An appraisal of Devonian-Mississippian shale strata in Yukon's Liard basin

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ABSTRACT

This study presents the first shale gas appraisal of Devonian-Mississippian shale strata in Yukon's Liard basin. Assessed volumes of 68 Tcf gas-in-place and 7.6 Tcf marketable gas are contained within two shale plays identified from an integrated wireline log and geochemical evaluation: the Devonian (Givetian-Frasnian) Horn River shale and the Devonian-Mississippian (Famennian-Tournaisian) Exshaw-Patry shale. Average burial depths of 3018 mTVD and net pay thicknesses of 73 m for the Horn River, and 2688 mTVD and 89 m for the Exshaw-Patry plays are interpreted. Both plays are dominated by black, organic-rich, siliceous mudstones, and exhibit: elevated TOC contents (0.6-6.9 wt%); maturities within or past the dry gas window (2.1-4.6 %R_o); very high biogenic silica proportions (averaging 80.2-90.3%); high mineralogical stiffness (0.80-0.87); and average porosities of 1.2% for the Horn River and 4.2% for the Exshaw-Patry play. Resource distribution models indicate 50% of Yukon's marketable gas will be found in 30% of its assessed area, with the best potential for significant volumes located in the very southeast of the territory where play depth and thickness increases.

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INTRODUCTION

In 2012, Yukon Geological Survey entered a multi-jurisdictional, collaborative research study of unconventional shale gas potential of the Liard basin. The project was initiated due to increasing industry exploration interests in Liard basin and the adjacent Horn River basin in northeast British Columbia (BC), where organic-rich Upper Devonian-Mississippian black shale formations comprise world-class, regionally extensive unconventional exploration targets (Adams *et al.*, 2015).

Previous work has focused on outcrop field studies of the Besa River Formation in BC (Ferri *et al.*, 2011, 2012, 2013), Yukon (Fraser *et al.*, 2012) and the Northwest Territories (e.g., Rocheleau *et al.*, 2014; Pyle *et al.*, 2016). In 2016, a basin-wide shale resource assessment was published by the National Energy Board (NEB, 2016; Johnson *et al.*, 2016), together with the supporting detailed analytical methodologies and non-interpretative compilation of outcrop and subsurface data specific to Yukon's part of the basin by Hutchison (2016). To date, no interpretative unconventional subsurface analysis has been undertaken specifically on Yukon's well material or wireline data, and no correlation has been attempted with the more robustly differentiated stratigraphy in northeast BC (e.g., Ferri *et al.*, 2013, 2015). This paper reports the first quantitative appraisal of frontier shale strata not only in Yukon's Liard basin, but also in the territory itself.

REGIONAL PETROLEUM GEOLOGY

Liard basin is located in southeastern Yukon straddling the border with BC and Northwest Territories (NWT), and constitutes the northernmost extension of the Western Canada Sedimentary basin (Fig. 1). In Yukon, it is approximately 6500 km^2 in area, and contains a sedimentary fill of >6000 m consisting of broadly folded Paleozoic and Mesozoic strata comparable to that of northeastern BC and northeastern Alberta (NEB, 2001). In the territory, 13 conventional wells have been drilled to date in the basin, and are focused in the Beaver River and Kotaneelee fields (Fraser and Hogue, 2007). Of these 13 wells, only three were put on production until eventual suspension of the Kotaneelee field in 2012 due to excessive water coning.

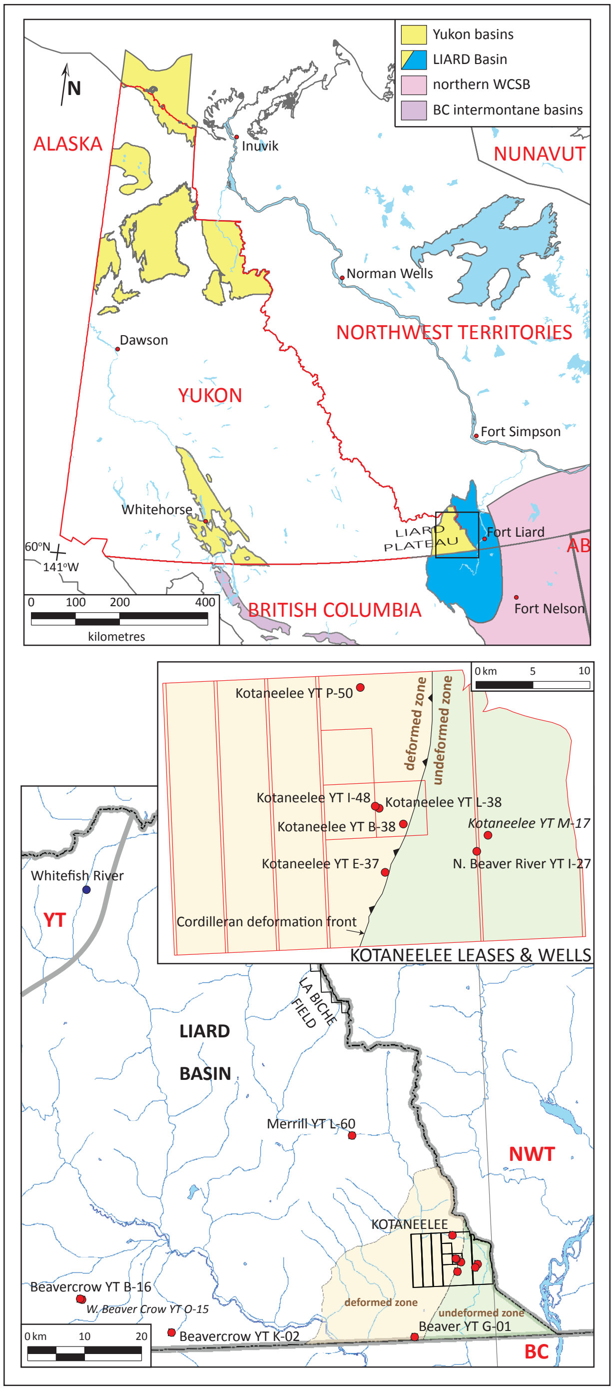


Figure 1. *Location of Liard basin in northwest Canada, with the Yukon portion shaded in yellow (after Hutchison, 2016, with basin margins from Mossop et al., 2004). The box on Liard Plateau in the upper map represents the area of the basin zoomed in below. Wells in italics in the lower map were not used in this study. The green and brown coloured 'zones' in the lower map refer to those areas assessed in the NEB (2016) resource calculations, with the boundary between the two representing the Cordillera deformation front. The red lines in the inset demark the Kotaneelee lease outlines.*

The strata of interest for this study are fissile, grey to black marine shales of the Devonian to Carboniferous Besa River Formation (Fig. 2): a generic unit used during surface mapping to describe thick successions of undifferentiated black shale (*e.g.*, Fallas *et al.*, 2014). These shales conformably overly the conventional gas-producing Cambrian through Middle Devonian platformal carbonate reservoirs of the Nahanni Formation (*see* Hutchison, 2016, for further detail). Stable organic carbon isotope data from Kotaneelee YT I-48 (see Hutchison, 2016), in conjunction with regional correlations and faunal and isotopic data from elsewhere in the WCSB (*e.g.*, Noble and Ferguson, 1971; Nadjiwon, 2001; Creaser *et al.*, 2002; Richards *et al.*, 2002; Selby and Creaser, 2005; Ferri *et al.*, 2015) have helped constrain the depositional age of the Horn River-Exshaw succession in Liard basin to Givetian to early Tournaisian (N. Sullivan *et al.*, in prep.).

In addition to the immature, proven conventional gas plays in the basin (NEB, 2001), unconventional play potential exists in two high quality source rocks within this Devonian-Mississippian basinal shale succession: the Exshaw-Patry and Horn River shale plays (NEB, 2016). The Exshaw-Patry play comprises shales of the Exshaw Formation and Ferri *et al.*'s (2015) underlying informal 'Patry member', and the Horn River play comprises shales of the Horn River Group in its entirety.

MATERIALS AND METHODS

Detailed sampling and analytical methods, re-interpreted formation tops, depths, gross thicknesses and net unconventional pay thicknesses and index data, together with Yukon's entire Liard basin sample database, are available for reference and digital download in Hutchison (2016). Sample data are summarized in Table 1 and methods are described briefly below (*see* Figure 1 for outcrop/well location map).

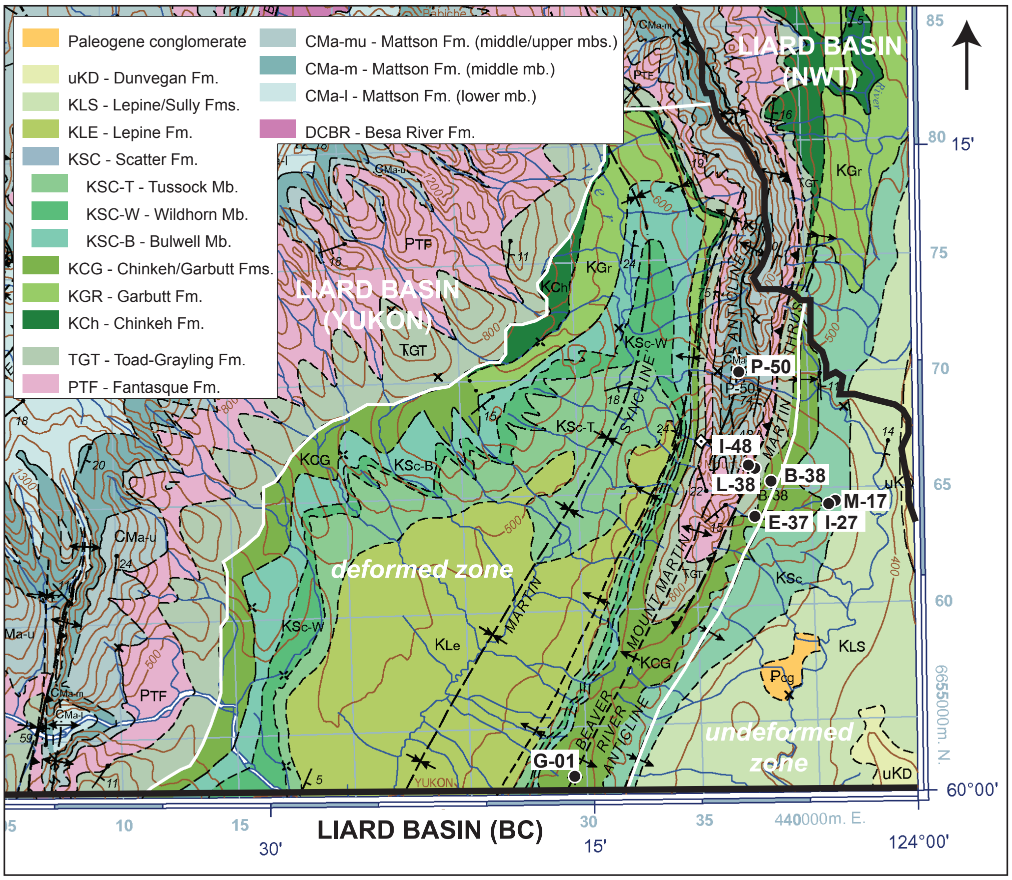


Figure 2. *Geology map of the southeastern part of Liard basin in Yukon with the undeformed and deformed assessment areas indicated. The Fort St John Group that defines the assessment area is composed of Chinkeh to Levine/Sully formations. Map modified from Fallas et al. (2014).*

Table 1. *Outcrop and well sample database for Yukon's Liard basin, reprinted from Hutchison (2016). Note that sample depth ranges for Kotaneelee YT I-48 are presented in post-shift measured depth (see text for discussion).*

