THERMAL MATURITY AND REGIONAL DISTRIBUTION OF THE MUSKWA FORMATION, NORTHEASTERN BRITISH COLUMBIA

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ABSTRACT

The Muskwa Formation represents an areally extensive, organic-rich horizon (up to 8 wt.% total organic carbon) that has become the focus of exploration for unconventional hydrocarbon resources in western Canada. Found throughout northeastern British Columbia, the Muskwa Formation is time-equivalent to the Duvernay Formation in Alberta and the Canol Formation in the Northwest Territories and the Yukon. This unit can be traced from the Peace River Arch area northwestward into the Horn River and Liard basins, where it becomes part of the Horn River Formation and eventually part of the Besa River Formation. The Muskwa Formation is less than 10 m thick in the Peace River Arch region, exceeds 40 m in thickness in the Horn River and Liard basins and reaches its thickest in the Rocky Mountain Foothills and near the Bovie Lake structure, where it exceeds 70 m. Compositionally, it is a silica-rich, silty shale to shale and is variably calcareous. In the NTS 094I block, vitrinite reflectance and converted bitumen reflectance fall between 1.3 and 1.8%, confirming that the Muskwa Formation has potential for in-situ gas and condensate generation.

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INTRODUCTION

The Muskwa Formation is a Late Devonian (Frasnian) unit that conformably underlies the Fort Simpson shale and is likely found throughout all of northeastern British Columbia, except in the region of the Peace River high (Fig. 1; Williams, 1990). In northeastern British Columbia, the Muskwa Formation also overlies the Slave Point, Waterways and Keg River formations (Evie reef complex) and Otter Park carbonates as its lower contact moves from shelf to basin (Fig. 1). In the Horn River Basin of British Columbia, Muskwa strata have been placed within the Horn River Formation and reduced to member status (Fig. 1; Williams, 1983). The base of the Muskwa Formation has been proposed as a widespread unconformity (Griffin, 1965), although this has been disputed by others (Pugh, 1983; Williams, 1983). In the type well south of Fort Nelson, British Columbia, and near the southern boundary of the Horn River Basin (a-95-J/94-J-10; Fig. 2), the Muskwa overlies the Otter Park member of the Horn River Formation. The Muskwa Formation is an approximate stratigraphic equivalent to the Duvernay Formation in Alberta (Switzer et al., 1994) and the Canol Formation in the Northwest Territories (Pugh, 1983). In northwestern British Columbia, the Muskwa and the Horn River Formation become a subset of the Besa River Formation as one approaches the deformation belt.

The Muskwa Formation is a pyritic, siliceous, variably calcareous and generally organic-rich dark grey to black shale and is viewed as a principal source horizon in the Western Canada Sedimentary Basin

(Williams, 1990). Total organic carbon (TOC) ranges from 0.14 to 8.39 wt.% with a mean of 2.75 wt.%, based on 474 samples taken from 56 wells (Ferri et al., 2013). Considering the typical overmature nature of this unit (based on limited thermal maturity data), it was likely a very rich source rock prior to the generation of hydrocarbons. In logs, it is characterized by high radioactivity and resistivity. The upper contact is picked by an increase in the gamma-ray and resistivity, as readings quickly transition from the inorganic Fort Simpson grey shale into the organic-rich Muskwa Formation. The lower contact is typically characterized by a drop in radioactivity, the intensity depending on whether it is positioned above shelf carbonates or basinal calcareous shales. Outside of the Horn River Basin, much of the Muskwa Formation sits on platform carbonates represented by the Slave Point Formation. The Muskwa Formation is relatively thin along the top of the Slave Point Formation and thickens into the Horn River Basin (Fig. 3).

