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Shield to Selwyn Basin Activity (Mackenzie Project, GEM). Report for 2015. Updates on Devonian stratigraphic study of Mackenzie River Corridor

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Abstract

The Devonian of the Mackenzie Project area is a thick (locally over 1 km) stratal package composed of carbonates, evaporites, and siliciclastics, recording the evolution of depositional environments from the passive-margin carbonate platform through the sediment-starved epiplatform anoxic basin to the foreland basin. The activity focuses on the economically prospective Lower Devonian Peel, Arnica, Landry, and Bear Rock / Fort Norman formations dominated by shallow-water carbonates and the Middle-Upper Devonian Horn River Group (Hare Indian, Ramparts, and Canol formations) dominated by kerogen-rich shales. New materials include 1847 m of measured cores, about 200 m of measured outcrop sections, chemostratigraphic data with ICP-MS/ES, Rock-Eval VI pyrolysis/combustion, XRD, and $\delta^{13}C$-$\delta^{18}O$ of carbonates. Multi-tool logging of best stratigraphic sections allows for refinements in lithostratigraphic (sequence stratigraphic) framework, which is underway.

Table of Contents

Foreword

The Geo-mapping for Energy and Minerals (GEM) program is laying the foundation for sustainable economic development in the North. The Program provides modern public geoscience that will set the stage for long-term decision making related to investment in responsible resource development. Geoscience knowledge produced by GEM supports evidence-based exploration for new energy and mineral resources and enables northern communities to make informed decisions about their land, economy and society. Building upon the success of its first five-years, GEM has been renewed until 2020 to continue producing new, publically available, regional-scale geoscience knowledge in Canada's North.

During the summer 2015, GEM program has successfully carried out 17 research activities that include geological, geochemical and geophysical surveying. These activities have been undertaken in collaboration with provincial and territorial governments, northerners and their institutions, academia and the private sector. GEM will continue to work with these key collaborators as the program advances.

Introduction

In the Mackenzie Project area (Fig.1), the Devonian is a thick (locally over 1 km) stratal succession composed of carbonates, evaporites, and siliciclastics (Fig. 2) recording the evolution of depositional environments from passive-margin carbonate platform through the sediment-starved epiplatform anoxic basin to the foreland basin (Hadlari et al., 2009; Morrow, 2012). The Late Devonian Imperial Formation is a thick clinothemic foreland succession with stratigraphic constraints put recently (Hadlari et al., 2009; Dixon, 2012; Morrow, 2012). The Shield to Selwyn Basin research activity focuses on older Devonian strata (sub-Imperial Devonian) that generally have less developed stratigraphy yet contain significant economic resources.

