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Devonian Horn River Group: A Reference Section, Lithogeochemical Characterization, Correlation of Measured Sections and Wells, and Petroleum-Potential Data, Mackenzie Plain area (NTS 95M, 95N, 96C, 96D, 96E, 106H, and 106I), NWT

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Appendix J. Core photos (reproduced from Gal and Pyle, 2012)

Appendix K. Lithogeochemistry profiles from partial measured sections including: Dahadinni River East, Grafe River, Imperial Anticline, Nainlin Brook, Ramparts, and Walker Creek

Appendix L. Revised tops picks for wells with Horn River Group in Mackenzie Plain exploration area

Appendix M. List of sections and sampled well locations

FOREWORD: PROJECT RATIONALE

Resource-based industries, including oil and natural gas exploration and production, mineral exploration, and mining, dominate the economy of the Northwest Territories (NWT). In 2007, mining and oil and gas extraction accounted for 51.1% of the gross domestic product (GDP) of the NWT. Although there was a decrease to 39.4% in 2012, including 10.9% from oil and gas extraction and 0.3% from support activities from oil and gas extraction, these industries contribute significantly to the territory's GDP (www.statsnwt.ca/economy/gdp). Publicly available, modern geoscience information is a foundation for these industries' efforts and investment. Government geoscience programs are a critical part of northern economic development. Project results support current exploration activity, as well as underpin land-use and resource-management policies and decisions.

The Mackenzie Plain exploration area contains one conventional oil field at Norman Wells, from which the Enbridge-owned pipeline carries crude oil south to gathering stations at Zama, Alberta. The Norman Wells oil pool was discovered by Imperial Oil Limited in 1920 and produces oil out of the Kee Scarp Member reef carbonates of the middle Devonian age Ramparts Formation. Mackenzie Plain is also transected by the proposed route of the Mackenzie Gas Project natural-gas pipeline.

New exploration investment in the unconventional Canol Formation shale-oil play is underway in the central Mackenzie Valley, where currently there are 14 exploration licenses held, totaling 627.5 million dollars in work-bid commitments (Aboriginal Affairs and Northern Development Canada, 2013). Six new exploration wells were drilled in the last three years in the central Mackenzie Valley. ConocoPhillips Canada, at the time of writing this report, was drilling the first of two horizontal wells planned for the 2014 winter drilling season.

The Mackenzie Plain Petroleum Project (2009-2014) was initiated by the Northwest Territories Geoscience Office (NTGO), after wrap-up of the Peel Petroleum Project (Pyle and Jones, 2009). The primary objective of the Mackenzie Plain project is to improve knowledge of the regional stratigraphy and petroleum geoscience in the Mackenzie Plain area, with emphasis on source rock evaluation of various units of the Devonian Horn River Group. This project is an initial effort to characterize unconventional shale-oil and -gas potential within the central Mackenzie Valley, for which little relevant information has been available other than source-rock organic-richness data obtained during conventional play assessments (Hannigan et al., 2011). Interim publications have been released throughout the project (Pyle and Gal, 2012, 2013; Gal and Pyle, 2012; Pyle et al., 2011). Funding for the Mackenzie Plain Petroleum Project has been from the federal Strategic Investment in Northern Economic Development (SINED) program, and has benefited from laboratory analyses provided by the Geo-mapping for Energy and Minerals program of the Geological Survey of Canada (GSC).

INTRODUCTION

A refinement of the Horn River Group stratigraphic framework in the Mackenzie Plain area, NWT (Figure 1) is important for current and future shale reservoir exploration. In central NWT, the Middle to Upper Devonian Horn River Group includes Hare Indian Formation, Ramparts Formation, and Canol Formation (Pugh, 1983). The succession records a complex depositional history that includes two phases of starved-basin conditions (basal Bluefish Member of Hare Indian Formation, and Canol Formation), with an intervening siliciclastic bank (upper Hare Indian Formation) and carbonate bank/reef (Ramparts Formation and Kee Scarp reef; Muir and Dixon, 1984, 1985). All three formations contain fine-grained siliciclastic rocks with high weight-percentages of total organic carbon (TOC) that are potential source rocks for conventional plays, as well as for self-sourcing, self-enclosed shale-reservoir plays. The Canol Formation is widespread in the study area and known to be the source rock for the Norman Wells oil field (Snowdon et al., 1987; Feinstein et al., 1988a). Good-quality source rocks are also present in the Bluefish Member of the Hare Indian Formation, in the upper part of the Hare Indian Formation (herein proposed to be called the Bell Creek member; see below), and in the Carcajou member of the Ramparts Formation (Gal and Pyle, 2012; Pyle and Gal, 2012, 2013; Pyle et al., 2011).

The homogenous nature of the Horn River Group shale units and gradational contact with the overlying Imperial Formation has led to undifferentiation of units in outcrop previously, as well as common misidentification in the subsurface. Where the carbonate-dominated Ramparts Formation is not developed, the lithologically similar, shale-on-shale succession was mapped as Canol-Hare Indian Formation (e.g., Tassonyi, 1969), or as an undifferentiated Dhci (Devonian Hare Indian-Canol-basal Imperial; e.g., Aitken et al., 1982). In the subsurface, some tops picks by Hogue and Gal (2008) are too shallow for both the Canol and Hare Indian formations, and the upper Hare Indian Formation was not differentiated.

The purpose of this study is to develop a robust characterization scheme to differentiate organic-rich Horn River Group units using lithology, spectral gamma ray profiles, TOC content, chemostratigraphy based on trace elements and major oxides, and changes in semi-quantitative modal mineralogy obtained by X-ray diffraction (XRD). A new reference section for the Horn River Group is designated at the Mountain River Tributary to serve as a standard from which to extend correlations. Outcrop characterizations are then extended to the subsurface primarily using gamma-ray logs and lithogeochemistry profiles from selected wells, leading to extensive revision of formation-top picks. For other Mackenzie Plain wells where lithogeochemical data were not gathered, significant revisions to tops picks are based on comparison of available log trends (primarily gamma), to the characterizations understood from the sampled wells. A future goal is to apply and extends the improved methods of correlation from central Mackenzie Valley to equivalent strata in Horn River Basin and Liard Basin of southern NWT and northeastern British Columbia (Figure 2).

LOCATION AND REGIONAL GEOLOGY

Mackenzie Plain is part of the Mackenzie Arc exploration region, within the Northern Canadian mainland sedimentary basin (Figure 1; Morrow et al., 2006). The project area is transected by the Mackenzie River and contains the communities of Norman Wells and Tulita (Figure 3). Mackenzie Plain is flanked to the west by the Mackenzie Mountains and to the east by the Franklin Mountains, both which contain sedimentary rocks deformed during late Cretaceous to Paleocene orogeny. The structure of the northern Mackenzie Mountains, which is dominated by broad anticlines and intervening narrow synclines, contrasts with the curvilinear, narrow, thrusted fold ridges of the northern Franklin Mountains. Mackenzie Plain is underlain by westward-thickening, flat-lying to folded Cretaceous strata, with some exposures of Devonian strata within structural uplifts such as the Imperial Hills and along the Mackenzie River (Aitken et al., 1982; Lemieux et al., 2009).

The Middle to Upper Devonian Horn River Group in the central Mackenzie Valley (Figure 4) represents the first significant basinal deposits following a long phase of deposition on the Mackenzie-Peel Shelf (Morrow and Geldsetzer, 1988), which was an open-marine, continental-margin platform that persisted from the latest Cambrian. The last phase of shelf deposition is marked by the Middle Devonian Hume Formation, an extensive and fairly uniform platform carbonate deposited across the Mackenzie-Peel Shelf (Williams, 1986). The tectonic setting recorded by Lower Paleozoic strata in the Mackenzie Plain area is a "passive" continental margin (Fritz et al., 1992); however, phases of rifting and extension persisted to create complex stratigraphic relationships (Morrow, 1991), influenced by intra-shelf tectonic highs such as the Mackenzie Arch (Aitken et al., 1973) and Keele Arch (Cook, 1975).

The Horn River Group consists of Hare Indian, Ramparts, and Canol formations (Pugh, 1983; Figure 4). Intervals of organic-rich source rocks are present within basinal facies of the Bluefish Member of Hare Indian Formation and also in the Canol Formation. The upper Hare Indian Formation that intervenes between Bluefish Member and Canol Formation consists of mixed siliciclastic-carbonate basin-margin facies. Where the upper Hare Indian Formation is present, it is overlain by shale ramp and platform-margin carbonate facies of the Ramparts Formation. Locally, the uppermost Ramparts Formation developed a reefal Kee Scarp Member, which is the primary reservoir of the Norman Wells oil field (Muir and Dixon, 1984; 1985).

In the Late Devonian, the Horn River Group was overlain by deposits of the Imperial Formation (Figure 4), representing a major sedimentological change in response to the onset of the Ellesmerian Orogeny (Lane, 2007). Siliciclastic-dominated deposits represent basin, slope, and shelf-shoreface environments (Pugh, 1983; Morrow and Geldsetzer, 1988; Hadlari et al., 2009a, b). A sub-Cretaceous unconformity at the base of the Martin House Formation (Figure 4) truncates the Imperial Formation (and sometimes the Canol and Ramparts Formation), and has locally removed a substantial portion of the section within the Mackenzie Plain area (Aitken et al., 1982). A Cretaceous-Tertiary foreland basin developed to the north and east of the rising Mackenzie Mountains, recorded by alternating sandstone-dominated units (Martin House, Trevor, Little Bear, and Summit Creek formations) and shale-dominated units (Arctic Red, Slater River, and East Fork formations; Figure 4; Yorath and Cook, 1981; Dixon, 1999).

METHODS

The Mackenzie Plain Petroleum Project involved study of 29 outcrop exposures of Horn River Group and a collection of well cuttings from 26 exploration wells, to obtain source-rock data from across the Mackenzie Plain (Figure 3).

Outcrop

Complete sections of Horn River Group are those in which the underlying Hume Formation and overlying Imperial Formation are exposed. Five of these sections were measured and sampled (highlighted in green, Table 1). It was determined that the best representative section for the whole Group is on a tributary of the Mountain River, at a location herein designated the Mountain River Tributary (or MR) section (Figure 3). Nearly complete sections are those for which the upper contact of the Canol Formation with the overlying Imperial Formation was too recessive to be exposed (e.g., Carcajou River 2 section, or CR2; highlighted in yellow, Table 1). Partial sections are those for which neither the base nor the top of the Group is exposed (highlighted in blue, Table 1). A total of more than 1600 m of outcrop were measured using a 1.5 m-long staff. Descriptions of the measured sections are in Appendix A. The exposure at some sites was suitable for only spot sampling; these sections were not measured, as indicated in Table 1. For cliff-forming units, such as the Canol Formation at Vermillion Creek, a laser rangefinder was used to estimate stratigraphic thickness.

Spectral gamma-radiation measurements were taken at either one-metre, 1.5 metre, or three-metre intervals throughout each measured section, with a hand-held spectrometer. In 2012, an RS-220 Super-Scint by Radiation Solutions Inc. was used with a two-minute data-collection period at each sampled location, providing total radiation in counts per second (cps), potassium concentration in percent (%), and equivalent uranium and equivalent thorium concentrations in parts per million (ppm). In the 2010 and 2011 field seasons, an RS-120 Super-Scint by Radiation Solutions Inc. was used to record total radiation in cps, averaged over a 20-second period.

Chip samples were taken throughout each measured section across one-, two-, or three-metre intervals, depending on the thickness of the units in outcrop. Chip samples were analysed to evaluate organic richness and source-rock potential using Rock-Eval pyrolysis and TOC measurement (451 samples, Appendix B), and vitrinite (or vitrinite equivalent) reflectance (33 samples total; Appendix C). These analyses were provided by GSC-Calgary. A ten-gram split from select samples was analysed for concentrations of major-element oxides, trace elements, and rare earth elements by Acme Analytical Laboratories in Vancouver, BC (Appendix D; 502 samples). Major-element oxides and some trace elements were determined by inductively-coupled plasma - emission spectroscopy (ICP-ES) on 0.2 g pulverized rock that had been fused with lithium metaborate/tetraborate and then dissolved in dilute nitric acid (Acme Labs' package 4A). Rare earth and refractory elements were determined by an inductively coupled plasma–mass spectroscopy (ICP-MS) finish on the fused sample (Acme Labs' package 4B). Loss on ignition (LOI) was calculated by weight difference after ignition at 1000°C. Carbon and sulphur were analysed by LECO induction furnace. A five-gram split from select samples was analysed for mineral species present by X-ray diffraction (XRD) at GSC-Calgary and GSC-Ottawa (semi-quantitatively; 217 samples total) and an additional 11 samples were analysed semi-qualitatively by Acme Analytical Laboratories (Appendices E1, E2, E3). Biostratigraphic analyses for conodont microfossils (5 samples) and palynomorphs (1 sample) were carried out at GSC-Calgary.

Section (Sample Code)	section base		section top		UTM NAD 83 Zone	Horn River Group unit (metres thickness)				
	UTM NAD 83 (easting, northing)		UTM NAD 83 (easting, northing)			Hume	Bluefish	Bell Creek	Ramparts	Canol
Bell Creek West (BW)	501061	7240021	501022	7240030	9			55.0+	15.0+	
Canyon Creek (CC)	618106	7239145	617858	7238903	9		7.5	7.5		57.0+
Carcajou River 1 (CR1)	604596	7180582	604654	7180543	9		8	19		37.5+
Carcajou River 2 (CR2)	603450	7185390	603744	7185420	9		10	19		142+
Carcajou River 3 (CR3)	604393	7181894	604437	7182270	9					not measured
Dahadinni River East (DRE)	395843	7065586	395831	7065620	10					36.0+
Dodo Canyon (DC)	578059	7210407	578091	7210429	9		5	7		12.0+
Dodo Canyon-East (DCE)	578964	7210364	578979	7210859	9					109.0+
Dodo Canyon-Hume (DCH)	577966	7209743	577699	7210313	9	64.5+				
Gayna Gorge (GG)	483343	7240920	483343	7240920	9	60.2+	5.1	170	33	3
Grafe River (GR)	569853	7212856	569919	7212925	9					39.0+
Imperial Anticline (IA)	514748	7259321	514809	7259272	9			12.0+	100.0+	
Imperial River (IR)	565499	7233722	565499	7233722	9					10.0+
Keele River (KR)	363345	7123940	363345	7123940	9					4.0+
Little Bear (LB)	620840	7152317	621055	7152487	9		5	25		75
Little Bear River 2 (LB2)	627330	7155802	627268	7155888	9		10	8.5		44.5+
MacKay Range West (MAC)	369926	7178229	369880	7178198	10	14.5+	8	15		19.5+
Moose Prairie Anticline (MPA)	375359	7063399	375335	7063406	10					10.5+
Mountain River 2 (MR2)	493981	7256998			9				not measured	
Mountain River Tributary (MR)	518945	7235192	519278	7235292	9		20	32	30.8	83.5
Nainlin Brook Area (NB)	572552	7120323	572541	7120282	9					19.0+
Powell Creek (POW)	511225	7239972	510561	7239399	9	136.1	4	130	80.5	18.2
Powell Creek West (PW)	509882	7239358	509881	7239364	9		9			
Prohibition Creek (PC)	630104	7232321	628741	7231365	9					75.0+
Quarry (Q)	605896	7243612			9					not measured
The Ramparts (R)	512091	7345411	512120	7345383	9			33.5+	24.0+	
Turnabout Creek (TC)	469931	7244780	469945	7244804	9	6.0+	2			19
Vermillion Creek (VC)	638585	7227651	637312	7227293	9			2		37.0+
Walker Creek (WC)	551616	7245351	551563	7245293	9					51.0+

Table 1. *List of outcrop localities and formation and member thicknesses in metres. Complete, nearly complete, and partial sections are highlighted in green, yellow, and blue, respectively. See Appendix A for details.*

Exploration Wells

Twenty-six wells were selected for study based on their location within or near Mackenzie Plain, and the availability of Horn River Group samples from the cuttings or core archived at the Core and Sample Repository of the GSC-Calgary. The selected wells are arranged in five roughly east-west transects that span the Mackenzie Plain (Figure 3). Intervals were selected for sampling after consulting published formation tops and well history reports, and visually examining vials of washed cuttings. Once approval was received from the National Energy Board, and after determining that enough suitable material was present, a twenty-gram sample was collected from the bagged unwashed cuttings of each selected interval. Sample material was weighed, sieved, washed and air-dried. The dried sample was divided into splits for the various analytical methods. Each split was picked under the microscope to remove (as far as possible) cavings, drilling mud, wood chips or other potential contaminants that had not been removed by sieving and washing. Cores were sampled from intervals as approved by the National Energy Board, and collected as small chips lying loose in the core boxes to avoid breaking intact core pieces.

The same analyses were conducted on cuttings and core as on the outcrop samples. Rock-Eval pyrolysis was carried out on 479 samples at GSC Calgary (Appendix F). Selected samples (37 in total) were submitted to GSC-Calgary for thermal-maturation analysis through reflected-light microscopy (vitrinite reflectance; Appendix G). Whole-rock lithogeochemical analyses were conducted on 369 samples by Acme Analytical Laboratories (Appendix H). A total of 187 samples were analysed for mineral species present by X-ray diffraction (XRD) at GSC-Ottawa (semi-quantitatively; Appendix I). Sampled cores were photographed to illustrate the quality of the core and to show sampling levels (Appendix J, reproduced from Gal and Pyle, 2012).

HORN RIVER NOMENCLATURE REVIEW

The present study uses the term Horn River Group as it was proposed by Pugh (1983) to refer to the Hare Indian, Ramparts and Canol formations in the Norman Wells area. Pugh (1983) proposed the use of Horn River Group to solve several nomenclatural inconsistencies involving the term "Horn River Formation". The historical evolution of the terminology was summarized by Williams (1983) as follows:

1) The Horn River shale is described at its type locality on the Horn River, NWT (Whittaker, 1922; Figure 2);
2) Mapping by Douglas and Norris (1960) and Douglas and Norris (1960, 1961) includes limestone overlying the Horn River shale and basal sandy shale (Horn River type B of Williams, 1983) into the Horn River unit;
3) Belyea and Norris (1962) used "Horn River" two ways: for just black shale, or for a threefold black shale - greenish-grey shale - black shale succession (units are both Horn River types A and B of Williams, 1983);
4) Definition of a threefold succession of Horn River Formation that includes Evie, Otter Park, and Muskwa members by Gray and Kassube (1963) in northeastern British Columbia. They also introduced the term "Klua Formation" for a tongue of the Otter Park shale (as interpreted by Williams, 1983);
5) Separation of the Muskwa unit from the Horn River Formation and change in the rank of Muskwa Member to Muskwa Formation by Griffin (1965), which left only the Evie and Otter Park members within the Horn River Formation;
6) Introduction of the term Horn River tongue (e.g., Norris, 1965; Griffin, 1965);

7) The implication of the equivalence of the two threefold successions Evie - Otter Park - Muskwa and Hare Indian – Ramparts - Canol are discussed by Douglas (1970) and Bassett and Stout (1967); the Horn River type B of Williams (1983) is equivalent to the Muskwa Member and Canol Formation and Horn River type A is equivalent to the rest of the Hare Indian Formation; and
8) Extended usage of the term Horn River Formation northward to replace usage of "Hare Indian - Canol Formation" where the two shale units are undifferentiated (Tassonyi, 1969).

