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

T.K. Wilson, The University of British Columbia, Vancouver BC, twilson@eos.ubc.ca

R.M. Bustin, The University of British Columbia, Vancouver BC

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.

Introduction

The Horn River and Liard basins located in northeastern British Columbia (BC), southern Yukon and Northwest Territories, and adjacent western Alberta contain immense volumes of hydrocarbons that are held within multiple stratigraphic intervals. The estimates of marketable gas reserves are significant, with volumes in the Liard Basin surpassing 200 trillion cubic feet (tcf), and another 78 and 8.8 tcf in the Horn River Basin and Cordova Embayment, respectively, as well as potential for significant liquid reserves (BC Ministry of Energy and Mines and National Energy Board, 2011; Ferri and Griffiths, 2014; BC Ministry of Natural Gas Development, 2015; National Energy Board, 2016). The majority of these gas reserves are hosted within Devonian strata. The Devonian stratigraphy of these basins comprises thick accumulations of organic-rich, highly prospective fine-grained formations including the Muskwa, Besa River and Horn River (Evie and Otter Park members) formations that occur over a large areal extent.

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, Cordova Embayment, and adjacent western Alberta. Specifically, the goal is to determine the geological factors controlling the distribution of potentially producible wet gas, condensate and oil. The multifaceted study uses petroleum systems analysis, ground-truthed with fluid analysis, and petrophysical and geochemical analyses of cuttings and core samples, to predict the types and volumes of generated and retained hydrocarbons throughout the basins' evolution (Figure 1).

Detailed core-based analysis of samples from across the study area will help refine the reservoir characterization of important intervals and elucidate regional trends. The emphasis of such laboratory work will be put on characterizing the porosity, pore structure and pore-size distribution of the core samples, and generating additional thermal-maturity data to add to the public database. In addition, basin modelling with a focus on thermal history will be used to resolve the timing of hydrocarbon generation and migration and to quantify hydrocarbon charge and retention within the formations. Since the study region encompasses a large area with spatially variable tectonic history but comprises strata of the same general lithology and kerogen type, this study further provides an opportunity to test the impact of tectonic history and variable heat flow on the timing of hydrocarbon generation.

This preliminary report outlines the main research goals of this study, and presents initial results of petrophysical and organic-content measurements of the Muskwa Formation.

Study Area

The Liard and Horn River basins are located in northernmost BC, and southern Yukon and Northwest Territories (Figure 2). Although the focus of the study is within the BC portion of the basins, the study area extends north of the 60º parallel into the territories and includes wells west of the 6th meridian in Alberta to encompass the geographic extent of the formations. The majority of wells in the study area are located within the Horn River Basin, Cordova Embayment and west into Alberta, where initial unconventional petroleum exploration has occurred. The Liard Basin has only recently become an area of active exploration (Ferri et al., 2015) due to the expense and difficulty associated with drilling to reach Paleozoic strata that are deeply buried as a result of displacement in the Bovie fault zone.

Geological Framework

During the Devonian and Mississippian periods northeastern BC was situated along the edge of the North American protocontinent. As in other parts of the Western Canada Sedimentary Basin, the stratigraphy during that time was dominated by shale and carbonate packages, which were

Keywords: *British Columbia, shale gas, unconventional reservoirs, petrophysics, porosity, basin modelling, thermal maturity*

This publication is also available, free of charge, as colour digital files in Adobe Acrobat® PDF format from the Geoscience BC website: http://www.geosciencebc.com/s/DataReleases.asp.

related to major transgressive and regressive cycles. The basinal setting of the study area resulted in deposition of thick packages of fine-grained sedimentary rocks, whereas stratigraphically equivalent carbonate units further to the east were deposited in shallower water (Figure 3). 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).

