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Geological and geochemical data from Mackenzie Corridor. Part VII: new geochemical, Rock-Eval 6, and field data from the Ramparts and Canol formations of northern Mackenzie Valley, Northwest Territories

P. Kabanov

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SUMMARY

The Canol Formation is thick in paleo-basinal regions of Mackenzie Valley and Peel area where it is considered a frontier shale hydrocarbon prospect. Between these two areas, the Canol thins to 2+ meters where it is draped over Kee Scarp carbonate banks. Stratigraphic position, physical properties, and sedimentary environment of Canol shale in this carbonate-bank area are not well understood. New elemental geochemistry and Rock-Eval6 results from two cored sections shed more light on thermal maturity and chemostratigraphic signatures of the Canol Formation, its correlation criteria with thick off-bank sections, and difference from the overlying black shales of the basal Imperial Formation. With these signatures, the new Mirror Lake Member appears to be a robust and viable unit marking the base of the Imperial Formation. Field notes from Norman Wells quarry provide details corroborating backstepping-drowning model of Kee Scarp carbonate banks and their co-deposition with Canol shales.

RÉSUMÉ

Dans les régions du paléo-bassin ancien de la vallée du Mackenzie et la région de Peel, la formation de Canol est épaisse et on considère qu'elle forme une zone d'intérêt frontière pour les hydrocarbures de schiste. Entre ces deux zones, cette formation s'amincit à un peu plus de deux mètres, alors qu'elle recouvre les bancs carbonatés de Kee Scarp. On ne comprend pas bien la position stratigraphique, les propriétés physiques et l'environnement sédimentaire des schistes de Canol dans cette région de bancs carbonatés. De nouveaux résultats de géochimie élémentaire et de la méthode Rock-Eval6 sur deux sections carottées donnent un meilleur éclairage sur la maturité thermique et les signatures chimio-stratigraphiques de la formation de Canol, ses critères de corrélation avec les parties épaisses ne reposant pas sur le banc, et les différences relativement aux schistes noirs sus-jacents de la formation d'Imperial basale. Grâce à ces signatures, le nouveau membre de Mirror Lake semble être une unité robuste et viable, indiquant la base de la formation d'Impérial. Les notes de terrain de la carrière de Norman Wells contiennent des détails qui corroborent le modèle de rétrogradation-ennoyage des bancs carbonatés de Kee Scarp et leur co-déposition avec les schistes de Canol.

INTRODUCTION

The Givetian-Frasnian Horn River Group occurs across the vast area in the Northwest Territories and is traced in Northern Yukon as the Canol Formation (Fig 1A). Thick (150-400 m) Hare Indian and Ramparts formations developed in the NTS map sheets 96E,L,M and 106H,I,P define the bank-and-trough paleogeographic area or BAT (Figs. 1B and 2; Kabanov and Gouwy, 2017). This succession of fossiliferous grey shales, siltstones, and limestones conformably overlies the basal black-shale unit of the Hare Indian Formation called the Bluefish Member (Fig. 2). In the central Mackenzie Valley south of Norman Wells, the Hare Indian-Ramparts of the BAT area thins into the black shale dominated package of only 20-50 m in thickness. Kabanov and Gouwy (2017) referred to this basinal area between Norman Wells and the axis of the Keele tectonic zone as the southern off-bank area or SOB. Immediately west of 130° meridian in the Peel Plain and Plateau and adjacent Mackenzies, the thick Hare Indian - Ramparts succession grades into thin black shales similar to those of the SOB (Fig. 2). The entire Hare Indian Formation including its basal Bluefish Member merges into the Canol Formation as the well log marker for the upper Hare Indian fades approximately westward of 132° meridian (Fig. 2). The overlying Canol Formation is composed of siliceous pyritic shales. This main unit of the “Canol shale hydrocarbon play” (AANDC, 2014) imprints the thickness variations of the Hare Indian and Ramparts formations. The Canol Formation is 60-120 m thick in off-bank areas but thins to a few meters above Ramparts carbonate banks (Fig. 2), up to its disappearance on tops of tallest carbonate banks intersected by wells in the subsurface of the San Saults Rapids area (NTS 106H). The latter was first noted in the Whirlpool # 1 well (Tassonyi, 1969).

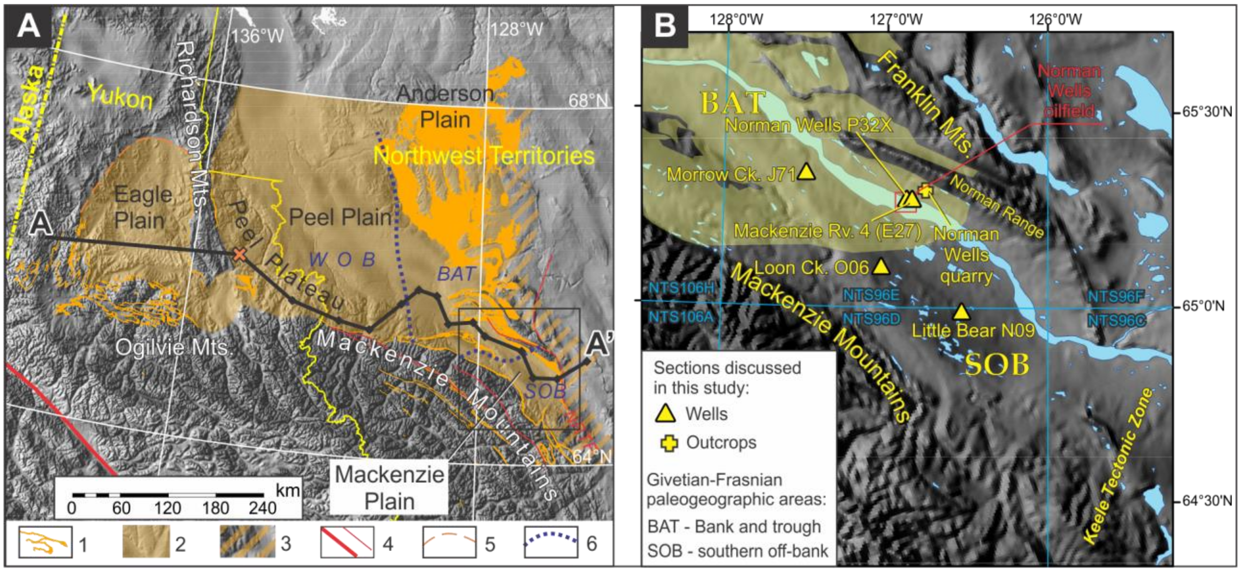

Figure 1. (A) Geographic spread of the Horn River Group (on N.W.T. side) and Canol Formation (on Yukon side) between 64°N and 68°N on an enhanced topographic basemap. (B) Location of studied sections in the Mackenzie Valley (inset on 1A). Legend to Fig. 1A: (1) outcrops; (2, 3) in the subsurface (2 is non-eroded presence and 3 is presence in erosional outliers); (4) Tintina Fault Zone (thick) and smaller-scale main faults in the Mackenzie Foldbelt (thin); (5) Canol Formation dips beneath thick siliciclastic wedge; (6) approximate limit of BAT area.

In pilot studies from the early 20^{th} century, the sharp thickness fluctuations of the Hare Indian – Ramparts succession were interpreted to result from erosion prior to deposition of the Canol black shale (Hume and Link, 1945). The upper Hare Indian in its black-shale facies equivalent was not recognized by then. The allegedly erosional nature of the pre-Canol surface gave rise to the “Late Middle Devonian unconformity” backed by missing conodont assemblages of the *hermanni-disparilis* zone interval (Braun et al., 1989; Norris, 1997). The upper Hare Indian Formation was assigned to the undifferentiated *varcus* conodont Zone (= *rhenanus-ansatus* zones), whereas the lower part of the Canol Formation was dated by conodontsas the lower *asymmetrica* Zone (≈*transitans-falsiovalis* zones) with speculative extension of the Canol base into the lowermost *asymmetrica* (Braun et al., 1989; Norris, 1997) or present-day *norrisi* Zone. However, scarce conodont data from the Ramparts limestone suggested its age ranges from the upper Hare Indian equivalent to the *asymmetrica* Zone. Other authors argued that the Canol base is conformable (Pugh, 1983; Pyle and Gal, 2016) and indicated Ramparts-Canol interfingering in allochthonous debris units (Muir, 1988). Nevertheless, the pre-Canol hiatus has survived in the territorial table of formations until recently (Morrow, 2012; Rocheleau and Fiess, 2014). Evidence for definitively retiring this hiatus is summarized by Kabanov and Gouwy (2017): (1) last updates in conodont data showing the base of the Canol time-gliding from the Frasnian transitans-punctata on top of Kee Scarp carbonate banks to the upper Givetian norrisi in off-bank depressions; (2) carbonate-bank slope depositional setting of allochthonous bioclastic debris interfingering with laminated black shales; and (3) absence of any evidence of subaerial exposure or vadose processes, like oxidation of pyrites and organic matter and characteristic redistribution of Fe and Mn, prior to the onset of Canol deposition.

