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Introduction

Vitrinite reflectance (VR) determinations were made on selected samples from 5 cores of Lower Cretaceous Garbutt shale and 29 cores of Devono-Mississippian shale located in or adjacent to the Liard Basin area of British Columbia (Figure 1). The Cretaceous cores came from 5 different boreholes. The Devono-Mississippian cores came from 9 different boreholes that intersected several stratigraphic units including the Golata, Banff, Besa River, Exshaw, Kotcho, Muskwa, Otter Park and Evie formations (Table 1). Rock-Eval 6/TOC results were obtained for a more extensive suite of samples from these same Devono-Mississippian cores and these results are published in McMechan et al. (2015).

Vitrinite reflectance has been used widely to calibrate thermal history and time-temperature models for stratigraphic successions within sedimentary basins, particularly for evaluating coal rank and oil and gas generation (Potter, 1998; Bustin et al., 1983; ICCP, 1975). Since the rate of coalification reactions and percent reflectance in oil (%Ro) of huminite, vitrinite and bitumen increase with increasing temperature, these macerals provide an indirect geothermometer for evaluating the thermal conditions during sediment burial (Potter, 1998; Stasiuk, 1991; Tyson, 1987; Bustin et al., 1983; Powell and Snowdon, 1983).

Methodology

Whole rock core samples are prepared by crushing them into 1-5 mm particulates. The samples are mounted in a one inch mold using two parts epoxy, which are then ground on 240, 600, 800, 1000, 1200 grit silicon carbide papers in water and polished on pellon, silk and Lecloth cloth in 0.30 µm and 0.05µm alumina silica. The hardness and overall quality of the samples determines the grit papers and cloth combinations to get the best results. Random percent reflectance in oil (%Ro) are measured on huminite, vitrinite and primary bitumen macerals (n = 5 to 50). Humotelinite and telovitrinite are the preferred maceral subgroups for measuring vitrinite reflectance, wherever possible. In the absence of vitrinite maceral, vitrinite equivalent ($\%Ro_{equivalent}$) are calculated using the measured reflectance of primary bitumen ($\%Ro_{bitumen}$) and Jacob (1989) equation, which should always be used with caution. Random reflectance ($\%R_{random}$) measurements are carried out using a Leitz reflected light microscope with a 50X oil immersion objective and white (halogen; 546nm) and fluorescent (HBO 100W) light sources. The actual %Ro measurements are taken by the Leitz MPV II – COMBI photometer system attached to a pc-controller system for %Ro data collection which is mounted on top of the microscope. Reflectance is calibrated using Schott precision glass standards with 0.506, 1.025, and 1.817 %Ro refractive index. The oil used is halogen free/low fluorescence oil with a refractive index of ne = 1.518 at 23^{o}C. Sample preparation and standard calibration and maceral identification and classification are in accordance with standard procedures based on or modified from ASTM D7708–11, 2011; ISO 7404-2, 2009; ISO 7404-3, 2009; ISO 7404-5, 2009; ICCP, 1998; Potter, 1998; Mackowsky, 1983; Bustin et al., 1983; ICCP, 1975. The burial heating peak temperatures is estimated using Barker and Pawlewicz (1994) equation (Eq. 1).

$$\text{Eq. 1.} \quad T_{peak} = [\ln(\%Ro) + 1.68] / 0.0124$$

Results

The measured VR (1.47%Ro to 3.70%Ro) of samples from Devono-Mississippian cores indicate that these strata are all within the dry gas window (Figure 2 and Figure 3, Tables 2-10) with estimated burial heating peak temperature (BHT_{peak}) of 169°C to 242°C based on Barker and Pawlewicz (1994) equation. Cores from the Evie, and Otter Park formations and most cores from the Besa River and Muskwa formations, have high VR, ranging from 2.15%Ro to 3.70%Ro with estimated BHT_{peak} of between 200°C to 242°C (Tables 7-10, Figures 2 and 3). Core samples from the Besa River and Muskwa formations taken from TRANSEURO ET AL BEAVER B-036-K (B-036-K/094-N-16) and LTS HZ POPLAR HILLS A-040-G (A-040-G/094-O-03) wells are showing much lower VR (1.47%Ro to 1.87%Ro, estimated BHT_{peak} of 163°C to 188°C) compared to the other wells (Figure 3, Table 4 and Table 6). The Exshaw and Kotcho formation core from the eastern edge of the basin have VR between 1.48%Ro and 1.78%Ro with an estimated BHT_{peak} ranging from 200°C to 235°C (Figure 3, Tables 4-5). The VR of the core sample from the Golata and Banff formations collected from TRANSEURO BEAVER D-064-K (D-064-K/094-N-16) well have VR ranging from 1.64%Ro to 2.68%Ro with estimated BHT_{peak} of 174 °C to 216°C (Figure 3, Tables 2-3).

