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K. Hu, Z. Chen, and S.E. Grasby

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

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SUMMARY

This publication compiles a dataset consisting of geophysical well logs, core analysis, X-ray powder diffraction, water analysis data and total organic carbon content from the Devonian Horn River Group shales from petroleum wells drilled in the Horn River Basin in northeastern British Columbia. Based on analysis of the collected data, various attributes are presented graphically for the Muskwa, Otter Park and Evie formations within the Horn River Group. This dataset forms the basis of quantitative analysis for reservoir characteristics for geothermal and other energy resource assessments in the basin.

INTRODUCTION

The Horn River Basin (HRB) is located in the northeast British Columbia, Canada and covers an area of approximately 11 000 km^2 within the Fort Nelson/Northern Plains region (Fig. 1a). The HRB hosts an unconventional shale play targeting dry gas from Middle and Upper Devonian Horn River Group (HRG) strata, consisting of the organic rich Muskwa, Otter Park and Evie formations. More than 480 wells penetrating the HRG were drilled between 1955 and 2014 in the basin (e.g., the selected wells in Fig. 1b). Over the past decade, extensive natural gas exploration and development has been conducted in the HRB. With the advent of horizontal well drilling combined with multi-stage hydraulic fracturing technology, production in the HRB has been steadily increasing. For example, over 800 Bcf has been produced from the Muskwa-Otter Park and Evie formations within the HRB between April 2005 and December 2014 (BC Oil and Gas Commission, 2014). Daily natural gas production from these formations accounted for approximately 11% of BC's total daily gas production of 4.6 Bcf/d in 2014 (Adams, et al., 2016). A mean estimate of recoverable methane gas resource was assessed at 114 TCF (trillion cubic feet) in the HRB (Chen and Hannigan, 2016). Over 107 TCF of the potential continuous gas resources was estimated in the Basin (USGS, 2019).

In the transition from traditional fossil fuels to a low carbon economy, geothermal resource has been sought as a replacement to offset CO_2 emission in hydrocarbon production sites to contribute the Canadian Government's goal of net zero carbon emission by 2050. Studies suggest that the HRB may contain large amount of geothermal resource in the Western Canada Sedimentary Basin (WCSB) (Palmer-Wilson, et al., 2018; Majorowicz and Grasby, 2021). Recently, the depleted Clarke Lake gas field in the HRB has been identified as a prospective site for geothermal resource development (GeoscienceBC, 2018; Palmer-Wilson, et al., 2018). The Geological Survey of Canada is studying the feasibility of converting existing shale gas production facilities into a geothermal energy extraction plant. This study will provide the data for the geothermal resource calculation.

GEOLOGICAL SETTING

The HRG shales are overlain by the Fort Simpson shales, and underlain by the Keg River platform carbonates in the HRB (Fig. 1c). From bottom up, the HRG is divided into the Evie, Otter Park and Muskwa shales. It is noteworthy that the Klua and Evie shales are grouped as Evie in this study.

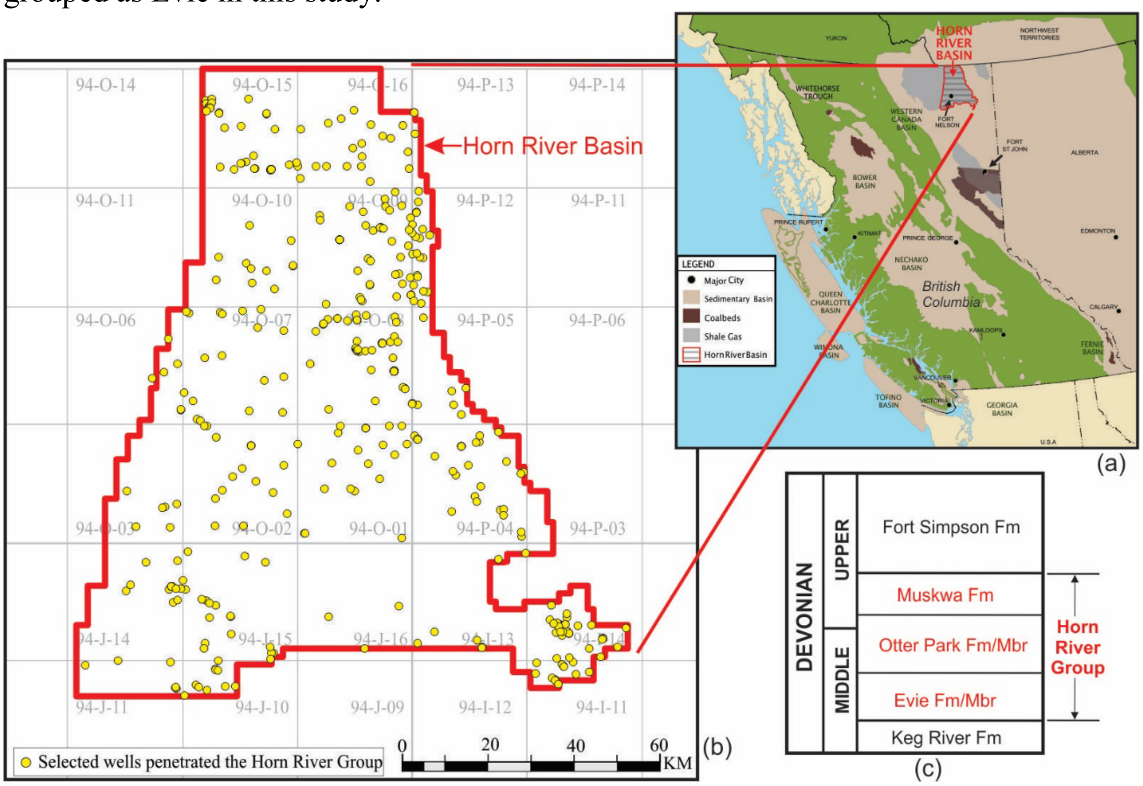

Fig.1. Map showing the location of the study area in Western Canada modified from BC Oil and Gas Commission, 2014 (a), drilled wells that have penetrated Horn River Group in the Horn River Basin (b), and schematic stratigraphic chart of the Horn River Group in the Horn River Basin adopted from Ferri et al., 2011, and BC Oil and Gas Commission, 2014 (c).

The Evie Shale consists of dark grey to black, radioactive, organic rich, pyritic, variably calcareous and siliceous shale. The Otter Park Shale reaches a maximum thickness of over 270 m in the southeast corner of the HRB, where it consists of medium to dark grey calcareous shale with lower radioactivity. The Muskwa Shale consists of grey to black, radioactive, organic rich, pyritic, and siliceous shale.

Although the HRB shale gas play is relatively new, there are many older wells (especially vertical wells) that penetrated the HRG shales (e.g., the wells shown in Fig. 1b). These wells provided a variety of basic information, such as petrophysical, geological, and engineering data. However, published well data, especially petrophysical data for detailed reservoir characterization are limited. This work aims to compile and analyze various well data, including well logs, core measurements (such as porosity and permeability), X-ray powder diffraction (XRD), water analysis data and total organic carbon content, providing an essential dataset for detailed reservoir descriptions in petroleum and geothermal resource assessment. Except for some wireline logs, the compiled raw data in Geological Survey of Canada's database were provided by the British Columbia Oil and Gas Commission.

GEOPHYSICAL WELL LOGS

Geophysical well logging is continually recording petrophysical properties using a variety of sensors for the geologic formations penetrated by a borehole. In general, a conventional logging set is performed for the entire interval (from start depth to total depth - TD) for the oil and gas wells. Whereas the geochemical logging tool only operates on the targeted interval of limited wells, and provides quantitative measurements of a wide range of elements and/or the mineralogy data. The geochemical logs in the study area were mainly acquired using Litho-scanner logging by Schlumberger Limited or Rock View logging by the Baker Hughes Company.

