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Recognition of Devonian hydrocarbon source rocks in Beluga O-23 well, Hudson Bay Basin

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ABSTRACT

The Hudson Bay Basin is a Phanerozoic sedimentary basin in the eastern Canadian Arctic, whose succession is dominated by Ordovician to Devonian sediments and for which the hydrocarbon potential remains poorly understood. In the recent years, the Hudson Bay-Foxe basins project under the Geological Mapping for Energy and Mineral (GEM) Program has paid a great attention to the lower part of the Paleozoic succession comprising the Upper Ordovician and Lower Silurian. This present report focuses on the study of petroleum potential source rocks of the Devonian succession (Stooping River, Kwataboahegan, Moose River, Murray Island and William Island formations).

A total of 50 well cutting samples were collected from 875 to 630 meter (Devonian succession) in the Beluga O-23 well, of which 28 contain dark, organic-rich fragments preferentially picked from the cuttings. The 28 samples were analyzed using Rock-Eval^6 Pyrolysis technique. The Rock-Eval^6 data show that the Devonian succession in the Beluga O-23 well contains immature high yield hydrocarbon potential source rocks with TOC ranging from 1.6 to17.64% (average 9.07%) and with a Type II kerogen signature. These hydrocarbon potential source rocks are mainly concentrated in five narrow zones within the selected interval from the upper part of the Stooping River Formation to the lower part of the Williams Island Formation as identified by the well log interpretation.

INTRODUCTION

Hydrocarbon exploration in the Hudson Bay offshore area occurred during the late 1960s to the early 1980s. Five wells (Netsiq N-01, Beluga O-23, Walrus A-71, Polar Bear C-11, Narwhal S. O-58) were drilled in the Hudson Bay at that time (Fig. 1). But none of the wells found commercial quantities of oil or gas.

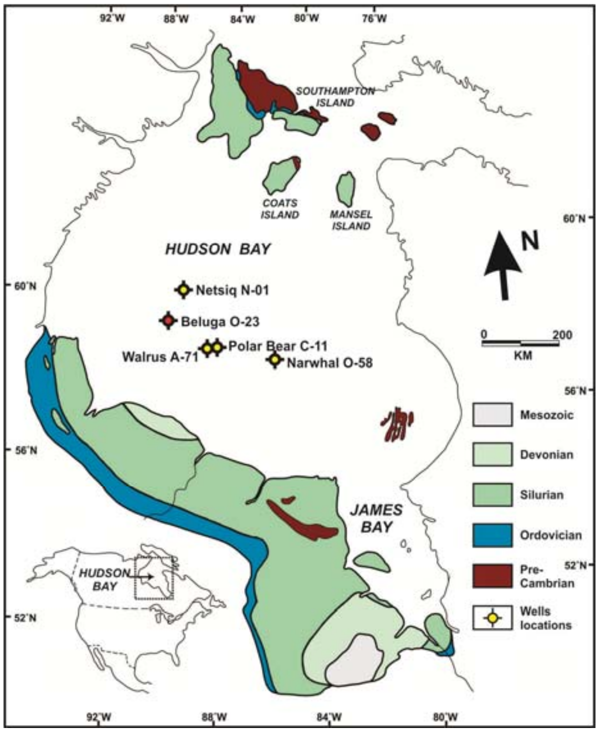

Figure 1. The Hudson Bay region showing onshore extension of the Paleozoic rocks and location of offshore wells drilled during the late 1960s to early 1980s (modified from Zhang and Barnes, 2007; fig. 1). The Beluga O-23 well studied here is shown in red.

With increased interest in hydrocarbon exploration in Arctic Canada, it is obvious that new data are needed to help re-assess the petroleum potential of Hudson Bay Basin. Without new drillings, the samples and logs from the five wells during the late 1960s to the early 1980s are key elements for re-evaluation and new analyses. As part of the 2008-2013 GEM Hudson Bay-Foxe basins research project, a lot attention has been paid on re-examining the well materials leading to improvement in our knowledge on Paleozoic stratigraphy, thermal maturity and petroleum potential in the Hudson Bay. This includes detailed studies on i) the Lower Paleozoic biostratigraphy in the Hudson Bay Basin (Zhang and Barnes, 2007), ii) Rock Eval analysis of the core and well cutting samples in both Hudson Bay and Foxe basins (Zhang and Dewing, 2008), iii) re-examining the well logs and correlating the Gamma Ray logs in the offshore area to the outcrops on Southampton Island, and suggesting that source rocks with high TOC in the Red Head Rapids Formation are likely present in the central part of Hudson Bay (Zhang, 2008), and iv) detailed well log interpretation and correlation among the five offshore wells (Hu et al., 2011;

Hu and Dietrich, 2012). However, this attention has been primarily focused on the Lower Paleozoic succession. Possible by-passed hydrocarbon zones were suggested from well log analysis (Hu et al., 2011; Hu and Dietrich, 2012); they are associated with Rock Eval data indicating an *in situ* immature thermal domain, therefore suggestive of migrated hydrocarbon in the Devonian part of the Beluga O-23 well. This study focuses on an interval between 875 and 630 m in the Beluga O-23 well, which contains a total of 50 well cutting samples. Among these 50 samples, 28 contain dark, possible organic-rich fragments, which are preferentially hand-picked and analyzed by using Rock-Eval^6 Pyrolysis technique. The Rock Eval^6 data presented here are also compared with the Beluga O-23 well logs.