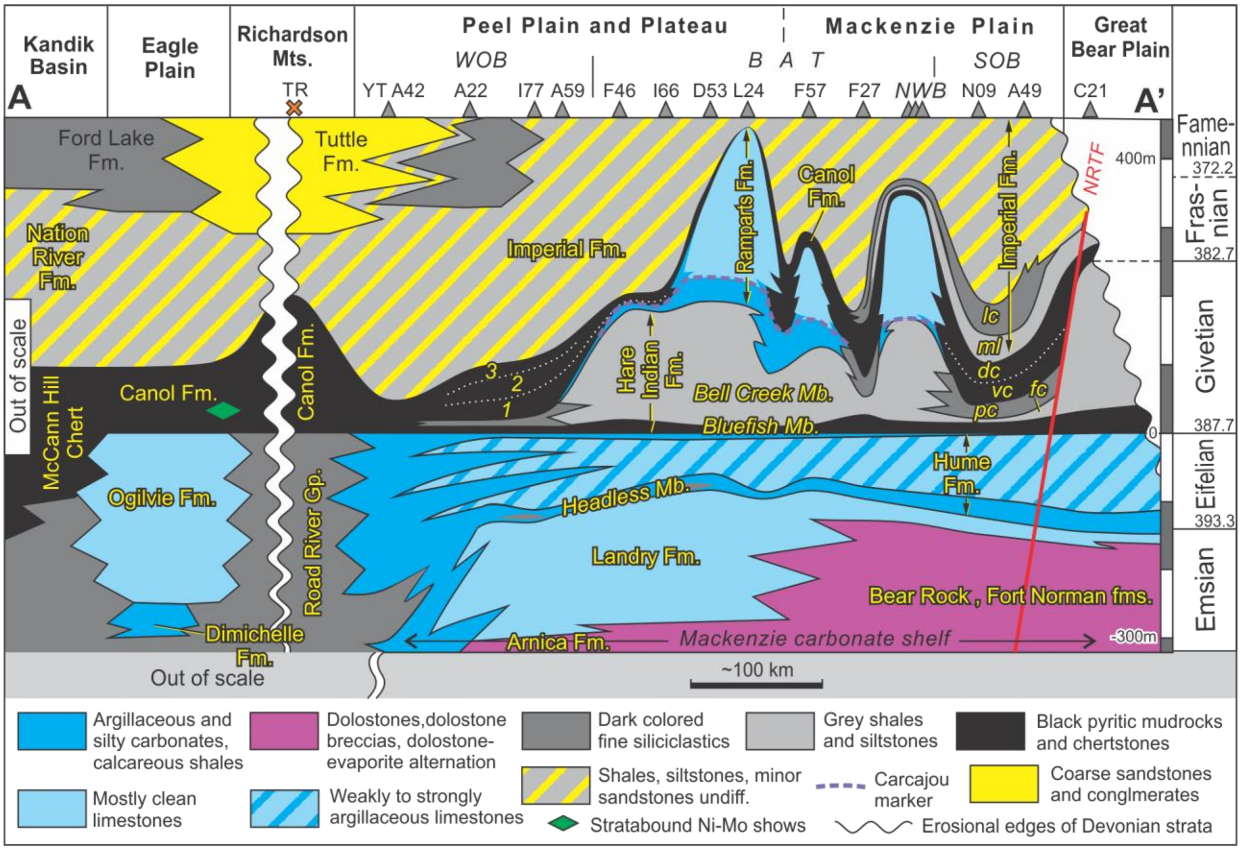

Figure 2. Cross-section A-A' leveled at Hume top. Thicknesses are controlled by wells east of Richardson Mountains and off scale to the west. NRTF is Norman Range thrust fault (other tectonic elements are not shown). Sections from left to right: Trail River (TR), Cranswick YTA-42, Cranswick A-22, S. Ramparts I-77, N. Ramparts A-59, Ramparts River F-46, Hume River I-66, Hume River D-53, Carcajou L-24, Maida Creek F-57, Hoosier F-27, NWB is Norman Wells bank with hundreds of wells, Little Bear N-09, Bluefish A-49, and Bracket Lake C-21. Stratigraphic members in SOB: (*fc*) Francis Creek (*ps*) Prohibition Creek; (*vs*) Vermillion Creek; (*dc*) Dodo Canyon; (*ml*) Mirror Lake; (*lc*) Loon Creek. Informal Canol units in the western off-bank area (WOB): 1. lower, 2. middle, 3. upper.

This paper reports on new elemental geochemistry and Rock-Eval 6 results, as well as new field observations of the Ramparts/Canol at Norman Wells quarry. New elemental geochemistry and Rock Eval 6 data come from Canol and basal Imperial mudrocks of Mackenzie River #4 (E27) and Morrow Creek J-71 wells. These are two thickest available cored sections of the Canol Formation and the overlying Mirror Lake and Loon Creek members in the BAT area. Unlikeliness of further drilling in the BAT area makes these cores particularly valuable for research. New data add more information on lithostratigraphic units defined in the Mackenzie Valley by Kabanov and Gouwy (2017), help to understand sedimentary conditions in the stratified Canol basin and the nature of the Ramparts/Canol contact, and contribute to the thermal maturity data collection of the Givetian and Frasnian shales of Mackenzie Corridor (Feinstein et al., 1988; Pyle et al., 2015).

METHODOLOGY

Cores were examined and sampled at the NEB Core and Sample Repository at the Geological Survey of Canada in Calgary. Descriptions of cored sections have been published previously (Kabanov, 2015; Kabanov et al., 2016a). Given the condensed nature of black-shale strata on tops of carbonate banks, the sampling interval was reduced to 30-35 cm, which is maximum density stipulated in the NEB sampling manual for frontier wells. Each sample represents an averaged material collected from a stratigraphic interval exceeding 1 cm (typically 2-5 cm) to ensure that none of the collected samples represented a single sedimentary lamina. Drilling mud was scraped off core sides prior to collecting. Samples were collected in polyethylene vials. Prior to sending aliquots to labs, occasional particulate contaminants such as paper flakes and cloth fibers were picked out under the binocular microscope.

Rock-Eval 6 pyrolysis

The pyrolysis-combustion tests were conducted at the Organic Petrology and Geochemistry Laboratory in GSC (Calgary) using the Rock-Eval 6 instrument. Approximately 1g of the unwashed core sample was crushed to powder using a mortar and pestle. A 70 mg aliquot of the sample was then inserted into a stainless steel crucible and heated in an open pyrolysis system. Initially, the samples are held at 300°C for 3 minutes to volatilize any free hydrocarbons (HC), which are represented by the S1 peak on the pyrograms. The S1 value (mg HC/g of rock) corresponds to the amount of free and adsorbed hydrocarbons generated naturally over time in the rock (Behar et al., 2001).

The next step in the procedure is to heat the samples from 300 to 650°C at a rate of 25°C/minute, which yields the S2 peak. The S2 value (mg HC/g of rock) represents the amount of hydrocarbon released due to thermal cracking of kerogen present in the sample. This is the remaining potential of the sample to generate hydrocarbons. It is important to note that drilling mud contamination and hydrocarbon migration can affect both the S1 and S2 values (Issler et al., 2012), however, in collected core samples the possibility of drilling mud contamination is considered negligible because of pre-sampling surface cleaning and extremely low permeability of shales precluding penetration of invert mud inside the rock.

The S3CO peak is a measure of the total CO emitted during heating from the beginning of measurement at 300°C up to the temperature where a minimum of CO production is observed (between 450° and 600°C). If no minimum is detected, the measurement is cut off at 550°C. The S3CO peak is linked to the organic matter pyrolysis. The S3'CO is the second peak of CO production found between the upper limit of S3 observation and the end of measurement. The S3'CO is produced by the reactivity of CO_2 released during the thermal breakdown of carbonates on the organic matter according to the so-called *Boudouard reactions*, producing two CO molecules, one with a carbon of organic origin integrated into the calculation of TOC, and the other one with a carbon of mineral origin integrated into the calculation of MinC (Behar et al., 2001).

Similarly, the CO_2 emitted during the pyrolysis stage is divided into S3, which corresponds to kerogen-derived CO_2 released at the same time as the S1 peak between 300° and 400°C, and the carbonate-derived CO_2 recorded between 400°C and the end of the measurement (Behar et al., 2001).

The comprehensive summary of Rock-Eval 6 parameters is given in the table 2a (acquired parameters) and 2b (calculated parameters) of Behar et al. (2001).