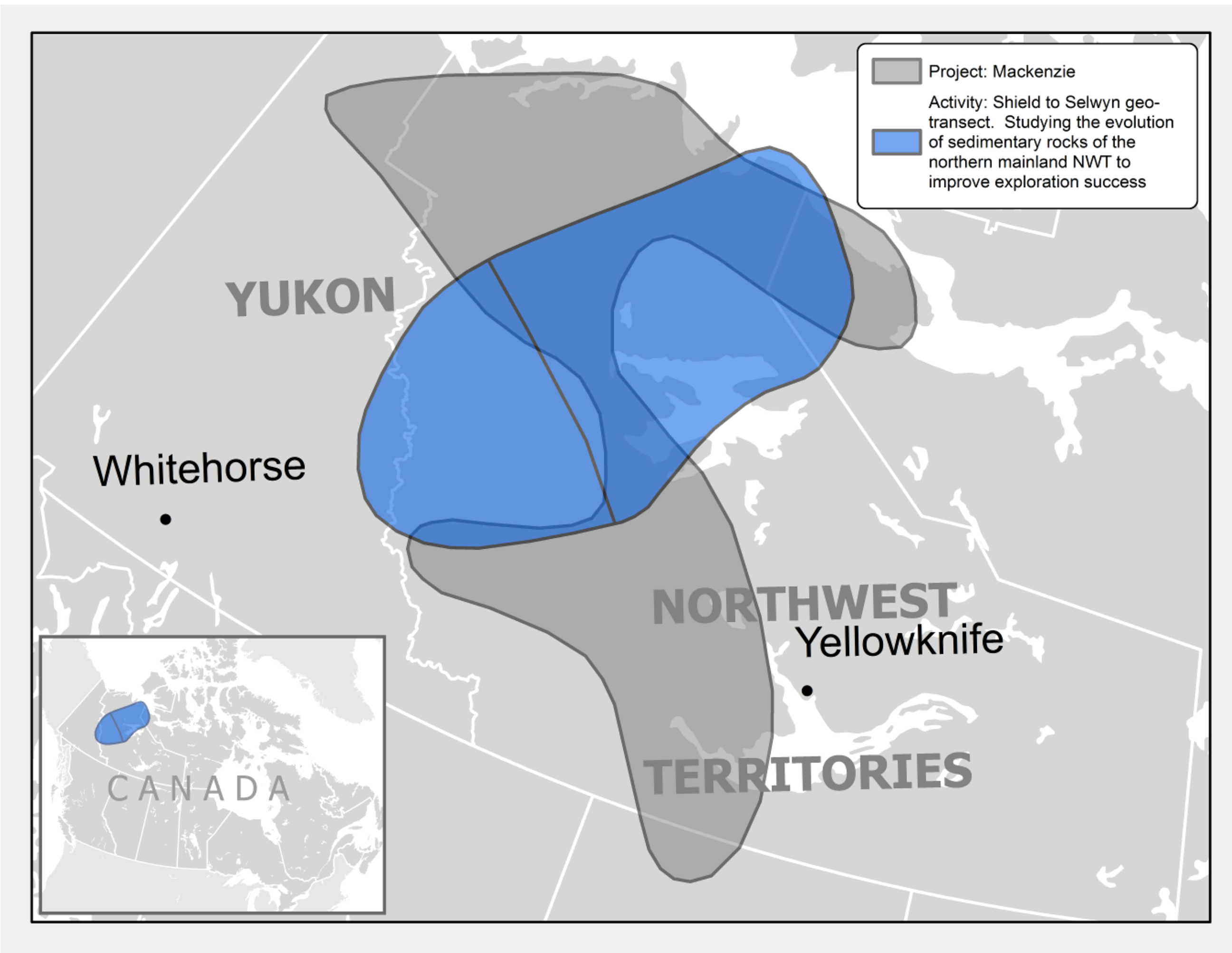

Figure 1: *Location of GEM Mackenzie Project area (2014-2017).*

The economic prospectivity of the sub-Imperial Devonian is tied to conventional and unconventional hydrocarbon plays. The Norman Wells oilfield is a giant mature oilfield with a microporous fractured carbonate reservoir in the Kee Scarp Member of the Ramparts Formation (Muir et al., 1984; Kaldi, 1989; Yose et al., 2001). The Kee Scarp reservoir is sealed by and sourced from the black shales of the Canol Formation (Snowdon et al., 1987; Hadlari, 2015). The original in-place oil volume in Norman Wells was estimated as $108*10^6$ m^3 (Yose et al., 2001). Other major conventional assets are the recently launched oil, gas, and condensate field of Summit Creek located in the Lower Devonian Bear Rock breccias and numerous oil and gas shows in Lower to lower Middle Devonian breccias, dolostones and limestones (Gal et al., 2009; Hannigan et al., 2011; Hannigan, 2012). To the south of the study area in the Liard Basin, a chain of fourteen gas fields produces gas from porous catagenetic (hydrothermal) saddle dolostone reservoirs (Manetoe facies) developed in Devonian-age carbonates (Morrow et al., 1990; Hannigan et al., 2011; Morrow, 2012).