As an advanced logging tool, nuclear magnetic resonance (NMR) logging measures the induced magnetic moment of hydrogen nuclei (protons) contained within the fluid-filled pore space of porous media (reservoir rocks) for the targeted layer of borehole, providing important information on reservoir properties, such as lithology-independent total porosity, free and bound fluid porosity and permeability.

This study compiled thousands of digital logs (in las format), which were acquired by Schlumberger Ltd., Baker Hughes Company, Weatherford Canada Ltd., or Halliburton Company from the wells in the Horn River Basin, were reviewed and merged. The well logs of approximately 400 wells are examined in accordance with the following criteria: 1) the wells penetrated the Devonian HRG that contains the Muskwa, and/or Otter Park and/or Evie formations, and 2) a basic suite of geophysical well logs was acquired, including (spectral) gamma ray (SGR or GR), deep resistivity (RD), bulk density (RHOB), photoelectric factor (PE; if available), neutron porosity, and compressional sonic transit time (DT, if available).

For some wells, the formation radioactive concentrations (uranium - U, thorium - Th and potassium - K) were recorded. In addition, quantitative measurements of the principal elements and available mineralogy logs were carried out. These logs mainly include the content of quartz, calcite, dolomite, feldspar, clay type materials and pyrite (mainly in dry weight percentage). Moreover, the basic petrophysical parameters such as porosity and permeability interpreted by NMR logging were also collected for 26 wells. Figure 2 shows all the wells that penetrated the HRG in which the conventional well logs, available mineralogy logs, and NMR well logging were performed in the HRB.

A composite plot with eight tracks (Fig. 3) illustrates extracted geophysical log records from a typical well that penetrated the HRG in the HRB. From left to right, in addition to depth and formation track, Track 1 shows lithological logs, including (spectral) gamma rays and spontaneous potential (if available). Track 2 displays the formation radioactive concentrations (U, Th and K) and the calculated Th/U ratio in this study. Track 3 shows the resistivity curves with different investigation depths (shallow - RS, medium - RM and deep - RD). Track 4 shows the compressional sonic transit time (DT), bulk density (RHOB), and photoelectric factor (PE). Track 5 illustrates the porosity curves, which mainly include the original density and neutron porosity logs calibrated with different lithologies (e.g., density porosity calibrated with limestone (PDL) and sandstone (PDS), and neutron porosity calibrated with limestone (POL) and sandstone (POS)). Track 6 displays the dry weight percent of total organic carbon (TOC) and total gas (TGAS, if available). Track 7 shows the major mineral content of quartz and carbonate. Track 8 displays the mineralogy logs, which primarily consist of the dry weight fraction of QFM containing quartz plus feldspar and mica, clay, calcite, dolomite, and pyrite.

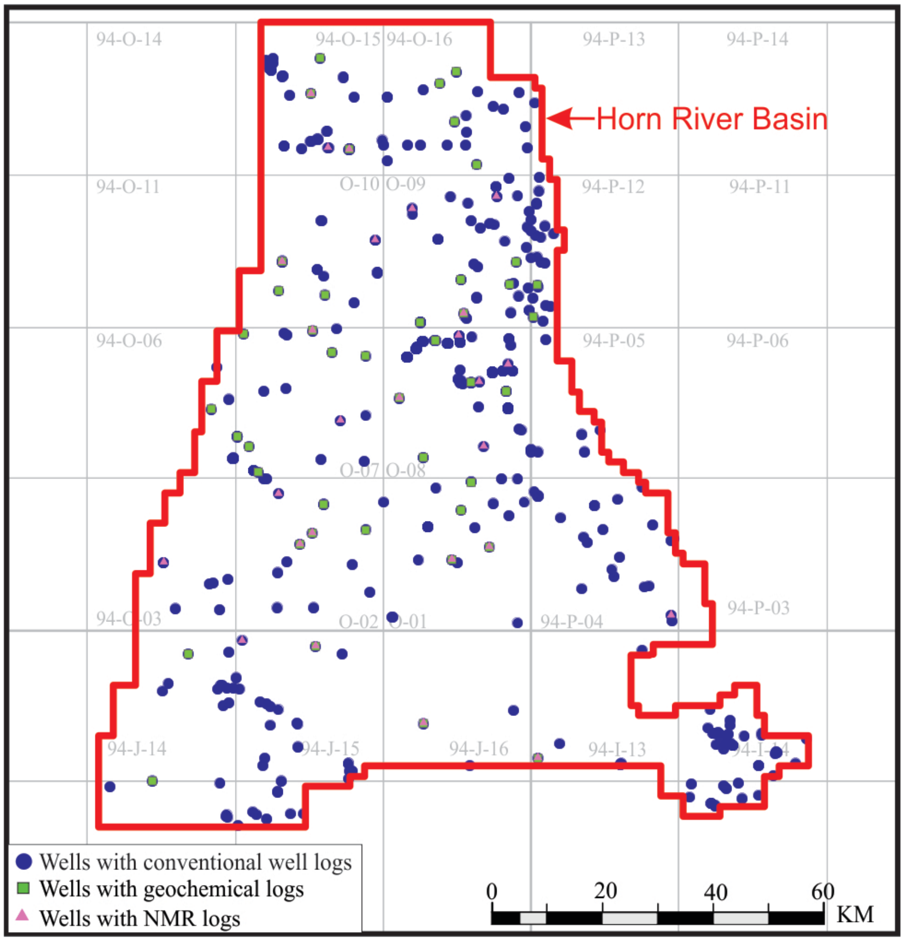

Fig. 2. Location of the drilled wells in which the conventional well logging, geochemical logging set and advanced nuclear magnetic resonance (NMR) were performed for the Horn River Group in the Horn River Basin.

Based on the mineralogy variation and log signatures (Fig. 3), the three formations within the HRG can be easily distinguished by wells logs and lithology because the lower (Evie) and upper (Muskwa) organic rich shales are characterized by abnormally high gamma ray and high uranium concentrations. The Evie Formation exhibits the highest gamma ray, uranium radioactive concentration and resistivity readings, with low Th/U ratios. The Otter Park Formation is the thickest (103 m) of the three formations in the well. It has relatively low radioactivity log readings and a high Th/U ratio, most of which have lower resistivity readings than the Evie shale. The main characteristics of the Muskwa Formation are relatively higher gamma ray and higher U concentration compared to the underlying Otter Park Formation. Moreover, compared with the Evie and Otter Park formations, the Muskwa Formation has higher quartz content and lower carbonate content. It appears that some gas potential zones with high total gas (TGAS) readings are identified in the lower Otter Park Formation (Track 6 in Fig. 3).