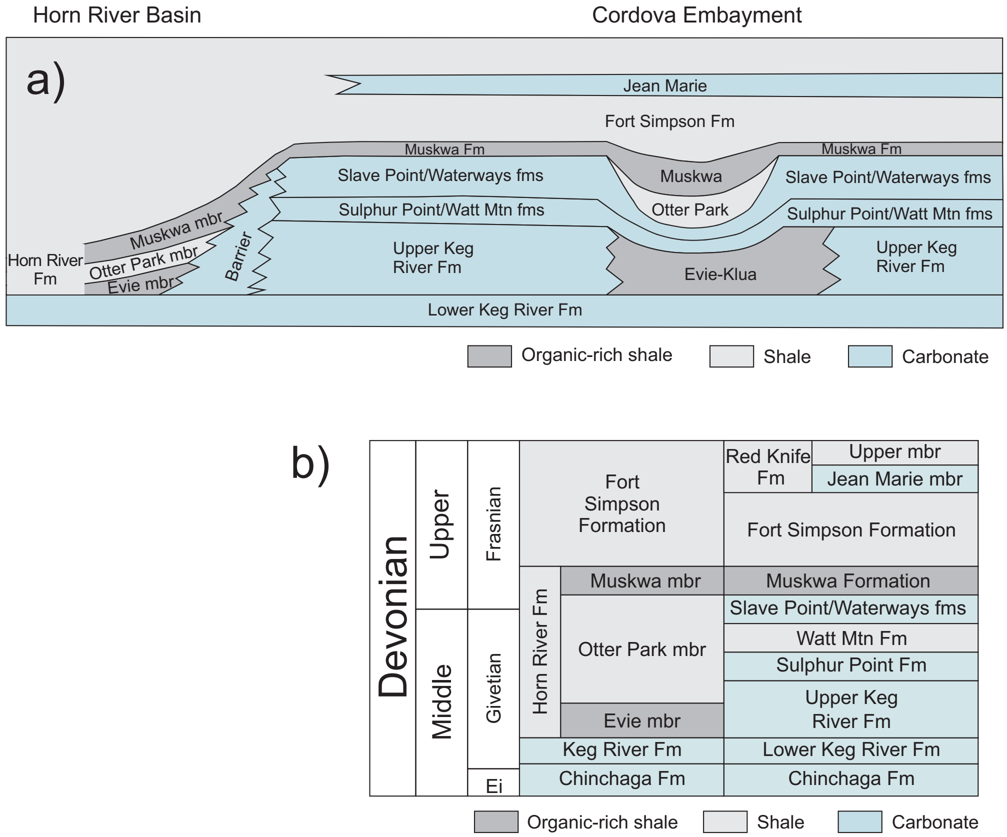

Figure 1. Stratigraphic relationships of Muskwa shales with other units: a) diagrammatic relationship of Muskwa shales to other units and b) time–stratigraphic chart. Ei: Eifelian.

General trends in thermal maturity for Muskwa shales suggest that the unit is overmature and within the dry gas window throughout much of northeastern British Columbia (Creaney et al., 1994). Yet, production data from the Jean Marie Formation in certain parts of NTS 094I in northeastern British Columbia show considerable condensate content (Fig. 4). It is unlikely that the organic-lean shales of the Redknife or Fort Simpson formations sourced this condensate. A more likely scenario is that the scattered nature of this production reflects localized faulting that has tapped the Muskwa shales, allowing this condensate to migrate through the thick Fort Simpson shales. Thermal maturity data collected from the Muskwa Formation on trend in Alberta and the Northwest Territories support this hypothesis (Stasiuk and Fowler, 2002; Beaton et al., 2010; Rokosh et al., 2012), because the units there are interpreted to be in the oil or wet gas thermal maturity windows. Extrapolation into British Columbia would suggest the Muskwa shales in the far northeast corner of northeastern British Columbia are likely in the wet gas zone. This assumption is supported by the recent test of Muskwa shales in the Bivouac area of NTS 094I, where Husky HZ Bivouac a-55-B/94-I-8 initially produced 19.5 bbl condensate/mmcf gas (bbl: barrel; mmcf: million cubic feet; 110 m^3 condensate/1000 m^3 gas).

This paper will describe the extent, thickness and thermal maturity of the organic-rich Muskwa shale horizon in British Columbia in hopes of defining zones of dry gas, condensate and oil. Unfortunately, there are limited reliable thermal maturity data for the Muskwa Formation in British Columbia; regardless, it can be demonstrated that a portion of the Muskwa Formation in the far northeast corner of northeastern British Columbia is in the condensate window.