Most of the Lower Cretaceous Garbutt samples are within the early to late hydrocarbon generating window (0.60 to 1.0%Ro, estimated BHT_{peak} range 95°C to 136°C) with the exception of TSOO A-13-H (A-13-H/ 94-O-14) well samples, that are in the dry gas window (>1.30%Ro) (Figures 2 and 3, Tables 11-15). These suggest that the Garbutt Formation in this area was subjected to a much higher temperature (>163°C) compared to the cores from further north in the Maxhamish Lake area (Figure 1).

Qualitative petrographic analyses of the dispersed organic matter (DOM), microfossils (siliceous and calcareous) and their microtextures in Devono-Mississippian and Lower Cretaceous core samples ranges from bright yellow fluorescing liptinite (alginite, sporinite, bituminite and solid bitumen) macerals to overmature, granular, spent amorphous kerogen at various concentration (See comments column in Appendix A1- A14). Most of the amorphous kerogens found in the Devono-Mississippian are derived from autochthonous unicellular prasinophyte alginite like *Tasmanites*. Conodont, chitinozoan, and siliceous radiolarian microfossils are observed in some core samples from Besa River/Muskwa, Muskwa and Otter Park formations collected from TRANSEURO ET AL BEAVER B-036-K (B-036-K/094-N-16), JOINT VENTURE NO. 1 C-010-E (C-010-E/094-N-07) and LTS HZ POPLAR HILLS A-040-G (A-040-G/094-O-03) (Appendix 4, 7 and 8). The occurrence of these organic microfossils are indicative of Type II/I kerogen deposited in deep marine paleodepositional environment and/or zone of upwelling (Reyes et al., 2013; Stasiuk and Fowler, 2004). Cores from the Evie and other cores from the Besa River and Muskwa formations (Appendix A5, A8-A9) are also Type II/I kerogen deposited in shallower paleodepositional environment compared to the well locations mentioned above. Core samples collected from the Mississipian Kotcho, Golata and Mattson formations contains reworked and allochthonous inertinite, vitrinite and liptinite macerals derived from early terrestrial plants (See comments column in Appendix A1 to A5), which suggest that these formations were deposited in shallow to intermediate marine paleodepositional environment and are characterized as Type II kerogen by source (Reyes et al., 2013; Stasiuk and Fowler, 2004).

The organic facies of Lower Cretaceous Garbutt Formation are mostly spent and partially spent amorphous kerogen with bright yellow to weak reddish fluorescing liptinite (alginite, bitumen, sporinite) inclusions. Thick coaly lenses derived from filamentous and/or algal mats, *Botryococcus* like colonial algae and terrestrial plant derived organic macerals are also observed in Garbutt Formation samples collected from AEC MAXHAMISH B-053-B (B-053-B/94-O-14) and STX MAXHAMISH B-006-C (B-006-C/094-O-11) well (Table A10). These organic facies are characterized as Type II kerogen by source that was deposited in shallow to intermediate marine paleodepositional environment (Figure 2).

The absence of terrestrial plant derived macerals, in itself, does not imply deep marine depositional environment. Other factors such as lithology (particle grain size), mineralogy, microfossils composition (calcareous or siliceous) and the age of the formation are also used as qualifiers in estimating relative paleobathymetry during the time of deposition. Likewise, paleobathymetry alone does not determine the temporal-vertical and lateral organic facies variation within the same strata. Tectonic events, oceanic paleothermocline, topography, sediment and nutrient loading during the time of deposition also play significant roles in determining organic richness and biodiversity (Reyes et al., 2013, Stasiuk and Fowler, 2004 and references therein).