Section/well ID	UWI	Easting	Northing	UTM zone	Elevation (KB asl)	Deviated?	TD (mMD)
Beaver YT G-01	300/G-01-6010-12415/0	429467	6652839	10	797.60	yes	4499.50
Beavercrow YT B-16	300/B-16-6010-12515/0	371896	6663005	10	1152.40	no	2288.40
Beavercrow YT K-02	300/K-02-6010-12500/0	387353	6656330	10	1133.90	no	3976.10
Kotaneelee YT B-38	300/B-38-6010-12400/1	438289	6665340	10	685.80	yes	3898.10
Kotaneelee YT E-37	300/E-37-6010-12400/2	437588	6663894	10	621.20	yes	4191.00
Kotaneelee YT I-48	300/I-48-6010-12400/4	437308	6666031	10	832.70	yes	4430.00
Kotaneelee YT I-48A	300/I-48-6010-12400/5	437308	6666031	10	832.70	yes	3915.00
Kotaneelee YT L-38A	300/L-38-6010-12400/0	437710	6666092	10	810.40	yes	4124.00
Kotaneelee YT M-17	300/M-17-6010-12400/1	441087	6664393	10	419.10	no	1333.00
Kotaneelee YT P-50	300/P-50-6010-12400/0	437108	6670086	10	454.20	yes	4410.50
Merrill YT L-60	300/L-60/6020-12415/0	420757	6688450	10	594.40	no	1634.30
North Beaver River YT I-27	300/I-27-6010-12540/3	440735	6664293	10	1445.80	yes	4418.10
West Beaver Crow YT O-15	300/O-15-6010-12515/0	372211	6662860	10	1147.90	yes	4418.10
Whitefish River	outcrop	378293	6734735	10			254.00

Section/well ID	SAMPLE RANGES (mMD)														
	Rock-Eval/TOC			Vitrinite reflectance			ICP-ES/MS			$\delta^{13}C_{org}$ (+TOC)			Porosity		
	No.	Top	Base	No.	Top	Base	No.	Top	Base	No.	Top	Base	No.	Top	Base
Beaver YT G-01	241	124.70	4395.52	69	125.00	4396.00	76	3529.58	4123.94				4	3608.83	4099.56
Beavercrow YT B-16	78	1189.00	1710.00	1	1505.71	1505.71	17	1453.90	1563.62						
Beavercrow YT K-02	53	935.74	1423.42	5	1018.30	1402.08	50	972.31	1423.42						
Kotaneelee YT B-38															
Kotaneelee YT E-37	86	3413.76	3958.44										5	3478.68	3883.30
Kotaneelee YT I-48	232	801.72	3640.00	5	3207.00	3634.00	114	3030.00	3697.00	184	2982.00	3684.00	1	3225.00	3225.00
Kotaneelee YT I-48A															
Kotaneelee YT L-38A															

Section/well ID	SAMPLE RANGES (mMD)														
	Rock-Eval/TOC			Vitrinite reflectance			ICP-ES/MS			$\delta^{13}C_{org}$ (+TOC)			Porosity		
	No.	Top	Base	No.	Top	Base	No.	Top	Base	No.	Top	Base	No.	Top	Base
Kotaneelee YT M-17															
Kotaneelee YT P-50															
Merrill YT L-60	27	1024.13	1514.86	1	1136.90	1136.90									
North Beaver River YT I-27	95	963.17	3819.00	42	45.72	3816.80	19	3611.88	3712.46				1	3621.02	3621.02
West Beaver Crow YT O-15															
Whitefish River	94	0.00	254.00	2	0.00	254.00	94	0.00	254.00						
	906			**125**			**370**			**184**			**11**		

blank cells = not sampled

SAMPLES

Outcrop samples were collected from the Whitefish River locality (378293E, 6734735N, UTM zone10) in the summer of 2012 (Fraser *et al.*, 2012), and consisted of homogenized, 2 m intervals of rock chips collected from fresh exposures. Yukon well cuttings were sampled at the GSC-C's core repository during December 2014 and transported to the Yukon Geological Survey in Whitehorse for subsequent preparation (washing, picking and weighing). Cuttings were sampled approximately every third bag (30 ft/9 m) in the wells selected, with every bag (10 ft/3 m) sampled in Kotaneelee YT I-48 from top Banff Formation into the Nahanni Formation (Table 1). Cuttings were also sampled every 500 ft (156 m) over the entire penetrated stratigraphy in North Beaver River YT I-27 to build a complete thermal maturation profile for this well based on vitrinite reflectance analysis. Six further cuttings samples and five core plug samples were collected for mercury porosimetry and helium stress porosity analyses respectively (Table 1).

The bulk of outcrop and cuttings samples were sent to Bureau Veritas Laboratories Ltd. (BVL; formerly Acme Analytical Laboratories Ltd.) in Whitehorse and then to Vancouver to be crushed. The resultant pulps were riffle-split, with half remaining with BVL in Vancouver for lithogeochemical analysis, and half shipped to the Geological Survey of Canada in Calgary's (GSC-C) Organic Petrology Laboratory for Rock-Eval/TOC analysis. Vitrinite reflectance and porosity samples were sent directly to the GSC-C and Trican Geological Solutions Ltd. in Calgary respectively.

WIRELINE DATA

Digital wireline data were available for 10 of the 13 Yukon wells, with a standard log suite consisting of gamma ray (GR), resistivity (ILD), density/neutron and sonic logs. Existing stratigraphic picks from Fraser and Hogue (2007) were reinterpreted using wireline signatures correlated using outcrop and core (Apache well b-023-K/094-O-05) from the basin in northeastern BC (*e.g.*, Ferri *et al.*, 2011, 2012, 2015). Formation tops in Yukon were picked using wireline logs only, except for the top Patry shale, which was picked based on its distinctive geochemical 'kick' signature (*see* EfMo, EfU, Th, TIP and Zr logs in Fig. 4).

Net pay thicknesses for the Horn River and Exshaw-Patry shales were calculated using cut-off values agreed to by the NEB (2016) project team for resistivity (>10 Ωm) and GR (>100 API), together with visual conditioning of the results where the density log approaches or crosses the neutron porosity log. The net pay connectivity index (see method in Hutchison, 2016) provides an initial indication of how vertically connected pay zones in the reservoir may be, and therefore how heterogeneous the reservoir may be to produce. Net pay indices approaching 1.00 indicate increasing pay homogeneity. Log data were plotted in metres in measured depth (mMD), due to analytical samples being collected in and referenced to measured rather than true vertical depth (TVD), using version 5.1 of ALT's WellCAD® software, and geoSCOUT® software was used to generate equivalent depth and thickness data in mTVD.

GRID DATA

Depth, net pay thickness and TOC grid data for the Horn River and Exshaw-Patry shales (presented in map format in the results section) were provided courtesy of the National Energy Board (M. Johnson, personal communication, 2016). These grid maps use the geographically sparse Yukon well data to generate and condition a tract-by-tract map of these parameters for the entire assessment area (*see* NEB, 2016, for further details on tract sizes) that was then used to calculate marketable resource (for the Exshaw-Patry) in the NEB (2016) resource assessment. As the stratigraphy and resource is basin-wide, these maps also rely on data from BC and the Northwest Territories with which to interpolate areas of missing data in Yukon, such as the far southeast of Yukon's portion of the basin. Results presented in this report refer to actual, known Yukon well data; however, these grid maps should be viewed with the caveat that the gridded data extent used here to illustrate general trends in Yukon will therefore show some differences to actual Yukon data outside of areas with well control.

RESULTS

Reinterpreted wireline log and new cuttings geochemical analyses have facilitated correlation of the Besa River Formation in Yukon's subsurface to more robustly differentiated shales farther to the southeast (Fig. 3), including the Horn River Group (Evie, Otter Park and Muskwa formations), and Fort Simpson, Kotcho (Patry member: *c.f.*, Ferri *et al.*, 2015), Exshaw and Banff formations (*e.g.*, Hutchison, 2016; Hutchison and Fraser, 2016; Ferri *et al.*, 2015; NEB, 2016).

LITHOLOGY & WIRELINE SIGNATURE

The Horn River Group in Yukon is identified based on its tripartite gamma ray signature (Fig. 4) which is also recognized in northeastern BC's subsurface (*e.g.,* well a-067-D in Fig. 3) and in BC outcrop from the Caribou and Stone Mountains (Ferri *et al.*, 2012, their Figure 15). In the Horn River Group, lower radioactivity shales of the Otter Park Formation separate typically higher radioactive shales of the underlying Evie and overlying Muskwa formations. In the latter two formations, GR logs often experience scale 'wrap-round' (*i.e.*, log values greater than 150 API), and this is seen in the upper Muskwa Formation in Kotaneelee YT I-48 in Figure 4, and in all wells with penetrated Horn River Group in Figure 3.

The Fort Simpson Formation is divided into three informal members (lower, middle and upper) in Yukon, and the formation potentially correlates into the Tetcho-Redknife platform carbonate stratigraphy observed in the Horn River basin and on the platform to the east (*see* Fig. 3). Two informal members of the Exshaw Formation were recognized, the wireline characters of which correlate robustly with the upper and lower Exshaw markers of Ferri *et al.* (2015). Two members were also observed in the Banff Formation: a lower, thin carbonate-predominant unit (possibly equivalent to one of the Banff Formation Member B mixed carbonate/siliclastic units that overly the Exshaw Formation in southwestern Northwest Territories' subsurface; Richards *et al.*, 1994); and an upper, thick, shale-dominated unit equivalent to Member A of the same region (Richards *et al.*, 1994).

Lithological cyclicity was observed in cuttings logs within the overall succession (Fig. 4), with units alternating between dark grey to black, pyritic chert and siliceous shale (Horn River Group, middle Fort Simpson and Patry-lower Exshaw intervals), and brown to light grey dolomitic shales (lower and upper Fort Simpson, upper Exshaw and Banff shale intervals). Units of black pyritic chert are characterized by high GR, higher resistivity, overlapping or narrowly-separated density/neutron, and slower sonic log signatures. Intervals of dolomitic shale typically display the opposite response, exhibiting a distinctive, wide density/neutron separation (especially in the lower and upper Fort Simpson Formation) that greatly facilitated correlation of the overall stratigraphic succession between wells.

