Regional Variability of Reservoir Properties of the Devonian Shales of Northeastern British Columbia

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Introduction

Organic-rich Devonian mudrocks with proven unconventional-resource potential are prevalent throughout the Western Canada Sedimentary Basin (WCSB). In northeastern British Columbia (BC) the Devonian Muskwa and Horn River formations host economically significant volumes of gas within the Horn River and Liard basins, and Cordova Embayment. Despite the proven gas reserves, exploitation and production of these reservoirs has not reached the prolific levels of other noteworthy shale plays due to market access and, arguably, a lack of natural-gas liquids, and thus the study of the variation in reservoir properties and hydrocarbons in place has received little attention.

The objective of this study is to contribute to the prediction of hydrocarbon distribution, reservoir quality and producibility of Devonian shales in the Horn River and Liard basins, and Cordova Embayment. Specifically, the goal is to determine the geological factors controlling the distribution of gas and condensate/natural-gas liquids. This multifaceted study uses petroleum systems analysis ground truthed with fluid analysis, and petrophysical and organic geochemical analyses of cuttings and core samples to predict the types and volumes of generated and retained hydrocarbons throughout the basins' evolution (Figure 1). This paper provides an update on the study, focusing on the characterization of various reservoir properties such as organic content, thermal maturity and mineralogy, their regional variations, and how the evolution of the basin may have affected the distribution of such properties.

Geological Background

During the Devonian and Mississippian periods, northeastern BC was situated along the edge of the North American protocontinent. As in other parts of the WCSB, the stratigraphy during that time was dominated by shale and carbonate packages, which were related to major transgressive and regressive cycles. The basinal setting of the study area resulted in the deposition of thick packages of fine-grained sedimentary rocks, whereas stratigraphically equivalent carbonate units further to the east were deposited in shallower water (Figure 2). Extensional block faulting, synchronous with the Antler orogeny, further influenced Paleozoic deposition by creating salient features such as the Liard Basin and Fort St. John graben (Wright et al., 1994). Subsequent evolution of the region was heavily affected by the formation and development of the Cordilleran foreland fold-and-thrust belt.

This study focuses on the BC portion of the Horn River and Liard basins, and Cordova Embayment (Figure 3). The Horn River Basin (HRB) is bounded by the Bovie fault zone to the west and terminates against the Presqu'ile barrier reef to the south and east; this same carbonate complex surrounds the Cordova Embayment. There is an overall shallowing of the basin and general thinning of Devonian shale units from the southwest to the northeast.

The overall depositional environment of the Devonian shale sequence is dominated by deep-water embayments (HRB and Cordova Embayment), representing two second-order sea level cycles in which the Muskwa Formation and Evie Member represent transgressive systems tracts (Potma et al., 2012). The Muskwa Formation is an especially significant event, which represents a basin-wide transgression that inundated the basin and led to extensive deep-water sedimentation throughout northeastern BC and western Alberta. (Switzer et al., 1994). Geochemical analysis data suggest that the organic-rich Devonian–Mississippian interval represents deep-basinal deposition with regional upwelling and connectivity to the open ocean. In addition, based on geochemical markers, as well as the lack of any substantial bioturbation, the environment is interpreted as having been anaerobic to dysaerobic (Fowler et al. 2001; Ross and Bustin, 2009; Bunnell and Hillier, 2014).

The Devonian shales are dominated by black siliceous mudstones, with rare pyritic laminae (Figure 4a–e). The siliceous nature of these rocks is of biogenic origin, due to the accumulation of pelagic radiolarians in an otherwise sedi-

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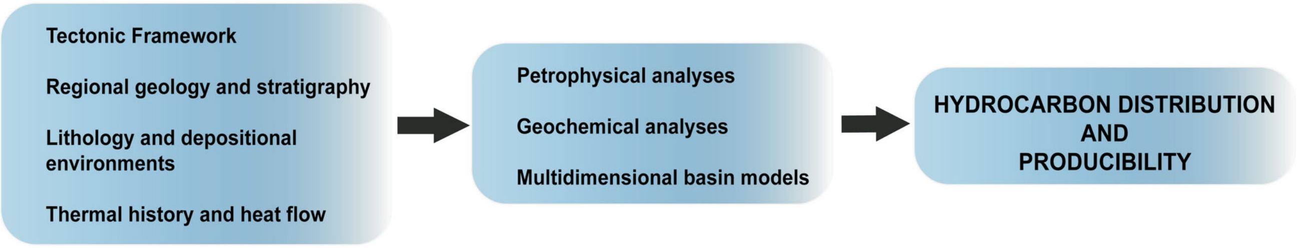

Figure 1. Flowchart illustrating the protocol for this study (from Wilson and Bustin, 2017).

ment-starved basin (Ross and Bustin, 2008). Subordinate lithofacies include grey silty mudstones, laminated grey mudstones, carbonate mudstones, and carbonate grainstone. Overall, sedimentary structures are rare, and bioturbation is sparse and diminutive, particularly within the Muskwa Formation (Dong et al., 2015). The shales generally become increasingly argillaceous from east to west (Ross and Bustin, 2008).

Materials and Methodology

Core and cuttings samples were collected from 20 wells along two southwest-trending transects. Where possible, these samples were collected at consistent intervals, while still making an effort to sample all major lithofacies present in the core. The cuttings were collected at 30 to 50 m intervals along the entire length of each well. Core samples were

