NWT Open Report 2016-015

Petroleum potential data for the Horn River Group from eight exploration wells – NTS 95N, 95O, 96C, 106H, 106J, 106K, and 106N, Northwest Territories

J. Rocheleau, L.J. Pyle, and K.M. Fiess

NORTHWEST TERRITORIES
GEOLOGICAL SURVEY

Government of
Northwest Territories

Cover Image:
Outcrop of the Horn River Group at Hume River, Northwest Territories.

NWT Open Report 2016-015

Petroleum potential data for the Horn River Group from eight exploration wells – NTS 95N, 95O, 96C, 106H, 106J, 106K, and 106N, Northwest Territories

J. Rocheleau, L.J. Pyle, and K.M. Fiess

Distributed by:
Northwest Territories Geological Survey
Department of Industry, Tourism and Investment
Government of Northwest Territories
P.O. Box 1320, 4601-B 52nd Avenue
Yellowknife, Northwest Territories
Canada
X1A 2L9
867-767-9211
www.nwtgeoscience.ca

Corresponding Author:
Jonathan Rocheleau
Northwest Territories Geological Survey
Email: Jonathan_Rocheleau@gov.nt.ca

Leanne J. Pyle
VI Geoscience Services
Email: lpyle@vigeoscience.com
Brentwood Bay, BC
V8M 1B2
250.652.4076
www.vigeoscience.com

Kathryn M. Fiess
Northwest Territories Geological Survey
Email: Kathryn_Fiess@gov.nt.ca

***Recommended Citation*:**
Rocheleau, J., Pyle, L.J., and Fiess, K.M., 2018. Petroleum potential data for the Horn River Group from eight exploration wells – NTS 95N, 95O, 96C, 106H, 106J, 106K, and 106N, Northwest Territories; Northwest Territories Geological Survey, NWT Open Report 2016-015, 30 pages and appendices.

Introduction

In 2014 the Northwest Territories Geological Survey (NTGS; previously the Northwest Territories Geoscience Office, NTGO) initiated the project, "Shale Basin Evolution in the Central NWT". The main objective of the project was to characterise the source rock potential of the Devonian and Cretaceous age shales to the north and south of the Mackenzie Plain using new outcrop and subsurface data. This report contains petroleum potential data for the Devonian subsurface component of the project, and is a companion paper to a report on surface petroleum potential data in the Mackenzie Plain area (Pyle *et al*. *in press*).

The Devonian Horn River Group consists of the Hare Indian, Ramparts, and Canol formations (Pugh 1983). In the Mackenzie Plain, the Hare Indian, Ramparts, and Canol formations have been extensively sampled and described by Pyle *et al*. (2011, 2014), Gal and Pyle (2012), and Pyle and Gal (2012, 2013). The Canol Formation is a major exploration target in the central Mackenzie Plain for shale-hosted hydrocarbons. The thermal maturation trends for the Canol Formation have been documented primarily in the central Mackenzie Plain (Feinstein *et al*. 1988; Snowdon 1990; Pyle and Gal 2009; Hannigan *et al*. 2011; Gal and Pyle 2012; Pyle *et al*. 2014; Hadlari *et al*. 2015) based on historical Geological Survey of Canada (GSC) data and studies conducted by NTGS. Previously published thermal maturity (T_{max}) data for the Canol Formation, from outcrop and exploratory wells suggest that the Canol Formation is in the oil window at depths greater than 600 m in most of the Peel Plain and parts of the Mackenzie Plain (Hadlari *et al*. 2015). The Canol Formation is comprised mostly of siliceous shale and mudstone with minor limestone (Pyle *et al*. 2014), and is informally divided into a lower recessive, middle resistant, and an upper recessive unit as defined at the reference section near the Mountain River (Pyle *et al*. 2016).

This paper reports on data from a sampling of well cuttings, from eight wells (Appendix 1), that penetrate the Canol Formation (sometimes identified in older wells as the generic "Horn River Group") in the southern Mackenzie and Peel plains (Figure 1). The petroleum potential data were derived from well cutting samples and analysed for source rock potential (thermal maturity, kerogen type, and total organic carbon (TOC) by Rock-Eval pyrolysis; Appendix 2); thermal maturity by reflected light microscopy (vitrinite reflectance; Appendix 3); and whole rock geochemistry, major oxides and trace elements via inductively coupled plasma-atomic emission spectroscopy (ICP-AES) and inductively coupled plasma-mass spectroscopy(ICP-MS)(Appendix 4).

Study location

Eight abandoned exploratory wells (Appendix 1) were selected for this study based on location, the availability of the Canol Formation samples from cuttings, and the lack of previous sampling in the target interval; four wells were selected from the southern edge of the Mackenzie Plain and four wells in the Peel Plain (Figure 2). The well cuttings are archived at the GSC Core and Sample Repository, in Calgary, Alberta.

Figure 1. Location of exploration regions included in this study (red outline), communities, and roads (Yellow: all-season road; Blue: winter road) on a topographic background. These include, from northwest to southeast: Peel Plain, Mackenzie Plain, and the Franklin Mountains. Inset map shows the position of Northwest Territories within Canada.

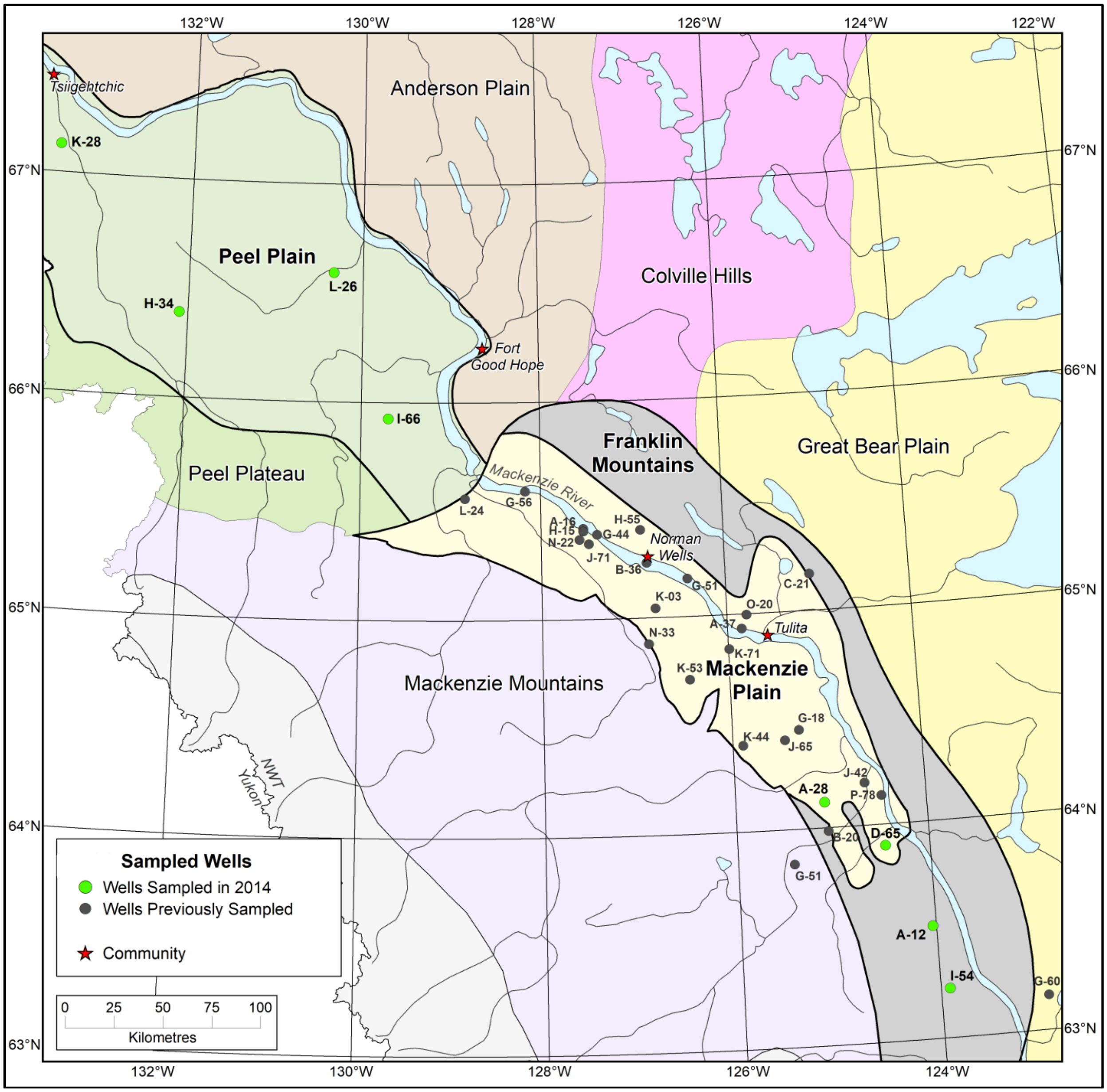

Figure 2. Location of the wells sampled in this study (green dots) and wells previously sampled by Northwest Territories Geological Survey (grey dots) and reported by Pyle *et al.* (2014) in the Northwest Territories, Canada. Coloured geophysical regions after Mossop *et al*. (2004).

Geologic background

The Mackenzie Plain is a geophysical region within the Northwest Territories (NWT), which contains the communities of Norman Wells and Tulita. It is bracketed by the Mackenzie Mountains to the southwest and the Franklin Mountains to the northeast

(Figure 1). To the northwest the Peel Plain forms a contiguous area of lowlands with the Mackenzie Plain.

The Middle to Upper Devonian Horn River Group unconformably overlies the shelf deposits of the Middle Devonian Hume Formation (Figure 3). The Horn River Group consists of the Hare Indian, Ramparts, and Canol formations (Pugh 1983). The Hare Indian Formation is divided into the lower Bluefish Member consisting of organic-rich shale, and an upper Bell Creek Member (previously referred to as the "Grey Shale Member") consisting of argillaceous shale (Pyle *et al.* 2016). In much of the Mackenzie Plain, the Hare Indian Formation is overlain by the Ramparts Formation. The Ramparts Formation consists of calcareous shale and fossiliferous carbonate, interpreted to represent a ramp and platform depositional setting (Pyle *et al.* 2014). The Kee Scarp Member, which represent reef facies of the Ramparts Formation, is locally present near Norman Wells and is a producing oil reservoir (Muir and Dixon 1985). The siliceous basinal shales of the Canol Formation overlie the Ramparts Formation (where the formation is present) and the Hare Indian Formation. The Canol Formation is the source rock for the Norman Wells oilfield and is considered to contain a significant quantity of hydrocarbons (Northwest Territories Geological Survey and National Energy Board 2015). The Horn River Group is conformably overlain by the thick basin to shelf deposits of the Imperial Formation (Pugh 1983).

Materials and methods

The sampled intervals from the eight wells (Appendix 1) were selected after consulting published formation tops and well history reports (Hogue and Gal 2008), and the examination of vials of washed cuttings, which were approved by the National Energy Board (NEB). Eighty-eight samples of approximately fifteen grams were collected from the unwashed cuttings, if there was enough suitable material available. Sample material was removed, weighed, sieved, washed, and air-dried. The dried samples were picked under a stereo microscope to remove cavings, drilling mud, wood chips, metal shavings, or other potential contaminants that were not removed by sieving and washing. The picked samples were divided into portions for analyses. Samples were analysed using a Rock-Eval pyrolysis VI instrument at the GSC in Calgary (88 samples total; Appendix 2). Select samples (23 total) were submitted to the GSC for thermal maturation analysis through reflected light microscopy (vitrinite reflectance; Appendix 3).