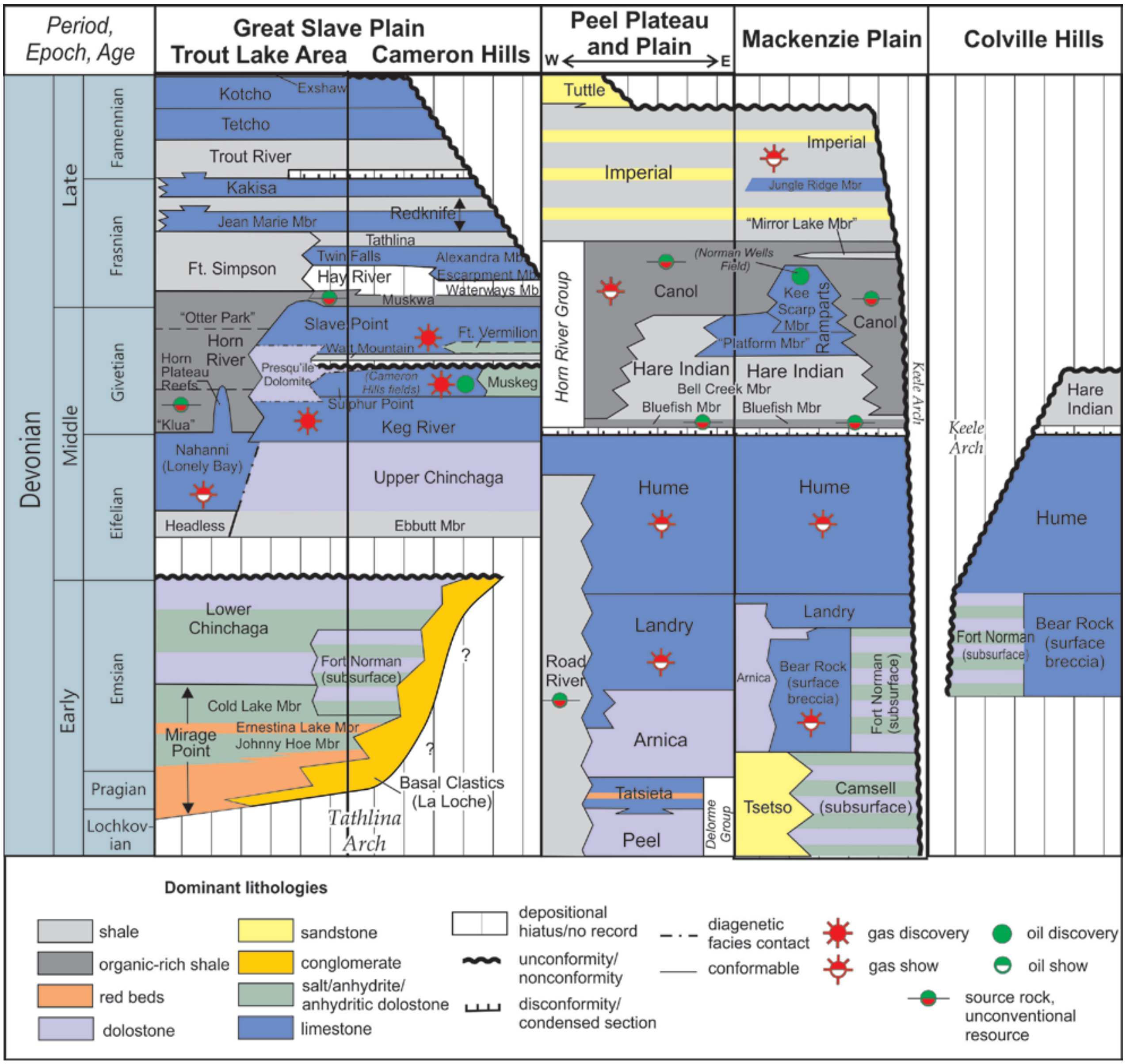

Figure 2: *Table of formations for the Devonian System of Northwest Territories. Note that northern and southern extremities of the study region (Beaufort-Mackenzie Basin and Liard Basin) are not included. Correlation of stratigraphic units is from Rocheleau and Fiess (2014) except for the Horn River Group of Mackenzie Plan with updates proposed by Kabanov et al. (in press).*

Devonian carbonates of the Mackenzie Mountains host Pb-Zn mineralization along fault zones with best showings in limestones of the Landry Formation. Further southwestward, in Selwyn Basin, SEDEX-type polymetal deposits occur in the Middle-Upper Devonian shales of the Besa River Group (Dewing et al., 2006; Ootes et al., 2013).

The black shales of the Middle-Upper Devonian Horn River Group were identified to host the largest unconventional hydrocarbon resource in the region (Hamblin, 2006) and have recently seen exploration investment in the central Mackenzie Plain (Hayes, 2011; AANDC, 2014). Referred to most recently as the Canol shale play (AANDC, 2014), this prospect consists of the thickest (up to 180 m) Canol Formation, with median TOC values of 4.6% and 17% maximum and the Bluefish Member of the Hare Indian Formation that is thinner (up to 23 m) and has 5.6% median value and maximum 10% TOC. The Canol Formation is also more brittle due to higher content of biogenic silica. The two organic-rich formations are divided by the informal “gray-shale member” (Morrow, 2012). Pyle et al. (2014a) propose to formalize this unit under the name Bell Creek Member. The Bell Creek (“gray-shale”) Member shows 1.5% median value of TOC. Thick swellings (prodelta lobes) of the Bell Creek Member are overbuilt by isolated carbonate platforms (banks and pinnacles) of the Ramparts Formation (Fig. 2). The argillaceous-carbonate Headless Member of the Hume Formation is locally organic-rich and indicated as another potential source rock (Hannigan et al., 2011) that can be also tested for tight reservoir properties. Most recent and complete thermal maturity, geochemical, mineralogical, lithofacies, and petrophysical data from the Horn River Group outcrops and wells have been published by Pyle et al. (2011), Gal and Pyle (2012), Pyle and Gal (2012, 2013), Pyle et al. (2014b), Jiang et al. (2014), Kabanov (2013, 2015), and Kabanov et al. (2015, in press).

Material and methods

Lithological observations and SGR surveys

The summary of observations and analyses retrieved to date are given in Table 1. Cores from the Devonian strata of the Mackenzie River Corridor were examined at the NEB Core and Sample Repository at the Geological Survey of Canada in Calgary. Lithofacies logs on outcrops and some core intervals are augmented by frequent (0.25 to 1.0 m) logs of spectral gamma (RC-230 BGO handheld scintillometer).