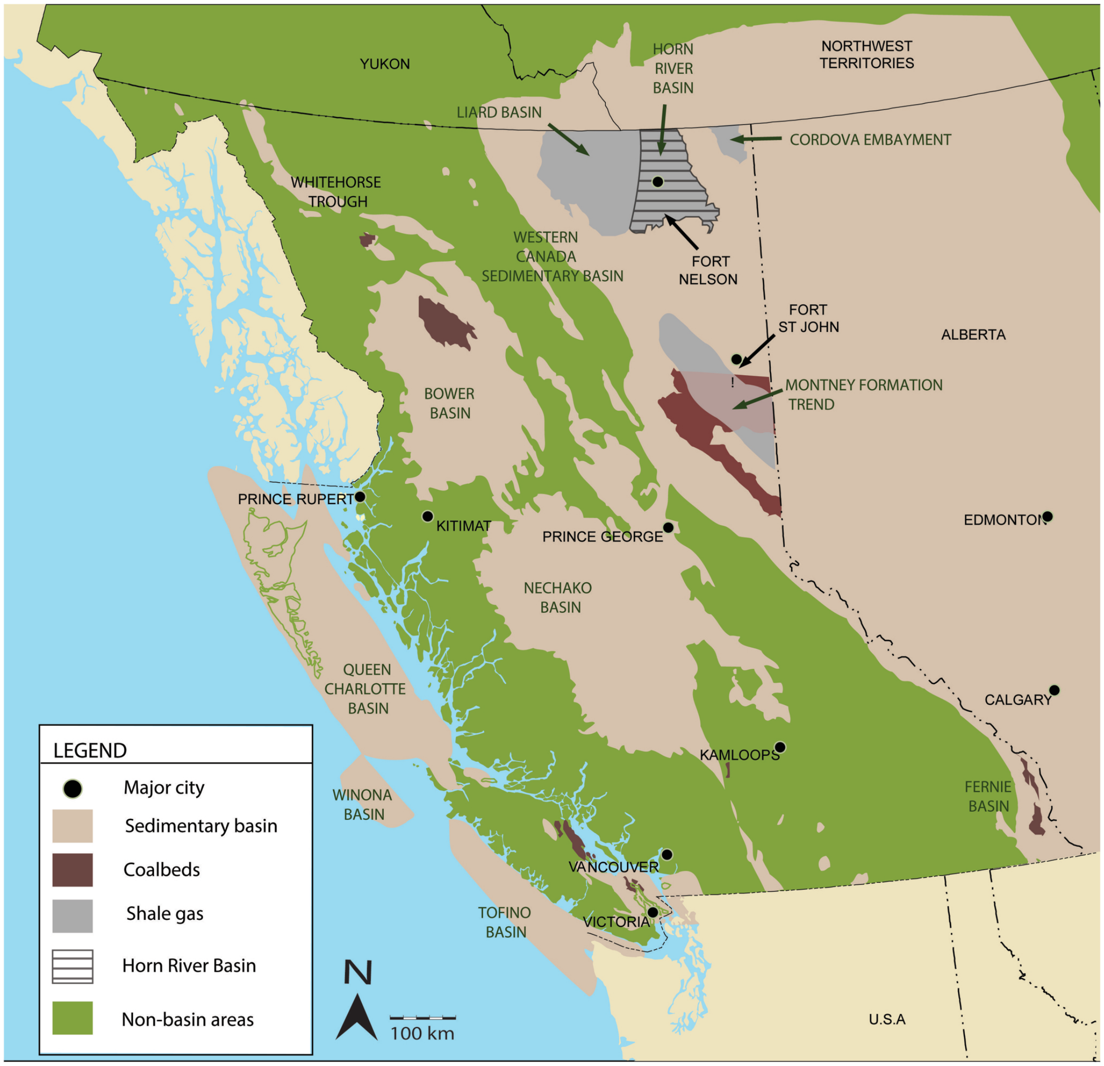

Figure 2. Location of the Liard and Horn River basins, and Cordova Embayment, in northeastern British Columbia (modified from BC Ministry of Energy, Mines and Petroleum Resources and National Energy Board et al., 2011).

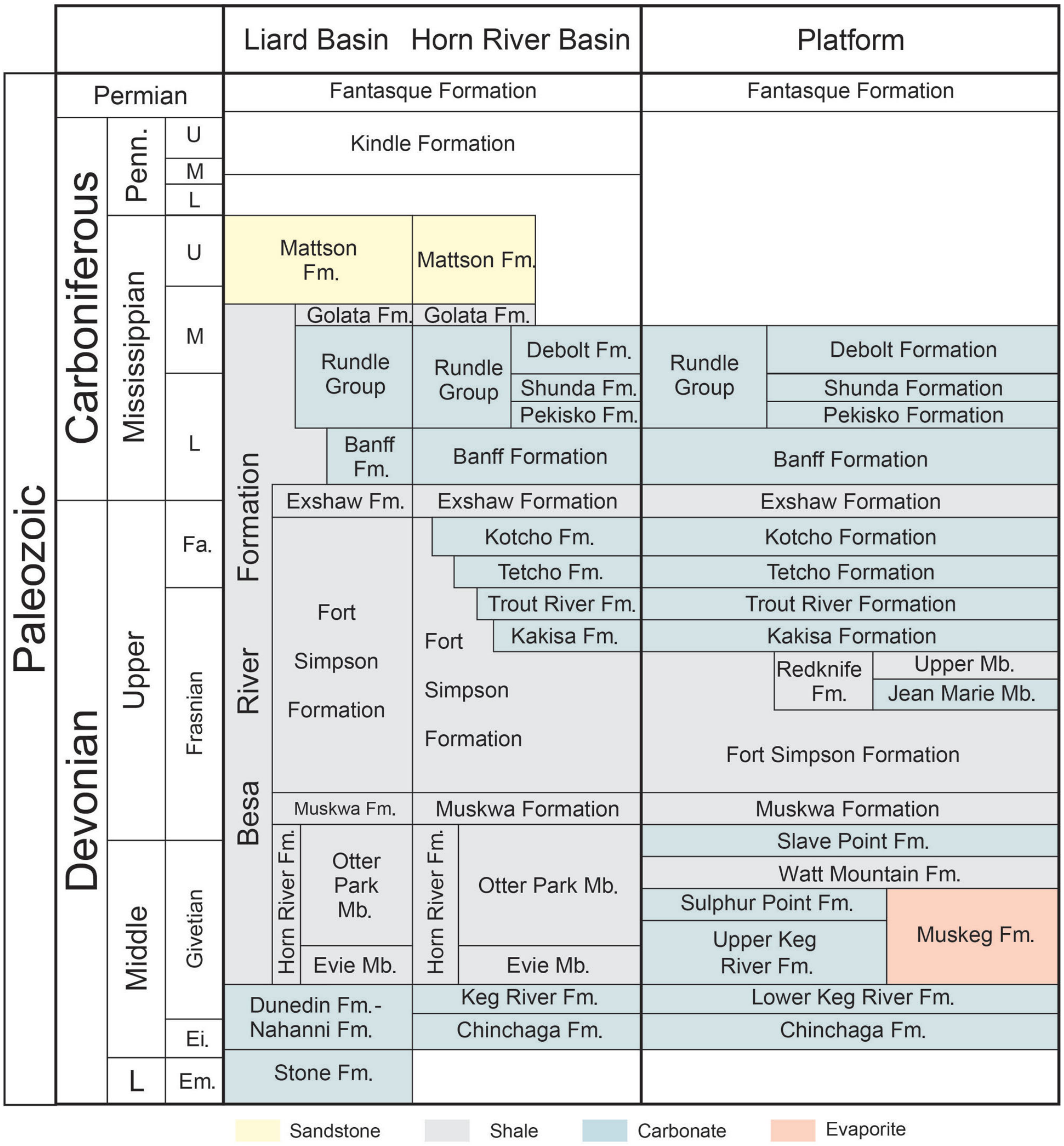

Figure 3. Upper Paleozoic stratigraphy for northeastern British Columbia (modified from Ferri et al., 2011). Abbreviations: Ei., Eifelian; Em., Emsian; Fa., Fammenian; Fm., formation; L, lower; M, middle; Mb., member; Penn, Pennsylvanian; U, upper.

analyzed using Rock-Eval pyrolysis, helium pycnometry, mercury intrusion porosimetry, X-ray diffraction, and low pressure N_2 and CO_2 gas adsorption. Additionally, pyrolysis was also completed for all of the collected cuttings samples, including samples from western Alberta. The location of the wells was selected to capture the variation in depth of burial and thermal history across the basins, and therefore the associated variability in reservoir quality (Figure 5). Only the methods employed in organic geochemistry and mineralogy analyses are described in this update.

Organic Geochemistry

Total organic carbon (TOC) contents and temperature of maximum rate of hydrocarbon generation (T_{max}) values from pyrolysis were determined using a HAWK™ pyrolysis instrument from Wildcat Technologies for all of the cuttings samples and 27 of the Muskwa Formation core samples. All samples were crushed to powder (<60 mesh) and approximately 100 mg of sample was analyzed. These analyses were used to complement regional data in public domain and data in the University of British Columbia database.