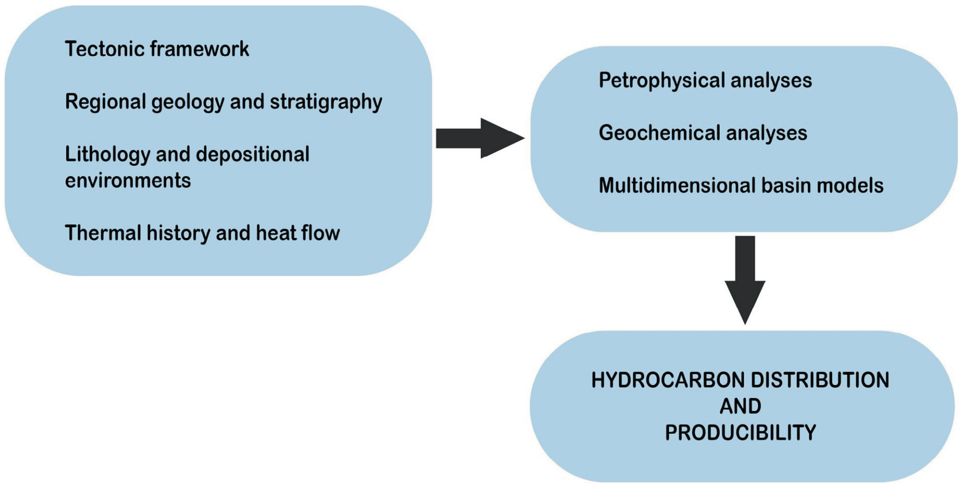

Figure 1. Flowchart illustrating the protocol for this study.

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

The Besa River Formation dominates the stratigraphy of the Liard Basin, representing an extended period of deposition in a sediment-starved anaerobic environment (Ross and Bustin, 2009). The formation contains organic-rich markers representative of the Muskwa and Exshaw formations (Ferri et al., 2011, 2015). In contrast to the more basinal Liard Basin, the Horn River Basin contains a number of carbonate packages interlayered with regionally extensive organic-rich transgressive shale intervals, including the Muskwa and Exshaw formations (Switzer et al., 1994; Ferri et al., 2011). The most common lithofacies within the Muskwa and Horn River formations is massive mudstone with abundant pyrite laminations (Dong et al., 2015). These formations thin and become shallow overall toward the east, where the Horn River Formation pinches out against the edge of the Presqu'ile barrier reef. The Muskwa Formation extends into Alberta (BC Ministry of Natural Gas Development, 2015). Maturity of the source rocks, which is a function of the interplay between burial depth, thermal history and kerogen type, is within the dry-gas window for most of the study area.

Preliminary Results and Work in Progress

To date, core samples have been collected from nine wells in BC along a southwest-trending transect. 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. Additionally, drill cuttings samples were collected from six wells along an adjacent southwest-trending transect. A total of ~300

