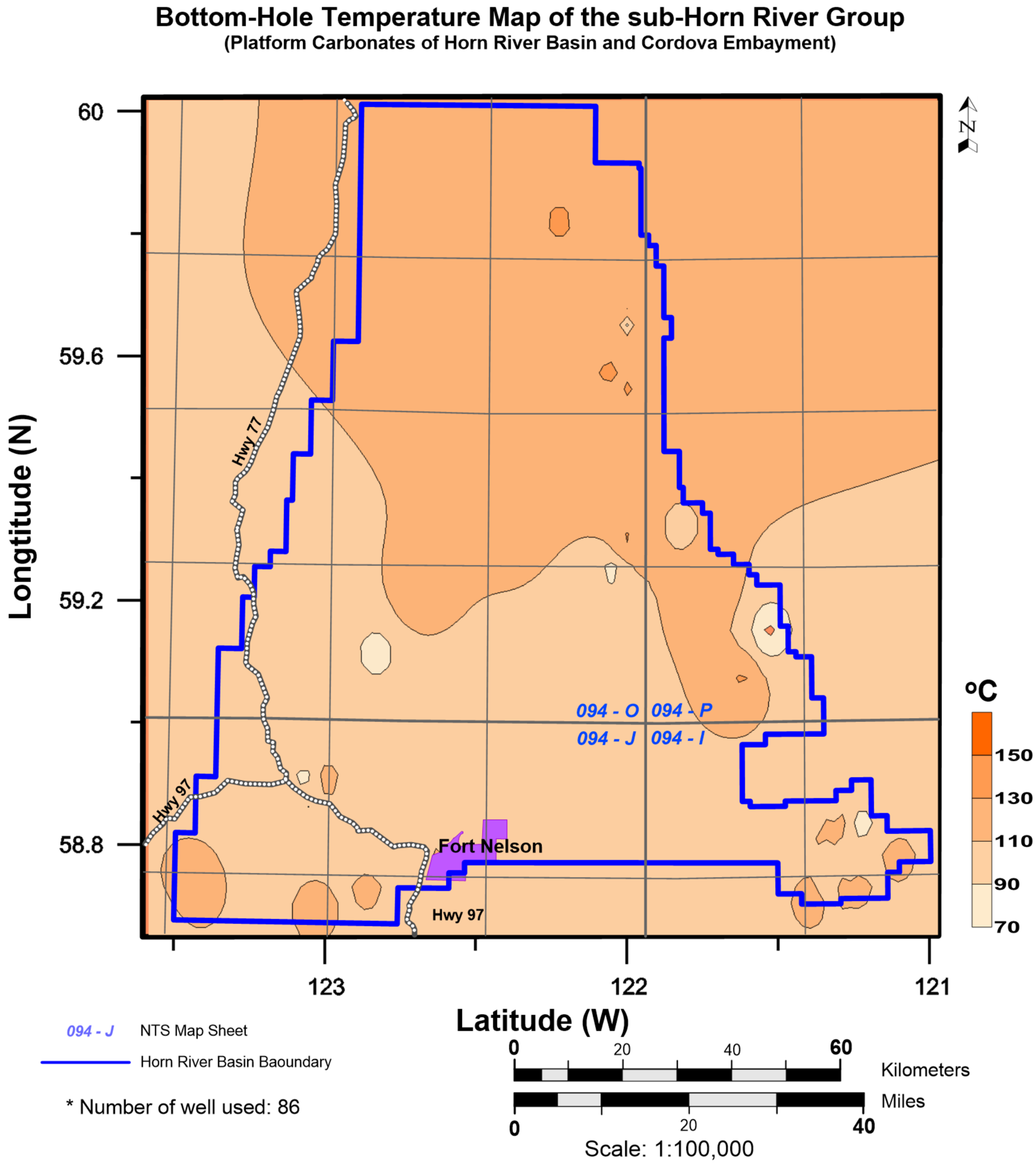


Figure 8: Isothermal contour map of the sub-HRG platform carbonates, Horn River Basin.

BHT data are classified into three groups by measured depth: (1) 2-3 km; the True Vertical Depth (TVD) from 139 BHTs is 2009.1-2966.6 meters below the ground (Fig. 9). (2) 3-4 km; TVD from 21 BHTs is 3000.8-3923.4 meters below the ground (Fig. 10a), and (3) >4 km; TVD from 27 BHTs is 4059.4-6453.7 meters below the ground (Fig. 10b).

To create isothermal contour maps, 101 BHTs were used for the HRG shale formations, and 86 BHTs for platform carbonate. These 187 BHTs were also utilized to generate three depth-based isothermal maps (Figs. 7-10). Seven BHTs were excluded from isotherm constructions as they were in other carbonate formations that are not the scope of this study.

6.2. Isothermal Maps by Formations

Temperature distribution of the basinal shale formations of the HRG, and the Middle Devonian carbonates occurring between Evie/Klua and Otter Park Formations are shown in Figure 7. These temperatures were measured at a depth range from 1943 m to 4673.8 m.

The isothermal contour map of the HRG (Fig. 7) indicates that the temperatures of the HRG shales are greater than 110°C in most of the Horn River Basin. Two high-temperature spots are in the north (NTS 094-O-10 and 094-O-15) and southeast (NTS 094-I-13) with measured temperatures exceeding 130°C. The temperature around the town of Fort Nelson ranges from 90 to 110°C.

The map shown in Figure 8 considers only the BHTs on the sub-HRG platform carbonates in the basin. The BHTs in the platform carbonate formations range from 60°C to 143°C (average 110.3°C) at depths of 583.3-2920.8 m. This map indicates that the lowest temperature of sub-HRG formations is 90°C. However, in the northern half of the basin, the temperatures are higher than 110°C. There are also several spots with temperatures exceeding 130°C in the northern part of the basin (NTS 094-O-09 and 094-O-16).

The temperature range and average temperature of each unit of the HRG and its underlying sub-HRG formations are shown in Table 1. Compared to the sub-HRG carbonates (110.3°C on average), the HRG shows a higher average temperature (118.8°C). The average temperature of the formations increases with depth in the sub-HRG but decreases with depth in the formations of the HRG. As shown in Fig. 2, occurrences of Slave Point and Keg River reefal carbonate in the central HRB has a greater impact on the deposition elevation of the basinal shales. This indicates that the depth ranges of the HRG formations are very broad. Table 1 also shows that the Otter Park shale in the HRG and Keg River carbonate formation of the sub-HRG are the hottest strata in the HRB.

Table 1: Temperatures of basinal shales (HRG) and platform carbonates in the Horn River Basin.

	# of wells with BHT	Temperature Range (°C)	Av. Temperature (°C)	Av. Depth of BHT measurements (m/masl)
MUSKWA F.	33	73-147	116.7	3377 (-2756)
OTTER PARK M.	34	64-146	123.9	3075 (-2400)
MIDDLE DEVONIAN	11	93-178	125.2	2481 (-1984)
EVIE/KLUA M.	23	77-147	118.8	3469 (-2883)
Basinal Shales (HRG)	**101**	**64-178**	**118.8**	**2858 (-2260)**
SULPHUR PNT F.	3	84.4-95.9	90.1	2072 (-1578)
SLAVE PNT F.	39	60-129	102.7	2188 (-1664)
PINE POINT F.	18	64.4-113	114.2	2227 (-1688)
KEG RIVER F.	26	92.1-143	120.5	2500 (-1837)
Platform Carbonates (sub-HRG)	**86**	**60-143**	**110.3**	**2284 (-628.5)**

6.3. Isothermal Maps by Depth

The temperature gradient map of the entire basin is generated in three depth intervals: 2-3 km, 3-4 km, and >4 km. Nine BHTs with a depth of less than 2 km were removed from the dataset, and a total of 187 BHTs were used to generate these maps (Figs. 9, 10a and 10b). Figure 9 shows that the lowest temperature at a depth of 2-3 km is 95°C, while the BHTs in the northern, central and southeastern areas reach 110°C. There are also several hot spots with temperatures exceeding 125°C in the northern half of the basin at 2-3 km deep (NTS 094-O-09, 094-O-10, 094-O-15, and 094-O-16). 139 BHTs were employed to create this isothermal contour map, the temperatures range between 54.4°C and 178°C (average = 111.8°C), and their true vertical depths are between 2009.6m and 2966.6 m.