Another issue is that the term Horn River Formation remains valid. It was defined by Gray and Kassube (1963; in Fort Nelson a-95-J, 94-J-10, 1984.2-2215.9 m) and applied to a belt of strata from northeastern British Columbia to Great Slave Lake in NWT. The name Horn River is based on the type locality proposed by Whittaker (1922) in outcrop along the Horn River at 61º 44'N, 117 º45'W. The term Horn River Formation is currently used to refer to the Evie-Otter Park-Muskwa assemblage. The problem with this nomenclature is that Griffin (1965) raised the Muskwa Member to Formation but did not address the resulting use of the name Horn River, which should have been dissolved as a formation name at that point. This therefore creates inconsistencies in the use of Muskwa Member, Muskwa Formation and Muskwa shale and has led to the nomenclatural bungle of using the general term of "Horn River shale."

A solution that provides consistency would be to elevate Evie Member and Otter Park Member to formation status and extend usage of the term Horn River Group south to the Horn River Basin. Such an effort is beyond the scope of the present study, but will be aided by comparing the revised lithogeochemical characterizations of the Horn River Group units in Mackenzie Plain, as understood through this study, to the equivalent units in the southern NWT and northeastern BC. In the present study of Horn River Group strata north of 64ºN latitude, we have used lithological differences and whole rock lithogeochemistry to differentiate the shale units in outcrop and the subsurface, particularly where the Ramparts Formation is absent and the Hare Indian Formation is directly overlain by the Canol Formation. More revision will be necessary to clarify the stratigraphic nomenclature on maps and in the subsurface south of 64ºN, where the term "Horn River" or undifferentiated "Hare Indian–Canol" was used. Nomenclatural revision and extension of the term Horn River Group may also provide a useful hierarchy for laterally correlative units such as the Klua Formation and Spence River Formation (of Hunt, 1954).

HORN RIVER GROUP OUTCROP AND REFERENCE SECTIONS

Introduction

The Hume Formation is overlain by Middle to Upper Devonian Hare Indian, Ramparts, and Canol formations (Horn River Group; Figure 4). Organic-rich shale of basal Hare Indian Formation (Bluefish Member) and Canol Formation record two phases of an oxygen-stratified basin. These units are separated by siliciclastic-dominated basin-margin deposits of the upper Hare Indian Formation, previously referred to as the grey shale member by Pugh (1983) and herein referred to as the Bell Creek member (new). A localized carbonate ramp to platform or reef of Ramparts Formation developed upon the upper Hare Indian Formation. The uppermost reefal Kee Scarp Member is the primary reservoir of the Norman Wells oil field (Muir and Dixon, 1984). Either the Upper Devonian to Carboniferous Imperial Formation or Cretaceous units overlie the Horn River Group (Figure 4). The age of the Horn River Group, based on conodont biostratigraphy, ranges from Givetian (middle *varcus* Zone) to Frasnian (*gigas* Zone; Figure 5). Within a sequence stratigraphic framework, a preliminary comparison to the Euramerican sea-level curve (of Johnson et al., 1985) suggests that some of the sea-level rises recorded by the Horn River Group, specifically the onset of deposition of each of Bluefish Member, Canol Formation and Imperial Formation, correspond with cycles IIa, IIb and IId, respectively, but more detailed work on the sedimentology and biostratigraphy of the succession is needed to confirm these correlations.

The purpose of establishing a principal reference section (North American Commission on Stratigraphic Nomenclature, 2005) at the Mountain River Tributary (MR) section (Figures 3 6; Appendix A) is to: 1) provide an accessible site (by helicopter from Norman Wells, NWT) that exposes all units of the Horn River Group; 2) serve as a standard for revision of the Hare Indian Formation into two members (Bluefish Member and Bell Creek member), and 3) to designate a site where most of the unit boundaries can be observed (Figures 6, 7, 9, 12). This is in contrast to the type sections for the Bluefish Member, Hare Indian Formation and Ramparts Formation, where unit boundaries are not exposed.

A supplementary reference section is designated for the Bell Creek member (new) at Carcajou River 2 (CR2) section (Figures 8, 10; Appendix A) because of the heterogeneity of this unit. At the MR section, where the Ramparts Formation is present, the Bell Creek member is “typical” green-grey upper Hare Indian Formation, but where the Ramparts Formation is absent, such as at CR2 section, the “atypical” Bell Creek member is dark grey and visually similar to the Canol Formation.

The following descriptions of the Hare Indian Formation, Bluefish Member, Bell Creek member, Carcajou member of the Ramparts Formation and Canol Formation review the definitions of each unit and expand upon these based on our observations at the reference sections.

Hare Indian Formation

Definition and New Reference Section

A type section for the Hare Indian River Shale was proposed in the Ramparts Gorge on the Mackenzie River by Kindle and Bosworth (1921). The name Hare Indian Formation was applied by Bassett (1961). The base of the unit is not exposed at the type locality; the top of the unit is obscured by blocks of Ramparts Formation talus which is typical at most sections where the Hare Indian and Ramparts formations are exposed. A reference section is therefore proposed at the MR section described herein where the base of the Bluefish Member is exposed near creek level, and the base and top of the Bell Creek member, depending on scree-cover, are visible either in the gulley-cut part of the section (blue dotted line in Figure 6), or in the cliff-face just above creek-level (Figure 7).

The Hare Indian Formation consists of two units: 1) a basal Bluefish Member that consists of organic-rich black shale with limestone interbeds (Pugh, 1983; formerly called the “spore-bearing member” by Tassonyi, 1969); and 2) an informal “grey shale member” that contains wackestone to packstone and grey-green shale (Pugh, 1983; Muir and Dixon, 1984), which warrants a name. We herein assign it the name of Bell Creek member.

Distribution and Thickness

The Hare Indian Formation extends from the Norman Wells area north toward Anderson River and south to Ram River area near Fort Simpson, NWT. It extends west toward the Snake River in Yukon (Bassett, 1961). Its zero-edge east lies in the Franklin Mountains (Fallas et al., 2013) where it is poorly exposed. In the present study, the unit thickens up to 195 m in the Gayna River area and is more than 200 m thick westward in the Arctic Red River and Cranswick River areas (Gal et al., 2009). Its westward depositional edge is around 132ºW (Pugh, 1983; Gal et al., 2009), where Hare Indian and Canol formations were mapped as an undifferentiated unit in the Snake River map area (map sheet 106F; Norris, 1982). In the Mackenzie Mountains south of 65°N, the western depositional edge is not as well known (e.g., Gordey et al., 2010, 2012).

Lithology

At the MR section, the Hare Indian Formation is a mixed siliciclastic and carbonate unit. It consists of a basal black and brown bituminous shale and limestone and an upper unit of greenish-grey, variably calcareous shale interbedded with limestone, silty limestone or siltstone. At the CR2 section, dark grey, slightly calcareous shale with interbedded limestone, silty limestone and siltstone characterizes the unit and is discussed further below as the Bell Creek member.

Contacts

Exposure is poor in the type area, where the base of the formation is not visible. At the MR section, the lower contact of the Hare Indian Formation with the Hume Formation is unconformable and sharp. The upper contact of Hare Indian Formation with the Ramparts Formation is gradational and placed where carbonate beds become predominant. Where the Ramparts Formation is absent such as at CR2 section, the upper contact with the Canol Formation is conformable but marked by an abrupt change to siliceous shale (a discernable difference in outcrop which has been verified lithogeochemically in this study).

Age

The Hare Indian Formation is lower to middle Givetian in age (*varcus* to *hermanni* zones; Uyeno, 1979, 1991) (Figure 5).

Bluefish Member

Definition and Reference Section

A type section for the Bluefish Member at Powell Creek was proposed by Pugh (1983) to replace the original type area near Bluefish Creek, a tributary to the Hare Indian River, where the exposure is poor. There are two Bluefish Creeks in NWT which is also confusing. The Powell Creek exposure is rather poor with partial tree cover, so the MR section (Figure 6, Table 1) is herein proposed as an accessible reference section.

Distribution and Thickness

The distribution of the Bluefish Member is the same as described for the Hare Indian Formation. The Bluefish Member ranges from 2 m to 20 m thick and thickens to the south within Mackenzie Plain.

Lithology

At the reference section, the Bluefish Member is a black to dark grey and brown, black and medium to dark grey weathering shale with less than 5% thin interbeds or laminae of blue-grey and light brown grey limestone (Figure 9A). The shale is soft, organic-rich, non-calcareous, and pyritic, and typically contains more silt upsection. Limestone beds range from lime mudstone to grainstone, the latter which commonly contain abundant conical microfossils (tentaculitids and stylolinids). Limestone beds are commonly lenticular and pyritic, with lenses up to 50 cm thick that are finely planar laminated. Limestone beds decrease upsection (Figure 9B). Thin fibrous calcite beds make up less than 1% of the unit but are characteristic (Mackenzie, 1972; Al-Aasm et al., 1992).

Contacts

The Bluefish Member overlies the Hume Formation sharply and with erosional down-cutting of a few centimetres (Figure 9A). At the reference section, thin limestone beds of the Bluefish Member lie abruptly on the brachiopod-rich upper Hume Formation limestone but elsewhere black shale sharply overlies the upper bed of Hume Formation. The upper contact of the Bluefish Member with the Bell Creek member is gradational, with an upward decrease in dark grey and black shale and increase of silty carbonate and shale beds. Where the Bell Creek member is absent, in the western part of the study area, the Canol Formation shale abruptly overlies the Bluefish Member but without evidence of erosion.

Age

Conodonts from the base of the Bluefish Member, collected in the Peel area west of Mackenzie Plain, yielded a mid-Givetian age in the middle *varcus* Zone. Conodonts from the underlying Hume Formation at Powell Creek indicate *australis* and *kockelianus* zones of Eifelian age and (Uyeno, 1991). Conodonts from the top of the Hume Formation, near the Rumbly Creek area west of Mackenzie Plain, indicate ages as young as *ensensis* to middle *varcus* zones, and as old as *patulus* to *costatus* zones (Gal et al., 2009). If the Hume Formation is as young as middle *varcus* zone, then there is likely not a significant time gap at the Bluefish contact. However, this relationship has not been verified in the Mackenzie Plain sections, so a questionable hiatus is shown in Figure 5.

Bell Creek member (new, informal)

Definition and Reference Sections

The upper part of the Hare Indian Formation, formerly called the "grey shale member" by Pugh (1983), is herein informally called the Bell Creek member, after Bell Creek in the Sans Sault Rapids map area (map sheet 106H). Its reference section is designated at the MR section (Figure 1), with the base of the member, in UTM coordinates, at 518931E, 7235247N and its top at 518923E, 7235302N (NAD 83, Zone 9). The site is reached by helicopter from the community of Norman Wells, NWT. The section is exposed along the northwest side of a tributary to the Mountain River. The problem with formalizing this locality as a type section is that the upper beds and upper contact with the Ramparts Formation are both poorly exposed, and this is unfortunately the case at most outcrop exposures of Bell Creek member.

The original type section for the Hare Indian Formation remains a useful place to see the upper contact of the Bell Creek member with the overlying Ramparts Formation. Muir (1988) suggested the West Powell Creek section as a reference section for the upper member of the Hare Indian Formation (95 m of exposed bed, however, the basal 60 m is covered), but the section is a cliff so it is not as readily accessible as the MR section. The Bell Creek member varies regionally and is locally overlain by Canol Formation without intervening Ramparts Formation, thus a supplementary reference section, the CR2 section (Figures 8, 10), is suggested to describe the Bell Creek member where it is overlain by Canol Formation. The top of the member at the supplementary reference section is at 603450E, 7185390N (NAD 83, Zone 9).

Distribution and Thickness

The distribution of the Bell Creek member is the same as described for the Hare Indian Formation, except that its western depositional limit is around 131ºW (Pugh, 1983). At the MR section, the Bell Creek member is 32.0 m thick, and its thickness exceeds 180 m in the western Mackenzie Plain area at Gayna River and westward into the Peel area (Gal et al., 2009).

Lithology

In northeastern Mackenzie Plain where the Ramparts Formation is present, the predominant lithologic association of the "typical" Bell Creek member is interbedded greenish-grey to dark grey, calcareous and non-calcareous, micaceous shale, calcareous siltstone, and argillaceous limestone. At sections such as Bell Creek West (Table 1), beds of wackestone and grainstone to rudstone containing brachiopods and crinoids become more common in the top of the unit. Other common allochems include fish scales and tentaculids.

The second lithologic association is that of the "atypical" Bell Creek member, which is present where the Ramparts Formation is absent (Figure 10A), throughout southern Mackenzie Plain. Dark grey, calcareous and non-calcareous shale dominates (Figure 10B), with about 1% lime mudstone or weakly calcareous mudstone in lenses, or rarely in beds up to 30 cm thick (Figure 10C). Fining upward of grainstone laminae to mudstone within thin beds is common.

Contacts

Pugh (1983) reported lateral interfingering of the upper Hare Indian Formation with the lower Ramparts Formation. The basal contact of the Bell Creek member with the Bluefish Member is gradational. Where the Ramparts Formation is absent, the contact with the overlying Canol Formation is marked by an abrupt change to siliceous shale (Figure 10A).

Age

The age range for the Bell Creek member of Hare Indian Formation is the *varcus* to *hermanni* zones (Uyeno, 1979, 1991). From the present study, conodonts from the upper part of the Bell Creek member at the Dodo Canyon section included species as young as the *asymmetricus* zone (McCracken, 2012).

Ramparts Formation and its Carcajou member

Definition

The Ramparts Formation has a history of nomenclatural controversy and varies regionally within the study area. Its Carcajou member merits a status beyond that of a "marker" or "subfacies" (Tassonyi, 1969; Muir, 1988) because it has regional stratigraphic significance. The Carcajou member separates the basal ramp member of the Ramparts Formation from the upper platform-reef member. This upper member varies and includes platform, reef core facies (referred to as Kee Scarp Member in the Norman Wells area), reef margin and reef flank facies (Pugh, 1983; Muir, 1988). The Ramparts Formation was originally referred to as the Ramparts "limestone" by Kindle and Bosworth (1921), after the Ramparts or narrow constriction of the Mackenzie River near Fort Good Hope, NWT. Formal use of Ramparts Formation was adopted by Caldwell (1964) and Tassonyi (1969). Pugh (1983) describes informal subunits of the Ramparts Formation, including a basal siltstone member, platform (ramp member of Muir, 1988) member, reef member, sandy member (or "Charrue sandstone"; Williams, 1986), and allochthonous limestone unit.

Distribution and Thickness

The Ramparts Formation extends from the Norman Wells area and Franklin Mountains northward beyond Fort Good Hope and southward to about Tulita. Its western depositional limit lies around 131ºW. It contains complex facies changes among its subunits and varies greatly in thickness across the study area, from just a few metres to more than 300 m thick. The Carcajou member ranges in thickness from just a few metres to 13.8 m measured at the MR section.

Lithology

The Carcajou member consists predominantly of dark brownish grey, calcareous shale with interbeds of thin- to medium-bedded lime mudstone and mudstone. There are some nodular lime mudstone beds near the top of the unit (Figures 9C, D).

Contacts

The Carcajou member lies abruptly but conformably above the ramp member of the Ramparts Formation (Figure 9C). At the reference section, the Carcajou member is overlain abruptly but conformably by the Canol Formation in absence of the platform-reef member of the Ramparts Formation (Figure 11A). Muir (1988) described the upper contact of the Carcajou member as gradational with the platform-reef member, where the latter member is present such as at Powell Creek to Bell Creek (Table 1).

The Ramparts Formation gradationally overlies the Hare Indian Formation. Its upper contact is abrupt and conformable with the Canol Formation. In some locations, the Ramparts is abruptly overlain by the Imperial Formation (Muir, 1988), or by the sub-Cretaceous unconformity (Aitken et al., 1982).

Age

Conodonts from the Ramparts Formation in Mackenzie Plain area indicate an age range from middle *varcus* to lowermost *asymmetricus* zones (Givetian to early Frasnian; Uyeno in Muir, 1988). The Carcajou member lies in an interval between middle *varcus* and lower *disparilis* zonal range (from Powell Creek, Uyeno in Muir, 1988).

Canol Formation

Definition

The Canol Formation was defined as a black shale unit by Bassett (1961), named after Camp Canol, located across the Mackenzie River from Norman Wells. Its type section was designated along the northwest side of Powell Creek at 65.28ºN, 128.77ºW.

Distribution and Thickness

The Canol Formation extends from the Franklin Mountains east of Norman Wells, west into the Richardson Trough of Yukon. It extends to just north of 68ºN and has been mapped as far south as the Ram River area west of Fort Simpson, NWT. In the study area, its thickness varies from a few metres, such as at Gayna River, to greater than 100 m thick.

Lithology

The Canol Formation consists predominantly of dark grey to black, siliceous shale and silty shale with interbeds of siltstone, dolomitic siltstone, mudstone, lime mudstone, and contains pyritic concretions or concretions of lime mudstone, mudstone, or dolomitic siltstone. It is characteristically rust, yellow, white and dark grey weathering. The Canol Formation can, in most places in the Mackenzie Plain, be divided into a lower recessive unit, a middle resistant unit, and an upper recessive unit. At the reference section, the lower recessive unit contains lime mudstone beds in its basal part, as well as thin, sandy limestone beds near its basal contact with the Carcajou member (Figure 11A, B). Typically, the lower recessive unit is dominated by siliceous shale (Figure 11C). The shale and mudstone of the middle resistant unit is more siliceous (Figure 12A) and contains common pyritic and dolomitic concretions (Figure 12B) and thin to medium beds of dolomitic siltstone that form prominent marker beds within the cliff section (Figure 6). The upper recessive unit of the Canol Formation is dominated by shale, with minor thin mudstone beds and rare concretions.

Contacts

The Canol Formation abruptly overlies the Ramparts Formation, or where it is absent, the Hare Indian Formation. The lower contact of the Canol Formation was reported as being disconformable (overview by Pugh, 1983). The lowermost Canol Formation has also been suggested to be both time-equivalent to and interfingering with the Ramparts Formation, and younger than the Ramparts Formation (Muir and Dixon, 1984, 1985). Where Ramparts Formation is absent, our studies suggest that the lower Canol Formation is, in part, time-equivalent to and likely interfingers with the Bell Creek member (Figure 5). The Canol Formation is gradationally overlain by the Imperial Formation. The contact is a transition over a few metres from dark grey, organic-rich, siliceous Canol shale to organic-lean, reddish weathering silty shale (Figure 12C). Likely the two units are, in part, time-equivalent (Figure 5; and illustrated by Yose et al., 2001).

Age

Most conodont collections from the Canol Formation indicate an early Frasnian age, such as those from Powell Creek (lower *Polygnathus asymmetricus* Zone; Uyeno, 1979), ranging into early Frasnian Zones 5-10 (*punctata* to *hassi* zones at the MR section; Gal et al., 2009). Some fauna suggest ages as young as late Givetian age (*disparilis* Zone) near Rumbly Creek in the Peel area (Gal et al., 2009) and at the base of the Canol Formation at Mountain River distributary

(Uyeno in Muir, 1988); and even younger (lowermost *asymmetricus* zones) at the base of the Canol Formation at Gayna River (Uyeno in Muir, 1988). The overlying Imperial Formation at Powell Creek yielded conodonts in the *A. triangularis* to *gigas* zones (Braman and Hills, 1992), suggesting some time equivalency of the Canol and Imperial formations in the middle Frasnian (Figure 5). In summary, available data suggest that the lower Canol Formation is time equivalent with the upper Hare Indian Formation (Bell Creek member) and lower Ramparts Formation. The upper Canol Formation is partly coeval with the lower part of the Imperial Formation.