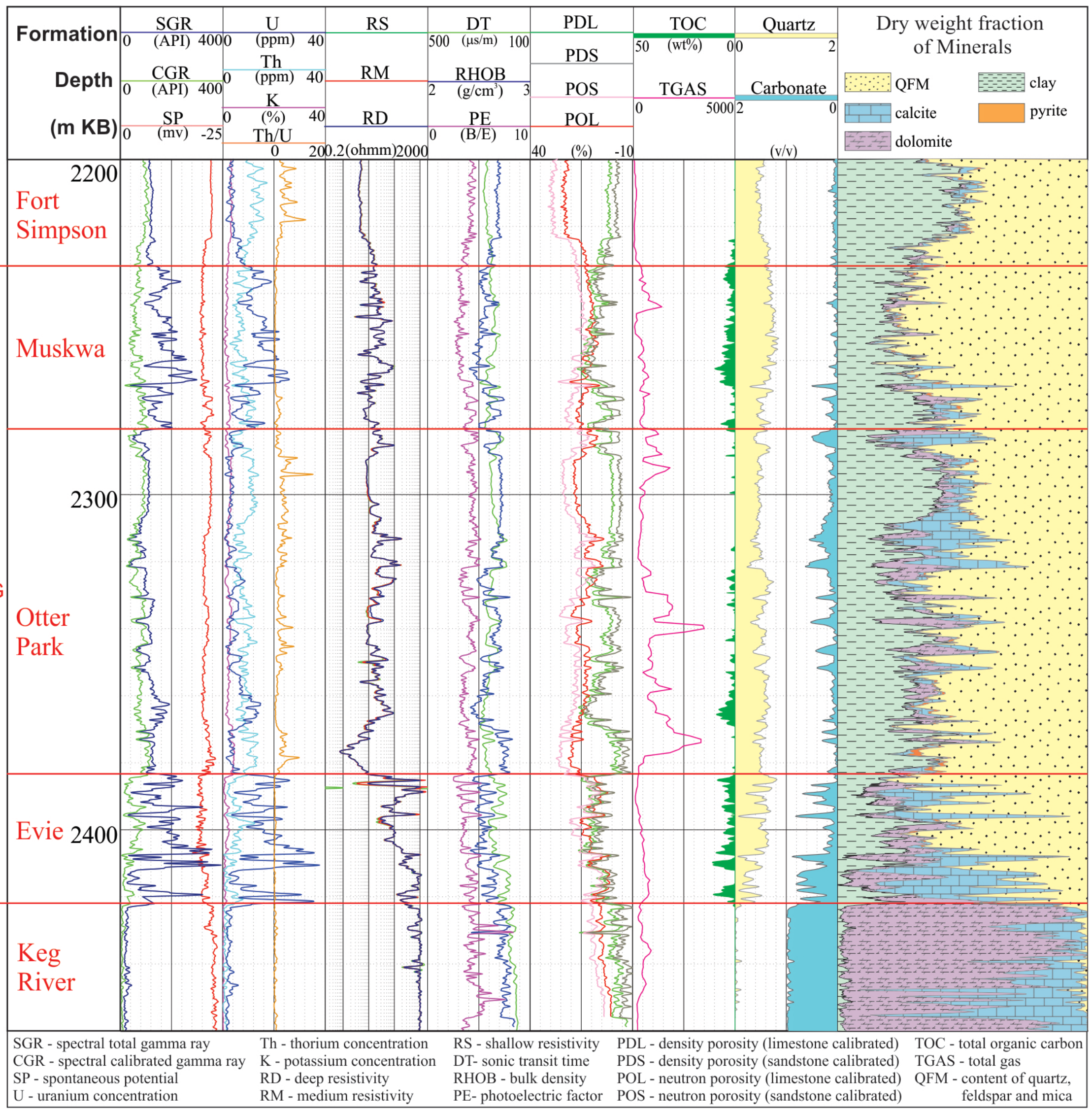

Fig. 3. Composite plot exemplifying lithology variation and well log signatures for the Horn River Group in the well IMP KOMIE D-047-J/094-O-02 in the Horn River Basin, including conventional well logs, available dry weight fraction of mineral components and compiled mineralogy logs.

As another example, Figure 4 shows not only most of the conventional well logs, but also some NMR well logs such as total porosity, effective porosity, free fluid porosity (Track

6 in Fig. 4), and permeability curves (Track 7 in Fig. 4) including KTIM (the NMR permeability from TIM model) and KSDR (the NMR permeability from SDR model). The extracted geochemical logs include the dry weight fractions of the elements (for example, aluminum, silicon, calcium, iron, sulfur and titanium; Track 8 and 9) and the mineral composition (e.g., QFM - quartz plus feldspar and mica, carbonate, clay and pyrite; Track 10 in Fig. 4), showing the lithology variation in the interval from the lower part of the Fort Simpson Formation through the HRG to the upper part of the Keg River Formation.

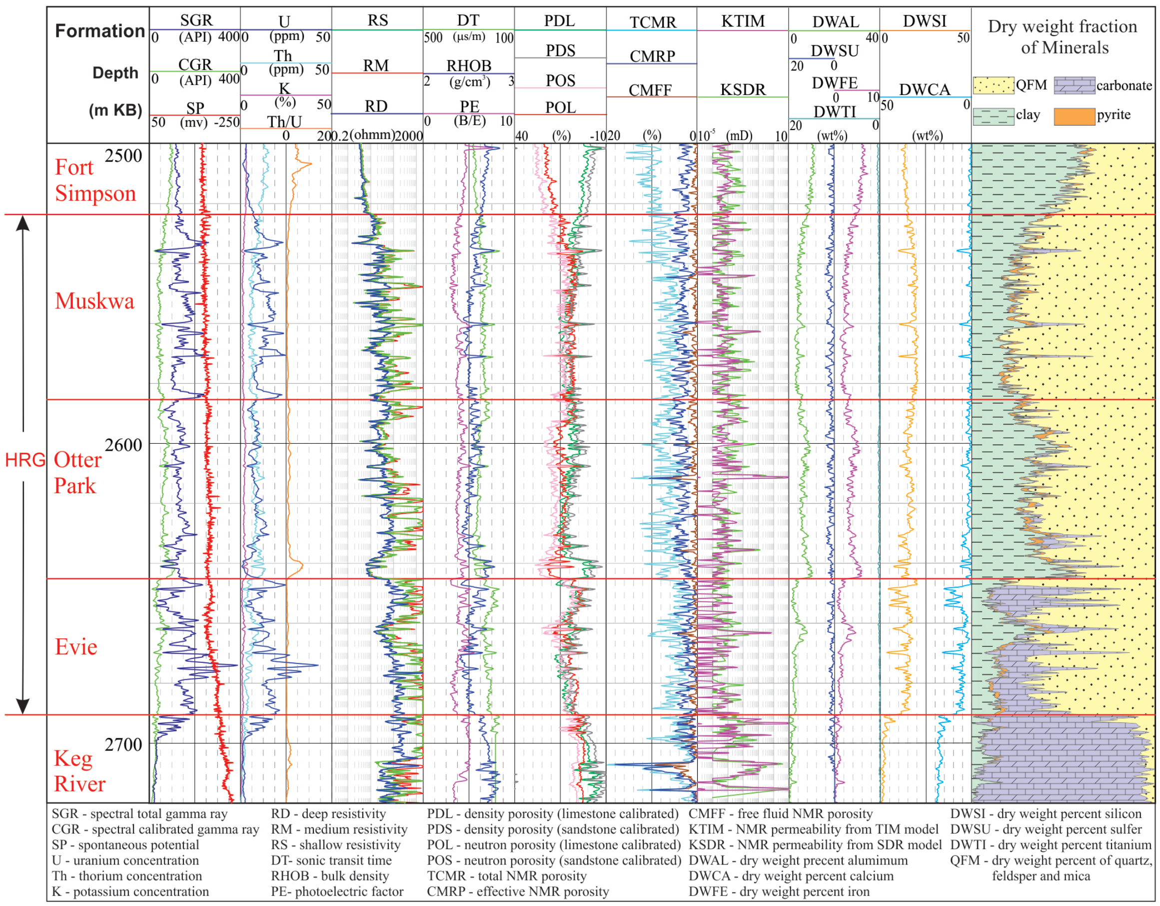

Fig. 4. Example showing well log responses and major mineralogy variation for the HRG in the well CNOOC Gote A-027-I/094-O-08, including conventional well logs, NMR logs and geochemical logs.

Unlike the well in Figure 3, the thicknesses of the three formations are not much different in the well of Figure 4. The Evie and Muskwa formations are identified by high U concentration and gamma ray readings. Compared with the Muskwa and Evie formations, the Otter Park Formation exhibits higher clay content. Among the three formations within the HRG, the Evie Formation has the lowest clay content and the highest carbonate content.

QUANTITATIVE X-RAY DIFFRACTION ANALYSES

X-ray powder diffraction (XRD) is widely used for the identification of unknown crystalline materials (e.g. minerals, inorganic compounds) because the determination of unknown solids is critical for geology, environmental science, material science, engineering and biology research.