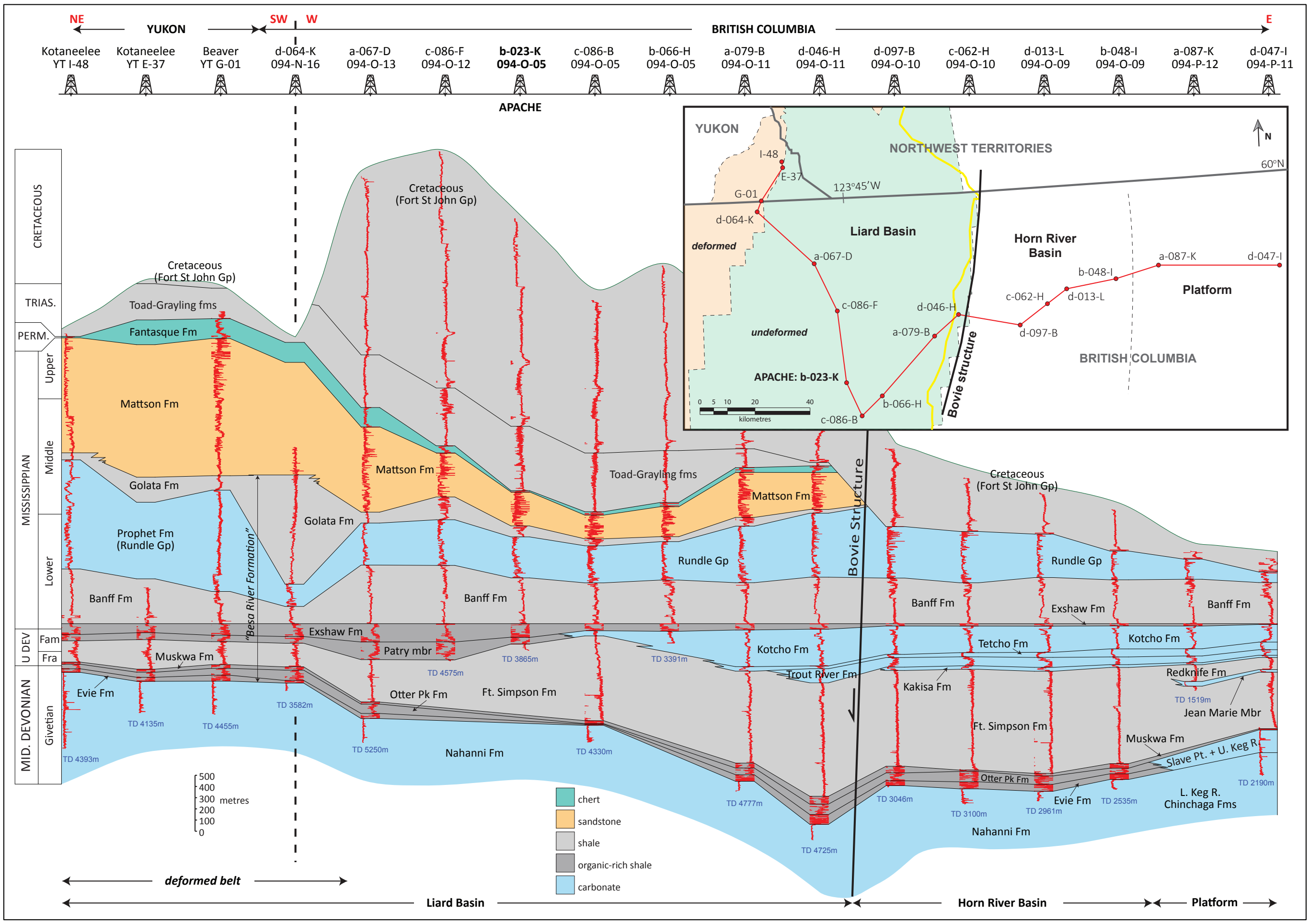
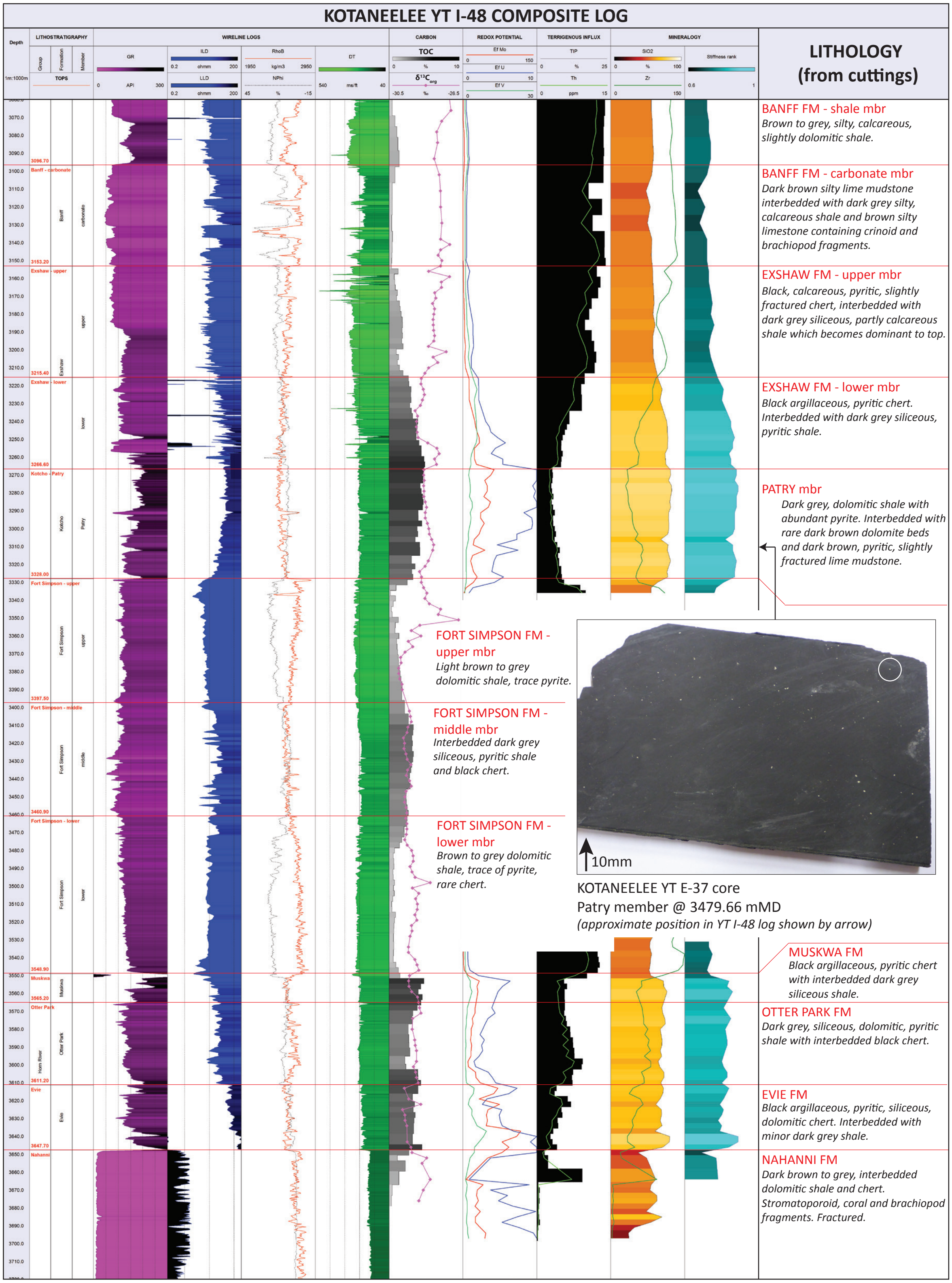


Figure 3. *Stratigraphic relationships of the Middle Devonian to Mississippian carbonate platform to shale basin succession in the northwestern WCSB. Inset map shows east to west correlation section. Note location of Apache's Patry well b-023-K in BC (referred to in text). The section datum is hung the top Exshaw Formation. Gamma ray logs are shown in red, with a log scale of 0-150 API (increasing to right). After Ferri et al. (2015).*

In core from Kotaneelee YT E-37, the Patry shale is black, siliceous, lacks sedimentary structure and exhibits disseminated pyrite blebs and rare pyritized radiolaria visible in hand specimen (Fig. 4). However, in cuttings logs the shale is also locally dolomitic, and is interbedded with rare dolostone beds (ranging from 1.4-4.7 mTVD in thickness) and 'marlstone'. Also of note is that the Otter Park Formation exhibits lithological and petrophysical characteristics more similar to those of the under and overlying Evie and Muskwa formations (Fig. 4), despite it typically being characterized in BC in the Liard and Horn River basins as calcareous (e.g., Johnson and Johnson, 2012) and clay-rich (e.g., Ayranci *et al.*, 2015; Harris *et al.*, 2017).

AREA, DEPTH & NET PAY THICKNESS

Prospective Horn River and Exshaw-Patry shale reservoirs were only assessed in the southeastern corner of the basin where structural deformation due to Cordilleran thrusting is anticipated to be of relatively minimal expression in the basin (*see* Fig. 2). The overall assessment area (657 km^2) also corresponds to the limit of Cretaceous Fort St John Group outcrop in the basin (Fig. 2). This was considered by the NEB (2016) project team to provide the minimum overburden thickness to generate sufficient Devonian-Carboniferous reservoir pressures at depth in Yukon and BC.



BANFF FM - shale mbr
Brown to grey, silty, calcareous, slightly dolomitic shale.

BANFF FM - carbonate mbr
Dark brown silty lime mudstone interbedded with dark grey silty, calcareous shale and brown silty limestone containing crinoid and brachiopod fragments.

EXSHAW FM - upper mbr
Black, calcareous, pyritic, slightly fractured chert, interbedded with dark grey siliceous, partly calcareous shale which becomes dominant to top.

EXSHAW FM - lower mbr
Black argillaceous, pyritic chert. Interbedded with dark grey siliceous, pyritic shale.

PATRY mbr
Dark grey, dolomitic shale with abundant pyrite. Interbedded with rare dark brown dolomite beds and dark brown, pyritic, slightly fractured lime mudstone.

FORT SIMPSON FM - upper mbr
Light brown to grey dolomitic shale, trace pyrite.

FORT SIMPSON FM - middle mbr
Interbedded dark grey siliceous, pyritic shale and black chert.

FORT SIMPSON FM - lower mbr
Brown to grey dolomitic shale, trace of pyrite, rare chert.

KOTANEELEE YT E-37 core
Patry member @ 3479.66 mMD
(approximate position in YT I-48 log shown by arrow)

MUSKWA FM
Black argillaceous, pyritic chert with interbedded dark grey siliceous shale.

OTTER PARK FM
Dark grey, siliceous, dolomitic, pyritic shale with interbedded black chert.

EVIE FM
Black argillaceous, pyritic, siliceous, dolomitic chert. Interbedded with minor dark grey shale.

NAHANNI FM
Dark brown to grey, interbedded dolomitic shale and chert. Stromatoporoid, coral and brachiopod fragments. Fractured.

Figure 4. *Composite wireline, geochemistry and cuttings-based lithology log for the Kotaneelee YT I-48 well. The core photo is from an equivalent Patry member section in Kotaneelee YT E-37 (the white blebs are pyrite, sometimes pyritised radiolaria - circled). Depths are plotted in mMD, of which a full log suite is presented in this figure for completeness (see Hutchison, 2016, for data and methodology: Ef=enrichment factor, TIP=terrigenous input profile).*

The depth to the top Horn River Group ranges from 1273.3 mTVD (Beavercrow YT K-02) to 4208.9 mTVD (Kotaneelee YT P-50), and averages 3017.9 mTVD (Fig. 5; Table 2). Burial depths decrease towards the north and west in association with the transition from undeformed to uplifted/deformed zones within the basin (Fig. 6a). Average gross play thicknesses range from 88.5-161.4 m, and net pay thickness typically increases with depth towards the southeast of the basin (Fig. 6b) where comparable Horn River shale thicknesses occur in BC wells d-064-K and a-067-D (*see* Fig. 3). The Otter Park Formation is the thickest constituent shale of this play (102.4 m in Kotaneelee YT L-38A) and averages 55.1 m across the basin. The formation therefore exhibits the maximum net pay thickness (45.7 m) and thickest average net pay interval (30.1 m) of the Horn River Group.

The Exshaw-Patry shale is shallower and thicker than the Horn River shale, with depths to the top of the Exshaw Formation ranging from 980.5 mTVD (Beavercrow YT K-02) to 4012.7 mTVD (Kotaneelee YT P-50) and averaging 2687.9 mTVD (Fig. 5; Table 2). The play averages 127.1 mTVD in total thickness, with the greatest thicknesses occurring in the southeast of the basin adjacent to the BC border (*e.g.*, 178.7 mTVD in Beaver YT G-01). As in the Horn River Group, burial depths (Fig. 6c) and gross and net pay thicknesses (Fig. 6d) decrease towards the northwest of the basin, and the shales start to outcrop substantially west of 124° 50′ W (Fallas *et al.*, 2014; *see* Fig. 2). Both the Patry member and the Exshaw Formation exhibit net pay thicknesses exceeding 40 m (Table 2), and combined play net pay thicknesses average 88.74 m (ranging from 46.2 m in North Beaver River YT I-27 to 116.8 m where the unit is thickest in Beaver YT G-01).