Summary/Conclusion

This open file releases vitrinite reflectance determinations obtained for samples from 30 cores of Devono-Mississippian or Lower Cretaceous shale in the Liard area of British Columbia. The core samples came from 13 different boreholes and 11 different formations. These VR data fill some of the gap in thermal maturity data for the Liard Basin. Devono-Mississippian formations are overmature and well within the dry gas window. VR results from the Lower Cretaceous Garbutt Formation suggest that it is thermally mature in the eastcentral part of the Liard Basin and overmature in the southeastern part (TSOO A-13-H (A-13-H/ 94-O-14) well). Qualitative petrographic analyses of Devono-Mississippian and Lower Cretaceous strata indicates they were deposited in shallow to deep marine paleodepositional environments and are characterized as Type II/I and II kerogen by source.

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Tables and Figures

Tables

Table 1. The list provides the well name, location, license number, core number and number of samples (in parenthesis) and unit formation.

Well Name	Location	License	Core No.	Unit
EOG MAXHAMISH D-012-L	D-012-L/094-O-15	WA21643	1, 4, 9	Muskwa
EOG MAXHAMISH D-012-L	D-012-L/094-O-15	WA21643	11	Otter Park
TSOO A-13-H	A-13-H/ 94-O-14	WA14517	1 (3)	Garbutt
AEC MAXHAMISH B-053-B	B-053-B/94-O-14	WA09950	1 (3)	Garbutt
EXXON MOBILE N PETITOT D-033-F	D-033-F/094-P-13	WA06468	1 (2)	Garbutt
STX MAXHAMISH B-006-C	B-006-C/094-O-11	WA18890	3 (5)	Garbutt
BP ENERGY GROUP DEER LAKE A-090-I	A-090-I/094-O-06	WA0531	1 (3)	Kotcho
LTS HZ POPLAR HILLS A-040-G	A-040-G/094-O-03	WA25913	1 (4)	Exshaw
LTS HZ POPLAR HILLS A-040-G	A-040-G/094-O-03	WA25913	1	Kotcho
LTS HZ POPLAR HILLS A-040-G	A-040-G/094-O-03	WA25913	2 (2)	Muskwa
TRANSEURO BEAVER B-019-K	B-019-K/094-N-16	WA02563	1 (4), 2 (2), 3	Besa River/ Evie
TRANSEURO BEAVER D-064-K	D-064-K/094-N-16	WA0325	1 (6)	Golata
TRANSEURO BEAVER D-064-K	D-064-K/094-N-16	WA0325	20 (2)	Banff
TRANSEURO BEAVER D-064-K	D-064-K/094-N-16	WA0325	21 (3)	Besa River/ Muskwa
TRANSEURO HZ BEAVER D-A064-K	D-A064-K/094-N-16	WA02547	6 (4)	Golata
TRANSEURO ET AL BEAVER B-036-K	B-036-K/094-N-16	WA21755	1-4, 6-7	Besa River
TRANSEURO ET AL BEAVER B-036-K	B-036-K/094-N-16	WA21755	8, 9	Mattson
IOE DUNEDIN D-075-E	D-075-E/094-N-08	WA01331	15 (5)	Besa River/ Golata?
IOE DUNEDIN D-075-E	D-075-E/094-N-08	WA01331	16 (2)	Besa River
IOE DUNEDIN D-075-E	D-075-E/094-N-08	WA01331	17 (4)	Besa River
JOINT VENTURE NO. 1 C-010-E	C-010-E/094-N-07	WA0038	11, 16	Kindle
JOINT VENTURE NO. 1 C-010-E	C-010-E/094-N-07	WA0038	35 (4)	Besa River/ Muskwa
HARVEST BAY B-017-H	B-017-H/094-I-09	WA13960	1	Garbutt

Table 2. Vitrinite reflectance data for Golata formation collected from TRANSEURO HZ BEAVER D-A064-K (WA2547) well.

No.	Catalog No.	License No.	Core No.	Depth (m)	Formation	Peller No.	*Organic Type	$\%Ro_R$	SD	N
1	C-572064	WA2547	6	1914.7	Golata	657/13	2	1.64	0.09	9
2	C-572068	WA2547	6	1917.7	Golata	658/13	2	1.72	0.11	11
3	C-572078	WA2547	6	1920.8	Golata	659/13	2	1.69	0.07	13
4	C-572089	WA2547	6	1923.8	Golata	660/13	2	1.81	0.06	11

***Organic Type**
2 = Vitrinite
3 = vitrinite equivalent (04) = 0.618 x %Ro(bitumen) + 0.40 values

Table 3. Vitrinite reflectance data for Golata and Besa River/Muskwa formations collected from TRANSEURO BEAVER D-064-K (WA325) well.