Mineralogy

Sample preparation for quantitative mineralogy determination followed the modified smear-mount method for X-ray diffraction analysis (Munson, 2015). Data were collected using a normal-focus Bruker® D8 FOCUS diffractometer

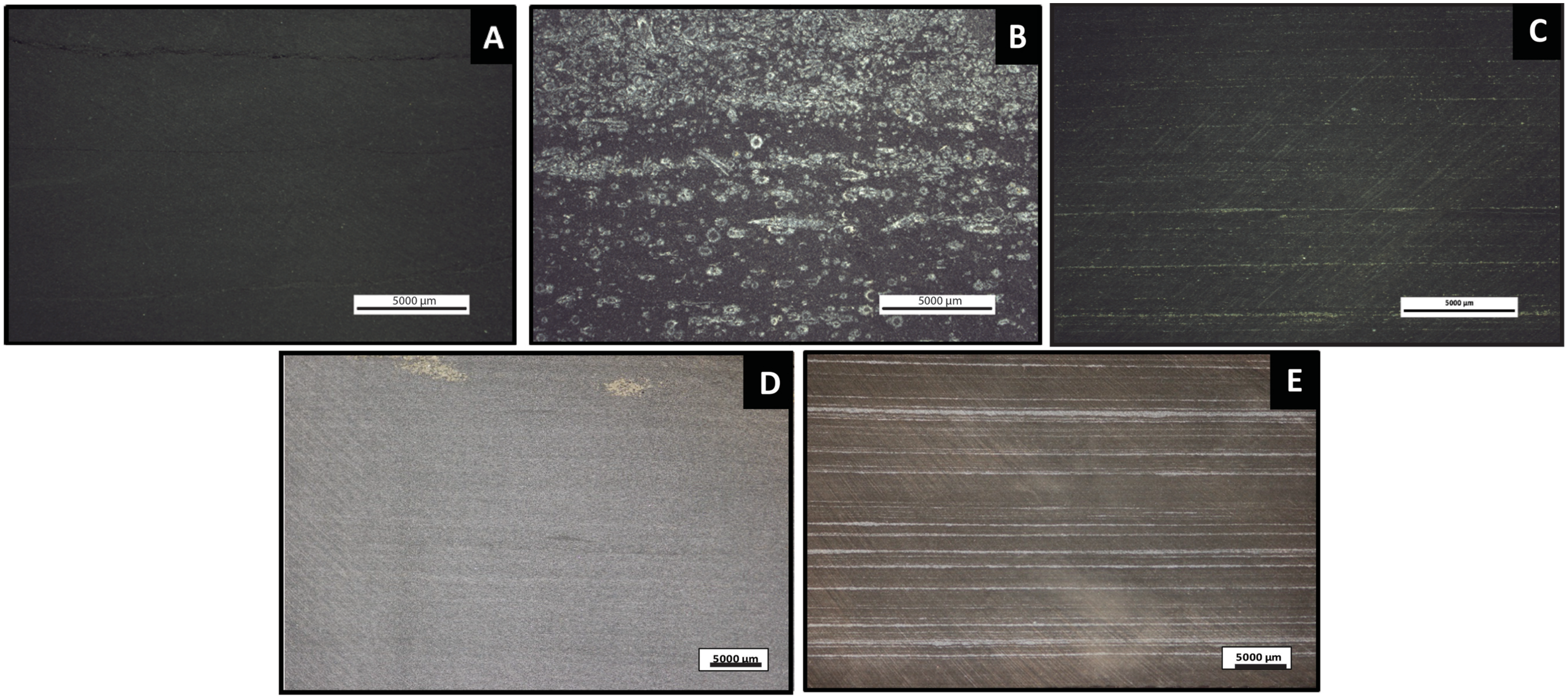

Figure 4. Examples of facies from the Muskwa and Horn River formations from core samples collected in northeastern British Columbia, showing **a)** siliceous black mudstone; **b)** skeletal lime mudstone containing mainly sponge spicules and radiolarians; **c)** siliceous black mudstone with pyritic laminations and lenses; **d)** carbonate mudstone; **e)** laminated mudstone.

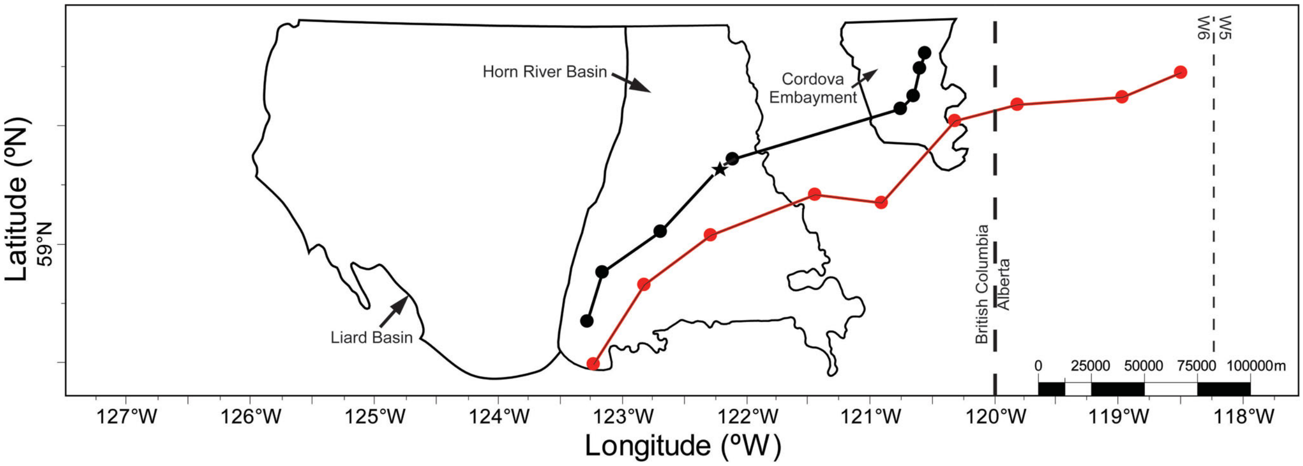

Figure 5. Top of the Muskwa Formation in northeastern British Columbia; the two cross-sections represent the location of wells from which core (black dots) and cuttings (red dots) samples were collected, and the star indicates the location of the well used for showing log-TOC calibration.

(CoKα radiation), with diffraction patterns obtained over a range of 3–70° 2θ at a scanning step of 0.03° 2θ and a counting time of 0.8 s/step. Diffraction patterns were quantified using the Rietveld full-pattern fitting method with the TOPAS software from Bruker AXS.

Results and Discussion

Maturity

Pyrolysis Results

Devonian shales in northeastern BC are generally overmature. Trends in T_{max} versus depth are rarely informative since the kerogen conversion (S2) peaks are low and indistinct for nearly all Devonian samples within northeastern BC, leading to anomalous T_{max} values (Figure 6a). Pyrolysis results for the Alberta samples exhibit more reliability due to lower maturity and more distinct S2 peaks. Maturity within western Alberta ranges from immature to the upper oil window (T_{max} values of 426 to 471 °C) and a general increase in T_{max} versus depth can be observed (Figure 6b). The following discussion on maturity will focus on the Muskwa Formation; however, similar trends exist in the more spatially constrained Horn River Formation.

Maturity Trends

Pyrolysis results from the two southwest–northeast transects (T_{max}, pyrograms, hydrogen and oxygen indices) demonstrate that overmaturity of Devonian shales persists throughout NTS areas 094J, 094O and 094P of northeastern BC. Vitrinite reflectance measurements are sparse in northeastern BC, with measured values ranging from 1.75 to 3.2 %Ro. The southwest to northeast increase in maturity extends into northeastern BC with the lowest vitrinite reflectance values of <2 %Ro occurring in the eastern portions of NTS areas 094I and 094P (Figure 7). Maturity generally tends to increase toward the north and northwest across the Cordova Embayment, Presqu'ile barrier and HRB, with the highest maturities occurring in the northwestern corner of the HRB.

Although Devonian strata are approximately 1500 m deeper on the western side of the Bovie fault, %Ro values are similar to those in the HRB (2.6 to 3.1 %Ro) to the east. Both to the east and west of the Bovie fault, there is a northward trend of increasing maturity. Considering the few reliable data points, they seem to suggest that maximum thermal exposure (and hence peak maturity) of the Devonian strata across northeastern BC predates the extensive displacement along the Bovie fault that occurred during the Late Cretaceous and Tertiary[1] (MacLean and Morrow, 2004).