DEVONIAN STRATIGRAPHY IN THE HUDSON BAY BASIN

Devonian strata in the Hudson Bay Basin are only known from the drillings. During the early exploration, the division of the Devonian strata was different from well to well. The stratigraphic nomenclature of Narwhal, Kenogami, Pen, Polar Bear and Walrus Limestone formations for the Beluga O-23 well was proposed by Canterra Energy Ltd. (http://basin.gdr.nrcan.gc.ca/wells/well_query_e.php). However, the nomenclature of Kenogami River, Stooping River, Kwataboahegan, Moose River, Murray Island, Williams Island and Long Rapids formations was proposed for the Walrus A-71 and Polar Bear C-11 wells (http://basin.gdr.nrcan.gc.ca/wells/well_query_e.php). Sanford and Norris (1975) included the upper Kenogami River (?), Stooping River and, Kwataboahegan formations into the Lower and Middle Devonian, the Moose River and Murray Island formations into the Middle Devonian, the Williams Island Formation into the Middle and Upper Devonian, and finally, the Long Rapids into the Upper Devonian for the Walrus A-71 well. These names have been continuously used for the entire Hudson Bay Basin since Sanford and Grant (1990, 1998), but the age designation for each unit is slightly different from time to time. Figure 2 shows the subdivision of Devonian strata and the age designation based mainly on the onshore and offshore drillings (Sanford and Grant 1998).

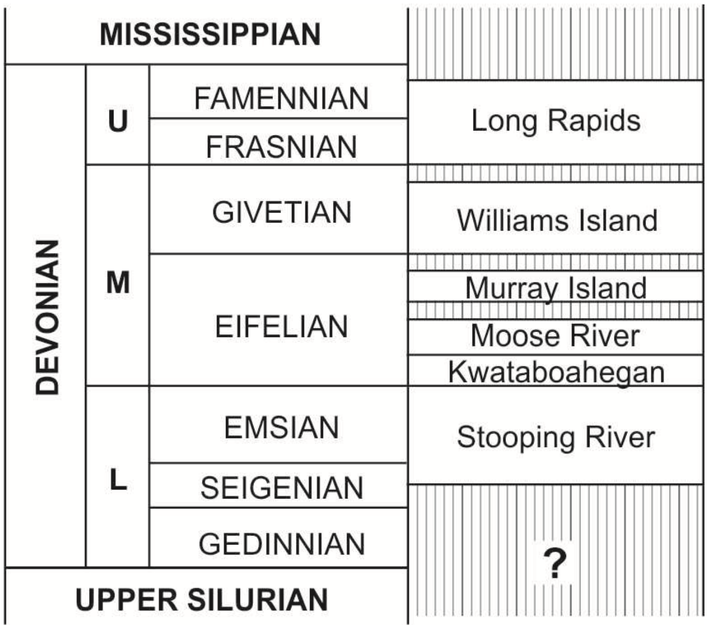

Figure 2. The Devonian stratigraphy of Hudson Bay Basin (modified from Sanford and Grant, 1998)

Hu et al. (2011) made a detailed well log interpretation and redefined the formation tops for the five wells in the Hudson Bay offshore area. Figure 3 shows the detailed interpretation of the lithology mainly from well logs for most part of the Devonian stratigraphy of the Beluga O-23 well. The log interpretation is consistent with the information from sidewall cores and well cutting descriptions, except for the upper salt interval, where even if well log indicates a salt-dominated interval, only mudstone cuttings were recovered: salt was most likely dissolved into the drilling mud. Based on the interpreted lithology from logs (Hu et al., 2011), the Stooping River Formation has a total thickness of 738 m (780.8–1518.4 m) and is characterized by a lower succession of interbedded shaly dolostone and dolomitic siltstone, as well as minor anhydrite; a massive halite section with minor carbonate and shale forms most of the formation, with a shale dominated section at the top (Fig. 3). The 58 m-thick (722.8–780.8 m) Kwataboahegan Formation is dominated by a succession of limestone and dolostone with an overall upward decreasing shale content. The Moose River Formation is 84 m-thick (638.4–722.8 m) and is primarily composed of evaporites and minor shales with an anhydrite-dominated succession at the base; the formation has variable shale content and two prominent thin shale intervals in the middle and upper part, and a thicker dolomitic shale occurs at the top. The Murray Island Formation is a thin unit (8 m from 630.7 to 638.4 m) mainly composed of limestone and dolostone with minor shale. Finally, the uppermost part of the Beluga O-23 well is made up of the lower section of the Williams Island Formation, which mainly consists of shale with minor limestone and dolostone.