No.	Catalog No.	License No.	Core No.	Depth (m)	Formation	Peller No.	Organic Type	$\%Ro_R$	SD	N
1	C-571599	WA325	1	2535.8	Golata	638/13	2	2.16	0.07	10
2	C-571594	WA325	1	2537.3	Golata	637/13	2	2.30	0.13	21
3	C-571589	WA325	1	2538.9	Golata	636/13	2	2.51	0.05	12
4	C-571579	WA325	1	2541.9	Golata	635/13	2	2.44	0.09	13
5	C-571569	WA325	1	2545.0	Golata	634/13	2	2.45	0.12	13
6	C-571559	WA325	1	2548.0	Golata	633/13	2	2.39	0.13	20
7	C-571602	WA325	20	2895.5	Banff	640/13	2	2.56	0.09	16
7	C-571600	WA325	20	2896.1	Banff	639/13	2	2.68	0.17	14
8	C-571627	WA325	21	3364.2	Besa River/ Muskwa	643/13	2	3.10	0.11	10
9	C-571615	WA325	21	3368.2	Besa River/ Muskwa	642/13	2	3.09	0.09	5
10	C-571603	WA325	21	3371.8	Besa River/ Muskwa	641/13	2	2.99	0.12	12

Table 4. Vitrinite reflectance data for Exhaw, Kotcho and Muskwa formations collected from LTS HZ POPLAR HILLS A-040-G (WA25913) well.

No.	Catalog No.	License No.	Core No.	Depth (m)	Formation	Peller No.	Organic Type	$\%Ro_R$	SD	N
3	C-572148	WA25913	1	1224.4	Exshaw	680/13	2	1.48	0.03	6
4	C-572158	WA25913	1	1227.8	Exshaw	681/13	2	1.59	0.08	14
5	C-572165	WA25913	1	1233.9	Kotcho	682/13	2	1.63	0.06	9
6	C-572166	WA25913	2	2145.1	Muskwa	676/13	2	1.81	0.09	10
7	C-572168	WA25913	2	2145.75	Muskwa	677/13	2	1.77	0.12	2

Table 5. Vitrinite reflectance data for Kotcho formation collected from BP ENERGY GROUP DEER LAKE A-090-I (WA531) well.

No.	Catalog No.	License No.	Core No.	Depth (m)	Formation	Peller No.	Organic Type	$\%Ro_R$	SD	N
1	C-572109	WA531	1	1658.6	Kotcho	665/13	2	1.78	0.01	2
2	C-572112	WA531	1	1661.6	Kotcho	666/13	2	1.75	0.11	7
3	C-572114	WA531	1	1663.6	Kotcho	667/13	2	1.69	0.09	6

Table 6. Vitrinite reflectance data for Mattson (lower) and Besa River formations collected from TRANSEURO ET AL BEAVER B-036-K (WA21755) well.

No.	Catalog No.	License No.	Core No.	Depth (m)	Formation	Peller No.	Organic Type	$\%Ro_R$	SD	N
1	C-572115	WA21755	9	1835	Mattson - lower	675/13	2	1.45	0.09	12
2	C-572116	WA21755	8	1838.5	Mattson - lower	674/13	2	1.47	0.06	15
3	C-572117	WA21755	7	1856	Besa River	673/13	2	1.47	0.06	15
4	C-572118	WA21755	6	1882.7	Besa River	672/13	2	1.56	0.09	23
5	C-572119	WA21755	2	1969.2	Besa River	669/13	2	1.66	0.06	10
6	C-572120	WA21755	4	1995.7	Besa River	671/13	2	1.69	0.09	18
7	C-572121	WA21755	3	2000.7	Besa River	670/13	2	1.74	0.08	8
8	C-572122	WA21755	1	2114	Besa River	668/13	2	1.87	0.07	14

Table 7. Vitrinite reflectance data for Kindle, Kindle/Mattson and Besa River/Muskwa formations collected from JOINT VENTURE NO. 1 C-010-E (WA0038) well.