Total Organic Carbon

TOC Results

The public database was used along with additional data acquired for this study to analyze TOC trends. Kerogen type for the Devonian shales is inferred to be type II, based on pseudo-van Krevelen plots for the lower maturity Alberta samples. The organic content of the Devonian shales in northeastern BC is generally greater than 1% in weight in the HRB and Cordova Embayment. Combining all available data for the Muskwa and Horn River formations, TOC averages around 3% in weight, with the Muskwa Formation and Evie Member generally exhibiting higher values than the Otter Park Member. Due to potential caving and mixing from organic-lean units within cuttings samples, the average values for cuttings are generally lower than

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[1] *Tertiary' is an historical term. The International Commission on Stratigraphy recommends using 'Paleogene' (comprising the Paleocene to Oligocene epochs) and 'Neogene' (comprising the Miocene and Pliocene epochs). The author used the term 'Tertiary' because it was used in the source material for this paper.*

core samples, with values of 2.07 and 2.88% in weight, respectively, for the Muskwa Formation.

Petrophysical Analysis – Log TOC

In the study area, spatial distribution of TOC data is limited and thus well logs calibrated with measured TOC were utilized. There are many methods that have been developed to calculate TOC from calibrated logs, all of which have limitations (Schmoker, 1980; Passey et al., 1990; Passey et al., 2010; Sondergeld et al., 2010; Ariketi, 2011; Herron et al., 2011). In this study, the modified ΔlogR method developed by Passey et al. (1990) and Sondergeld et al. (2010) has

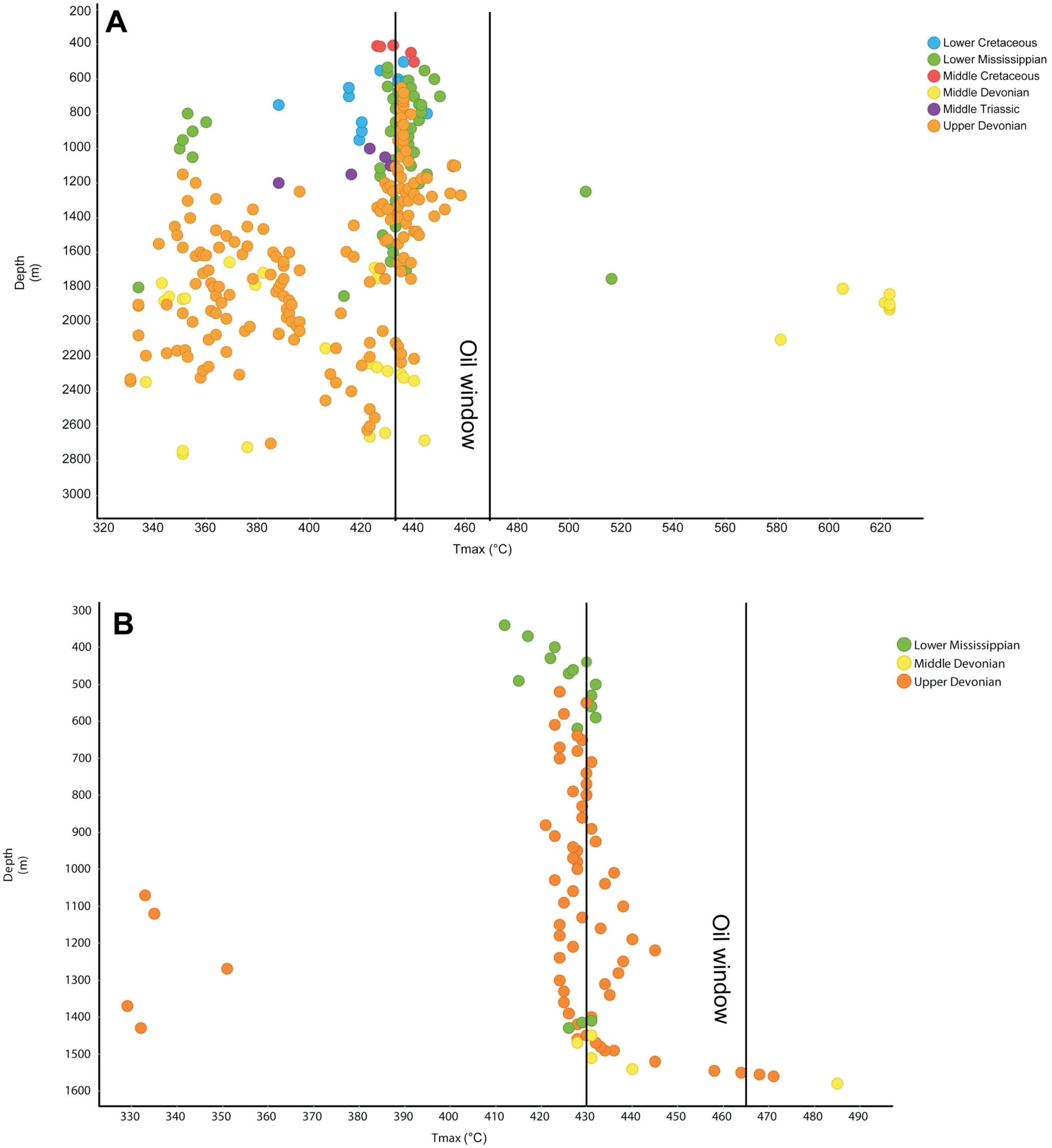

Figure 6. Depth versus temperature of maximum rate of hydrocarbon generation (T_{max}; °C) from pyrolysis analyses on cuttings samples from **a)** British Columbia (Horn River Basin and Cordova Embayment) and **b)** western Alberta. The colours correspond to the period of deposition (for sample locations, refer to Figure 5).

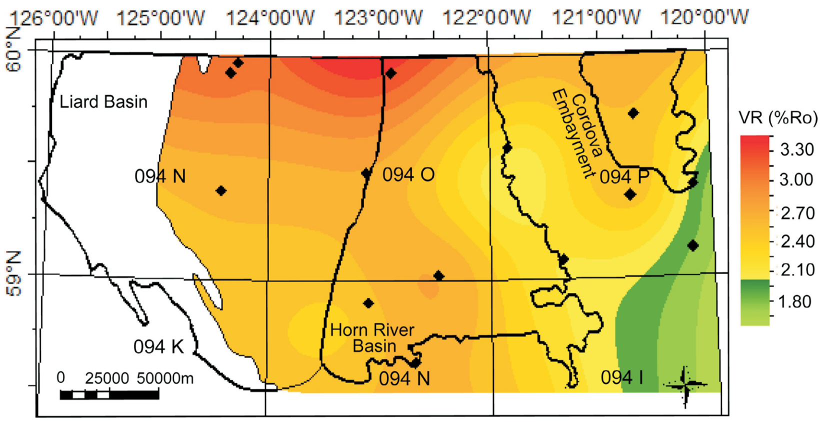

Figure 7. Isoreflectance map for the Muskwa Formation in northeastern British Columbia, based on publicly available vitrinite reflectance (VR) analyses. Areas of potential wet gas are represented by green and are related to %Ro values <2. Maturity generally increases to the northwest.

been used to calculate log-derived TOC (equations 1 and 2):

$$\Delta\log R = \log_{10}\left(\frac{R}{R_o}\right) - 1.4(\rho - \rho_o) \tag{1}$$

$$TOC = (\Delta\log R)\times 10^{(2.297-0.1688\times LOM)} \tag{2}$$

where R is the resistivity log values; ρ is the bulk density log values; R_o is the resistivity log baseline value; ρ_o is the bulk density log baseline value; 1.4 represents the scale ratio factor; LOM is the level of organic maturity; and C is the high maturity modification factor. The high maturity of the HRB requires the use of the modified method, with the additional term, C, to account for underestimation of TOC in formations exceeding 10.5 on the level of organic maturity (LOM) scale. For this study, a LOM value of 14 to 16 was used along with a C of 4 to 5 to correct for the high maturity of the HRB and to achieve a higher level of correlation with the laboratory values. Figure 8 shows measured TOC plotted alongside calculated-log TOC for a well in the central portion of the HRB. The difference between measured and calculated TOC values is <0.5% in weight for most wells.