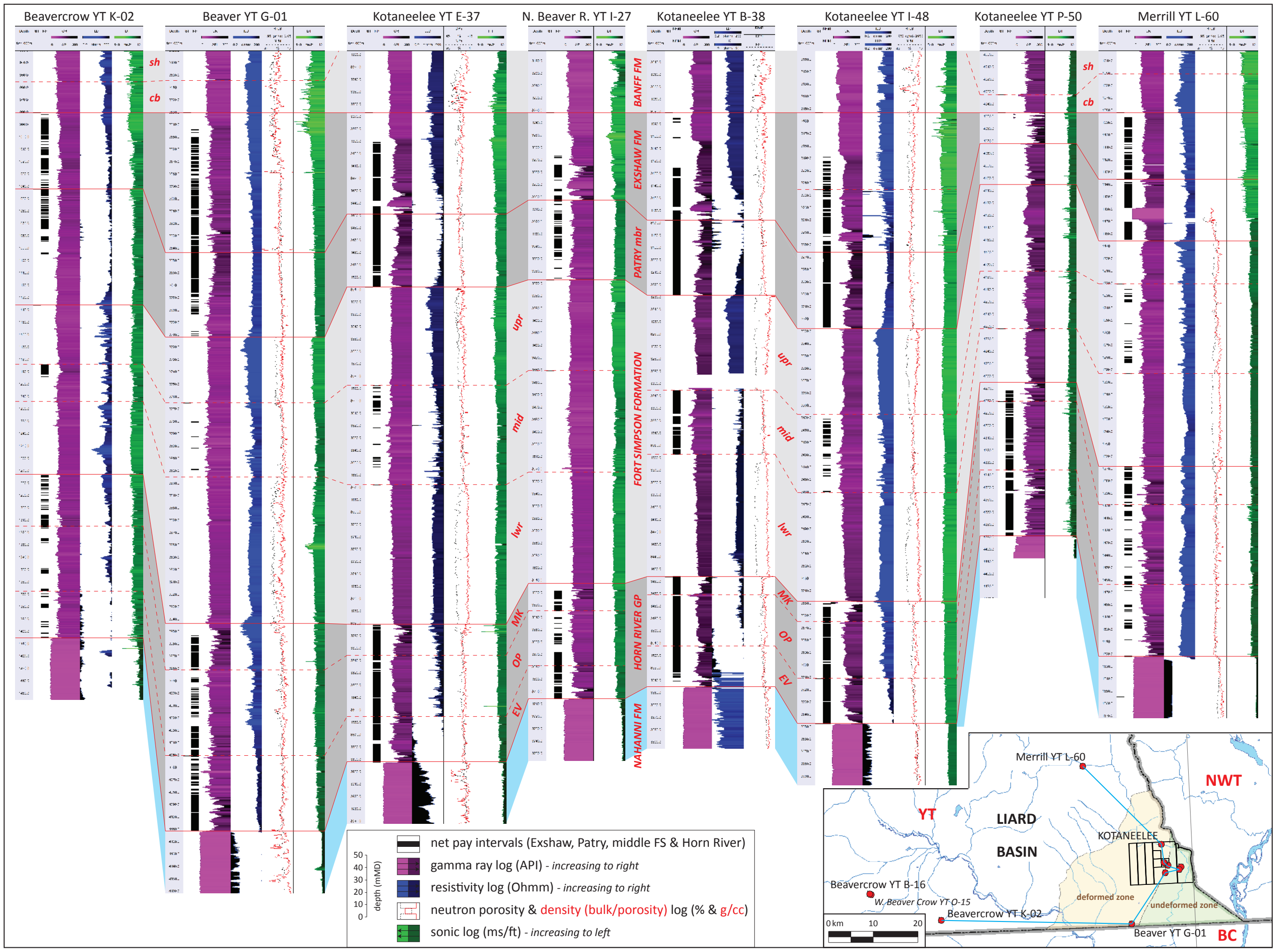


Figure 5. *Wireline log correlation panel across Yukon's Liard basin. Horizontal datum is the top of the Exshaw Formation and data extend 50 m into the Banff and Nahanni formations. The Exshaw-Patry and Horn River shale correlation is shaded in dark grey. Abbreviations: middle FS – middle member of the Fort Simpson Formation; EV – Evie Formation; OP – Otter Park Formation; MK – Muskwa Formation.*

Table 2. *Horn River and Exshaw-Patry shale play characteristics in Yukon's Liard basin. Note that upper values are averages and lower italicized values in parentheses are ranges. Also note that mineralogical data, except stiffness rank, are presented as ternary diagram proportional percentages (for actual concentration data refer to Hutchison, 2016).*

		Evie	Otter Park	Muskwa	HORN RIVER	Patry	Exshaw	EXSHAW-PATRY
Depth (mTVD)		3097.92 *(1368 - 4273)*	3042.83 *(1315 - 4223)*	3017.88 *(1273 - 4209)*	3017.88 *(1273 - 4209)*	2760.02 *(1042 - 4035)*	2687.91 *(981 - 4013)*	2687.91 *(981 - 4013)*
Thickness (mTVD)		41.05 *(26.70 - 58.40)*	55.09 *(34.90 - 102.38)*	24.95 *(13.70 - 42.00)*	121.08 *(88.50 - 161.40)*	57.95 *(29.80 - 93.90)*	69.19 *(22.50 - 112.80)*	127.14 *(52.30 - 178.70)*
Net pay (mTVD)		25.04 *(8.55 - 41.73)*	30.11 *(9.45 - 45.71)*	17.90 *(6.72 - 25.95)*	73.29 *(41.25 - 102.10)*	43.48 *(28.95 - 60.45)*	45.05 *(17.10 - 74.30)*	88.74 *(46.20 - 116.77)*
Net pay connectivity (%)		0.88	0.87	0.91	0.90	0.92	0.91	0.92
TOC (wt%)		3.00 *(0.85 - 6.06)*	2.64 *(0.60 - 4.84)*	2.59 *(0.69 - 4.75)*	2.75 *(0.60 - 6.06)*	4.10 *(2.16 - 6.86)*	3.60 *(1.04 - 6.05)*	3.86 *(1.04 - 6.86)*
Maturity (%Ro)		3.44 *(3.01 - 4.18)*	3.36 *(2.52 - 4.20)*	3.62 *(2.69 - 4.60)*	3.48 *(2.52 - 4.60)*	2.88 *(2.16 - 3.91)*	2.78 *(2.09 - 3.50)*	2.84 *(2.09 - 3.91)*
Mineralogy	**SiO_2 (%)**	82.3 *(66.9 - 91.0)* biogenic	82.5 *(72.0 - 92.0)* biogenic	80.2 *(70.0 - 91.3)* biogenic	81.9 *(66.9 - 92.0)* biogenic	90.3 *(81.9 - 97.1)* biogenic	85.3 *(69.5 - 96.8)* biogenic	87.8 *(69.5 - 97.1)* biogenic
	CaO+MgO (%)	8.4 *(2.6 - 21.4)*	4.8 *(1.5 - 8.4)*	5.3 *(1.4 - 12.0)*	6.3 *(1.4 - 21.4)*	2.8 *(0.2 - 12.1)*	3.1 *(0.2 - 8.7)*	2.9 *(0.2 - 12.1)*
	Al_2O_3 (%)	8.8 *(4.0 - 22.3)*	12.8 *(6.5 - 22.7)*	14.5 *(7.2 - 21.4)*	11.8 *(4.0 - 22.7)*	6.9 *(2.7 - 13.5)*	11.7 *(3.0 - 24.3)*	9.3 *(2.7 - 24.3)*
	Stiffness rank	0.81	0.81	0.80	0.81	0.87	0.83	0.85
Porosity (%)		0.98 *(0.12 - 1.71)*	1.93 -	1.66 *(1.39 - 1.94)*	1.21 *(0.12 - 1.94)*	4.43 *(2.99 - 6.04)*	3.23 *(2.86 - 3.59)*	4.21 *(2.86 - 6.04)*

Net pay zones (delineated on Fig. 5 by black strip log bars) are thick and continuous in the Kotaneelee field and in Beaver YT G-01 along strike to the south, exhibiting very high reservoir homogeneity (*e.g.*, 0.98 in the Exshaw-Patry shale in Kotaneelee YT B-38). Net pay strip logs that display as thin, discontinuous bars correspond to relatively high heterogeneity, for example in the Horn River Group of Merrill YT L-60 (0.78) or Beavercrow YT K-02 (0.75). On average, net pay connectivity indices are greater than 0.87 in both plays.

TOTAL ORGANIC CARBON

TOC values in Horn River Group shales range between 0.6-6.1 wt% (Table 2). Average TOC values decrease up-section in this play, with the highest recorded in the Evie Formation (3.0 wt%) and lowest in the Muskwa Formation (2.6 wt%). In general, the average TOC for Horn River Group per well increases to the northwest (Fig. 7a) from 1.7 wt% in North Beaver River YT I-27 to 3.9 wt% in Merrill YT L-60. TOC concentrations in the Exshaw-Patry shale play exhibit a similar range (1.0-6.9 wt%), however both shales within this play exhibit higher average TOCs than any of the Horn River Group formations, with the highest average (4.1 wt%) and maximum concentration recorded in the Patry shale. In contrast to the older Horn River Group, TOC values in the Exshaw-Patry shale play decrease from east to west in the basin (Fig. 7b).

Wireline logs from both plays indicate that intervals of elevated TOC typically exhibit high gamma ray (>100 API). Hydrocarbon presence is also suggested in these intervals by higher than background resistivity (>10 Ωm) values and a density curve that approaches or crosses the neutron curve on a RhoB or DPhi/NPhi log (Fig. 3). Cross-plots of TOC vs. S1 + S2 used to interpret conventional source rocks indicate that Yukon shales in Liard basin are of good quality (*i.e.*, TOC greater than 2 wt%: Peters and Cassa 1994) but low generative potential (Fig. 8). Unconventional reservoir potential is also supported in these shales with most TOC values greater than 2 wt% (Zou, 2013). Spatial relationships in organic matter quality are cryptic in Liard; however, shales from Kotaneelee YT I-48, Beaver YT G-01 and Merrill YT L-60 appear to consistently plot closest to or