A split of approximately 10 g from each sample (88 total from 8 wells) was analysed by ICP-MS for whole-rock, trace-, and rare earth element abundances (Appendix 4 and Appendix 5). The washed and picked cuttings were sent to Bureau Veritas Commodities Canada Ltd. in Vancouver, British Columbia for sample preparation and analysis. Major oxides were calculated by ICP-AES of a 0.2 g pulverized rock sample that was fused utilizing lithium metaborate/tetraborate fusion and then dissolved in dilute nitric acid. Loss on ignition (LOI) was calculated by sample weight difference after ignition at 1000 °C. Carbon and sulphur were analysed by LECO induction furnace. Trace elements were determined by ICP-AES and some by ICP-MS, after dissolution in aqua regia.

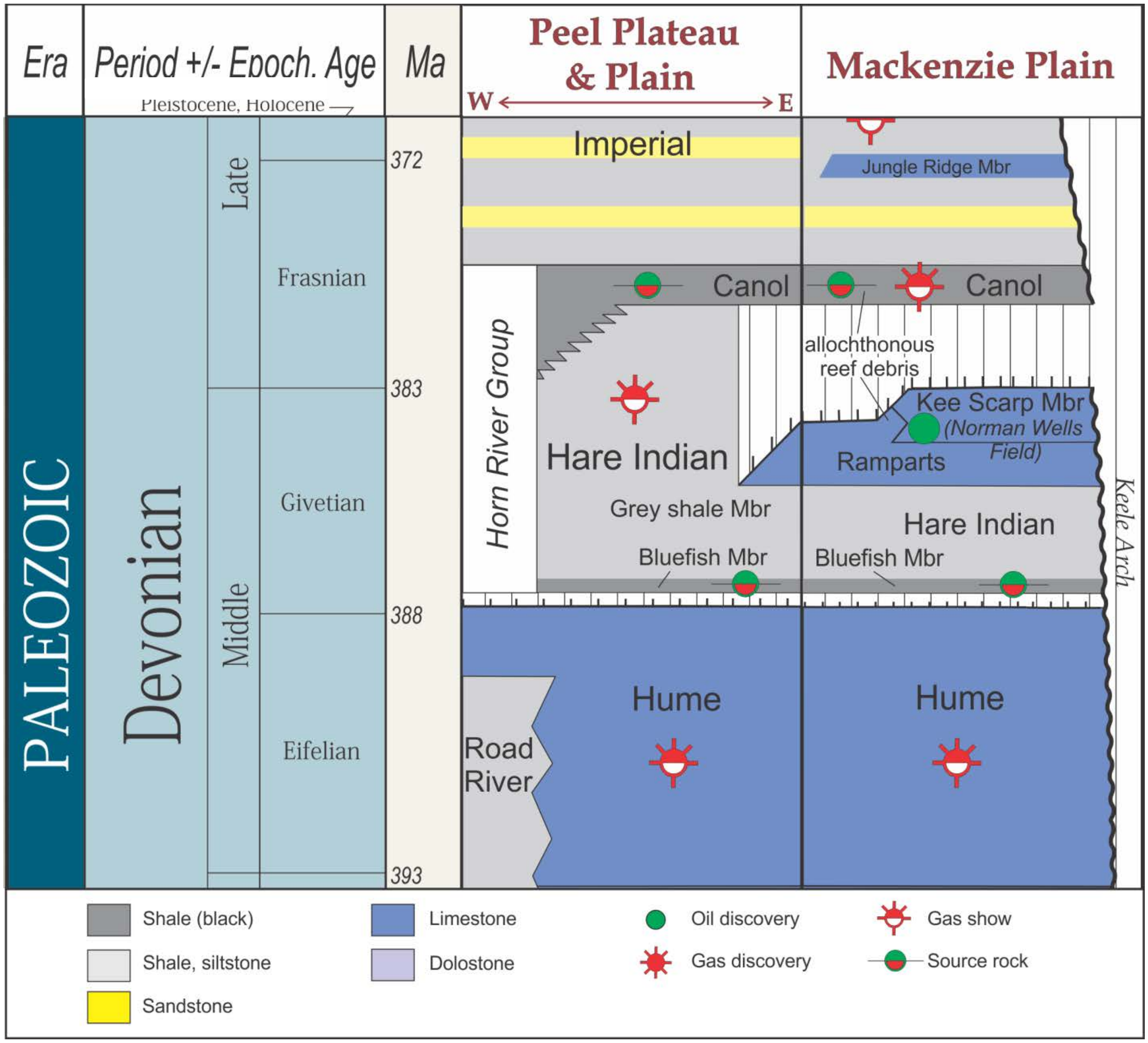

Figure 3. Regional time stratigraphic columns for the Peel and Mackenzie plains. Modified from Rocheleau and Fiess (2014).

Rock-Eval and total organic carbon analyses

Rock-Eval pyrolysis and TOC analyses from the Mackenzie Plain exploration wells (Figure 2) have been previously compiled and reported by Feinstein *et al.* (1988), Snowdon (1990), Pyle and Gal (2009), Hannigan *et al*. (2011), Gal and Pyle (2012), and the latter superseded by Pyle *et al.* (2014). The Mackenzie Plain outcrop sample results for the Canol Formation were reported by Pyle *et al*. (2014) and Pyle *et al.* (2016).

Table 1 shows the average TOC values in weight percent (wt. %) from each well for the Canol and other formations of the Horn River Group. The Imperial Formation samples in Table 1 were retroactively identified based on results from the lithogeochemical analysis. Figure 4 shows histograms of TOC values for the Peel Plain and southern Mackenzie Plain wells, and a histogram showing the combined data from both areas.

Median TOC values for the Canol Formation are > 2 wt. % from both the Peel Plain and southern Mackenzie Plain wells, which suggests that the Canol Formation generally has good source rock potential in both of these areas. Three of the four wells sampled in the Peel Plain have average TOC values ranging from 3 wt. % to 5.22 wt. %, which indicates excellent source rock potential. However, results from the northernmost well, Swan lake K-28, with an average TOC of 0.99 wt. %, suggest a more organic-lean Canol Formation. More sampling is required to determine if this is a typical TOC range in that part of the Peel Plain. In the Mackenzie Plain wells, the Canol Formation TOC values range from 1.56 wt. % to 2.91 wt. % with a subtle increase southwards.

Table 1. Average total organic carbon values from the Horn River Group, and the Imperial Formation samples from the Peel Plain and the southern Mackenzie Plain wells.

Well site identification	Location		Average total organic carbon (wt. %) and sample number (n)				
	Latitude	Longitude	Imperial Formation	Canol Formation	Ramparts Formation	Hare Indian Formation	Bluefish Member
Swan Lake K-28	67.1283	-133.5789	1.01 (n=5)	0.99 (n=8)	–	–	0.93 (n=1)
Ontaratue H-34	66.3896	-132.0976	–	3.99 (n=4)	–	–	6.30 (n=1)
Grandview L-26	65.5922	-130.3392	–	5.11 (n=5)	–	–	–
Hume River I-66	65.9261	-129.6943	–	3.00 (n=4)	–	–	–
Keele S. A-28	64.1175	-125.0694	0.56 (n=1)	1.56 (n=9)	–	–	–
Dahadinni D-65	63.9021	-124.4648	–	2.21 (n=14)	–	1.92 (n=1)	–
Johnson A-12	63.5172	-124.0375	–	2.30 (n=6)	1.26 (n=1)	–	–
Wrigley I-54	63.2258	-123.9089	–	2.91 (n=13)	1.44 (n=3)	–	–

Five samples, taken between 1350 m to 1375 m depth, in the Swan Lake K-28 well were interpreted to be from the Imperial Formation and have fair source rock quality averaging a TOC value of 1.01 wt %, not appreciably different than the values from the Canol Formation in the same well. Another sample, taken at a depth of 2253 m is the uppermost sample in the Keele S. A-28 well, was interpreted to be from the Imperial Formation. This sample, however, shows a decrease in TOC from 1.56 wt. % in the Canol Formation to 0.56 wt. % in the Imperial Formation.

Three samples, taken between 174 m to 189 m depth from the Wrigley I-54 well and one from the Johnson A-12 well (649 m) were interpreted to be from the top of the Ramparts Formation. These samples indicate fair source rock potential with TOC values of 1.44 wt. % (Wrigley I-54) and 1.26 wt. % (Johnson A-12) respectively. One sample (1369 m) from the Dahadinni D-65 well was interpreted to be from the Hare Indian Formation and suggests fair source rock potential with a TOC value of 1.92 wt. %. One sample (972 m) from the Ontaraute H-34 well, was interpreted to be from the Bluefish Member and suggests excellent source rock potential with a TOC value of 6.30 wt. %. The second sample, at 1420 m from Swan Lake K-28, was interpreted to be from the same member but yielded a TOC value of 0.93 wt. %, and may instead represent the organic-lean upper part of the Hare Indian Formation (Bell Creek Member). More analyses are required to reaffirm or modify the interpretation.

Average S_1, S_2, T_{max}, and Production Index (PI) values from Rock-Eval analysis, for the Canol Formation samples from each well, are presented in Table 2. In the Peel Plain, the samples from the Swan Lake K-28 well have an average T_{max} of 457.5 °C and a PI of 0.31, which puts these values in the upper end of the oil window. The average T_{max} of 462.3 °C and PI of 0.43 places samples from the Ontaratue H-34 well in the lower gas window. The Canol Formation, in the Grandview L-26 well, is immature with an average T_{max} of 429.0 °C and PI of 0.08. Finally, the Average T_{max} of 460.3 °C in the Hume River I-66 well places in the lower gas window while the PI of 0.28 places the Canol Formation in the upper oil window. In the southern Mackenzie Plain, samples from the Canol Formation in all four wells have average T_{max} values that would suggest the Canol Formation is immature in that region. These results are probably unreliable, due to S_2 values near or below to 0.2 mg Hc/g (Peters 1986). However, average PI values range between 0.6 and 0.7, which indicates overmaturity.

Figure 5 shows a map with T_{max} values for the Canol Formation across the Mackenzie Plain and Peel Plain. Data for the map are based on Rock-Eval pyrolysis analyses from wells in this study, from previous NTGS well sampling (Pyle *et al*. 2014) and GSC sampled wells (Feinstein *et al.* 1988; Snowdon 1990; Dougherty *et al.* 1991; Stasiuk *et al.* 2003; Issler *et al*. 2005). Following the methodology proposed by Peters (1986), the T_{max} values shown on the map were calculated by averaging well data and discarding T_{max} values corresponding to an S_2 <0.2. The T_{max} values for the southern Mackenzie Plain indicate immaturity, and are anomalously low. These values do not correspond well with the average PI values from the same wells, which indicates overmaturity. This is thought to indicate a separate heat regime in the southernmost Mackenzie Plain, with the transition from the northern regime occuring at the Keele Fault (see Figure 5 for location), the approximate northern boundary of the Paleozoic Root Basin (Feinstein *et al.* 1991). The limited data in the Peel Plain from this study appear to follow the southwest to northeast trend of decreasing maturity found in the Mackenzie Plain well and outcrop samples (Pyle *et al.* 2014).

A Pseudo-van Krevelen crossplot of hydrogen index (HI) versus oxygen index (OI) for the Canol Formation from the eight wells sampled in this study is shown in Figure 6, and indicates Type I and/or Type II kerogen in the Peel Plain wells. Data from the southern Mackenzie Plain wells with low S_2 values cluster on the x-axis near the origin, due to overmaturity (Dahl *et al.* 2004). Samples from the Grandview L-26 and Hume River I-66 wells indicate Type I and Type II kerogens, those from the Ontaratue H-34 well indicate Type I kerogen, and samples from the Swan Lake K-28 plot solely in the Type II Kerogen field. This is consistent with observations from samples from the prior subsurface study in the Mackenzie Plain and past interpretations of the depositional environment (Pyle *et al*. 2014). Kerogen types are indistinguishable for samples with high levels of thermal maturity from the southern Mackenzie Plain.