Regional TOC Trends

The regional maps of TOC for the Muskwa and Horn River formations (Otter Park and Evie members) show a similar trend of higher levels of organic richness within the central HRB, and further to the north and west (Figure 9a–d). This trend is most obvious within the more spatially extensive Muskwa Formation. Along the reef complex, TOC content drops to near zero and increases significantly to the east and west of the platform within the Cordova Embayment and HRB.

The Presqu'ile barrier reef persisted throughout the deposition of the Muskwa and Horn River formations, creating a restricted basin environment within the two depocentres (Dong, 2016). The shallow-water environments near or along the carbonate trends caused the shales to thin (Muskwa) and pinch out (Horn River), and would not have been a conducive environment for the accumulation and preservation of organic matter. However, reducing conditions would have formed further basinward. Coupled with low levels of detrital influx, it would have created a favourable environment for organic accumulation (Dong, 2016), which is supported by the increase in TOC. Eustatic sea-level changes also played an important role in the distribution of organic content. The distal portions of the basin were within a deep-water anoxic environment for the entirety of this depositional period. A rise in sea level, as the one interpreted to have occurred during the Muskwa Formation and Evie Member deposition (Potma et al., 2012), would have expanded anoxia and further restricted high influxes of detrital matter to the basin edge (Dong, 2016). Dong (2016) interpreted the Muskwa Formation and Evie Member as corresponding to a 3rd order transgressive systems tract, and the Otter Park Member, to a 2nd order lowstand systems tract The transgressive nature of the Muskwa and Evie units allowed for increased productivity and preservation of organic matter, and thus led to the elevated TOC content observed within the basin today.

The delineation of highly organic-rich zones required an understanding of the interplay between proximity to the surrounding platform and eustatic sea-level changes. The ongoing mapping of separate zones within these main shale units will provide further information on smaller scale basin influences and localized variability.

Mineralogy

The mineralogy of the Muskwa and Horn River formations comprises quartz, feldspar, clay and carbonate minerals, with minor amounts of pyrite. Quartz and feldspar (mainly albite) dominate the mineralogy in the Muskwa Formation, ranging in amount from 7 to 95 wt. % and averaging

71 wt. %; with quartz being overwhelmingly dominant in this fraction. The average contents of carbonate (calcite and dolomite, with minor ankerite) and clay (illite/muscovite and chlorite groups) components are of 8 and 19 wt. %, respectively. In comparison to the Muskwa Formation, the Horn River Formation contains less quartz and feldspar and more carbonate minerals. In the Evie Member, the carbonate component (calcite, dolomite, ankerite) is dominant, with a range of 18 to 97 wt. % and an average of 52 wt. %. Total quartz and feldspar averages 41 wt. % and clay content (illite/muscovite) is minor, with an average of 5.7 wt. %. The Otter Park Member is the most clay rich with an average of 18 wt. % clay, and 46 and 34 wt. % for quartz/feldspar and carbonate minerals, respectively.

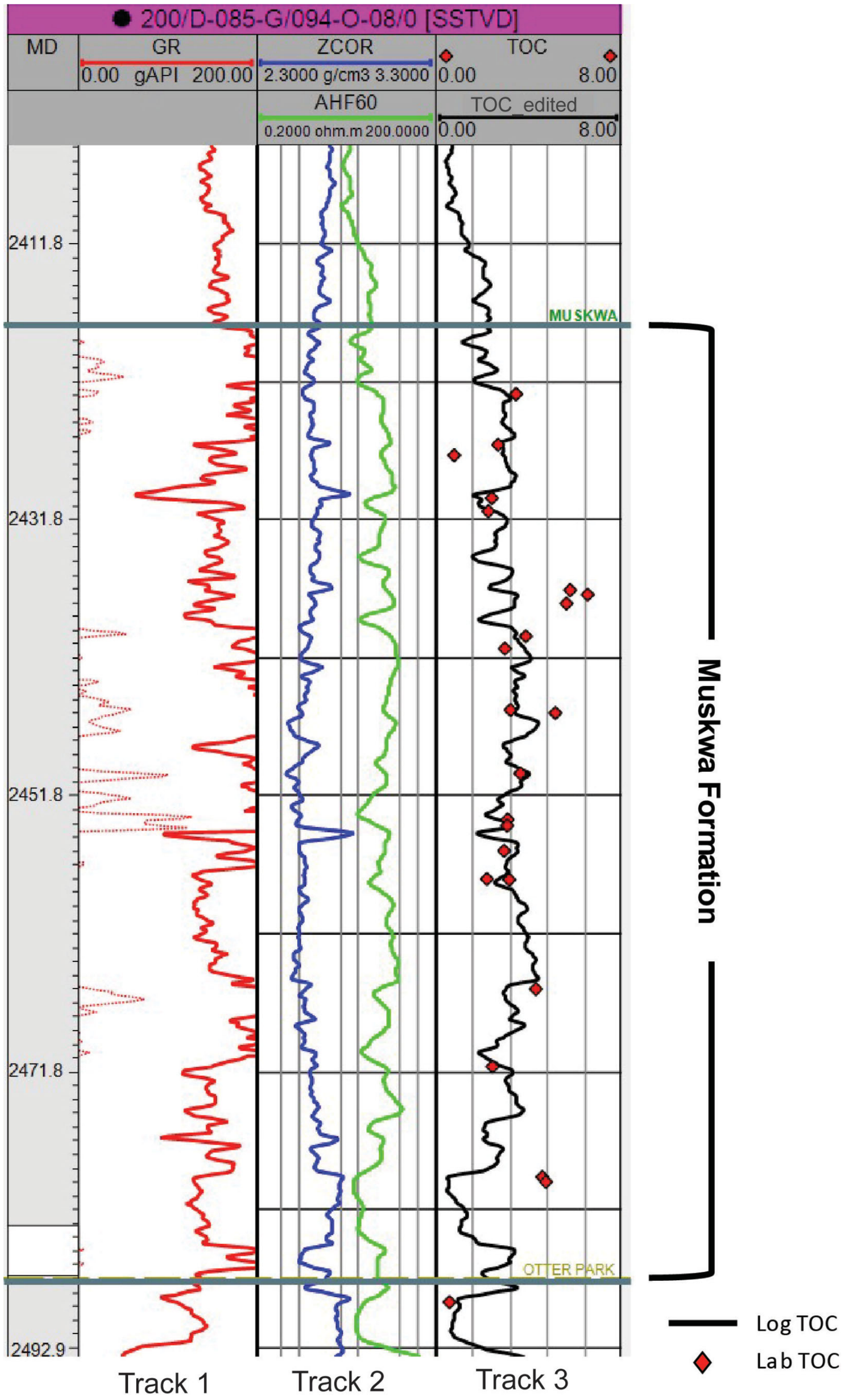

Figure 8. Example of the calibration of log TOC using the modified ΔlogR method (Passey et al., 1990; Sondergeld et al., 2010). For the location of this well refer to Figure 5.