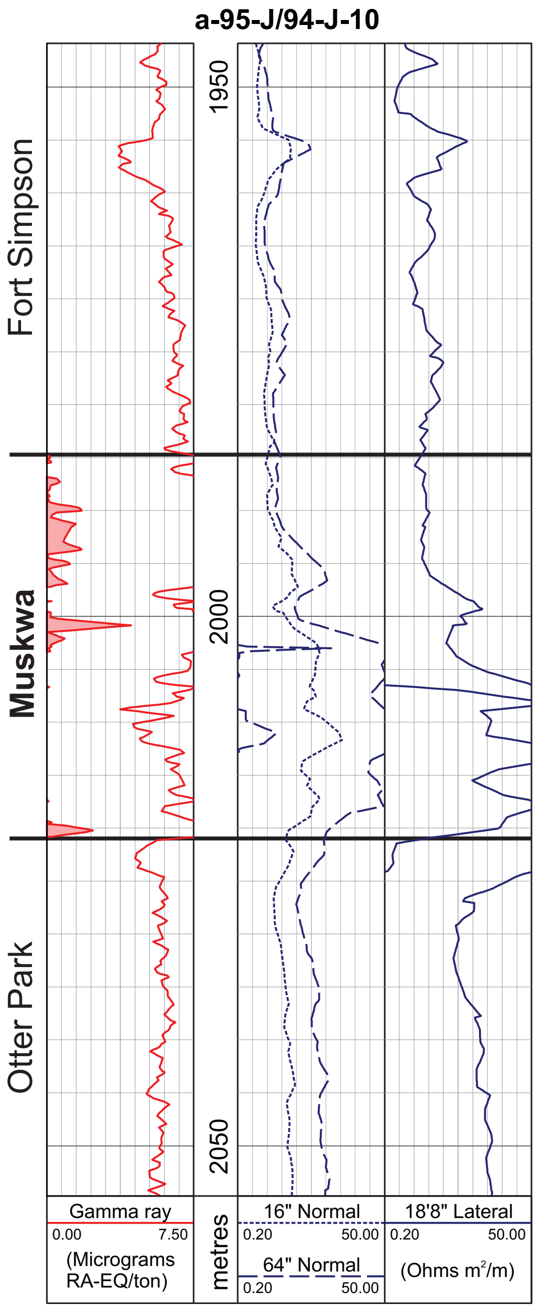

Figure 2. Gamma-ray and resistivity signature of the Muskwa Formation from the type well, a-95-J/94-J-10. RA-EQ/ton: micrograms radium equivalent per ton.

METHODS

A database of the Muskwa interval was compiled based on gamma-ray, resistivity and sonic logs, and by consulting core and cutting descriptions in the well documents. Regional cross-sections were constructed to check the consistency of the Muskwa Formation picks (Fig. 4). These were supplemented by more localized cross sections.

Structural data were then exported from geoSCOUT® to Surfer® contour software and isopach contours were generated using the Kriging method. The top of the Muskwa structure map was contoured using a minimum curvature method to accommodate the Bovie fault. The surface trace of the Bovie fault at the Muskwa Formation level was based on high dip values between wells and published data on the fault (Wright et al., 1994; MacLean and Morrow, 2004).

One parameter of hydrocarbon generation is the peak temperature, or thermal maturity, attained by the source rock. Several thermal maturity indicators (or paleothermometers) are used in hydrocarbon exploration, such as Rock Eval™ pyrolysis and vitrinite reflectance. Due to the possible presence of early oil generation and/or the use of petroleum-based drilling muds, thermal maturity values based on Rock Eval data (T_{max}) are erroneously low for much of the Muskwa Formation in northeastern British Columbia. As a result, only reflectance data were used, and this was of limited areal extent (Fig. 5).

Vitrinite reflectance is a widely accepted paleothermometric technique used to assess coal rank and other organic material. In the Muskwa Formation, reflectance of bitumen has been measured and a vitrinite equivalent value was calculated using an empirical relation described by Jacob (1985).

Thermal maturity data in the form of vitrinite and converted bitumen reflectance were compiled from various sources (Potter, 1998; Stasiuk and Fowler, 2002; Ferri et al., 2013). In addition, regional reflectance data for the Muskwa Formation in Alberta and the Northwest Territories were used in the compilation (Stasiuk and Fowler, 2002; Beaton et al., 2010). Several data points from the bottom of the