LITHOGEOCHEMISTRY AND MINERALOGICAL STUDIES OF OUTCROP

Introduction

A multi-proxy approach using the changing profiles in whole rock geochemical data throughout the Horn River Group succession has been fundamental to understand the regional stratigraphy. This approach has enabled revision and refinement of the correlation of units among outcrop exposures and within the subsurface, particularly where the carbonate-dominated Ramparts Formation is absent and the visually similar, organic-rich, fine-grained siliciclastics of the Canol and Hare Indian formations appear homogenous.

Lithogeochemical Characterization of the Reference Section

To characterize the subunits of the Horn River Group at the reference section, vertical (with respect to stratigraphy) variations in selected trace-element and major-element oxide concentrations and ratios were used. These include: uranium concentration, silica to zirconium ratio, terrigenous input profile (TIP, which is the sum of aluminum oxide, iron oxide, potassium oxide, and titanium oxide), thorium to uranium ratio, calcium oxide concentration, and a number of paleo-redox proxies that use the trace elements molybdenum, vanadium, and nickel (Figure 13).

Organic Richness (TOC, U, gamma radiation)

The spectral gamma ray profile from outcrop is mimicked by both the TOC and U profiles; high TOC, U and radiation are present in organic-rich intervals. One exception to this relationship is the high TOC content in the Carcajou member that yielded lower scintillometer readings and U concentration.

There are elevated scintillometer counts within the Bluefish Member and middle part of the middle resistant member of the Canol Formation. The overall spectral gamma-ray responses of both the Bluefish Member and Canol Formation are higher than those of the organic-lean Bell Creek member and Ramparts Formation, including the Carcajou member (Figure 13). The Carcajou member does, however, contain some TOC values greater than 7%, comparable with the higher values in the Bluefish Member and Canol Formation.

High uranium concentrations characterize the Bluefish Member in contrast to lower values in the organically lean Bell Creek member. The lowest uranium values are throughout the Ramparts Formation. Within the Canol Formation, uranium values are elevated compared to the Bell Creek member and Ramparts Formation (Figure 13).

Silica (SiO_2)

A brittle mineralogical composition of an unconventional reservoir is important for successful hydraulic fracturing. This brittleness is created by the presence of silica within the clay fabric of mudstones (Blood et al., 2013). The amount of SiO_2 is corroborated by the XRD analyses discussed below (Pyle and Gal, 2012). The nature of the silica, whether biogenic or terrestrially derived, is also important. Wright et al. (2010) and Hall et al. (2013) illustrate with a cross plot of zirconium (Zr) versus silicon (Si), in their studies where detrital quartz is present mainly in sandstone, that biogenic silica is suggested by a negative Si/Zr slope in contrast to samples with terrestrially derived silica that have a positive slope. In the present study, biogenic and detrital silica trends are differentiated in a plot of SiO_2 (rather than Si in the Wright et al., 2010 and Hall et al., 2013 studies) versus Zr, which displays a positive linear relationship of the two elements when both increase in concentration due to terrigenous input (Figure 14).

The bulk of Canol Formation samples, lie on a short, negatively sloped trend at the high end of the silica scale suggesting significant biogenic silica enrichment. "Atypical" Bell Creek member samples and Bluefish Member samples show no enrichment trends, though they are mostly more silica-rich than would be expected from purely terrigenous sources, suggesting that excess SiO_2 is biogenic. Samples from "typical" Bell Creek member and the Ramparts Formation have a positive slope, suggesting a predominantly terrigenous input. Some samples from both units lie off the trend toward the silica-rich side, showing some enrichment in biogenic silica.

In the lithogeochemical profiles for the reference section (Figure 13), the high SiO_2/Zr ratio, suggestive of biogenic silica enrichment, is characteristically higher in the Canol Formation than the rest of the Horn River Group. A prominent elevation in this ratio is present at the base of the Canol Formation and is significant in distinguishing this black shale from the underlying shale of the Carcajou member (Figure 13). Consistently high silica enrichment characterizes the middle member of the Canol Formation, and values decrease upsection toward the Imperial Formation.

Terrigenous Input

Two proxies are used to approximate the relative input of terrigenous material at the time of deposition: the terrigenous input profile and the thorium to uranium ratio (Th/U). For the Horn River Formation in British Columbia, Hildred and Rice (2012) used a terrigenous input profile (herein called TIP) to illustrate fluctuations in the concentrations of major oxides related to land-derived sediments. The TIP is the sum of aluminum oxide, iron oxide, potassium oxide, and titanium oxide (weight % of Al_2O_3+Fe_2O_3+K_2O+TiO_2). In the reference section, TIP values are high within the Bluefish and Bell Creek members, and are mirrored by high values of the Th/U ratio for this unit, a ratio that accentuates the abundance of terrigenous input and clays relative to organic matter (Hildred and Rice, 2012; Hildred et al., 2011). Detrital input remained prevalent throughout the Ramparts Formation, but sharply decreased at the beginning of Canol Formation deposition and remained low for most of the duration of Canol deposition. The upper member of the Canol Formation has increased TIP values, perhaps heralding onset of major siliciclastic influx during Imperial Formation deposition.

Calcium Oxide (CaO)

CaO enrichment serves as a proxy for carbonate-rich intervals, that are common in the mixed siliciclastic-carbonate succession of the Horn River Group. This proxy can be used because the section does not contain immature arkosic or volcanic-derived detritus that would contain Ca-feldspar. Several factors control the abundance of carbonate, which is greatest in the Ramparts Formation, including paleoenvironment, depth position in the sedimentary basin, sedimentary dilution by clastic input, and possibly dissolution of carbonate by acidic conditions associated with redox processes in high-TOC facies (ver Straeten et al., 2011). At the reference section, the Hare Indian Formation contains alternations of limestone and shale, and the Canol Formation contains some lime mudstone beds in its basal member and lower part of the middle member. These are reflected in the CaO profile (Figure 13).

Paleoredox Indicators: Enrichment Factor of Vanadium (EFV), Molybdenum (Mo), and Nickel/Cobalt (Ni/Co) Ratio

Enrichment of redox-sensitive trace elements such as U, molybdenum (Mo) and vanadium (V) in oxygen-depleted sediment make these elements useful proxies for paleoredox conditions (Tribovillard et al., 2006). A strong positive covariance between TOC and Mo concentrations is due to enrichment of Mo under euxinic conditions (Sageman and Lyons, 2003). Mo is also suggested to indicate anoxic conditions (Dean et al., 1994), as is Ni to Co ratio (Dypvik, 1984; Jones and Manning, 1994; Rimmer, 2003). Fluctuations in relative profiles of these redox-sensitive elements provide a framework for changing oxygenation conditions throughout the Horn River Group.

The enrichment factor of vanadium (EFV) is a parameter calculated as:
$EFV = (V_{sample}/Al_2O_{3sample})/(V_{average\ shale} / Al_2O_{3average\ shale})$, using the method outlined by Tribovillard et al. (2006), in which trace-element concentrations are normalized to aluminum content, assumed to represent the detrital influx (Rimmer, 2003). The average shale values are from Wedepohl (1971, 1991). An EFV value greater than 1 indicates enrichment of V under anoxic conditions (Tribovillard et al., 2006). At the reference section, the EFV values are notably high in the middle Bluefish Member, basal Canol Formation, and middle part of the middle member of the Canol Formation (Figure 13). Values are lower in the upper part of the Bluefish Member, throughout the Bell Creek member and Ramparts Formation, and in the upper part of the Canol Formation.

High Mo and Ni/Co ratio correspond to a high EFV value in the middle of the Bluefish Member and base of the Canol Formation; however, the strong peak in EFV in the middle Canol Formation is not reflected in the Mo and Ni/Co ratio. Mo enrichment is also present in at least two intervals in the middle unit of the Canol but these do show a corresponding increase in the Ni/Co ratio values (Figure 13).

Lithogeochemical Characterization of Horn River Units Regionally from Outcrop Data

The chemostratigraphic framework established for the MR reference section (Figure 13) can be compared to the profiles from other sections to characterize each Horn River unit regionally (Figures 15 through 23). Differences within units are discussed below, unit by unit, followed by a discussion of the key comparative geochemical features among units. Partial measured sections in which not enough strata were measured to develop profiles are illustrated with select lithogeochemical profiles are reproduced from Pyle and Gal (2012; 2013) in Appendix K). Data for all sections, available in Appendix D, have been compiled from Pyle et al. (2011) and Pyle and Gal (2012, 2013) with intervals updated as Bell Creek member.

Bluefish Member

At the reference section, the organic-rich Bluefish Member is characterized by elevated scintillometer counts, high TOC values (up to more than 6% TOC), and high U concentrations, with peaks up to 30 ppm (Figure 13). In the studied sections, all of these parameters fluctuate but tend toward higher values in the Bluefish Member compared to the overlying Bell Creek member (Carcajou River 1, CR2, Little Bear River 1 and 2 sections, Dodo Canyon, and Mackay Range West sections, Figures 15 to 20). This tendency is most evident from sections where both units were sampled at metre-scale or less (CR2 and Little Bear River 2 sections, Figures 16, 18). Carcajou River 1 section (Figure 15) was intended to complement CR2 section (Figure 16), where scintillometer counts and TOC values are absent in the latter because the Hare Indian Formation was scree-covered here in 2011. In 2013, this part of the CR2 section was exposed and accessible for detailed whole rock lithogeochemistry sampling that provided the U profile. More detailed sampling was also completed at Little Bear River 2 (LB2) section in 2013 (Figure 18).

The SiO_2/Zr ratio is typically less than 1.0 for Bluefish samples in contrast to values greater than 2.0 locally in the Canol Formation and typically low SiO_2/Zr ratios in the Bell Creek member (Figures 13, 16, 18).

Terrigenous input profile (TIP) and thorium to uranium ratio (Th/U) profiles for the Bluefish Member are lower than those for the Bell Creek member, a contrast that is striking where sampling intervals were at one metre or less (e.g., CR2 and LB2 sections, Figures 16, 18), and apparent even with more widely spaced sampling intervals (e.g., Carcajou River 1 section, Figure 15). The upper part of the Bluefish Member at the reference section shows an increase in both TIP (strong) and Th/U ratio (subtle) in its upper 10 m as it grades into the Bell Creek member, with an average decreasing in TOC and U (Figure 13).

CaO values are variable within the Bluefish Member, where thin carbonate beds are present in the unit (Figures 13, 15-19). Four cycles of high CaO values are apparent in the reference section and at CR2 section (Figures 13, 16), but this pattern is not as clear in the LB2 section (Figure 18), where the basal peak may be missing because the base of the section was covered and not sampled.

High values of each of the redox proxies (Mo, EFV, and Ni/Co ratio) are present in the base, middle and near the top of the Bluefish Member at the reference section (Figure 13), and these profiles correlate to both the CR2 section (Figure 16) and Dodo Canyon section (Figure 19). This correlation can likely also extend to the LB2 section (Figure 18) where three similar high values are seen at the base, middle and at the top of the Bluefish Member but the very basal high fluctuation is absent (not sampled). The LB2 profiles show three high excursions within the Mo value near the base, middle and top, with the middle value at 7 m above unit base mirrored by the EFV and Ni/Co ratio. The profiles from Dodo Canyon section (Figure 19) show high variability with three single-sample peaks of enrichment in all three proxies, within only 5 m of Bluefish Member.

“Typical” Bell Creek member

The “typical” Bell Creek member was sampled at the MR section (Figure 13), which is the main source for comparison, and for only the basal part of the unit. At the MR section, the unit is organic-lean as shown by lower scintillometer counts, TOC values, and U concentrations compared to the underlying Bluefish Member. Its TIP profile contains high values comparable to the underlying Bluefish Member but the Th/U ratio values are strikingly higher than those in the Bluefish samples. CaO shows slight variation in the lower part. There are no excursions within the Mo, EFV and Ni/Co ratio proxies for anoxia. The unit was also sampled at the original Hare Indian type section at The Ramparts and at Imperial Anticline (Appendix K), but these sections lack the underlying Bluefish Member for profile comparison. The unit is organic-lean at both of these locations.

“Atypical” Bell Creek member

The “atypical” dark grey Bell Creek member was sampled at Carcajou River 1 (Figure 15), CR2 (Figure 16), Little Bear River 1 and 2 sections (Figures 17, 18), Dodo Canyon (Figure 19) and MacKay Range West section (Figure 20). It was previously misidentified as the Canol Formation by Pyle et al. (2011) and Pyle and Gal (2012). The CR2 section serves as a supplementary reference section and although the unit was scree covered when originally measured by Pyle and Gal in 2011, the strata were exposed during a site visit in 2013 which afforded lithogeochemistry sample collection through the whole Hare Indian Formation. At the CR2 section, the dark shale of the Bell Creek member has elevated U and contains some values as high as in the underlying Bluefish Member. At LB2 section, the scintillometer, TOC, and U profiles have lower values than those of the Bluefish Member (Figure 18).

At the CR2 section, the unit’s SiO_2/Zr ratio is typically less than 1.0, which contrasts it with the overlying Canol Formation and underlying Bluefish Member (Figure 15). Dense sampling at the LB2 section shows the SiO_2/Zr ratio of the Bell Creek member slowly elevate from values less than 1 to values greater than 1 toward the Canol Formation (Figure 16). The TIP is elevated compared to both the Bluefish and Canol units, and the Th/U ratio shows a marked elevation at the top of the unit.

CaO is highly variable, especially where the unit was sampled at high resolution such as at CR2. High-resolution sampling at LB2 only yielded one high value for CaO, otherwise the unit was shale-dominated. In contrast to “typical” Bell Creek member, there are elevated values of Mo, EFV, and Ni/Co ratio, particularly noticeable with the high-resolution sampling at CR2 and LB2 sections and also at Carcajou River 1 and Little Bear River 1 sections (compare Figure 13 with Figures 16, 17 and 18).

The differentiation of this unit at the Mackay Range West section was difficult, but the lower contact was placed at a sharp drop in TOC and U that coincides with a sharp increase in TIP and Th/U, and decrease in the three redox proxies (Figure 20). The overlying Canol Formation was distinguished by a gradual increase in TOC and U, and slight increase in silica with corresponding decrease in TIP and Th/U (subtle, and not as striking as in other sections). Mineralogy was also important in characterizing the units at this section, and is discussed below.

The geochemical characteristics of the Bell Creek member also helped to differentiate it from the Canol and Bluefish units at the Canyon Creek section (Figure 21), where all units are visually similar. Here, the elevated TIP and Th/U ratios were most useful in distinguishing the Bell Creek member.

Ramparts Formation

The purpose of sampling the Ramparts Formation was to understand the organic-rich portions in the lower ramp unit and Carcajou member. The Ramparts Formation is present only where the "typical" Bell Creek member is developed, so descriptions herein are from the MR section and Powell Creek section (Figures 13 and 22). It has less variation in its spectral gamma-radiation profile and lower U concentrations than the Hare Indian Formation, but does contain some high TOC values within the lower ramp and Carcajou members at both sections. The Ramparts Formation has a low SiO_2/Zr ratio throughout, and corresponding elevated TIP and Th/U values, in contrast to the overlying Canol Formation. Its CaO profile is consistently high compared to other Horn River units. The Mo, EFV, and Ni/Co profiles are flat, in marked contrast to the Hare Indian and Canol formations.

Canol Formation

The organic-rich Canol Formation is characterized by high scintillometer counts, high TOC values (greater than 4% and 5% median TOC values from all sections), and U levels typically greater than 10 ppm. It can be divided into three informal members based on their weathering resistance, which is a function of the amount of silica, most of which is likely biogenic (Figure 14).

At the reference section (Figure 13), the lower and middle members have the highest SiO_2/Zr ratios, up to a value of 2, as well as high TOC values and the upper recessive member has comparatively low TOC values and a lower SiO_2/Zr ratio. At other sections, such as CR2 and Dodo Canyon (Figures 16 and 19), the SiO_2/Zr ratio is highest within the middle part of the middle member. At LB2 section, the prominent increase in the SiO_2/Zr ratio marks the base of the Canol Formation (Figure 18).

In the upper part of the middle member at MR section, and continuing into the upper member, there is a slow rise in the TIP and Th/U values toward the gradational boundary with the overlying Imperial Formation (Figure 13). This trend is clear in the profiles at CR2 and Powell Creek sections as well (Figures 16 and 22), and evident but less striking at Little Bear 1 and Dodo Canyon sections (Figures 17 and 19). The TIP and Th/U profiles at the Little Bear 1 section are not markedly different than those in the Bell Creek member (Figure 17).

The CaO values are high in the basal member of the Canol Formation where it overlies carbonate of the Ramparts Formation at the reference section (Figure 13), and where it has an interfingering relationship such as with the allochthonous beds at Powell Creek section (Figure 22). Where the Canol Formation overlies "atypical" Bell Creek member such as at Carcajou 1 and 2 sections, there is some carbonate basally (Figures 15, 16). Distal from the Ramparts Formation development, such as at the LB2 section (Figure 18), there is only one CaO peak in the basal part. At Little Bear River 1 section, a CaO peak is present in the upper recessive unit, likely due to localized carbonate concretions (Figure 17). At the distal Turnabout Creek section (Figure 23), there are no CaO peaks.

At the MR section, high values of each of the proxies for anoxic conditions (Mo, EFV, and Ni/Co ratio) are present near the base of the Canol Formation. The Ni/Co ratio shows three or four rises that correspond well to more striking peaks in the EFV but not so clearly to peaks in the Mo profile (Figure 13). Nonetheless, these fluctuations differentiate the Canol Formation from the underlying Carcajou member where the profiles of these proxies are flat. At the CR2 section, where there is a 142 m-thick section of Canol Formation, there are five elevated zones in the Ni/Co ratio, three of which correspond to elevations in the EFV, but not so clearly with the Mo profile (Figure 16). Prominent elevated values throughout the Canol Formation, notably at its base, are also present at Carcajou River 1 (Figure 15), Little Bear 1 (Figure 17), Dodo Canyon sections (Figure 19). In the middle member at Little Bear River 1 section, there are at least three strong rises in two or more of the values, evident also at CR2, Dodo Canyon and Powell Creek sections (Figures 15, 17, 19 and 22).

Distinctive Geochemical Characteristics of Horn River Units

The Bluefish and Bell Creek member are clearly distinguished from each other using the multi-proxy approach outlined above, at least when comparing data from the most completely sampled sections (MR, CR2, LB2; Figures 13, 16, 18). The units are not always distinctive for every parameter used, but using multiple parameters distinguished these units at every section except Mackay Range West (Figure 20), where mineralogical data proved indispensable.