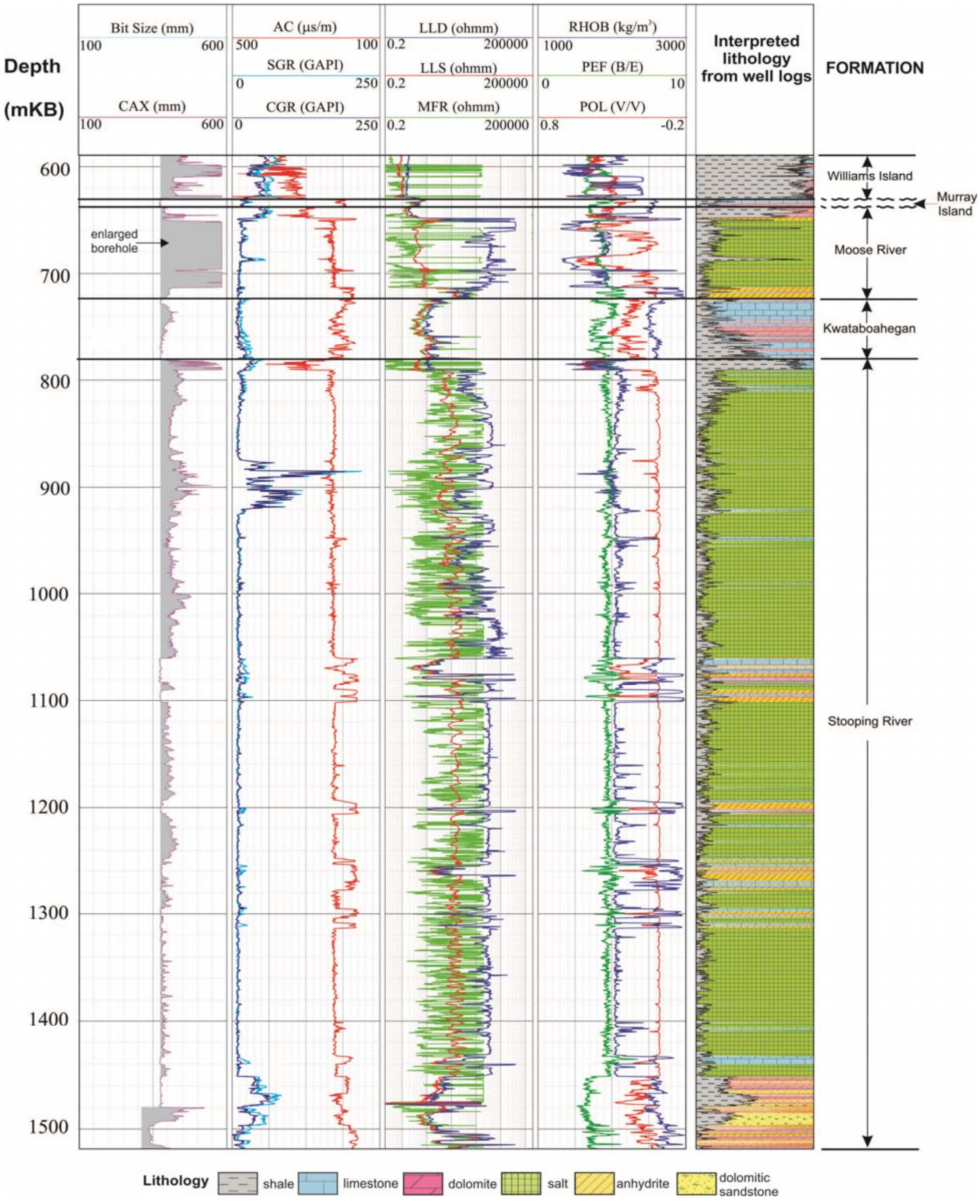

Figure 3. Lithology interpretation mainly based on well logs for most part of the Devonian succession of the Beluga O-23 well, Hudson Bay Basin.

Figure 4. Part of the well cutting samples from the Beluga O-23 well. A. part of the washed well cuttings; B. possible organic-rich fragments preferentially hand-picked from 28 samples within an interval of 875-630 m; C. possible organic-rich fragment from the sample at a depth of 630 m (red box in A and B).

SAMPLES, EXPERIMENT, AND BASICS OF ROCK EVAL^6 DATA

All the well cutting samples within the 2185–580 m interval of the Beluga O-23 well were collected and washed using a 250 microns sieve. The weight of clean cuttings of most samples was 35–70 g. On the basis of recognized fairly significant Gamma Ray kicks in the Devonian part of the Beluga O-23 well (Hu et al. 2011) and the visible dark fragments in the cuttings, this study focuses on the interval between 875 and 630 m, which comprises a total of 50 well cutting samples. Most of these samples consist of limestone/dolostone with minor black shale fragments, but some are composed of mudstone with minor black shale fragments (Fig. 4).