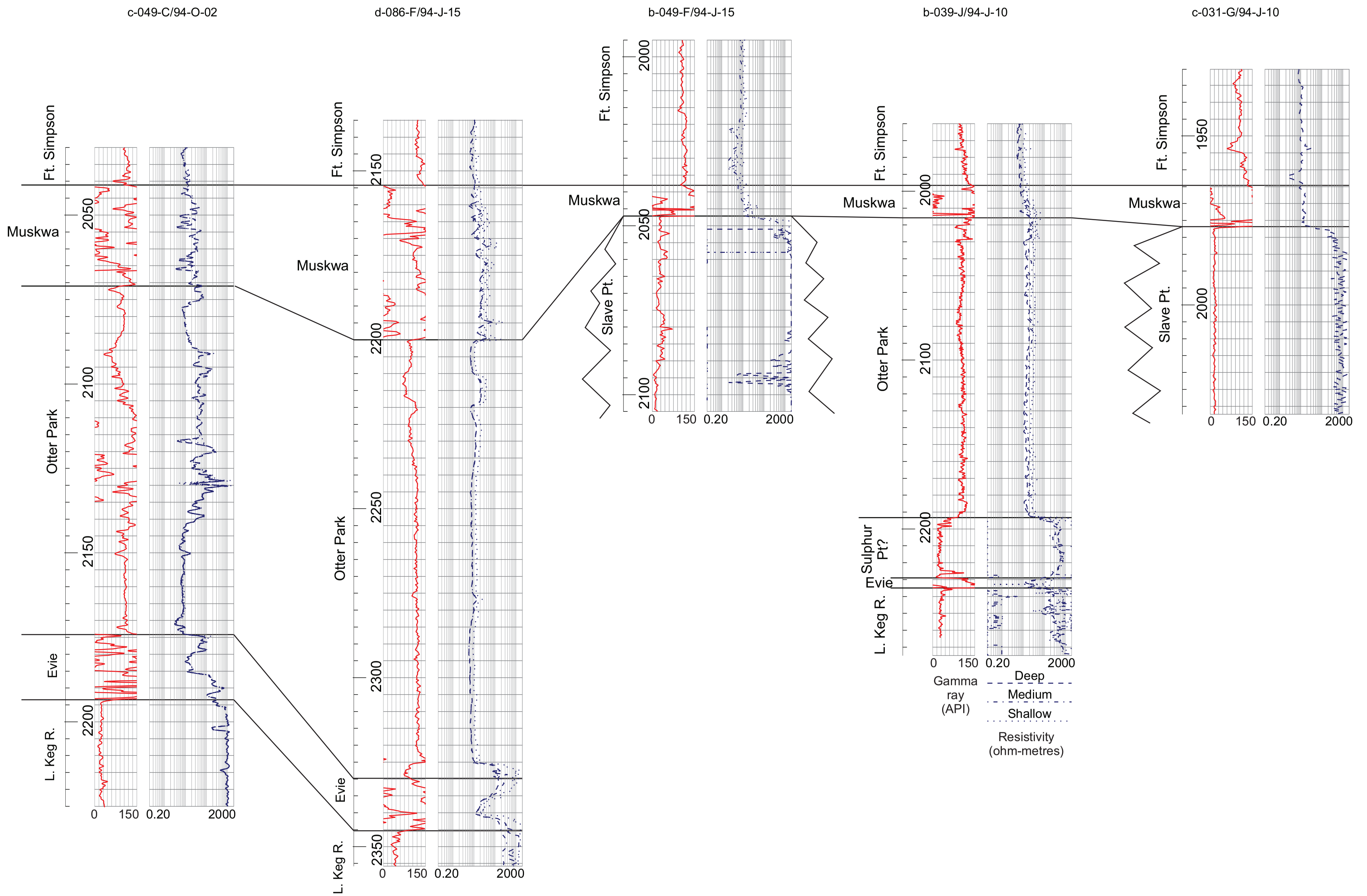

Figure 3. Cross-section showing stratigraphic relationships of Muskwa shales with underlying carbonates and succeeding shales along the western edge of the Horn River Basin. See Figure 5 for location of the cross-section.