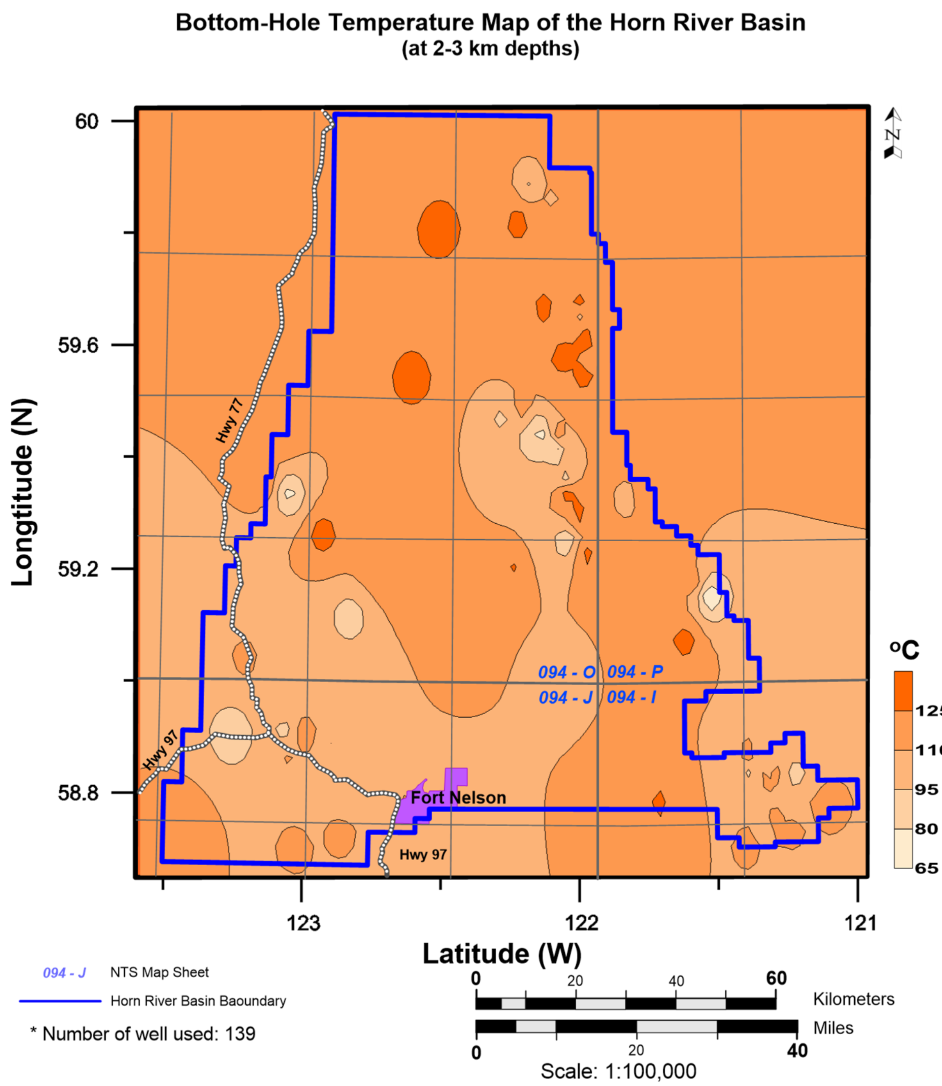
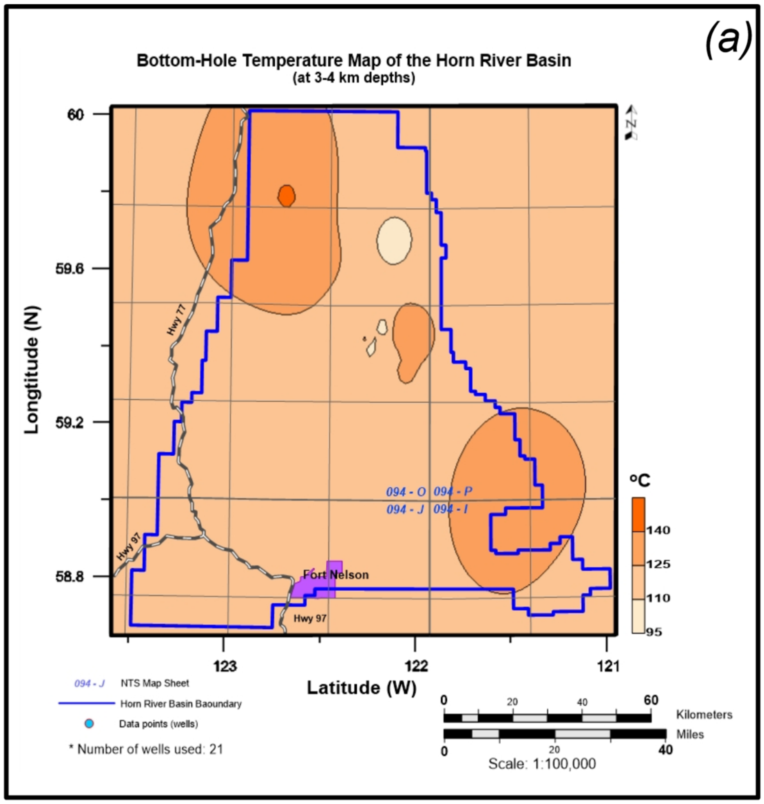


Figure 9: Temperature isothermal contour map of the Horn River Basin at 2–3 km depths.



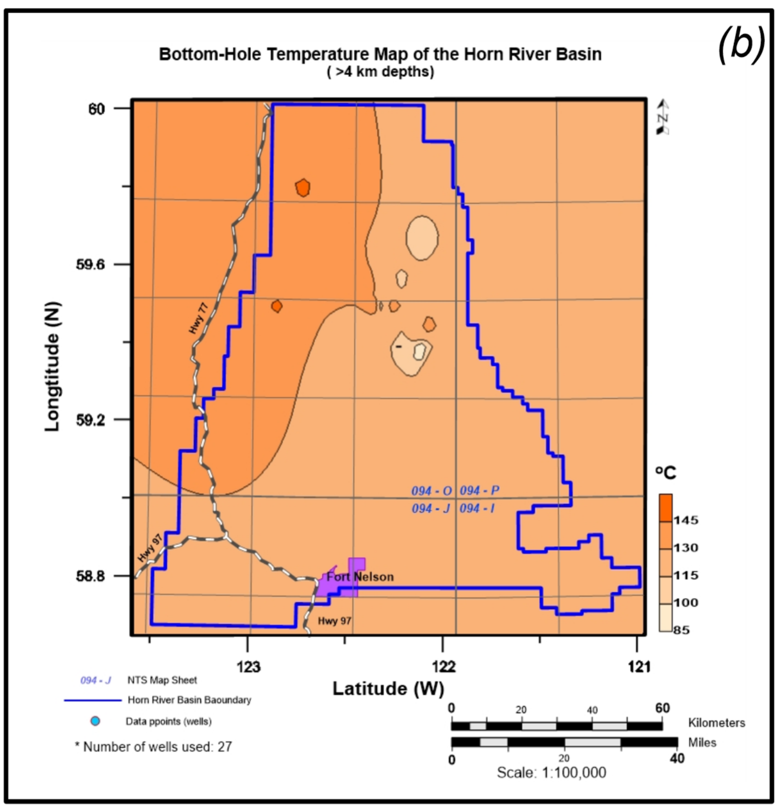


Figure 10: Temperature isothermal contour map of the Horn River Basin, (a) at depths of 3–4 km, and (b) at depths >4 km.

Isotherms at depths of 3-4 km (21 BHTs) and >4 km (27 BHTs), respectively are shown in Figs. 10a-b. The subsurface temperature at a depth of 3-4 km in most areas of the HRB exceeds 110°C, while the temperature in parts of the northwest and southeast of the basin exceeds 125°C (NTS 094-O-10 and 094-O-15 in NW, and 904-P-04 and 094-I-13 in SE). The BHTs measured at depths of 3-4 km range from 73°C to 146°C (average = 120.4°C). The northeastern parts of the basin have relatively high temperatures (at 130°C), while the lowest temperature of the entire HRB at a depth of >4 km is 115°C. The BHT values are between 76°C and 147°C (average = 129.1°C), which were measured at depths of 4059.4 - 6453.7 m. The hottest wells are located in the northern part of the HRB, with temperatures exceeding 145°C (NTS 094-O-07, and 094-O-15).

The isothermal contour maps of different strata or depth intervals (Figs. 7-10) illustrate that the northern half and southeast corner of the HRB are the hottest areas. After the Middle Devonian carbonate member (MDDC) (125.2°C), the Otter Park Formation (HRG) and Keg River (sub-HRG) formation are the hottest aquifers in the basin. The temperature maps also show the NW-SE lineation hot spots (Figs. 8, 9, 10a), which can be identified in the isotherm contours that are plotted by lithology and depth. This trend may be an artificial effect of uneven distribution of wells in the area. However, it coincides with potential geothermal areas in the northern, northeastern, and southeastern parts of the basin. This trend is confirmed by the occurrence of the coolest shale formations (the HRG) in the area around Fort Nelson, suggesting other controls of geological factors on heat distribution.

6.4. Depth-to-Top-of-Formation Maps

Three boreholes in the basin reached the pre-Cambrian basement rock with a depth ranging from 2211.3 to 2917.9 m (average = 2542.1 m). Figure 11 and the attached table show the location of these wells in the HRB, as well as some properties of the HRG formations and Devonian Strata in the wells. In contrast to the sub-HRG, the general thickness of the HRG increases from west to east (well #1 to well #3). This also indicates that the basement and overlying sedimentary formations, including the HRG, are deeper in the west (well #1), which may imply that the basement is dipping westward.

The ground level in the HRB varies between 286.6 and 914 meters above sea level (average = 550 masl). Geological data from 188 wells available suggest that the basinal (HRG) and platform (CE) shales, and carbonate formations both underlie the Simpson Formation in the HRB (Fig. 3). The Muskwa Formation occurs at the top of the HRG at depths between -679.5 and -2403 masl (average = -1383.6 masl); 916 - 2807 m (average = 1180.8 m). The contour map created for the top of the HRG formations (Fig. 12a) shows a distinct subsided area in the NW quadrant, and that overall, formations dip towards the NW (deepening northwestward). The HRG is shallower in the south and east of the basin with the shallowest depth occurring at the SE and SW quadrant of the map (NTS 094-I-13, 094-I-14, 094-J-14, 094-J-15).

The same trends and structure present in the contour map, showing the depth to formations tops underlying the HRG (Figure 12b). The top formation of the sub-HRG varies depending on wells and can include any of the 6 units; Salve Point, Sulphur Point, Keg River (upper, reef), Pine Point, Elk Point, and Watt Mountain (Table 2). The top of the sub-HRG varies between -789.8 and -2680 masl (average = -1769.1) (1870 - 3283 m, average = 2339 m). The NE trending shale-dominated structure of the HRG and carbonate-dominated sub-HRG formations (Figures 12a and 12b) confirm that the geothermal target formations are shallower in the southern half of the basin, particularly at SE and SW quadrant of the elevation maps (NTS 094-I-13, 094-I-14, 094-J-14, 094-J-15). The Slave Point Formation is the shallowest formation with an average elevation of -1560 masl (2058 m). It directly underlies the Muskwa-Otter Park formations in the platform part of the basin (HRB and CE) and is the top formation of the sub-HRG in 69 wells. The Keg River is the aquifer located immediately under Muskwa-Otter Park at an average elevation of -1865 masl (2504 m) in 104 wells.