Bulk-element geochemistry

The samples were analyzed for elemental concentration at Bureau Veritas (former Acme) Analytical Laboratories in Vancouver, BC using inductively coupled plasma-mass spectrometry (ICP-MS). The commercial LF204 code of Bureau Veritas uses two sample preparation techniques before running through the ICP-MS.

The first technique was the lithogeochemical whole rock fusion technique, which involves mixing a 200 mg sample with a lithium metaborate (LiBO2)/ lithium tetraborate ($Li_2B_4O_7$) flux in a crucible. The crucibles are then placed in a furnace and heated in order to fuse the sample. The bead that develops is cooled then dissolved in nitric acid and run for ICP-MS in order to analyze the concentrations of rare earth and refractory elements (11 compounds, 33 elements) (see Appendix 1). LOI is also measured by heating and then weighing an aliquot of the sample in order to determine weight loss. This is used as a rough approximation of organic matter (carbon) minus water and light hydrocarbons that were burned off.

The second technique was the 4-acid digestion allowing for more complete release of chalcophyle elements than in the previously used aqua regia solution (AQ200).A 0.25 g split is heated in HNO3-HClO4-HF to fuming and taken to dryness. The residue is dissolved inHCl, made to volume with dilute HCl, and analyzed by the ICP-ES/MS (MA200 code).

In addition, total carbon and total sulphur were measured using the LECO instrument. In this procedure, the induction flux is added to the crushed sample and ignited in an induction furnace. A carrier gas sweeps up the released carbon which is measured by adsorption in an infrared spectrometric cell. The results represent all forms of carbon and sulphur that are present in the sample. The detection limit for this procedure is 0.02%.

On-core spectral gamma ray

The RS-230 BGO scintillometer of Radiation Solutions Inc. has been used to acquire spectral gamma-ray logs (SGR) of core and outcrop sections. The technique was described in preceding reports (Kabanov et al., 2016a,c). The total GR acquired from core allows for borehole-core depth adjustment (Fig. 3). CGR on the same log stands for the U-stripped Th + K signal, also known as the computed gamma ray, which characterizes terrigenous input in logged sections (Ellis and Singer, 2008).

GEOCHEMICAL AND PYROLYSIS RESULTS

Mackenzie River # 4

Quantified results are given in Appendices 1 and 2, and Rock-Eval 6 pyrograms are archived in Appendix 3. The lower part of the Canol Formation in the Mackenzie River # 4 is characterized by median TOC of 6.3%, T_{max} < 435°, and PI values which place the interval in the immature-early oil windows (Fig. 3). These observations agree with the Canol dataset from Norman Wells oilfield (Fig. 4; Feinstein et al., 1988; Pyle et al., 2015), including recently acquired data from Norman Wells P32X (Table 1). Based on 16 samples from the same core, Feinstein et al. (1988) report slightly lower T_{max} of 421-429ºC. This immature to early mature character is traced along the eastern flank of Mackenzie Valley Anticlinorium (i.e., Norman Range) where the Canol Formation occurs in shallow burial and outcrops (Fig. 4). Although showing overall advanced maturity compared to T_{max} and PI, vitrinite of this zone is consistently suppressed (<0.5 %Ro) with respect to outcrop samples of the Mackenzie Mountain flank (up to 2%Ro; Pyle et al., 2015).

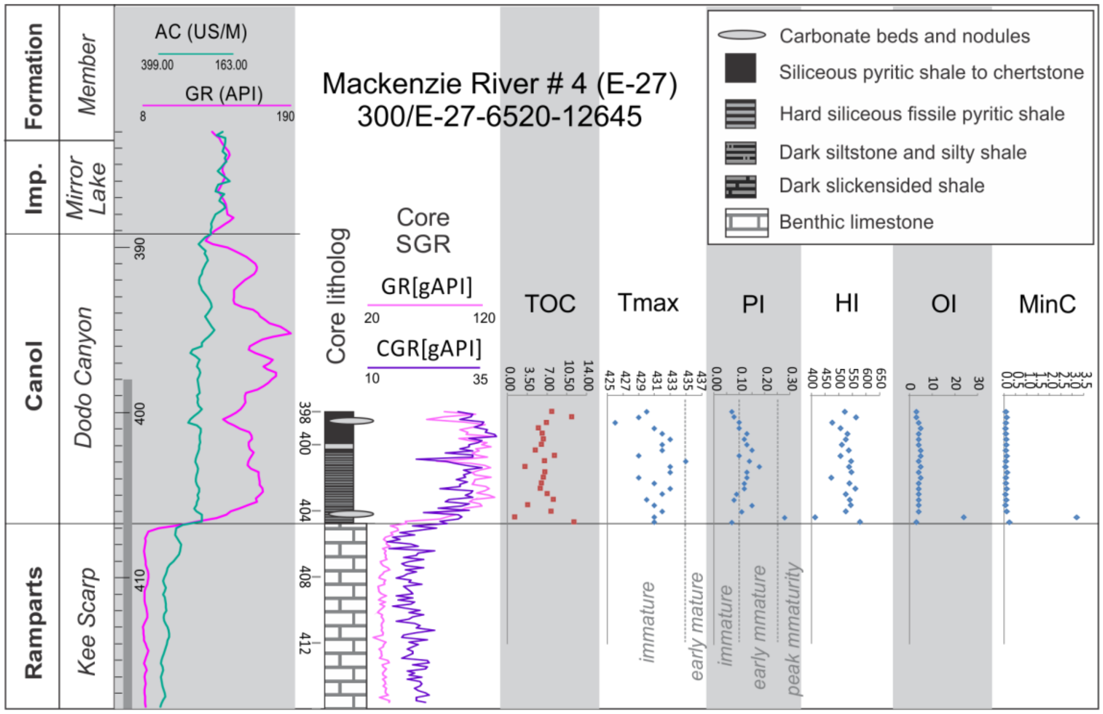

Figure 3.Cored section of Mackenzie River no. 4 (E-27) with selected RockEval 6 logs. Note 2 m core-borehole offset corrected with gamma ray correlation. Classes of maturation level are taken from Peters and Cassa (1994).

This paper marks a significant advance in understanding of the geochemistry of the thin Canol Formation of carbonate-bank areas, since data were previously exceedingly scarce. Logs of the major oxides are typical of Canol with high SiO_2 (median 74.8%) and low Al_2O_3 (median 6.4%). The background content of carbonates is close to zero, which is in good agreement with the low Rock-Eval MinC values (Fig. 3; Jiang et al., 2017). The calcite composition of a carbonate nodule illustrated by the CaO log (Fig. 5) is also characteristic of carbonate nodules in the Canol Formation of the Norman Wells quarry. However, calcite nodules are not as common in the upper Canol of thick basinal sections where dolomite normally predominates or is the only quantifiable carbonate species (Kabanov et al., 2016d), but thick calcareous intervals have been also reported from SOB wells (Pugh, 1993; Kabanov and Gouwy, 2017). The terrigenous input proxy (TIP) is low (median 8.6%). TIP is the summed weight % of Al_2O_3, Fe_2O_3, K_2O, and TiO_2. This proxy is used in regional studies (Pyle and Gal, 2016; Fraser and Hutchison, 2017). The strongly anoxic sedimentary environment of Canol Formation is evaluated using DOP_T, EFU and EFMo (Fig. 5). The degree of pyritization based on total Sulphur (DOP_T) will be discussed further below. EFU and EFMo are enrichment factors for U and Mo. The enrichment factor is defined as $EF_{(element\ X)} = (X/Al_{sample})/(X/Al_{average\ shale})$ with the average shale values taken from Wedepohl (1991). If EFX is greater than 1, then element X shows enrichment, and if it is less than 1, then it is considered depleted (Tribovillard et al., 2006). The EFMo in the Mackenzie River # 4 is very high (median 138%), exceeding the EFMo of the Dodo Canyon Member of SOB region (median 112-113%; Kabanov and Gouwy, 2017). EFU in Mackenzie River # 4 is also higher (median 16.6%) than in the correlative interval of Loon Creek O-06 (median 13.8%) and Little Bear N-09 (median 8.6%).