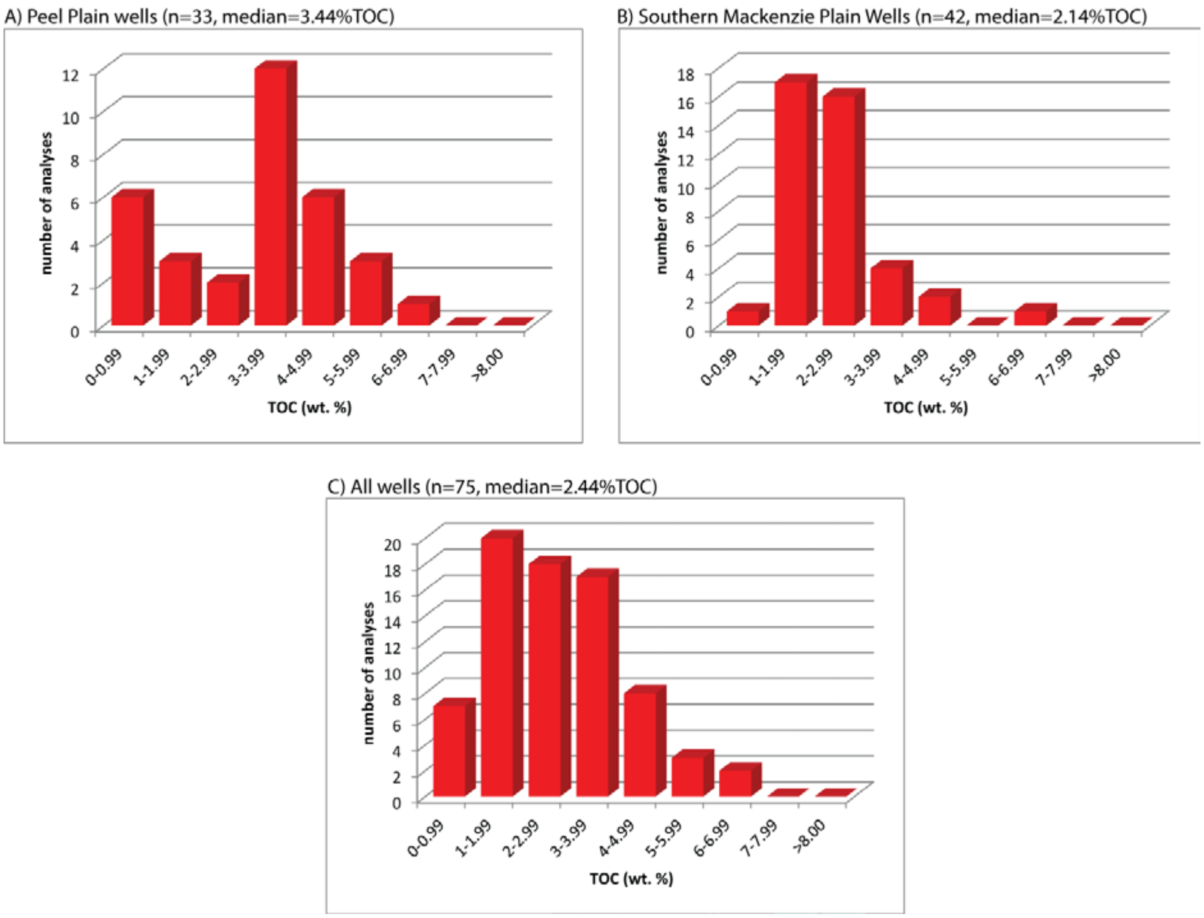

Figure 4. Histograms showing total organic carbon values (TOC) from sampled wells in the Canol Formation. A) Wells in the Peel Plain area. B) Wells in the Southern Mackenzie Plain area. C) Combined histogram showing all wells.

Table 2. The average S_1, S_2, and the production index (PI) of samples from the Canol Formation at the average temperature max (T_{max}) from Rock-Eval pyrolysis analyses.

Well Name	Number of samples	Average S_1 (mg Hc/g rock)	Average S_2 (mg Hc/g rock)	Average T_{max} (°C)	Average PI
Swan Lake K-28	8	0.27	0.60	457.5	0.31
Ontaratue H-34	16	1.81	2.49	462.3	0.43
Grandview L-26	5	1.94	21.20	429.0	0.08
Hume River I-66	4	1.25	3.80	460.3	0.28
Keele S. A-28	9	0.22	0.15	379.4[2]	0.60
Dahadinni D-65	14	0.31	0.17	333.6[3]	0.64
Johnson A-12	6	0.36	0.21	329.3[1]	0.62
Wrigley I-54	13	0.84	0.27	312.9[4]	0.76

[1]=average T_{max} has been calculated without including three samples with S_2 values less than 0.2 mg Hc/g;
[2]=average T_{max} suspect because all S_2 values were less than 0.2 mg Hc/g;
[3]=average T_{max} has been calculated without including ten samples with S_2 values less than 0.2 mg Hc/g;
[4]=average T_{max} has been calculated without including three samples with S_2 values less than 0.2 mg Hc/g (Peters 1986).

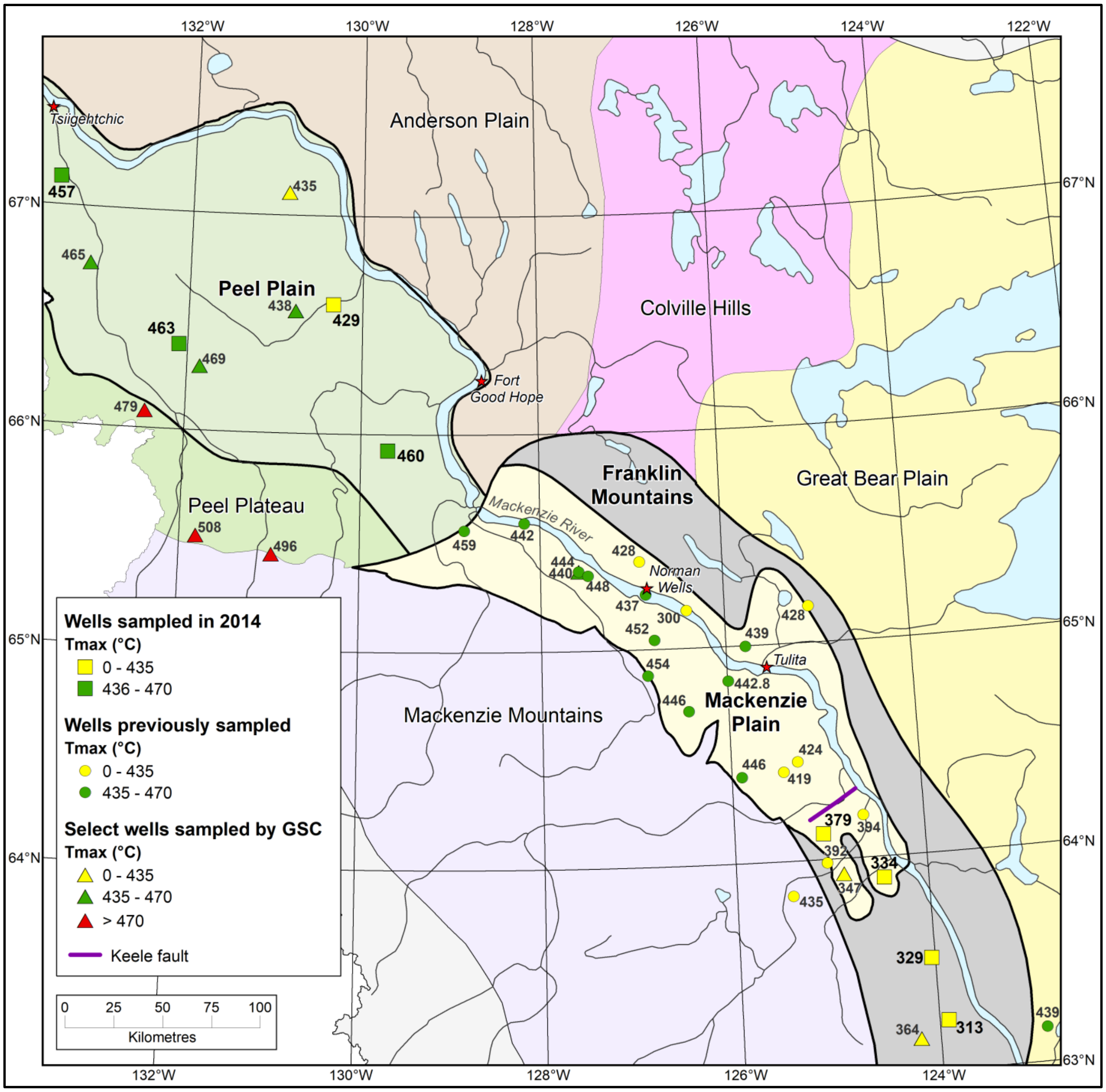

Figure 5. Thermal maturity of the Canol Formation indicated by T_{max} (°C) values from Rock-Eval pyrolysis analyses. Wells sampled in this study are represented by squares, wells sampled by the Northwest Territories Geological Survey previously are represented by circles, and selected wells sampled by the Geological Survey of Canada are represented by triangles (Feinstein *et al*. 1988; Snowdon 1990; Dougherty *et al.* 1991; Stasiuk *et al.* 2003; Issler *et al.* 2005).The colours indicate thermal maturity: yellow represents immature, green mature, and red overmature samples. Location of Keele Fault after Feinstein *et al.* (1991). Geophysical regions after Mossop *et al.* (2004).

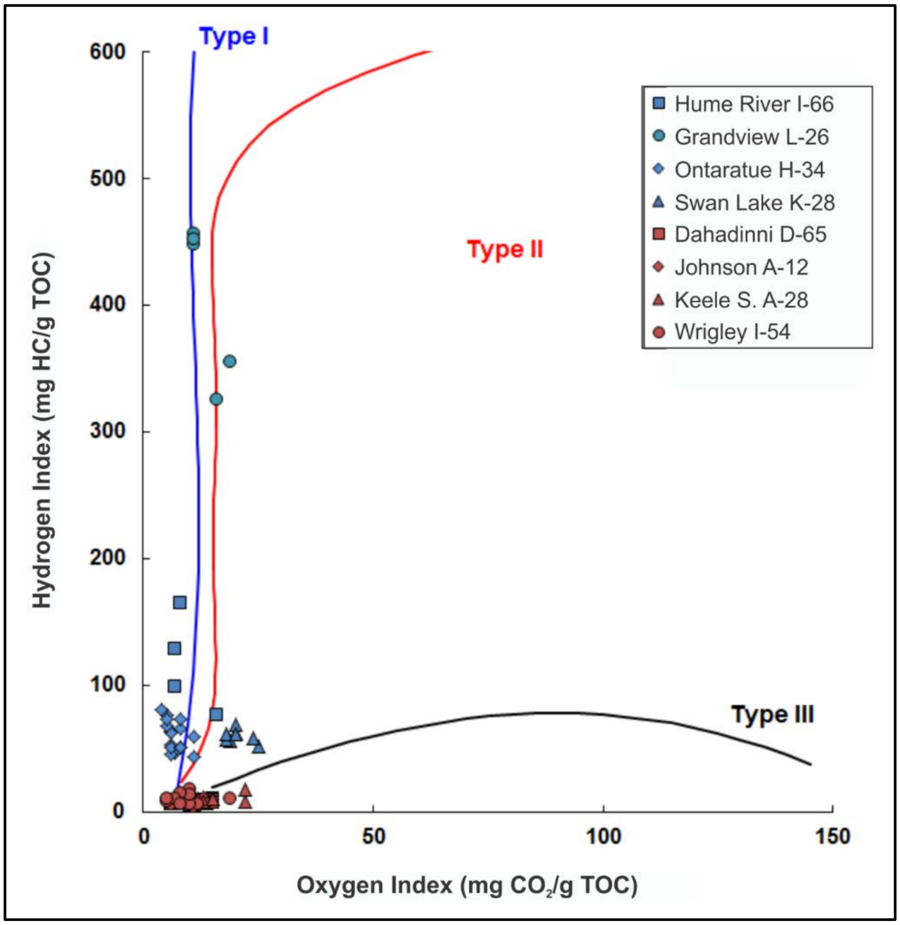

Figure 6. Pseudo-van Krevelen crossplot of hydrogen index (HI) versus oxygen index (OI) from the Rock-Eval pyrolysis for the Canol Formation samples analysed in this study. HI is a ratio which depicts the convertibility of S_2 (nonvolatile organic material to oil and gas; mg HC/g dry rock) to the total organic carbon (TOC; grams, g). OI is a ratio which depicts the amount of S_3 (organic carbon dioxide released during pyrolysis; mg HC/g dry rock) to TOC (grams). Samples from the Peel Plain wells (blue) suggest Type I and/or Type II kerogen; those from the southern Mackenzie Plain wells (red) are overmature.