Well	UWID	Drilled to TD	Interval measured, m	Year measured	Cored section deviation	Stratigraphic units measured	ICP-MS/ES	Rock-Eval VI	$\delta^{13}C$-$\delta^{18}O$	On-core SGR*, m
MGM East MacKay I-78	300/I-78-64501-25300	2013	1820-1959.7	2015	vertical	Canol, Hare Indian, and uppermost Hume fms.	N/A	N/A	N/A	1820-1851.3
COPRC Mirror Lake N-20	300/O-06-6500-12645	2013	1896-1970	2015	vertical	Imperial and upper Canol fms.	N/A	N/A	N/A	N/A
COPRC Loon Creek O-06	300/O-06-6510-12700	2013	1622-1813	2015	vertical	Imperial, Canol, Hare Indian (basinal), uppermost Hume fms.	380	380	N/A	N/A
TRIAD Ebbutt D-50	300/D-50-6220-12215	1964	538.6-612.8	2015	vertical	Headless, Landry, Manetou fms.	44	N/A	27	538.6-612.8
Tattoo D-A028	D-A028-F/94-O10	2010	3083-3286	2015	vertical	Fort Simpson, Muskwa, Otter Park, Evie, Keg River fms.	N/A	N/A	N/A	3083-3293.25
CPOG Kugaluk N-02	300/N-02-6840-13130	1965	1172.0-1689.0	2014-2015	vertical	Peel and uppermost Mt. Kindle fms.	N/A	N/A	N/A	1234.4-1245.2
TRIAD Ebbutt D-50	300/D-50-6220-12215	1964	434.6-482.8	2014	vertical	Imperial, Canol, Hare Indian and Hume fms.	83	N/A	32	434.6-482.8
Husky et al Little Bear N-09	300/N-09-6500-12630	2012	1670-1837.4	2014	vertical	Canol, Hare Indian, Hume fms.	N/A	N/A	N/A	N/A
MCD CAN GCO Maida Creek G-56	300/G-56-6540-12800	1970	517.2-550.2	2014	vertical	Canol and Ramparts fms.	15	N/A	18	517.2-550.2
Suncor et al Morrow Creek J-71	300/J-71-6530-12715	1984	861.0-897.60	2014	vertical	Canol and Ramparts fms.	N/A	N/A	N/A	N/A
Eog et al Devo Creek P-45	300/P-45-6530-12730	2002	327-345	2012-2013	vertical	Hume Fm.	N/A	N/A	N/A	N/A
Imperial Norman Wells P32X	304/M-46-6520-12645	1997	752.0 – 850.57	2012-2013	deviated	Canol and Ramparts fms.	N/A	15	10	N/A
CPOG Kugaluk N-02	300/N-02-6840-13130	1965	794.6 - 1172.0	2012-2013	vertical	Imperial Fm, Horn River Gp. (undivided); Hume & Landry fms.	70	38	46	1036.2-1047.7
MCD CAN GCO Maida Creek F-57	300/F-57-6540-12800	1970	464.2-491.9	2012-2013	vertical	Ramparts Fm.	N/A	N/A	N/A	N/A
Imperial Bear Island R34X	302/E-46-6520-12645	1979	674.0-728.0	2012-2013	vertical	lower Ramparts and upper Hare Indian fms.	N/A	N/A	N/A	N/A
Mackenzie River # 4 (E-27)	300/E-27-6520-12645/0	1980	398.0-408.0	2015	deviated	Canol and Ramparts fms.	N/A	N/A	N/A	398.0-416.0
Dahadinni 2M-43	302/M-43-6400-12430	1971	N/A	N/A	vertical	Landry Fm. (sampled)	N/A	N/A	20	N/A
IOE Clare F-79	300/F-79-6710-13300	1965	N/A	N/A	vertical	Hume Fm.	N/A	N/A	N/A	N/A

Table 1: *Summary of visual observations of cores and analyses retrieved to November 2015 under Devonian Stratigraphic Framework sub-activity of the Mackenzie Project. New thin sections and ED-XRF surveys are not included.*