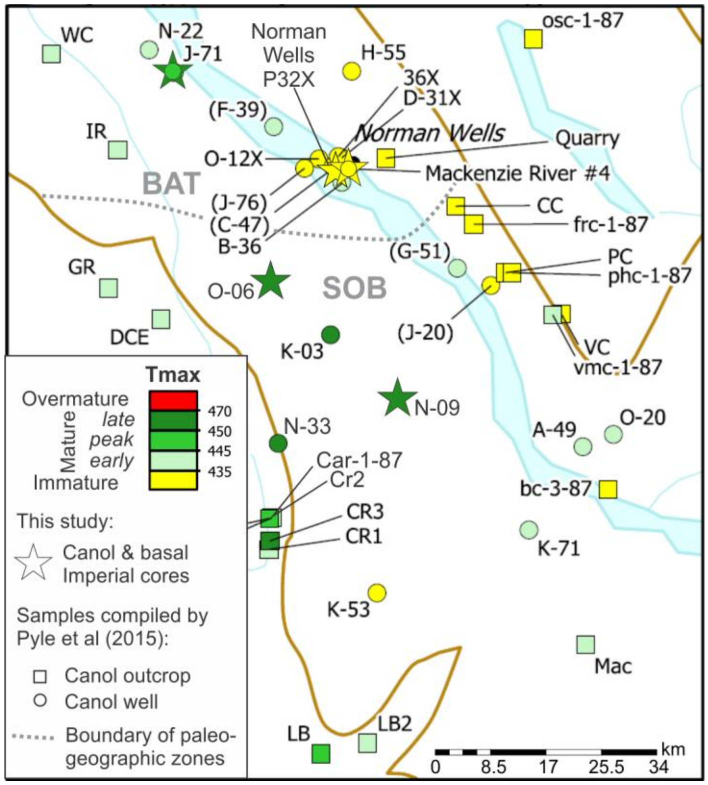

Figure 4. Color-coded average T_{max} values for Canol Formation in the central-northern Mackenzie Valley; modified from figure 7 of Pyle et al. (2015) by addition of average T_{max} values from core samples (Table 1).

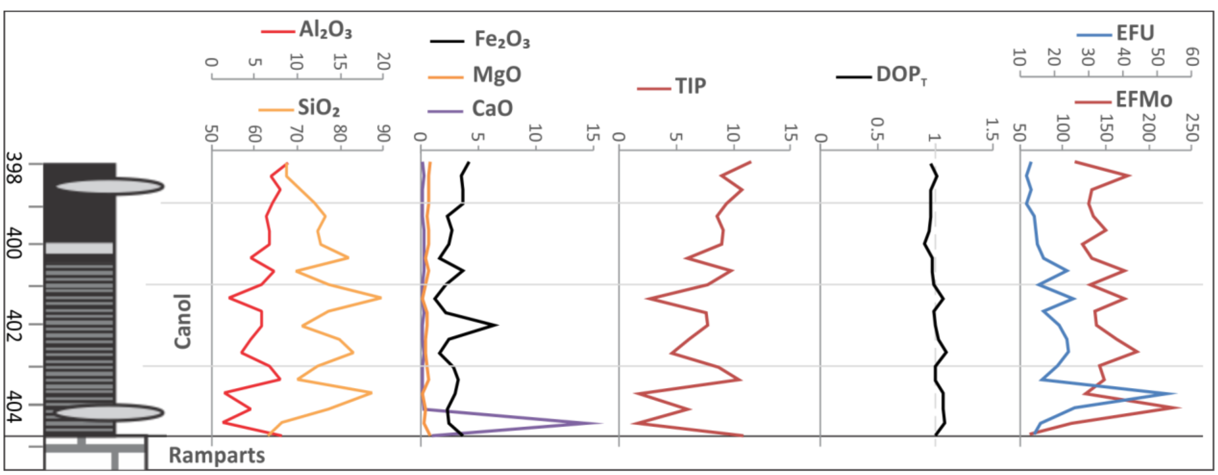

Figure 5. Elemental logs and proxies in the Canol Formation of Mackenzie River no. 4 (E-27).

Morrow Creek J-71

The sampled interval of Morrow Creek J-71 (Fig. 6), previously assigned to the Canol Formation (Pyle et al., 2014, 2015), has been moved to the basal Imperial based on log signatures (Kabanov et al., 2016b; Kabanov and Gouwy, 2017). Although the entire core occurs in black-shale facies, it shows low visual pyritization and enhanced clay content on 864.0-874.0 m expressed in relative softness, fissility, and extensive slickensiding (core description in Kabanov, 2015). Through geochemical logs (Fig. 7) these visual observations are confirmed with DOP_T median value of 0.66 (0.63 in Mirror Lake subset), lower

SiO_2, and Al_2O_3 with median 14.2% exceeding the Canol value more than twofold. Median EFMo and EFU drop five times (26.8 and 3.7, respectively) compared to the Canol section of Mackenzie River #4.

The low resistivity marker developed at 864.0-874.0 m of this well is considered diagnostic of the Mirror Lake Member (Kabanov and Gouwy, 2017). TOC below normal Canol values with a distinct depression in the middle of the low resistivity zone, as well as elevated OI and HI (Fig. 6) and vivid lithogeochemical expression (Fig. 7), definitely relate this core to the basal Imperial rather than Canol. Eleven cutting samples from 861-880 m of this well combined in the Canol Formation by Pyle et al. (2014) come mostly from the basal Imperial (861.2-873.2 m), one sample from 875.0 m occurs at the Canol/Imperial transition, and only one sample from 880.0 m represents the upper Canol (Fig. 6). This latter has Canol-grade TOC of 5.08%, whereas in basal Imperial TOC ranges between 1.8-4.1% save for one sample with a suspiciously high TOC of 25.3% (Appendix F in Pyle et al., 2014). The median T_{max} of basal Imperial cuttings of Pyle et al. (2014) is 448°, which is very close to the value in core samples (Table 1).

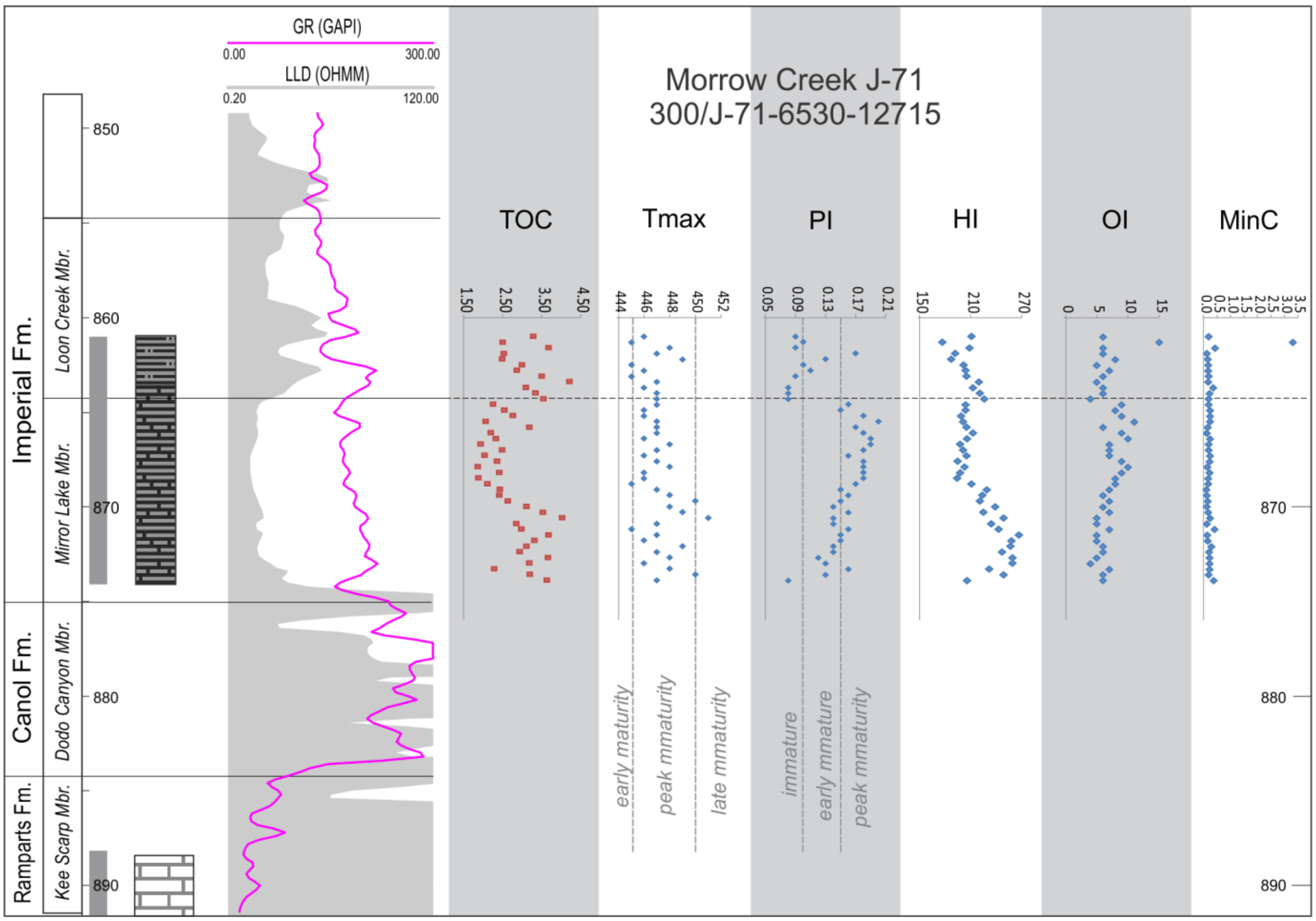

Figure 6. Cored section in the basal Imperial beds of Morrow Creek J-71 with Rock Eval 6 logs. Thicker stratigraphic interval demonstrates log signatures of the Kee Scarp/Canol contact and overlying black-shale units. Classes of maturation level are taken from Peters and Cassa (1994). Legend for the core litholog is the same as in Figure 3.