An S_2 vs TOC cross plot of the Canol Formation samples is shown in Figure 7. The slope of the cross plot is a measure of HI; slopes of 700 and 200 divide the cross plot into fields representing Type I, Type II, and Type III kerogen (Dahl *et al.* 2004). The cross plot suggests Type II and Type III kerogen are present in the Canol Formation, with the latter possibly present due to contamination from the Imperial Formation or Cretaceous cuttings. Similarly, a crossplot of HI versus T_{max} (Figure 8) also suggests Type II and Type III kerogen in the Canol Formation. The discrepancy between crossplots may be due to the effects of maturation, because HI decreases with increasing maturity (Dahl *et al.* 2004). This causes more mature samples to plot closer to the origin (see Figure 6), or closer to the x-axis (Figure 7 and Figure 8). In all three crossplots, the least mature samples plot mostly in the Type I and/or Type II kerogen fields.

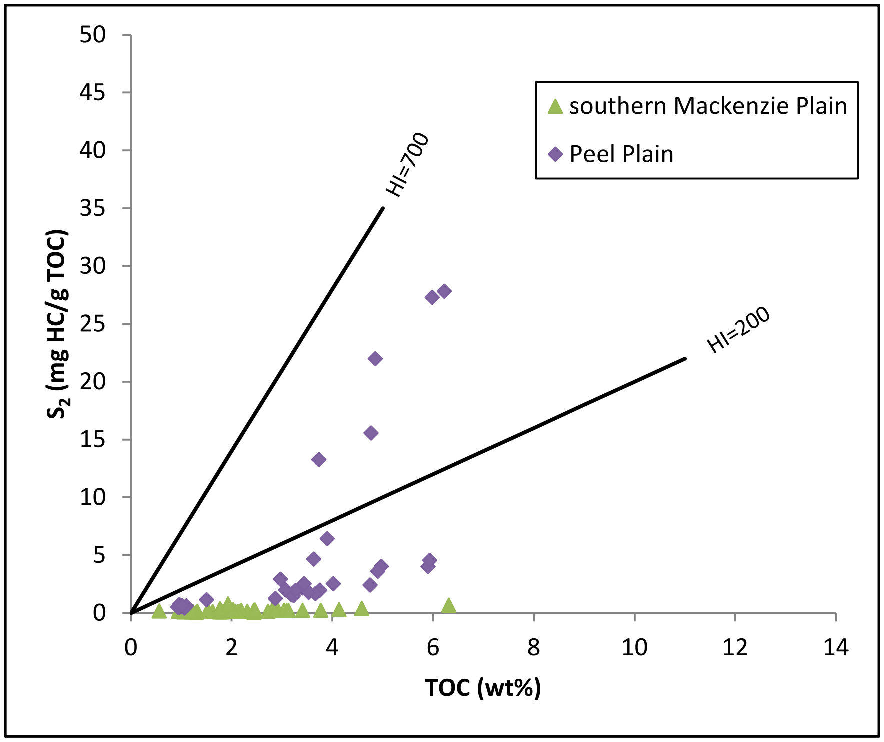

Figure 7. Cross plot of S_2 versus total organic carbon (TOC) of the Canol Formation samples analysed in this study. The field is divided into kerogen types by slope lines that represent hydrogen index (HI).

Vitrinite reflectance

A total of 23 samples from eight wells were analysed for vitrinite reflectance to determine source rock maturity (Table 3). Of these 23 samples, based on lithogeochemistry profiles, 21 samples are interpreted to be from the Canol Formation and 2 samples from the Imperial Formation. Reflectance determinations were carried out by Julito Reyes at the GSC, Calgary (for full results and petrographic descriptions see Appendix 3).

Reflectance values from the four wells in the southern Mackenzie Plain all exceed 1.80% R_o (Table 3), which suggests a range in the the dry gas window (Hunt 1996; Figure 9). A comparison with T_{max} values for these wells is not instructive, because many of these values are < 435 °C, and unreliable due to low S_2 values.

In the Peel Plain, reflectance values for the Hume River I-66, Grandview L-26, and Ontaratue H-34 wells suggest maturity in the wet gas and oil window, with one value at the base of the Canol Formation in the Ontaratue H-34 well suggesting the more mature wet gas zone (> 1.35 % R_o; Table 3). Reflectance values from the most western well, Swan Lake K-28, suggest the wet gas window (> 1.35 % R_o; Table 3). For these wells, reflectance and T_{max} values are in agreement for maturity in the Ontaratue H-34 well and for one sample from the Hume River I-66 well. The lower sample from the Canol Formation in the I-66 well is indicated to be mature in the wet gas and oil window based on reflectance, but mature based on a T_{max} of 487 °C. Reflectance values from the Grandview L-26 well suggest maturity (0.71 % R_o to 0.72 % R_o) within the wet gas and oil window. Here, however, the T_{max} values suggest immaturity (427 °C to 430 °C). The reflectance values from the Swan

Lake K-28 well suggest the wet gas window (>1.35 % R_o), whereas T_{max} values suggest a range of maturity within the oil window (average T_{max} of 455 °C).

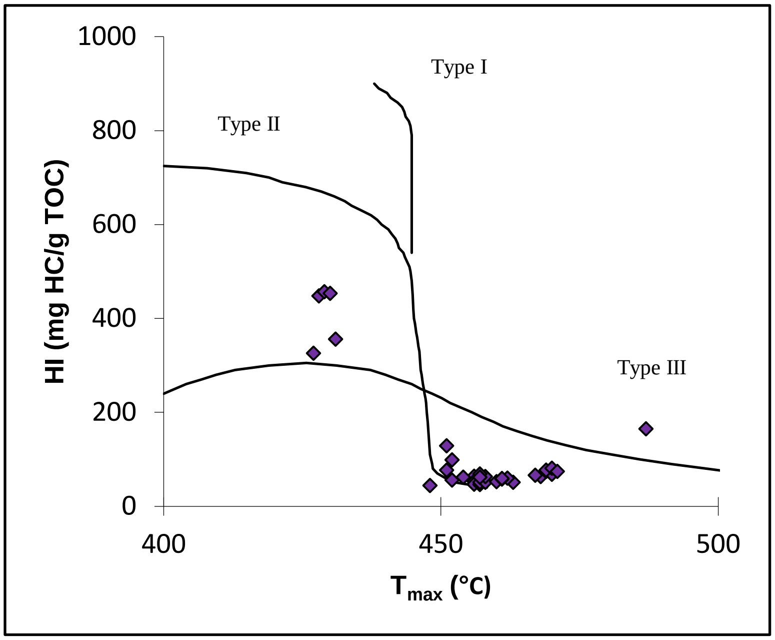

Figure 8. Cross plot of the hydrogen index (HI) versus T_{max} (°C) of the Canol Formation samples from the wells in the Peel Plain.

Lithological Characterization

Whole rock geochemistry analyses were carried out on a total of 88 samples from the eight wells with the aim to geochemically compare the samples from the current wells to previously sampled wells and outcrops.

The silica (SiO_2) content of shales is an important parameter that can be used as a proxy for brittleness. Silica content of the Canol Formation in the Peel Plain and southern Mackenzie Plain ranges from 45 wt. % to 78 wt. %, with an average of 65 wt. % (Figure 10; Appendix 4). This is comparable to values reported from previous subsurface sampling in the Mackenzie Plain (Pyle *et al.* 2014). High total SiO_2 values obtained by the analysis do not distinguish biogenic SiO_2 from detrital quartz. A cross plot of zirconium (Zr) versus SiO_2 (Figure 10) shows most samples from the Canol Formation have relatively high SiO_2 and low Zr (negative Si/Zr slope) compared to the other sampled formations. The excess SiO_2 in these samples is interpreted to be biogenically derived (Wright *et al.* 2010). In contrast, samples of the Ramparts Formation have lower weight percent of SiO_2, and the few samples from the Hare Indian and Imperial formations have a positive correlation of the two elements, likely due to terrigenous input. Note that some of the Canol Formation samples from the Swan Lake K-28 well cluster with samples of the Imperial Formation from this well, which either indicates that the Canol Formation also had higher terrestrial input and dilution of organic matter at this locality, or that the samples were contaminated by cavings.

Inferences about the depositional environment can be made using geochemical proxies derived from the whole rock chemistry results. By calculating a ratio of SiO_2/Zr, intervals with excess silica can be identified. The terrigenous input profile (TIP) is the sum of major oxides most related to detrital input: aluminum oxide (Al_2O_3), potassium oxide (K_2O), titanium oxide (TiO_2) and iron oxide (Fe_2O_3). The Th/U ratio can be used as a proxy for detrital clay input and typically correlates well with the TIP. Several geochemical proxies can be used to characterize the depositional environment of the Canol Formation. Certain trace elements, such as uranium (U), molybdenum (Mo) and vanadium (V) are redox sensitive and tend to be enriched in oxygen-depleted sediments. The enrichment factor (EF) of these elements can be used to infer anoxic vs oxic depositional conditions. The principle redox proxy used in this study is EFV, which is the ratio of V to Al_2O_3 of the sample divided by the ratio of V to Al_2O_3 of average shale (Tribovillard *et al.* 2006). The Ni/Co ratio can be used to distinguish oxic (0 to 5), dysoxic (5 to 7), and anoxic (> 7) conditions based on the magnitude of the ratio (Rimmer 2003). Figure 11 to Figure 18 illustrate profiles for select parameters that provide a standard for comparison across the study area, and profiles for select oxides and elements are illustrated for each well in Appendix 5.

The Canol Formation is characterized by high, sustained gamma and corresponding high TOC and U levels. It is distinguished by a markedly higher SiO_2/Zr ratio profile and lower TIP and Th/U profile values compared to the underlying Ramparts and Hare Indian formations (including the Bluefish Member). The contrast in TIP and Th/U profiles from the Hare Indian Formation to the Canol Formation can be seen in the Swan Lake K-28 well (Figure 11), the Ontaratue H-34 well (Figure 12), and the Dahadinni D-65 well (Figure 16). In the Wrigley I-54 well, the top of the Ramparts Formation is interpreted to be around 571 feet (174 m) due to the higher TIP and Th/U values in the underlying interval (Figure 18).

An increase in the TIP and Th/U parameters, associated with a decrease in SiO_2, typically mark the contact between the Canol Formation and the overlying Imperial Formation. The top pick for the Canol Formation in the Swan Lake K-28 well was presumed to be at 4430 feet (1350 m) upon initial sampling, but could be re-interpreted to be at 4540 feet (1384 m) based on the increase in the TIP value to > 25, and Th/U ratio > 2 (up to 3), and lower U concentration and SiO_2/Zr ratio values compared to the underlying interval of the Canol Formation shale. Similarly, in the Keele South A-28 well, an increase in the TIP value to > 25 and Th/U ratio > 3, and a decrease in the SiO_2/Zr ratio, suggests that the uppermost sample might be interpreted to be the Imperial Formation, but this conclusion is reserved until additional sampling through the Imperial Formation interval can ascertain this interpretation. A third well that requires additional sampling to pinpoint the base of the Imperial Formation is Wrigley I-54, where TOC and SiO_2 values decrease around 361 feet (110 m), and the TIP and Th/U profile values increase at the same horizon (Figure 17).