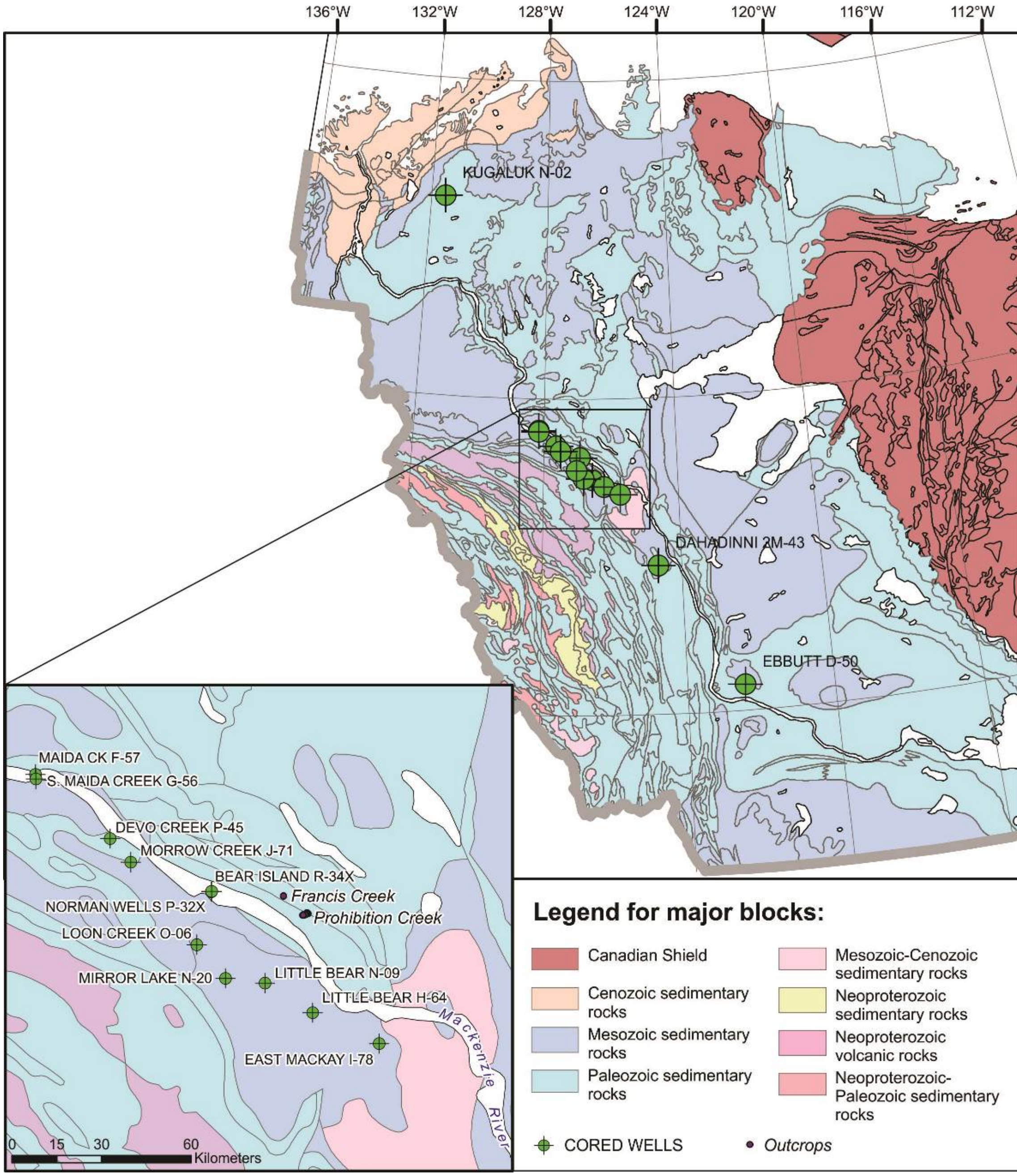

Figure 3: *Location of studied well and outcrop sections put on Geological Map of Northwestern Canada (based on Wheeler et al., 1997). Wells of the Mackenzie Valley and adjacent outcrops of the Norman Range are in the inset.*

To April 2015, 1378 m of cores have been measured (Kabanov, 2015), and the additional 488.9 m of cores from the project area have been examined during April-November 2015 (Kabanov et al., In press). Studied sections are located between 62°N and 69°N, within NTS map sheets 97B, 106, 96C-F, and 95I-P (Fig. 3). The core has been recovered mostly from vertical exploration wells drilled during the period of 1964 through 2013 (Fig. 3). In addition, two reference outcrop sections of the Horn River Group have been measured in July 2015 at the Norman Range (Kabanov et al., In press), and one continuously cored well Tattoo-D-A028 from the type Horn River Group succession (Horn River Basin) has been measured at the BCOGC facility in Ft. St. John, BC (Table 1).

Geochemistry

Samples for ICP-MS/ES geochemistry were collected from core sides and loose chips. Each sample represents an averaged material collected from a stratigraphic interval exceeding 1 cm (typically 2-5 cm), that is, none of the collected samples represents a single sedimentary lamina. The samples were analyzed at Acme Analytical Laboratories in Vancouver, BC with the induced coupled plasma (ICP) instrumentation technique. Samples were run under LF200 (lithogeochemical whole-rock fusion) and AQ200 (geochemical aqua regia digestion) lab codes.

The LF200 code is described as follows. The prepared sample is mixed with $LiBO_2/Li_2B_4O_7$ flux. Crucibles were fused in a furnace. The cooled bead is dissolved in ACS grade nitric acid and analyzed by ICP and/or ICP-MS. Loss on ignition (LOI) is determined by igniting a sample split and then measuring the weight loss.

In the AQ200 code, the prepared sample is digested with a modified Aqua Regia solution of equal parts concentrated HCl, HNO_3 and DIH_2O for one hour in a heating block or hot water bath. The sample then is made up to volume with dilute HCl. Sample splits of 0.5g are analyzed.

In addition, total carbon and total sulphur were measured by Leco combustion (TC000 lab code). In this procedure, the induction flux is added to the prepared sample, then ignited in an induction furnace. A carrier gas sweeps up released carbon to be measured by adsorption in an infrared spectrometric cell. Results are total and attributed to the presence of carbon and sulphur in all forms.

Carbon and oxygen stable isotope analysis

The carbonate samples for $\delta^{13}C$-$\delta^{18}O$ have been run at the G.G. Hatch Isotope Laboratory of the Faculty of Science (Earth Science) of the University of Ottawa. Samples were weighed into exetainers, 0.1mL of H3PO4 (S.P. 1.91) was added to the side, exetainers were capped and Helium-flushed while horizontal. Reaction at 25.0C for 24hrs (calcite) or 50.0C for 24hrs (dolomite) was followed by extraction in continuous flow. The measurements were performed on a Delta XP and a Gas Bench II, both from Thermo Finnigan. Analytical precision (2 sigma) is +/- 0.1‰.

Rock-Eval VI pyrolysis-combustion

The pyrolysis-combustion tests were conducted at the Organic Petrology and Geochemistry Laboratory in GSC (Calgary) using the Rock-Eval VI instrument. Approximately 1g of the unwashed core sample was crushed to powder form using a mortar and pestle. A 70mg aliquot of the sample was then inserted into a stainless steel crucible and heated in an open pyrolysis system. Initially, the samples are heated 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°C 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 if conditions had allowed it. It is important to note that drilling mud contamination and hydrocarbon migration can affect both the S1 and S2 values, 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 mud cake formation.