XRD can be used as a stand-alone method or used in conjunction with other tools to provide a comprehensive and integrated approach for petrologic evaluation. In general, XRD analysis provides qualitative and semi-quantitative mineral characterization of rock samples. Most laboratories offer two types of analyses, including bulk powder analysis of whole rock samples suitable for quick mineral identification, and <2 μm clay mineral analysis, which is used mainly for identification of clay (or shale) minerals.

In this study, the compiled XRD analysis data mainly includes bulk powder and clay mineralogy analyses of 1501 samples from 42 wells (blue triangles in Fig. 5), which were carried out by different laboratories, such as Core Lab., Calgary Rock and Materials Services Inc., and TerraTek (a Schlumberger company). Among the 1501 samples, the weight percentage and volume fraction of mineral compositions come from 162 samples from eight wells (star-shaped wells in Fig. 5). Of the 1339 samples with weight percent, 430 are from the Muskwa Formation, 609 are from the Otter Park Formation, and 300 are from the Evie Formation.

The mineral components identified by XRD analysis primarily include quartz, carbonate primarily consisting of calcite and dolomite, feldspar mainly containing K-feldspar and plagioclase, pyrite, and clay minerals; other minerals accounted for less than 0.2 wt.% of the average total content, consisting of apatite, fluorapatite, barite, magnetite, anhydrite, and gypsum, all too minor to be illustrated. Figure 6 shows the average contents of the major mineral components from XRD mineral analyses for the Muskwa (Fig. 6a), Otter Park (Fig. 6b) and Evie (Fig. 6c) formations, while Figure 7 illustrates the distribution of mineral composition for the three formations. In addition, the average proportion of the clay mineral components to the total clay content for the three formations is presented in Figure 8.

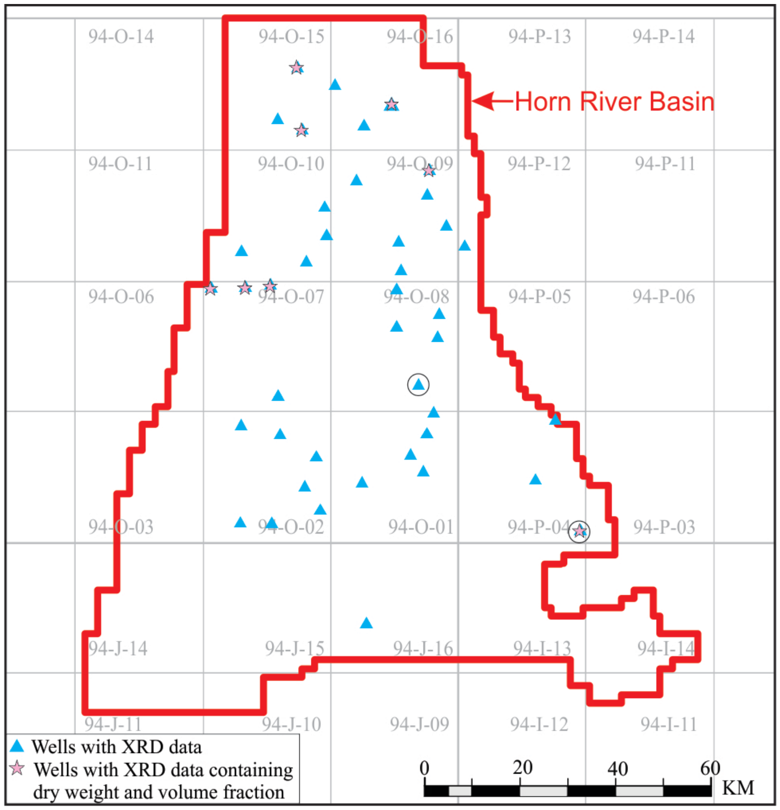

Fig. 5. Location of the wells in which X-ray powder diffraction (XRD) were examined for some samples from the Horn River Group in the Horn River Basin in northeast BC.

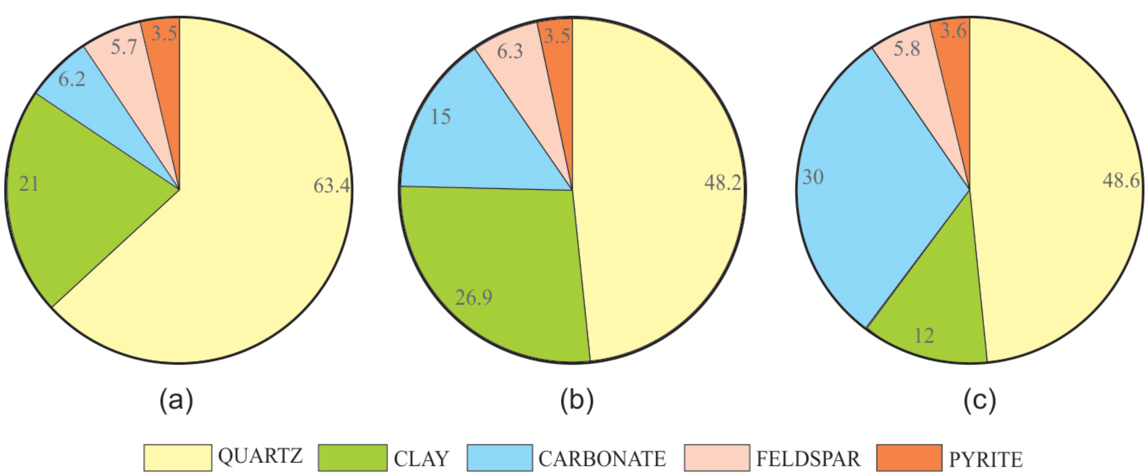

Fig. 6. Pie chart showing the average contents (with weight fraction unit, wt.%) of mineral components identified by XRD analysis, including quartz, clay, carbonate, feldspar, and pyrite for the Muskwa (a), Otter Park (b) and Evie (c) formations, in the Horn River Basin, NE of BC.

The quartz content of the Muskwa Formation has a range of 50 - 92 wt.%, with an average value of 63.4 wt.%, which is higher than that of the Otter Park Formation (30-70 wt.%; average 48.2 wt.%) and the Evie Formation (40-70 wt.%; average 48.6 wt.%), as shown in the yellow slice in Figure 6 and yellow bar in Figure 7.