Core	Stratigr. unit	Samples		S1	S2	PI	Tmax	TOC	HI	OI
Mackenzie Rv. #4 (E-27)	Canol	21	**Median**	**4.5**	**32.4**	**0.12**	**431.0**	**6.3**	**532.0**	**4.0**
Mackenzie Rv. #4 (E-27)	Canol	21	StDev	0.9	13.4	0.04	1.9	2.3	35.1	4.3
Mackenzie Rv. #4 (E-27)	Canol	21	Mean	4.2	34.3	0.12	431.2	6.5	524.4	5.0
Norman Wells P32X	Canol	7	**Median**	**5.3**	**30.5**	**0.11**	**430.0**	**6.2**	**529.0**	**5.0**
Norman Wells P32X	Canol	7	StDev	1.5	29.0	0.03	2.4	4.9	29.6	0.7
Norman Wells P32X	Canol	7	Mean	5.0	46.3	0.11	429.6	8.5	529.1	4.4
Loon Creek O-06	Canol	181	**Median**	**4.1**	**4.6**	**0.47**	**463.0**	**4.9**	**92.0**	**4.0**
Loon Creek O-06	Canol	181	StDev	1.3	1.4	0.04	5.3	1.4	13.0	2.4
Loon Creek O-06	Canol	181	Mean	4.1	4.6	0.47	461.8	5.0	91.3	4.3
Little Bear N-09	Canol	177	**Median**	**3.7**	**5.6**	**0.40**	**462.0**	**5.1**	**111.0**	**4.0**
Little Bear N-09	Canol	177	StDev	1.2	1.8	0.06	4.3	1.4	15.9	2.9
Little Bear N-09	Canol	177	Mean	3.8	5.8	0.40	461.7	5.2	111.6	5.1
Morrow Creek J-71	Mirror Lk. + Loon Ck.	44	**Median**	**1.0**	**5.9**	**0.15**	**447.0**	**2.8**	**211.0**	**6.5**
Morrow Creek J-71	Mirror Lk. + Loon Ck.	44	StDev	0.3	1.7	0.04	1.4	0.6	22.2	2.0
Morrow Creek J-71	Mirror Lk. + Loon Ck.	44	Mean	3.0	4.0	0.40	456.1	4.0	102.1	21.9
Loon Creek O-06	Mirror Lk. + Loon Ck.	98	**Median**	**2.0**	**2.7**	**0.42**	**459.0**	**2.3**	**118.5**	**8.0**
Loon Creek O-06	Mirror Lk. + Loon Ck.	98	StDev	0.6	0.8	0.02	3.9	0.6	8.5	5.3
Loon Creek O-06	Mirror Lk. + Loon Ck.	98	Mean	2.1	2.8	0.43	458.5	2.4	118.3	9.0
Little Bear N-09	Mirror Lk. + Loon Ck.	59	**Median**	**1.8**	**3.1**	**0.36**	**453.0**	**1.9**	**166.0**	**18.0**
Little Bear N-09	Mirror Lk. + Loon Ck.	59	StDev	0.7	1.1	0.03	16.6	0.7	21.8	8.3
Little Bear N-09	Mirror Lk. + Loon Ck.	59	Mean	1.9	3.3	0.37	451.5	2.0	167.3	18.7

Table 1. Thermal maturity parameters for Canol Formation and basal Imperial shales collected through Devonian Stratigraphic Framework study of GEM Mackenzie Project. Rock-Eval data from Loon Creek O-06, Little Bear N-09, and Norman Wells P32X were reported earlier (Kabanov, 2015; Kabanov et al., 2015, 2016a).

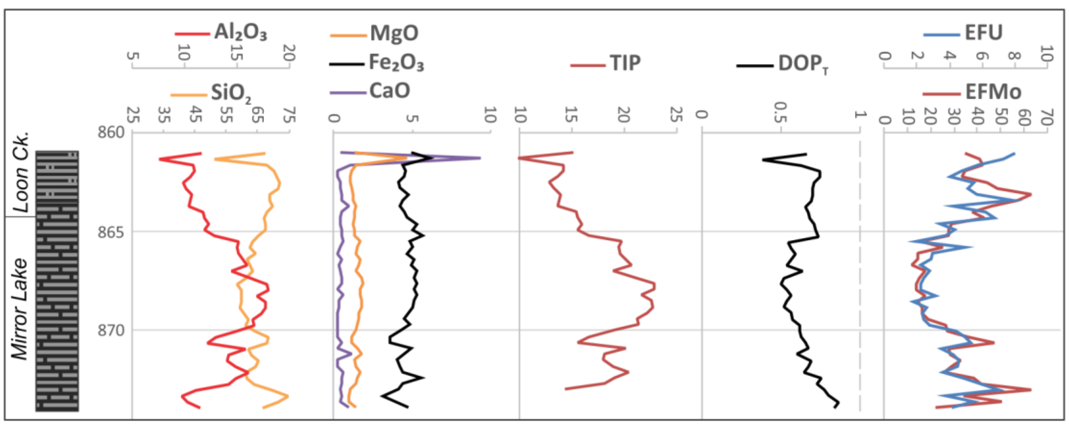

Figure 7. Elemental logs and proxies in basal Imperial shales of Morrow Creek J-71 well.

DOP_T in chemostratigraphy

The degree of pyritization based on total Fe and S (DOP_T) is an easier-to-get substitute of the true degree of pyritization (DOP). The latter stands for the ratio of sulfide-hosted Fe to total reactive Fe (Raiswell, 1988, 2001). DOP_T and DOP show good correlation in anoxic shales (Algeo and Maynard, 2004, 2008). DOP_T is the ratio of total Fe to iron calculated from total S, based on the assumption that sulphur is entirely bound in iron disulphides represented by pyrite and possibly marcasite (Algeo and Maynard, 2008). DOP_T is a useful proxy gaining popularity in regional studies as a paleoredox indicator (e.g., Rowe et al., 2008), however, it has not been applied so far to the Devonian shales of Northwestern Canada. This proxy seems to have robust chemostratigraphic resolution in the Horn River Group (Fig. 8). In particular, it allows to differentiate mudrocks deposited in strongly anoxic and siliciclastic-lean environment of Canol basin ($DOP_T \approx 1$) from underlying and overlying shales deposited in milder anoxic to hypoxic settings with higher influx of siliciclastic fines and having $DOP_T << 1$ (Fig. 8).

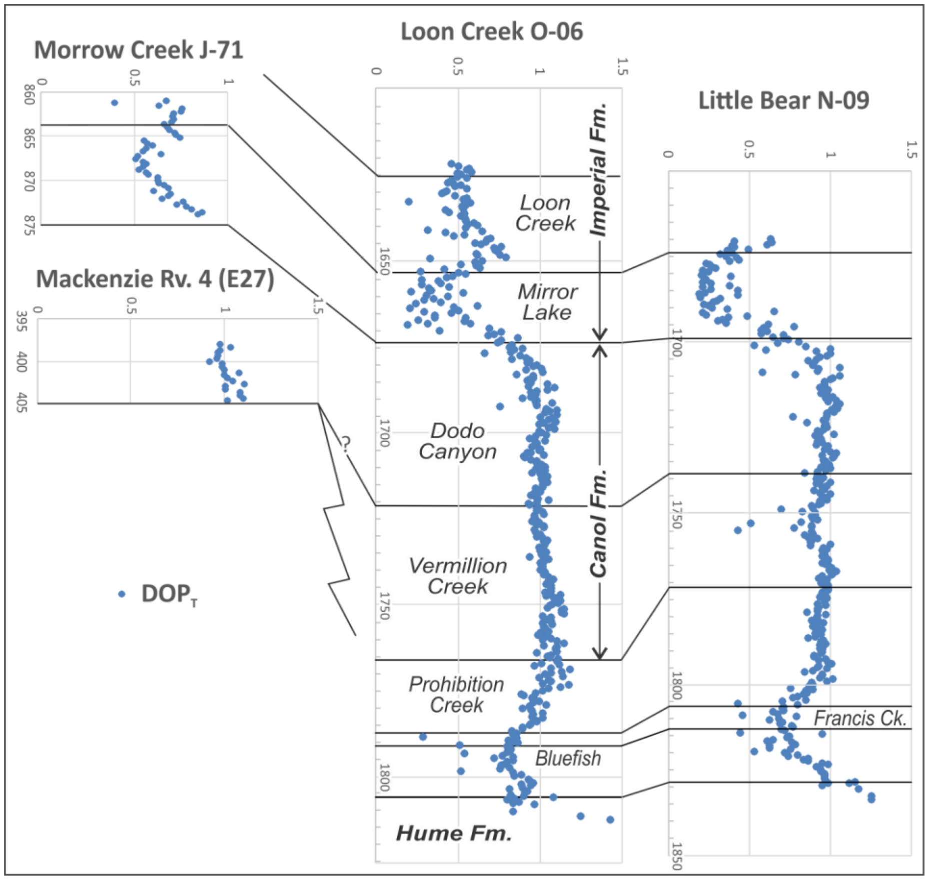

Figure 8. DOP_T correlation of BAT sections (this study) with off-bank sections Loon Creek O-06 and Little Bear N-09.