In some outcrops and wells, the Canol Formation contains a significant spike in barium (up to 12 500 ppm at the Mountain River reference section; Pyle *et al.* 2014). This anomaly is present in one well in the Peel Plain (Ontaratue H-34 well) and in three wells in the southern Mackenzie Plain (Johnson A-12, Dahadinni D-65, and Wrigley I-54; see Appendix 5).

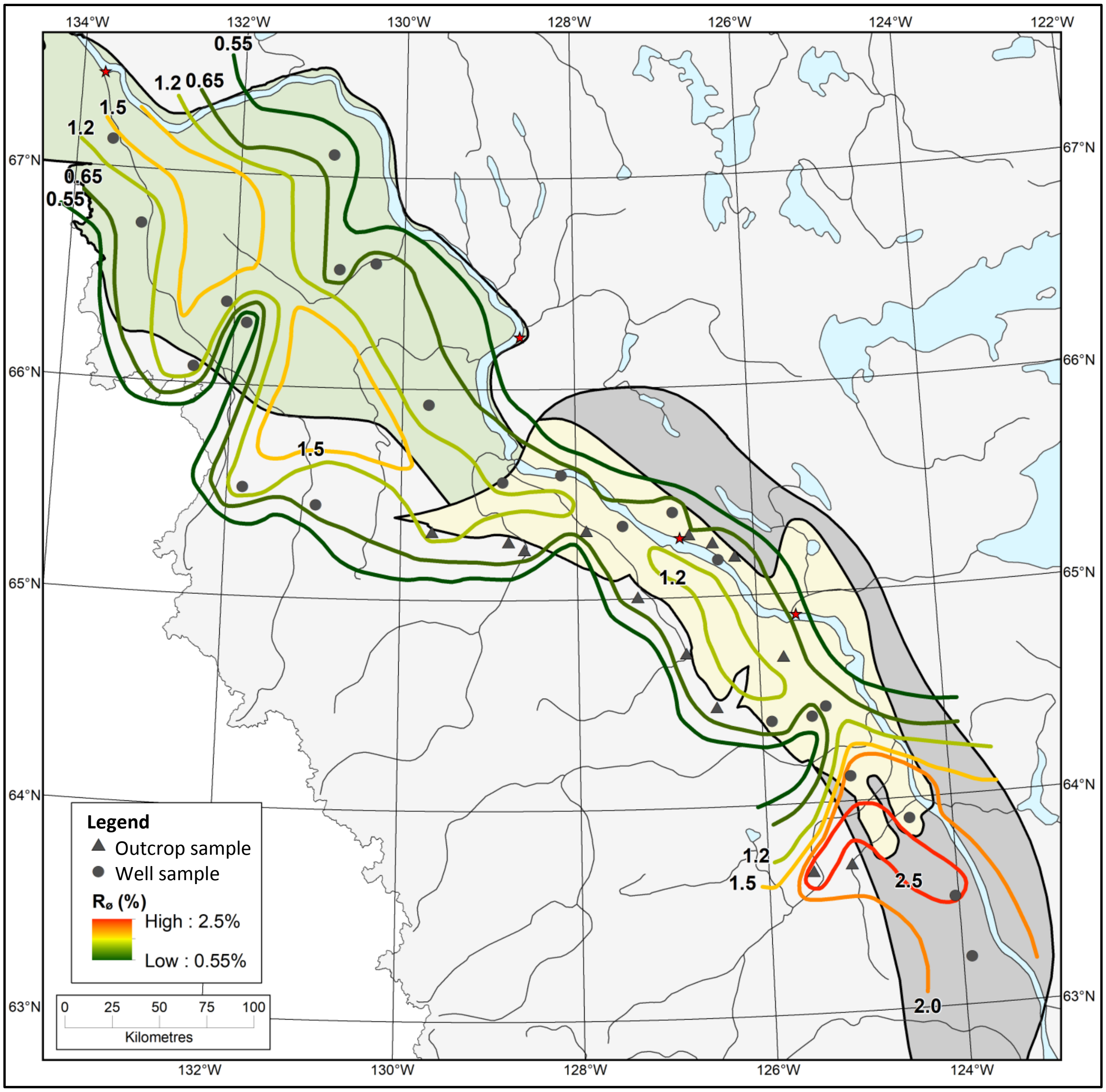

Figure 9. Contoured thermal maturity of the Canol Formation indicated by average vitrinite (or equivalent) reflectance (%Ro) values from vitrinite reflectance analyses. Both the Northwest Territories Geological Survey and the Geological Survey of Canada sampled wells are represented by circles. The Northwest Territories Geological Survey surface outcrop sample locations are represented by triangles. Coloured and outlined areas include: Peel Plain (green), Mackenzie Plain (yellow), and Franklin Mountains (grey).Geophysical regions after Mossop *et al.* (2004).

Table 3. Comparison of average vitrinite (or equivalent) reflectance (% R_o) and T_{max} from Rock-Eval pyrolysis analyses of wells samples. Green indicates values in the oil window, purple indicates immature values and red indicates post-mature for oil.

Well, Sample Number, Stratigraphic Location	Number of data points for average vitrinite reflectance (maceral)	Average vitrinite (or *equivalent) reflectance (%Ro)	Tmax from Rock-Eval (°C)
Hume River I-66			
670 m, Canol	5 vitrinite equivalent	**1.10**	**451**
685 m, Canol	4 vitrinite equivalent + bitumen	**1.01**	**487**
Grandview L-26			
510 feet, Canol	27 vitrinite	**0.71**	**427**
540 feet, Canol	13 vitrinite	**0.72**	**428**
580 feet, Canol	6 vitrinite	**0.71**	**430**
Ontaratue H-34			
2920 feet, Canol	14 vitrinite	**1.27**	**448**
3080 feet, Canol	4 vitrinite	**1.28**	**468**
3190 feet, Canol	17 vitrinite equivalent	**1.36**	**472**
Swan Lake K-28			
4430 feet, Canol (Imperial)	14 vitrinite	**1.46**	**455**
4570 feet, Canol	8 vitrinite	**1.50**	**458**
4660 feet, Canol	4 vitrinite	**1.48**	**461**
Dahadinni D-65			
4220 feet, Canol	2 vitrinite	**1.81**	**331**
4360 feet, Canol	22 pyrobitumen	**1.87**	**299**
4490 feet, Canol	25 pyrobitumen	**2.03**	**346**
Johnson A-12			
2010 feet, Canol	2 vitrinite	**2.55**	**342**
2070 feet, Canol	9 pyrobitumen	**2.17**	**334**
2130 feet, Canol	5 pyrobitumen	**2.14**	**342**
Keele South A-28			
7390 feet, Canol (Imperial)	13 pyrobitumen	**1.99**	**416**
7470 feet, Canol	8 pyrobitumen	**2.15**	**335**
7550 feet, Canol	6 pyrobitumen	**2.26**	**327**
Wrigley I-54			
350 feet, Canol	10 pyrobitumen	**2.18**	**329**
470 feet, Canol	3 pyrobitumen	**2.25**	**308**
620 feet, Canol-Ramparts	5 pyrobitumen	**2.14**	**364**

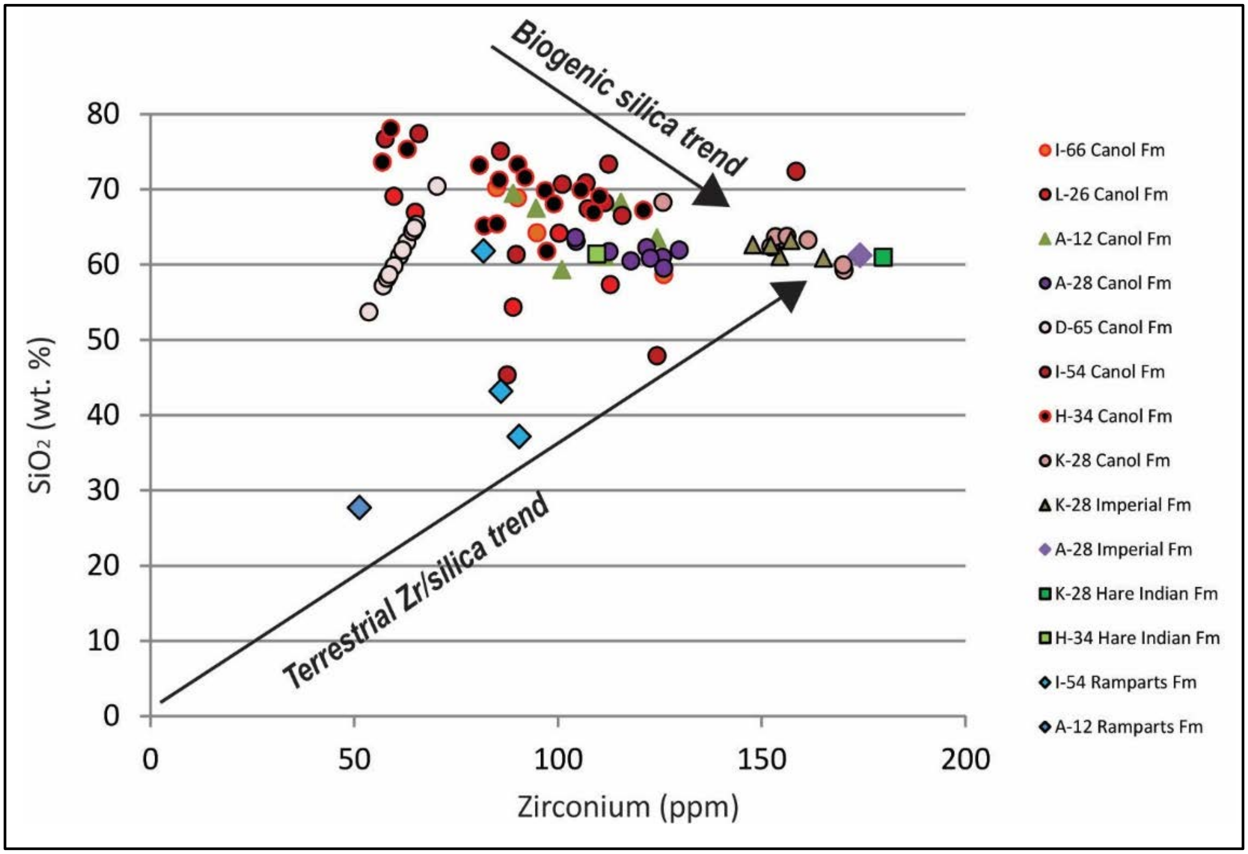

Figure 10. Cross-plot of zirconium (Zr) against silica (SiO_2) of the well samples. The plot illustrates the difference between biogenic silica and terrestrially derived silica (input from detrital quartz in siltstone and sandstone). Sample points are coloured according to formation and well.