The S3 peak is a measure of the total amount of CO_2 (mg CO_2/g of initial rock) generated over the entire pyrolysis measurement. The S3 curve accounts for the CO_2 measured during the first stage (0-300°C) and second stage (from300°C to 400°C), which corresponds to CO_2 generated from organic matter. The S3' curve accounts for the CO_2 generated between 400°C and 650°C, which corresponds to mineral decomposition. The S3 peak is the combination of S3 and S3' (Behar et al., 2001).

The final step is the oxidation of the samples, which measures the total amount of organic carbon generated during this stage. Here, the samples are heated from 300°C to 850°C and the CO and CO2 are detected by IR cells, producing the S4 curve which measures the residual organic carbon (RC). The S5 curve corresponds to the mineral carbon from CO and CO2 generated during mineral oxidation (Behar et al., 2001), mainly calcination of carbonate salts.

The sum of the pyrolysable organic carbon (PC) and residual organic carbon (RC) is the total organic carbon (TOC; wt%) in the sample. Tmax is measured at the maximum of the S2 peak and indicates the maturity of the samples, which is dependent on the kerogen type (see Tissot et al., 1980). Other calculated parameters include: HI (S2X100/TOC), OI (S3X100/TOC) and PI (S1/S2+S3). These parameters aid in identifying the kerogen type (I-IV) and whether the organic matter in the sample is oil vs. gas prone.

ED-XRF geochemistry

The energy-dispersive X-ray diffraction tools (ED-XRF) became widely used in chemostratigraphic surveys in mudrock successions and other types of sedimentary rocks (Rowe et al., 2012). The Bruker Tracer IV-SD Turbo tool has been dispatched to Calgary in 2014 through SLN network of NRCan for chemostratigraphic method development. The tool is currently used to acquire quick non-destructive surveys of sedimentary structures in Devonian cores. The tool is usually operated in non-vacuum mode using the Mining Light Elements factory calibration, which is suitable to qualitative to semi-quantitative assessment of light elements (Mg, Al, Si, P, S, Ca, K, Ti) and generally more accurate values of elements with higher atomic numbers and higher Kα excitation energies. Detection limits for elements with ED-XRF tools are discussed by Rowe et al. (2012) and Hall et al. (2014).

Results

Studied sections (Table 1) provide the basis to upgrade the sequence stratigraphic framework of the Devonian succession with most significant modifications anticipated in the Lower Devonian shallow-water carbonate package of the Peel and Anderson plains and the Horn River Group of the Mackenzie Plain (Kabanov, 2014, 2015; Kabanov et al., 2015, In press).

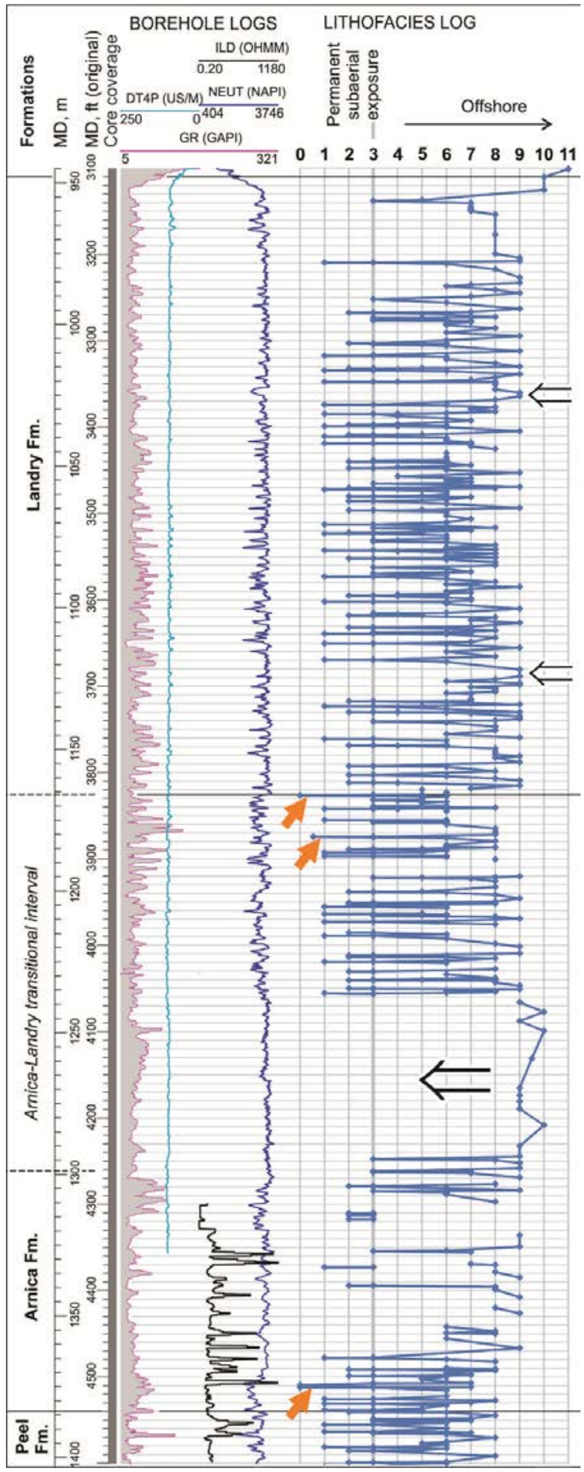

Figure 4: *A lithofacies log for the Arnica-Landry succession of Kugaluk N-02 Well (Kabanov, 2015). On the Lithofacies log, each facies point represents a mid-point of the descriptive interval, and most subaerial disconformities represent plain surfaces as they have no thickness. Lithofacies groups and ranks of subaerial disconformities are listed on Figure 11. Gaps in joint line indicate intervals with lost sedimentary structure due to fabric-destructive dolomitization and/or fractured "lost core" intervals. Black hollow arrows indicate prominent highstand intervals with thick offshore lithofacies*