THERMAL MATURITY AND BURIAL HISTORY

In deeply buried parts of the Mackenzie Valley Synclinorium just south of Norman Wells, the Canol occurs in late mature state, as confirmed by Rock-Eval results from Little Bear N-09 and Loon Creek O-06 (Fig. 4). In this area, the top of the Canol occurs at depth 1699-1640 m. Further south, in Blueberry Creek K-53, Pyle et al. (2015) report immature T_{max}, which originates from two likely contaminated low- T_{max} samples in a small Canol subset of 13 samples (Appendix F in Pyle et al., 2014). Median T_{max} value for this subset is 471°, which is consistent with late mature to overmature kerogens and greater depth of 2239 m at Canol top. Thermal maturity parameters decrease updip on the eastern limb of the synclinorium as attested by Bluefish K-71 well where Canol occurs at 1271-1197 m and has early mature T_{max} and PI signatures (Fig. 4; Pyle et al., 2014, 2015).

Provisional interpretation of this Canol dataset indicates that thermal maturity closely follows the present-day structural layout of the northern and central Mackenzie Valley Synclinorium, although the pattern may be more complicated in the Keele Zone and other areas of Mackenzie Corridor assessed by Pyle et al. (2015). Secondly, arithmetic mean notation used by Pyle et al. (2014, 2015) for T_{max}, PI, and other parameters is not the optimal interpretive tool for thermal maturity evaluation unless anomalous values, which likely come from contamination, are screened off. This notation seems to be the reason for at least some discrepancies faced by Pyle et al. (2015) even after they excluded anomalous averages.

The thermal maturity pattern in the study area favors Laramide-associated maturation, which does not appear consistent with low-temperature thermochronology models of Issler et al. (2005) and Powell et al. (in press). The vitrinite reflectance log and AFT thermal history model from East McKay I-77 of the SOB area indicated a pre-Cretaceous heating of Devonian rocks with greatest burial and maturation likely achieved in the Triassic to Middle Jurassic (Issler et al. 2005). Recenly obtained apatite and zircon (U-Th)/He data from Mackenzie Plain allow reconstruction of maximum burial of the Imperial Formation up to 120-160°C during the Pennsylvanian - Late Triassic time (Powell et al., in press). Laramide foreland load in these models buried Imperial strata to depths between 2.2 and 3.8 km with only ~100°C heating, which would not overprint the late Paleozoic – early Mesozoic maximum burial trend. The apatite (U-Th)/He evidence for kilometer-scale erosion of late Paleozoic – early Mesozoic sedimentary rocks is strong as it extends beyond the Mackenzie Plain to adjacent Mackenzie Mountains (Powell et al., 2016) and the western portion of Canadian Shield (Ault et al., 2013), which awaits reconciliation with apparently immature state of Canol kerogens along the Norman Range side of Mackenzie Valley.

KEE SCARP / CANOL CONTACT

Ramparts Formation and its Kee Scarp Member

The Ramparts Formation was named after the Ramparts Gorge cliffs (Kindle and Bosworth, 1921). It is composed of three major parts: the lower platform (or lower ramp) informal member, middle Carcajou Member, and upper Kee Scarp Member. This triple subdivision is a simplification and the result of a long development of the Ramparts nomenclature discussed in many publications (Bassett, 1961; Pugh 1983, 1993; Muir 1988; Gal et al. 2009; Pyle et al. 2014). The lower platform member refers to an argillaceous and silty fossiliferous bedded limestone intergrading with shalier and siltier Bell Creek Member of the Hare Indian Formation. The upper part of the lower platform limestone grades into the Carcajou unit, which is a thin (1.5-3.0 m) limestone with benthic fossils distinct from underlying and overlying Ramparts limestones by its dark argillaceous and bituminous matrix. The Carcajou bed is traced in the subsurface by its elevated GR justifying its reference as a Carcajou marker (Muir 1988). In some sections at Norman Wells, the limestone of the lower platform member is absent or not sufficiently developed, and the Carcajou marker overlies the calcareous and bioturbated siltstone attributed to the Bell Creek Member.

The name Kee Scarp appeared as an equivalent to the Ramparts Formation (Bassett, 1961) and evolved to its present-day usage a decade ago (Gal et al., 2009). The Kee Scarp Member applies to the informal reef member of Tassonyi (1969) and Pugh (1983).It is defined as a portion of the Ramparts Formation developed above the Carcajou marker and forming spatially restricted carbonate pinnacles or banks commonly referred to as reefs (Pyle et al., 2014). The Kee Scarp Member merges the “upper platform member” and the “reef member” of Muir (1988) because these two are usually impossible to separate in surface and subsurface sections. The Kee Scarp Member is composed of limestones that are cleaner than underlying argillaceous and silty limestones of the Carcajou and the lower platform members. The Kee Scarp limestones are rich in corals and stromatoporoids that locally seem to build framework but mostly float in the bioclastic wackestones and packstones apparently accumulated as muds rather than reef cements. These buildups record backstepped development from broader “upper platform member” upward into narrow carbonate “reefs” (Muir et al. 1984; Muir 1988). A more general term “carbonate banks” was previously applied to these buildups (Mackenzie, 1973; Yose et al., 2001) and is favored here, because the actual extent of metazoan reef building is not clear. It is known that massive stromatoporoid boundstones are not the dominant facies in the NW-facing high-energy margin of the oilfield bank and do not form a continuous reef rim (Yose et al., 2001). Carbonate-bank interiors show stacking pattern of meter-scale cycles or parasequences (Muir et al., 1985; Muir 1988).

Minor lithostratigraphic units historically placed into the Ramparts Formation are Charrue sandstone (Mackenzie et al., 1975; Williams, 1986) and the allochthonous limestone unit (Mackenzie, 1970, 1973; Pugh, 1983). The latter refers to thin (up to 5.5 m) strata found in the Powell Creek outcrop and several wells in proximity to carbonate banks. These strata are composed of graded laminated calcisiltites and bioclastic calcarenites often interbedded with Canol-type shales. Based on this character and localized occurrence, these limestones were interpreted as off-reef allochthonous debris (MacKenzie, 1970, 1973). The genesis of the allochthonous member and interbedding with shales are characteristics which place it in the Canol Formation (Pugh, 1993).

Kee Scarp / Canol contact in Norman Wells quarry

The Norman Wells municipal quarry exposes the upper part of the Kee Scarp carbonate bank and the lower 1-5 meters of the Canol Formation (Fig. 9). This quarry was repeatedly aiding to develop Norman Wells reservoir model (e.g., Yose et al., 2001). Field notes were taken on the evening of July 17, 2017 during the last day of Glacial Limits fieldwork (GEM Mackenzie Project).

Figure 9. Norman Wells quarry, July 2017.

Station 1 (65º17'53" N, 126°43'35"W, 170m ASL). The northwestern face of the quarry shows carbonate-bank parasequences where finer-grained bank-interior facies alternate with boundstones dominated by massive stromatoporoids (Fig. 10). These massive bulbous forms are thought to be characteristic of high-energy bank interiors and bank margins (Yose et al., 2001) or “reef flat facies” (Muir, 1988).

Station 2 (65º17.917'N, 126º44.03'W, 154m ASL). This freshly excavated pit exposes the thick (3.0-3.5m) Canol section of buckled platy siliceous shale (Fig. 9B). Buckled and imbricated condition may be a result of downdip slumping, bulldozing, or both. Shales contain elliptical calcareous nodules expelling thick petroliferous odor when crushed. These nodules are composed of microsparitic and finely sparitic calcite. The bedrock is overlain by old backfill dump of the same shale (Fig. 9B). The Kee Scarp limestone is not exposed.