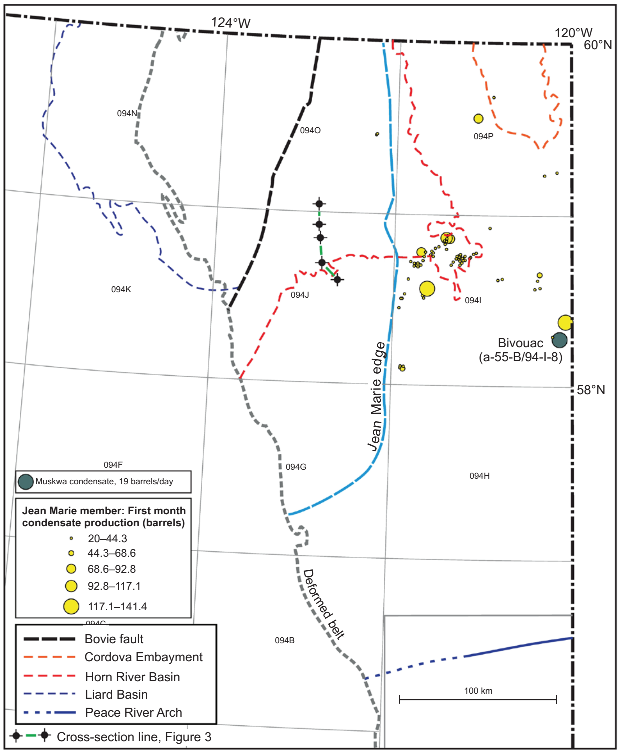

Figure 4. Location of the condensate-rich Jean Marie Formation in northeastern British Columbia with respect to various depositional elements. Also shown is the location of the Husky Bivouac a-55-B/94-I-8 well, which has shown significant condensate production from the Muskwa Formation.

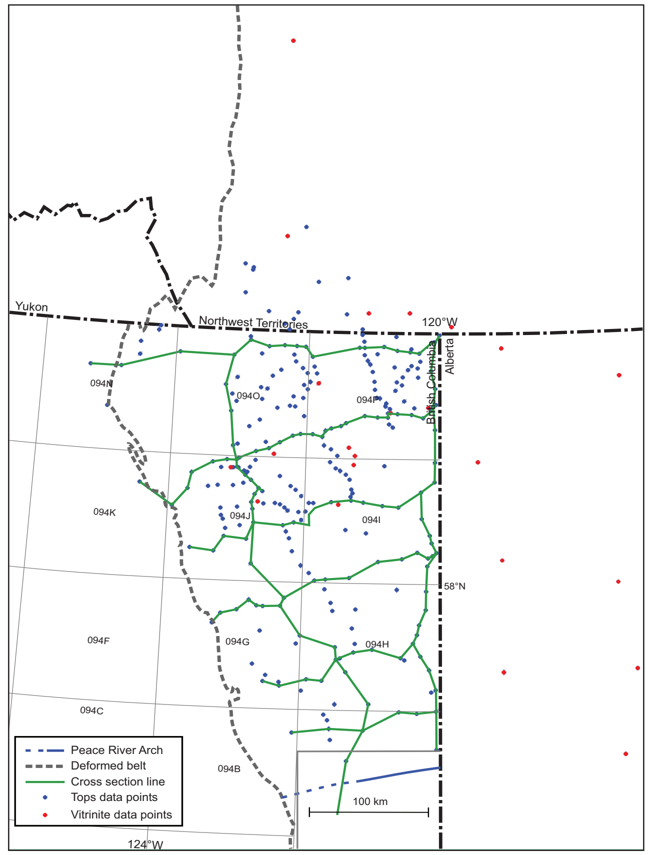

Figure 5. Data points and regional cross-sections used in producing the various maps of the Muskwa Formation. The cross-sections were used to be internally consistent.

Fort Simpson Formation and the top of the Otter Park Formation were also used because they were within 10 m of the Muskwa interval. Vitrinite and vitrinite equivalents were then averaged for each location and isoreflectance contours were generated using the Kriging method in Surfer®.

RESULTS

Regional distribution and structure

Areally, the Muskwa Formation extends from the northern edge of the Peace River Arch (PRA) northward into the Yukon and Northwest Territories and eastward into northern Alberta. Data are lacking south of the PRA in British Columbia where the Muskwa Formation likely lies well in excess of 5000 m within the Deep Basin, but in Alberta the correlative Duvernay Formation is penetrated south of the PRA, suggesting this unit likely extends into British Columbia. In the western Liard Basin, it becomes difficult to distinguish the Muskwa Formation because the thickness of the Fort Simpson Formation decreases dramatically and becomes more organic rich, and the Otter Park Formation thins significantly. It is at this point that the shale units of the Muskwa Formation are amalgamated with the Besa River Formation. The Muskwa Formation is an average of 30 m thick; it is less than 10 m where it overlies platform carbonates, in excess of 70 m thick near the Bovie Lake fault, more than 80 m in the Liard Basin and attains a maximum thickness of just more than 100 m in the Rocky Mountain Foothills (Fig. 6).