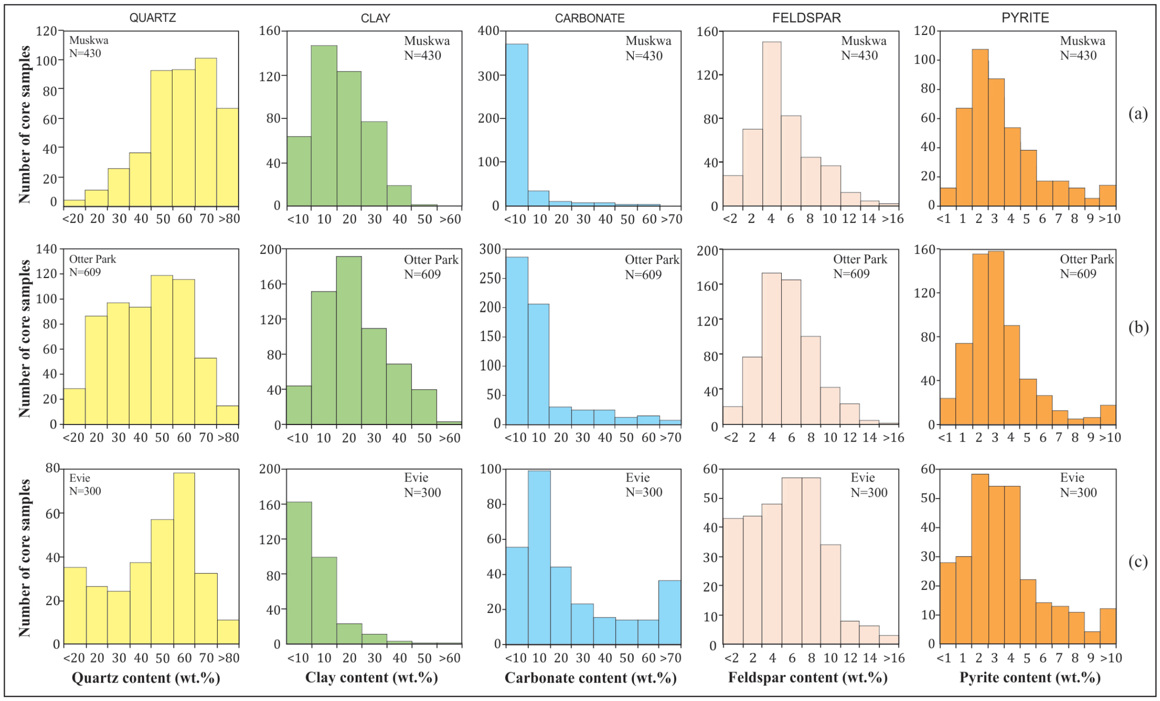

Fig. 7. The distribution of mineral components determined by XRD analysis, including quartz, clay, carbonate, feldspar, and pyrite for the HRG consisting of the Muskwa (a), Otter Park (b) and Evie (c) formations, in the Horn River Basin in northeast BC. N – Number of core samples.

Clay contents from XRD analyses are primarily in the range of 0-40 wt.%, 10-40 wt.%, and 0-20 wt.%, with an average of 21.0 wt.%, 26.9 wt.% and 12.0 wt.% for the Muskwa, Otter Park and Evie formations, respectively (the green slice in Figure 6 and the green bar in Figure 7). In general, the clay mineral components are mainly comprised of illite (average proportion range 21.1-49.4%) and mixed-layer of illite/mica (average proportion range 36.6-52.4%) and/or illite/smectite (average proportion range 13.5-23.0%), with minor or trace amounts of chlorite (average percentage <3.0%) and kaolinite (average percentage <1.0 %) for some samples (Fig. 8). The exception is that a few samples from the Muskwa and Otter Park formations in two wells (circled wells in Fig. 5) contain chlorite content of more than 10 wt.%.

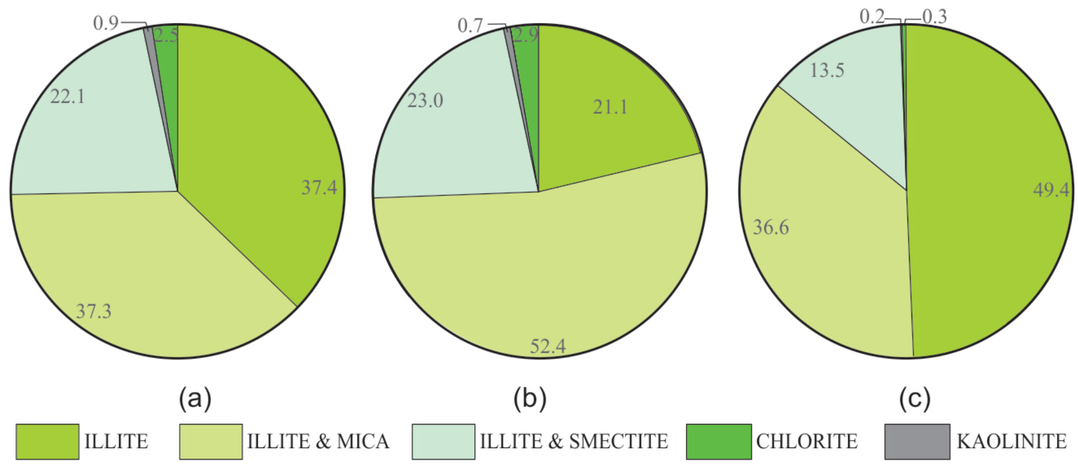

Fig. 8. Pie chart showing the average proportion of clay mineral components to the total clay content from XRD analysis for the Muskwa (a), Otter Park (b) and Evie (c) formations, in the Horn River Basin, NE of BC.

The carbonate content values from the Muskwa Formation are mainly between 0 and 10 wt.% (average 6.2 wt.%), which are lower than that from the Otter Park Formation (range of 0-20 wt.% and 15.0 wt.% average) and the Evie Formation (range 2-40 wt.%, and 30.0 wt.% average). In addition, more than 26% of the samples from the Evie Formation contained >40 wt.% carbonate, which was considerably higher than that from the other two formations, compared to 2.6 % from the Muskwa Formation and 8.9 % from the Otter Park Formation (the blue slice in Figure 6 and the blue bar in Figure 7).

The samples from the Muskwa Formation have an average feldspar content of 5.7 wt.%, which is slightly lower than that from the Otter Park Formation (6.3 wt.%) but very close to that from the Evie Formation (5.8 wt%; the pink slice in Figure 6). Despite the feldspar contents from the Muskwa and Evie formations having very close average values (5.7 and 5.8 wt.%; Fig. 6), the histograms show different distributions and the Evie Formation appears to be more dispersed (the pink bars in Figure 7a and c).

Although the distributions observed from the three formations are slightly different (Fig. 7), the pyrite content exhibits a similar main range of variation (1-5 wt.%) and the same median value of 3.0 wt.%, with a very close average value of 3.5 wt.%, 3.5 wt.% and 3.6 wt.% for the Muskwa, Otter Park and Evie formations, respectively (the orange slice in Figure 6 and the orange bar in Figure 7).

PETROPHYSICAL CORE ANALYSIS

Core analysis data provides a direct measure of key petrophysical parameters used for reservoir characterization. In the study area, hundreds of core samples from the HRG were subject to core analysis, including various core parameter measurements: core porosity (gas filled porosity, total porosity, effective porosity); permeability (matrix permeability); bulk density (as received bulk density, dry bulk density); grain density (as received grain density, dry grain density), and fluid saturation (as received water saturation, oil saturation and gas saturation), which were carried out in different labs such as TerraTek – A Schlumberger company, Calgary Rock and Materials Services Inc., Core Laboratories Canada Ltd., and HYCAL Energy Research Laboratories Limited.

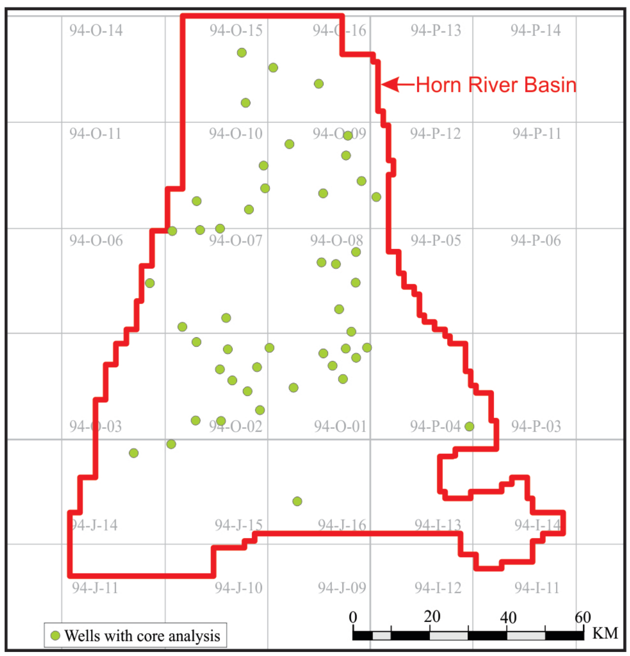

Fig. 9. Location of the wells in which core porosity and matrix permeability were measured for the Horn River Group in the Horn River Basin, NE of BC.