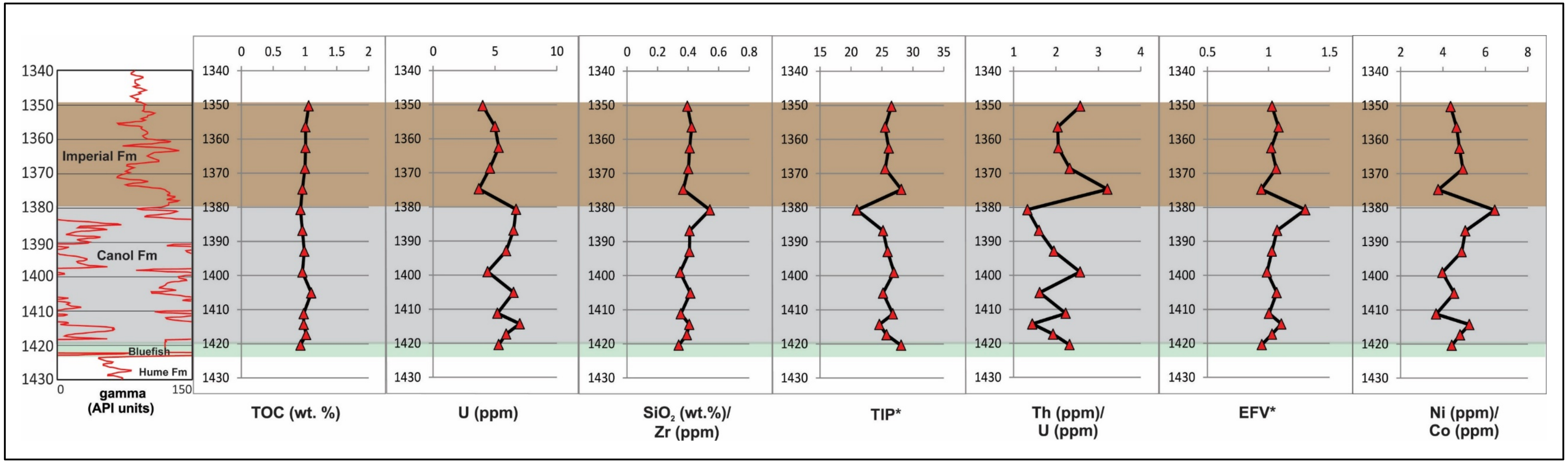

Figure 11. Swan Lake K-28 well gamma log profile with depth in metres along the y-axis, plotted with total organic carbon (TOC; wt.%) from Rock-Eval, and the following parameters from whole-rock geochemical analyses: uranium (U; part per million, ppm), ratio of silica (SiO2; wt.%) to zirconium (Zr; ppm), terrigenous input profile (TIP*), which is the summation Al_2O_3+Fe_2O_3+ K_2O +TiO_2, all in weight percent (wt.%); ratio of thorium (Th;ppm) to U (ppm); enrichment factor of vanadium (EFV*; Tribovillard *et al.* 2006); and ratio of nickel (Ni; ppm) to copper (Co; ppm). *see text for description of these parameters. Background colours indicate the formation or member found at depth; the Imperial Formation (brown), the Canol Formation (grey), the Bluefish Member (green), and the Hume Formation (white).

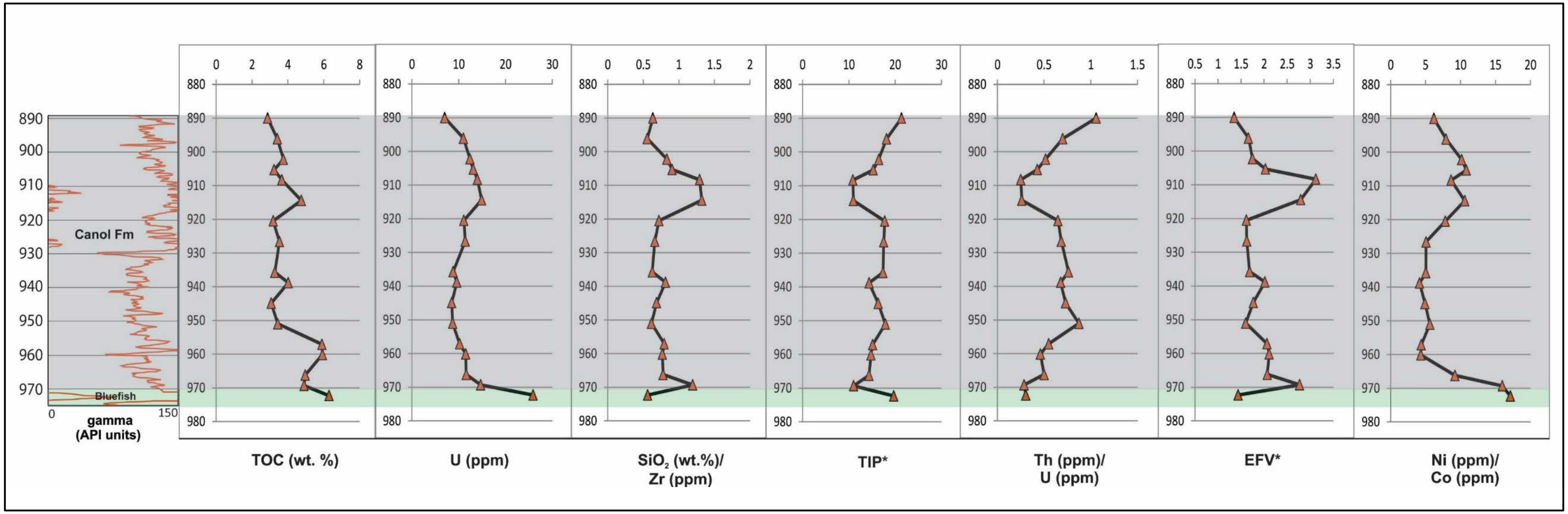

Figure 12. Ontaratue H-34 well gamma log profile with depth in metres along the y-axis, plotted with total organic carbon (TOC; wt.%) from Rock-Eval, and the following parameters from whole-rock geochemical analyses: uranium (U; part per million, ppm), ratio of silica (SiO2; wt.%) to zirconium (Zr; ppm), terrigenous input profile (TIP*), which is the summation Al_2O_3+Fe_2O_3+ K_2O +TiO_2, all in weight percent (wt.%); ratio of thorium (Th;ppm) to U (ppm); enrichment factor of vanadium (EFV*; Tribovillard *et al.* 2006); and ratio of nickel (Ni; ppm) to copper (Co; ppm). *see text for description of these parameters. Background colours indicate the formation or member found at depth; the Canol Formation (grey), the Bluefish Member (green), and the Hume Formation (white).

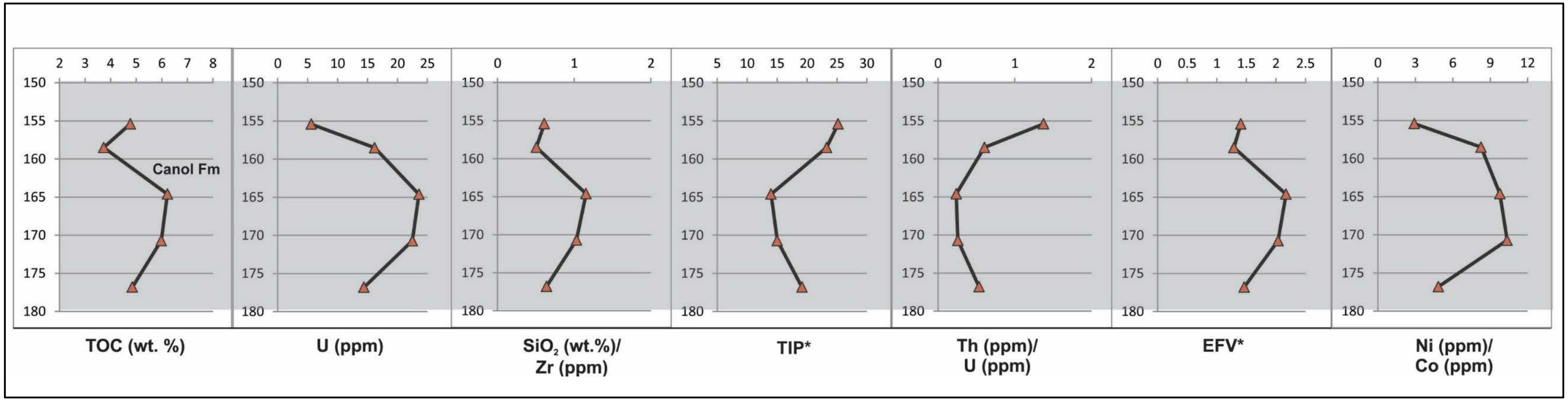

Figure 13. Grandview L-26 well (gamma log profile not available) with depth in metres along the y-axis, plotted with total organic carbon (TOC; wt.%) from Rock-Eval, and the following parameters from whole-rock geochemical analyses: uranium (U; part per million, ppm), ratio of silica (SiO2; wt.%) to zirconium (Zr; ppm), terrigenous input profile (TIP*), which is the summation Al_2O_3+Fe_2O_3+ K_2O +TiO_2, all in weight percent (wt.%); ratio of thorium (Th;ppm) to U (ppm); enrichment factor of vanadium (EFV*; Tribovillard *et al.* 2006); and ratio of nickel (Ni; ppm) to copper (Co; ppm). *see text for description of these parameters. Background colours indicate the formation or member found at depth; the Canol Formation (grey).

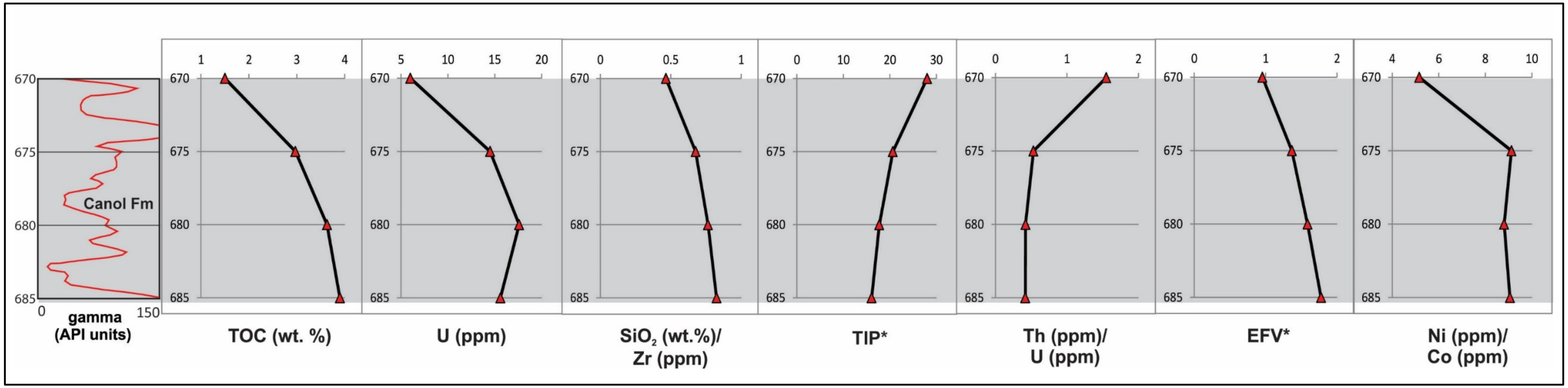

Figure 14. Hume River I-66 well gamma log profile with depth in metres along the y-axis, plotted with total organic carbon (TOC; wt.%) from Rock-Eval, and the following parameters from whole-rock geochemical analyses: uranium (U; part per million, ppm), ratio of silica (SiO2; wt.%) to zirconium (Zr; ppm), terrigenous input profile (TIP*), which is the summation Al_2O_3+Fe_2O_3+ K_2O +TiO_2, all in weight percent (wt.%); ratio of thorium (Th;ppm) to U (ppm); enrichment factor of vanadium (EFV*; Tribovillard *et al*. 2006); and ratio of nickel (Ni; ppm) to copper (Co; ppm). *see text for description of these parameters. Background colours indicate the formation or member found at depth; the Canol Formation (grey).