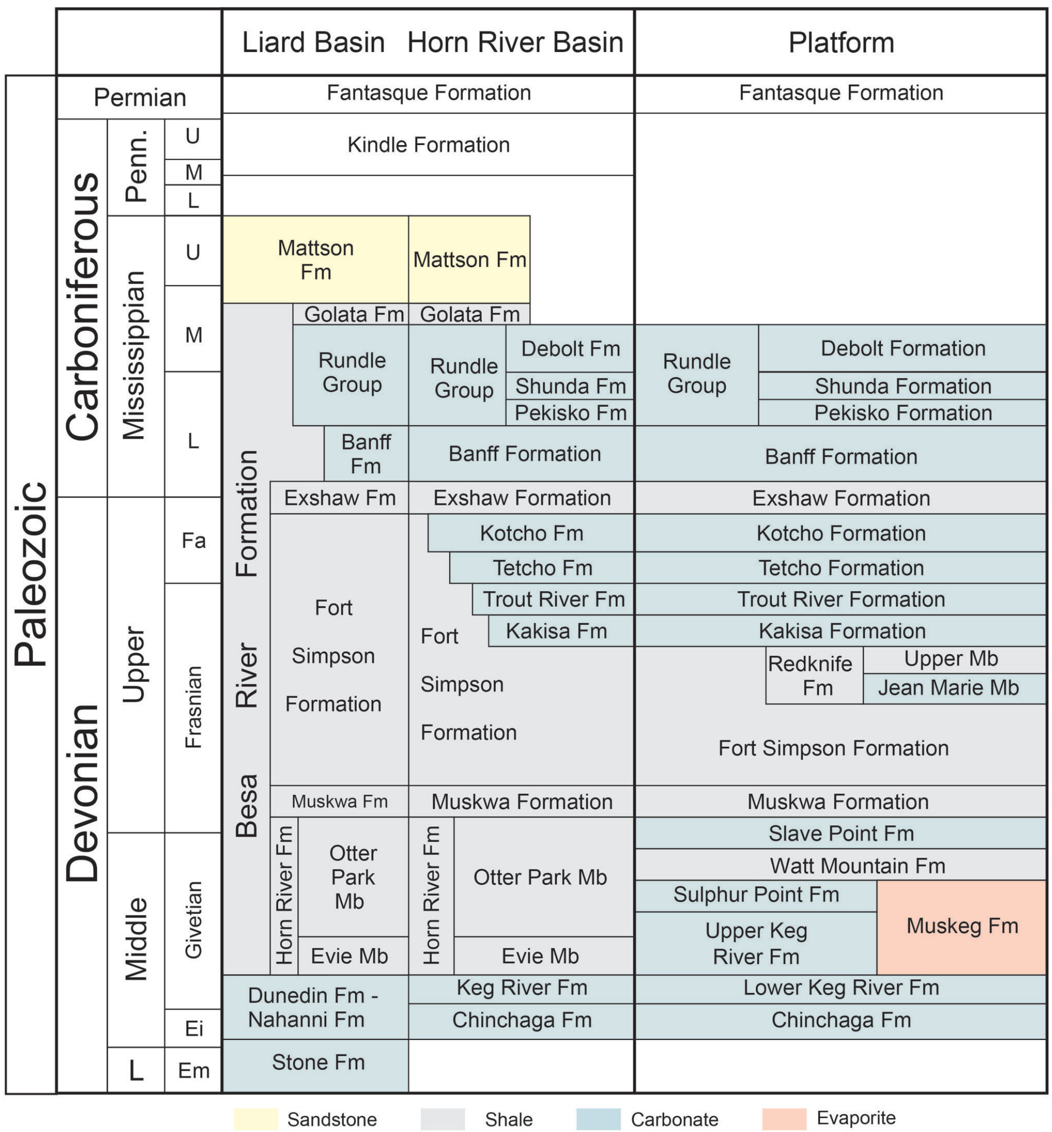

Figure 3. Upper Paleozoic stratigraphy for northeastern British Columbia (modified from Ferri et al., 2011). Abbreviations: Ei, Eifelian; Em, Emsian; Fa, Famennian; Fm, formation; L, lower; M, middle; Mb, member; Penn., Pennsylvanian; U, upper.

samples were collected by sampling at 30 to 50 m intervals along the entire length of each well. Initial data have been collected for a suite of samples from the Muskwa Formation in the Horn River Basin and Cordova Embayment, and include results from total organic carbon (TOC)/pyrolysis, helium pycnometry and mercury intrusion porosimetry (MIP). In addition, TOC/pyrolysis data have been collected for the entire suite of ~300 cuttings samples.

TOC/Pyrolysis

The average TOC of the Muskwa Formation was mapped across the study area using a dataset that includes both publicly available data and new analyses from cuttings and core samples collected for this study. The TOC is generally <2%, with the highest organic potential being located in the northwestern corner of the Horn River Basin (Figure 4). Due to sampling bias, the densest region shown by the dataset is located in the Horn River Basin and Cordova Embayment areas, where the database for the Muskwa Formation is more extensive. There is a positive correlation between porosity and TOC (Figure 5), although the correlation itself does not necessarily suggest a direct genetic relationship. For instance, it has been demonstrated in this area that there is a correlation between quartz content and TOC (Chalmers et al., 2012; Dong et al., 2015). Future mineralogical analysis as a part of this study will address such relationships.

Mercury Intrusion Porosimetry and Helium Pycnometry

The pore structure of shale-oil and shale-gas–reservoir rocks in part determines their storage capacity and fluid-transport properties, which in turn govern the economic producibility of the hydrocarbons. Due to their importance, pore structures will be characterized in this study using a combination of mercury intrusion porosimetry (MIP), helium pycnometry, CO_2 and N_2 gas adsorption, and field emission scanning electron microscopy. Each technique has limitations, but collectively they will provide a quantitative and qualitative understanding of pore structure within the study area.