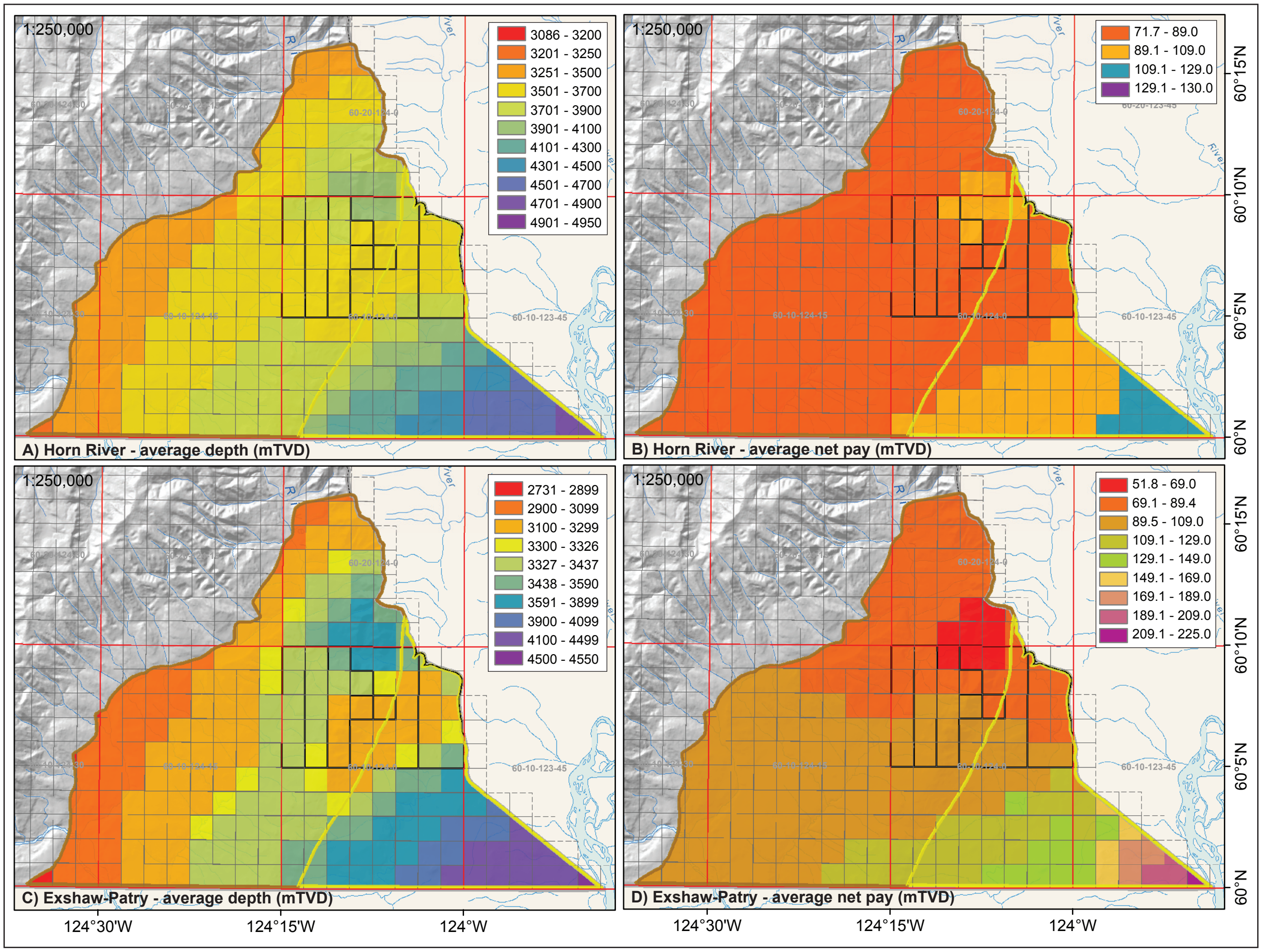


Figure 6. Gridded, tract-by-tract data (in mTVD) for Yukon's portion of Liard basin (see text and NEB, 2016, for discussion of tract sizes and grid methods). ***(A)*** Average depth to top Horn River Group. ***(B)*** Average net pay thickness of the Horn River Group. ***(C)*** Average depth to top Exshaw-Patry shale. ***(D)*** Average net pay thickness of the Exshaw-Patry shale. See Figure 12 for map legend.

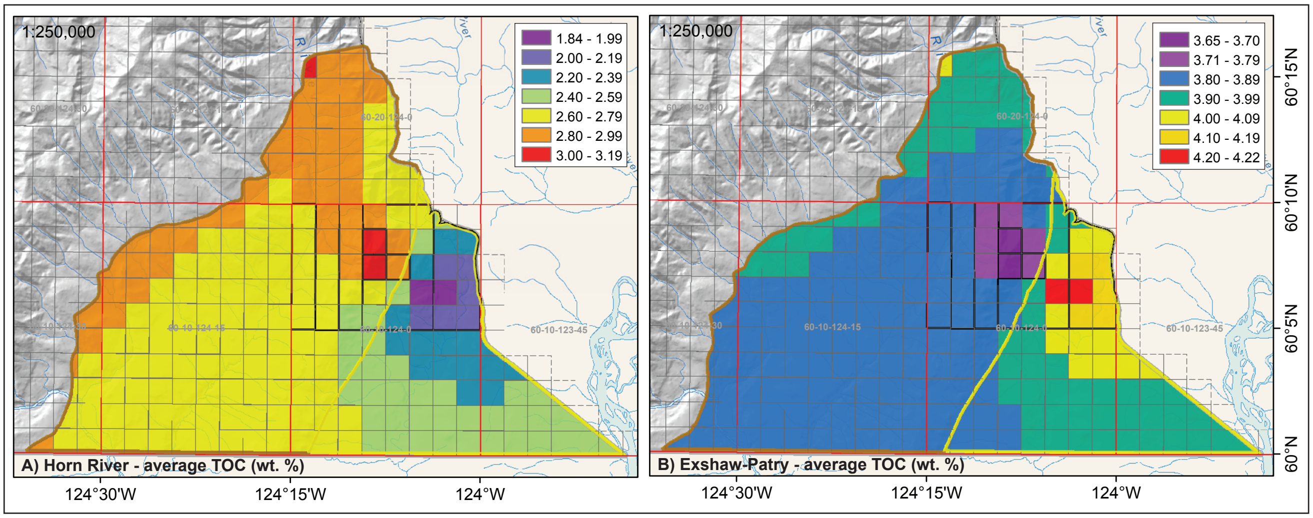


Figure 7. Gridded, tract-by-tract TOC data (in wt%) for Yukon's portion of Liard basin (see text and NEB, 2016, for discussion of tract sizes and grid methods). ***(A)*** Average Horn River Group TOC. ***(B)*** Average Exshaw-Patry shale TOC. See Figure 12 for map legend.

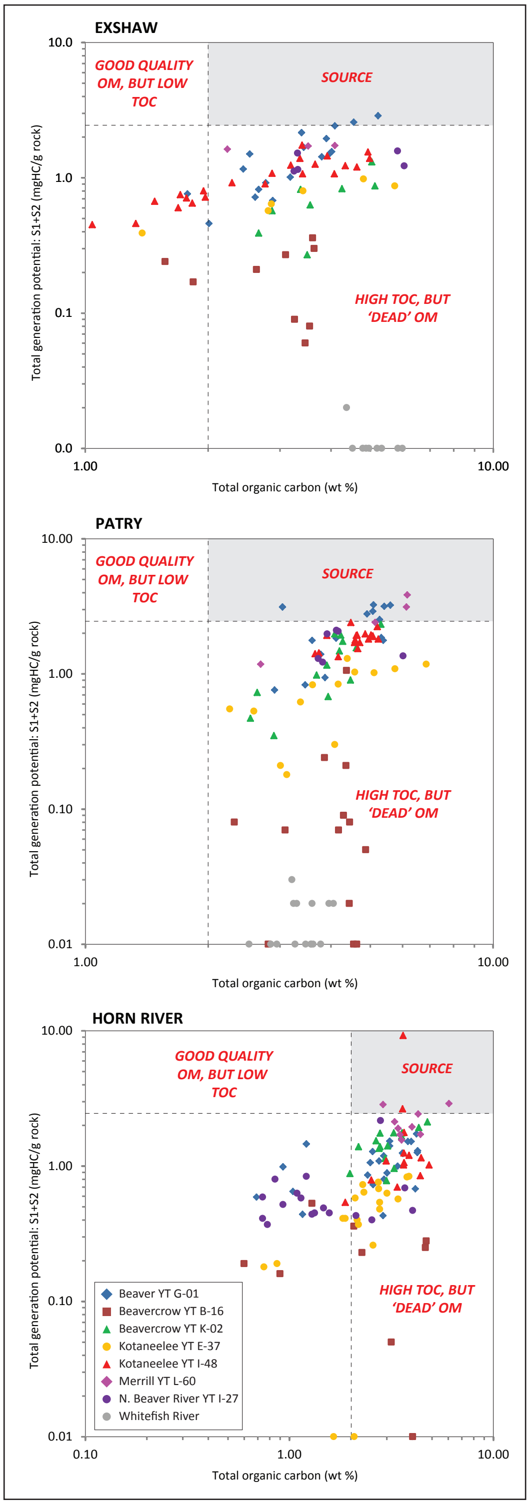


Figure 8. *Organic richness (TOC content) and total generative potential of the Exshaw, Patry and Horn River shales. The TOC lower boundary is here set at 2 wt% to represent good conventional source rock quality (c.f., Peters and Cassa, 1994) and potential unconventional reservoir quality (c.f., Zou, 2013).*

within the source window. Yukon basin data obtained from Beavercrow YT B-16 and the Whitefish River outcrop display very low to zero total generative potential despite elevated TOC values. The Patry shale exhibits the best overall quality relative to the overlying Exshaw Formation or older Horn River Group shales.

VITRINITE REFLECTANCE

Maturity profiles generated from vitrinite reflectance data support the low S1 and S2 values obtained from RockEval analysis, with both shale plays being highly mature and well within or past the dry gas window (based on a dry gas preservation limit of 3.0 %$R_{o;}$ Dow, 1977) (Fig. 9; Table 2). Within each shale play, the Otter Park and Exshaw formations are the least mature (3.36 %R_o and 2.78 %R_o respectively), with maturity typically increasing towards the south of the basin in the Horn River shale and to the north in the Exshaw-Patry shale. Overall, maturity values for individual shales within these plays do not vary significantly from the overall play mean (Horn River = 3.48 %R_o, Exshaw-Patry = 2.84 %R_o).

MINERALOGY AND GEOCHEMISTRY

All Horn River Group and Exshaw-Patry shales are silica-rich (Table 2), with average SiO_2 concentrations between 80.2% (Muskwa Formation) to 90.3% (Patry shale) when plotted proportionally on SiO_2-Al_2O_3-(CaO + MgO) ternary diagrams (Fig. 10a,b). Overall, a dominance of biogenic silica (as opposed to detritally-derived silica) is indicated by the shallow, negative SiO_2-Zr correlation trend (e.g., Fraser and Hutchison, 2017; Blood *et al.*, 2013; Wright *et al.*, 2010; Fig. 10c). Carbonate content is low, even in the Otter Park Formation, and average CaO + MgO proportions range from 2.8% in the Patry shale to 8.4% in the Evie Formation (Table 2). Al_2O_3 (used as a proxy for clay) proportions range up to 24.3% in the Exshaw Formation, with values consistently greater than 10% in the Otter Park, Muskwa and Exshaw formations.

The high SiO_2 and very low Al_2O_3 composition of these shales indicates a high fraction of stiff minerals (high Young's Modulus and low Poisson's Ratio) that comprise the matrix volume of the rock (Figs. 4 and 10d). The very high overall fraction of stiff minerals corresponds well to the black, siliceous lithology of these prospective shale plays. Average shale stiffness mirrors average shale silica trends, with the Muskwa Formation being the least stiff (0.80) and the Patry shale the most (0.87). The moderate positive correlation (R^2 = 0.33) that exists between stiffness

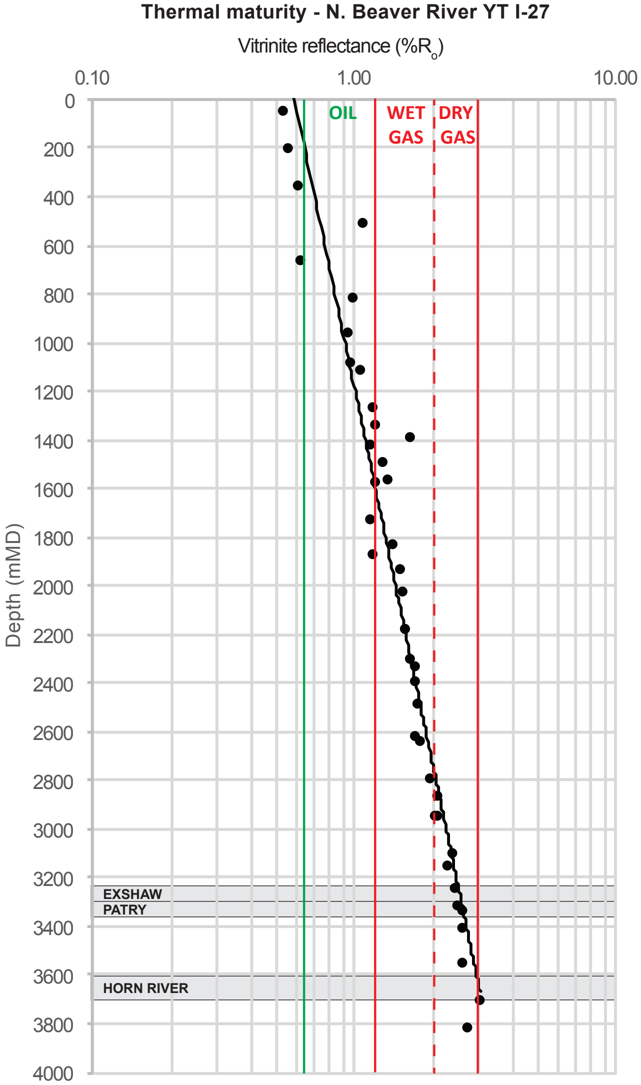


Figure 9. *Vitrinite reflectance maturity profile for North Beaver River YT I-27 in Yukon's Liard basin. Both shale plays of interest plot within the dry gas generation zone (R_o >1.35: Peters and Cassa, 1994) but below the wet gas floor (R_o >2.0: Dow, 1997).*

rank and TOC initially suggests zones of elevated TOC (and therefore enhanced unconventional reservoir quality) will respond well to artificial stimulation during production. Intra-play mineralogical stiffness is more variable in the Exshaw-Patry shale (0.73-0.95) than in the Horn River Group (0.70-0.89), and stiffness and TOC visually covary within these shale units (*see* Fig. 4).