The Bluefish Member has consistently elevated scintillometer counts and high TOC and U values in contrast to consistently lower values in the "typical" Bell Creek member; however, some organic-rich intervals are present in the "atypical" Bell Creek member (compare Figure 13 to Figure 16). Bluefish Member SiO_2/Zr ratio values are generally higher than both "typical" and "atypical" Bell Creek member values (reference sections, Figures 13, 16), with the exception of the LB2 section where the SiO_2/Zr ratio values of the "atypical" Bell Creek member were comparable to or greater than those of the Bluefish Member (Figure 18). TIP and Th/U ratio values are elevated in the Bluefish Member but not as dramatically as in the Bell Creek member at most sections. The higher TIP and Th/U values and lower SiO_2/Zr ratio are the most distinctive characteristic of the Bell Creek member when comparing the unit's profiles to those of the Bluefish Member. The CaO profile of the Bluefish Member is more elevated and has more peaks than that for the Bell Creek member. Three to four zones of enrichment in Mo, EFV, and Ni/Co ratio may be correlative with each other in the Bluefish Member. Three peaks are evident within the Bell Creek member Mo and Ni/Co ratio profiles at CR2 and LB2 sections (compare Figures 16 and 18), but these profiles are variable in other sections.

The carbonate-dominated Ramparts Formation is characterized by a less varied scintillometer profile and low U values, with some high TOC zones. The SiO_2/Zr ratio profile is low and TIP and Th/U values are higher and more similar to the Hare Indian Formation than overlying Canol Formation. Its CaO values are consistently high and Mo, EFV, and Ni/Co profiles are flat, all of which contrast other Horn River Group units (Figures 13, 22).

The Canol Formation is characterized by high, sustained scintillometer counts, and high TOC and U levels; however, these parameters may be similar to those of the "atypical" Bell Creek member. The distinguishing parameters are the markedly higher SiO_2/Zr ratio profile of the Canol Formation, together with its lower TIP and Th/U profile values compared to those of the Bell Creek member. The TIP and Th/U parameters within the Canol Formation show a gradual rise upsection toward the Imperial Formation at MR and CR2 sections (Figures 13 and 16). Indications of changing detrital influences are evident in fluctuating TIP and Th/U profiles of the Canol Formation such as at Little Bear River 1 and Dodo Canyon sections (Figures 17 and 19) where these parameters are not as clearly distinguishable from those of the Bell Creek member. CaO values are high in the basal Canol Formation where it overlies the Ramparts Formation, otherwise the profile is relatively flat. Enrichment in the Mo, EFV, and Ni/Co ratio proxies is common, notably at the base and within three or four zones in the middle unit of the Canol Formation.

Mineralogical Analyses from Outcrop Sections

Samples were collected in each field season to analyse mineralogy using X-ray diffraction (XRD). Samples from 2010 were submitted for semi-quantitative analysis to both GSC-Calgary and GSC-Ottawa, thus the method of reporting of phyllosilicates varies (e.g., mica/illite versus muscovite; Appendix E1). A small suite of samples from 2011 were analysed qualitatively by Acme Labs in Vancouver (Appendix E2). In 2012, a more complete suite of samples was taken from throughout the MR reference section and submitted to GSC-Ottawa (Appendix E3). The XRD data complement the whole-rock lithogeochemistry by indicating the phyllosilicates present and regional variations in the accessory minerals within the quartz-dominated Canol Formation. The analyses described here are taken from data compiled from Pyle et al. (2011), and Pyle and Gal (2012, 2013), in which the Bell Creek member samples are labelled in the present report (Appendices E1, E2, E3).

Mountain River Tributary Section (the Reference Section)

Semi-quantitative XRD analyses of samples from the Horn River Group at the reference section illustrate significant mineralogical differences between units, and trends within the Canol Formation (Figure 24). The Canol Formation is very quartz rich, with an average of 83.4 weight percent, and an average of 5.6 weight percent muscovite. Kaolinite +/- chlorite phyllosilicate assemblages are helpful in differentiating “atypical” Bell Creek member and Canol Formation, whereas the Ramparts Formation contains abundant carbonate minerals.

In the Canol Formation, chlorite is present only in the uppermost sample, and is likely a mixed-layer clay, generally chlorite-illite. Muscovite is ubiquitous (up to 15% in one sample), although in lesser amounts compared to other units. Quartz is significantly higher, generally above 80 weight percent, whereas carbonate minerals are minor constituents in most samples. Calcite and dolomite are present in variable amounts in the lower recessive unit and lower part of the middle resistant unit, but are rare elsewhere in the formation. Dolomite is present in some samples and is up to 35% in one sample in the middle resistant member, where the sample included a dolomitic siltstone bed. Gypsum is present in small amounts in the lower and upper units of Canol Formation. Pyrite is ubiquitous in Canol samples, with a slight increase up section. Trace amounts of jarosite are present in the upper part of the section (Appendix E3).

The Bluefish Member, in contrast to the Canol Formation, contains significant muscovite and kaolinite and variable quartz. Kaolinite is significant at the top of Bluefish Member where that member grades into the overlying Bell Creek member, which is about 50% quartz, with abundant muscovite and kaolinite. Carbonate minerals and pyrite are significant accessory minerals in both members of the Hare Indian Formation. The Ramparts Formation samples are dominated by quartz and carbonate minerals, with accessory kaolinite, chlorite, mica, and pyrite (Figure 24; Appendix E3).

Powell Creek Section (Type Section of the Canol Formation)

Semi-quantitive analyses indicate the Canol Formation is quartz-rich at its type section, averaging 90.8% quartz from 18 samples through the 18.2 m thick section (Figure 25; Appendix E1). This number excludes the analysis from the basal pyritic layer at the base of the unit which yielded 17% pyrite and only 30% quartz. As at the reference section, the Canol samples all contain mica (likely muscovite; reporting of mineralogy differs between labs at GSC-Calgary and GSC-Ottawa). Localized carbonate-rich beds and bedding parallel concretions contribute to the high proportion of calcite and dolomite (+/- ankerite). Gypsum is locally an important accessory mineral; however, much of this may be epigenetic rather than depositional.

Other Sections

At Carcajou River 1 section, semi-quantitative analyses indicates a distinction between the Bluefish and Bell Creek members that both contain expanded mixed-layer clays and mica/illite compared to predominantly mica/illite within the Canol Formation samples (Figure 26; Appendix E1). The mineralogy within the upper two samples of Bell Creek member contained only trace amounts of expanded mixed-layer clays and are therefore more Canol-like; however, when compared to whole rock lithogeochemistry data (Appendix D), these two samples are transitional in their TIP values decreasing and SiO_2/Zr ratio increasing toward sample LP-10-081 where a distinct Canol-like signature is apparent (Figure 19).

In the Carcajou River 2 section samples, the basal 11 samples were analysed at GSC-Calgary and therefore do not have chlorite reported, and muscovite is reported as mica/illite; the subsequent samples were analysed at GSC-Ottawa and report both muscovite and chlorite within the remainder of the Canol samples. The members of the Canol Formation are differentiated by the increase in quartz within the middle member compared to the basal and upper recessive members, and by the increase in muscovite and potassium feldspars within the upper recessive unit (Figure 27; Appendix E1).

At the Little Bear River 1 Section, where the whole rock lithogeochemistry revealed the least striking contrasts between the Hare Indian and Canol Formation. The mineralogy also showed no significant differences between the two formations since quartz is present in high percentages throughout both, and kaolinite is absent in the Hare Indian Formation, unlike in most other sections where it is present (Figure 28; Appendix E1).

At Turnabout Creek, the entire Canol Formation and Bluefish Member were sampled, although each unit was thin. The two metres comprising Bluefish Member is dominated by quartz and dolomite, with significant muscovite (Figure 29). The Canol Formation is dominated by quartz, with a median value of 84.5 weight percent, and an apparent decrease up section as muscovite increased (median 14 wt.%). Carbonate minerals were absent in the Canol Formation.

The mineralogy of the Canol Formation at other sections sampled (data not plotted graphically but in Appendix E1) such as Prohibition Creek and Carcajou River 3 sections, is similar to those at the type and reference section with dominant quartz, common muscovite and accessory chlorite, plagioclase, potassium feldspars, pyrite, calcite and dolomite. The lowest sample at the Prohibition Creek section lacks kaolinite but is considered to be Hare Indian Formation because of its lower quartz content compared to the Canol samples. The overlying Imperial sample at Prohibition Creek contains less quartz (69%) and more muscovite and chlorite (20% total) compared to the Canol samples. One spot sample (not sampled through an interval) from the Canol Formation at Carcajou Ridge has only 41% quartz but 33% calcite, where it overlies the Ramparts Formation (Appendix E1).

At the Imperial River section, the uppermost 10.6 m of Canol Formation was sampled. The samples were very quartz rich (> 85 wt.%), except for the uppermost sample (12-IR-4), directly under the Imperial Formation contact, which yielded 63% quartz, 25% muscovite and 10% gypsum (Appendix E3).

Two samples analysed from Vermillion Creek yielded more than 80 wt. % quartz, with accessory muscovite. The lower sample from an interval of ?Hare Indian Formation did not yield kaolinite or chlorite, which would suggest it is likely part of the Canol Formation. The Canol sample contained 7% pyrite (Appendix E3).

Importance of Mineralogical Characterization: MacKay Range West Section

At the MacKay Range West section, the Horn River Group is homogenous and it is difficult to distinguish visually the Hare Indian from Canol formations, as well as the Bluefish from Bell Creek members. Sixteen samples were taken from the basal 41 m of the Horn River Group. Quartz and muscovite are ubiquitous, with median values of 70.5 and 13 weight percent, respectively (Figure 30). Carbonate minerals are present in variable amounts throughout the section, up to 20% calcite and 12% dolomite. The basal 6.5 m of section is assigned to Bluefish Member based on relatively high TOC and high quartz (average 69 wt.%) with common carbonate minerals. There is also a distinct decrease in U concentrations bracketing the Bluefish Member (Figure 20). The succeeding 18 m is assigned to the Bell Creek member, with an average of 54.5 wt.% quartz, and distinguishing averages of 28.7 wt.% muscovite + kaolinite + chlorite. Kaolinite and chlorite are absent in Bluefish and Canol samples. The uppermost 16.5 m of measured section is assigned to Canol Formation, with an average of 78.3 wt.% quartz and 13.2 wt.% muscovite.

Distinctive Mineralogical Characteristics of Horn River Units

In summary, the Canol Formation is characterized by high amounts of quartz (MR section averages 83.4%), ubiquitous muscovite and lack of kaolinite. The most distinguishing minerals present in both the Bluefish and Bell Creek members are kaolinite and chlorite, in association with variable amounts of quartz, but typically less quartz than present in the Canol Formation. Bell Creek samples from Little Bear River 1 section are the exception to this generalization because they did not yield any kaolinite. Ramparts Formation samples from the MR section are dominated by quartz and carbonate minerals and contain accessory kaolinite, chlorite, and mica.

SOURCE ROCK QUALITY AND MATURITY FROM OUTCROP SAMPLES

Rock-Eval Results from Outcrop Samples

A total of 451 outcrop samples were collected from 29 measured sections and field stations (Figure 3), for pyrolysis with a Rock-Eval VI instrument at GSC-Calgary. Samples were generally collected as continuous or representative chip samples with hand tools over 1 to 3 m measured intervals, or at spot locations. Canol Formation samples accounted for the bulk of those collected (298), with 33 Ramparts Formation samples, 64 from Bell Creek member and 56 from Bluefish Member (Appendix B). These data were previously reported (Pyle and Gal, 2012, 2013; Pyle et al., 2011); however, here we present a revised stratigraphy of Bell Creek member, based multi-proxy chemostratigraphic analysis, which necessitates re-designation of some samples previously labelled as either Bluefish Member or Canol Formation. Some additional sample data from the northern Mackenzie Plain are reported by Gal et al. (2007) and Pyle et al. (2007). Geological Survey of Canada publications, and geological reports filed with the National Energy Board are further sources of outcrop Rock-Eval data.

Total organic carbon (TOC) content of rocks is a basic measure of potential richness as a source rock, or unconventional reservoir. Consideration of current and historic data, within the stratigraphic framework established in this report, confirms our previous assertion that units of Horn River Group, in particular the Canol Formation and Bluefish Member, are rich potential source rocks (>4% TOC; Peters, 1986). Thin organic-rich shale intervals within the Ramparts Formation, including the Carcajou member, are additionally potential rich source rocks, although with generally limited rock volumes. The only poor source rocks are the “typical” greenish grey, calcareous Bell Creek member, which is restricted to lenses that underlie Ramparts Formation. Where Ramparts Formation is absent, Bell Creek member is “atypical” and is dark grey shale, grossly similar to Canol Formation, although geochemically distinct.

Histograms displaying TOC for four Horn River Group units (Figure 31) show median values for Canol Formation and Bluefish Member each greater than 5% TOC, and the data distributions appear normal. The median value for Ramparts Formation samples is almost 4% TOC, but it should be noted that over 80% of Ramparts samples were collected from only two sections (Powell Creek and MR section). The data appear to have a normal distribution, with some high value outliers. The Bell Creek member samples appear bimodally distributed, with a normal distribution peaking at about 4% TOC, and a concentration of sub-1% TOC samples representing about 45% of all analyses. These sub-1% values correspond largely to “typical” Bell Creek member samples.

Table 2 lists the median TOC values by unit for select (complete or nearly complete) measured sections. Median TOC values for the Canol Formation ranges between 4.2% and 6% TOC. Bluefish sample medians range from 3.7 to 6.8%, although with fewer samples per site. Bell Creek sample medians range from 3.4 to 6.8%, except for the reference MR section where the median was 1.6% TOC, and the unit was characterized as “typical” Bell Creek member.

Location	Median Canol TOC (wt. %)	Median Ramparts TOC (wt. %)	Median Bell Creek TOC (wt. %)	Median Bluefish TOC (wt. %)
Canyon Creek	5.09 (19)	unit absent	4.54 (3)	5.38 (3)

Powell Creek	4.50 (18)	3.67 (13)	no data	4.33 (3)
Mountain River Tributary	4.17 (32)	4.62 (14)	1.59 (6)	4.20 (22)
Dodo Canyon/ Dodo Canyon East	5.03 (39)	unit absent	4.73 (2)	6.43 (6)
Carcajou 1	5.96 (13)	unit absent	4.14 (6)	3.70 (2)
MacKay Range West	4.60 (6)	unit absent	3.56 (5)	6.79 (5)
Little Bear 1	5.15 (26)	unit absent	6.83 (8)	5.69 (1)
Little Bear 2	5.34 (13)	unit absent	3.35 (3)	5.25 (8)
Turnabout Creek	4.24 (7)	unit absent	unit absent	5.42 (1)

Table 2. *Median TOC values in weight percent, of Horn River Group units at select measured sections, with number of samples in brackets. Bell Creek member at Mountain River tributary section is "typical" grey green shale. Bluefish Member data for Powell Creek is from Powell Creek West location (see Figure 3).*

The presence of types I-II kerogen are indicated by the high hydrogen index (HI) and low oxygen index (OI) of most of the Canol and Bluefish samples. This is illustrated in a series of pseudo- von Krevelen cross plots of HI versus OI calculated from Rock Eval VI parameters (sample location indicated by symbol and unit by colour in Figures 32A-32E). Maturation trends of type I-III kerogen are also plotted. Type II kerogen in these rocks has also been suggested by cross plots of HI versus Tmax (in Pyle and Gal, 2012, 2013). Type III kerogen is suggested in "typical" Bell Creek member shale. The relative immaturity of Horn River Group beds in northeast Mackenzie Plain compared to the south and west is apparent.

The increase in maturity recorded by Tmax values from the Canol Formation (Figure 33) trends from sub-mature to marginally mature north and east of Norman Wells, to over-mature or post-mature to the west and south. Anomalously immature Tmax values in southern Mackenzie Plain wells are most likely due to contamination of well cuttings from Cretaceous cavings (discussed further within "Rock-Eval Results from Subsurface Samples"). Also Tmax values with low organic matter content and high maturity are unreliable and should be regarded cautiously. Maturity trends in the present report are in general agreement with subsurface maturity trend maps by Feinstein et al. (1988b), Snowdon (1990), and Gal and Pyle (2012).

In summary, the Canol Formation, thin intervals in the Ramparts Formation, "atypical" Bell Creek member and Bluefish Member contain zones of good to excellent source rock, containing largely Type II kerogen. Based on Tmax values, samples range from marginally mature to overmature throughout Mackenzie Plain, but are mainly within the oil window (Tmax 435-470°C) throughout a large part of northern and central Mackenzie Plain.

Vitrinite Reflectance Results from Outcrop Samples

In total, 32 samples from 17 sections were collected from Horn River Group and 1 sample from Imperial Formation for vitrinite reflectance to determine source-rock maturity. Reflectance determinations, carried out by Julito Reyes at Geological Survey of Canada, Calgary (full results and petrographic descriptions in Appendix C) show fairly good agreement with the Rock-Eval data (Table 3).

Maturity trends are apparent across Mackenzie Plain and within sections. Both reflectance and Tmax values indicate increasing maturity from east to west, from the Norman Wells area (Quarry, Prohibition Creek and Canyon Creek samples just within the oil window) to the Mackenzie Mountains, where most samples are well within the oil window (Figure 34). Samples from Turnabout Creek, the westernmost site, indicate the upper margin of the oil window. From Canyon Creek south, samples trend from just within the oil window to about the middle of the oil window at MacKay Range. Increasing Canol maturity from Dahadinni River East section to Moose Prairie Anticline is also indicated; however, this gradient was beyond the resolution of Rock-Eval data (suspect Tmax values due to very low S2 in these overmature rocks). The increase in maturity southeastward from Powell Creek to Little Bear River is the same trend seen in Tmax values and the HI vs. OI cross plot. Decreasing maturity in an upsection direction can be discerned at several locations, notably at Canyon Creek and the MR reference section.