No.	Catalog No.	License No.	Core No.	Depth (m)	Formation	Peller No.	Organic Type	$\%Ro_R$	SD	N
1	C-572207	WA0038	16	593.7	Kindle	693/13	2	2.81	0.15	19
2	C-572208	WA0038	11	631.4	Kindle/Mattson	694/13	2	2.81	0.15	16
3	C-572209	WA0038	35	1573.3	Besa River/ Muskwa	695/13	2	3.28	0.07	4
4	C-572218	WA0038	35	1576.0	Besa River/ Muskwa	696/13	2	3.19	0.22	18
5	C-572226	WA0038	35	1578.5	Besa River/ Muskwa	697/13	2	3.21	0.22	13
6	C-572234	WA0038	35	1580.9	Besa River/ Muskwa	698/13	2	3.16	0.20	11

Table 8. Vitrinite reflectance data for Muskwa and Otter formations collected from EOG MAXHAMISH D-012-L (WA21643) well.

No.	Catalog No.	License No.	Core No.	Depth (m)	Formation	Peller No.	Organic Type	$\%Ro_R$	SD	N
1	C-572235	WA21643	1	2956.15	Muskwa	699/13	2	3.34	0.13	8
2	C-572238	WA21643	4	2966.5	Muskwa	700/13	2	3.40	0.00	1
3	C-572243	WA21643	9	2971.1	Muskwa	701/13	2	3.19	0.03	2
4	C-572247	WA21643	11	2978.7	Otter Park	702/13	2	3.18	0.09	6

Table 9. Vitrinite reflectance data for Besa River/Golata? and Besa River formations collected from IOE DUNEDIN D-075-E (WA1331) well.

No.	Catalog No.	License No.	Core No.	Depth (m)	Formation	Peller No.	Organic Type	$\%Ro_R$	SD	N
1	C-571628	WA1331	15	3688.8	Besa River/ Golata?	644/13	2	2.49	0.12	4
2	C-571638	WA1331	15	3691.9	Besa River/ Golata?	645/13	2	2.15	0.00	1
3	C-571649	WA1331	15	3695.2	Besa River/ Golata?	646/13	2	2.30	0.10	6
4	C-571660	WA1331	15	3698.6	Besa River/ Golata?	647/13	2	2.24	0.20	13
5	C-571672	WA1331	15	3702.2	Besa River/ Golata?	648/13	2	2.38	0.01	2
6	C-571673	WA1331	16	3773.2	Besa River	649/13	2	2.88	0.09	7
7	C-571679	WA1331	16	3775.0	Besa River	650/13	2	2.58	0.11	15
8	C-571680	WA1331	17	3889.7	Besa River	651/13	2	2.97	0.14	17
9	C-571685	WA1331	17	3891.5	Besa River	652/13	2	2.91	0.07	4
10	C-571692	WA1331	17	3893.3	Besa River	653/13	2	3.07	0.11	19
11	C-571701	WA1331	17	3895.5	Besa River	654/13	2	3.05	0.13	6

Table 10. Vitrinite reflectance data for Besa River/Evie and Besa River formations collected from TRANSEURO BEAVER B-019-K (WA02563) well.

No.	Catalog No.	License No.	Core No.	Depth (m)	Formation	Peller No.	Organic Type	$\%Ro_R$	SD	N
1	C-572181	WA02563	1	3777.8	Besa River/Evie	686/13	2	2.75	0.17	9
2	C-572184	WA02563	1	3778.7	Besa River/Evie	687/13	2	2.74	0.10	12
3	C-572188	WA02563	1	3779.9	Besa River/Evie	688/13	2	3.05	0.21	13
4	C-572192	WA02563	1	3781.2	Besa River/Evie	689/13	2	3.22	0.20	17
5	C-572193	WA02563	2	3781.5	Besa River/Evie	690/13	2	3.10	0.00	1
6	C-572200	WA02563	2	3783.6	Besa River/Evie	691/13	2	3.10	0.21	14
7	C-572206	WA02563	3	3785.4	Besa River/Evie	692/13	2	3.70	0.00	1

Table 11. Vitrinite reflectance data for Garbutt formation collected from AEC MAXHAMISH B-053-B (WA9950) well.

No.	Catalog No.	License No.	Core No.	Depth (m)	Formation	Peller No.	Organic Type	$\%Ro_R$	SD	N
1	C-572090	WA9950	1	1260.0	Garbutt	661/13	2	0.65	0.07	27
2	C-572096	WA9950	1	1266.0	Garbutt	662/13	2	0.68	0.07	27
3	C-572101	WA9950	1	1272.0	Garbutt	663/13	2	0.72	0.07	26

Table 12. Vitrinite reflectance data for Garbutt formation collected from HARVEST BAY B-017-H (WA13960) well.