Among these 50 samples, 28 contain dark, possibly organic-rich fragments, these fragments were preferentially hand-picked from the washed well cuttings under a stereo microscope (Figs. 4B, 4C); the amount of these dark fragments in each sample is more than enough for running Rock-Eval analysis. Figure 4C shows the possible organic-rich shale fragments from a sample at a depth of 630 m. All the 28 samples were analyzed using the Rock-Eval^6 apparatus located at GSC Calgary.

The Rock-Eval^6 experimental procedures and its application to hydrocarbon exploration are presented in Lafargue et al. (1998) and Behar et al. (2001). The guidelines developed by Peters (1986) for Rock-Eval^2 were used in interpreting the data herein. Samples with an $S_2<0.2$ mg HC/g rock are considered to produce unreliable Tmax values. Samples with an $S_2<0.2$ mg HC/g rock or with TOC<0.3% produce unreliable HI values. Among the 28 analysed samples, all have $S_2\geq5.21$ mg HC/g rock and all TOC≥1.6% (Table 1); therefore, the data are reliable for evaluation of source rock quality and maturation.

RESULTS FROM ROCK EVAL^6 ANALYSES

Table 1 contains the Rock-Eval^6 data and corresponding depth and stratigraphic units. Figure 5 displays plots of selected Rock-Eval^6 parameters, including Tmax (°C), Production Index ($PI=S_1/(S_1+S_2)$), Total Organic Carbon (TOC; wt%) and Hydrogen Index ($HI=S_2/TOC\times100$) versus depth. S_1 is the amount of hydrocarbons per gram of rock sample (mg HC/g rock) that is volatilized at 300°C during sample pre-heating; S_2 is the amount of hydrocarbons per gram of rock (mg HC/g rock) liberated from sample during ramped heating from 300 to 600°C; Tmax is the temperature (ºC) at peak hydrocarbon generation on S_2 curve. In Figure 5, the vertical dashed lines indicate thresholds for the onset of oil generation (Tmax=435; PI=0.1) and good HC source rock attributes (TOC>2wt%; HI>300).

For the entire 875–630 m interval, the TOC values of the 28 samples range between 1.6 and 17.64% with an average of 9.07%, and HI values are between 142 and 495, with an average of 390; these two elements suggest excellent hydrocarbon source rocks. However, all the samples have Tmax values ranging between 412ºC and 426ºC with an average of 416ºC, which is far below 435ºC considered as the threshold of oil generation. Moreover, all samples have PI values ranging between 0.06 and 0.1 with an average of 0.08, which indicate that these source rocks have not reached the thresholds of oil generation. The HI *versus* OI diagram (Fig. 6) shows that most of the samples contain Type II kerogen.

Table 1. Rock-Eval[6] data for 28 samples of preferntially picked possible organic-rich fragments from well cuttings (875-630 m) in Beluga O-23 well