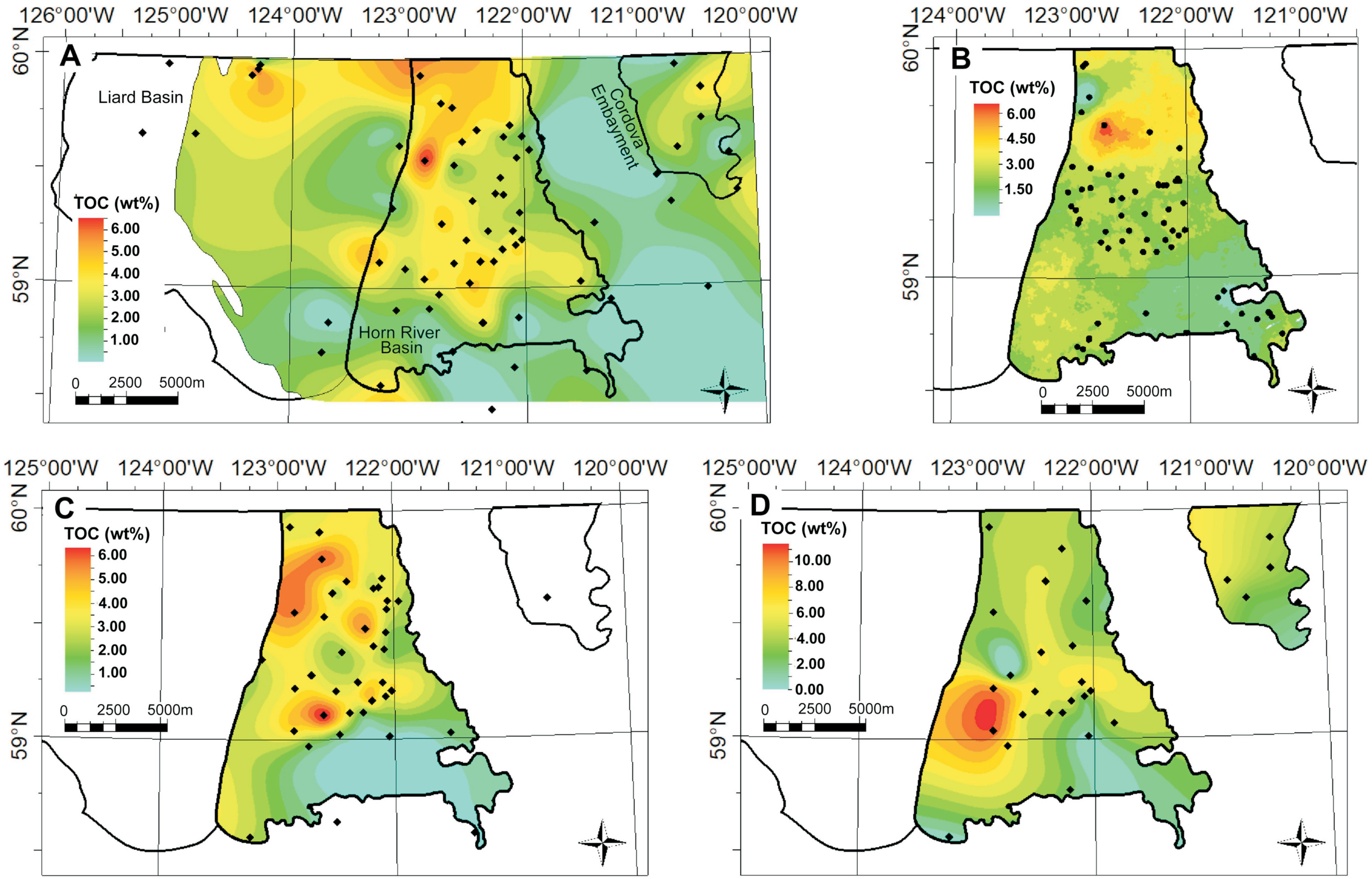

Figure 9. Regional total organic carbon (TOC) variability for the Muskwa and Horn River formations in northeastern British Columbia: **a)** Muskwa Formation (and equivalent mark in the Liard Basin); **b)** log-derived TOC for the Muskwa Formation within the Horn River Basin (note the similarity with the trends exhibited by laboratory data); **c)** Otter Park Member; **d)** Evie Member.

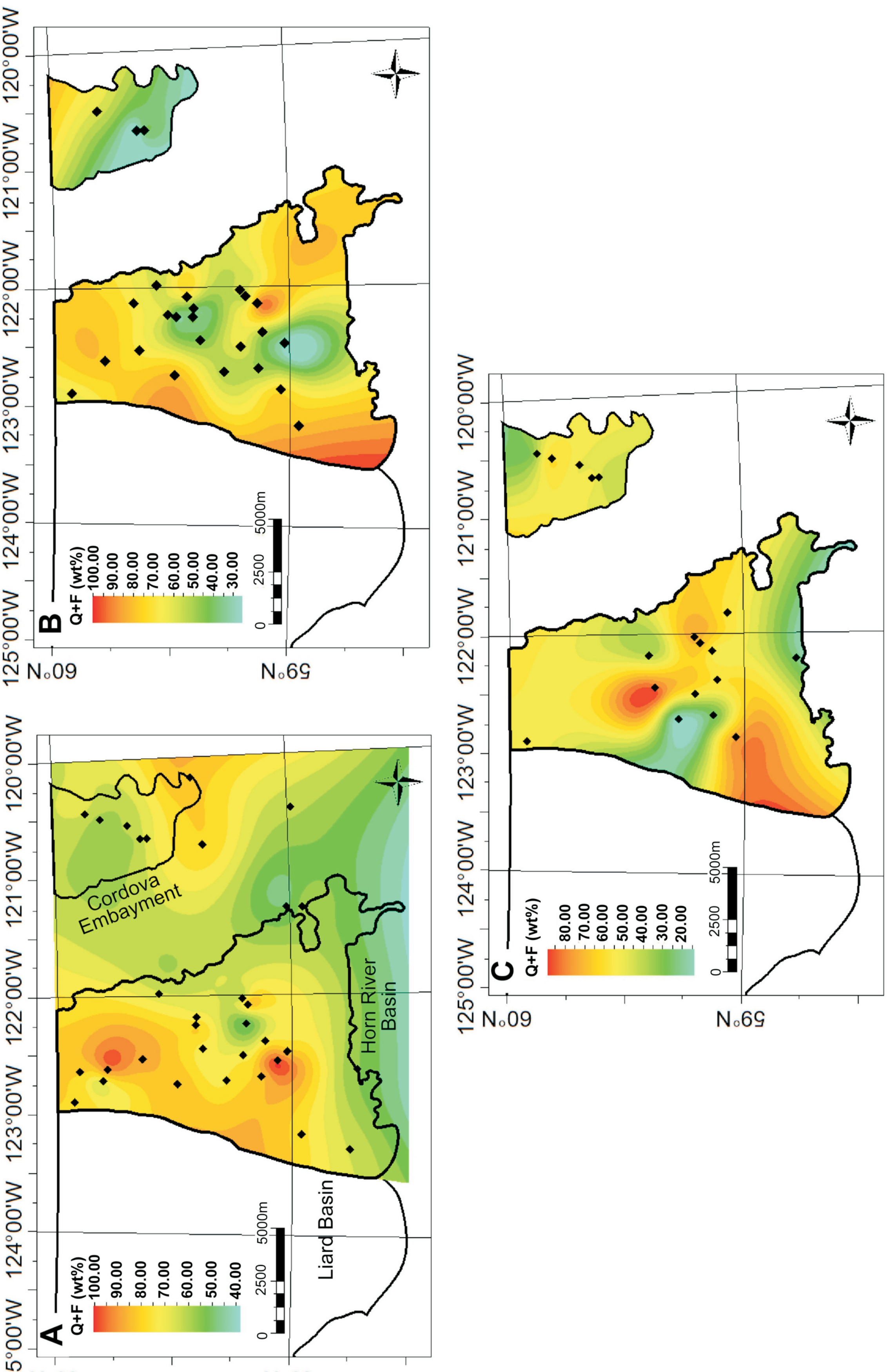

Figure 10. Regional quartz (Q) and feldspar (F) variability for the Muskwa and Horn River formations In northeastern British Columbia: **a)** Muskwa Formation; **b)** Otter Park Member; **c)** Evie Member.