Sample Number, Stratigraphic Location	Number of data points for average vitrinite reflectance (maceral)	Average vitrinite (or *equivalent) reflectance	Tmax from Rock-Eval
Mountain River Tributary (518945E, 7235192N)			
12-MR-01, Bluefish base	40 bitumen	1.08*	450
12-MR-21, Bell Creek base	33 (vitrinite & bitumen)	0.94*	453
12-MR-27, Ramparts	36 (vitrinite & bitumen)	1.02*	452
12-MR-32, Carcajou	39 bitumen	1.12*	449
12-MR-38, Canol basal	7 bitumen	0.94*	448
12-MR-63, Canol upper	22 bitumen	0.88*	444
MacKay Range West (369910E, 7178208N, Zone 10)			
12-MAC-04, Bluefish	18 vitrinite	0.87	438
12-MAC-19, Canol	10 vitrinite	0.87	442
Turnabout Creek (469931E, 7244780N)			
12-TC-1, Bluefish	33 bitumen	1.23*	457
12-TC-2, Canol basal	14 bitumen	1.26*	448
12-TC-9, Canol upper	14 bitumen	1.27*	469
Norman Wells Quarry (605840E, 7243608N)			
11Q-001 Canol base	9	0.66	425 (Canol, sample 11Q-002)
11Q-003 Ramparts near top	54	0.75*	
Walker Creek (551616E, 7245351N)			
11WC-001 Canol	3	0.76	435
11WC-017 Canol	7	0.72	434
Canyon Creek (618297E, 7239347N)			
11CC-001 Canol near base	3	0.83	438
11CC-025 Canol near top	28	0.66	433
Bell Creek West (501061E, 7240021N)			
11BW-001 Bell Creek	10	0.83	454†
11BW-011 Bell Creek	10	0.84	448†
Dodo Canyon East (578964E, 7210364N)			
11DCE-033 Canol near top	14 (vitrinite & bitumen)	0.90	443
Dodo Canyon (578063E, 7210399N)			

11DC-001 Bluefish near base	44 (vitrinite & bitumen)	1.02	448
11DC-005 Bluefish near top	12 (vitrinite & bitumen)	1.05	450
11DC-007 Bell Creek near base	21 (vitrinite & bitumen)	1.00	448
Little Bear 2 (627330E, 7155802)			
11LB-001Bluefish near base	10	1.06	440
11LB-008 Bluefish near top	1	1.11	450
11LB-009 Bell Creek base	10	1.09	455

Sample Number, Stratigraphic Location	Number of data points for average vitrinite reflectance (maceral)	Average vitrinite (or *equivalent) reflectance	Tmax from Rock-Eval
Dahadinni River East (395843E, 7065586N)			
11DRE-012 Canol	8	2.23*	609†
Moose Prairie Anticline (375359E, 7063399N)			
11MPA-001 Canol	7	2.98*	610†
Prohibition Creek (630072E, 7232282N)			
LP10-142 Canol near base	5 (vitrinite & bitumen)	0.83	443
LP10-143 Canol basal	2 (vitrinite & bitumen)	0.84	434
LP10-152 Canol, upper	4 (vitrinite & bitumen)	0.77	n/a
LP10-153 Imperial	6 (vitrinite & bitumen)	1.22	436
Powell Creek (510548E, 7239390N)			
LP10-001 Canol, base	4	1.08*	444
LP10-002 Canol	4	1.00*	442
LP10-017 Canol	3	1.00*	441
LP10-018 Canol, top	2	0.97*	440
Carcajou 2 (603740E, 7185418N)			
LP10-139	3	0.9*	456
LP10-140	4	1.05*	452
Carcajou 1 (604596E, 7180582N)			
LP10-074 Bluefish	3	1.14*	443
LP10-076 Bell Creek	4	1.22*	449
LP10-077 Bell Creek	4 (vitrinite & bitumen)	1.22*	449
LP10-093 Canol, base	3	1.03*	437
LP10-094 Canol, base	5	1.09*	443
Little Bear River (620840E, 7152317N)			
LG10-019 Bluefish	3 (vitrinite & bitumen)	1.08*	459
LG10-025 Bell Creek	2 (vitrinite & bitumen)	1.11*	458
LG10-026 Bell Creek	4 (vitrinite & bitumen)	1.19*	444
LG10-027 Bell Creek	4 (vitrinite & bitumen)	1.25*	450
LG10-051 Canol upper	3 (vitrinite & bitumen)	1.17*	447
LG10-052 Canol top	3 (vitrinite & bitumen)	1.10*	449

Table 3. *Comparison of average vitrinite (or equivalent) reflectance (%R_o) and Tmax from Rock-Eval analyses of Horn River Group samples. † denotes suspect values of Tmax, due to very low S2 values.*

HORN RIVER GROUP SUBSURFACE REVISION

The revised understanding of Horn River Group stratigraphy from outcrop studies prompted a re-examination of tops picks within Mackenzie Plain. Significant adjustment to tops picks are based on changes in values of multiple geochemical and mineralogical parameters from sampled wells (data compiled in Appendix H, from Gal and Pyle, 2012). Tops picks were revised subsequent to determining the intervals to be sampled, therefore the data set now includes several Imperial Formation samples that were originally included with Canol Formation. Differentiation of the Bell Creek member of Hare Indian Formation is a revision to the picks reported by Gal and Pyle (2012) for an interval either grouped previously with the Bluefish Member or Canol Formation. Furthermore, because of the lag time in collecting cuttings during drilling, some samples assigned to the top of a particular unit (based on log-determined tops) may actually represent the overlying unit; the lag was not corrected for in this data analysis. Finally, cavings from Imperial Formation and particularly Cretaceous units presented a contamination problem with some Horn River Group samples, discussed below.

In the current study, 15 wells were sampled for whole rock geochemistry from the five transects across Mackenzie Plain (Figure 3, Appendix H). A description of the source-rock quality and maturity is based on a suite of Rock-Eval analyses from 26 sampled wells. The names of intervals from which vitrinite reflectance data was collected is also updated to account for tops picks adjustments (Appendices F and G). Semi-quantitative XRD results support the lithogeochemical results and are described for select wells (Appendix I), also with revised tops picks. Formation tops picks are then applied to all wells for which there were available logs. A description of log signatures is summarized for each Horn River Group unit, based on newly revised picks from the studied wells (Appendix L).

Lithogeochemical Characterization of Horn River Group in Fifteen Wells

Introduction

The same multi-parameter approach used to interpret the whole-rock geochemical data from Horn River Group outcrop sections is applied to 15 wells from the five transects (Figure 3) across Mackenzie Plain (367 samples total, Appendix H). Characteristics for each Horn River unit are similar to those described from outcrop, using profiles of the following parameters and proxies: TOC, uranium, silica to zirconium ratio, terrigenous input profile (TIP is a summation of aluminum oxide, iron oxide, potassium oxide, and titanium oxide), thorium to uranium ratio, calcium oxide concentration, and redox proxies using molybdenum, vanadium, and nickel. These new data have been critical in revising tops picks for the Horn River Group.

Sampling focused mainly on the Canol Formation, but several Imperial Formation samples are characterized because they were sampled from intervals presumed to be Canol Formation when the sample intervals were chosen. The Ramparts Formation was only sparsely sampled (10 samples total) and was intersected only in the Northern Transect and Central Transect 1. The differentiation of the Hare Indian Formation into a "typical" Bell Creek member (green grey shale), “atypical” Bell Creek member (dark grey shale), and Bluefish Member was possible in every well sampled. The “typical” Bell Creek member is present where the Ramparts Formation is developed.

Northern Transect

Three wells in the Northern Transect (Carcajou L-24, Hoosier Ridge N-22, and Discovery Ridge H-55; Figure 35) are correlated using revised picks based on whole-rock lithogeochemistry profiles (Figures 36, 37, 38). The H-55 well lies east of Mackenzie River (Figure 3). In this northern part of Mackenzie Plain, the Canol Formation is thin where the Ramparts Formation is thick, and in the Carcajou L-24 well, the Canol Formation may be absent, with the Imperial Formation directly overlying the Ramparts Formation (Figure 35). Designation of the Bell Creek member is new. Only TOC data are illustrated for Morrow Creek J-71 well because this well was not sampled for lithogeochemistry (Figure 39).

The H-55 well (Figure 36) illustrates characteristics of the Imperial Formation that are in contrast to the underlying Canol Formation: TOC and U values as well as the SiO_2/Zr ratio values decrease markedly with a rise in the TIP and Th/U ratio values. The Canol Formation has elevated TOC and U values, high SiO_2/Zr ratio values and low TIP and Th/U ratio values in contrast to both the Imperial and Hare Indian formations. The Mo, EFV, and Ni/Co ratio values show the most marked excursions of all formations within the profile. One upper Ramparts sample has an elevated CaO value, but also yielded high TOC and U values. The gamma and sonic logs, both with lower responses, distinguish the Ramparts Formation from both the Canol and Hare Indian formations. The Bluefish Member is distinct on the logs for the H-55 well and it is characterized by higher TOC values compared to the overlying Bell Creek member. The Bell Creek Member is distinguished by its leaner TOC values, lower U and low SiO_2/Zr ratio values compared to the Canol Formation. The most distinguishing Bell Creek characteristic is its elevated TIP values and high Th/U ratio values in contrast to the Canol Formation. The Bell Creek member also shows increasing CaO values upsection toward the Ramparts Formation. The Mo, EFV, and Ni/Co ratio values are all flat.

Eight samples from the Hoosier Ridge N-22 (Figure 37) show the same characteristics as described above for the units in the H-55 well. The uppermost Imperial sample shows lower TOC, U, and SiO_2/Zr ratio values compared to the Canol Formation, with elevated TIP proxy and Th/U ratio values. The upper Ramparts sample is within one metre of the top of the formation and thus has characteristics more in common with the Canol Formation. The Bell Creek member here is organic-lean, with low U and SiO_2/Zr ratio values and elevated TIP proxy and Th/U ratio values. The Bluefish Member has higher TOC and U values than the Bell Creek member.

The Carcajou L-24 well (Figure 38) in northwestern Mackenzie Plain contains a 21.3 m thick shale unit questionably assigned to the Canol Formation, based on two samples that do not yield strongly characteristic profiles. Samples have only a slight increase in TOC and U compared to the underlying Ramparts Formation samples, and the SiO_2/Zr ratio values are much lower (< 0.4) than typical Canol values (> 0.7). The elevated TIP proxy and Th/U ratio may indicate this shale is Imperial Formation rather than Canol Formation. The Bell Creek member is picked in this well based on its low SiO_2/Zr ratio values, and elevated TIP and Th/U ratio values compared to the overlying Ramparts Formation. The Bluefish Member is characterized by higher TOC, U, and

SiO_2/Zr ratio values compared to the Bell Creek member, and also has elevated Mo, EFV and Ni/Co ratios.

TOC values for the Canol Formation in J-71 well are elevated, in contrast to those from the Hare Indian Formation (Figure 39).

Central Transect 1

On the easternmost edge of Mackenzie Plain within Central Transect 1 is Brackett Lake C-21 well (Figure 40), and the westernmost well sampled along this transect is Dodo Canyon K-03 (Figure 41). The four samples were taken from Canyon Creek G-51, also along this transect (Appendix H) are insufficient to determine lithogeochemistry profiles from this well.

Brackett Lake C-21 well is interesting because it contains an outlier of Ramparts Formation at the eastern edge of Mackenzie Plain (Figure 3), and an anomalously thick Hare Indian Formation. Two samples of Canol Formation from the C-21 well show the characteristics for this unit including high TOC and U values, and the highest SiO_2/Zr ratio values within the whole Horn River Group profile with the exception of one Ramparts Formation sample (Figure 40). The Canol samples also have low TIP and Th/U ratio values, and show an elevation in the Mo, EFV and Ni/Co ratio. In contrast to the Canol Formation profiles, the Bell Creek samples have low TOC, U and SiO_2/Zr ratio values with a corresponding high TIP and Th/U ratio values. The CaO profile has two elevated values near the top of the unit toward the Ramparts Formation, and flat profiles for the Mo, EFV and Ni/Co ratio. Eight Bluefish Member samples show two pulses of high TOC and elevated U values that also correspond to a slight elevation in the SiO_2/Zr ratio values. Where the TOC and U values are lowest in the Bluefish samples, the TIP and Th/U values are highest, suggesting dilution by siliciclastics. The Bluefish Member also contains CaO, in most abundance near the top of the unit. In parallel with the high TOC concentrations are two phases of enrichment in Mo, EFV and Ni/Co within the Bluefish Member.

The Dodo Canyon K-03 well (Figure 41) is an example where the pick for the Canol Formation was much higher based on the cuttings. The upper 19 samples are actually Imperial Formation based on lower TOC and U values and a sharp decrease in the SiO_2/Zr ratio values above 1650 m. This revision is also corroborated by the increase in TIP and Th/U ratio values throughout the Imperial Formation. The true Canol Formation was sparsely sampled since this interval was presumed to be part of the Hare Indian Formation; however, its revised picks are corroborated by its characteristic profiles of high TOC and U concentrations, and high SiO_2/Zr ratio values with corresponding low TIP and Th/U ratio values. In the middle of the Canol Formation there is enrichment in Mo, EFV and Ni/Co ratio values. Only one Bell Creek member sample was analysed and indicative of the “atypical” organic-rich variety of this unit in contrast to the organic-lean samples from the C-21 well to the east. The Bell Creek sample is Canol-like in having a higher SiO_2/Zr ratio value and low TIP and Th/U ratio values compared to the underlying Bluefish Member samples. Its gamma log signature, however, shows slightly less radioactivity compared to the underlying Bluefish Member and overlying Canol Formation (Figure 41). Although there are only five Bluefish Member samples, there are two single-sample pulses of high TOC concentrations in parallel with enrichment in Mo, EFV and Ni/Co near the base and top of the Bluefish Member, very similar to profiles in the C-21 well (compare to Figure 40).

Central Transect 2

The Central Transect 2 (Figure 3) consists of three wells: Bear Rock O-20 (east of Mackenzie River), Bluefish K-71 and Mirror Lake N-33 wells (west of Mackenzie River, Figure 42). In the three wells with whole rock geochemistry analyses discussed herein (Figures 43, 44, 45), significant revision has been made to the top pick for the Canol Formation. Samples taken (32 in total) from intervals presumed to be the Canol Formation are now inferred to be Imperial Formation. The Bell Creek member has also been newly identified. Additional TOC data from the Blueberry Creek K-53 well just to the south (Figure 3) is shown with its revised picks (Figure 46); mineralogical data from this well is discussed in the next section.

In the Bear Rock O-20 well (Figure 43), the interval sampled was presumed to all be within the Canol Formation. There were no digital logs available at the time of the present study. The TOC and lithogeochemistry profiles illustrate the interpretation of both the Imperial and Hare Indian formations. The Imperial Formation is characterized by lower TOC and U values and a sharp decrease in the SiO_2/Zr ratio values above 105 m, as well as an increase in TIP and Th/U ratio values. The Canol Formation has characteristic profiles of high TOC and U concentrations, and high SiO_2/Zr ratio values with corresponding lower TIP and Th/U ratio values compared to the Imperial Formation and Bell Creek member. In the lower, middle, and upper Canol Formation there is a marked enrichment in EFV and Ni/Co ratio values. The Bell Creek member shows a decrease in TOC and U values in contrast to the underlying Bluefish Member and overlying Canol Formation. It also contains higher TIP and Th/U ratio values. The two lower samples are interpreted as Bluefish Member based on elevated TOC and U values.

In the Bluefish K-71 well to the southwest of O-20, the top of the Canol Formation has been revised due to recognition of Imperial Formation signatures. The Bell Creek member was picked based on its lithogeochemistry profiles and lower gamma log signature compared to the Bluefish Member and Canol Formation (Figures 42 and 44). Lower TOC and U values and decrease in the SiO_2/Zr ratio values above 1198 m indicate the presence of the Imperial Formation. The Canol Formation has overall elevated TOC and U values, with high SiO_2/Zr ratio values with corresponding lower TIP and Th/U ratio values compared to the Imperial Formation and Bell Creek member. There is an interval in the middle part of the Canol Formation where TOC values decrease to about 3 wt.% and TIP and Th/U ratio values are elevated. There is also an elevated CaO value in this less siliceous interval. One major enrichment in Mo, EFV and Ni/Co ratio values is evident within the middle part of the Canol Formation and another of lesser magnitude near the base. The lower two Bell Creek member samples have lower TOC and U values and elevated TIP and Th/U ratio values compared to the Bluefish Member and Canol Formation. The uppermost Bell Creek member sample is more Canol-like because it was taken right at the contact of these units. The Bluefish Member contains high TOC and U values, with increasing TIP and Th/U ratio values near its top. CaO decreases upward toward the Bell Creek member. There is one interval of enriched Mo, EFV and Ni/Co ratio values just above the base of the Bluefish Member.

The Mirror Lake N-33 well (Figure 45) is directly west of Bluefish K-71 well and it tops picks have been revised similarly to the other wells in this transect (Figure 42). The TOC and lithogeochemistry profiles for the Imperial samples show lower TOC and U values and decrease in the SiO_2/Zr ratio values above 935 m. The TIP and Th/U ratio values are elevated for the

Imperial samples in contrast to both the Canol and Bell Creek samples in this well. In the Imperial Formation, there are elevated values of Mo, EFV and Ni/Co ratio, more notable than the single elevated values within the K-71 and O-20 wells and also in the H-55 well from the Northern Transect. The Canol Formation in the N-33 well has lower TOC values toward the top, with decreasing SiO_2/Zr ratio values and concomitant spike in TIP and Th/U ratio values near the top. A similar profile was seen in the K-71 and O-20 Canol samples but within the middle of the unit. The CaO profile is flat in N-33 Canol samples in contrast to some enriched values in the other wells of this transect. The Mo, EFV and Ni/Co ratio values show three intervals of enrichment near the base, in the middle, and near the top are very similar to those recorded in the O-20 well, and less so within the K-71 well. The Bell Creek samples have Canol-like characteristics in this well except for the elevated CaO values. TOC values are greater than 4 and 5 wt. %, the SiO_2/Zr ratio profile is elevated and the TIP and Th/U ratio values are not markedly elevated. The gamma response for the Bell Creek is slightly less radioactive where it lies between the Bluefish Member and Canol Formation. The Bell Creek member contains enrichment in Mo, EFV and Ni/Co ratio values in the middle of the unit. The Bluefish Member has its usual characteristics, including the marked Mo, EFV and Ni/Co ratio value enrichment at its base.

Southern Transect 1

Southern Transect 1 consists of three wells, all west of Mackenzie River: Tate G-18, Tate J-65 and Summit Creek K-44. The Canol Formation in these wells is overlain by the Cretaceous Slater River Formation (Figure 47). The Bell Creek member was once again identified using lithogeochemistry profiles in each well (Figures 48, 49, 50).

The Tate G-18 (Figure 48) and J-65 (Figure 49) wells have similar TOC and lithogeochemistry profiles for the Canol Formation. In both wells are characteristic high TOC and U values, high SiO_2/Zr ratio values that decrease in the upper part of the unit, and low TIP and Th/U ratio values overall that increase near the top of the unit. The CaO profile is flat with only a slight enrichment near the top of the unit in the J-65 well. Enrichment in Mo, EFV, and Ni/Co ratio values do not correlate well, but in G-18 samples, the EFV is elevated near the base and middle of the Canol Formation and mirrored by increases in Mo and Ni/Co ratio. The spike in EFV near the top of the Canol Formation, however, is not mirrored by the other proxies. In the J-65 well, there is a slight enrichment in Mo and Ni/Co ratio values near the base of the Canol Formation, and in all three proxies near the top.

In G-18, the Bell Creek member differs in having elevated TOC and U values compared to the Bluefish Member, but not quite as high as those values in the Canol Formation. Its high SiO_2/Zr ratio values are Canol-like, yet the TIP and Th/U ratio values are characteristically Bell Creek-like and elevated compared to those of the Canol Formation. CaO profile is flat with the exception of a slight increase near the top of the unit in both the G-18 and J-65 wells (Figures 48 and 49). Enrichment in Mo, EFV and Ni/Co ratio values within the middle of the Bell Creek member, but this is very subtle in the J-65 well. In J-65, the Bell Creek member is organic-lean compared to the Bluefish and Canol units and its lower SiO_2/Zr ratio values and higher TIP and Th/U ratio values differentiate it clearly from the Canol Formation. The Bluefish Member in the J-65 well is more organic-rich compared to the Bell Creek member, but it shares a low SiO_2/Zr ratio values and elevated TIP and Th/U ratio values. Enrichment in Mo, EFV and Ni/Co ratio values is evident only in the basal Bluefish Member of the J-65 well (Figure 49).