and no disconformities. Orange arrows indicate deepest subaerial exposure profiles with preserved paleosols (Rank 0 disconformities of Kabanov, 2014).

Lower Devonian carbonates

The shallow-water carbonate packages (Peel, Tatsieta, Arnica and Landry formations and partly Hume Formation) contain hundreds of subaerial exposure surfaces that cannot be traced on conventional well logs in old exploration wells and do not form seismic reflectors (Fig. 4). Although metre-scale cyclicity in this succession was known for decades, permanent subaerial exposure surfaces have not been recognized. Visually these surfaces range from incipient stratigraphic discontinuities with solution vugs to paleokarst profiles of several metres in thickness and occasionally preserved rubbly paleosols (Kabanov, 2014, 2015). Paleokarsts are usually imprinted on tidal-flat laminites and in the Landry Formation are associated with thin shallow-water carbonate beds without marine fossils interpreted as palustrine facies (Kabanov, 2014). The succession of subaerial exposure surfaces and highstand intervals with relatively thick and conformable offshore intervals define a hierarchy of T-R sequences/parasequences (Fig. 4; Kabanov, 2014). The distinctive horizons in this succession, such as major highstands and major disconformities, can potentially be traced over long distances to augment the conventional lithostratigraphic framework. A set of stable isotope, Rock-Eval, and geochemical analyses have been done from the shallow-water intervals in the Arnica-Landry succession containing subaerial exposure profiles. Preliminary results on $\delta^{13}C$ and $\delta^{18}O$ show that negative $\delta^{13}C$ excursions in paleosols and paleokarsts that are characteristic of younger Phanerozoic subaerial exposure profiles are not expressed in studied Lower-Middle Devonian examples (Kabanov, 2015).

Headless drowning event

The Headless Member is a regionally traced shale-rich lower part of the Hume Formation sometimes regarded in the formation status (Gal et al., 2009; Morrow, 2012). Observed lithofacies features in core from Kugaluk N-02 indicate an offshore character with suppressed bioturbation (Kabanov, 2013, 2014). The spatial extent of this “Headless drowning horizon” remains unknown until more observations from other sections are collected. New geochemical data from the Headless interval of Kugaluk N-02 (Kabanov, 2015) well indicate elevated aluminosilicate content pointing to terrigenous source. The Headless Member is also characterized by elevated dolomite content. Manganese does not reach significant concentrations (max. 90 ppm of MnO), however, its negative covariation with anoxia-sensitive trace metals such as Cu, Pb, Zn, Ni, and V may be an indication of moderate Mn accumulation in response to reduction-oxidation fluctuations at or just beneath the seafloor. Flat Al^{3+}-normalized logs for trace metals and essential absence of U indicate that anoxia has not been achieved and that trace metals are mostly bound in siliciclastics. Earlier reported occurrences of dark organic-rich shales in the Headless Member (Gal et al., 2009; Hannigan et al., 2011) should have restricted spatial distribution and thus probably little interest for tight-reservoir hydrocarbon exploration.

Horn River Group

There were very few representative cored sections of the Hare Indian and Canol formations until recent exploration activity in the central Mackenzie Valley (Hayes, 2011). The most complete cored sections repeatedly appeared in the literature are Kugaluk N-02 and Ebbutt D-50 on northern and southern extremities of the study area (Fig. 3). Recently released cored sections from the Sahtu exploration area (Little Bear N-09, Little Bear H-64, East MacKay I-78, Loon Creek O-06, and Mirror Lake N-20, Table 1) provide new resolution for the stratigraphy of the Horn River Group, including detailed chemostratigraphic, organic-matter, and petrophysical surveys (Kabanov et al., 2015, In press). New field data on outcrops adjacent to exploration licenses of the Canol shale play (Fig. 5) provide the tool for outcrop-subsurface correlation given the sufficient resolution of the spectral gamma log (Kabanov et al., In press). Outcrops also remain the only reasonable source of massive sampling, as available core material is limited by the Frontier lands regulation (National Energy Board, 2011). In particular, better conodont biostratigraphic constraints will hopefully be obtained from large (5-8 kg) samples collected from calcareous nodules in the Canol Formation during the field works of 2015 (Kabanov et al., In press).