POROSITY

Cuttings samples have a corrected porosity range from 1.4 to 3.6% with the highest porosity in the Exshaw Formation, and an overall average porosity of 2.2% (*see* Hutchison, 2016, for methodology). Pore size for the entire sample set ranged from <3 to 1900 nm, with peak pore sizes between 3 and 38 nm. Pore size distribution is similar for the two Exshaw samples and the two Muskwa samples, and the Exshaw samples exhibited the greatest intrusion. A strong correlation exists between depth and cuttings porosity (R^2=0.81), and initial data suggest that intra-shale porosity decreases with increasing depth (Fig. 11a).

Plugs from the Evie Formation had lower stressed helium porosity values throughout the testing (average 0.9%) relative to the Patry shale (4.4%) in Kotaneelee YT E-37. The three Patry plugs show a general trend of decreasing pore compressibility as depth increases (Fig. 11b), with porosity reductions between low and high confining pressure conditions approximately 40% for samples T1 and T2 but only 8% for the deepest T3 sample. Pore compressibility was higher in the deeper Evie Formation plugs, with significant differences observed between the two samples (T4=44%, T5=93%).

DISCUSSION

YUKON RESERVOIR POTENTIAL

Reservoir net pay continuity between individual shale stratigraphic units in the Horn River Group, and between the Exshaw Formation and Patry member confirms that the basin's potential is best illustrated by combining these units into two 'productive' shale plays – the Horn River shale (Evie, Otter Park and Muskwa formations) and the Exshaw-Patry shale (*e.g.,* Table 2). However, the stratigraphic breakdown of these plays into their constituent units in this study (as opposed to the higher-level assessment by the NEB in 2016) has also resulted in a more precise resolution of 'sweet spot' reservoir intervals for targeting during initial exploration.

Within the Horn River play in Yukon, the available data suggest the Otter Park Formation exhibits the best unconventional gas reservoir potential (Table 2), with average net pay thicknesses in excess of 30 m, TOC contents ranging from 0.6 to 4.8 wt%, and porosities approaching 2%. In Yukon, the Otter Park Formation exhibits lithological and petrophysical characteristics more like those of the prospective under and overlying Evie and

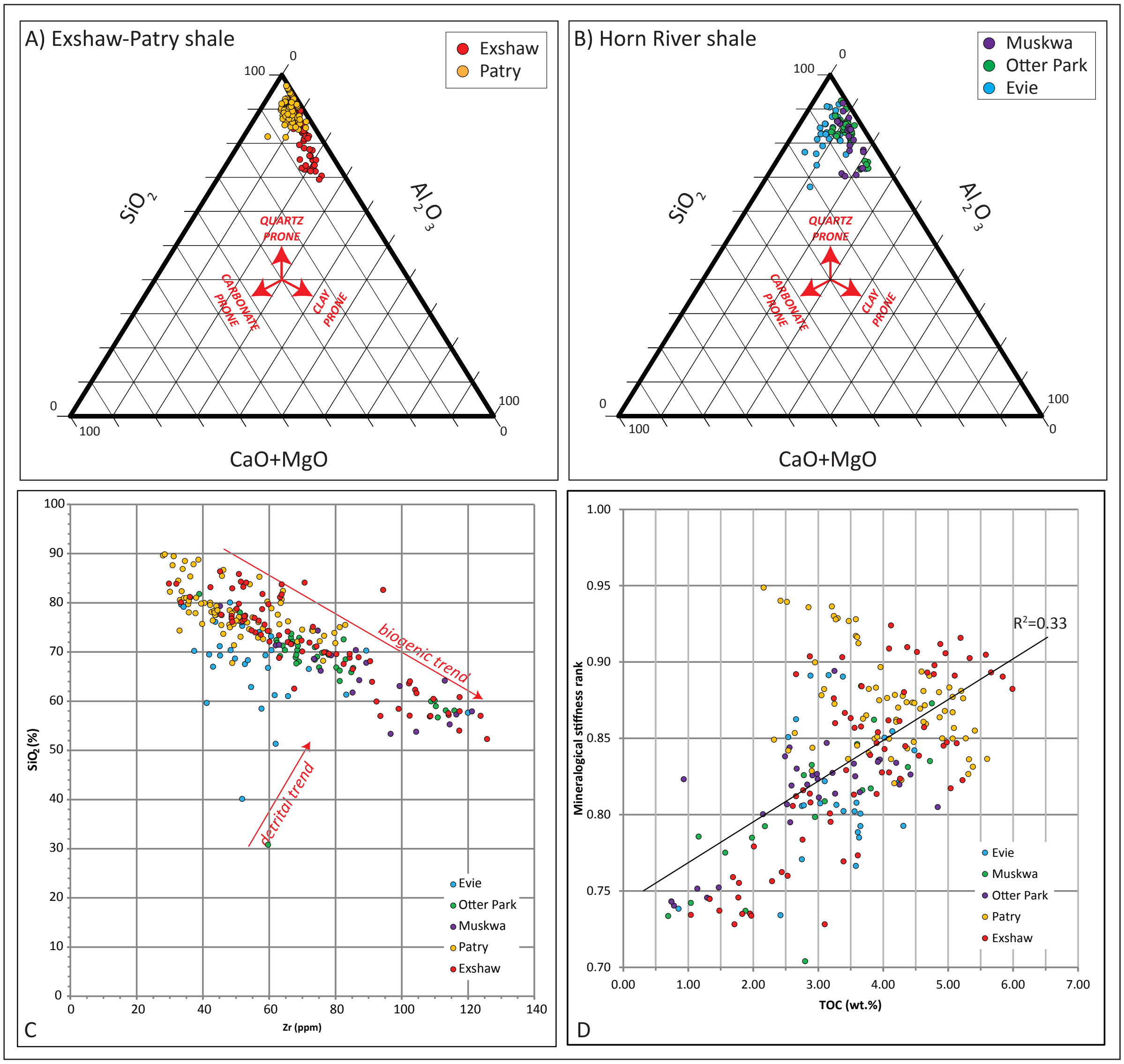


***Figure 10. (A and B** Shale proxy-mineralogical ternary diagrams for the Exshaw-Patry and Horn River plays respectively. **(C)** The silica is biogenic in origin as shown by the inverse correlation between SiO_2 and Zr. **(D)** Correlation between TOC and stiffness rank.*

Muskwa formations; differing markedly to those made from the same formation towards the southeast of Liard basin and in the Horn River basin. In these locations in BC, the Otter Park consists of calcareous to clay-rich sediments with relatively low TOC (2.2 wt%; Ayranci *et al.*, 2015) that were deposited within transitional to oxygenated shallow water environments adjacent to the Slave Point and Upper Keg River Formation shelf-break and platform carbonates (e.g., Johnson and Johnson, 2012).

In Yukon, deeper, more distal depositional environments, as suggested by darker black colouration, higher TOC, biogenic silica and pyrite content and low carbonate, highlight the potential for noticeable lateral facies variability in the Horn River play (c.f., Ayranci *et al.*, 2015), with reservoir properties ultimately controlled by water depth, oxygenation, sediment input and proximity to basin margin (e.g., Bohacs *et al.*, 2005). Whilst a detailed lithogeochemical appraisal is beyond the scope of this initial report, redox-sensitive trace elemental data were collected for some of the wells included in this study (*see* Fig. 4) that could be used in future to investigate such depositional controls in Yukon and supplement similar redox studies conducted on this stratigraphy in BC (e.g., Harris *et al.*, 2017). Furthermore, these results

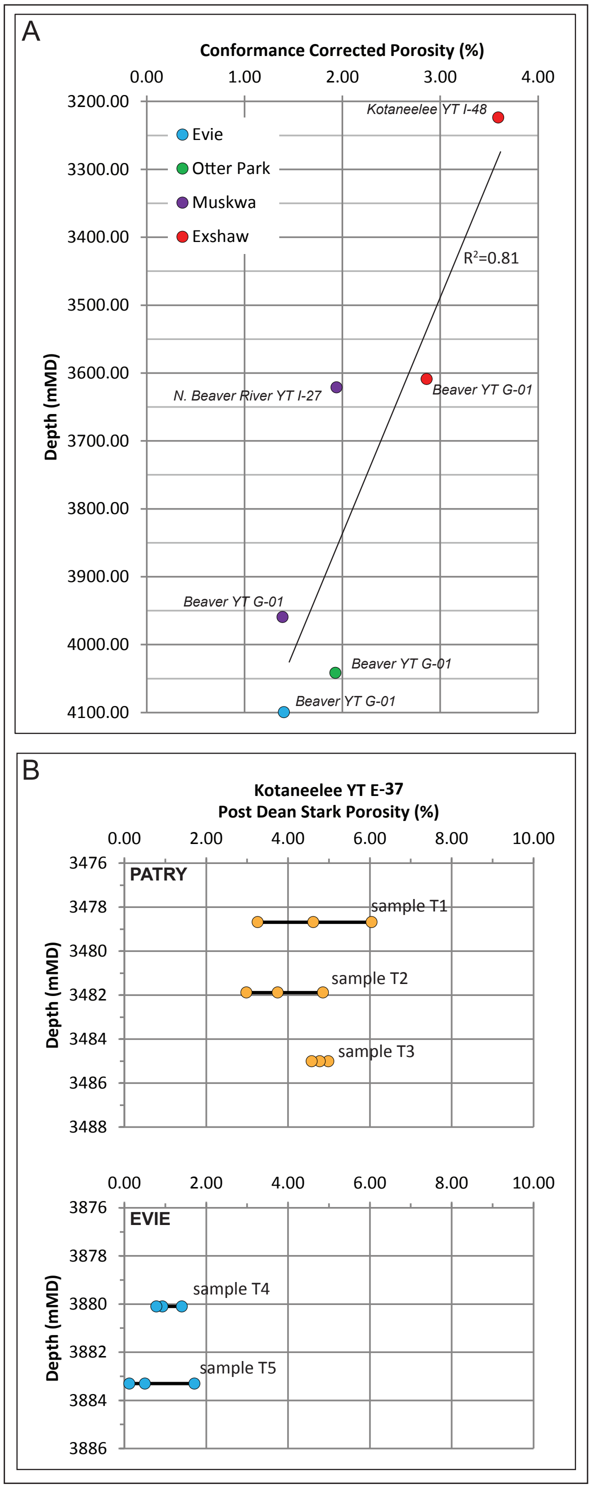


Figure 11. ***(A)*** *Porosity measured from MICP analysis on cuttings, and* ***(B)*** *from stressed helium analysis on core from the Evie and Patry shales in Kotaneelee YT E-37.*

suggest initial caution is required in extrapolating analogous reservoir properties for the Horn River play from areas of relatively dense well-control into the more frontier, deeper-water basin. The key for unlocking the accurate potential of Yukon's Liard will stem only from future exploration in the territory, especially due to the significant depth challenges of accessing this play in BC (Johnson *et al.*, 2016).