In the Summit Creek K-44 well, the Canol Formation has characteristic high TOC and U values, high overall SiO_2/Zr ratio values that decrease in the upper 10 m of the unit, and corresponding low TIP and Th/U ratio values overall with enrichments where the SiO_2/Zr ratio values are low (Figure 50). The CaO profile is flat with three intervals of enrichment. The Mo and EFV profiles show three marked excursions in parallel (near the base, in the middle, and near the top), also mirrored by the Ni/Co ratio values but not as markedly. The Bell Creek and Bluefish members are both organic-rich, the former with two high TOC values of 7.83 and 8.0 wt.%. The gamma log of the Bell Creek member shows the characteristically less radioactive signature overall compared to the underlying Bluefish Member and overlying Canol Formation. Lower SiO_2/Zr ratio values and higher TIP and Th/U ratio values differentiate the Bell Creek member from the Canol Formation. These profiles for the Bluefish Member are more Canol-like, however, but the Bluefish contains much more CaO compared to both the Canol and Bell Creek members. The Bell Creek member contains two prominent enrichments in Mo, EFV, and Ni/Co ratio values at the base of the unit and in the middle. The Bluefish Member contains its characteristic elevation of the EFV and Ni/Co ratio value at its base. An elevation in Mo near the top is not paralleled by the other two proxies.

Southern Transect 2

Southern Transect 2 crosses the southern tip of the Mackenzie Plain exploration area and contains three sampled wells: Silvan Plateau G-51, Dahadinni B-20, and Redstone P-78 west of Mackenzie River (Figure 51). Lithogeochemistry profiles for each well have enabled revision of the picks (Figures 52, 53, 54). Accessory TOC data comes from Redstone No. 1 (J-42) well where Canol Formation was sampled but is organic-lean (Appendix F).

In the Redstone P-78 well (Figure 52), only three samples of Canol Formation were analysed. They yielded TOC values less than 3 wt.%, but these values and elevated U values distinguish the Canol Formation from the organic-lean Bell Creek member. The SiO_2/Zr ratio values are not strikingly different from those of the underlying Bell Creek member, but the overall trend of the TIP and Th/U ratio profiles distinguish the two units, with the TIP and Th/U ratio values being characteristically high for the Bell Creek member. The upper Canol sample shows a slight elevation in CaO, as well as enrichment in Mo and EFV, but not in the Ni/Co ratio. The Bell Creek member has relatively flat CaO, Mo, EFV and Ni/Co ratio profiles. A single Bluefish Member sample shows typical characteristics: high TOC and U but low TIP and Th/U ratio values, and elevated CaO, Mo, EFV, and Ni/Co ratio values.

In the Dahadinni B-20 well (Figure 53), the Canol Formation is much more organic-rich and with elevated U values and SiO_2/Zr ratio values in contrast to the underlying Bell Creek member. The elevated TIP and Th/U ratio values for the Bell Creek member are in striking contrast to low overall values for the Canol Formation, except where SiO_2/Zr ratio values decrease at the top of the Canol and the TIP and Th/U ratio values increase. CaO values are elevated in the middle and near the top of the Canol Formation, and the Bell Creek member has a flat profile with the exception of an elevated value at the top of the unit. The Mo, EFV and Ni/Co ratio values are enriched at the base of the Canol, with three or four peaks of enrichment toward the top of the Canol Formation. These profiles are flat for the Bell Creek, but show two peaks within the Bluefish Member, a subtle one at the base and one near the top. The Bluefish Member shows the same characteristics as in the P-78 well.

In the Silvan Plateau G-51 well (Figure 54), as in the K-03, N-33 and O-20 wells, samples analysed through an interval presumed to be Canol Formation were found to be part of the Imperial Formation. In contrast to the Canol Formation, the Imperial samples show low TOC and U values, lower overall SiO_2/Zr ratio values, and elevated TIP and Th/U ratio values. The CaO profile is flat. A notable enrichment in EFV, mirrored by slight rises in Mo and Ni/Co ratio values is evident near the base of the Imperial Formation. The Canol Formation has high SiO_2/Zr ratio values that become lower upsection with concomitant increase in TIP and Th/U ratio values. The CaO profile is flat for the Canol Formation in contrast to two elevated values within each of the Bell Creek and Bluefish members. Three prominent enrichments are present in the Mo, EFV and Ni/Co ratio profiles at the base, in the middle, and near the top of the Canol Formation. The Bell Creek member does have some high TOC values (up to 4.93%) and corresponding high U values, but these are not as numerous as in the Bluefish Member and Canol Formation, thus distinguishing these units and evident in the slightly less radioactive signature of the gamma log for the Bell Creek member. The SiO_2/Zr ratio values are not distinctively low for the Bell Creek member in this well, but its TIP and Th/U ratio values are elevated near the base of the unit and decrease upward. There is one zone of enrichment in EFV and Ni/Co ratio but this is not paralleled by the Mo value. The Bluefish Member shows the same characteristics as in the P-78 and B-20 wells, but with a greater sample size, the consistently high TOC and U values are evident. As with the Bell Creek samples, the SiO_2/Zr ratio values are not distinctively low and Th/U ratio values are low whereas the TIP shows some elevated levels. The CaO profile of the Bluefish Member is more elevated compared to that for the Bell Creek member. Two zones of enrichment in Mo, EFV, and Ni/Co ratio are evident at the base of the Bluefish Member and near its top.

Distinctive Geochemical Characteristics of Horn River Units in the Subsurface

The Horn River Group lies above the Hume Formation carbonate. The Bluefish Member is a reliable regional marker. The Group is overlain by either the Imperial Formation or a Cretaceous unit. Each Horn River unit has distinguishing chemostratigraphic profiles that have helped revise tops picks across Mackenzie Plain (Appendix L).

The Imperial Formation is marked by the following characteristics, in contrast to the underlying Canol Formation: TOC and U values as well as the SiO_2/Zr ratio values decrease markedly with a rise in the TIP and Th/U ratio values. The CaO profile is typically flat. Enriched values of Mo, EFV and Ni/Co ratio are prominent in the N-33 well (Figure 45), and also noted in H-55, K-03, O-20, K-71, and G-51 wells (Figures 36, 41, 43, 44, 54).

The Canol Formation is a highly organic, radioactive shale with a gamma curve sustained at high API unit levels (100 to 300+API) and corresponding high TOC and U values (Figures 35-54). Its siliceous nature with low amounts of terrigenous siliciclastic input is evident in the antithetic relationship of sustained high SiO_2/Zr ratio values to low TIP values and low Th/U ratio values. CaO values are typically low but show fluctuations, particularly in those wells where Ramparts Formation is developed (e.g., H-55 well, Figure 36). A pattern of three intervals of enrichment in Mo (ppm), EFV, and Ni/Co ratio is notable across Central Transect 2 (Figures 43, 44, 45) and in K-44 and G-51 wells (Figures 50 and 54).

The Ramparts Formation was not the focus of this study and only sparsely sampled in the Northern Transect (Figure 35) and as an outlier in C-21 well in Central Transect 1 (Figure 40). It does have some high TOC values but in thin intervals.

The “typical” Bell Creek member is present where the Ramparts Formation is developed and its generally low gamma response contrasts to that of the underlying radioactive, high TOC black shale of the Bluefish Member (H-55, N-22, L-24, and C-21 wells; Figures 36, 37, 38 and 40). It is characterized by low TOC and low U values. Low SiO_2/Zr ratio values have an antithetic relationship to high TIP values and high Th/U ratio values. CaO varies but is higher than that of the Canol Formation but lower than that of the Ramparts Formation, and increases upsection. Mo (ppm), EFV and Ni/Co ratio profiles are flat.

“Atypical” Bell Creek member becomes difficult to distinguish in some logs from the overlying Canol Formation or underlying Bluefish Member, but typically has a lower gamma response overall with thin highly radioactive zones. Its lithogeochemical profiles are quite similar to those of “typical” Bell Creek member, with the exception that the former can be quite organic-rich (e.g., K-44 well, Figure 50). Lower SiO_2/Zr ratio values and higher TIP and Th/U ratio values differentiate the “atypical” Bell Creek member from the Canol Formation (obvious in B-20 well, Figure 53). CaO profiles are variable but can show high values such as in N-33 and G-51 wells (Figures 45 and 54). Mo, EFV and Ni/Co ratio profiles are typically flat, but enrichment mid-unit is prominent in N-33 and K-44 well (Figures 45 and 50). Denser sampling would better reveal profile trends.

The Bluefish Member has consistently high TOC and U values and is thin with a high gamma (200 to 300 API units) log response. Its SiO_2/Zr ratio values vary, but are higher in contrast to “typical” Bell Creek member (e.g., C-21 well, Figure 40). Where “atypical” Bell Creek member is present (e.g., G-51 well, Figure 54), SiO_2/Zr ratio values are comparable to those of the Bluefish Member. TIP values are usually high in the Bluefish Member, but not as high as in the Bell Creek member. The CaO profile of the Bluefish Member is more elevated compared to that for the Bell Creek member. Two zones of enrichment in Mo, EFV, and Ni/Co ratio are evident at the base of the Bluefish Member and near its top in intervals of dense sampling (e.g., C-21, B-20, and G-51; Figure 40, 53 and 54).

Mineralogical Analyses from the Subsurface

Whole rock lithogeochemistry is augmented by semi-quantitative XRD analyses to determine mineral species present in 187 surface samples from 6 wells: Brackett Lake C-21 (Central Transect 1), Bear Rock O-20 and Bluefish K-71 (Central Transect 2), Blueberry Creek K-53 (south of Central Transect 2), and Dahadinni B-20 and Silvan Plateau G-51 (Southern Transect 2; Appendix I). Data was reported in Gal and Pyle (2012), but is updated here with revised picks, namely the recognition of the Bell Creek member.

The Canol Formation is quartz rich, with an average of 77.24% quartz in 78 samples. This is comparable to quartz content of as high as 80% in Horn River Group shale in northeast BC (Chalmers et al., 2012). This contrasts with lower averages for the Imperial Formation (64.15% from 34 samples), for the Bell Creek member (62.55% from 31 samples) and for the Bluefish Member (65.52% from 44 samples) (Table 6). In a comparison of other minerals, the Bell Creek and Imperial samples have the highest micas, clay, and chlorite (23.26% and 25.59%, respectively), and the Bluefish samples have the most carbonate minerals (average 12.5%, Table 6 and Figure 57). Plagioclase, dolomite, and pyrite are common accessory minerals, present in many samples (Appendix I). In comparison to the XRD results from outcrop samples, the absence of kaolinite in the Canol samples is characteristic in all of the subsurface wells except for K-71, and with trace amounts in K-53.

		Imperial (34)	Canol (78)	Bell Creek (31)	Bluefish (44)
Percent Quartz	Average	64.15	77.24	62.55	65.52
	Median	66.5	76	61	67
Percent "clay" (muscovite, kaolinite, chlorite)	Average	25.59	11.51	23.26	15.36
	Median	26	10	23	11.5
Percent carbonates (calcite, dolomite, siderite, ankerite	Average	5.44	5.18	8.42	13.39
	Median	5	4	6	12.5

Table 6. *Average and median quantitative estimates of minerals present in well cutting samples from XRD analyses.*

SOURCE-ROCK QUALITY AND MATURITY FROM SAMPLED CUTTINGS

Rock-Eval Results from Subsurface Samples

A total of 479 well-cuttings samples were collected from 26 wells for pyrolysis analysis at GSC-Calgary with a Rock-Eval VI instrument. These data were previously reported by Gal and Pyle (2012) and Pyle and Gal (2009); however new interpretations have been made based on the new tops determinations (Appendix F). Of the 352 Horn River Group samples, 160 are from the Canol Formation, 11 from the Ramparts Formation, 99 from Bell Creek member (newly recognized in the present report) and 82 from Bluefish Member. Tops picks were revised since originally determining intervals to be sampled, so the data set now includes 78 Imperial Formation samples that were originally included with Canol Formation. Furthermore, because of the lag time in collecting cuttings during drilling, some samples assigned to the top of a particular unit (based on log-determined tops) may actually represent the overlying unit. The lag was not corrected for in the data analysis in the present study. Finally, cavings from Imperial Formation and particularly Cretaceous units presented a contamination problem with some Horn River Group samples, discussed below. Rock-Eval analyses from Mackenzie Plain wells have also been reported by Feinstein et al. (1988b) and Snowdon (1990).

Re-examination of the subsurface data, within the stratigraphic framework established in this report, confirms Canol Formation and Bluefish Member as rich potential source rocks (>4% TOC; Peters, 1986). Too few Ramparts Formation samples were collected to give a complete picture of subsurface organic richness. The “atypical” facies of the Bell Creek member is a potential rich source rock as well.

Histograms displaying TOC for all four Horn River Group units (Figure 55) show median values for Canol Formation and Bluefish Member each greater than 4% TOC, and the data distributions appear normal. The median value for Ramparts Formation samples is only 1.45% TOC, based on a small number of samples because the unit was not the focus of subsurface sampling. The Bell Creek member samples have a median value of 2.1%, however the distribution is skewed, with over 35% of samples yielding <1% TOC. These sub-1% values correspond largely to "typical" Bell Creek member samples.

The difference in organic matter between "typical", organic-poor and "atypical" organic-rich Bell Creek member is shown in Table 4. The average TOC of Bell Creek member is listed for wells in which Ramparts Formation was encountered (underlain by "typical" Bell Creek) and compared to wells where no Ramparts was encountered (Horn River Group includes "atypical" Bell Creek). With few exceptions, the atypical Bell Creek member wells average higher TOC.

Well	**Ramparts Fm present**	**Average TOC (wt. %) Bell Creek mbr**
Carcajou L-24	Y	0.33
Discovery Ridge H-55	Y	1.98
Morrow Creek J-71	Y	0.71
Hoosier Ridge N-22	Y	0.46
Brackett Lake C-21	Y	1.23
Summit Creek K-44	N	5.57
Mirror Lake N-33	N	4.65
Redstone P-78	N	0.63
Tate G-18	N	4.51
Tate J-65	N	2.51
Dahadinni B-20	N	2.18
Bluefish K-71	N	3.88
Bear Rock O-20	N	3.20
Silvan Plateau G-51	N	3.32
Blueberry Creek K-53	N	3.88

Table 4. *Average TOC in weight percent for Bell Creek member samples from well cuttings. The first five wells have Ramparts Formation present, and are considered to contain "typical", light grey-green Bell Creek member shale. The latter wells have no detected Ramparts Formation, and the Bell Creek member is "atypical" dark grey shale. he difference in TOC between the two groups is apparent, with the exception of the organic-lean values in Redstone P-78.*

Pseudo- von Krevelen cross plots of hydrogen index (HI) versus oxygen index (OI) calculated from Rock Eval VI parameters are shown with samples plotted by well (symbol) and unit (colour; Figures 56A-E). Some samples are omitted for clarity, as they plot directly beneath others. Maturation trends of types I-III kerogen are also plotted. Generally, type I-II kerogen are indicated by the high HI and low OI of most of the Canol and Bluefish samples, and "atypical" Bell Creek member. Type III kerogen is suggested in "typical" Bell Creek member shale in the northern transect (Figure 56A). The generally increasing maturity of Horn River Group units from east to west along each transect is also illustrated. The Tate G-18 well (Figure 56D) displays anomalously high HI suggesting that cavings from Cretaceous Slater River Formation have contaminated the sample. The Dahadinni B-20 well (Figure 56E) may also show evidence of contamination by cavings.

In summary, the Horn River Group shale units contain largely Type II kerogen, and are good potential source rocks. “Typical” Bell Creek member probably has Type III kerogen dominantly. Based on Tmax values, Canol samples range from marginally mature to overmature throughout Mackenzie Plain, but are mainly within the oil window (Tmax 435-470°C) throughout a large part of northern and central Mackenzie Plain (Figure 33).

Vitrinite Reflectance Results from Subsurface Samples

Thirty-seven cuttings samples from 13 wells were submitted to the Organic Petrology Lab of the Geological Survey of Canada, Calgary, for vitrinite reflectance studies to determine source-rock maturity of Horn River units. Vitrinite (or vitrinite equivalent) reflectance determinations were carried out by Julito Reyes (GSC-Calgary). These data have been previously reported by Gal and Pyle (2012), however they are reproduced here with new unit assignments for some samples (Appendix G).

Overall, the results show reasonable agreement with the Rock-Eval data (Table 5). Maturity levels generally increase down hole, and an overall increase in maturity from northeast Mackenzie Plain (Discovery Ridge H-55 well), toward the west (Carcajou L-24 well) and southwest (Summit Creek K-44 well) is indicated.

The Tate G-18 and J-65 wells have anomalously low reflectance values (%Ro of 0.62 and 0.63), and the G-18 has different values for vitrinite and bitumen, suggesting the two materials are of different ages. Reyes (GSC-Calgary, Appendix G) noted many caved particles of different formations and maturities in the J-65 well. Contamination from Cretaceous shale cavings is likely as the Cretaceous directly overlies Canol Formation. The Redstone P-78 well yielded disparate reflectance values 0.83 and 1.96 $\%R_o$ for samples less than 80 m apart in well depth. The lower value is considered to represent Cretaceous cavings, while the higher value may be from re-worked material.

Thermal maturity of Canol Formation (and selected data from other formations) based on vitrinite reflectance (and equivalent) from well and outcrop samples (Figure 34) show a general increase from sub-mature to marginally mature north and east of Norman Wells, to over-mature or post-mature to the west and south. his is in agreement with Tmax data (Figure 33). It also seems that the reflectance values have better recorded the higher maturity Canol Formation in southern Mackenzie Plain compared to the Tmax values (Figure 34).