No.	Catalog No.	License No.	Core No.	Depth (m)	Formation	Peller No.	Organic Type	%Ro_R	SD	N
1	C-591340	WA13960	1	339.7	Garbutt	462/14	2	0.77	0.07	12

Table 13. Vitrinite reflectance data for Garbutt formation collected from EXXON MOBILE N PETITOT D-033-F (WA06468) well.

No.	Catalog No.	License No.	Core No.	Depth (m)	Formation	Peller No.	Organic Type	%Ro_R	SD	N
1	C-591347	WA06468	1	298.0	Garbutt	460/14	2	0.79	0.06	17
2	C-591348	WA06468	1	309.0	Garbutt	461/14	2	0.81	0.10	19

Table 14. Vitrinite reflectance data for Garbutt formation collected from STX MAXHAMISH B-006-C (WA18890) well.

No.	Catalog No.	License No.	Core No.	Depth (m)	Formation	Peller No.	Organic Type	%Ro_R	SD	N
1	C-571537	WA18890	3	1476	Garbutt	628/13	2	0.79	0.03	8
2	C-571538	WA18890	3	1476.6	Garbutt	629/13	2	0.82	0.07	18
3	C-571544	WA18890	3	1481.4	Garbutt	630/13	2	0.93	0.05	14
4	C-571551	WA18890	3	1487.7	Garbutt	631/13	2	0.91	0.03	11
5	C-571558	WA18890	3	1494	Garbutt	632/13	2	0.92	0.07	11

Table 15. Vitrinite reflectance data for Garbutt formation collected from TSOO A-13-H (WA14517) well.

No.	Catalog No.	License No.	Core No.	Depth (m)	Formation	Peller No.	Organic Type	%Ro_R	SD	N
1	C-572169	WA14517	1	1403.2	Garbutt	683/13	2	1.41	0.06	22
2	C-572174	WA14517	1	1408	Garbutt	684/13	2	1.50	0.09	13
3	C-572180	WA14517	1	1414.2	Garbutt	685/13	2	1.46	0.09	6

Figures

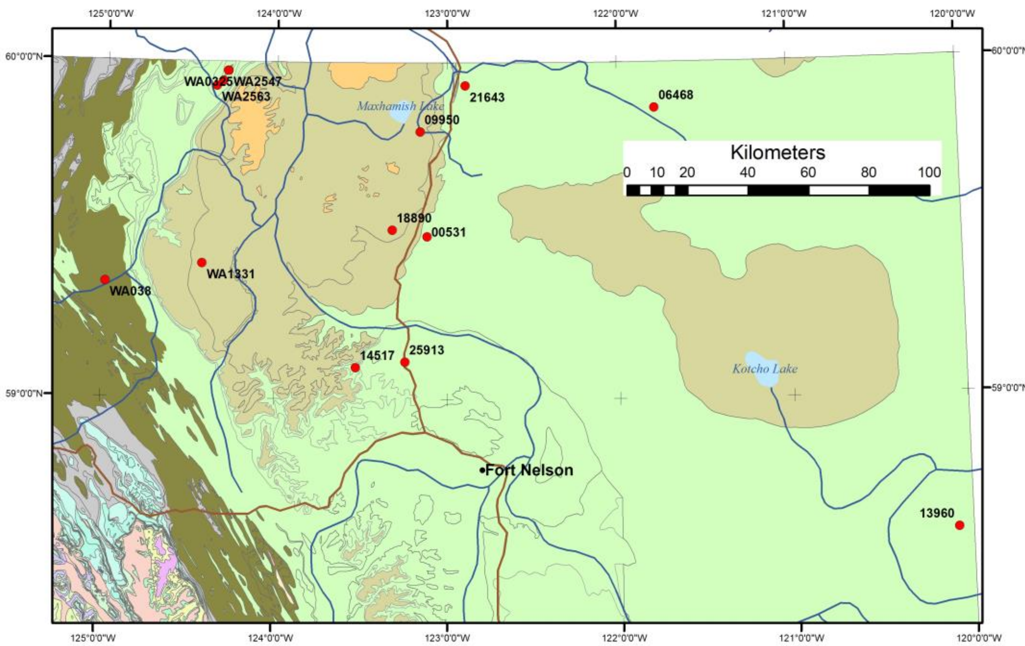

Figure 1. Map of the study area showing the locations of the wells in the Liard Basin northeast British Columbia.