	Unique Well ID	HRG Units	Sub-HRG Units	Depth of Pre-Cam (m/masl)	Depth to Top of HRG (m/masl)
1	200/b-**094-L 094-J-11**/00	Muskwa	Nahanni, Stone	2917 (-2337.7)	2531.9 (-1952.6)
2	200/b-**097-A 094-O-03**/00	Muskwa, Otter Park	Slave Pnt., Watt Mnt., Pine Pnt, Chinchga,	2211.3 (-1825.2)	1891.5 (-1505.4)
3	200/b-**014-A 094-O-01**/00	Muskwa, Otter Park, Evie	Nahanni, Chinchga, Red Bed,	2498.1 (-2018.7)	2038.5 (-1559.1)
	Average	-	-	2542.1 (-2060.5)	2154 (-1672.4)

	Unique Well ID	Gross Thickness (m)				
		Muskwa	Otter P.	Evie	Tot HRG	Sub-HRG
1	200/b-**094-L 094-J-11**/00	103	-	-	103	290.5
2	200/b-**097-A 094-O-03**/00	40.6	55.2	-	95.8	224
3	200/b-**014-A 094-O-01**/00	4.8	239.3	39.9	284	175.6
	Average	49.5	147.3	39.9	160.9	230

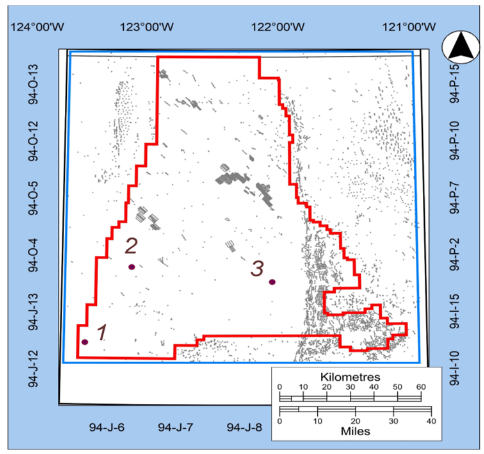
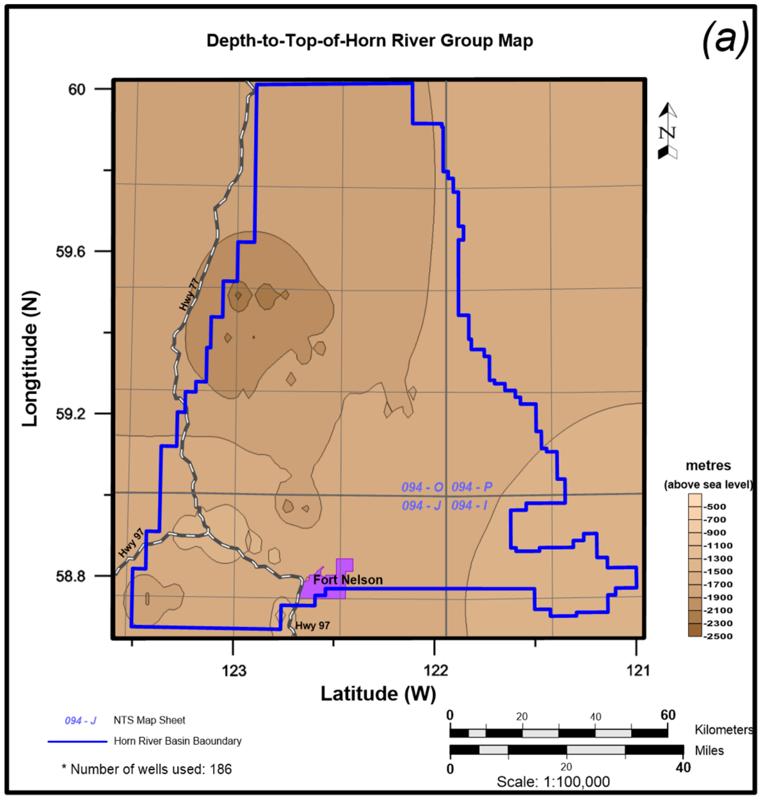


Figure 11: Location map of wells that cut the entire sedimentary crust of the HRB and tapped the pre-Cambrian basement.

Table 2: Average thickness of the basinal shales (HRG) and platform carbonates (sub-HRG) in the Horn River Basin.

	Formation	# of Wells	Thickness Range (m)	Average Thickness (m)
HORN RIVER GROUP (Shales & Carbonates)	MUSKWA F.	442	1.3-306.6	45.6
	OTTER PARK F.	294	0.9-320	86.5
	M. DEVONIAN F.	45	1-88.5	15.4
	EVIE/KLUA F.	156	1.5-144.5	42.6
	Total	**156**	**0.9 - 320**	**176.8**
SUB-HORN RIVER GROUP (Carbonates & Shales/Sst.)	SLAVE PNT F.	38	7-376.1	110.4
	WATT MNT. F	14	0.8-18.3	5.1
	GRANITE WASH F.	1	119.8	119.8
	SULPHUR PNT. F.	27	5.7-144	35.3
	KEG R. (U. & RF) F.	31	25.3-401.2	123.4
	PINE PNT. F.	13	12.1-321.6	107.1
	Total	**66**	**0.8-401.2**	**86.6**



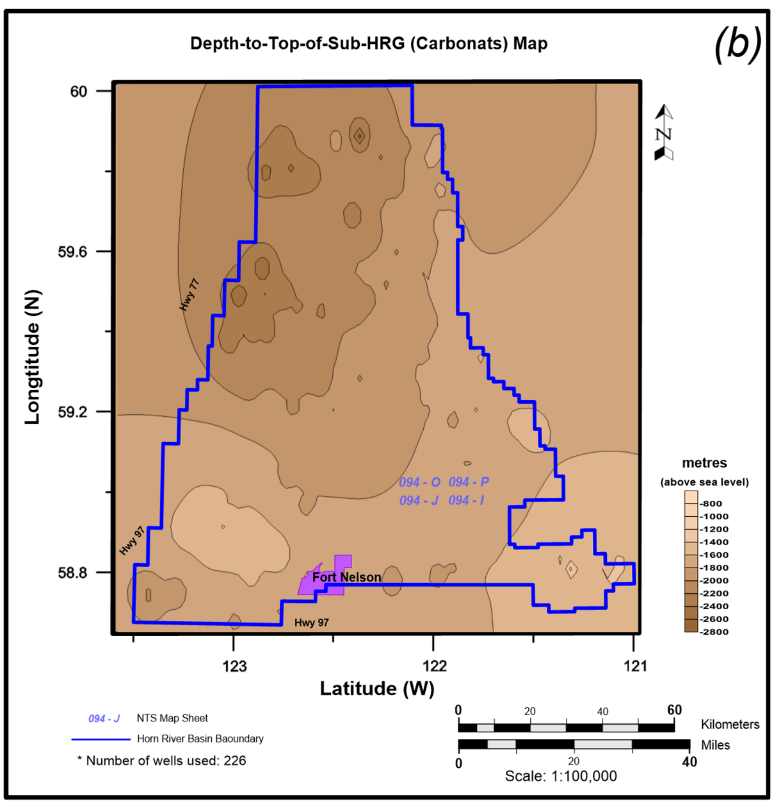


Figure 12: Elevation maps to the tops of a) the Horn River Group (Muskwa-Otter Park Formations), b) the sub-Horn River Group (Carbonate Formations) in the Horn River Basin.

6.5. Gross Thickness (Isopach) Maps

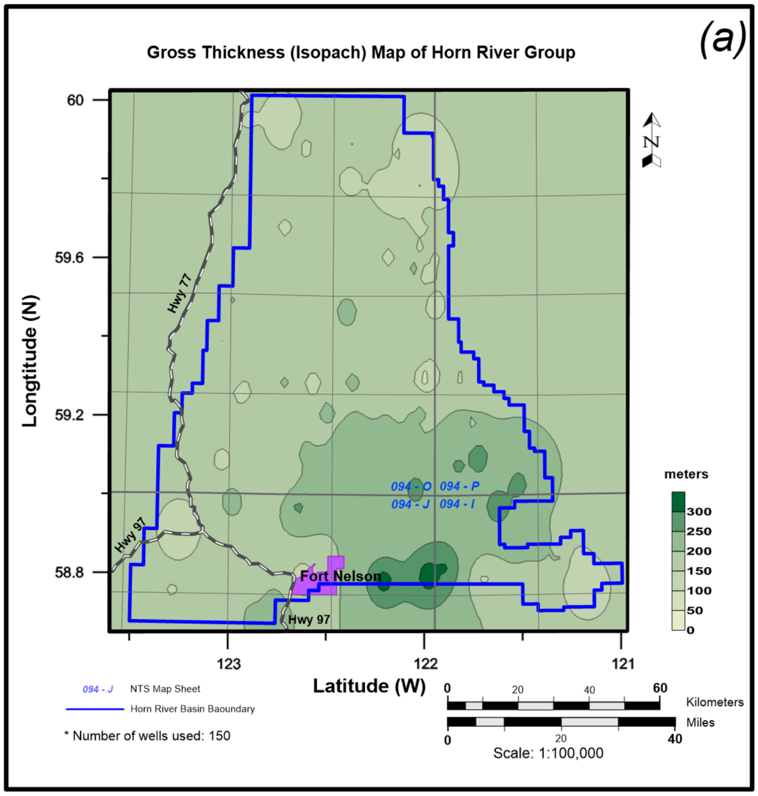
A total of 156 wells penetrated all the HRG formations. Figures 13a and 13b are isopach maps for the HRG shale and sub-HRG in the HRB, respectively, showing the variation in formation thickness in the basin. Overall, the formations are thicker in the southern part of the basin. The HRG has an average gross thickness of 176.8 m (ranging from 0.9 m to 320 m), and its thickness in the south and southeast of the HRB (east of Fort Nelson) is greater than 200 m, covering a larger area (NTS 094-O-01, 094-P-04, 094-J-16, 094-I-13) (Figure 13a). The thickness of the sub-HRG is in the range of 0.8 - 401 m (average 86.6 m) and its thickest part (>160 m) covers a restricted area, including the west of the Fort Nelson (NTS 094-J-14 and 094-J-15) and east of the HRB (NTS 094-O-8) (Figure 13b).

As shown in Table 2, the Otter Park is the thickest shale formation in the HRG, with an average thickness of 86.5 m. While the Keg River Formation is the thickest carbonate succession in the sub-HRG, with an average thickness of 123.4 m. The Granite Wash Formation is the thickest sandstone-shale formation underlying the HRG where only one well was drilled.

The thickness of each HRG formation, including Muskwa (Fig. 14a), Otter Park (Fig. 14b), Middle Devonian Carbonates (Fig. 14c), and Evie/Klua (Fig. 14d) Formations are shown in Fig.14. The average thickness of the Muskwa Formation (Fig. 14a) is 45.6 m, and the thickness is greater than 50 m in the north and northwest (ranging from 1.5 to 306.6m). Several wells in the northern part of the basin (NTS 094-O-07) represent the Muskwa Formation, with a gross thickness over 100 m.