Results of MIP and helium pycnometry/bulk density obtained to date are summarized in Figure 6. The MIP data were corrected using the workflow outlined by Munson (2015; Figure 7). When comparing porosity values from MIP and helium pycnometry, helium porosity is always higher (Figure 6), as anticipated, due to helium molecules being smaller than mercury molecules and therefore able to access smaller pores. Initial pore-size–distribution results from MIP indicate that most samples contain pores in the mesopore range (Figure 8). Additionally, CO_2 and N_2 gas adsorption will provide insight as to the quantity and size distribution of micropores in the samples.

Basin History

One-dimensional basin modelling is underway, beginning with wells that contain extensive thermal maturity data. Numerous one-dimensional models will provide control points for a three-dimensional model that will assess basin history throughout the area of interest. A preliminary model for a well in the northwestern corner of the Horn River Basin has been constructed to show the general basin history and present-day temperature for this portion of the study area (Figure 9).

Future Work

The petrophysical and geochemical analyses in progress will be used to map lateral trends in reservoir properties and thermal maturity. Construction of basin models using these

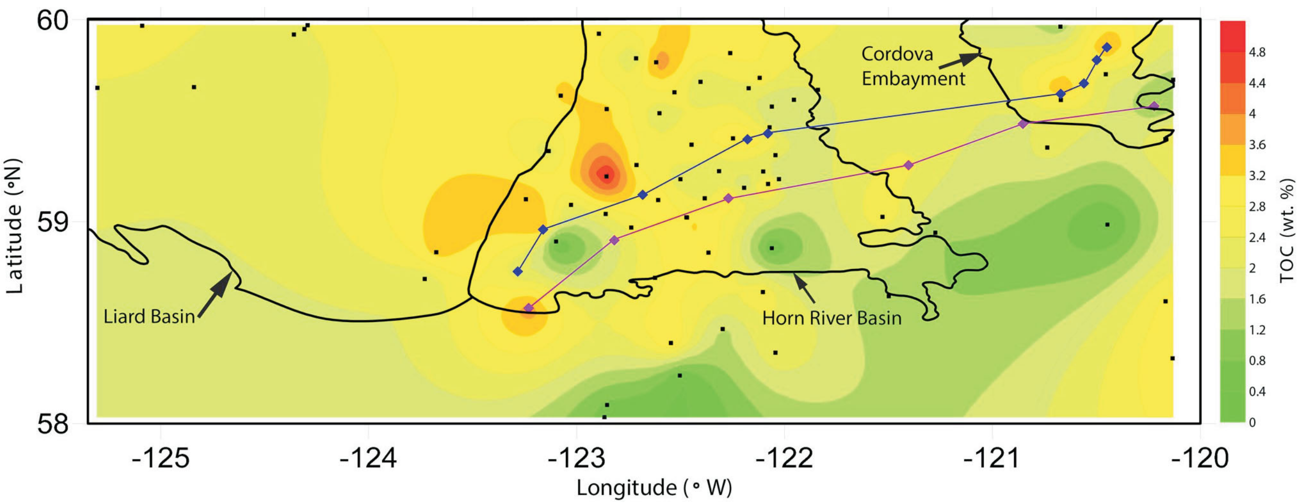

Figure 4. Average total organic carbon (TOC; wt. %) map of the study area. The Liard and Horn River basins and Cordova Embayment are outlined from west to east. The purple and blue cross-sections correspond to the well location of collected cuttings and core samples, respectively. The remaining well locations (black) contain publicly available TOC data.