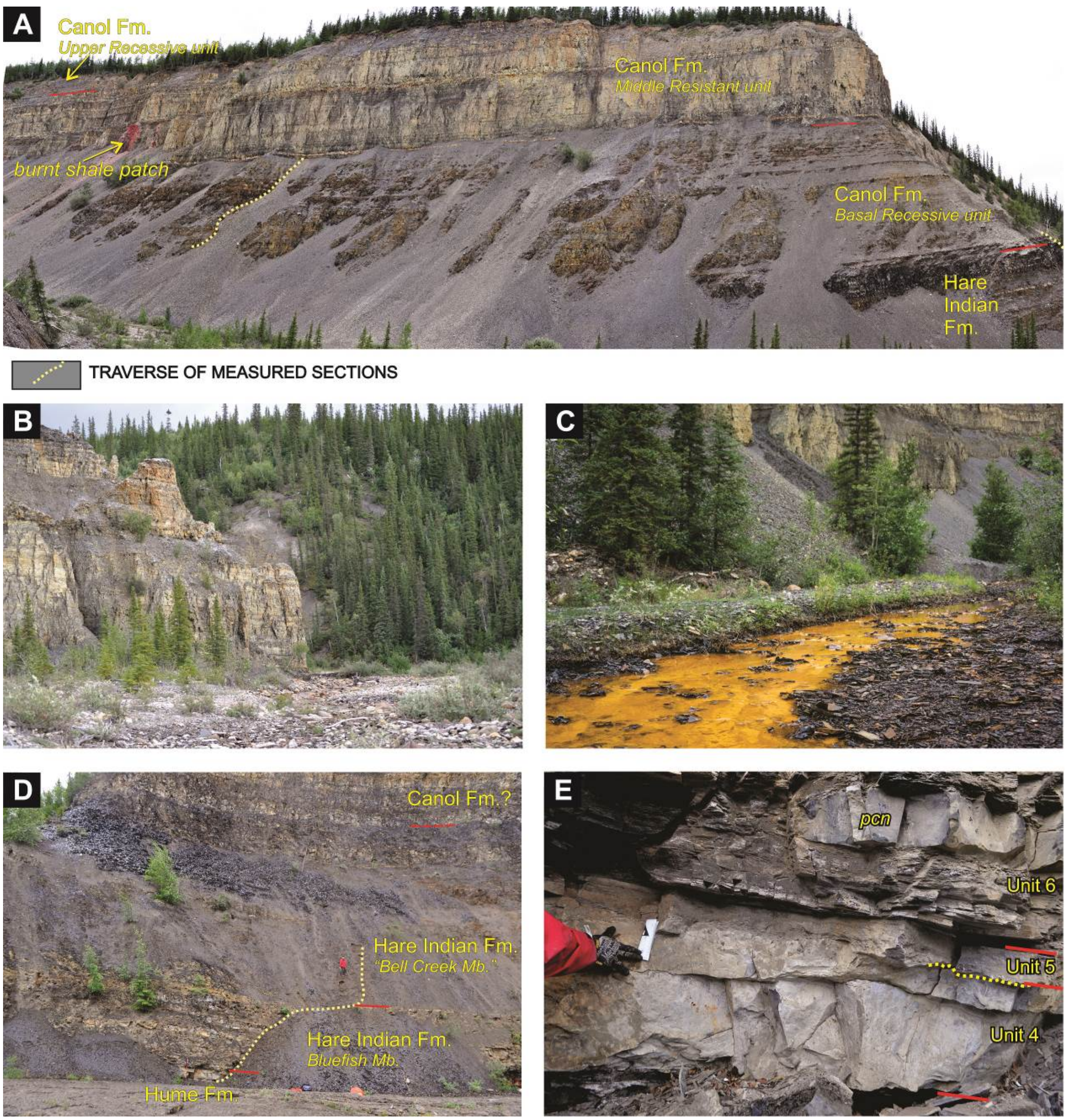

Figure 5: *Outcrop sections of Horn River Group measured in 2015: (A-C) Prohibition Creek; (A) panorama of Canol Formation at campsite (126°13'25"W 65°11'16"N), note the red burnt shale patch resulted from organic matter combustion caused by natural lightning; (B) Cliff and hoodoo forming hard siliceous shales of Middle Resistant unit downstream of (A); (C) Acidic,* Fe^{3+} *precipitating*

springs under the cliff visualizing intense decomposition of pyrites in the Canol shale. (D and E) Francis Creek, Hume/Hare Indian contact; (D) measured section and the gully bed formed by a rugged surface in Hume limestone; (E) Close-up of the Hume/Hare Indian contact showing undulating hardground surface (partly traced from the right) onlapped by tentaculitid-brachiopod coquina (Unit 5) and the overlying shale of Unit 6 with large pre-compactional authigenic limestone nodules (pcn). Description of units and SGR data are available in Kabanov et al. (In press).

Conclusion and future work

Measured representative cored sections, outcrops, and multi-tool logging provide the new resolution for the Lower- basal Upper Devonian succession of the Mackenzie River Corridor (Peel-Tatsieta, Arnica, Landry, Hume, Hare Indian, and Canol formations). New data on the stratigraphic variation of organic matter and petrophysical properties in the Horn River Group improve the basis for hydrocarbon exploration in Canol shale play. Updates in stratigraphic subdivision, formation tops, and chemostratigraphic framework of shale-dominated economic units are underway. Interim summaries on specific results are available (Kabanov, 2014, 2015; Kabanov et al., 2015, In press).

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