Depth (m)	Formation	Sample	Qty	S1	S2	PI	S3	Tmax	Tpeak	S3CO	PC(%)	TOC	RC%	HI	OICO	OI	MINC%
630	Williams Island	12SZ-01-01	70.8	4.22	52.73	0.07	3.53	416	455	1.67	4.93	12.10	7.17	436	14	29	7.0
635	Murry Island	12SZ-01-02	70.5	4.63	49.17	0.09	3.32	414	453	1.63	4.66	11.60	6.94	424	14	29	7.0
640	Moose River	12SZ-01-03	70.5	2.63	32.75	0.07	2.58	416	455	1.04	3.08	7.49	4.41	437	14	34	6.5
645	Moose River	12SZ-01-04	70.0	4.01	48.00	0.08	3.30	416	455	1.50	4.51	10.86	6.35	442	14	30	7.0
650	Moose River	12SZ-01-06	70.4	3.29	39.14	0.08	2.86	413	452	1.33	3.70	9.29	5.59	421	14	31	8.8
655	Moose River	12SZ-01-06	70.1	0.31	5.21	0.06	3.10	423	462	0.49	0.59	2.40	1.81	217	20	129	5.7
660	Moose River	12SZ-01-07	69.8	4.17	45.72	0.08	3.24	414	453	1.50	4.34	10.68	6.34	428	14	30	7.9
665	Moose River	12SZ-01-08	70.4	1.15	15.27	0.07	1.22	416	455	0.52	1.44	3.57	2.13	428	15	34	8.1
675	Moose River	12SZ-01-09	70.2	3.19	36.27	0.08	2.58	415	454	1.14	3.42	8.09	4.67	448	14	32	6.1
680	Moose River	12SZ-01-10	70.2	2.03	24.36	0.08	1.77	416	455	0.79	2.30	5.61	3.31	434	14	32	9.0
685	Moose River	12SZ-01-11	70.5	4.43	47.57	0.09	2.95	413	452	1.51	4.50	10.97	6.47	434	14	27	7.7
690	Moose River	12SZ-01-12	70.6	5.07	48.68	0.09	3.04	415	454	1.46	4.64	10.83	6.19	449	13	28	6.2
695	Moose River	12SZ-01-13	71.0	3.45	40.18	0.08	2.73	416	455	1.25	3.78	9.08	5.30	443	14	30	5.8
700	Moose River	12SZ-01-14	70.5	7.19	74.61	0.09	4.89	414	453	2.37	7.07	17.64	10.57	423	13	28	5.8
710	Moose River	12SZ-01-15	70.0	5.05	58.45	0.08	3.99	418	457	1.84	5.50	13.17	7.67	444	14	30	6.7
715	Moose River	12SZ-01-16	70.8	1.99	25.30	0.07	2.08	416	455	0.85	2.38	5.96	3.58	424	14	35	9.0
720	Moose River	12SZ-01-17	69.7	2.57	29.02	0.08	2.25	415	454	0.98	2.75	6.48	3.73	448	15	35	5.3
730	Kwataboahegen	12SZ-01-18	70.7	0.53	5.89	0.08	0.86	416	455	0.37	0.59	1.60	1.01	368	23	54	11.4
760	Kwataboahegen	12SZ-01-19	70.8	3.03	40.12	0.07	2.52	423	462	1.06	3.73	8.11	4.38	495	13	31	9.2
765	Kwataboahegen	12SZ-01-20	70.4	3.73	37.98	0.09	2.66	416	455	1.18	3.61	8.71	5.10	436	14	31	8.0
770	Kwataboahegen	12SZ-01-21	70.2	0.67	6.55	0.09	2.75	420	459	0.38	0.72	2.57	1.85	255	15	107	5.7
775	Kwataboahegen	12SZ-01-22	70.7	4.78	51.63	0.08	4.39	413	452	1.79	4.92	12.97	8.05	398	14	34	6.7
780	Kwataboahegen	12SZ-01-23	70.6	3.85	45.76	0.08	4.45	412	451	1.72	4.36	11.74	7.38	390	15	38	7.7
785	Stooping River	12SZ-01-24	25.7	8.53	78.14	0.10	4.91	412	451	2.08	7.46	18.74	11.28	417	11	26	5.5
810	Stooping River	12SZ-01-25	70.4	0.55	6.64	0.08	6.34	426	465	0.90	0.86	4.68	3.82	142	19	135	4.1
835	Stooping River	12SZ-01-26	70.7	1.72	23.36	0.07	4.93	417	456	1.25	2.31	8.79	6.48	266	14	56	4.6
850	Stooping River	12SZ-01-27	70.4	1.00	9.53	0.10	6.12	420	459	0.80	1.15	5.45	4.30	175	15	112	4.7
875	Stooping River	12SZ-01-28	70.5	6.58	59.92	0.10	4.42	413	452	2.03	5.78	14.82	9.04	404	14	30	5.1