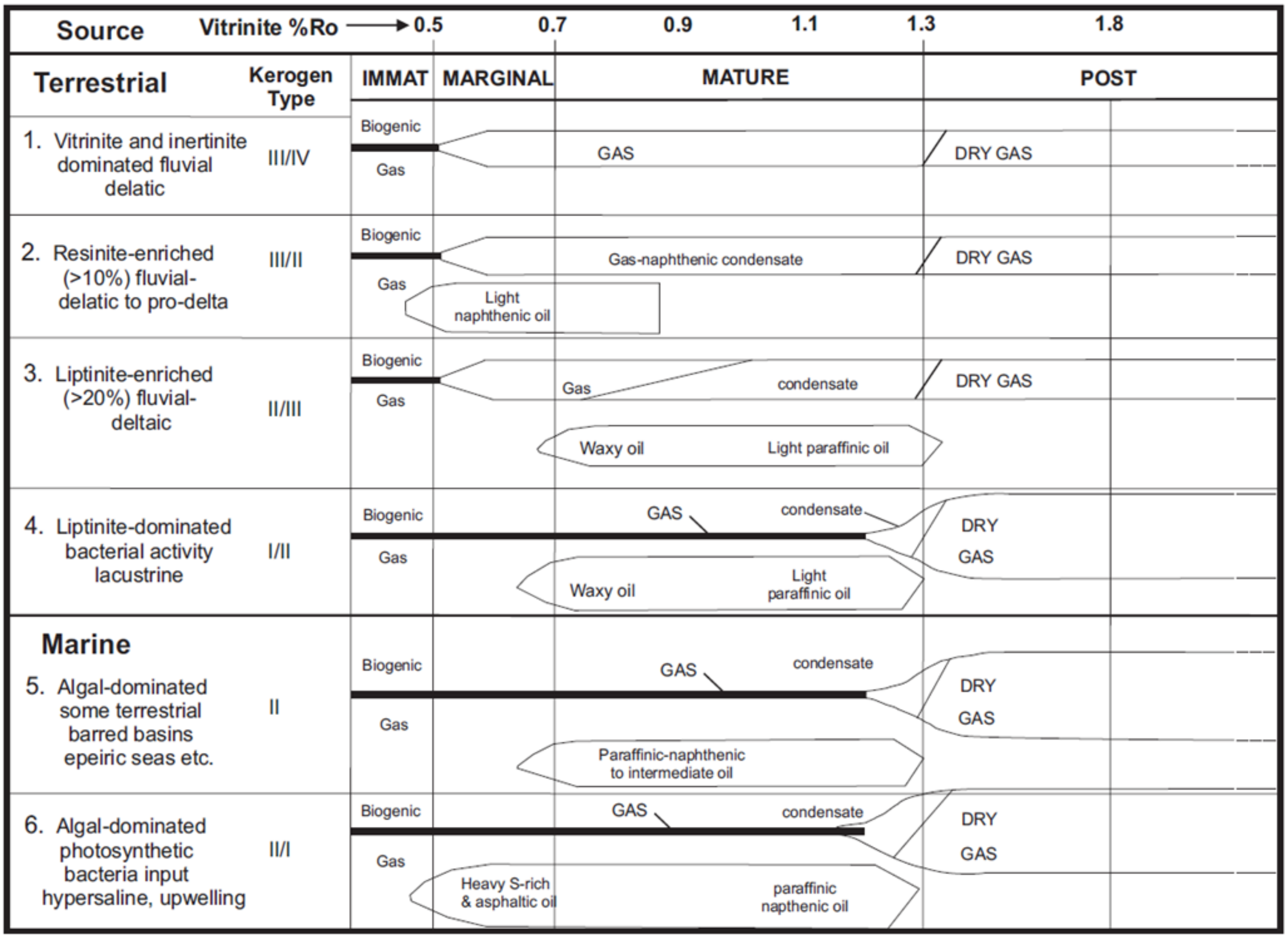

Figure 2. Hydrocarbon generation model using vitrinite reflectance (%Ro) values used to determine form of hydrocarbon generated depending on the kerogen type and source rock paleodepositional environment . (Modified from Potter, 1998 and Stasiuk, 1991). See also Powell and Snowdon, 1983).