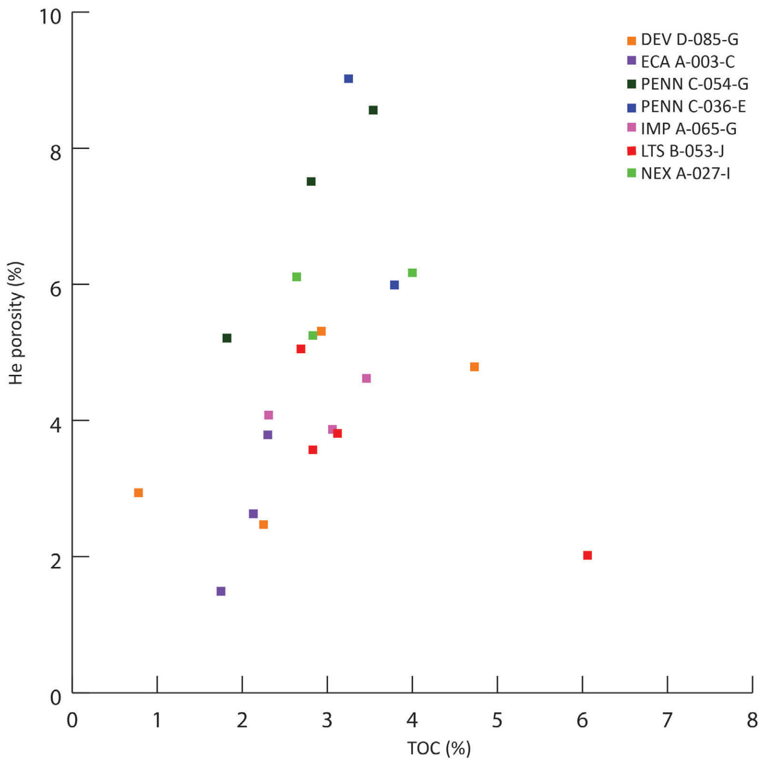

Figure 5. Helium porosity (%) versus total organic carbon (TOC; wt. %) from Muskwa Formation core samples. In general, there is a positive correlation between the two properties. The coloured symbols correspond to data points from seven different well locations that have been analyzed thus far.

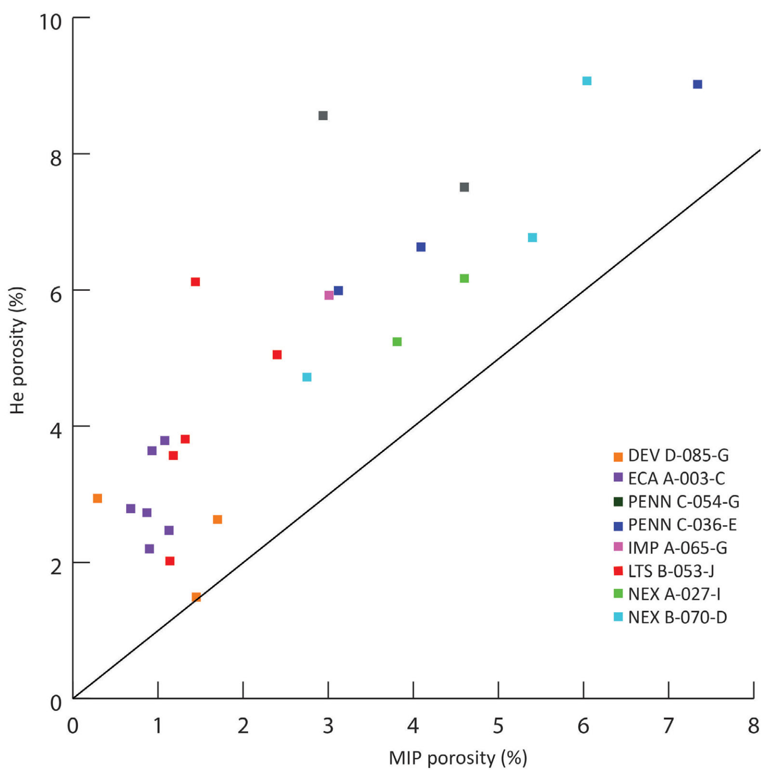

Figure 6. Helium porosity (%) versus porosity (%) evaluated using the mercury intrusion porosimetry (MIP) technique for core samples from the Muskwa Formation. In all instances, helium porosity is higher than porosity evaluated using the MIP technique. The coloured symbols correspond to data points from different well locations that have been analyzed thus far.