The Otter Park Formation thickens toward the southeast and reaches the maximum in the south (094-J-16), with a thickness range from 0.9 m to 320 m. 45 wells penetrated through the Middle Devonian Carbonate Member (MDDC) of the HRG. The average thickness of the MDCC is 15.4 m (from 1 to 88.5 m), and the thickest layer of the member appears to be in the northern part of the HRB (094-O-09). The Evie/Klua Formations in the area has an average thickness of 42.6 m but exceeds 100 m thick in the southeastern part of the basin (NTS 094-J-16). This formation has a large coverage in the north and southeast of the basin, with a thickness >40 m.

According to Figures 13 and 14, the thickest accumulation of the HRG shale strata and the underlying carbonate-dominated formations appear to occur predominantly in the south and southeast of the HRB.



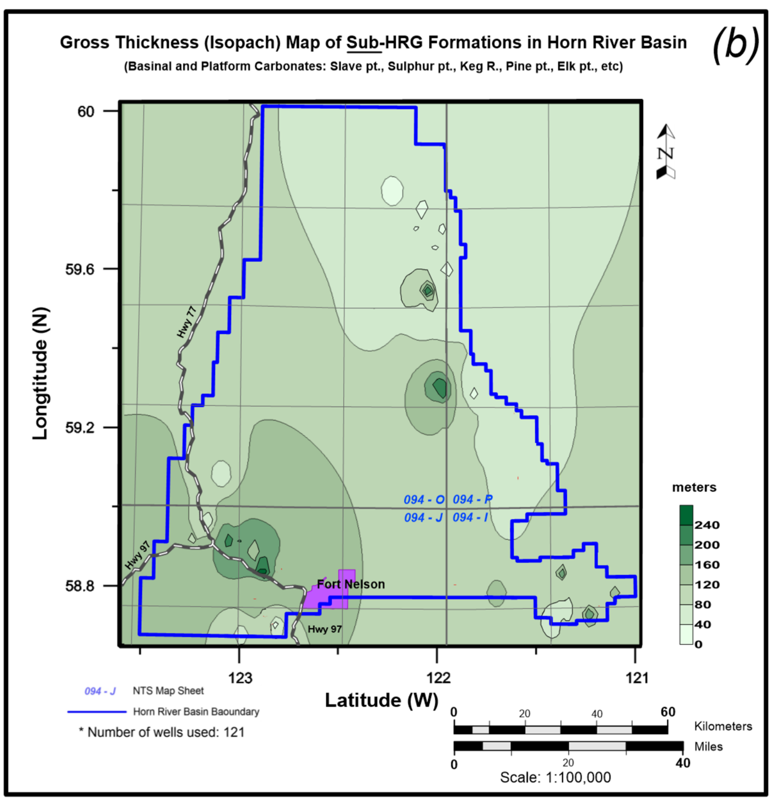


Figure 13: Gross thickness (isopach) map of a) the Horn River Group, and b) sub-HRG formations in the Horn River Basin.

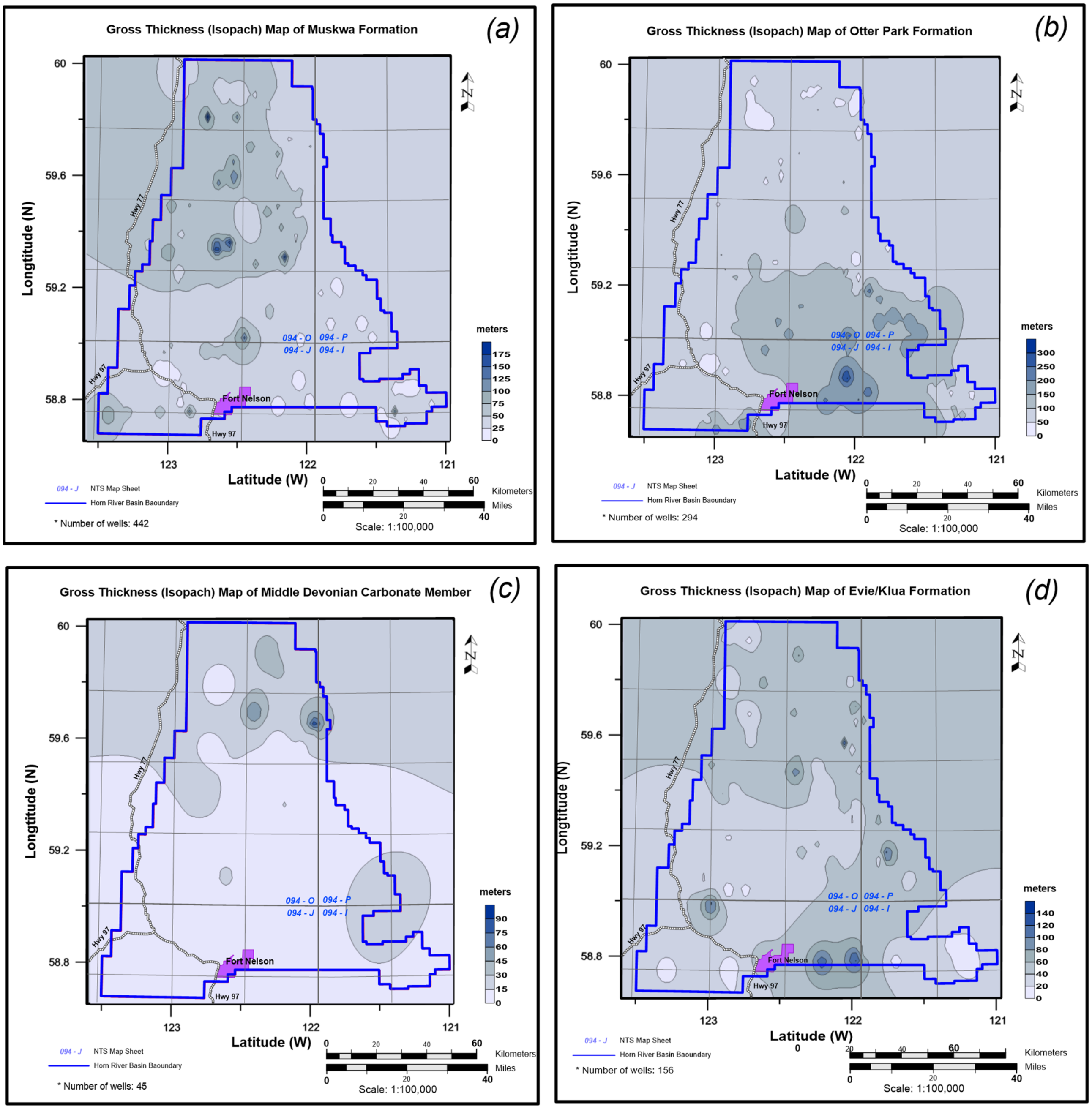
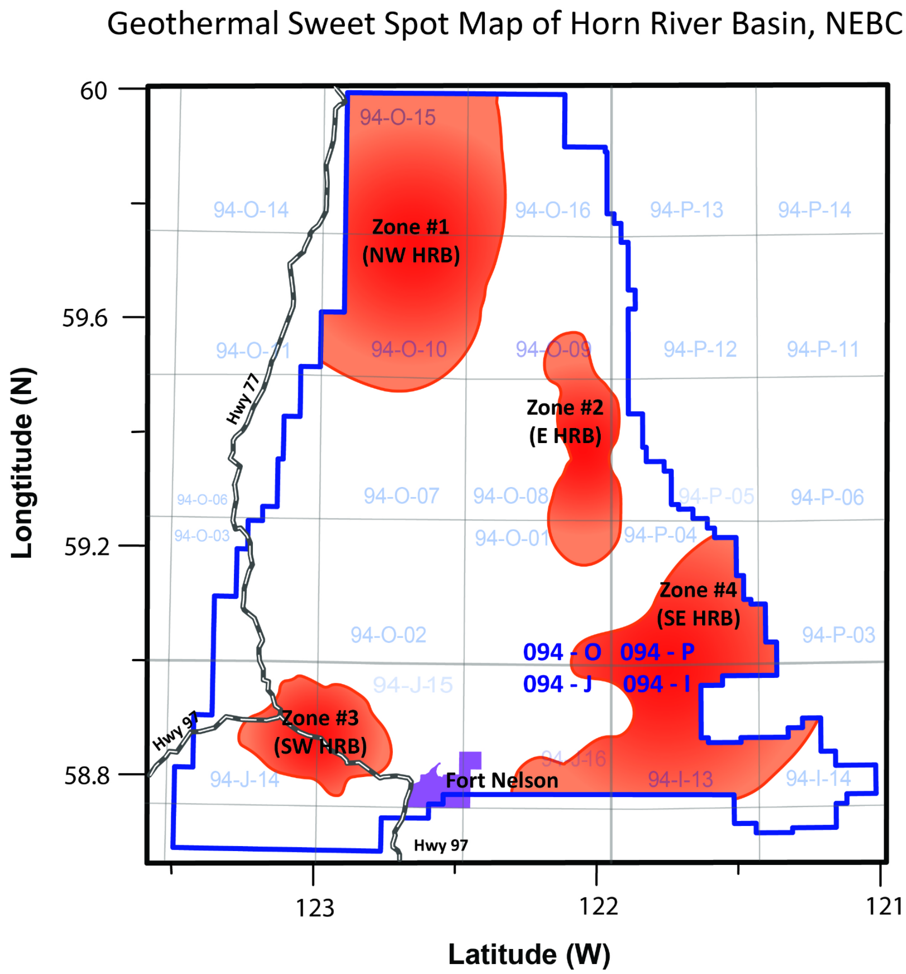


Figure 14: Gross thickness (isopach) map of four members of the Horn River Group in the Horn River Basin, a) Muskwa, b) Otter Park, c) Middle Devonian Carbonates, and d) Evie/Klua.

6.6. Geothermal Favorability Mapping

Combination of temperature maps of formations with depths greater than 3 km (Figs. 10a and 10b), gross thickness map of the HRG and sub-HRG (Figures 13a and 13b), and elevation map of the HRG and sub-HRG formations (Figures 12a and 12b) allowed us to create a schematic map showing the variation of geothermal resource potential in the HRB (Fig. 15). The map contains a table showing the temperature, thickness, and burial depth values, which make these areas notably different due to the high geothermal potential.