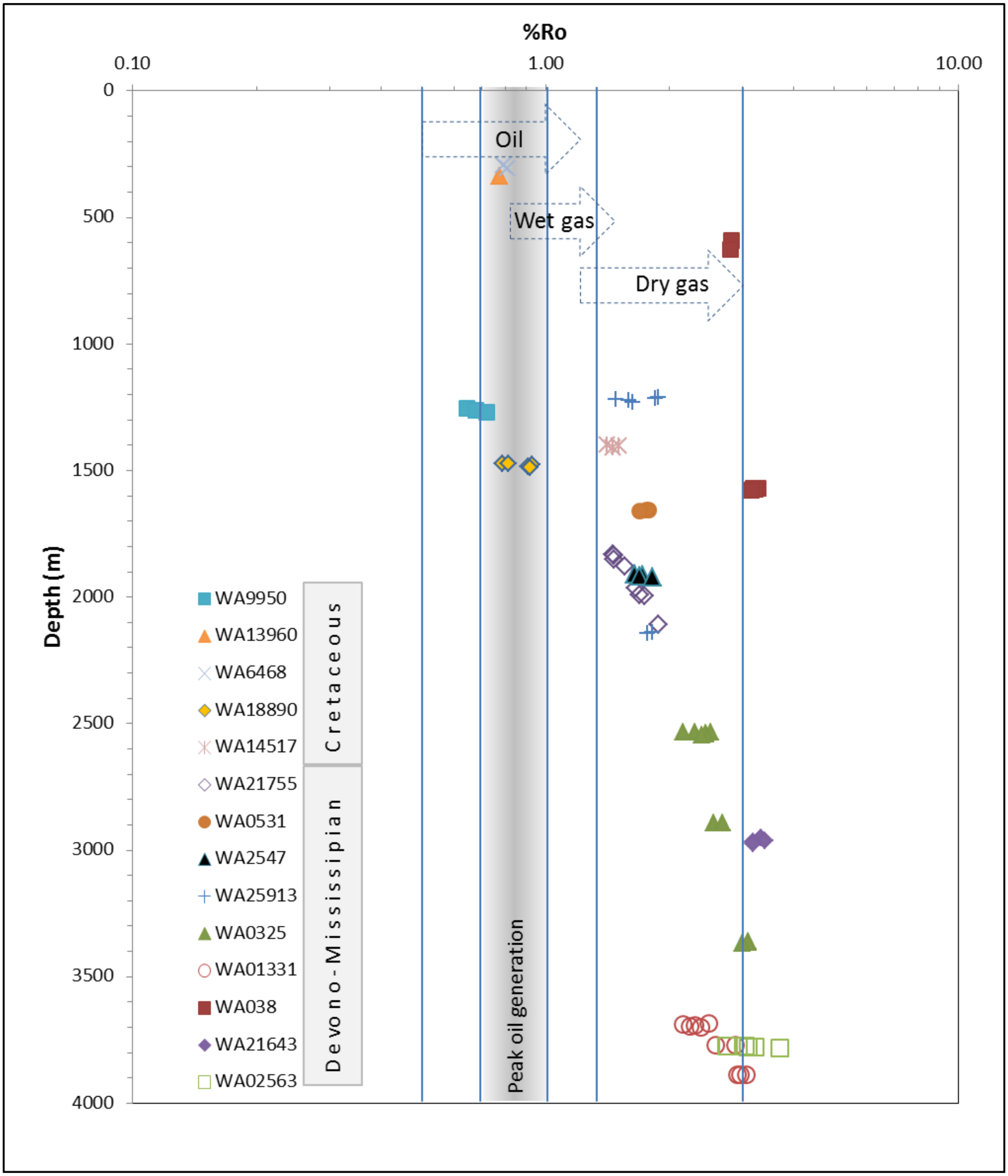

Figure 3. Vitrinite reflectance (%Ro) versus depth (m) profile of selected core samples of Devono-Mississippian and Lower Cretaceous shale from Liard Basin British Columbia overlain on the estimated maturation pathways for oil, wet gas and dry gas generation based measured %Ro and observed kerogen types.

Appendix

Open_File_1902 Appendix 1 to 14 contains detailed vitrinite reflectance data including qualitative assessment of each sample.