Sample Depth (m)	Formation or member	Number of vitrinite fragments analysed for reflectance (* and/or equivalent, generally bitumen)	Average %R_o vitrinite (*and/or vitrinite equivalent)	Average T_{max} from Rock-Eval
Discovery Ridge H-55 (300H556530126450)				
310	**Imperial**	37	0.67	426
380	Canol	5, 53*	0.75, 0.73*	427
385	Ramparts	16, 45*	0.71, 0.72*	430
415	**Bell Creek**	4, 28*	0.82, 0.84*	429
535	**Bell Creek**	15*	0.80*	435
550	Bluefish	1, 27*	0.91, 0.84*	437
Morrow Creek G-44 (300G446530127150)				
488.1	Bluefish	17	0.86	442
490.5	Bluefish	19	0.90	443
872.3	Canol	8, 62*	0.87, 0.83*	446
Maida Creek G-56 (300G566540128000)				
1697.5	Canol	18	0.76	446
1721	Canol	19, 21*	0.76, 0.78*	440
Carcajou L-24 (300L246540128450)				
923.8	Canol	34*	1.17*	462
929.9	**Ramparts**	25*	1.12*	456
1149.4	Ramparts	33*	1.36*	468
1198.2	**Bell Creek**	16*	1.45*	462
1375.0	Bluefish	18*	1.43*	472
1384.1	Bluefish	31*	1.51*	466
Canyon Creek G-51 (300G516520126150)				
424.4	Canol	1, 58*	0.91, 0.81*	435
568.0	Bluefish	11, 40*	0.85, 0.84*	442
571.0	Bluefish	6, 31*	0.91, 0.89*	438
Bluefish 1A (302A376500125450)				
629.3	**Bell Creek**	6, 15*	0.95, 0.85*	440
752.4	**Bell Creek**	46	0.94	446
Mirror Lake N-33 (300N336500126450)				
875	Imperial	11*	0.95*	449
920	Imperial	30*	1.04*	451
1045	Bluefish	35*, 10*	1.08*, 1.21*	458
Tate G-18 (300G186430125150)				
1365	Canol	23	0.63	408
1400	Canol	8, 30*	0.97, 0.88*	422
1440	**Bell Creek**	3, 16*	0.66, 0.92*	439
Tate J-65 (300J656430125150)				
1753.0	Canol	20	0.62	411
1807.9	**Bell Creek**	***3***	***0.61***	421
Summit Creek K-44 (300K446430125450)				
2270	Canol	22*	1.17*	456
2350	**Bell Creek**	11*	1.31*	442
2370	**Bell Creek**	39*	1.25*	443
2390	Bluefish	23*	1.20*	446
Redstone P-78 (300P786410124150)				
484.8	Hare Indian	10	0.83	425
557.9	Bluefish	14*	1.96*	594

Table 5. *Comparison of average vitrinite (or equivalent, indicated by asterisks) reflectance (%R_o) and average T_{max} from Rock-Eval. A few Imperial Formation samples are included, and those units in* ***bold*** *are those that have been made based on revised picks since publication of these results in Gal and Pyle (2012). The Tate G-18, J-65, and Redstone P-78 wells have anomalously low vitrinite values that are due to contamination from caved Cretaceous units.*

CHARACTERISTIC GEOPHYSICAL LOG REPONSES OF HORN RIVER UNITS AND THEIR CONTACTS

Bluefish Member, Hare Indian Formation

The lower contact of Bluefish Member with underlying Hume Formation is consistently sharp and easily picked throughout Mackenzie Plain. The top of the Hume Formation carbonate-dominated succession makes a sensible stratigraphic and convenient structural datum. The contact is expressed well in the log responses of gamma and sonic logs (Figures 35, 42, 47, 51). In gamma logs, a sharp deflection from high gamma (200-300 API units are common) in Bluefish Member to low gamma in Hume Formation is present. The gamma-log profile of Bluefish Member is generally somewhat ragged, and because the unit is generally thin, the gamma curve commonly forms a spiky peak. The high gamma response is due chiefly to uranium in the black organic shale. The sonic log shows a strong deflection to faster travel times in limestone of the Hume Formation from the slow shale of Bluefish Member. There are commonly high gamma-response, thin shale beds in the upper Hume Formation, so its top contact is generally picked at the top of the highest resolvable clean limestone.

Bell Creek member, Hare Indian Formation

The lower contact of Bell Creek member with Bluefish Member varies from sharp to gradational, depending on the lithology of the Bell Creek member. In north central and northeastern Mackenzie Plain, the Bell Creek member is represented by a light greenish-grey, calcareous and micaceous shale. These lithologies are always present where Ramparts Formation is also present. In these areas, the contact with Bluefish Member is generally sharp, marked by an abrupt lithological change from greenish grey shale of Bell Creek member to brownish black shale of Bluefish Member. The gamma log shows a large deflection at the contact, since the grey-green shale is generally organic-lean and not radioactive (Figures 35, 40). Sonic and density logs (no examples of the latter included in the present report) may also indicate a denser Bluefish Member. There are commonly organic rich, high-gamma shales at the top of the Bell Creek member. These are generally separated from Bluefish Member by an expanse, several tens of metres thick, of quiescent, uniform shale with muted and slightly uneven (not blocky) gamma response.

In the southern part of the Mackenzie Plain, the Bell Creek member is a grey to black shale that is difficult to differentiate from the overlying Canol Formation or underlying Bluefish Member. Since all three units are dominated by shale, the gamma log is generally the key to differentiating them, as the Bell Creek member has a lower gamma response overall with narrow, highly radioactive zones that give a ragged profile (Figures 42, 47, 51). Thus the top Bluefish Member in such cases is picked at the top of strong and sustained gamma spikes. Bluefish Member rarely exceeds 30-40 m thickness above the Hume Formation limestone.

Ramparts Formation

The lower contact of the Ramparts Formation with the Hare Indian Formation is gradational, and variability is seen in the gamma, sonic, resistivity and density logs (examples of the latter two are not included in this report). The change is marked by a downward increase in gamma response from Ramparts Formation limestone to low organic shale with low gamma response in the underlying greenish grey shale of the "typical" Bell Creek member. However, there is typically a modest deflection to higher gamma response in the Bell Creek member, given the increased potassium in clay minerals in the shale, in contrast to limestone. The sonic log almost always indicates a slower travel time. The gradational contact is accompanied by thin, black, moderately organic shale interbedded with limestone in the lowest part of Ramparts Formation, and some thin black shales may be present near the top of Hare Indian Formation as well. Therefore, the top Hare Indian Formation is generally picked as the top of the radioactively quiet, "slow" shale package of tens to a couple hundred metres thick, making allowances for increased gamma spikiness at the top. The very contact can typically be placed conveniently at a narrow gamma spike (Figure 35).

Further complications arise in the Carcajou member of Ramparts Formation, an interbedded limestone and black, organic, radioactive shale package with up to tens of metres thickness. This unit generally is present at the base of the massive reefal facies of Ramparts Formation limestone (Kee Scarp member), above an interbedded limestone-shale platform or ramp facies. The ramp facies may have log characteristics suggestive of limestone or shale and is typically present close to the base of the Ramparts Formation. It can be difficult to distinguish from Carcajou member when the ramp member is shale-dominated. One caveat when picking the top Hare Indian Formation is to include any limestone that can be resolved by the logged suite (low-gamma, higher sonic, blocky log curves) with the Ramparts Formation, where it will usually be just below a considerably radioactive Carcajou member.

Canol Formation

Where Canol Formation overlies reefal Ramparts Formation, the lower contact with Ramparts Formation generally appears sharp at the scale of log viewing (Figures 35, 42, 47, 51). The Canol Formation is a dark grey to black, highly organic and siliceous shale that results in strongly contrasting gamma and sonic logs compared to the underlying massive Ramparts Formation carbonate. The contrast from spiky (Canol Formation) to quiet (Ramparts Formation) gamma profile and the blocky form of the Ramparts Formation sonic curve are characteristic. In off-reef areas, the Canol Formation may overlie platform or shaly Ramparts Formation (including highly organic Carcajou member shales) where differentiation is more difficult, although Canol Formation may be denser and have a faster sonic travel time due to its siliceous nature. The entire thickness of the Canol Formation, ranging from a few metres to almost 200 m, consists of relatively high-organic, radioactive shale. Thus the gamma curve is sustained at high API levels (100 to 300+ API) but is very ragged in appearance.

Where the Ramparts Formation is not present, the Canol Formation overlies the Hare Indian Formation sharply to gradationally. Throughout the southern Mackenzie Plain, the Canol Formation overlies the Bell Creek member that is, overall, slightly less radioactive (due to less U associated with organic matter). The gamma-curve transition downward to somewhat lower radioactivity marks the upper Hare Indian Formation (e.g., in G-51 well, Figure 51). There are rare instances in outcrop (e.g., Hume River) where Canol Formation overlies greenish grey shale of "typical" Bell Creek member. In these cases, logs should clearly indicate a sharp transition from highly radioactive to poorly radioactive shale, in which the latter also has lower density.

The upper contact of the Canol Formation is indicated throughout Mackenzie Plain by a subtle gamma curve excursion into still relatively high API of overlying units (Imperial Formation siltstone and fine-grained sandstone, or Cretaceous shale and sandstone; Figures 35, 42, 47, 51). In some places the Upper Cretaceous Slater River Formation, a highly organic shale, may overlie the Canol Formation (Figure 47); however, the latter may be differentiated by density, sonic, or possibly resistivity curves. Where no gamma kick can be found above the Ramparts Formation, the Canol Formation has been eroded away under the sub-Cretaceous unconformity.

THICKNESS TRENDS AND ISOPACH MAPS

From Carcajou River/Dodo Canyon area west-northwest to Turnabout Creek (Figure 3), several thickness trends are evident from outcrop (Figure 58) and revised subsurface picks (Figures 35-54; Figures 59-63). The Hume Formation maintains a thickness of about 100 m across the project area, but the units of the Horn River Group vary markedly.

The Bluefish Member is a reliable regional marker, ranging from 2 m to 20 m thick in outcrop. Marked thickness increases are apparent in the subsurface, where the unit is 62.3 m thick in the southern portion of Mackenzie Plain, referred to as Root Basin (Morrow, 1991). An outlier of strata 35.2 m thick occurs in at the eastern edge of Mackenzie Plain (Figure 59).

The “typical” Bell Creek member is localized, present only in association with the Ramparts Formation, which is restricted approximately to north of 65ºN (Figures 60, 61). The “typical” Bell Creek member ranges from 32 m to 170 m thick in outcrop and is thicker within the Peel Plain exploration area to the northwest (greater than 200 m thick; Gal et al., 2009). It is up to 317.5 m thick in the subsurface of the study area (Figure 60). The Bell Creek member is absent at Turnabout Creek section, but does outcrop further west toward the Hume River (Gal et al., 2009). The Canol Formation is also thin here and thickens again westward but the reason for this localized thinning is not yet understood. There is an outlier of Bell Creek member northeast of Tulita, at the eastern edge of the Mackenzie Plain area, where the Bell Creek member is 173.5 m thick. The “atypical” facies ranges up to 238.4 m thick, and thickens to the south, similar to the pattern of the Bluefish Member (compare to Figure 59).

The Ramparts Formation is a localized carbonate build-up around Norman Wells and to the northwest in Peel Plain. It ranges from 30 m to greater than 150 m thick in outcrop, and up to 270.3 m thick in the subsurface (Figure 61). Its western edge is a depositional zero edge (after Pugh, 1983). There is an eastern outlier of the unit northeast of Tulita (Figure 61). Where the Ramparts Formation is thick, the Canol Formation is thin to absent (e.g., Carcajou L-24 well likely has Imperial Formation overlying Ramparts Formation; Figure 38). The Ramparts Formation is typically present where the “atypical” Bell Creek member is also present (Figure 58). The Carcajou member is a prominent marker within the Ramparts Formation, ranging from 2.8 to 27.2 m thick in the subsurface, based on the revised picks presented here (Figure 62, Appendix L).

The Canol Formation is regionally extensive, ranging from 3 m to greater than 142 m in outcrop and from less than 1 m to 175 m thick in the subsurface. In the Mackenzie Plain area, two northeast or east-northeast trending areas of thickest Canol Formation are evident at the Carcajou River/Dodo Canyon area and in the southern portion of Mackenzie Plain within Root Basin (Silvan Plateau G-51 well, Figure 63; Appendix L). Each of these areas contains and axis of

150+ m of Canol Formation with thicknesses decreasing to 100-150 m to the northwest and southeast. The Canol Formation thickens westward into the central Peel Plain area and toward Richardson Trough (Gal et al., 2009).

DEPOSITIONAL HISTORY OF HORN RIVER GROUP

The Hume Formation represents the last phase of a long-lived carbonate platform on the Mackenzie-Peel Shelf, which became the site of deeper water basinal settings from the early Givetian to the Frasnian (Figure 64). Sea-level rise that drowned the Hume platform marked the onset of an anoxic, starved basin during deposition of the Bluefish Member. The overlying progradational clastic wedge of the Bell Creek member of the Hare Indian Formation represents basin fill (Figure 64 after interpretations by Muir, 1988). In the vicinity of the Mackenzie Mountains reef complex, this clastic wedge consists of typical grey-green Bell Creek member, but east toward Dodo Canyon/Carcajou River, a deeper basinal setting received turbidites and interbedded shale of the darker grey atypical Bell Creek member. Al-Aasm et al. (1992) postulated a high rate of sedimentation (around 15-23 cm/1000 years) for the progradation of the Hare Indian clastic wedge. The upper part of the "typical" Bell Creek member is transitional to the ramp facies of the Ramparts Formation. The "atypical" Bell Creek member may represent a condensed sequence that is a lateral facies equivalent of both the typical Bell Creek member and lower Ramparts Formation. One more phase of significant carbonate deposition occurred during development of the reef complexes that make up the upper part of the Ramparts Formation, near Norman Wells and in the frontal ranges of the Mackenzie Mountains near Powell Creek and Bell Creek (Figure 58).

The Carcajou member represents another significant sea-level rise, since it separates basin-fill deposits below from a platform to reef development. At Mountain River Tributary section, east of the main body of the reef, the Carcajou member is overlain directly by the Canol Formation (Figure 58). At Dodo Canyon, and east to southeast of the MR section, the "atypical" Bell Creek member is overlain directly by the Canol Formation (Figures 58, 64). Muir (1988) describes several reef cycles through the platform carbonate succession of the Ramparts Formation, in which the Norman Wells reef complex was drowned before development of the Mackenzie Mountains reef complex. Deposition of the Canol Formation persisted in the surrounding basin during aggradation of these reefs. Both the Ramparts and Canol formations were ultimately covered by prograding siltstone, shale and sandstone of the Imperial Formation in the late Frasnian.

SUMMARY AND CONCLUSIONS

1. The Horn River Group consists of the Hare Indian, Ramparts, and Canol formations in central NWT. Organic-rich zones that are potential shale reservoirs are present in each unit, with the Canol Formation containing the thickest, most siliceous shale and mudstone facies.
2. A reference section for the Horn River Group is proposed at the Mountain River Tributary section. The TOC, spectrometric, and various lithogeochemical profiles for each unit at this section provide a standard for comparison across the study area, and permit division of the Hare Indian Formation into Bluefish and Bell Creek members. The

Bell Creek member is newly proposed for "typical" green-grey shale, siltstone and lime mudstone facies formerly called the upper or grey shale member of Hare Indian Formation. A supplementary reference section is designated for "atypical" dark grey shale and limestone beds of the Bell Creek member at the Carcajou River 2 section to illustrate of the heterogeneity of this unit.

3. In outcrop and the subsurface, profiles of TOC and selected lithogeochemical parameters permit differentiation of the Hare Indian, Canol and Imperial formations even where they form a visually homogenous, mudrock-dominated succession. The Bluefish Member has elevated gamma-radiation counts, high TOC and U values, elevated SiO_2/Zr, terrigenous input profile (TIP) and Th/U values, elevated CaO concentration, and prominent enrichment in Mo, EFV, and Ni/Co values, particularly the latter. The key characteristics of the Bell Creek member as compared to the underlying Bluefish Member are lower radiation, TOC, U and CaO values, except for some organic-rich intervals in the "atypical" Bell Creek member, and elevated TIP and Th/U ratio values. The Ramparts Formation contrasts with both the Hare Indian and Canol formations in its less varied scintillometer and gamma-radiation profiles and low U values, although it has some high-TOC zones. Its SiO_2/Zr profile is low, and elevated TIP and Th/U values are more similar to the Hare Indian Formation than to overlying Canol Formation. The Ramparts Formation CaO values are consistently high, and Mo, EFV, and Ni/Co profiles are flat. The Canol Formation is characterized by high, sustained scintillometer counts and gamma-radiation profile, high TOC and U levels, and markedly higher SiO_2/Zr ratio profile than other Horn River units. Its TIP and Th/U profiles are lower than those of underlying units. CaO profiles are flat, with some elevation in the basal Canol Formation where it overlies the Ramparts Formation. Enrichment in the Mo, EFV, and Ni/Co redox proxies is common in the Canol Formation. Characteristics of the Imperial Formation contrast with those of the underlying Canol Formation, namely in lower TOC and U values, lower SiO_2/Zr ratio values, and markedly greater TIP and Th/U ratio values.
4. Mineralogy from outcrop and subsurface samples, as determined by XRD, indicate that the Canol Formation is characterized by high amounts of quartz (the reference section averages 83.4% and subsurface samples average 77.24%) and ubiquitous muscovite, but lacks kaolinite. The latter is typically present in the Bell Creek member.
5. Rock-Eval 6 analyses from outcrop and subsurface indicate that the Canol Formation, thin intervals in the Ramparts Formation, "atypical" Bell Creek member, and Bluefish Member all contain zones of good to excellent source rock, containing largely Type II kerogen. The subsurface sample set for "typical" Bell Creek member indicates that it contains Type III kerogen. As determined from Tmax values, samples range from marginally mature to overmature throughout the Mackenzie Plain, but are mainly within the oil window (Tmax 435-470°C) throughout a large part of northern and central Mackenzie Plain. Thermal maturity based on vitrinite reflectance (and equivalent) from well and outcrop samples of the Canol Formation shows a similar maturity trend, from sub-mature to marginally mature north and east of Norman Wells, to over-mature or post-mature to the west and south.
6. Thickness trends for each unit, based on revised tops picks, show that the Horn River Group is extensive across Mackenzie Plain, with thick developments of organic-rich source rocks. Based on limited subsurface data, the Bluefish Member is up to 63 m thick, and the Canol Formation is up to 233 m thick.

RECOMMENDATIONS FOR FUTURE WORK

The following are research recommendations:

1. The application of the Horn River Group nomenclature will be useful as studies progress north and south of the Mackenzie Plain area in NWT. Where units of the Horn River Group have not been differentiated (for example, where Horn River or undivided Hare Indian-Canol units are mapped) these units can be subdivided by applying the lithological and geochemical characterizations of each unit outlined above (especially high silica and lack of clay minerals in the Canol Formation). These techniques may also be useful to correlate units of the Horn River Group with the Muskwa Formation and to subdivide undifferentiated Besa River Formation.
2. The Bell Creek member could be formalized if a good reference section was found and studied in detail. The proposed Horn River Group reference section at the Mountain River Tributary is not suitable because of scree cover. The unit thickens westward but finding a section with exposed base and top might be a challenge because scree cover is common, such as at Powell Creek and its namesake Bell Creek area. Accessibility is also an important factor, and the Mountain River Tributary section has relatively easy access. The Carcajou River 2 site is an excellent spot for a supplementary reference section for the dark grey Bell Creek member, depending on the nature of scree cover. For this site to be used as such, hand-held spectral gamma-radiation measurements will have to be taken, to create a comparative profile for the region, and detailed sedimentology and paleontology studies will have to done.
3. The existing biostratigraphic framework is broad, so refinement would reveal much more about the degree of diachroneity of the units and their interfingering relationships to permit better resolution on the timing of sea level changes.
4. Lithogeochemistry profiles have proven to be an effective tool in differentiating the Horn River Group units in Mackenzie Plain outcrops, and these techniques could be applied elsewhere to clarify correlations. Where sample spacing is 1 m or less, trends are greatly clarified. Finer-scale sampling could be applied on a reservoir scale to identify those parts of the succession that are both organic-rich and high in silica, amenable to hydraulic fracturing. More lithogeochemical sampling into the overlying Imperial Formation from outcrop would provide a better characterization of this unit for correlation to the subsurface and for regional comparison in outcrop.
5. XRD analyses have proven to be an important addition to the whole rock lithogeochemistry, allowing differentiation of the types of phyllosilicates present, which can be diagnostic of specific units. These analyses are therefore recommended for future sample collection.
6. Additional study of the source-rock characteristics, including their organic-richness and thermal-maturity trends, is needed within Mackenzie Plain and to extend potential fairways beyond this exploration area.
7. In order to build on the robust chemostratigraphic framework established in this report, detailed sedimentology, ichnology, biostratigraphy, finer-scale geochemical work, and porosity studies should be done. These would improve understanding of the depositional conditions across the basin. For example, the Bluefish Member lies disconformably on the Hume Formation, but more biostratigraphic collections regionally are needed to ascertain the degree of hiatus. Lateral facies relationships and timing of deposition for the atypical Bell Creek member relative to the typical Bell Creek member and lower

Ramparts Formation are also poorly understood, and would be clarified by studies of this type.