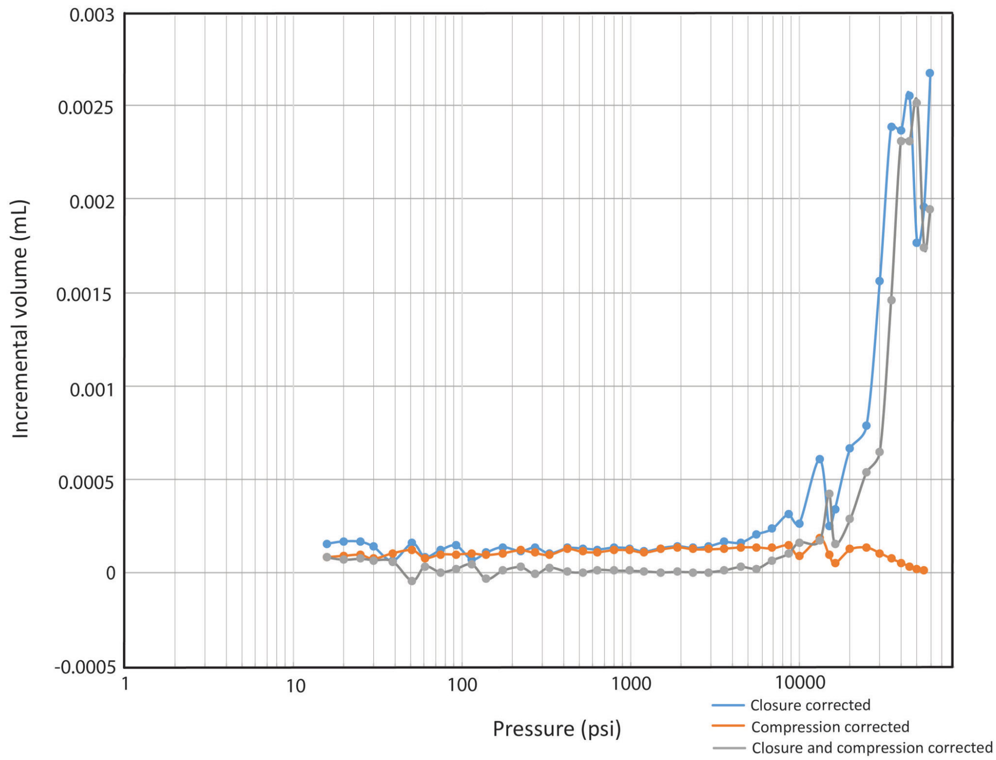

Figure 7. Incremental intrusion (mL) versus injection pressure (psi)—an example of applying closure and compression corrections to uncorrected raw mercury intrusion porosimetry data using the workflow developed by Munson (2015).