In the Exshaw-Patry play, the upper part of the Patry member and the lower member of the Exshaw Formation offer the best reservoir potential for gas; with reservoir quality deteriorating up-section into the upper Exshaw Formation (Fig. 4). The Patry member exhibits average net pay thicknesses of 43.5 m, in addition to the highest average net pay connectivity, TOC content, silica versus clay and carbonate proportion, mineralogical stiffness and porosity of the study (Table 2), and offers the best potential for significant gas volumes within the combined Exshaw-Patry play. Hydrocarbon presence is also suggested in these intervals in Yukon by higher than background resistivity (>10 Ωm) values and a density curve that typically crosses the neutron curve on a RhoB or DPhi/NPhi log plot (*see* Fig. 4).

These observations compare favorably to the cored Exshaw-Patry interval in BC well b-023-K, where Ferri *et al.* (2015) document the highest TOC (~8 wt%), porosity (~9%) and gas saturation (~80%) associated with resistivities ranging between 20 and 60 Ωm across the middle to upper Patry shale. In particular, Patry shale porosities are comparable to those obtained from this interval in the Apache Patry b-023-K well in northeastern BC where they average 4-9% (Ferri *et al.*, 2015). The Patry b-023-K well also displays the same trend as Yukon for decreasing porosity with depth, in which samples from the principal gas-prone zone in the middle to upper Patry shale (9%) yield higher porosities than those towards the base of the unit (4-6% in BC, 4.4% average in Yukon).

There are significant volumes of gas to be found in these frontier Yukon plays - recently illustrated by the NEB (2016) assessment of the Exshaw-Patry shale play of the entire Liard basin as the ninth largest unconventional marketable gas resource in the world, and the second largest in Canada. The NEB (2016) unconventional resource assessment indicates a total expected gas in place volume of 68 Tcf (47 Tcf from the Exshaw-Patry shale and 21 Tcf from the Horn River). Using an expected recovery factor of approximately 17% in Yukon, the

NEB (2016) calculates dry expected ultimate P50 recoveries of 7.6 Tcf from the Exshaw-Patry shale in Yukon's portion of the basin (the Horn River marketable gas was not calculated in this assessment). The entire basin's total 219 Tcf of marketable gas is estimated to extend Canada's gas supplies for a further 68 years (based on the country's 2014 consumption of 3.2 Tcf – Statistics Canada, 2014), and more significantly for Yukon itself, the 7.6 Tcf from this play alone would deliver approximately 1800 years of the territory's 2014 energy usage (Statistics Canada, 2014).

YUKON'S SHALE RESOURCE DISTRIBUTION

The small GIP and marketable volumes in Yukon relative to the Northwest Territories and British Columbia are due to the small basin area chosen for this jurisdiction for assessment rather than an indication of poor reservoir quality or significant geological or extraction risks in the deformed zone (risks estimated at 10% *vs.* no risk for the undeformed zone; NEB, 2016). The assessed area covers approximately one tenth of the basin's areal extent in Yukon, and although these Middle Devonian-Mississippian plays are typically present across the entire basin, exposure at surface and intense folding and faulting on the Liard Plateau impart significant challenges to exploration and extraction of this gas based on today's technology and economics. Favourable Exshaw-Patry reservoir data from: Merrill YT L-60 (4.28 wt% average TOC, 73.35 mTVD net pay); Beavercrow YT K-02 (3.87 wt% average TOC, 69.30 mTVD net pay); and the Whitefish River outcrop (4.08 wt% average TOC) confirm the play's geological extension west of the currently defined deformed zone in Yukon's Liard basin.

It is important to note, however, that the resource in Yukon is not uniformly spread within the territory (Fig. 12). Exshaw-Patry marketable P50 gas volumes per tract area (3.2 km^2 in

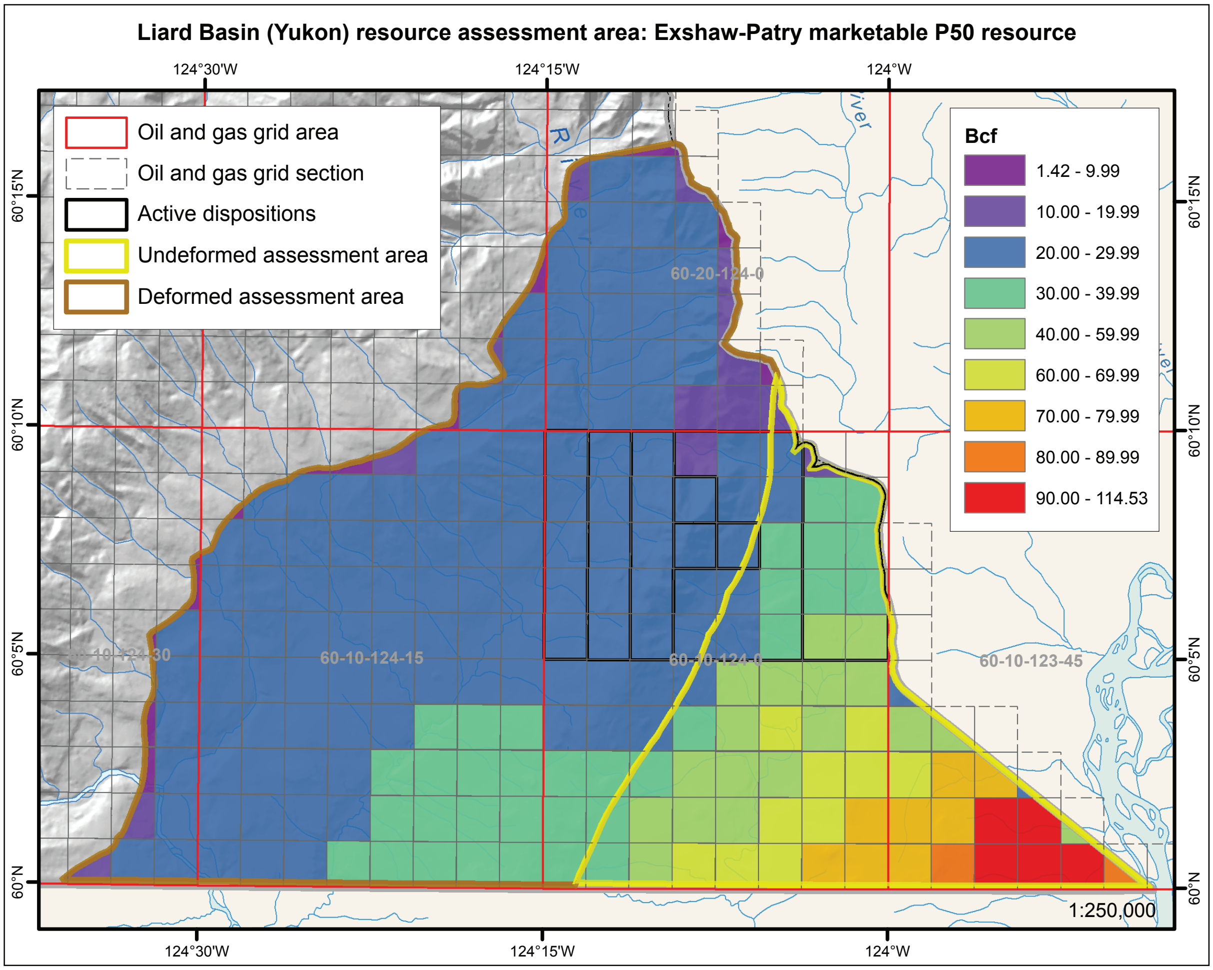


Figure 12. *Gridded, tract-by-tract P50 marketable gas resource for Yukon's portion of Liard basin (see text and NEB, 2016, for discussion of tract sizes and grid methods).*

Yukon) calculated by the NEB (M. Johnson, 2016, personal communication) suggest a relatively flat resource spread until the 70th percentile of tracts (as ranked by Bcf/tract) is reached, at which point the resource volumes start increasing significantly (Fig. 13). In addition, 50% of Yukon's Exshaw-Patry cumulative marketable resource is also reached at approximately the 70th percentile, suggesting that resource percentage occurs in only 30% of the area assessed in Yukon. The Exshaw-Patry reservoir exhibits relatively consistent depths and net pay thicknesses across the deformed zone in Yukon (where well-control exists). However, the NEB (2016) modelled the thickness and depth to increase dramatically towards the southeast of the territory into the core of the basin, with the result that these combined effects increase the reservoir pressure and therefore the volumes of gas able to be stored per assessed tract of land. Apart from this qualitative inference based on overburden pressures increasing with depth, quantitative models predicting regional shale reservoir pore pressure regimes in the basin are not yet able to be built in Yukon using the currently archived historical well or drilling data (*see* Green, 2016). In summary, resource distribution data suggest that the largest potential areal recoveries of marketable gas will be derived from wells spudded in the undeformed zone as close to the BC and NWT borders and the basin's core as possible.

Two further shale gas plays have been identified as secondary exploration targets in Yukon: the interbedded dark grey siliceous shales and black cherts of the middle member of the Fort Simpson Formation (Figs. 3 and 4); and the shale member of the Banff Formation. The middle member of the Fort Simpson exhibits very good TOC contents (averaging 2.59 wt%), and, in Kotaneelee YT B-38 at least, a thick and homogeneous net pay interval (Fig. 5). The Banff Formation's shale member ranges from 100.4 to 504.0 mTVD in thickness across the study area; however, the brown to grey, silty, calcareous lithology and relatively subdued TOC contents (1.39 wt%) initially suggest low reservoir quality. Despite this, significant gas shows were reported during drilling of the Kotaneelee YT L-38 well: gas readings of up to 8074 units over a sustained background of 175 units confirm the potential of this play (Wasylyk, 2005). In summary, these observations suggest that there is the ultimate potential for up to four stacked shale gas plays to be present in the southeast of Yukon's Liard basin.