Area	T (°C)	Thickness (m)	Depth (m)
#1 (NW)	> 130	150	2710
#2 (East)	> 125	240	2343
#3 (SW)	> 115	240	1979
#4 (SE)	> 130	300	2016

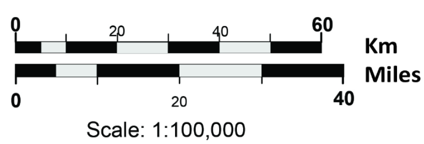


Figure 15: Geothermal favourability map of the Horn River Basin.

As shown in Figure 15, four areas are identified as favourable areas with shallow, thick, and hot formations, representing four geothermally potential zones:

a) Zone 1 – Northwest HRB area: The northwestern part of the HRB is considered the hottest area, with temperatures exceeding 110 to 130°C. However, the formation thickness and depth of the uppermost layer are not in the optimal state (thickness 40-150 m, depth range 2439 to 3080 m). This area relatively covers the entire NTS map sheets 094-O-10 and 094-O-15.

b) Zone 2 – East HRB area: The hot spot in the central and eastern parts of the HRB indicates that the temperature at a depth of 3-4 km exceeds 125°C, and the gross thickness of the sub-HRG formations is 240m. The thickness of the HRG formations is less than 150 m and the depth can reach 2023 to 2511 m. This area predominantly covers the eastern part of the NTS map sheets 094-O-08.

c) Zone 3 - Southwest HRB area: temperature is below 150°C at any given depth in the Southwestern part of the HRB zone, but the thickness of the sub-HRG formations in this zone may exceed 240 m at depth approximately 1979 m. The HRG formations are thin (50-150 m) and deep (1877 to 2114 m). The hot spot covers the western part of NTS 094-J-14 and the eastern part of NTS 094-J-15. Because the distance between Zone 3 and Fort Nelson is relatively short, Zone 3 is accessible by highways, which is considered an advantage.

d) Zone 4 – Southeast HRB: The well drilling density in the southeast part of the HRB is greater than in other areas, which will lead to more accurate data acquisition. Some parts of the area have the highest temperature (over 130°C), the thickest HRG formations (over 300 m) and the shallowest uppermost depths of the HRG and sub-HRG formations (1107 to 2248 m). Zone 4 covers most parts of the NTS map sheets NTS 094-I-13 and NTS 094-P-04, and some parts of NTS 094-I-14 and NTS 094-J-16.

6.7. Transmissivity (Porosity and Permeability)

For this study, porosity and permeability data were acquired from measurements conducted on 1363 core samples in the laboratory from 47 wells. The 456, 595 and 312 core samples are from the Muskwa Formation, Otter Park Formation, and Evie Formation, respectively.

The core samples from the Muskwa Formation have a porosity in the range of 0.52-12.58% (4.79% on average) and a permeability value between 1.04 10^{-10} and 0.609 mD, with an average of 6.36 10^{-3} mD (Fig. 16a). For the Otter Park Formation (Fig. 16b), the core porosity values are between 0.2% and 9.71% (average 4.05%), and the measured permeability ranges from 7.29 10^{-13} mD to 7.62 10^{-3} mD (average 2.81 10^{-4} mD). For the core samples from the Evie Formation (Fig. 16c), the measured porosity and permeability is in the range of 0.03-10.41% and 2.5 10^{-13}-0.308 mD with average values of 4.46% and 3.87 10^{-3} mD, respectively. It suggests that the Muskwa Formation has the best reservoir quality with the highest porosity and permeability, whereas the Otter Park Formation exhibits the lowest porosity and permeability.

Table 3 represents the porosity, permeability and water saturation from the sub-HRG and HRG formations, indicating that the average permeability of the sub-HRG formations is much higher than those of the HRG units although their average porosities are close. However, natural fractures exist in the HRG shales, the permeability in the HRG formations will dramatically increase with fracturing. The table also shows that the average water saturation from the HRG formations is higher than that in sub-HRG. In the sub-HRG formations, the sandstone-dominated Granite Wash Formation and carbonate-dominated Pine Point Formation have the highest average porosity of 8% and 7%, respectively. The Pine Point Formation also reveals the highest average permeability value of 9.8 mD.

Overall, the studied core data confirm that the HRG has a similar porosity range as the underlying strata, whereas its natural permeability is much lower than the sub-HRG formations. The Muskwa Formation of the HRG and Pine Point Formation of the sub-HRG are good target formations, whereas the Granite Wash, and Evie/Klua formations are also suitable targets. Comparison between these findings with the gross thickness map of HRG and sub-HRG (Figure 13) indicates that HRG at the

Southeast HRB - Zone 4 and sub-HRG at the Southwest HRB - Zone 3 are the thickest and most porous and permeable formations among the others.

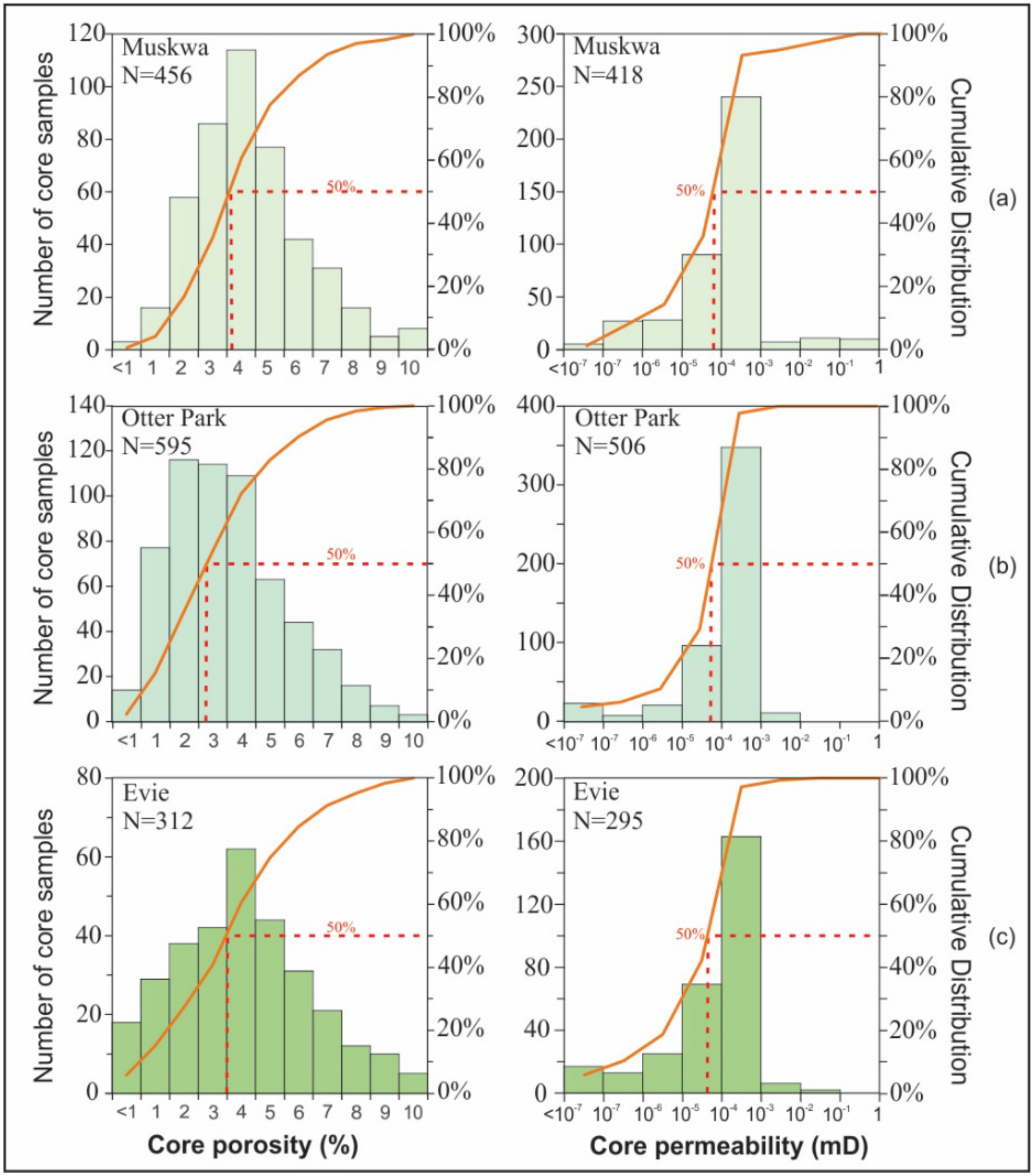


Figure 16: Histograms showing the distribution of porosity and matrix permeability measured on the cores for the Muskwa (a), Otter Park (b), and Evie (c) formations of the HRG in the Horn River Basin, northeast BC. Cumulative distribution curves are shown in solid red. N – number of core samples.

Table 3: Porosity, permeability, and water-pore volume characteristics of the HRG and sub-HRG formations. The permeability is matrix permeability, which is only from core measurements.

	FORMATION	# of Wells Cored & Logged/Total Sample Length (m)	Porosity Range/(Av.) (frac.)	Permeability Range/(Av.) (mD)	Average Water Saturation (frac.)
HORN RIVER GROUP (Shales & Carbonates)	MUSKWA F.	34/813.4	0.0052-0.126 (0.048)	$1.04\ 10^{-10}$ – 0.609 ($6.63\ 10^{-3}$)	0.212
	OTTER PARK F.	23/1143	0.002-0.097 (0.041)	$7.29\ 10^{-13}$ – $7.62\ 10^{-3}$ ($2.80\ 10^{-4}$)	0.206
	M. DEVONIAN F.	49/61.8	0.001-0.094 (0.039)	$1.47\ 10^{-5}$ – $6.90\ 10^{-3}$ ($4.47\ 10^{-4}$)	0.241
	EVIE/KLUA F.	22/377.6	0.003-0.104 (0.045)	$2.5\ 10^{-13}$ – 0.308 ($3.87\ 10^{-3}$)	0.173
	HRG	**128/2395.8**	**0.001-0.126 (0.043)**	**$2.5\ 10^{-13}$ – 0.609 ($2.74\ 10^{-3}$)**	**0.208**
SUB-HORN RIVER GROUP (Carbonates & Shales/Sst)	SLAVE PNT F.	6/77.5	0.005-0.11 (0.03)	0.01-6.4 (0.35)	0.015
	GRANITE WASH F.	1/4.8	0.04-0.12 (0.08)	0.15-0.8 (0.27)	-
	KEG R. F.	10/261.8	0.002-0.17 (0.03)	0.01-270 (8.6)	0.015
	PINE PNT. F.	2/17	0.02-0.12 (0.07)	0.07 -67.2 (9.8)	-
	sub-HRG	**19/361.1**	**0.002-0.17 (0.05)**	**0.01-270 (4.75)**	**0.015**

6.8. Water Production

Table 4 shows the co-produced water production statistics of the gas wells studied in the HRB. The average cumulative water production (CWP) from the sub-HRG formations is about 13 times that of the HRG formations, while the number of production wells are 21% and the production hours are 43% higher than the HRG formations. It suggests that the sub-HRG strata preserve more water. The hourly rate of water production (flow rate) of each well also indicates that the sub-HRG carbonate formations have great potential for sustainable production of geothermal water as compared with the HRG formations under the conventional geothermal production method.