In this study, porosity and matrix permeability data were acquired from laboratory measurements conducted on 1363 core samples from 47 wells (Fig. 9). The compiled core measurements are grouped into the Muskwa (456 samples), Otter Park (595 samples) and Evie (312 samples) formations. Figure 10 presents the histograms and cumulative curves of the core porosity and matrix permeability for the Muskwa, Otter Park and Evie formations in the HRB. The core samples from the three formations show different main range of variation, average and median value in measured porosity and permeability (Table 1 and Fig. 10). It is obvious that the Muskwa Formation exhibits the best reservoir quality characterized by the highest porosity and matrix permeability, whereas the lowest average porosity and matrix permeability occur in the Otter Park Formation.

Table 1. Core porosity and permeability from the Horn River Group containing the Muskwa, Otter Park and Evie formations in the Horn River Basin, northeast of BC.

Formation	Core porosity (%)			Core Permeability (mD)		
	Main variation range	Average	Median	Main variation range	Average	Median
Muskwa	0.52 -12.58	4.79	4.67	1.04 10^{-10} - 0.609	6.36 10^{-3}	1.93 10^{-4}
Otter Park	0.2 - 9.71	4.05	3.83	7.29 10^{-13} -7.62 10^{-3}	2.81 10^{-4}	1.85 10^{-4}
Evie	0.03 - 10.41	4.46	4.48	2.5 10^{-13} - 0.308	3.87 10^{-3}	1.69 10^{-4}

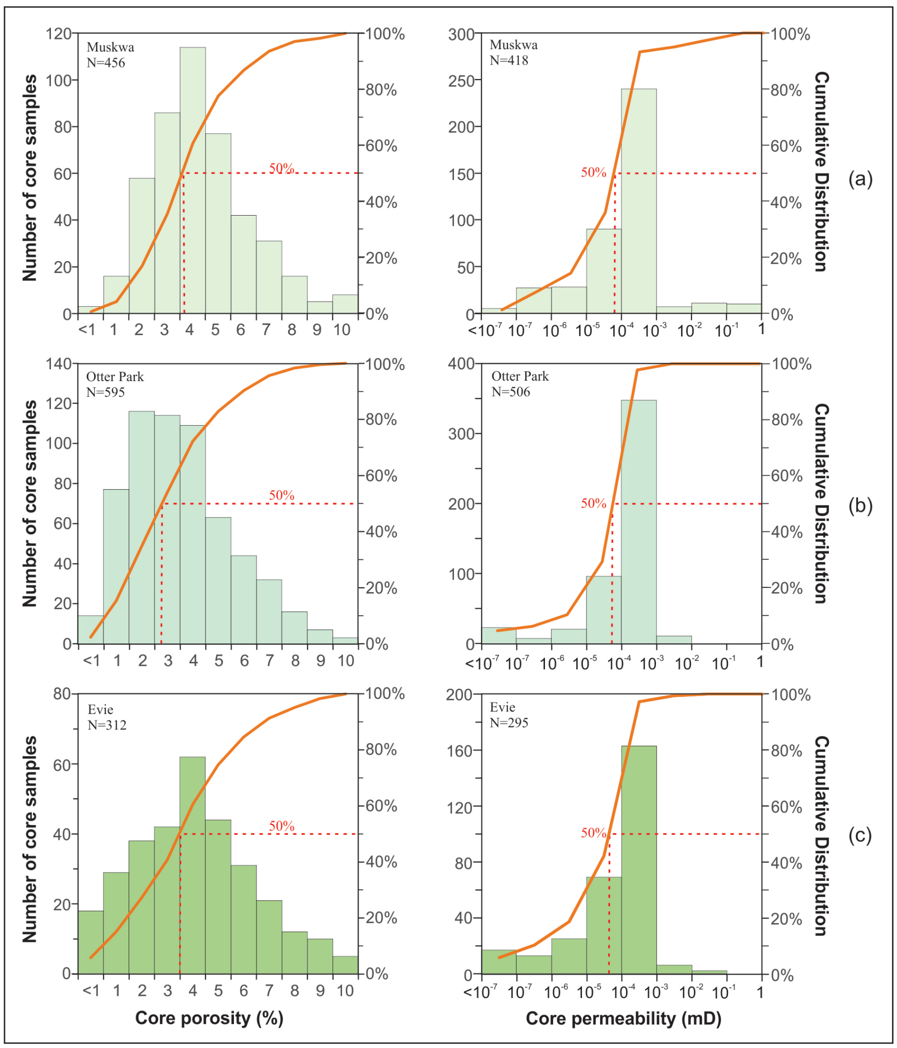

Fig. 10. Histograms showing the distribution of porosity and matrix permeability measured on core for the Muskwa (a), Otter Park (b) and Evie (c) formations of the HRG Group in the Horn River Basin, northeast BC. Cumulative distribution curves shown in solid red. N – Number of core samples.

The grain density distribution from core analysis illustrates that two grain density peaks exhibit for each formation, with the same peak range of 2590 - 2620 kg/m^3 for the three formations, whereas the second peak range occurs at 2710-2740 kg/m^3 for the Muskwa and Otter Park formations, and at 2680-2710 kg/m^3 for the Evie Formation (left panel in Fig. 11). The average grain density is 2642 kg/m^3, 2653 kg/m^3 and 2638 kg/m^3 for the Muskwa, Otter Park and Evie formations, respectively. Most of the core samples from the three formations have water saturation values less than 20%, but their distribution is slightly different (right panel in Fig. 11).

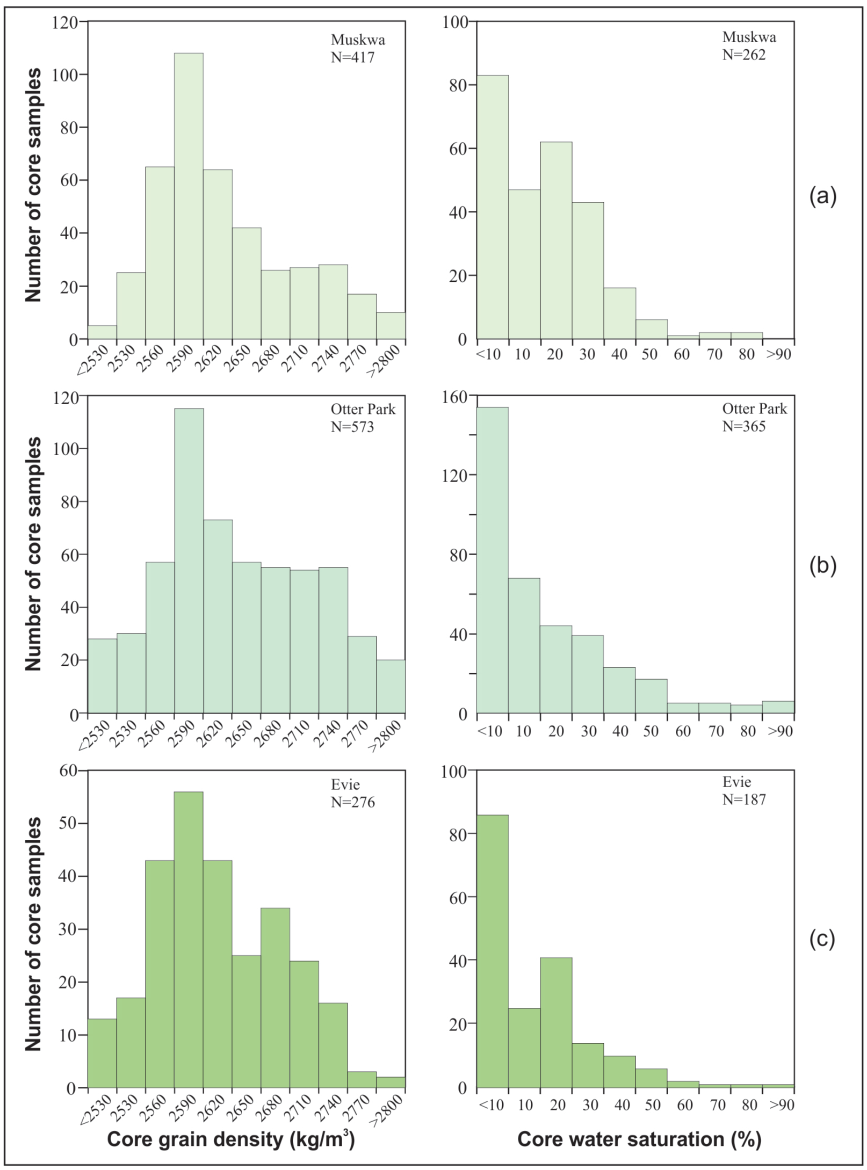

Fig. 11. Distributions of measured grain density and water saturation from core analysis for the Muskwa (a), Otter Park (b), and Evie (c) formations of the HRG Group in the Horn River Basin in northeast BC. N – Number of core samples.