The Muskwa Formation is at its shallowest in the far northeast British Columbia (Fig. 7). It deepens southwestward into the Deep Basin and westward into the Horn River Basin. In the study area, the unit is at its deepest within the Liard Basin, where it reaches a depth of 4850 m. This is primarily due to displacement on the Bovie Lake fault, which has a maximum displacement of 1600 m near the Windflower gas field (NTS 094N/11). The shallowing of the Muskwa Formation in the western Liard Basin is likely the result of a disturbance along the Rocky Mountain Foothills.

Thermal maturity

Reflectance data for the Muskwa Formation in British Columbia are mostly confined to the NTS 094P block, with values ranging from 1.59 to 2.45%. Maturity levels are lowest in the east, along the Alberta–British Columbia border, and increase to the west and southwest, the latter due to subsidence within the Deep Basin. Interpolated reflectance values in the NTS 094I block range between 1.4 and 1.8%, indicating that the Muskwa Formation has condensate potential consistent with recent condensate production in the Bivouac field (Figs. 8, 9).

DISCUSSION

Based on limited thermal maturity data for Muskwa shales in NTS 094I, J, O and P, together with data from the adjacent Alberta and Northwest Territories, a zone falling within the upper limit of maximum wet gas generation (approximately 1.4 R_o) is defined along the border with Alberta in NTS 094P and I (Fig. 9). Considering the thermal maturity trends in Alberta and the Northwest Territories, one would have expected this zone to be much wider in British Columbia. The relatively narrow condensate zone in British Columbia and the north-south trend of isotherm is likely a reflection of the higher geothermal gradients in this part of the Western Canada Sedimentary Basin (Bachu and Burwash, 1994).

Recent exploration of Muskwa shales in this area supports the inference that these rocks are in the upper oil (condensate) window. Data from a recent horizontal well into Muskwa shales (a-55-B/094-I-08) in the Bivouac area by Husky Exploration Ltd. show, in a four-month period, a daily average production of 22 barrels of condensate (3.6 m^3) and 1.15 mmcf of gas (32.3 e^3m^3). The Muskwa Formation is approximately 27 m thick and occurs at a depth of 1820 m. Completion

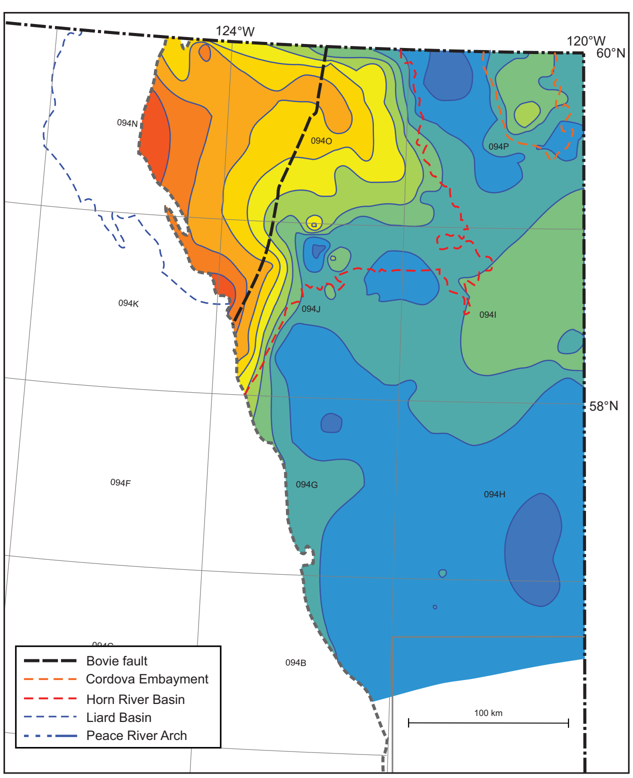

Figure 6. Isopach of the Muskwa Formation, northeastern British Columbia.