A large part of gas production, and consequently cumulative water production from the wells that penetrated the HRG belong to the Muskwa and Otter Park formations. The eight existing wells that are simultaneously producing from the Muskwa and Otter Park formations produced a total of 31,119 m^3 cumulative water with an average of 3,890 m^3/well, which is 57-87% higher than the production of other formation. The average flow rate of 0.99 m3/hr is the highest among the HRG shale formations.

In the sub-HRG units within the HRB, the Slave Point Formation represents excellent flow conditions (9.2 l/s, 33.1 m^3/hr), and also has high CWP/well. After the Sulphur Point Formation, the Slave Point Formation has the second-highest water production among the sub-HRG aquifers (10% less production per well). Production data also shows that the Keg River Formation produced more water per well per hour (0.031 m^3/well/hr) compared with the Slave Point Formation.

In the mapped area, 111 wells produced more than 100,000 m^3 of water (Fig. 17). There are only 3 wells that produced water from the HRG (2 wells from the Muskwa and 1 well from the Otter Park Formation), and they are all located in the northern half of the HRB. A total of 108 wells produced water from the sub-HRG formations mostly in the south and southeast of the map area, among which only 14 wells, mostly located in the southeast corner of the HRB, produced from the Pine Point Formation (average CWP of 370,779 m^3, average flow rate of 0.6 l/s, 2.2 m^3/h). The remaining 97 wells, most out of the HRB boundary, are producing from both Pine Point and Slave Point

Formations. The Muskwa, Otter Park, and Pine Point formations are the high water-producing strata in the HRB.

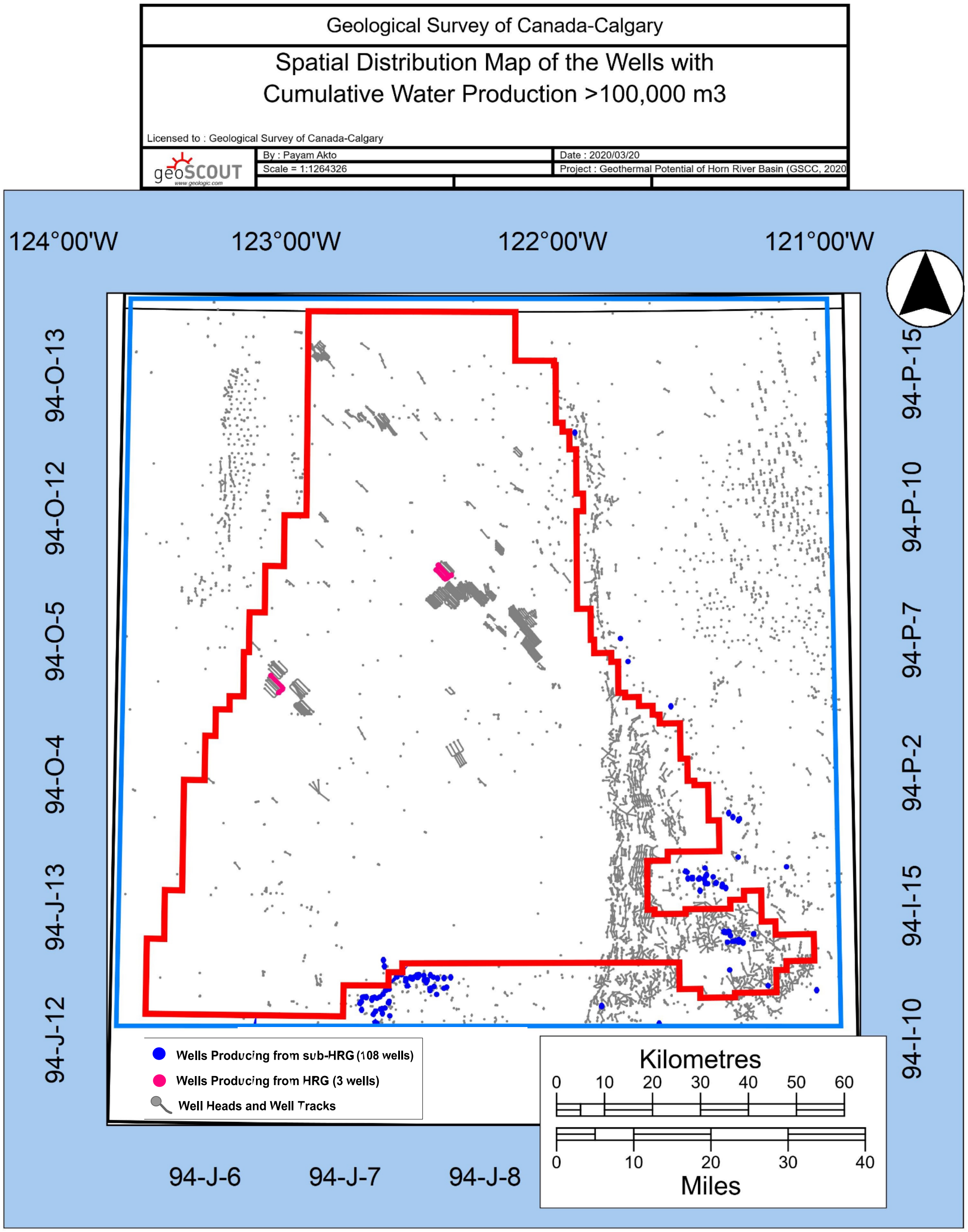


Figure 17: Distribution map for wells with cumulative water production greater than 100,000 m^3.

Table 4: Cumulative co-produced water production (CWP) and the co-produced water flow rate of the gas wells drilled in the mapped area, including the HRB (Figure 17).

	Unique Well ID	# of Wells Studied	Days/Hours on Production	Av. CWP (m^3)	Av. Flow Rate (m^3/hr, l/s)	CWP per Well (m^3)	CWP per Well per Hour (m^3)
HORN RIVER GROUP	MUSKWA F.	99	2,979 / 57,713	27,257	0.48/ 0.13	275.3	5 e-3
	OTTER PARK F.	51	2,467 / 48,684	17,875	0.34/ 0.1	350.5	7 e-3
	EVIE/KLUA F.	63	2,594 / 42,053	19,237	0.99 / 0.27	305.3	7 e-3
	MUSK/OTPARK Fs.	8	3,187 / 70,274	31,119	0.42/ 0.12	3,890	55 e-3
	MSK/OP/EVKL Fs.	6	12,521 / 204,425	28,054	0.14 / 0.04	4,676	100 e-3
	HRG	**227**	**Tot. 0.63 e6 / 11.7 e6**	**Tot. 5,112,241**	**0.58 / 0.16**	**Tot. 22,521**	**2 e-3**
SUB-HORN RIVER G.	SLAVE PNT F.	164	31,885 / 68,440	326,830	33.1 / 9.2	1,993	29 e-3
	PINE PNT. F.	115	33,209 / 77,479	112,023	2.7 / 0.75	974	12 e-3
	KEG R. F. (Upper & Reef)	5	37,803 / 33,031	5,191	0.12 / 0.03	1,038	31 e-3
	SULPHUR PNT. F.	4	30,042 / 11,428	8,893	0.45 / 0.12	2,223	31 e-3
	Sub-HRG	**288**	**Tot. 9.4 e6 / 20.6 e6**	**Tot. 66,544,569**	**19.9 / 5.5**	**Tot. 231,057**	**11 e-3**

Figure 18 is a location map of the wells with the highest CWP and the highest flow rate within the HRB. Among the top 50 wells with high CWP and flow rate from the sub-HRG formations, only 7 production wells are located within the HRB boundary in the south and southeast of the basin, and producing water from the Pine Point Formation. In contrast, the wells with the greatest CWP and flow rate from the HRG are all located in the northern part of the basin.

Table 5 lists the production data of the top 10 wells with the highest CWP and flow rate from both the HRG and sub-HRG, showing a remarkable difference in flow rate between the HRG shales and the carbonates-dominated sub-HRG. The Slave Point Formation has the highest average flow rate (70.4 l/s), consistent with other geothermal studies in WCSB (e.g., Palmer-Wilson et al., 2018; Ferguson and Ufondu, 2017).

By comparing the thickness maps (Figures 13 and 14) with the schematic high resource potential zones (Figure 15), we conclude that all the highlighted areas can produce a large amount of water with a high flow rate from mostly Muskwa, Otter Park in the HRG, and Slave Point and Sulphur Point in the sub-HRG.

Table 5: Production data from the top 10 wells with the highest Cumulative Water Production (CWP) and flow rate.