FORMATION WATER ANALYSIS

A total of 339 water samples from 106 wells of the Horn River Group were subject to analysis in which the green diamonds represent the wells in the HRB and the blue diamonds are that closely bordering on HRB (Fig. 12). The compiled data includes calculated total dissolved solids and water resistivity at 25 ˚C of temperature. Of the 339 water samples, 127, 148 and 65 are from the Muskwa, Otter Park, and Evie formations, respectively.

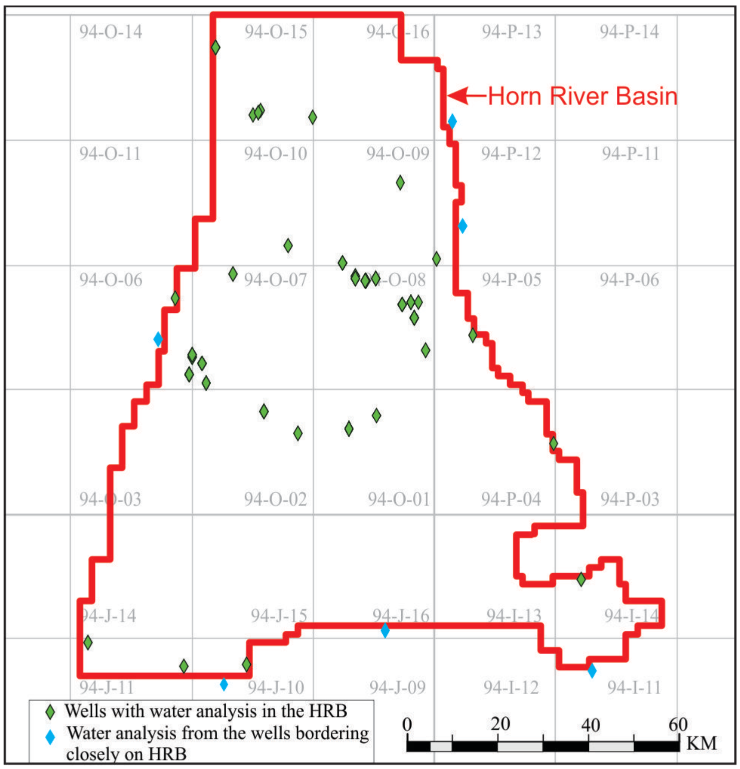

Fig. 12. Location of the wells with water analysis from the Horn River Group in the Horn River Basin and closely bordered on the HRB.

Figure 13 displays the distributions of the calculated total analytical solids (left panels) and resistivity (right panels) of the formation water samples from the three formations. For the water samples from the Muskwa Formation (Fig. 13a), the total dissolved solids ranges from 420 to 158,000 mg/L, with an average value of 31,000 mg/L and an median value of 28,000 mg/L (left panel in Fig. 13a). The corresponding water resistivity value (at a temperature of 25 ˚C) is between 0.06 and 1.97 ohmm (average 0.31 ohmm, median 0.25 ohmm). Water samples from the Otter Park Formation have a total dissolved solids in the range of 6200-161,000 mg/L (average 23,000 mg/L, median 21,000 mg/L) and a resistivity value between 0.07 and 1.43 ohmm (average 0.32 ohmm, median 0.28 ohmm) (Fig. 13b). For the water samples from the Evie Formation, the total dissolved solids varies from 2400 to 113,000 mg/L, with an average of 46,000 mg/L and an median of 36,000 mg/L (left panel in Fig. 13c), and the resistivity at a temperature of 25 ˚C ranges from 0.07 to 1.60 ohmm (average 0.27 ohmm, median 0.19 ohmm) (right panel in Fig. 13c). Overall, the formation water samples from the Evie Formation have relatively higher calculated total dissolved solids and lower resistivity values compared to the Muskwa and Otter Park formations.

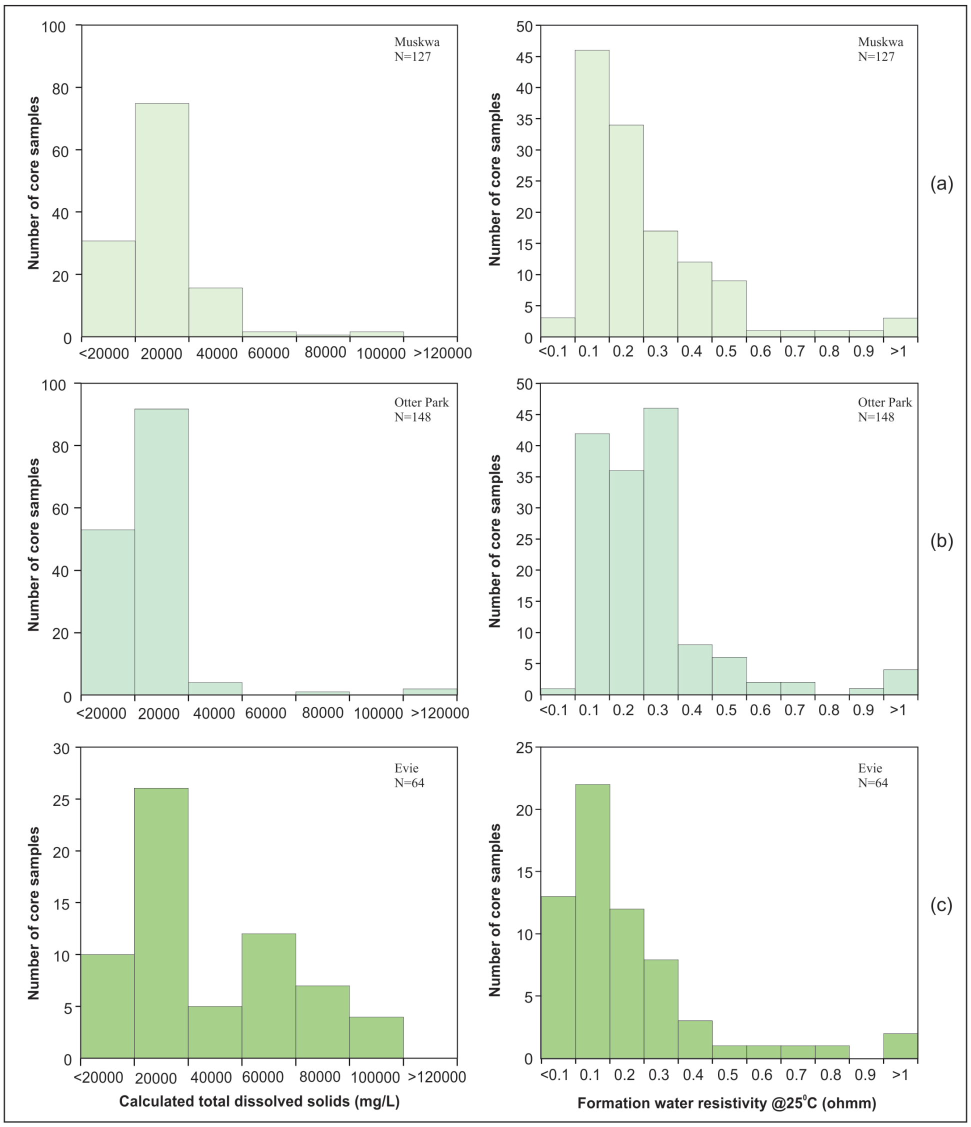

Fig. 13. Histograms showing the calculated total dissolved solids that is the sum of cations (positively charged) and anionic (negatively charged) ions in the water sample (left panel) and the resistivity (right panel) of formation water samples from the Horn River Group, including Muskwa (a), Otter Park (b), and Evie (c) formations in the Horn River Basin, northeastern BC. N – Number of core samples.