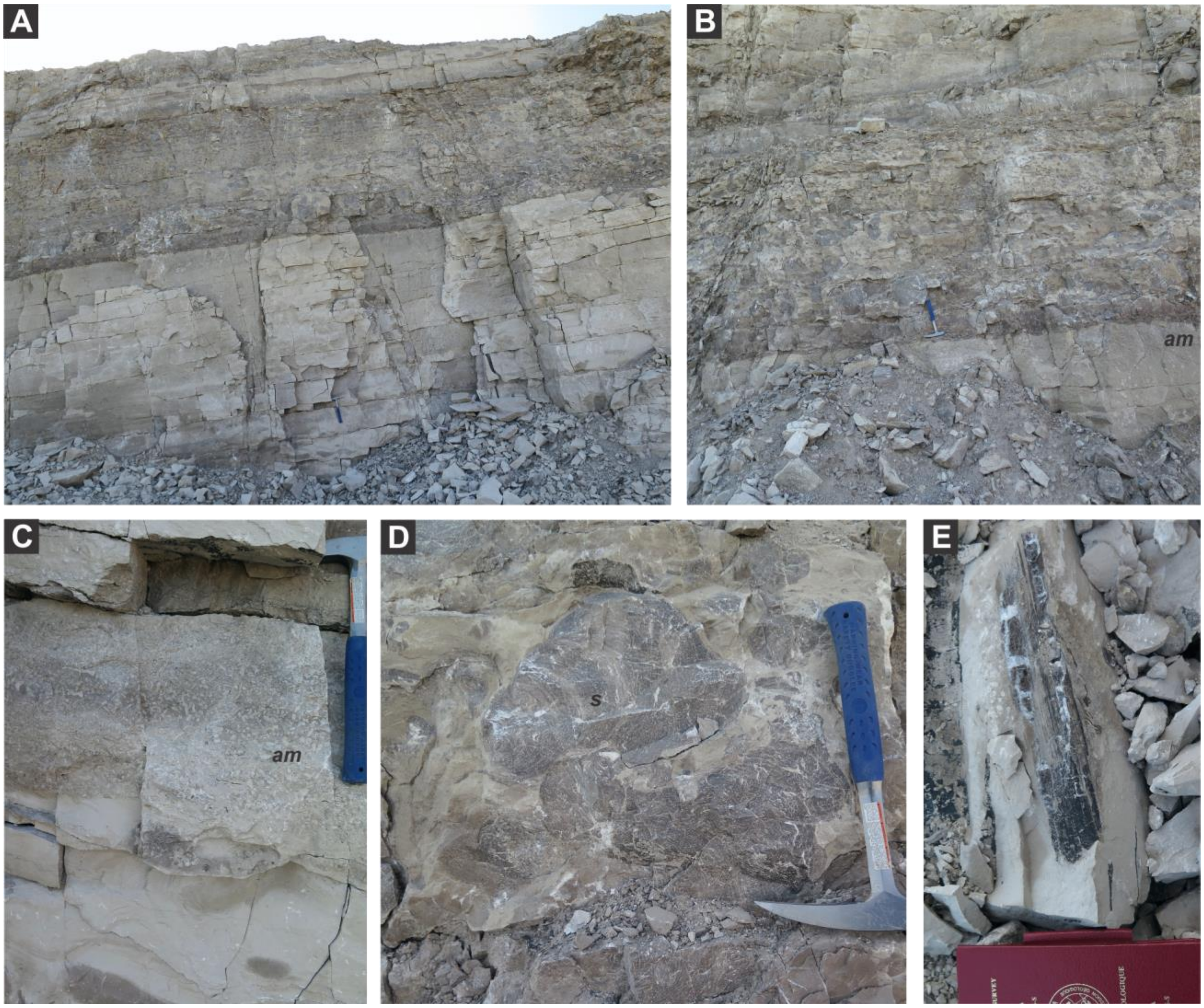

Figure 10. Parasequences in a carbonate bank at Station 1: (A,B) successive downdip view at a sharp parasequence contact; the lower parasequences is finer grained chalkified packstone interbedded with *Amphipora*-dominated bafflestone (*am*); the upper parasequence in its lower part is a massive stromatoporan boundstone usually ascribed to bank-margin zone (Yose, 2001). (C) Detail of the lower parasequence with *Amphipora*-dominated bafflestone overlying packstone.(D) Detail of the massive boundstone from the upper parasequences, (*s*) is bulbous *Stromatopora*. (E) Drifted wood fragment in finer-grained shallow-water packstone.

Station 3 (65º17.927'N, 126º43.843'W, 182m ASL). Stations 3 and 4 occur close to each other in the area of the carbonate-bank top partly stripped of Canol shale. The limestone top is uneven with relief 2-3 m in a 50-m radius, allowing for observation of the undisturbed contact (Figs. 11-13). Excavation of the contact at Station 3 exposes from base to top (Fig. 11A): 1. Recrystallized massive limestone with ferruginous skins; 2. Thin-bedded limestone with beds separated by thin (1-2 mm) dark steel grey shales, 10-15 cm in thickness (Fig. 11B); the Kee Scarp / Canol contact is smooth, intersected by rusty and pyrobitumen crusts and penetrative stringers; 3. Alternation of black (weathering steel grey) laminated shales and siltstones, minor deviations into very fine-grained sandstone; large plant fragments are common. A horizon of carbonate nodules is traced in 1.3-1.4 m above the Canol base. Nodules consist of microsparitic and finely sparitic calcite and locally preserve inflated lamination without any signs of burrowing disturbance. The non-disturbed Canol section is 2.3-2.5 m thick (Fig. 11A). Carbonate nodules are very common in the Canol shale, some of them massive and others concretionary with rusty outer rind (Fig. 11D). Samples for conodonts (Fig. 11A): KOA17-3-1 from massive limestone (bed 1); KOA17-3-2 from thin-bedded limestone (bed 2); KOA17-3-3 from calcareous nodules 1.3 m above Canol base (Fig. 11C).

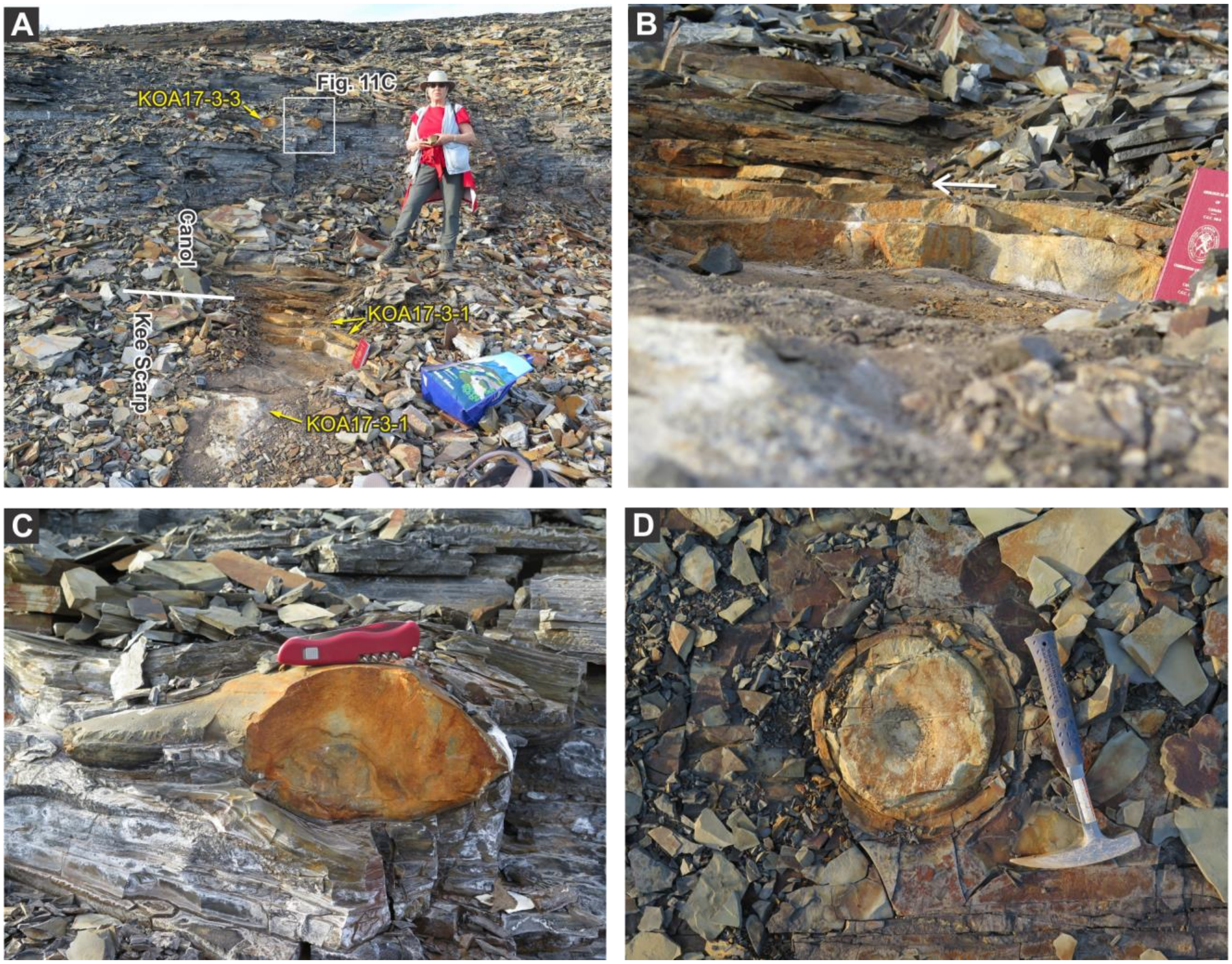

Figure 11. Kee Scarp/Canol contact at Station 3. Samples for conodonts are labelled and arrowed in yellow. (B) is the detail of contact with arrowed top of Kee Scarp Member. (C) A calcareous nodule in 1.3 m above Canol. (D) Another calcareous nodule in basal 1-2 m of Canol Formation.