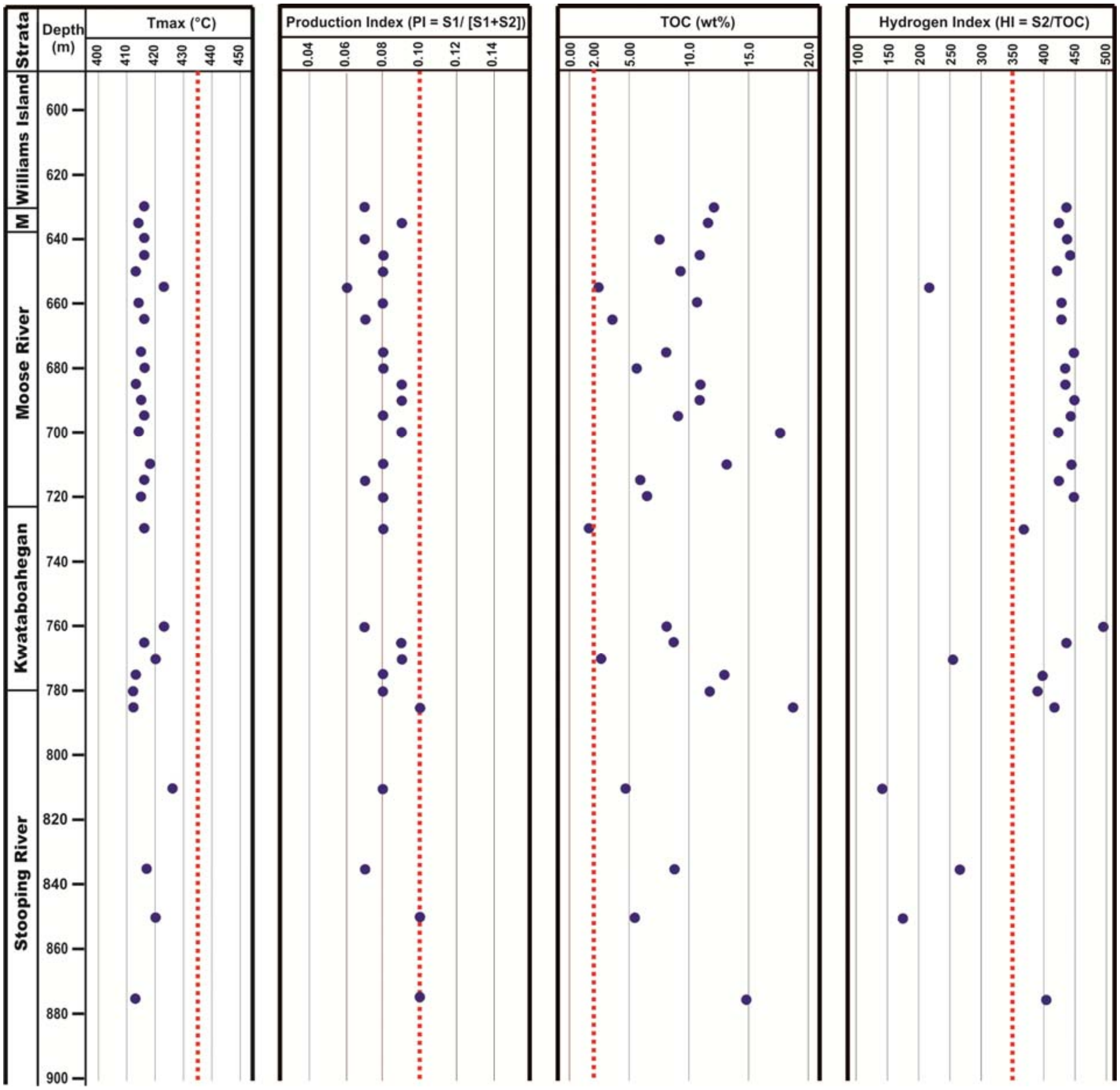

Figure 5. Selected Rock Eval^6 parameters with depth and stratigraphic units for 28 preferentially picked organic-rich fragments from washed cutting samples from Beluga O-23 well.

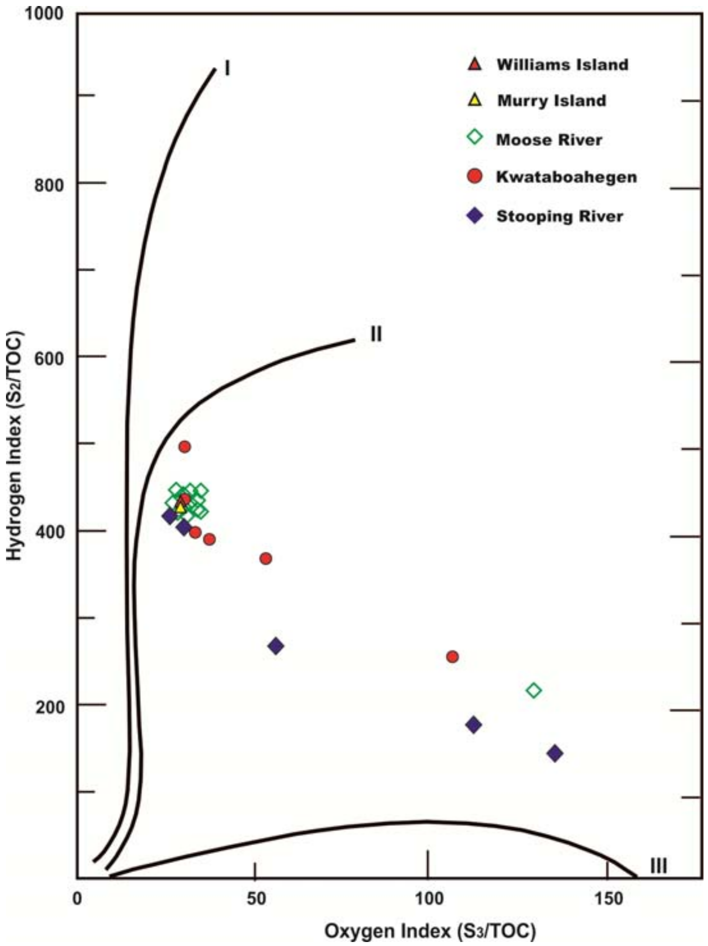

Figure 6. Modified van Krevelen diagram showing relationship between Hydrogen and Oxygen indices of 28 samples of preferentially picked organic-rich fragments from washed cutting samples from Beluga O-23 well.

RECOGNITION OF HYDROCARBON SOURCE ROCKS FROM WELL LOGS

The content of Total Organic Carbon (TOC) in potential source rocks significantly affects the response of conventional well logs, including gamma ray, acoustic transit time, neutron porosity, bulk density, and resistivity. For mixed carbonate evaporites successions, higher total gamma ray values are not only associated with organic matter as they may also indicate higher concentrations of other radioactive materials or glauconite in organic matter lean carbonate, or can be related to potassium-bearing evaporites (Glover, 2012).