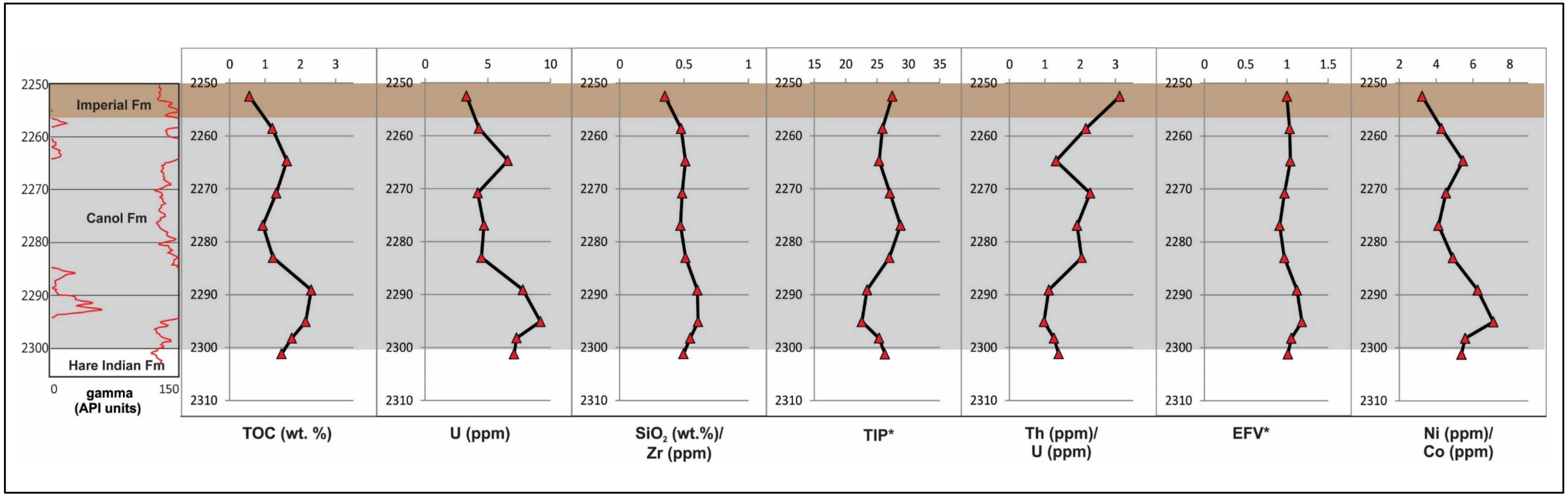

Figure 15. Keele South A-28 well gamma log profile with depth in metres along the y-axis, plotted with total organic carbon (TOC; wt.%) from Rock-Eval, and the following parameters from whole-rock geochemical analyses: uranium (U; part per million, ppm), ratio of silica (SiO2; wt.%) to zirconium (Zr; ppm), terrigenous input profile (TIP*), which is the summation Al_2O_3+Fe_2O_3+ K_2O +TiO_2, all in weight percent (wt.%); ratio of thorium (Th;ppm) to U (ppm); enrichment factor of vanadium (EFV*; Tribovillard *et al.* 2006); and ratio of nickel (Ni; ppm) to copper (Co; ppm). *see text for description of these parameters. Background colours indicate the formation or member found at depth; the Imperial Formation (brown), the Canol Formation (grey), and the Hare Indian Formation (white).

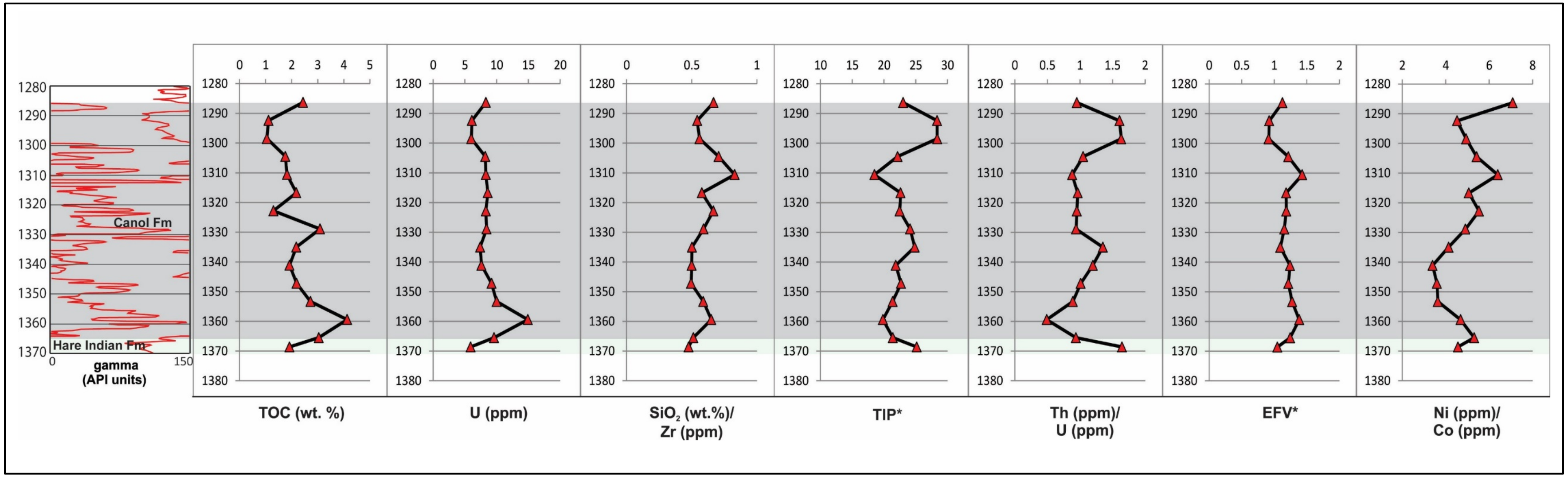

Figure 16. Dahadinni D-65 well gamma log profile with depth in metres along the y-axis, plotted with total organic carbon (TOC; wt.%) from Rock-Eval, and the following parameters from whole-rock geochemical analyses: uranium (U; part per million, ppm), ratio of silica (SiO2; wt.%) to zirconium (Zr; ppm), terrigenous input profile (TIP*), which is the summation Al_2O_3+Fe_2O_3+ K_2O +TiO_2, all in weight percent (wt.%); ratio of thorium (Th;ppm) to U (ppm); enrichment factor of vanadium (EFV*; Tribovillard *et al.* 2006); and ratio of nickel (Ni; ppm) to copper (Co; ppm). *see text for description of these parameters. Background colours indicate the formation or member found at depth; the Canol Formation (grey) and the Hare Indian Formation (light green).

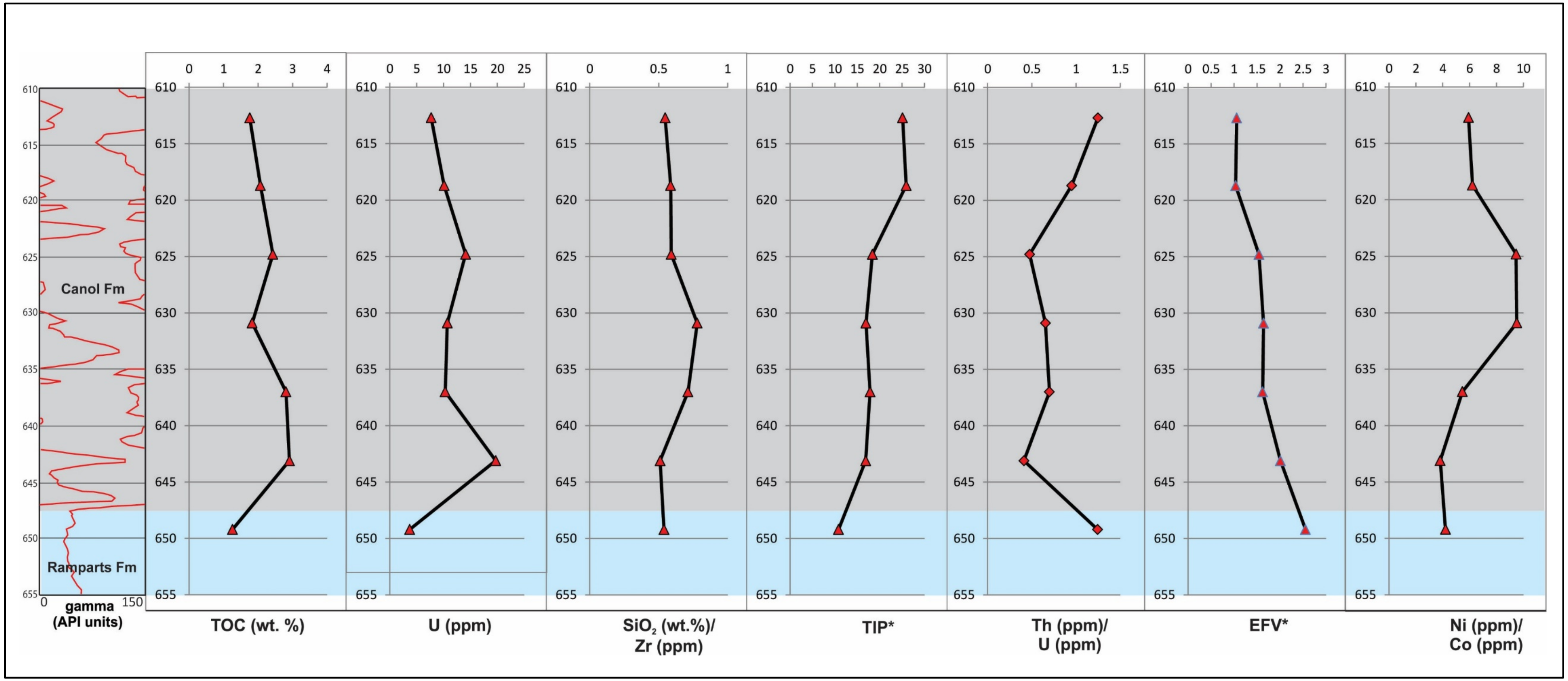

Figure 17. Johnson A-12 well gamma log profile with depth in metres along the y-axis, plotted with total organic carbon (TOC; wt.%) from Rock-Eval, and the following parameters from whole-rock geochemical analyses: uranium (U; part per million, ppm), ratio of silica (SiO2; wt.%) to zirconium (Zr; ppm), terrigenous input profile (TIP*), which is the summation Al_2O_3+Fe_2O_3+ K_2O +TiO_2, all in weight percent (wt.%); ratio of thorium (Th;ppm) to U (ppm); enrichment factor of vanadium (EFV*; Tribovillard *et al*. 2006); and ratio of nickel (Ni; ppm) to copper (Co; ppm). *see text for description of these parameters. Background colours indicate the formation or member found at depth; the Canol Formation (grey) and the Ramparts Formation (Blue).