Regional Mineralogical Trends

The quartz content of the Muskwa and Horn River formations increases to the north and west within the HRB (Figure 10a–c). This trend is similar to that of TOC, due to the strong correlation exhibited between organic accumulation and pelagic radiolarian accumulation within the distal portions of the HRB (Ross and Bustin, 2008). Away from the carbonate platform, carbonate and detrital clay are anticipated to decrease. The Muskwa and Evie units have a lower clay content as a result of the increased sea level, causing accommodation space to move shoreward, which led to less clastic material settling within the basin. Analyzing mineralogical trends and eventual anomalies in more detail may reveal additional insights on the paleogeometry of the basin and delineate more local trends.

Condensate Potential

The potential for the occurrence of producible liquid hydrocarbons in unconventional reservoirs is dependent on the complex interplay between the maturation, migration pathways, kerogen type and abundance, and retention of hydrocarbons during generation and production.

Production data from the Jean Marie Member and Muskwa Formation have been analyzed. The Jean Marie Member is likely sourced from the underlying Muskwa Formation (Ferri and Griffiths, 2014) and can provide additional insight into liquid-hydrocarbon potential and distribution. The bubble map of produced condensate for the Jean Marie Member and Muskwa Formation from the first month of production shows higher levels of condensate within NTS area 094I in northeastern BC (Figure 11). The higher condensate production correlates with lower levels of maturity determined by vitrinite reflectance. Minor volumes of condensate have been produced from the Jean Marie Member and Muskwa Formation within the eastern and central HRB, respectively. Gas-wetness ratios can be calculated to further constrain condensate potential; in this study, gas wetness is calculated using the formula developed by Unrau and Nagel (2012)

$$\text{Wetness ratio} = \frac{C2 + C3 + C4 + C5}{C1 + C2 + C3 + C4 + C5} \times 100 \qquad (3)$$

where <0.5 indicates light, dry gas.

In the HRB, all values for the wetness ratio fall below 0.4 (average = 0.12), indicating dry gas, and wetness shows a general decrease toward the west (Figure 12).

In general, condensate production corresponds to observed maturity trends, with the largest volumes of condensate being produced from the area to the southeast of the HRB. The single well producing directly from the Muskwa Formation within NTS area 094I is at a depth of 1850 m, with a reservoir temperature of approximately 80 °C. Similar reservoir temperatures occur throughout the southeastern corner of the study area; therefore, further potential for condensate production from the Muskwa Formation within this area is likely. Minor condensate is present in the Jean Marie Member and Muskwa Formation throughout the HRB, pointing toward hydrocarbon migration from the south.

Conclusions and Future Work

The purpose of this research is to further understand the Devonian petroleum systems within northeastern BC, including a regional understanding of reservoir properties. The central portion of the HRB is the most organic and quartz rich, and is associated with a deep anoxic environment. This environment is further influenced by eustatic sea level, causing preferable zones to be more common within transgressive systems, such as the Muskwa Formation and Evie Member. The majority of the study area is within the dry-gas window, due to significant burial depths and peak maturation during tectonic events in the Canadian Cordillera.

Based on production and gas-composition data, it is evident that condensate potential is minor, with maximum burial depths and temperatures during foreland subsidence having ultimately created a dry-gas environment in the study area. The Muskwa Formation does contain producible condensate in the southern portion of NTS area 09I, possibly extending along the Jean Marie Member subcrop in BC, due to migration. In the northwestern corner of Alberta, there is also some potential for oil production. The organic-rich Devonian–Mississippian Exshaw Formation is significantly less mature (often ~1000 m shallower) throughout the study area and may be a prospective formation for condensate production.

Future work will include analyzing the maturity, organic richness and mineralogy in more detail, along with an analysis of variability in porosity. A detailed study of reservoir properties, both stratigraphically and spatially, will help to further elucidate trends and lead to a more comprehensive understanding of the basin petroleum system(s). Basin modelling in progress will contribute to the understanding of hydrocarbon generation and migration, and will assess the impact of basin history on the type and quantity of migrated and retained hydrocarbons, and ultimately their producibility.

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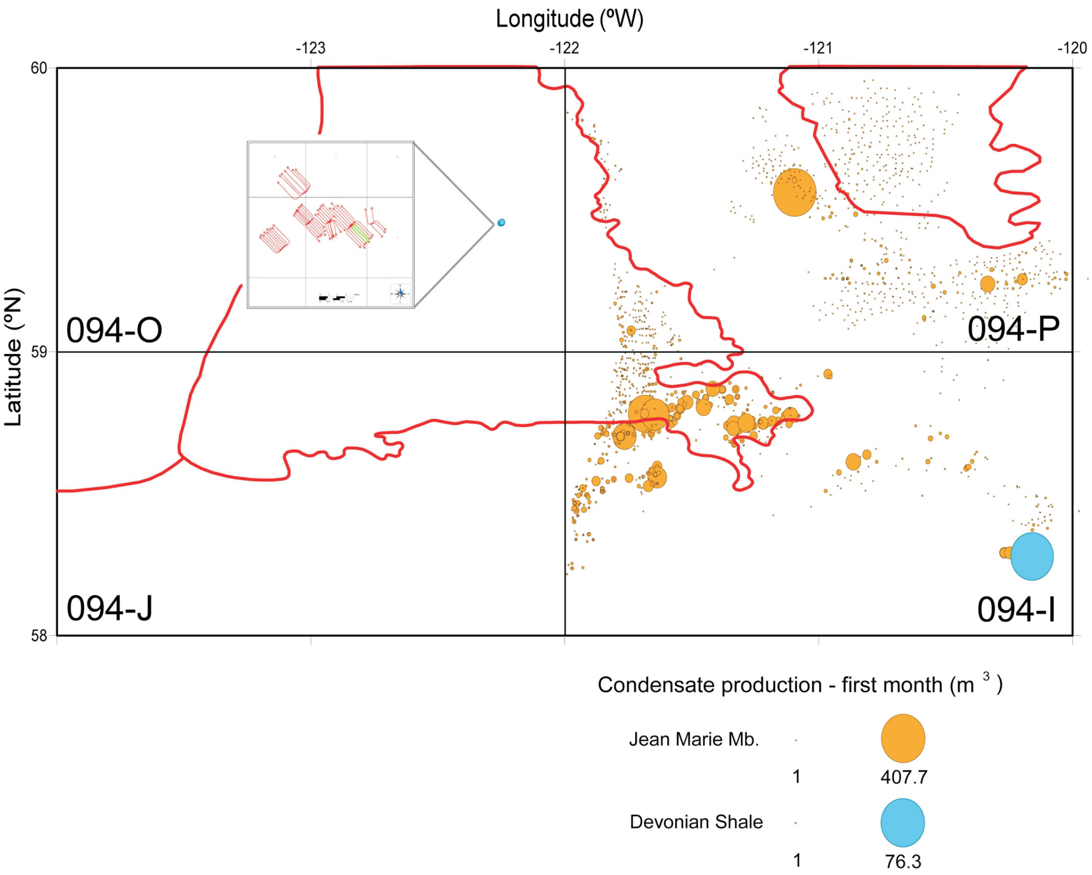

Figure 11. Bubble map showing the first month of condensate production from Devonian shales (blue) and the Jean Marie Member (orange). Note that the scales differ between the two units. The largest condensate potential is located in the southeastern corner of the map. The insert represents the horizontal wells within NTS area 094O that have reported minor condensate production. Abbreviation: Mb., Member.