	10 Top Water Producing Wells	Production Formation	# of Wells	Range of CWP (e3 m^3)	Av. of CWP (e3m^3)	Range of Flow Rate (m^3/hr , l/s)	Av. of Flow Rate (m^3/hr , l/s)
HORN RIVER GROUP	Highest CWP	Muskwa F.	6	70.1 – 109.1	89.4	1.2-2.4 / 0.3-0.7	1.5 / 0.43
		Otter P. F.	2	97.3 – 105.4	101.3	1.4-1.5 / 0.4-0.4	1.4 / 0.4
		Evie/Klua F.	2	67.3 – 76.4	71.8	2.1-4.5 / 0.6-1.2	3.3 / 0.9
		Total	**10**	**67.3 – 97.3**	**88.3**	**1.2-4.5 / 0.3-1.2**	**1.5 / 0.43**
	Highest Flow Rate	Muskwa F.	2	79.4 – 109	94.2	1.7-2.4 / 0.5-0.7	2.1 / 0.6
		Evie/Klua F.	8	33– 76.4	57.8	1.9-16.8 / 0.5-4.7	5.5 / 1.5
		Total	**10**	**33 - 109**	**65.0**	**1.8-3.4 / 0.5-1.9**	**3.4 / 0.94**
SUB-HORN RIVER G.	Highest CWP	**Slave Pnt. F.**	**10**	**1,177.2– 6,215.7**	**2,354.8**	**4.6-229 / 1.2-63.6**	**11.4 / 3.2**
	Highest Flow Rate	Slave Pnt. F.	9	45 – 1,308.9	404.5	110-1,842 / 30-512	229 / 70.4
		Pine Pnt. F.	1	3.2	3.2	130.8 / 36.3	130.8 / 36.3
		Total	**10**	**3.2 - 1,308.9**	**396.7**	**110-1,842 / 30-512**	**241.2 / 67**

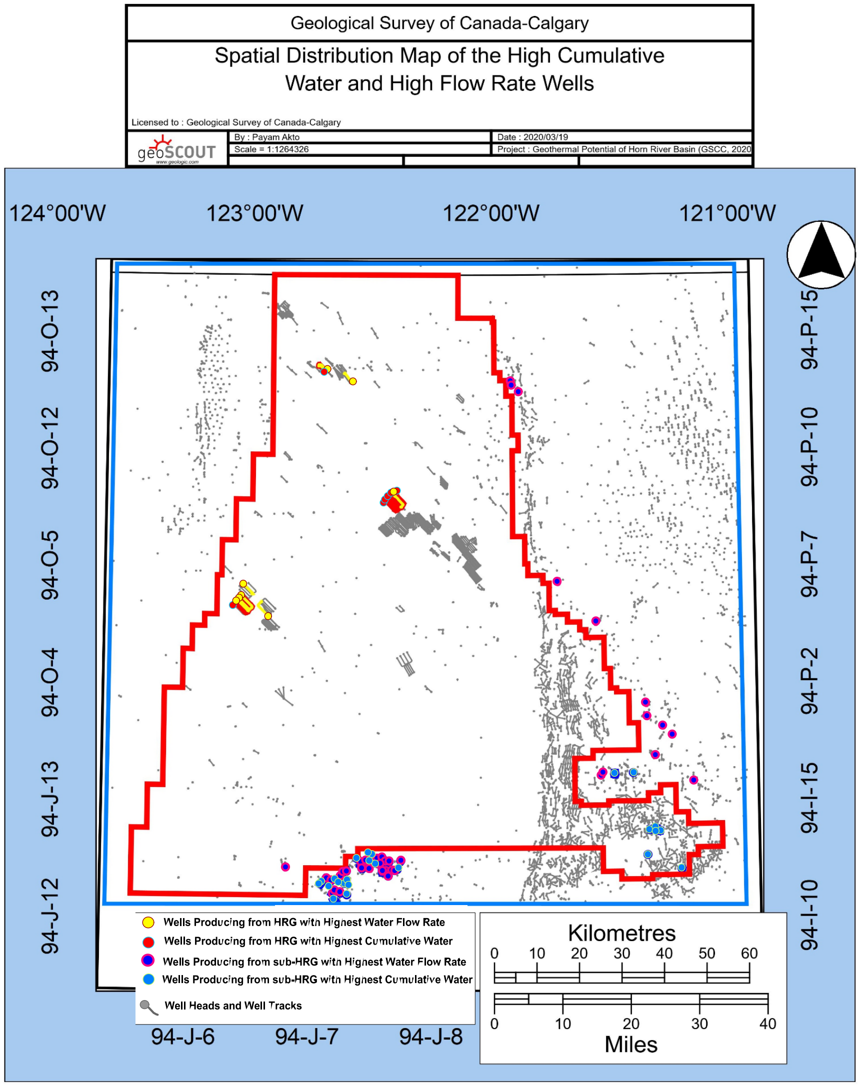


Figure 18: Location map of the top 50 wells with the highest CWP and top 10 wells with the highest flow rate, produced from the HRG and sub-HRG aquifers.

6.9. Formation ranking for geothermal resource potential

Four categories of features including temperature, formation thickness and depth, porosity and permeability, and production criteria, were used to rank the formations in the HRG and sub-HRG based on their relative importance to the quality and quantity of the geothermal resources, and weight was assigned to each parameter (Table 6). A sub-ranking was generated first for each parameter and the sum of all weighted sub-ranks results in the final ranking for each formation in the HRG and sub-HRG respectively (Table 6). Generally, the total weights in each category should be equal (25%). As the temperature is the most important for evaluating the geothermal potential, a slightly higher weight (30%) is given. In contrast, the weight of water production is 20% because of large uncertainty in the flow rate, and sparse data within the HRB.

Considering that the permeability is induced or enhanced artificially, in the scoring and ranking analysis, the weight of porosity is 5% greater than that of permeability. The production sub-factors include the CWP of all wells in the basin, the CWP of top10 high-yield water productive wells, the flow rate of all wells, and the flow rate of top-10 wells with the greatest water flow rate, each with a weight of 5%.

Table 6: Multi-feature criteria for members within the HRG and Sub-HRG ([0.25] is the weight used in favorability ranking).

	Geology: Average Temperature (°C) / [0.3]	Geology: Average Depth (m)/[0.05]	Geology: Average Thickness (m)/[0.2]	Transmissivity: Porosity (%)/[0.15]	Transmissivity: Permeability (mD)/[0.1]	Water production: Cumulative water production/well: All wells /[0.05]	Water production: Cumulative water production/well: Top 10 wells/[0.05]	Water production: Cumulative water production/hours: All wells /[0.05]	Water production: Cumulative water production/hours: Top 10 wells/[0.05]	Rank
Muskwa	116.7	2345	45.6	4.8	0.00636	275.3		0.13	0.43	2
Otter Park	123.9		86.5	4.1	0.000281	350.5	50			1
MDDC	125.2		15.4	3.9	0.000447					4
Evie/Klua	118.8		42.6	4.5	0.00387	305.3	35	0.27	0.9	3
Slave Point	102.7	2058	110.4	3	0.35	1993	3.2	9.2	40	2
Granite Wash			119.3	8	0.27					3
Sulphur Point	90.1		35.3			2223				5
Keg River	120.5		123.4	3	8.6	1038				1
Pine Point	114.2		107.1	7	9.8	974		0.75		4

Extensive analysis and detailed studies of the subsurface geology and production characteristics of the HRG and sub-HRG (Table 6) indicate that the Otter Park is the hottest formation in the HRG and the entire Devonian strata under the Fort Simpson Formation. It is only 1.3°C cooler than the MDDC, whereas its average thickness of 562% is thicker than the MDDC (86.5 m vs 15.4 m). Among the HRG formations, the Otter Park Formation also produces the largest amount of cumulative water in each well (350.5 m^3).

The Muskwa is the second suitable formation in comparison due to greater thickness, higher porosity, and permeability, and shallower depth of occurrence with a relative high average cumulative water production compared to the Evie/Klua Formations (Table 4).

For the sub-HRG, the Keg River is the hottest, thickest, and the second most permeable formation. The Slave Point is the shallowest formation that has the highest CWP and flow rate. It is the main formation that charges the 10-top cumulative water-producing wells. The wells that are producing from the Slave Point Formation have a significantly higher flow rate in the HRB (9.2 l/s).

7. CONCLUSIONS

Geological and reservoir data, and flow rates from petroleum wells were compiled from the HRG and sub-HRG, which form the basis for the data analysis, favourability mapping, and stratigraphic formation ranking for geothermal resource potential in the basin.

The subsurface data analysis in the Horn River Basin suggests that the Horn River Group and its underlying formations have geothermal resources for potential production. Table 7 summarizes the status of the four geological and production criteria used to evaluate the geothermal potential of the HRG and sub-HRG formations. The result exhibits that the HRG shale-dominated formations are hotter and thicker, but less permeable. Compared with the sub-HRG formations, the HRG can also be reached by drilling at relatively shallower depths. These advantages make it attractive to conduct a comprehensive feasibility study with the idea of hybrid energy production using the existing network of hydraulic fracturing shale gas production wells.

Table 7: Comparison of multi-feature criteria for the HRG and sub-HRG.

		Horn River Group (HRG)	Sub-Horn River Group (sub-HRG)
TEMPERATURE	*Temperature*	✓ *110°C*	*90°C*
GEOLOGY	*Depth*	✓ *2,092 m*	*2,355 m*
	Thickness	✓ *176.8 m*	*86.6 m*
RESEVOIR	*Porosity*	*4.30%*	✓ *5%*
	Permeability	*0.002 mD*	✓ *4.75 mD*
WATER RPODUCTION	*Cumulative*	*22,521 m^3*	✓ *231,057 m^3*
	Flow Rate	*0.16 liters/sec.*	✓ *5.54 liters/sec.*

Although the average temperature is 20°C lower in the sub-HRG and the gross thickness is about half of that of the HRG, its high water-production potential (100 times that of the HRG) makes the sub-HRG a favourable target for conventional geothermal production, while the feasibility of geothermal resource utilization from shale strata with hydro-fracturing treatment remains the subject of another study.

Combining the geological and temperature maps of the HRB, we created a schematic map that indicates the favourable zones for further research and evaluation (Figure 15). The map suggests that the northwest (Zone1, NTS sheet maps 094-O-10 and 094-O-15) and southeast (Zone 4, NTS map sheets 094-I-13 and 094-P-04) are the hottest areas of the HRB, with the thick reservoirs at shallower depths. The temperature of these two areas exceeds 130°C at depths greater than 3 km, and the thickness of the geothermal reservoir in Zone 4 is twice that of Zone 1 (>300 m). However, data wells in this study are sparse and unevenly distributed crossing the basin. Re-examination or update may be necessary when more data becomes available.

ACKNOWLEDGEMENTS

This study was funded by Geothermal project of the Natural Resources Canada led by Dr. Edward Little. The authors would like to thank Dr. Makram Hedhli at the Geological Survey of Canada-Calgary for providing a comprehensive review and valuable comments and suggestions.

REFERENCES

Ardakani, E. and Schmitt, D., 2016, Geothermal energy potential of sedimentary formations in the Athabasca region, northeast Alberta, Canada. Interpretation, 4, SR19-SR33, 15 pages.