However, organic-rich shale can be discriminated by spectral gamma ray log, which records the total gamma ray (*SGR*), with the individual contributions of potassium-40 isotope (K^{40}), uranium series nuclide bismuth (U^{208}), and thorium series nuclide thallium (Th^{214}), as well as the computed gamma ray (*CGR*), which consists of the sum of the potassium and thorium responses. Direct measurements of U concentrations from the spectral gamma ray tool are potentially a more direct indicator of organic matter because this tool isolates the influences of Th and K associated with mica and clay minerals (Stocks and Lawrence, 1990). In pure carbonate rocks, the uranium response is usually associated with organic matter, phosphates and stylolites (Schlumberger, 1989; Serra and Serra, 2004). In clay-bearing carbonate rocks, high gamma ray values are commonly associated with shales and derived from thorium and potassium contributions, but higher uranium contribution indicates organic matter, while potassium-bearing evaporite can be discriminated with the potassium log (Glover, 2012). It is possible to evaluate the organic carbon content of source rock from its uranium content after calibration with core data (Serra and Serra, 2004).

In the Hudson Bay Basin, the spectral gamma ray log was only examined in the Beluga O-23 well. For the study interval of the well, higher uranium values mainly indicate material of organic origin because no obvious glauconite or phosphates have been recognized (from sidewall core description, thin section, and sample description). Relative uranium content for identification of organic matter rich zones can be obtained from the uranium log by using the equation: $Vu = (U-Umin)/(Umax-Umin)$ (U: readings from uranium curve; Umin: minimum uranium reading for evaluated interval; Umax: maximum uranium reading for evaluated interval). Figure 7 shows the combination of conventional well logs with calculated curve from spectral gamma rays for part of the Devonian succession of the Beluga O-23 well, together with lithology interpretation. The plot includes seven data tracks: the first track displays stratigraphy and borehole condition, where enlarged borehole intervals are recognized from caliper log (CAX) and bit size; the second track shows gamma ray logs (SGR, CGR) and acoustic transit time (AC); the third track illustrates detailed thorium (THOR), potassium (POTA) and uranium (URAN) curves; the fourth track shows the calculated relative uranium content (Vu), and measured TOC data; the fifth track displays the resistivity logs, including deep (LLD), medium (LLS) and shallow (MFR) resistivity; the sixth track shows the density log (RHOB), photoelectric index (PEF) and neutron porosity log (POL); the seventh track presents the interpreted lithology primarily from well logs, integrated with core, thin section data and sample descriptions.

From Fig. 7, the evaporite intervals with minor shale exhibit low thorium, potassium and uranium, similar to that of carbonates with minor shale, except a thin zone (depth>876 m) with higher potassium values at the bottom, possibly associated with the presence of sylvite (KCL). Five zones in the shale intervals are characterized by higher uranium values, these cover an overall thickness of about 31 m. These higher uranium content zones are associated with higher organic matter content as indicated by the higher TOC values. Zone A has a thickness of about 4 m, it is located at the base of Williams Island Formation and consists of mudstone from sidewall core description, corresponding good borehole condition. The zone is characterized by low thorium, low potassium but very high uranium values, and the highest relative uranium content in the study interval, indicating an organic matter rich zone confirmed by the measured TOC (12.1%) from well cuttings (Table 1). Zone B, in the Moose River Formation, has a thickness of about 8 m and, based on well logs, is made up of dolomitic shale. On Fig. 7, this zone is characterized by typical shale log responses of increased sonic transit time and neutron porosity,