The Canol section in 10 m S of Station 3 contains several thin (1-2 cm) rusty calcareous beds (Fig. 12). The lower bed occurring in 0.5 m above the Canol top is most continuous and connects to large (0.7 X 0.3 m) lenticular calcareous nodules (Fig. 12A). Limestone bed texture is mostly recrystallized microsparite and fine sparite, but locally preserves remnants of bioclastic crinoid-rich texture. This bed in 0.5 m above Canol base was collected for conodonts (KOA17-3-4).

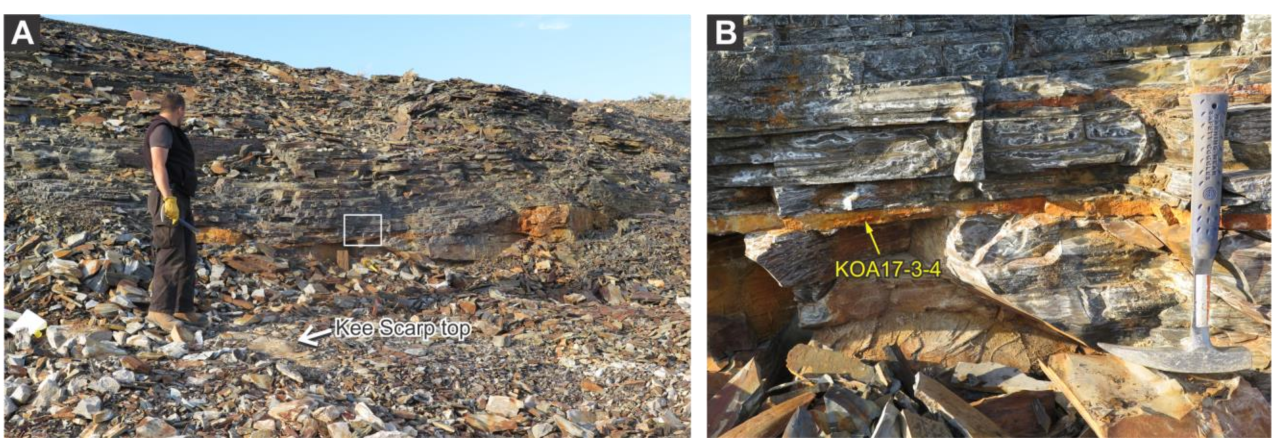

Figure 12. Calcareous bioclastic beds and nodules in 10 m S of Station 3; Figure 12B is boxed on 12A.

Station 4 (65°17'54.28"N, 126°43'40.15"W, 185m ASL). Here the limestone top is climbing no less than 2 m southeastward (towards the quarry brink) if looking along strike (Figs. 13A,B). This paleo-slope is complicated by small escarpments or benches (Fig. 13C). A bench observed at the reference point shows a rugged surface which is very rusty from decomposed pyrites (Figs. 13C,D). Non-disturbed laminated Canol shale fills pockets and grooves in this surface indicating its sedimentary origin. This escarpment protrudes about 1 m above the limestone surface exposed in 3 m to NW (Fig. 13B).

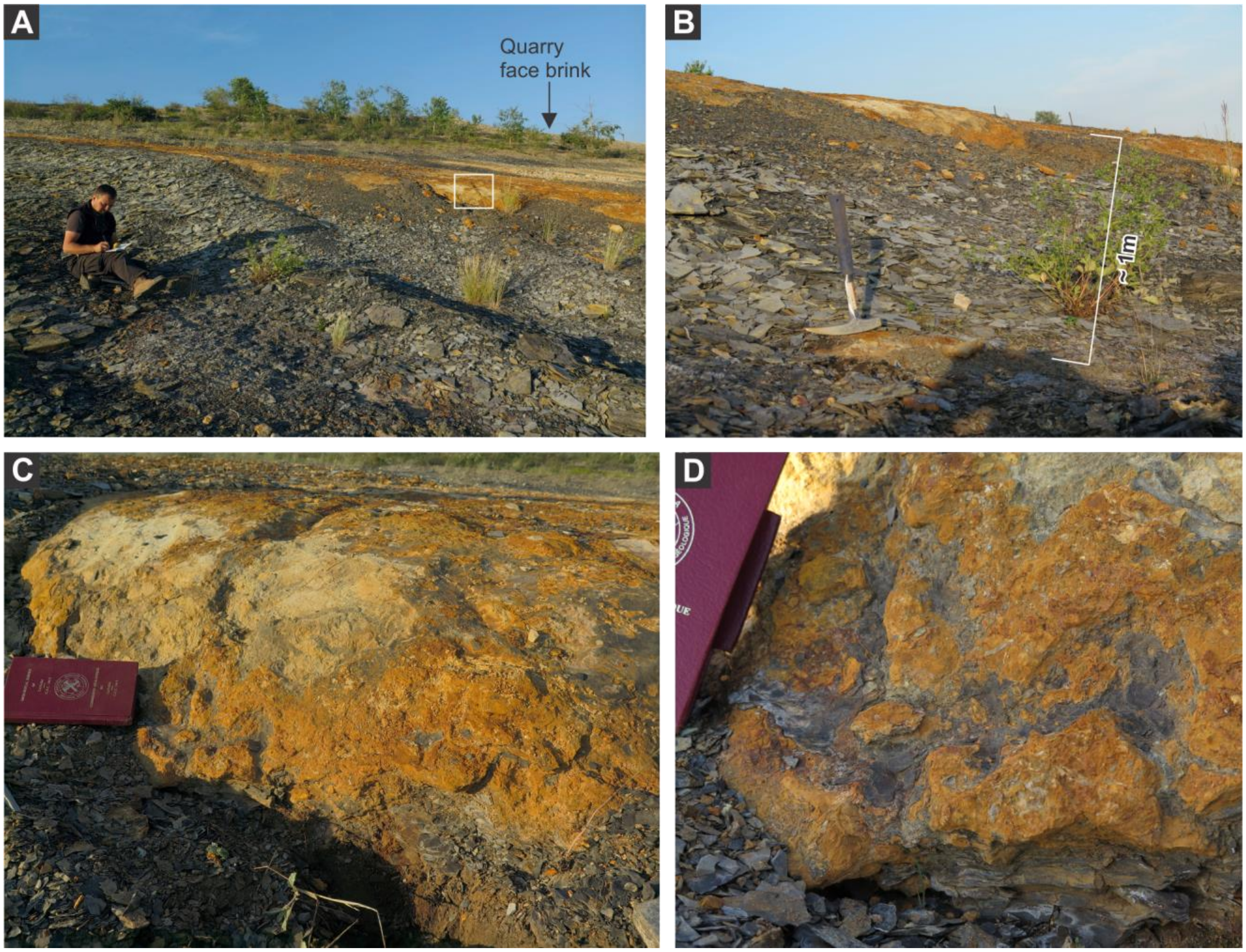

Figure 13. Kee Scarp top at Station 4 with a small sedimentary escarpment. Boxed on (A) is the observation site from (C) and (D); (B) is alongstrike view at the escarpment.

Interpretation. As highlighted in the new observations, the Kee Scarp top appears both conformable and unconformable and varies in this regard at the decameter scale. Station 3 is apparently conformable, and the rugged surface exposed at Station 4 indicates a ruptured stratigraphic record i.e. unconformable. Earlier observations in Norman Wells cores do not corroborate the gap in sedimentation between the Ramparts and Canol deposition as no hardgrounds were encountered (Kabanov et al., 2016a). Thin limestones observed in the lower 1.5 m of Canol shale and sampled for conodonts should represent bioclastic debris shed into anoxic waters off the living carbonate bank rather than material from its post-mortem erosion. This is very consistent with Muir's (1988) conclusion that the quarry bank exposes very narrow, late-stage portion of Kee Scarp (reef cycles 5 and 6) deposited after the Norman Wells bank had drowned in anoxic waters.

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