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REFERENCES

Aboriginal Affairs and Northern Development Canada, 2013. www.aadnc-aandc.gc.ca.

Aitken, J.D., MacQueen, R.W., and Usher, J.L., 1973. Reconnaissance studies of Proterozoic and Cambrian stratigraphy, Lower Mackenzie River area (Operation Norman), District of Mackenzie; Geological Survey of Canada, Paper 73-9, 178 p.

Aitken, J.D., Cook, D.G., and Yorath, C.J., 1982. Upper Ramparts River (106G) and Sans Sault Rapids (106H) map areas, District of Mackenzie; Geological Survey of Canada, Memoir 388, 48 p.

Al-Aasm, I.S., Muir, I., and Morad, S., 1992. Diagenetic conditions of fibrous calcite vein formation in black shales: petrographic, chemical and isotopic evidence; Bulletin of Canadian Petroleum Geology; v. 41, p. 456-56.

Bassett, H.G., 1961. Devonian stratigraphy, central Mackenzie River region, Northwest Territories, Canada; Geology of the Arctic, v. 1, p. 481-495.

Bassett, H.G. and Stout, J.G., 1967. Devonian of Western Canada; *in* International Symposium on the Devonian System, Calgary, 1967; Alberta Society of Petroleum Geologists, v. 1, p. 717-752.

Belyea, H.R. and Norris, A.W., 1962. Middle Devonian and older Paleozoic formations of southern District of Mackenzie and adjacent areas; Geological Survey of Canada, Paper 62-15.

Blood, R., Lash, G., and Bridges, L., 2013. Biogenic silica in the Devonian Shale Succession of the Appalachian Basin, USA; Search and Discovery Article #50864, posted September 23, 2013.

Braman, D.R. and Hills, L.V., 1992. Upper Devonian and Lower Carboniferous miospores, western District of Mackenzie and Yukon Territory, Canada; Palaeontographica Canadiana No. 8, 97 p.

Caldwell, W.G.E., 1964. The nomenclature of the Devonian formations in the lower Mackenzie River valley; Bulletin of Canadian Petroleum Geology, v. 12, p. 611-622.

Chalmers, G.R., Bustin, R.M., and Bustin, A.M.M., 2012. Geological controls on permeability of gas shales: Examples from the Triassic Montney/Doig Formations and Devonian Strata of the Horn River Basin, northeastern British Columbia, Canada; abstract, GeoConvention 2012: Vision; Canadian Society of Petroleum Geologists.

Cook, D.G., 1975. The Keele Arch – A Pre-Devonian and Pre-Late Cretaceous paleo-upland in the northern Franklin Mountains and Colville Hills; Geological Survey of Canada Paper 75-1C, p. 243-246.

Dean, W.E., Gardner, J.V., Piper, D.Z., 1997. Inorganic geochemical indicators of glacial–interglacial changes in productivity and anoxia on the California continental margin. Geochimica et Cosmochimica Acta, v. 61, p. 4507-4518.

Dixon, J., 1999. Mesozoic-Cenozoic stratigraphy of the northern Interior Plains and plateaux, Northwest Territories; Geological Survey of Canada, Bulletin 536, 56 p.

Douglas, R.J.W. (ed.), 1970. Geology and economic minerals of Canada; Geological Survey of Canada, Economic Geology Report No. 1.

Douglas, R.J.W. and Norris, A.W., 1960. Horn River map-area, Northwest Territories; Geological Survey of Canada, Paper 59-11.

Douglas, R.J.W. and Norris, D.K., 1960. Virginia Falls and Sibbeston Lake map-areas, Northwest Territories; Geological Survey of Canada, Paper 60-19.

Douglas, R.J.W. and Norris, D.K., 1961. Camsell Bend and Root River map-area, District of Mackenzie, Northwest Territories; Geological Survey of Canada, Paper 61-13.

Dypvik, H., 1984. Geochemical compositions and depositional conditions of upper Jurassic and lower Cretaceous Yorkshire clays, England; Geological Magazine, v. 121, 489–504.

Fallas, K.M., MacNaughton, R.B., MacLean, B.C. and Hadlari, T., 2013. Geology, Norman Wells (southwest), Northwest Territories; Geological Survey of Canada, Canadian Geoscience Map 101, scale 1:100 000.

Feinstein, S., Brooks, P.W., Fowler, M.G., Snowdon, L.R. and Williams, G.K., 1988a. Families of oils and source rocks in the Central Mackenzie Corridor: A geochemical oil-oil and oil-source rock correlation; in Sequence, Stratigraphy, Sedimentology: Surface and Subsurface, edited by D.P. James and D.A. Leckie, Canadian Society of Petroleum Geologists, Memoir 15, p. 543-552.

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

Fritz, W.H., Cecile, M.P., Norford, B.S., Morrow, D., and Geldsetzer, H.H.J., 1992. Cambrian to Middle Devonian assemblages; *in* Geology of the Cordilleran Orogen in Canada, edited by H. Gabrielse and C.J. Yorath; Geological Survey of Canada, Geology of Canada, p. 151-218.

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; Northwest Territories Geoscience Office, NWT Open Report 2012-009.

Gal, L.P., Allen, T.L., Fraser, T.A., Hadlari, T., Lemieux, Y., Pyle, L.J. and Zaantvoort, W.G., 2007. Rock Eval 6 / TOC analyses from outcrop samples in northern Mackenzie Mountains, eastern Richardson Mountains, and southern Peel Plateau and Plain, Northwest

Territories and Yukon, Canada; Northwest Territories Geoscience Office and Yukon Geological Survey, NWT Open Report 2007-002 / YGS Open File 2007-1, 11 p., Microsoft Excel® spreadsheet and ESRI ArcView® files.

Gal, L.P., Pyle, L.J., Hadlari, T. and Allen, T.L., 2009. Chapter 6 – Lower to Upper Devonian Strata, Arnica-Landry play, and Kee Scarp Play; *in* Regional Geoscience Studies and Petroleum Potential, Peel Plateau and Plain, Northwest Territories and Yukon: Project Volume, edited by L.J. Pyle and A.L. Jones, Northwest Territories Geoscience Office and Yukon Geological Survey, NWT Open File 2009-02 and YGS Open File 2009-25, p. 187-289.

Gordey, S.P., Martel, E., MacDonald, J., MacNaughton, R., Roots, C.F., and Fallas, K. (compilers), 2010. Geology of Mount Eduni, NTS 106A Northwest, Mackenzie Mountains, Northwest Territories; Northwest Territories Geoscience Office, NWT Open File 2010-09. 1 map, scale 1:100,000.

Gordey, S.P., Pierce, K.L., Fallas, K., Martel, E., and Roots, C.F. (compilers), 2012. GIS compilation for the geology of Sekwi Mountain, Mount Eduni, and northwest Wrigley Lake areas (NTS 105P, 106A, and 95M NW), Mackenzie Mountains, Northwest Territories; Northwest Territories Geoscience Office, NWT Open Report 2012-002. Digital Files.

Grass, D.B., 1988. Surface geological field program, lower Mackenzie Valley, Northwest Territories. Report on geological examination of Devonian outcrop, Mackenzie River Valley and Mackenzie Mountains, NWT. Amoco Canada Petroleum Company Limited. National Energy Board Report #9233-A4-2E.

Gray, F.F. and Kassube, J.B., 1963. Geology and stratigraphy of Clark Lake gas field, British Columbia; American Association of Petroleum Geologists Bulletin, v. 47, p. 467-483.

Griffin, D.L., 1965. The Devonian Slave Point, Beaverhill Lake and Muskwa Formations of Northeastern British Columbia and adjacent areas; British Columbia Department of Mines and Petroleum Resources, Bulletin No. 50.

Hadlari, T., Gal, L.P., Zantvoort, W.G., Tylosky, S.A., Allen, T.L., Fraser, T.A., Lemieux, Y., and Catuneanu, O., 2009a. Chapter 7 – Upper Devonian to Carboniferous Strata I – Imperial Formation play. In: Regional Geoscience Studies and Petroleum Potential, Peel Plateau and Plain, Northwest Territories and Yukon: Project Volume, edited by L.J. Pyle and A.L. Jones. Northwest Territories Geoscience Office, NWT Open File 2009-002, p. 290-364.

Hadlari, T., Tylosky, S.A., Lemieux, Y., Zantvoort, W.G., and Catuneanu, O., 2009b. Slope and submarine fan turbidite facies of the Upper Devonian Imperial Formation, northern Mackenzie Mountains, NWT: Bulletin of Canadian Petroleum Geology, 57, 192-208.

Hall, D., Sterner, M., and Shukla, R., 2013. Application of cuttings gas/oil analysis, rapid XRF and high-resolution photography to reservoir evaluation; World Oil, April 2013 issue, p. 163-168.

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, 260 p.

Hildred, G.V. and Rice, C., 2012. Using High Resolution Chemostratigraphy to Determine Well-bore Pathways in Multilateral Drilling Campaigns: an Example from the Horn River Formation, British Columbia, Canada; Canadian Society of Petroleum Geologists Geoconvention, May 2012, Calgary Alberta.

Hildred, G.V., Ratcliffe, K., and Schmidt, K., 2011. Application of inorganic whole-rock geochemistry to shale resource plays: an example from the Eagle Ford Shale, Texas; Houston Geological Society Bulletin, April 2011, p. 31-38.

Hogue, B.C. and Gal, L.P., 2008. NWT Formation Tops for Petroleum Exploration and Production Wells: 60 to 80ºN; Northwest Territories Geoscience Office, NWT Open Report 2008-002.

Hunt, C.W., 1954. Normal Devonian sequence in southern Mackenzie Basin, western Canada; American Association of Petroleum Geologists Bulletin, v. 38, p. 2290-2301.

Jacob, H., 1989. Classification, structure, genesis and practical importance of natural solid oil bitumen; International Journal of Coal Geology, v. 11, p. 65–79.

Johnson, J.G., Klapper, G., and Sandberg, C.A., 1985. Devonian eustatic fluctuations in Euramerica; Geological Society of America Bulletin, v., 96, p. 567-587.

Jones, B., and Manning, D.A.C., 1994. Comparison of geochemical indices used for the interpretation of palaeoredox conditions in ancient mudstones; Chemical Geology v. 111, p. 111-129.

Kaufman, B., 2006. Calibrating the Devonian time scale: a synthesis of U-Pb-ID-TIMS ages and conodont stratigraphy; Earth Science Reviews, v. 76, p. 175-190.

Kindle, E.M. and Bosworth, T.O., 1921. Oil-bearing rocks of lower Mackenzie River valley; Geological Survey of Canada, Summary Report 1920, Part B, p. 37-63.

Lane, L.S., 2007. Devonian-Carboniferous paleogeography and orogenesis, northern Yukon and adjacent Arctic Alaska; Canadian Journal of Earth Sciences, v. 44, p. 679-694.

Lemieux, Y., MacLean, B.C., and Pyle, L.P., 2009. Chapter 2 - Regional Structure of Peel Plateau and Plain; *in* Regional Geoscience Studies and Petroleum Potential, Peel Plateau and Plain, Northwest Territories and Yukon: Project Volume, edited by L.J. Pyle and A.L. Jones, Northwest Territories Geoscience Office and Yukon Geological Survey, NWT Open File 2009-02 and YGS Open File 2009-25, p. 43-82.

Mackenzie, W.S., 1972. Fibrous calcite, a Middle Devonian geological marker with stratigraphic significance, District of Mackenzie, Northwest Territories; Canadian Journal of Earth Sciences; v. 9, p. 1431-1440.

MacLean B.C. and Cook, D.G., 1999. Salt tectonism in the Fort Norman area, Northwest Territories, Canada; Bulletin of Canadian Petroleum Geology, v. 47, p. 104-135.

McCracken, A.D., 2012. Report on one Upper Devonian conodont sample from the Canol Formation, Dodo Canyon, NWT collected by Adrienne Jones (NTGO) and submitted under R.B. MacNaughton's Mackenzie Delta and Corridor: Mapping for Energy (MADACOR) Project in 2011. NTS 096E/03. Con. No. 1767-1; Geological Survey of Canada, Paleontological Report 1-ADM-2012, 8 p.

Morrow, D.W., **1991.** The Silurian-Devonian sequence in the northern part of the Mackenzie Shelf, Northwest Territories; Geological Survey of Canada, Bulletin 413, 121 p.

Morrow, D.W. and Geldsetzer, H.H.J., **1988.** Devonian of the eastern Canadian Cordillera; *in* Devonian of the World, Proceedings of the Second International Symposium on the Devonian System, Volume I, Regional Syntheses, edited by N. J. McMillian, A. F. Embry and D. J. Glass, Canadian Society of Petroleum Geologists, Memoir 14, p. 85-121.

Morrow, D.W., Jones, A.L., and Dixon, J., **2006.** Infrastructure and resources of the Northern Canadian Mainland Sedimentary Basin; Geological Survey of Canada, Open File 5152, 59 p.

Muir, 1988. Devonian Hare Indian and Ramparts Formations, Mackenzie Mountains, NWT; Basin Fill, platform and reef development; Ph. D thesis, University of Ottawa.

Muir, I. and Dixon, O.A., 1984. Facies analysis of a Middle Devonian sequence in the Mountain River-Gayna River; *in* Contributions to the geology of the Northwest Territories; Volume 1; edited by J.A. Brophy, INAC EGS 1984-6, p. 55-62.

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.

Norris, A.W., 1985. Stratigraphy of Devonian outcrop belts in northern Yukon Territory and Northwest Territories, District of Mackenzie (Operation Porcupine area); Geological Survey of Canada, Memoir 410, 81 p.

Norris, A.W., 1965. Stratigraphy of Middle Devonian and older Paleozoic rocks of the Great Slave Lake Region, Northwest Territories; Geological Survey of Canada, Memoir 322.

Norris, D.K., 1982. Geology: Snake River, Yukon-Northwest Territories; Geological Survey of Canada, Map 1529A, 1:250:000.

North American Commission on Stratigraphic Nomenclature, 2005. The North American Stratigraphic Code; AAPG Bulletin, v. 89, p. 1547-1591.

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, 61 p.

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

Pyle, L.J. and Gal, L.P., 2007. Lower to Middle Paleozoic stratigraphy and measured sections, NTS 106F, G, H, I, Northwest Territories; Northwest Territories Geoscience Office, NWT Open Report 2007-004.

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 p., 1 CD-ROM.

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 2; Northwest Territories Geoscience Office, NWT Open Report 2012-008.

Pyle, L.J. and Gal, L.P., 2013. Measured Sections and Petroleum Potential Data (Conventional and Unconventional) of Horn River Group Outcrops – Part 3, NTS 96C, 96E, and 106H, Northwest Territories; Northwest Territories Geoscience Office, NWT Open Report 2013-005.

Pyle, L.J. and Jones, A.L. (editors), 2009. Regional Geoscience Studies and Petroleum Potential, Peel Plateau and Plain, Northwest Territories and Yukon: Project Volume; Northwest Territories Geoscience Office and Yukon Geological Survey, NWT Open File 2009-02 and YGS Open File 2009-25, 549 p.

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; Northwest Territories Geoscience Office, NWT Open File 2011-09.

Pyle, L.J., Allen, T.L., Fraser, T.A., Gal, L.P., Hadlari, T., Jones, A.L., Lemieux, Y., and Zantvoort, W.G., 2007. Field-based stratigraphic studies in the Peel Plateau, Peel Plain, and adjacent areas, Northwest Territories and Yukon; Geological Survey of Canada, Current Research 2007-A7, 11p.

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

Sageman, B.B. and Lyons, T.W., 2003. Geochemistry of fine-grained sediments and sedimentary rocks; *in* Sediments, Diagenesis, and Sedimentary Rocks, volume 7, Treatise of Geochemistry, edited by F.T. Mackenzie; Elsevier, p.114-156.

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.

Snowdon, L.R., Brooks, P.W., Williams, G.K. and Goodarzi, F., 1987. Correlation of the Canol Formation source rock with oil from Norman Wells; Organic Geochemistry, v. 11, p. 529-548.

Tassonyi, E.J., 1969. Subsurface geology, lower Mackenzie River and Anderson River area, District of Mackenzie; Geological Survey of Canada, Paper 68-25, 207 p.

Tribovillard, N., Algeo, T., Lyons, T.W. and Riboulleau, A., 2006. Trace metals as paleoredox and paleoproductivity proxies; an update; Chemical Geology, v. 232, p. 12-32.

Uyeno, T.T., 1979. Devonian conodont biostratigraphy of Powell Creek and adjacent areas, western District of Mackenzie; *in* Western and Arctic Canadian Biostratigraphy, edited by C.R. Stelck and B.D.E. Chatterton; Geological Association of Canada Special Paper 18, p. 233-257.

Uyeno, T.T., 1991. Pre-Famennian Devonian conodont biostratigraphy of selected intervals in the eastern Canadian Cordillera; *in* Ordovician to Triassic conodont paleontology of the Canadian Cordillera; edited by M.J. Orchard, and A.D. McCracken; Geological Survey of Canada, Bulletin 417, p. 129-161.

Ver Straeten, C.A., Brett, C.E., and Sageman, B.B., 2011. Mudrock sequence stratigraphy: a multi-proxy (sedimentological, paleobiological and geochemical) approach, Devonian Appalachian Basin; Palaeogeography, Palaeoclimatology, and Palaeoecology, v. 304, p. 54-73.

Wedepohl, K.H., 1971. Environmental influences on the chemical composition of shales and clays; *in* Physics and Chemistry of the Earth, edited by L.H. Ahrens, F. Press, S.K. Runcorn, and H.C. Urey; Pergamon, Oxford, p. 305-333.

Wedepohl, K.H., 1991. The composition of the upper Earth's crust and the natural cycles of select metals; *in* Metals and their Compounds in the Environment, edited by E. Merian; VCH-Verlagsgesellschaft, Weinheim, p. 3-17.

Whittaker, E.J., 1922. Mackenzie River district between Great Slave Lake and Simpson; Geological Survey of Canada, Summary Report, 1921, Part B, p. 45-55.

Williams, G.K., 1983. What does the term "Horn River Formation" mean?; Bulletin of Canadian Petroleum Geology, v. 31, p. 117-122.

Williams, G.K., 1986. Hume Formation, lower Mackenzie River area; Geological Survey of Canada, Open File 1336, 8 p.

Williams, G.K., 1986. Middle Devonian facies belts, Mackenzie Corridor; Geological Survey of Canada, Open File 1353, 10 p.

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, October 2010, Calgary, Alberta, Canada.

Yorath, C.J. and Cook, D.G., 1981. Cretaceous and Tertiary stratigraphy and paleogeography, northern Interior Plains, District of Mackenzie; Geological Survey of Canada, Memoir 398, 76 p.

Yose, L.A., Brown, S., Davis, T.L., Eiben, T., Kompanik, G.S. and Maxwell, S.R., 2001. 3-D geologic model of a fractured carbonate reservoir, Norman Wells Field, NWT, Canada; Bulletin of Canadian Petroleum Geology, v. 49, p. 86-116.