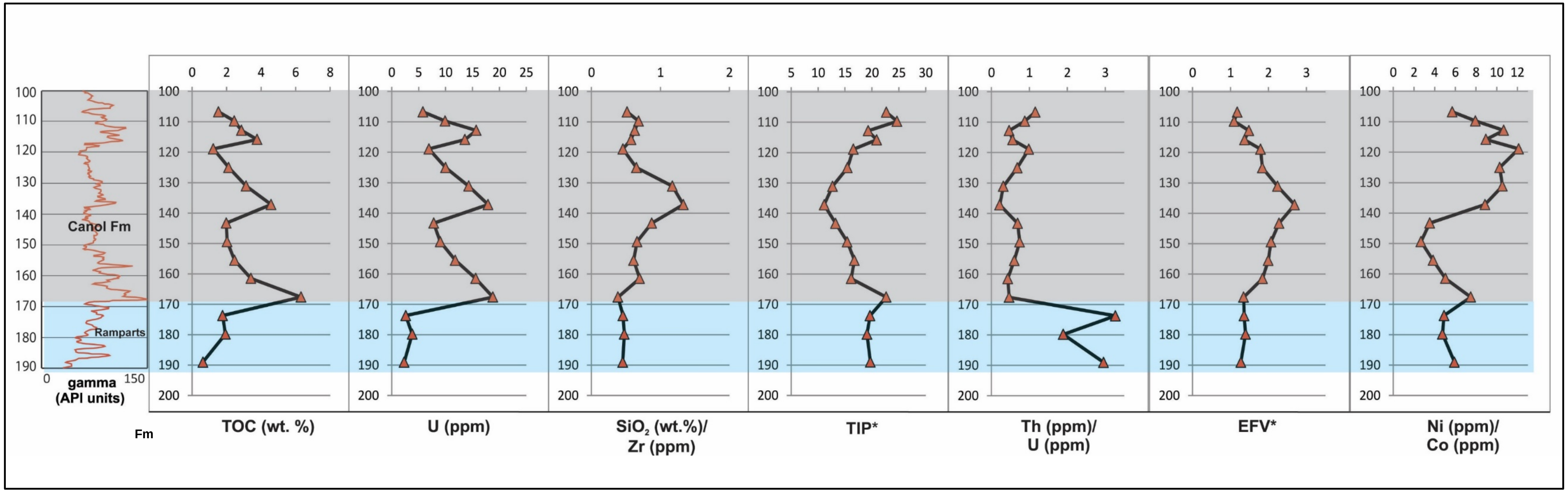

Figure 18. Wrigley I-54 well gamma log profile with depth in metres along the y-axis, plotted with total organic carbon (TOC; wt.%) from Rock-Eval, and the following parameters from whole-rock geochemical analyses: uranium (U; part per million, ppm), ratio of silica (SiO2; wt.%) to zirconium (Zr; ppm), terrigenous input profile (TIP*), which is the summation Al_2O_3+Fe_2O_3+ K_2O +TiO_2, all in weight percent (wt.%); ratio of thorium (Th;ppm) to U (ppm); enrichment factor of vanadium (EFV*; Tribovillard *et al*. 2006); and ratio of nickel (Ni; ppm) to copper (Co; ppm). *see text for description of these parameters. Background colours indicate the formation or member found at depth; the Canol Formation (grey) and the Ramparts Formation (Blue).

Summary

The Canol Formation is present throughout the Peel Plain and the southern Mackenzie Plain, but shallows considerably south of 64 °N. To extend correlations of the Canol Formation from the Central Mackenzie Valley, eight wells were sampled, four in the Peel Plain and four in the southern Mackenzie Plain. The sampling program increases the currently available data base of the unconventional resource potential of the Canol Formation:

- The average TOC values for the Canol Formation from the Peel Plain and the southern Mackenzie Plain wells are 3.27 wt. % and 2.25 wt. %, respectively. Type II kerogen is indicated primarily, with minor contributions of Type I and or Type III kerogens. However, kerogen determinations with more mature samples may be suspect, due to maturation effects on HI and OI values (Dahl *et al*. 2004).

- The TOC values for the Canol Formation are anomalously low in the Swan Lake K-28 well (average 0.99 wt. %). More sampling in nearby wells would be necessary to determine if the sample results are typical of that part of the Peel Plain.

- The T_{max} values indicate that the Canol Formation is mature throughout the central portion of the Peel Plain. Rock-Eval results are, however, unreliable in the southern Mackenzie Plain due to low S_2 values. Production Index values indicate overmaturity in all four southern Mackenzie Plain wells.

- The vitrinite reflectance results generally agree with the Rock-Eval pyrolysis analysis results in the Peel Plain area, and PI values in the southern Mackenzie Plain.

- The lithogeochemistry parameters, such as the SiO_2/Zr and Th/U ratios, distinguish the Canol Formation from the underlying Ramparts and Hare Indian formations and overlying Imperial Formation, and identify silica-rich intervals.

Acknowledgements

Laboratory analyses (Rock-Eval pyrolysis and vitrinite reflectance) were funded by the Northwest Territories Geological Survey. The authors thank Viktor Terlaky for a review of this report.

Appendix 1 – List of intervals sampled from eight exploratory wells in Peel and Mackenzie plains.

Appendix 2 – Rock-Eval pyrolysis and total organic carbon analyses.

Appendix 3 – Report of organic type, % R_o, and comments on samples from the Geologic Survey Canada Organic Petrology Laboratory.

Appendix 4 – Major oxide and trace element analyses.

Appendix 5 – Gamma log profiles, plotted with total organic carbon from Rock-Eval pyrolysis, and select profiles based on the lithogeochemistry data from Appendix 4.

Appendix 6 – Glossary of Terms.

Publication Disclaimer

Publication Terms of Use

References

Dahl, B., Bojesen-Koefoed, J., Holm, A., Justwan, H., Rasmussen, E., and Thomsen, E., 2004. A new approach to interpreting Rock-Eval S2 and TOC data for kerogen quality assessment; Organic Geochemistry, Volume 35, p. 1461-1477.

Dougherty, B.J., Abercrombie, H.J., Achab, A., Bertrand, R, Goodarzi, F., Snowdon, L.R., and Utting, J., 1991. Correlation of thermal maturity indicators for the Tenlen A-73, Crossley Lake South K-60, and Kugaluk N-02 wells in the northern district of Mackenzie, Northwest Territories; *in* Current Research, Part E; Geological Survey of Canada Paper number 91-1E, p.197-202.

Feinstein, S., Brooks, P.W., Gentzis, T., Goodarzi, F., Snowdon, L.R., and Williams, G.K., 1988. Thermal maturity in the Mackenzie Corridor, Northwest and Yukon Territories; Canada; Geological Survey of Canada, Open File 1944, 23 pages.

Feinstein, S., Williams, G.K., Snowdon, L.R., Goodarzi, F., and Gentzis, T., 1991. Thermal maturity of organic matter in the Middle Devonian to Tertiary section, Fort Norman area (Central Mackenzie Plain); Canadian Journal of Earth Sciences, Volume 28, p. 1009-1018.

Gal, L.P. and Pyle, L.J., 2012. Petroleum potential data (conventional and unconventional) for Horn River Group from 26 exploration wells – NTS 95N, 96C, 96D, 96E, 96F, and 106H, Northwest Territories Geological Survey, NWT Open Report 2012-009, 41 pages.

Hadlari, T., MacLean B.C., Pyle L.J., Fallas K.M., and Durbano, A.M., 2015. A combined depth and thermal maturity map of the Canol Formation, northern Mackenzie Valley, NWT; Geological Survey of Canada, Open File 7865, 7 pages (1 sheet).

Hannigan, P.K., Morrow, D.W., and MacLean, B.C., 2011. Petroleum resource potential of the northern mainland of Canada (Mackenzie Corridor); Geological Survey of Canada, Open File 6757, 271 pages.

Hogue, B.C. and Gal, L.P. (compilers), 2008. NWT formation tops for petroleum exploration and production wells: 60° N to 80° N; Northwest Territories Geoscience Office, NWT Open Report 2008-002, 5 pages and Microsoft® Excel spreadsheet.

Hunt, J. M., 1996. Petroleum geochemistry and geology; W.H. Freeman and Company, San Francisco, 743 pages.

Issler, D.R., Stasiuk, L.D., and Snowdon, L.R., 2005. Rock-Eval pyrolysis data for the east Mackay I-77 well, Northwest Territories, Canada; Geological Survey of Canada, Open File 4936, 19 pages, 1 CD-ROM.

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 map.

Muir, I. and Dixon, O.A., 1985. Devonian Hare Indian-Ramparts evolution, Mackenzie Mountains, NWT, basin-fill and platform-reef development; *in* Contributions to the Geology of the Northwest Territories; Volume 2; edited by J.A. Brophy, p. 85-90.

Northwest Territories and National Energy Board, 2015. An assessment of the unconventional petroleum resources of the Bluefish Shale and the Canol Shale in the Northwest Territories; Northwest Territories Geological Survey, NWT Open File 2015-05; National Energy Board, Energy Briefing Note (May 2015), 10 pages.

Peters, K.E., 1986. Guidelines for evaluating petroleum source rock using programmed pyrolysis; American Association of Petroleum Geologists Bulletin, Volume 70, p. 318-329.

Pugh, D.C., 1983. Pre-Mesozoic geology in the subsurface of Peel River map area, Yukon Territory and district of Mackenzie; Geological Survey of Canada, Memoir 401, 73 pages.

Pyle, L.J. and Gal, L.P., 2009. Petroleum play data for the Kee Scarp Play (Ramparts Formation), Mackenzie Corridor, Northwest Territories; Geological Survey of Canada, Open File 6125, 21 pages.

Pyle, L.J., Gal, L.P., and Lemiski, R.T., 2011. Measured sections and petroleum potential data (conventional and unconventional) of Horn River Group outcrops – Part 1, NTS 96D, 96E, and 106H, Northwest Territories Geoscience Office, NWT Open File 2011-09, 116 pages and Microsoft® Excel files.

Pyle, L.J. and Gal, L.P., 2012. Measured sections and petroleum potential data (conventional and unconventional) of Horn River Group outcrops, NTS 95M, 95N, 96C, 96D, 96E, 106H, and 106I, Northwest Territories – Part II; Northwest Territories Geoscience Office, NWT Open Report 2012-008, 114 pages.

Pyle, L.J. and Gal, L.P., 2013. Measured sections and petroleum potential data (conventional and unconventional) of Horn River Group outcrops, NTS 96C, 96E, and 106H, Northwest Territories – Part III; Northwest Territories Geoscience Office, NWT Open Report 2013-005, 73 pages.

Pyle, L.J., Gal. L.P., and Fiess, K.M., 2014. Devonian Horn River Group: A reference section, lithogeochemical characterization, correlations of measured sections and wells, and petroleum-potential data, Makenzie Plain area (NTS 95M, 95N, 96C, 96D, 96E, 106H and 106I), NWT; Northwest Territories Geological Survey, NWT Open File 2014-06, 70 pages.

Pyle, L.J., Gal, L.P., and Chow, N., 2016. Reference section for the Horn River Group and definition of the Bell Creek Member, Hare Indian Formation in central Northwest Territories; Bulletin of Canadian Petroleum Geology, Volume 64, Number 1, p. 67-98.

Pyle, L.J., Rocheleau, J., and Fiess, K.M., *in press*. Source rock characterization data from the Devonian Horn River Group, Imperial Formation, and Cretaceous Slater River Formation outcrops - NTS 96D, 96E, and 106H, Northwest Territories; Northwest Territories Geological Survey, NWT Open Report 2016-013.

Rimmer, S.M., 2003. Geochemical paleoredox indicators in Devonian-Mississippian black shales, central Appalachian Basin (USA); Chemical Geology, Volume 206, p. 373-391.

Rocheleau, J. and Fiess, K.M., 2014. Northwest Territories oil and gas poster series: Basins and petroleum resources, table of formations, schematic cross sections; Northwest Territories Geoscience Office, NWT Open File 2014-03, 3 Posters (Supersedes NWT Open File 2007-03).

Snowdon, L.R., 1990. Rock-Eval/TOC data for 55 Northwest and Yukon Territories wells (60°-69° N); Geological Survey of Canada, Open File 2327, 211 pages.

Stasiuk, L.D., Issler, D.R., Potter, J., and Tomica, M., 2003. Thermal maturity (vitrinite reflectance) of Cretaceous and Devonian strata in North Little Bear L-21 and East Mackay I-77, Northwest Territories, Canada; Geological Survey of Canada, Open File 1459, 1 CD-ROM.

Tribovillard, N., Algeo, T., Lyons, T.W., and Riboulleau, A., 2006. Trace metals as paleoredox and paleoproductivity proxies; an Update; Chemical Geology, Volume 232, p. 373-391.

Wright, A.M., Spain, D., and Ratcliffe, K.T., 2010. Application of inorganic whole rock geochemistry to shale resource plays; Canadian Unconventional Resources and International Petroleum Conference.