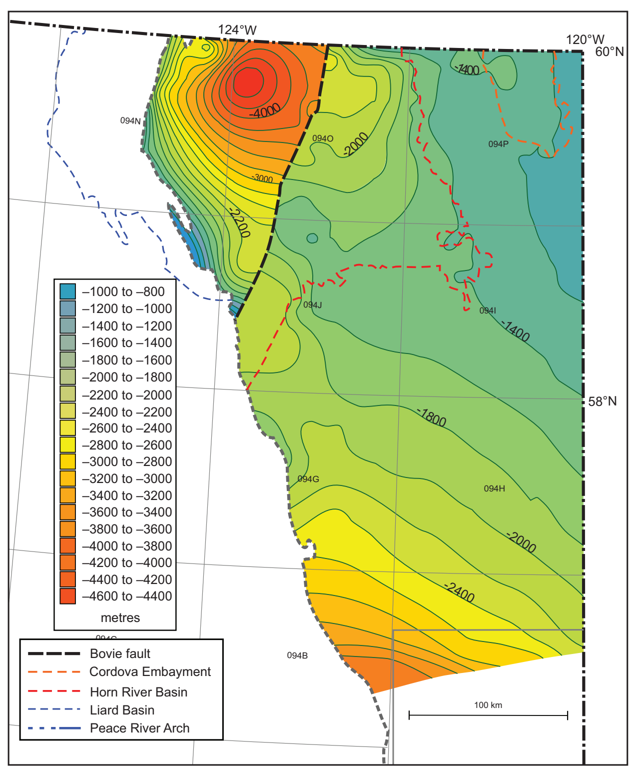

Figure 7. Structure for the top of the Muskwa Formation, northeastern British Columbia.

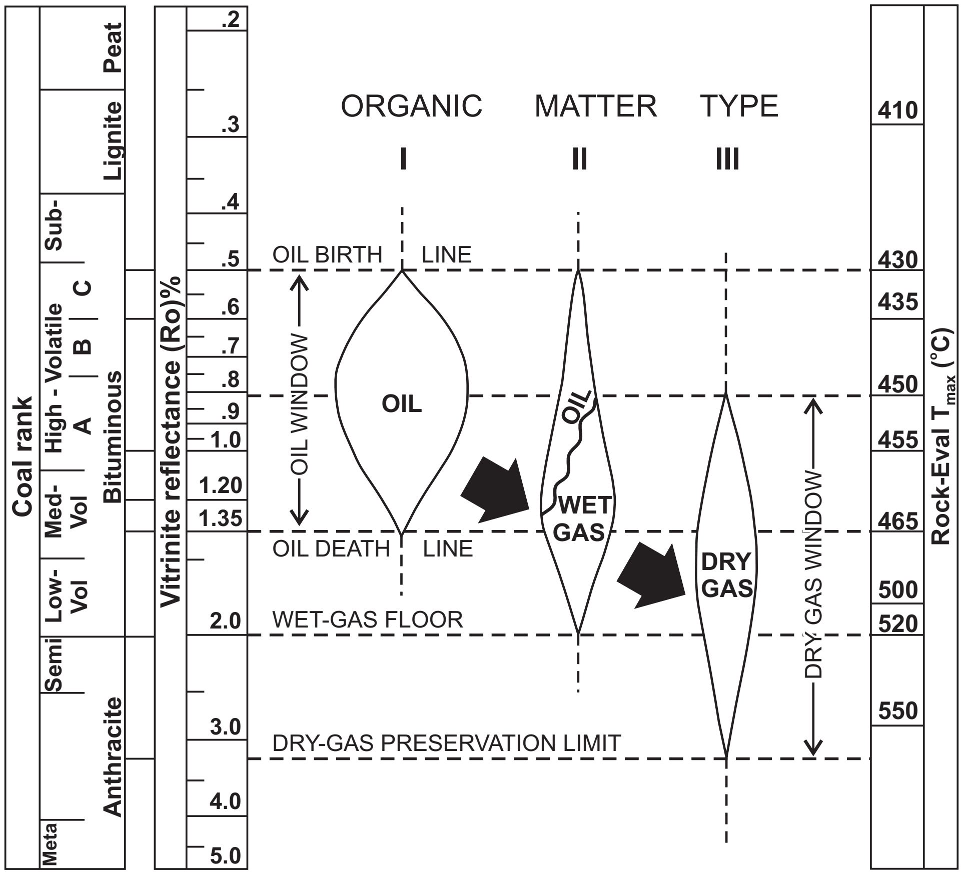

Figure 8. Petroleum thermal maturation zones (modified from Leckie et al., 1988; cf. Dow, 1977; Teichmuller and Durand, 1983).

was along a 1600 m horizontal leg and consisted of an 18-stage hydraulic fracture.