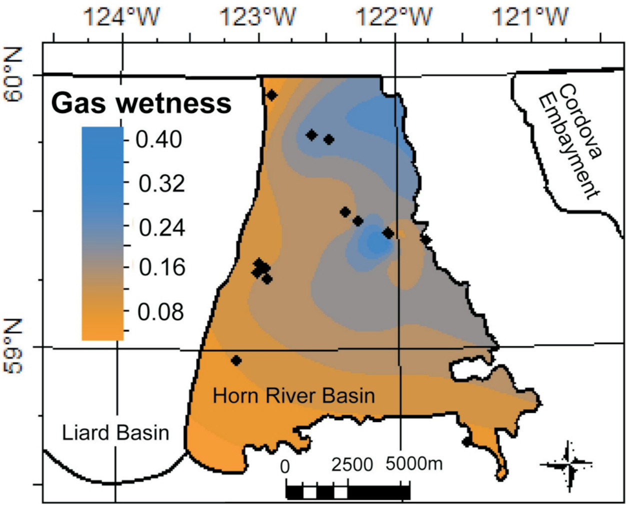

Figure 12. Gas wetness for the Muskwa Formation within the Horn River Basin in northeastern British Columbia. Wetness was calculated using the equation developed by Unrau and Nagel (2012).

References

Ariketi, R. (2011): Estimation of level of organic maturity (LOM) and total organic carbon (TOC) in absence of geochemical data by using resistivity and density logs – example from Cambay Shale, Tarapur area, Cambay Basin, India; Journal of the Indian Association of Sedimentologists, v. 30, p. 55–63.

BC Ministry of Energy, Mines and Petroleum Resources and National Energy Board (2011): Ultimate potential for unconventional natural gas in northeastern British Columbia's Horn River Basin; BC Ministry of Energy, Mines and Petroleum Resources and National Energy Board Report, Oil and Gas reports 2011-1, 50 p.

Bunnell, C. and Hillier, C. (2014): Integration of lithofacies and natural fractures in a Nexen Horn River shales gas core; Canadian Society of Petroleum Geologists, GeoConvention 2014, May 12–16, 2014, Calgary, Alberta, extended abstract, 5 p.

Dong, T. (2016): Geochemical, petrophysical and geochemical properties of stratigraphic sequences in Horn River shale, Middle and Upper Devonian, northeastern British Columbia, Canada; Ph.D. thesis, University of Alberta, Edmonton, 258 p.

Dong, T., Harris, N.B., Ayranci, K., Twemlow, C.E. and 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, v. 141-142, p. 74–90.

Ferri, F. and Griffiths, M. (2014): Thermal maturity and regional distribution of the Muskwa Formation, northeastern British Columbia; *in* Geoscience Reports 2014, BC Ministry of Natural Gas Development, p. 37–45.

Ferri, F., Hickin, A.S. and Huntley, D.H. (2011): Besa River Formation, western Liard Basin, British Columbia (NTS 094N): geochemistry and regional correlations; *in* Geoscience Reports 2011, BC Ministry of Energy, Mines and Petroleum Resources, BC Geological Survey, p. 1–18.

Fowler, M.G., Stasiuk, L.D., Hearn, M. and Obermajer, M. (2001): Devonian hydrocarbon source rocks and their derived oils in the Western Canada Sedimentary Basin; Bulletin of Canadian Petroleum Geology, v. 48, p. 117–148.

Herron, M.M., Grau, J.A., Herron, S.L., Kleinberg, R.L., Machlus, M., Reeder, S.L., Vissapragada, B., Burnham, A.K., Day, R.L. and Allix, P. (2011): Total organic carbon and formation evaluation with wireline logs in the Green River oil shale; Society of Petroleum Engineers, Annual Technical Conference and Exhibition, October 30, 2011, Denver, Colorado, paper for presentation, SPE 147184, 20 p.

MacLean, B.C. and Morrow, D.W. (2004): Bovie structure; its evolution and regional context; Bulletin of Canadian Petroleum Geology, v. 52, p. 302–324.

Munson, E.O. (2015): Reservoir characterization of the Duvernay Formation, Alberta: a pore to basin-scale investigation; Ph.D. thesis, University of British Columbia, Vancouver, 289 p.

Passey, Q.R., Bohacs, W.L., Esch, W.L., Klimentidis, R. and Sinha, S. (2010): From oil-prone source rock to gas-producing shale reservoir – geological and petrophysical characterization of unconventional shale-gas reservoirs; Society of Petroleum Engineers, International Oil and Gas Conference and Exhibition, June 8-11, 2010, Beijing, China, paper for presentation, SPE 13150, 29 p.

Passey, Q.R., Creaney, S., Kulla, J.B., Moretti, F.J. and Stroud, J.D. (1990): A practical model for organic richness from porosity and resistivity logs; American Association of Petroleum Geologists Bulletin, v. 74, p. 1777–1794.

Potma, K., Jonk, R., Davie, M. and Austin, N. (2012): A mudstone lithofacies classification of the Horn River Group, British Columbia: integrated stratigraphic analysis and inversion from wireline log and seismic data; Canadian Society of Petroleum Geologists, GeoConvention 2012, May 14–18, 2012, Calgary, Alberta, extended abstract, 3 p.

Ross, D.J.K. and 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; American Association of Petroleum Geologists Bulletin, v. 92, p. 87–125.

Ross, D.J.K. and Bustin, R.M. (2009): Investigating the use of sedimentary geochemical proxies for paleoenvironment interpretation of thermal mature organic rich strata: examples from the Devonian–Mississippian shales, Western Canadian Sedimentary Basin; Chemical Geology, v. 260, p. 1–19.

Schmoker, J.W. (1980): Determination of organic-matter of Appalachian Devonian shales from gamma ray logs; American Association of Petroleum Geologists Bulletin, v. 64, p. 2156–2165.

Sondergeld, C.H., Newsham, K.E., Comisky, J.T., Rice, M.C. and Rai, C.S. (2010): Petrophysical consideration in evaluating and producing shale gas resources; Society of Petroleum Engineers, Unconventional Gas Conference, February 23–25 2010, Pittsburgh, Pennsylvania, paper for presentation, SPE 131768, p. 34.

Stasiuk, L.D. and Fowler, M.G. (2002): Thermal maturity evaluation (vitrinite and vitrinite reflectance equivalent) of Middle Devonian, Upper Devonian, and Mississippian strata in the Western Canada Sedimentary Basin; Geological Survey of Canada, Open File 4341, 1 CD-ROM.

Switzer, S.B., Holland, W.G., Christie, D.S., Graf, G.C., Hedinger, A.S., McAuley, R.J., Wierzbicki, R.A. and Packard, J.J. (1994): Devonian Woodbend–Winterburn strata of the Western Canada Sedimentary Basin; *in* Geological Atlas of the Western Canadian Sedimentary Basin, G.D. Mossop and I. Shetsen (comp.), Canadian Society of Petroleum Geologists, Calgary, Alberta and Alberta Research Council, Edmonton, Alberta, p. 165–202.

Unrau, S. and Nagel, B. (2012): Using compositional gas data for horizontal drilling and practical detection of natural gas liquids (NGL); Canadian Society of Petroleum Geologists, GeoConvention 2012, May 14–18,2012, Calgary, Alberta, extended abstract, 4 p.

Wilson, T.K. and Bustin, R.M. (2017): Unconventional petroleum systems analysis of Upper Devonian organic-rich shale units in the Horn River and Liard basins, northeastern British Columbia, and adjacent western Alberta: preliminary report; *in* Geoscience BC Summary of Activities 2016, Geoscience BC, Report 2017-1, p. 29–36.

Wright, G. N., McMechan, M.E. and Potter, D.E.G. (1994): Structure and architecture of the Western Canadian Sedimentary Basin; *in* Geological Atlas of the Western Canadian Sedimentary Basin, G.D. Mossop and I. Shetsen (comp.), Canadian Society of Petroleum Geologists, Calgary, Alberta and Alberta Research Council, Edmonton, Alberta, p. 25–39.