Banks, J., 2017. Deep-Dive Analysis of the Best Geothermal Reservoirs for Commercial Development in Alberta: Final Report, University of Alberta, Earth and Atmospheric Sciences, 93 pages.

BC MEM/NEB, 2011. Ultimate Potential for Unconventional Gas in Northeastern British Columbia's Horn River Basin, Report 2011-1, 49 pages.

BC Oil and Gas Commission, 2017. British Columbia's Oil and Gas Reserves and Production Report, 40 pages.

Canadian Geothermal Energy Association (CanGEA), Alberta Geothermal Resources Favourability Maps - Summary Report, 2013, 96 pages

Deming D., 1989. Application of bottom-hole temperature corrections in geothermal studies, Geothermics 18, 775-786.

Dong, T., Harris, N.B., Ayranci, K., Twemlow, C.E., Nassichuk, B.R., 2015. Porosity characteristics of the Devonian Horn River shale, Canada: Insights from lithofacies classification and shale composition. International Journal of Coal Geology 141-142, 74-90.

Dong, T., 2016. Geochemical, petrophysical, and geomechanical properties of stratigraphic sequences in Horn River Shale, Middle and Upper Devonian, Northeastern British Columbia, Canada. Unpublished Ph.D. thesis, University of Alberta, 258 pages.

Ferguson, G. and Ufondu, L. (2017). Geothermal energy potential of the Western Canada Sedimentary Basin: Clues from coproduced and injected water. Environmental Geosciences, v. 24, no. 3 (September 2017), pp. 113–121, DOI:10.1306/eg.0206171600917003

Field, M.B., Givens, J.W., Paxman, D.S., 1970, Kaybob South – Reservoir simulation of a gas cycling project with bottom water drive. Journal of Petroleum Technology 22(4): 481-492.

Fridleifsson, I.B., R. Bertani, E. Huenges, J. W. Lund, A. Ragnarsson, and L. Rybach 2008. The possible role and contribution of geothermal energy to the mitigation of climate change. In: O.

Hohmeyer, O. and Trittin, T. (Eds.) IPCC Scoping Meeting on Renewable Energy Sources, Proceedings, Luebeck, Germany, 20-25 January 2008, 59-80.

Grasby, S.E.; Allen, D.M.; Chen, Z.; Ferguson, G.; Jessop, A.; Kelman, M.; Majorowicz, J.; Moore, M.; Raymond, J.; Therrien, R., 2012, Geothermal Energy Resource Potential of Canada, Geological Survey of Canada, Open File 6913, 322 pages

Graf, T., 2009. Simulation of geothermal flow in deep sedimentary basins in Alberta. ERCB/AGS Open file report 2009-11.

Gray, A., Majorowicz, J., Unsworth, M., 2012. Investigation of the geothermal state of sedimentary basins using oil industry thermal data: A case study from northern Alberta exhibiting the need to systematically remove biased data. Journal of Geophysics and Engineering 9, 534–548.

Hickson C., Huang H., Cotterill D., Gosnold W., Benoit D., 2020, A Relook at Canada’s Western Canada Sedimentary Basin for Power Generation and Direct-Use Energy Production, GRC Transactions, Vol. 44, 17psges.

Hoffman H., 2015, Development of Enhanced Geothermal Systems (EGS) in Northern Alberta, A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Petroleum Engineering, 362 pages

Hulsey, K.M., 2011. Lithofacies characterization and sequence stratigraphic framework for some gas-bearing shales within the Horn River basin, Northeastern British Columbia. Unpublished M.Sc. thesis, University of Oklahoma, 76 pages.

Jessop, A., et al, 1991. Geothermal Energy in Canada, Geothermics, Vol. 20, No. 5/6, 17 pages

Majorowicz J., Grasby S.E., 2010. Heat flow, depth-temperature variations, and stored thermal energy for enhanced geothermal systems in Canada. Journal of Geophysics and Engineering, 7(3), 232-241.

Majorowicz, J. and Grasby, S.E.: 2010 High Potential Regions for Enhanced Geothermal Systems in Canada, J Natural Resources Research, Vol. 19, No. 3, 12 pages

Majorowicz, J., Grasby, S.E., 2014. Geothermal Energy for Northern Canada: Is it Economical? Natural Resources Research, 23(1), 15 pages.

Majorowicz, J.; Grasby, S.E., 2021, Deep Geothermal Heating Potential for the Communities of the Western Canadian Sedimentary Basin. Energies, 14, 706, 37 pages

Majorowicz, J.A., and Moore, M., 2008, Enhanced geothermal systems (EGS) potential in the Alberta basin, ISEEE Research Paper, 50 pages

Majorowicz J., Unsworth M., Chacko T., Gray A., Heaman L., Potter D. K., Schmitt D., Babadagli T., 2012, Geothermal Energy as a Source of Heat for Oil Sands Processing in Northern Alberta, Canada, The American Association of Petroleum Geologists

Majorowicz, J., Moore, M., 2014. The feasibility and potential of geothermal heat in the deep Alberta foreland basin-Canada for CO_2 savings. Renewable Energy 66, 541–549. http://dx.doi.org/10.1016/j.renene.2013.12.044

Majorowicz, J.A., 2018. Heat flow–heat production relationship not found: what drives heat flow variability of the Western Canadian foreland basin? International Journal of Earth Sciences (Geol Rundsch) 107, 5-18. https://doi.org/10.1007/s00531-016-1352-x.

McPhail, S., Walsh, W., Lee, C., Monahan, P.A., 2008. Shale units of the Horn River Formation, Horn River basin and Cordova Embayment, Northeastern British Columbia: (abs.), Canadian Society of Petroleum Geologists and Canadian Well Logging Society Convention, 14 pages.

Meijer Drees, N.C., 1994. Devonian Elk Point Group of the Western Canada Sedimentary Basin. In: Mossop, G. D., Shetsen, I. (Eds.), (Compos.), Geological Atlas of the Western Canada Sedimentary Basin. Canadian Society of Petroleum Geologists and Alberta Research Council 16, 129–147.

Morrow, D.W., Zhao, M., and Stasiuk, L.D., 2002. The gas-bearing Devonian Presqu'ile Dolomite of the Cordova embayment region of British Columbia, Canada: Dolomitiztion and the stratigraphic template, AAPG Bulletin, V. 86, No. 9, 1609-1638.

Mossop, G., and Shetsen, I., comps., 1994, Geological atlas of the Western Canada Sedimentary Basin: Calgary, Alberta, Canadian Society of Petroleum Geologists and Alberta Research Council, accessed June 1, 2022, at http://www.ags.gov.ab.ca/publications/wcsb_atlas/ atlas.html.

Ness, S.G., Benteau R., Leggit S., 2010. Horn River Shales…boring or black?... or…beautifully complex? GeoCanada 2010, 9 pages.

Oldale, H.S., Munday, R.J., 1994. Devonian Beaverhill Lake Group of the Western Canada Sedimentary Basin. In: Mossop, G.D., Shetsen, I. (Eds.), (Compos.), Geological Atlas of the Western Canada Sedimentary Basin. Canadian Society of Petroleum Geologists and Alberta Research Council 16, 149–163.

Palmer-Wilson, K., Walsh, W., Banks, J., and Wild, P. 2018. Techno-Economic Assessment of Geothermal Energy Resources in the Sedimentary Basin in Northeastern British Columbia, Canada, Geoscience BC Report 2018-18, 67 pages.

Peters, K.E., Nelson, P.H., 2009. Criteria to Determine Borehole Formation Temperatures for Calibration of Basin and Petroleum System Models, Search and Discovery, Article #40463, 5-15.

Renaud E., Harris N., Banks J., Weissenberger J., 2018, Geothermal Resource Characterization of the Slave Point Formation in Clarke Lake Field, Fort Nelson, British Columbia, Canada, Adapted from an oral presentation given at AAPG 2018 AAPG Annual Convention and Exhibition, Salt Lake City, Utah,

Reynolds, M.M., Munn, D.L., 2010. Development update for an emerging shale gas giant field-Horn River Basin, British Columbia, Canada. SPE Unconventional Gas Conference, Pittsburgh, USA, SPE Paper 130103, 17 pages.

Rogers, M.B., 2017. Stratigraphy of the Middle Devonian Keg River and Prairie Evaporite formations, northeast Alberta, Canada. Bulletin of Canadian Petroleum Geology 65 (1), 5-63.

Ross, D.J.K., Bustin, R.M., 2008. Characterizing the shale gas resource potential of Devonian-Mississippian strata in the western Canada sedimentary basin: Application of an integrated formation evaluation. AAPG Bulletin 92, 87-125.

Sanyal, S.K., 2005. Classification of Geothermal Systems – A Possible Scheme. Proceedings, Thirtieth Workshop on Geothermal Reservoir Engineering, Stanford University, SGP-TR-176, 5 pages.

Skall, H., 1975. The paleoenvironment of the Pine Point Lead-Zinc district, Economic Geology 70, 22-47.

Walsh W., Tu A., 2014, Geothermal Potential Within Devonian Carbonates in the Clarke Lake Gas Field, Northeastern British Columbia, Canada, GRC Transactions, Vol. 38, 655

Weides S, Moeck I, Schmitt D, Majorowicz J, and Ardakani E., 2013, Characterization of geothermal reservoir units in northwestern Alberta by 3D structural geological modeling and rock property mapping based on 2D seismic and well data. Proceedings, 83rd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA.

Weides S., Moeck I., Schmitt D., Majorowicz J., 2014. An integrative geothermal resource assessment study for the siliciclastic Granite Wash Unit, northwestern Alberta (Canada). Environ Earth Sci. 72, 4141-4154. doi: 10.1007/s12665- 014-3309-3.

Weides S., Majorowicz J., 2014. Implications of spatial variability in heat flow for geothermal resource evaluation in large foreland basins: the case of the Western Canada Sedimentary Basin. Energies 7(4), 2573-2594. doi: 10.3390/en7042573.

Williams, G. K., 1983, What does the term Horn River Formation mean? Bulletin of Canadian Petroleum Geology, v. 31, 117–122.

Zahrani, A.A., 2011. Interpretation of 3D multicomponent seismic data for investigating natural fractures in the Horn River Basin, northeast British Columbia. M.Sc. thesis, University of Calgary, 118 pages.