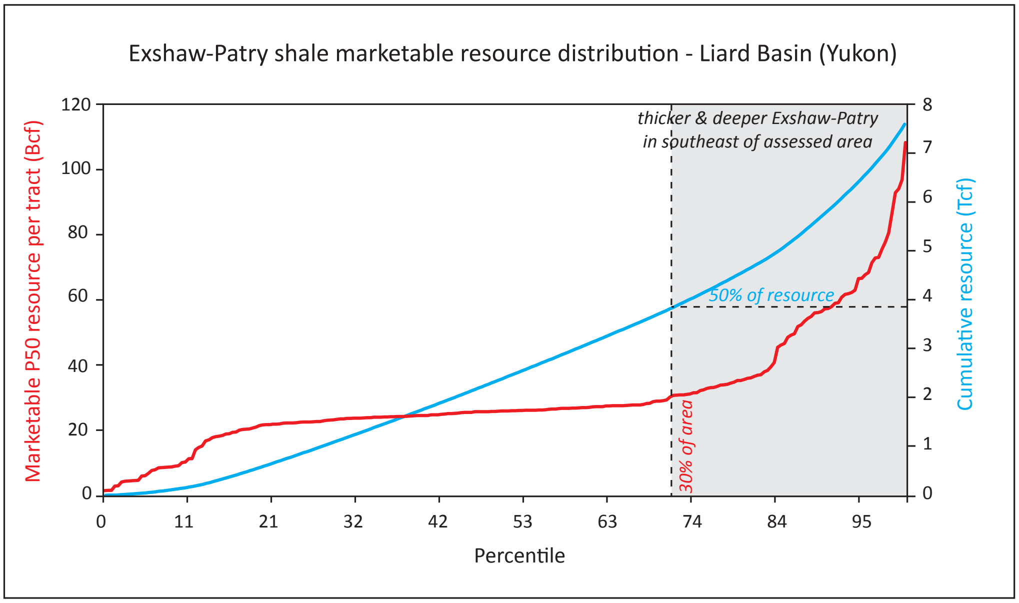


Figure 13. *Exshaw-Patry marketable P50 resource distribution in Yukon's Liard basin (data courtesy of the National Energy Board = M. Johnson, personal communication, 2016).*

CONCLUSION

Organic-rich Upper Devonian-Mississippian black shale formations are one of the most prospective unconventional exploration targets in the Western Canada Sedimentary basin. With an assessed GIP of 68 Tcf and 7.6 Tcf of marketable gas, this paper reports the first shale gas appraisal of these strata in Yukon's Liard basin (and the appraisal in the territory itself). Wireline log reinterpretation has resolved the previously undifferentiated Besa River Formation shales into four potentially stacked shale plays, with the best prospectivity in Yukon occurring in the Horn River shale play (Otter Park Formation) and upper Patry/lower Exshaw units of the Exshaw-Patry shale play. Resource distribution assessments estimate approximately 50% of Yukon's Exshaw-Patry cumulative marketable resource in 30% of its area, with the best potential for significant volumes located in the southeast of the territory's undeformed zone where play burial depths and thicknesses increase towards the basin's depocentre.

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REFERENCES

Adams, C., Janicki, E. and Balogun, A., 2015. British Columbia Oil & Gas Industry Activity Report 2014. British Columbia Ministry of Natural Gas Development, Oil and Gas Geoscience Reports, 2015, p. 1-39.

Ayranci, K., Dong, T. and Harris, N., 2015. Paleoenvironmental interpretations and sequence stratigraphy of the Horn River Group, British Columbia, Canada. Presented at the 2015 Gussow Conference, http://www.cspg.org/cspg/documents/Conference%20Website/Gussow/2015/Gussow2015_Abstract_Ayranci.pdf [accessed 26 April 2017].

Bohacs, K.M., Grabowski Jr., G.J., Carroll, A.R., Mankiewicz, P.J., Miskell-Gerhadt, K., Schwalbach, J.R., Wegner, M.B. and Simo, J.A., 2005. Production, destruction, and dilution – the many paths to source-rock development. *In:* Deposition of organic-carbon-rich sediments: models, N.B. Harris, (ed.), Society for Sedimentary Geology, Special Publication, vol. 82, 61-101.

Blood, R., Lash, G. and L. Bridges, 2013. Biogenic silica in the Devonian shale succession of the Appalachian basin, USA. American Association of Petroleum Geologists Search and Discovery Article #50864 (2013), http://www.searchanddiscovery.com/pdfz/documents/2013/50864blood/ndx_blood.pdf.html [accessed 26 April 2017].

Creaser, R.A., Sannigrahi, P., Chacko, T. and Selby, D., 2002. Further evaluation of the Re-Os geochronometer in organic-rich sedimentary rocks: a test of hydrocarbon maturation effects in the Exshaw Formation, Western Canada Sedimentary basin. Geochimica et Cosmochimica, vol. 66, p. 3441-3452.

Dow, W.G. 1977. Kerogen studies and geological interpretations. Journal of Geochemical Exploration, vol. **7**, p. 79-99.

Fallas, K.M., Lane, L.S. and Pigage, L.C., 2014. Geology La Biche River Yukon-Northwest Territories. Natural Resources Canada, Canadian Geoscience Map 144, 1 sheet, doi: 10.4095/294606.

Ferri, F., Hickin, A.S and Huntley, D.H., 2011. Besa River Formation, western Liard basin, British Columbia (NTS 094N): geochemistry and regional correlations. British Columbia Ministry of Energy and Mines, Geoscience Reports 2011, p. 1-18.

Ferri, F., Hickin, A.S and Reyes, J., 2012, Horn River basin – equivalent strata in Besa River Formation shale, northeastern British Columbia (NTS 094K/15). British Columbia Ministry of Energy and Mines, Geoscience Reports 2012, p. 1-15.

Ferri, F., McMechan, M., Fraser, T., Fiess, K., Pyle, L. and Cordey, F., 2013. Summary of field activities in the western Liard basin, British Columbia. British Columbia Ministry of Natural Gas Development, Oil and Gas Geoscience Reports 2013, p. 13-31.

Ferri, F., McMechan, M. and Creaser, R., 2015. The Besa River Formation in Liard basin, British Columbia. British Columbia Ministry of Natural Gas Development, Oil and Gas Geoscience Reports 2015, p. 1-27.

Fraser, T.A. and Hogue, B.C., 2007. List of wells and formation tops, Yukon Territory, version 1.0. Yukon Geological Survey, Open File 2007-05.

Fraser, T.A. and Hutchison, M.P., 2017. Lithogeochemical characterization of the Middle-Upper Devonian Road River Group, Canol and Imperial formations on Trail River, east Richardson Mountains, Yukon: age constraints and a depositional model for fine-grained strata in the Lower Paleozoic Richardson Trough. Canadian Journal of Earth Sciences, vol. 54, p. 731-765.

Fraser, T.F., Ferri, F., Fiess, K. and Pyle, L., 2012. Besa River Formation in Liard basin, southeast Yukon: Report on 2012 reconnaissance fieldwork. *In:* Yukon Exploration and Geology 2012, K.E. MacFarlane, M.G. Nordling and P.J. Sack, (eds.), Yukon Geological Survey, p. 37-46.

Green, S., 2016. Pressure data assessment, Liard basin, Yukon. Yukon Geological Survey, Miscellaneous Report 16.

Harris, N.B., Dong, T. and Ayranci, K., 2017. High resolution stratigraphic variability in black shale geochemistry: Horn River Group, British Columbia. American Association of Petroleum Geologists Search and Discovery Article #90291 (2017), http://www.searchanddiscovery.com/abstracts/html/2017/90291ace/abstracts/2611981.html [accessed 26 April 2017].

Hutchison, M.P., 2016. Analytical methods and non-interpretative data compilation for unconventional shale plays of Yukon's Liard basin. Yukon Geological Survey, Open File 2016-33.

Hutchison, M.P. and Fraser, T.A., 2016. Frontier shale gas plays of Yukon's Liard basin, Canada. Presented at the Canadian Society of Petroleum Geologists GeoConvention 2016 (abstract missing from online archive).

Johnson, E.G. and Johnson, L.A., 2012. Hydraulic fracture water usage in northeast British Columbia: locations, volumes and trends. British Columbia Ministry of Energy and Mines, Geoscience Reports 2012, p. 41-64.

Johnson, M., Doubrovina, G., Ferri, F., Hayes, M., Johnson, J., Fiess, K., Rocheleau, J. and Hutchison, M., 2016. The unconventional gas resources of Devonian-Mississippian shales in the Liard basin of British Columbia, Yukon Territory, and the Northwest Territories. Presented at the 10th British Columbia Unconventional Gas Technical Forum.

Mossop, G.D., Wallace-Dudley, K.E., Smith, G.G. and Harrison, J.C., 2004. Sedimentary basins of Canada. Geological Survey of Canada, Open File 4673, 1 sheet, doi 10.4095/215559.

Nadjiwon, L.M., 2001. Facies analysis, diagenesis and correlation of the Middle Devonian Dunedin and Keg River formations, northeastern BC. MSc thesis, University of Waterloo.

NEB, 2001. Petroleum resource assessment of the Liard Plateau, Yukon Territory, Canada: Oil & Gas Resources Branch, Department of Economic Development, Government of the Yukon.

NEB, 2016. The unconventional gas resources of Mississippian-Devonian shales in the Liard basin of British Columbia, the Northwest Territories, and Yukon. National Energy Board Energy Briefing Note.

Noble, J.P.A. and Ferguson, R.D., 1971. Facies and faunal relations at edge of Early-Mid Devonian carbonate shelf South Nahanni River area, N.W.T. Bulletin of Canadian Petroleum Geology, vol. 19, p. 570-588.

Peters, K.E. and Cassa, M.R., 1994., Applied source-rock geochemistry. *In:* The petroleum system. From source to trap, L.B. Magoon and W.G. Dow (eds.), American Association of Petroleum Geologists, p. 93-120.

Pyle, L.J., Rocheleau, J., Fiess, K.M., Fraser, T.A. and Ferri, F., 2016. Petroleum potential, lithogeochemical, and mineralogical data from Devonian and Carboniferous sections in Liard basin, Northwest Territories. Northwest Territories Geological Survey, Open Report 2016-007.

Richards, B.C., Barclay, J.E., Bryan, D., Hartling, A., Henderson, C.M. and Hinds, R.C., 1994. Carboniferous strata of the Western Canada Sedimentary basin. *In:* Geological Atlas of the Western Canada Sedimentary basin, G.D. Mossop and I. Shetsen (eds.), Canadian Society of Petroleum Geologists and Alberta Research Council, http://www.ags.aer.ca/publications/atlas-of-the-western-canada-sedimentary-basin [accessed 28 March 2016].

Richards, B.C., Ross, G.M. and Utting, J., 2002. U Pb geochronology, lithostratigraphy and biostratigraphy of tuff in the upper Famennian to Tournaisian Exshaw Formation: evidence for a mid-Paleozoic magmatic arc on the northwestern margin of North America. *In:* Carboniferous and Permian of the World, L.V. Hills, C.M. Henderson and E.W. Bamber (eds.), Canadian Society of Petroleum Geologists Memoir, vol. 19, p. 158-207.

Rocheleau, J., Fiess, K.M., Pyle, L.J., Ferri, F. and Fraser, T.A., 2014. Source rock characterization of the Carboniferous Golata Formation and Devonian Besa River Formation outcrops, Liard basin, Northwest Territories. Canadian Society of Petroleum Geologists GeoConvention 2014, http://www.geoconvention.com/archives/2014/301_GC2014_Source_Rock_Characterization_of_Carboniferous_Golata_Fm.pdf [accessed 26 April 2017].

Selby, D. and Creaser, R.A., 2005. Direct radiometric dating of the Devonian-Carboniferous timescale boundary using the Re-Os black shale geochronometer. Geology, vol. 33, p. 545-548.

Statistics Canada, 2014. Report on Energy Supply and Demand in Canada (CANSIM table 57-003-X). Statistics Canada, http://www5.statcan.gc.ca/-pub/57-003-x/57-003-x2016002-eng.htm [accessed 14 November 2016].

Wasylyk, P., 2005. Geological wellsite report – Devon et al Kotaneelee L-38, L-38/ST1, L-38A, L-38A/ST3. Devon Canada Corporation. Available from Oil & Gas Resources Branch, Government of Yukon.

Wright, A.M., Ratcliffe, K.T., Zaitlin, B.A. and Wray, D.S., 2010. The application of chemostratigraphic techniques to distinguish compound incised valleys in low-accommodation incised-valley systems in a foreland-basin setting: an example from the Lower Cretaceous Mannville Group and Basal Colorado Sandstone (Colorado Group), Western Canadian Sedimentary basin. SEPM Special Publication, vol. 94, p. 93-107.

Zou, C., 2013. Unconventional petroleum geology. Elsevier, 384 p.