There is sporadic condensate production from Jean Marie carbonates in NTS 094I (Fig. 4). This production roughly defines a northwesterly trend, extending from the Bivouac area to the Jean Marie edge. If Muskwa shales are supplying condensate and light oil to overlying Jean Marie carbonates, this is likely accomplished by fault structures allowing the migration of hydrocarbons through the thick, impermeable Fort Simpson shales. It is uncertain if this trend results from larger, regional faults or from localized structures.

Although condensate production from the Jean Marie member at Bivouac is consistent with thermal maturity values in underlying Muskwa Formation, similar production from this unit in wells to the northwest falls within areas where Muskwa shales are overmature (Fig. 9). Considering the paucity of thermal maturity data, these production data could very well define a low thermal maturity re-entrant within the Muskwa Formation.

In addition, there is higher condensate production within overlying Jean Marie carbonates in this zone of lower thermal maturity defined within the Muskwa Formation (Figs. 4, 9). The assumption is that this condensate is sourced from underlying Muskwa shales as opposed to the organic-lean Fort Simpson shales encompassing the Jean Marie member. Interestingly, there are wells to the northwest of Bivouac with equally high condensate production values in the Jean Marie member, located an area outside the condensate window for Muskwa shales. Perhaps this low thermal maturity re-entrant to the north might be wider than currently defined with the limited data available.

CONCLUSIONS

The Muskwa Formation represents a widespread, organic-rich (mean TOC of 2.75 wt.%) unit in the Western Canada Sedimentary Basin and is identified as one of the principle source-bed horizons. It is commonly between 10 and 25 m thick where it overlies the Slave Point and Waterways formations but thickens significantly into the Cordova Embayment, Horn River and Liard basins, exceeding 40, 60 and 80 m, respectively. The unit is being extensively developed for its shale gas potential in the Horn River Basin and Cordova Embayment, where production is dry gas.

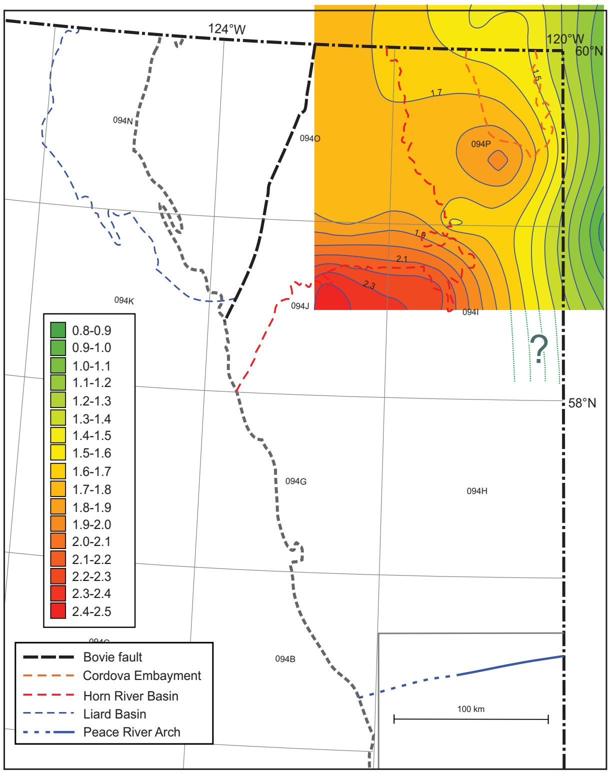

Figure 9. Isoreflectance map of Muskwa shales in northeastern British Columbia; 0.1% contour interval. Contouring was approximately limited to the extent of available data, although extrapolation of contour data to the south suggests some potential.

Robust, regional thermal maturity data for Muskwa shales in British Columbia are lacking. Limited thermal maturity values of 1.3–1.6 R_o along the British Columbia–Alberta border in NTS 094P and 094I, together with similar data in Alberta and the Northwest Territories, define a narrow zone in northeastern British Columbia with condensate potential. More thermal maturity data for Muskwa shales are needed to accurately define the spatial distribution of maturity levels within this unit.

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