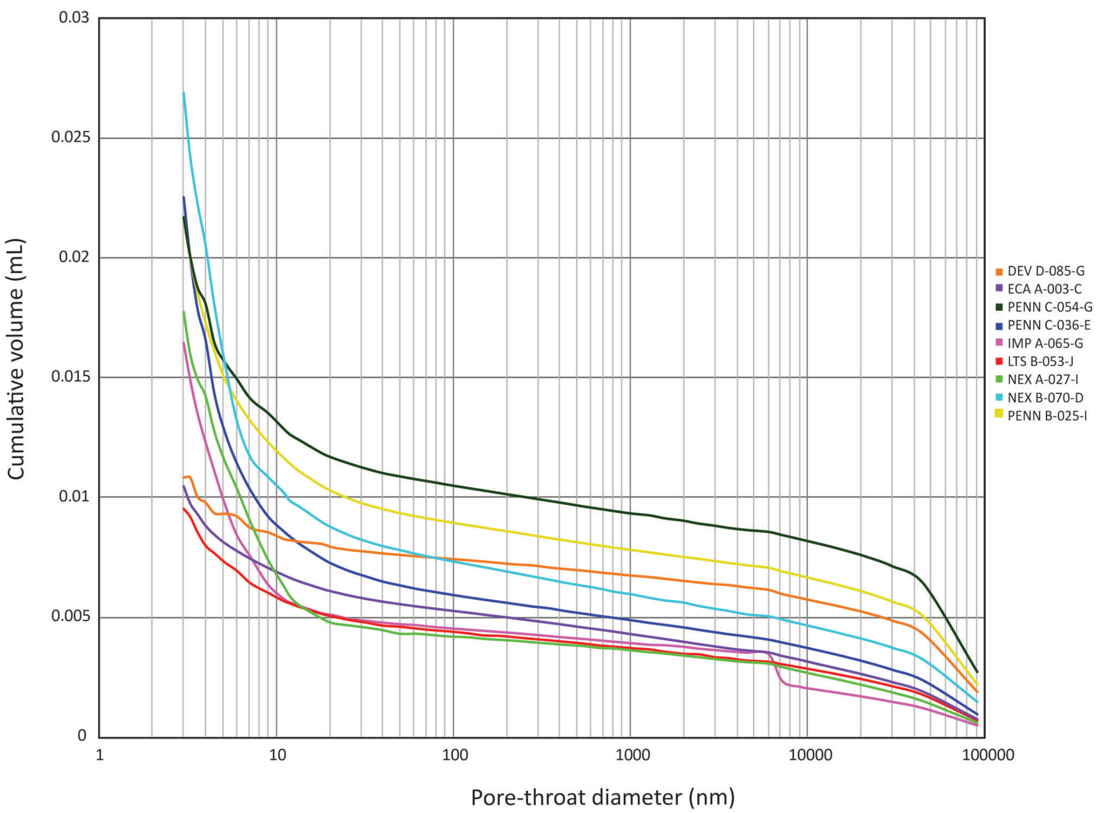

Figure 8. Cumulative intrusion (mL) versus pore-throat diameter (nm)—initial pore-size distributions for Muskwa Formation samples all exhibit similar results with the majority of pores measuring from 3 to 20 nm, which is in the mesopore range. The coloured symbols correspond to data points from different well locations that have been analyzed thus far.