TOTAL ORGANIC CARBON CONTENT

Total organic carbon (TOC) is a measure of the total amount of carbon in organic compounds in rock expressed as a weight percent. TOC has become the one of most important parameters in evaluating shale gas system. High TOC content is favorable for both gas generation and storage.

In this report, the TOC content of the total 2238 samples was compiled and plotted from 64 wells that penetrated the Horn River Group in the HRB (Fig. 14), most of which were determined by LECO combustion. The extract TOC data is divided into three groups by formation, 776, 1045 and 417 samples are from the Muskwa, Otter Park and Evie formations, respectively.

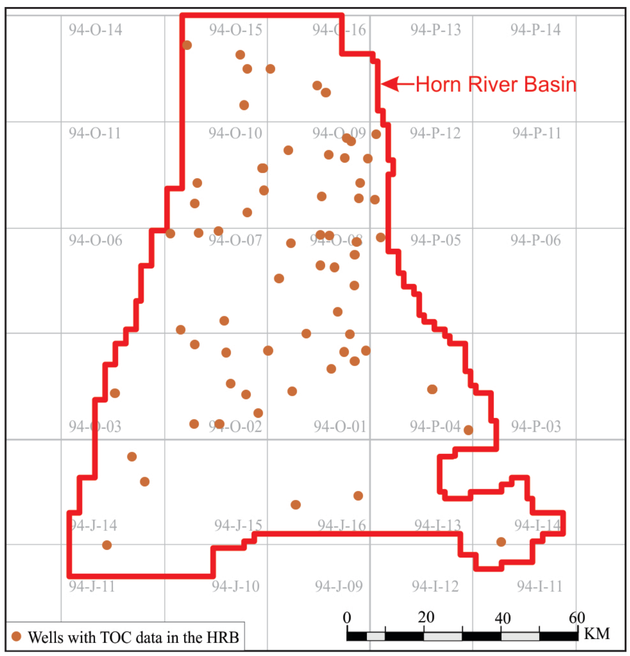

Fig. 14. Location of the wells with TOC data from the Horn River Group in the Horn River Basin.

Figure 15 presents the histogram plots of measured TOC. The core samples from the Muskwa Formation have a TOC measurement ranging from 0.32 to 12.02 wt.%, with an average of 3.45 wt.% (median value of 3.22 wt.%; Fig. 15a). For the Otter Park Formation (Fig. 15b), the measured TOC values fluctuate between 0.10 and 11.30 wt.% (2.86 wt.% average, 2.71 wt.% median). The TOC measurements of the core samples from the Evie Formation (Fig. 15c) are in the range of 0.19-22.93 wt.%, while their average value is 4.31 wt.% (4.29 wt.% as median). Besides, the measured TOC values are mainly in the range of 2 - 4 wt.% for the Muskwa Formation, and <3 wt.% for the Otter Park Formation. However, more than 63% of the TOC measurements from the Evie Formation are greater than 3.5 wt.%. Overall, the TOC is the highest in the Evie Formation, the lowest in the Otter Park Formation, and intermediate in the Muskwa Formation.

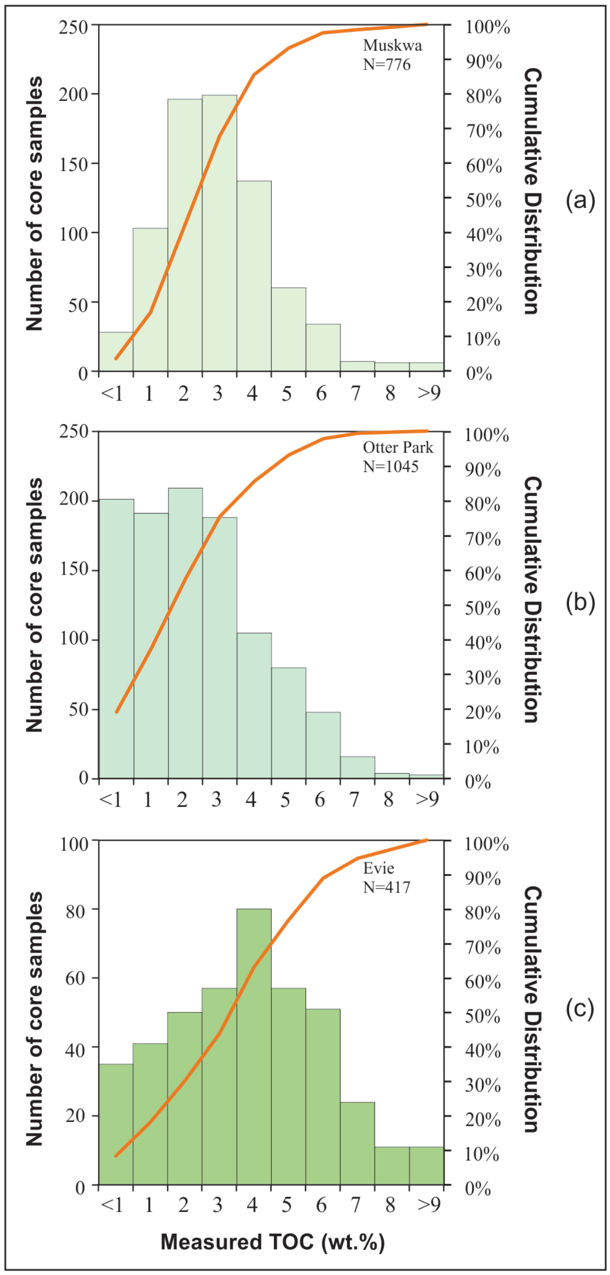

Fig. 15. Histograms showing measured total organic carbon content from the Horn River Group, including Muskwa (a), Otter Park (b) and Evie (c) formations in the Horn River Basin, northeastern BC. Cumulative distribution curves shown in solid red. N – Number of core samples.

CONCLUSIONS

A dataset has been compiled and preliminary analysis of the data was conducted from the Horn River Group in the Horn River Basin in the northeast British Columbia. Thousands of digital well log LAS files including available conventional log data, geochemical and nuclear magnetic resonance logging data were reviewed and merged by well. In addition, a variety of data sets from core analysis, such as, X-ray diffraction analysis, petrophysical core analysis, water analysis and total organic carbon content, have been included in the data compilation.

For each type of data, the measurement results were plotted as histograms and cumulative distributions for each formation (Muskwa, Otter Park and Evie) to display the data distribution, main range of variation, and general trends for the Muskwa, Otter Park and Evie formations within the Horn River Group in the study area. The dataset and data analysis provides important information for formation evaluation, geothermal study and basin study for the Horn River Basin.

ACKNOWLEDGEMENTS

We would like to thank Christopher Lister for providing a comprehensive review of this report. This study is greatly facilitated by available raw well data reports and most digital las files provided by the British Columbia Oil and Gas Commission, as well as some Sams datasheets generated by Dr. Andy Mort and his team. We are thankful to Dr. Edward Little, leader of the Geothermal project for his support. Special thanks to Dr. Sonya Dehler, director of GSC-Calgary for signing the agreement with BCOGC to open all available well data sets to GSC.

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