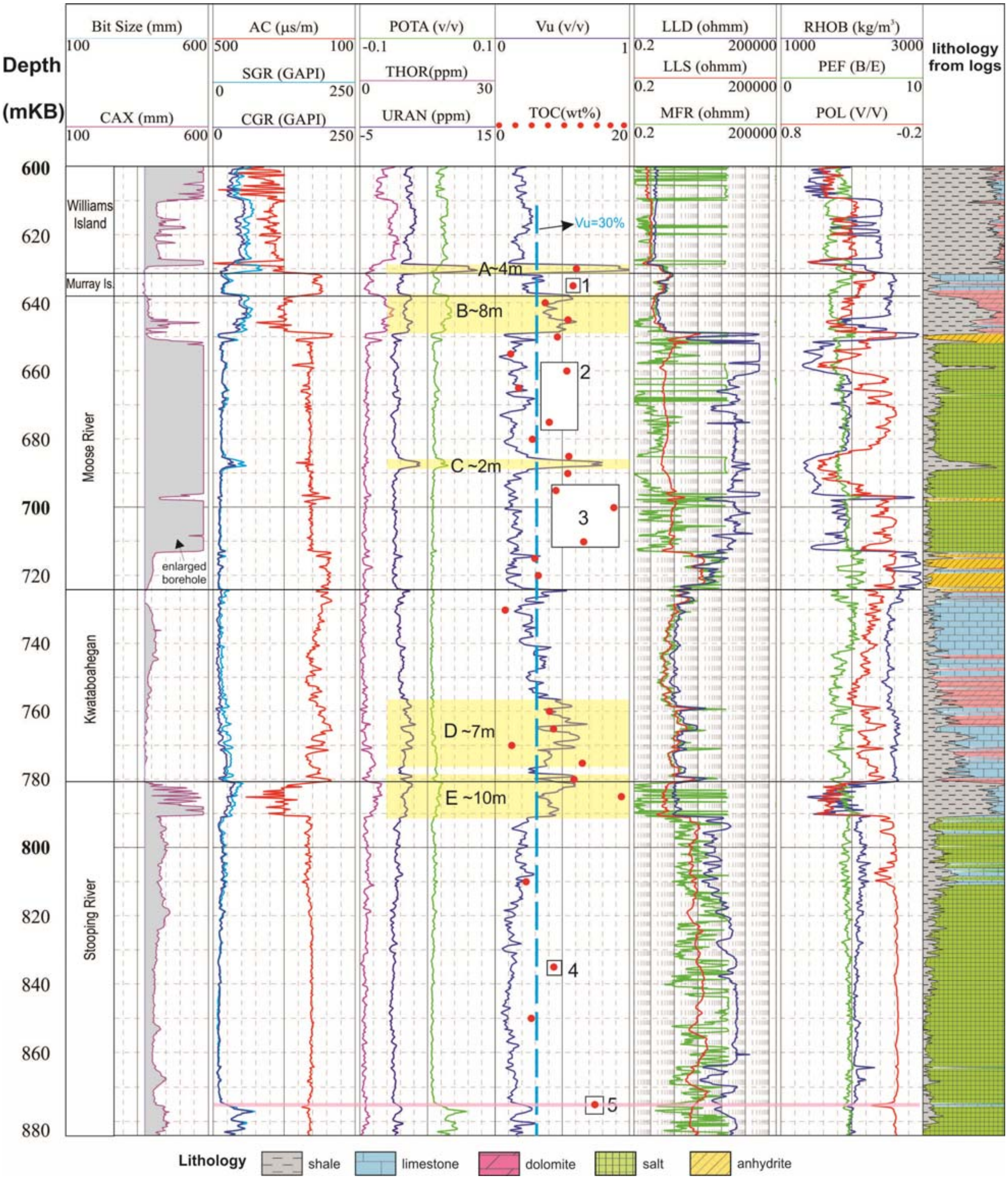

Figure 7. Well log characteristics and organic rich intervals (Zones A to E) for part of the Devonian succession of Beluga O-23 well, Hudson Bay Basin. Boxes 1 to 5 are discussed in text.

higher thorium and potassium. Moreover, higher uranium values for Zone B matches high TOC values of that interval (7.49%, 10.86%, 9.29%; Table 1). Zone C, in the Moose River Formation, corresponding enlarged but uniform borehole condition, is a 2 m thin shale present in thick salt interval, where very high calculated relative uranium content (Vu) indicates the presence of an organic matter rich interval; the log response is consistent with the measured TOC data for that zone (10.97%, 10.83%: Table 1). Zone D, in the Kwataboahegan Formation, consists of a 7 m thick interval of very shaly limestone and dolostone. This zone is characterized by higher uranium value and relative uranium content (Vu), suggesting the presence of organic matter, an interpretation supported by TOC values (8.11%, 8.71%; Table 1) and description of sidewall core mentioning presence of organic material. Zone E straddles the contact Kwataboahegan and Stooping River formations and is about 10 m thick, the log responses suggest the dominance of shale, the caliper log clearly suggest that this zone has been washed out. The higher uranium values and calculated relative uranium content (Vu) support the presence of high content of organic matter, this interpretation agrees with high TOC values (11.7%, 18.7%; Table 1), even though observed uranium log value is lower, which was probably caused by the effect of intensive varying borehole diameters, resulting in lower relative uranium content for the middle and lower part of the Zone E.

DISCUSSION

Based on well log interpretation (Fig. 7), the samples from the five zones (A to E) (with total shale thickness of about 31 m) were probably from the *in-situ* rocks, where both measured TOC and calculated relative uranium content indicate the presence of organic-rich matter. Based on the relative uranium content curve (Vu), the remaining Devonian section consists of lower organic matter units. However, significant discrepancies (boxes 1 to 5, Fig. 7) are suggested by comparing the relative uranium content curve (Vu) and TOC values (Table 1).

The sample in box 1 shows high TOC (11.6%; Table 1), the cutting sample could well originate from either Zone A or B given the 5 m sampling interval. For the evaporite interval of the Moose River Formation, TOC values are high for most of the samples (boxes 2 and 3). This likely results from cavings as the calliper log clearly indicates an enlarged borehole as salt was first encountered (Fig. 7). The salt was likely dissolved with caving and sampling of shale fragments from zones B and (or) C. All but one sample of the Moose River Formation have nearly identical HI and OI values (Fig. 6) again supporting a common origin.

Samples in boxes 4 and 5 are from the salt-rich interval of the Stooping River Formation. For the sample in box 4, from the various logs, it is hard to determine whether it is from the *in situ* rock or from the overlying shale. However, the sample in box 5 is probably from *in situ* shale, where only neutron log shows a big kick but no response from other logs is observed (the purple belt of Fig. 7), because the interval is too thin to investigate.

ACKNOWLEDGEMENTS

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