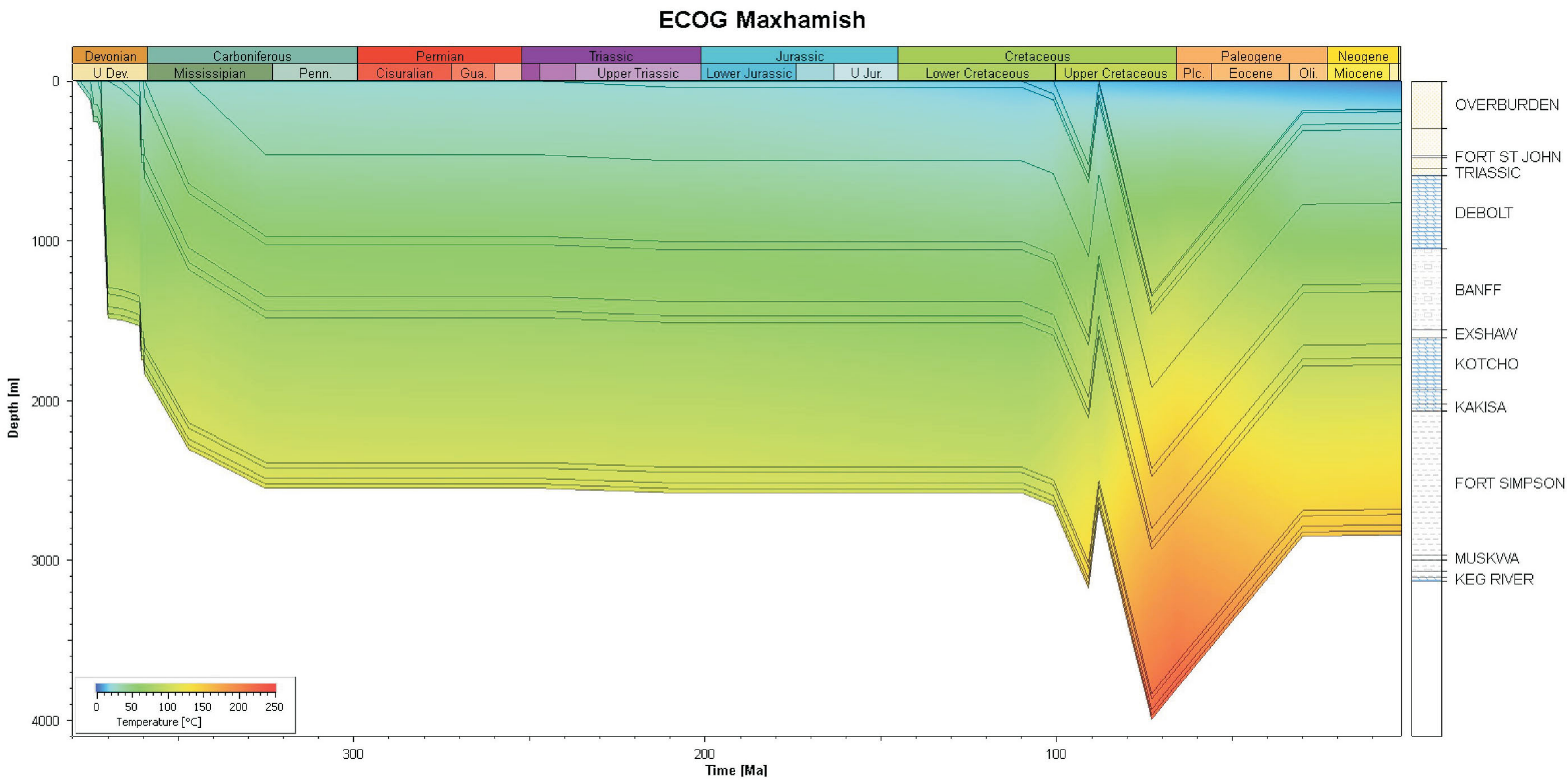

Figure 9. An example of a one-dimensional basin model showing burial depth (m) versus time (Ma) for a well in the Horn River Basin. The colour overlay on the burial history is a present-day temperature profile for this location. The stratigraphic column on the right is based on formation tops from well logs. Abbreviations: Gua, Guadalupian; L Jur., Lower Jurassic; Mio., Miocene; Oli., Oligocene; Plc., Paleocene; U Crt., Upper Cretaceous; U Dev., Upper Devonian; U Jur., Upper Jurassic.

data combined with lithostratigraphy and interpretation of tectonic history will provide a framework for determining the thermal history and the timing of hydrocarbon generation and migration. Together, these research aspects will assess the impact of basin history on the type and quantity of migrated and retained hydrocarbons, and ultimately their producibility.

Acknowledgments

The authors thank Trican Geological Solutions for their logistic support and generosity in providing laboratory analyses. Financial support from Geoscience BC, Encana Corporation, Devon Energy Corporation, Husky Energy Inc., Chevron Canada Limited, Canadian Natural Resources Limited and geoLOGIC systems ltd. are greatly appreciated. The senior author thanks Geoscience BC for the awarding of their research scholarship for 2016. This paper benefited from a careful review by E. Letham.

References

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

BC Ministry of Natural Gas Development (2015): Unconventional natural gas assessment for the Cordova embayment in northeastern British Columbia; BC Ministry of Natural Gas Development, Oil and Gas Report 2015-1, 12 p.

Chalmers, G.R., Ross., D.J.K. and Bustin, R.M. (2012): Geological controls on matrix permeability of Devonian gas shales in the Horn River and Liard basins, northeastern British Columbia, Canada; International Journal of Coal Geology, v. 103, p. 120–131.

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* Oil and Gas 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 and Mines, p. 1–18.

Ferri, F., McMechan, M. and Creaser, R. (2015): The Besa River Formation in Liard Basin, British Columbia; *in* Oil and Gas Geoscience Reports 2015, BC Ministry of Natural Gas Development, p. 1–27.

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.

National Energy Board (2016): The unconventional gas resources of Mississippian–Devonian shales in the Liard Basin of British Columbia, the Northwest Territories, and Yukon–Energy Briefing Note; National Energy Board, 16 p., URL <https://www.neb-one.gc.ca/nrg/sttstc/ntrlgs/rprt/ltmtptntlbcnwtkn2016/index-eng.html> [October 2016]

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.

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.

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.