Preliminary results from a diamond drill hole study to assess shale gas potential of Devonian strata, Eagle Plain, Yukon

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ABSTRACT

An evaluation of hydrocarbon resource potential in Eagle Plain is one aspect of the Yukon Sedimentary Basins Project, a five-year (2008-2013), collaborative Geo-Mapping for Energy and Minerals (GEM) Program of the Geological Survey of Canada (GSC), in partnership with the territorial governments and universities. As part of this project, Yukon Geological Survey (YGS) and Northern Cross (Yukon) Limited (NCY) are collaborating with the GSC to assess shale gas potential of Devonian shale at Eagle Plain.

Diamond drill core was retrieved from mineral exploration properties to evaluate shale gas potential of Devonian shale of Road River Group and Canol and Imperial formations. Diamond drill core from four holes, located on the Rich property east of Eagle Plain Hotel, were examined and sampled. The core was systematically sampled and analysed by Rock-Eval pyrolysis, optical microscopy, X-ray diffraction (XRD) mineralogy, and palynology.

The results indicate that the succession is thermally overmature with respect to hydrocarbon generation. Due to the high levels of thermal maturity, the Rock-Eval data are unreliable. However, high amounts of residual organic carbon suggest that the Canol Formation has the potential to be an important source rock in the region, under favourable burial conditions. The very high level of thermal maturity of the strata also resulted in very few identifiable Palynomorphs; however, Canol and Imperial formation samples yielded dates of Middle to Late Devonian and Frasnian to Famennian, respectively. XRD analyses indicate Canol Formation shale is highly siliceous whereas Road River Group shale and silty shale of the Imperial Formation are less siliceous and exhibit a more varied lithology. This study suggests that the Canol Formation is more prospective for shale gas than strata of the Imperial Formation or Road River Group.

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INTRODUCTION

Eagle Plain basin is an underdeveloped prospective hydrocarbon exploration area in north Yukon that is only broadly understood. Minimal hydrocarbon exploration has been conducted in the region since the height of exploration in the 1950s through the 1970s.

A large part of Eagle Plain Devonian stratigraphy underlies thick Cretaceous sedimentary cover. Continuously exposed outcrop is rare. Dempster Highway roadcuts and borrow pits provide discontinuous exposure of Cretaceous and Paleozoic strata. Drainages along the western flank of the Richardson Mountains provide limited exposures, though they are not always accessible due to the small valley sizes, abundant tree cover, and local fluvial and lacustrine deposits.

Previously, Late Devonian shales were sampled along the highway, in river cutbanks, and in petroleum exploration wells; samples were subjected to Rock-Eval pyrolysis (Link *et al.*, 1989; Snowdon, 1988, 1990). Recently, more outcrop samples from the neighbouring Peel Plateau and Plain were analysed using Rock-Eval (Gal *et al.*, 2007; Allen and Fraser, 2008; Allen *et al.*, 2008; Allen, 2010). Surface samples collected and analysed in the past have demonstrated source rock potential but the effects of surface weathering, permafrost and associated fracturing and mineral oxidation common to surface samples may have compromised the accuracy of analytical data. Additional limitations are related to the distance between in-situ exposures areally and vertically, so variations in the petroleum source characteristics are not readily quantifiable.

Exploration activities in the region conducted by Archer, Cathro and Associates (1981) Ltd. during 2007-08, on behalf of a mineral industry client, resulted in Devonian strata being cored continuously over an interval up to 565 m, providing composite stratigraphic sections that include uppermost Road River Group, Canol and Imperial formations (Dumala, 2007; Gregory, 2008). Examining and analysing this drill core can greatly improve our understanding of these stratigraphic units including their lithology, contact relationships, sedimentary structures, and regional variations. The core also provides an opportunity to analyse fresh intact samples, which will significantly reduce analytical problems associated with surface weathering. The full exploration drilling program extended over a distance of 170 km in an approximate north-south direction. Core extracted from this mineral exploration program was donated to the Yukon Geological Survey, Geological Survey of Canada and Northern Cross Yukon. This report focuses on preliminary results from the Rich property where the thickest composite section was recovered.

Results enhance our understanding of both conventional and unconventional petroleum potential in the region and will be integrated in future petroleum resource assessments of Eagle Plain.

STUDY AREA

Eagle Plain basin lies between 65°N and 67°N latitudes and 136°W and 140°W longitudes, bound to the east by the Richardson Mountains, to the northeast by the Keele Range, and south and west by the Ogilvie Mountains (Taiga and Nahoni ranges, respectively; Fig. 1). North to south, the region is approximately 170 km long, and extends approximately 80 km east to west, covering an area of 20 600 km^2. Traversing the southeast corner of the basin is Yukon Highway 5, known as the Dempster Highway. The Eagle Plains Hotel and government maintenance camp are situated in the southeastern portion of the basin, at kilometre 369 of the highway.

The diamond drilling program, from which the core for this study originates, was conducted on the Rich property, located on NTS map sheet 116I/08 at latitude 66°19′N and longitude 136°14′W (Fig. 2). The property is 23 km east of Eagle Plains Hotel, along the western flank of the southern Richardson anticlinorium. Access to the property is via helicopter from the Hotel.

GEOLOGICAL SETTING

PHYSIOGRAPHIC AND TECTONIC SETTING

The Eagle Plain basin exploration region, as identified by the Yukon Oil and Gas Resources Branch (Oil and Gas Resources, 2010) roughly corresponds to the limit of Cretaceous cover (Fig. 1), and includes the Eagle Lowland and part of the southern Richardson Mountains physiographic regions of Matthews (1986).

Eagle Plain basin includes the Eagle fold belt and minor parts of the western Richardson anticlinorium and northern Taiga-Nahoni fold belt of D.K. Norris (1997; Fig. 3). The Eagle fold belt is characterized by a thick Cretaceous sediment cover, and symmetrical and open folds trending almost north, up to 120 km long.

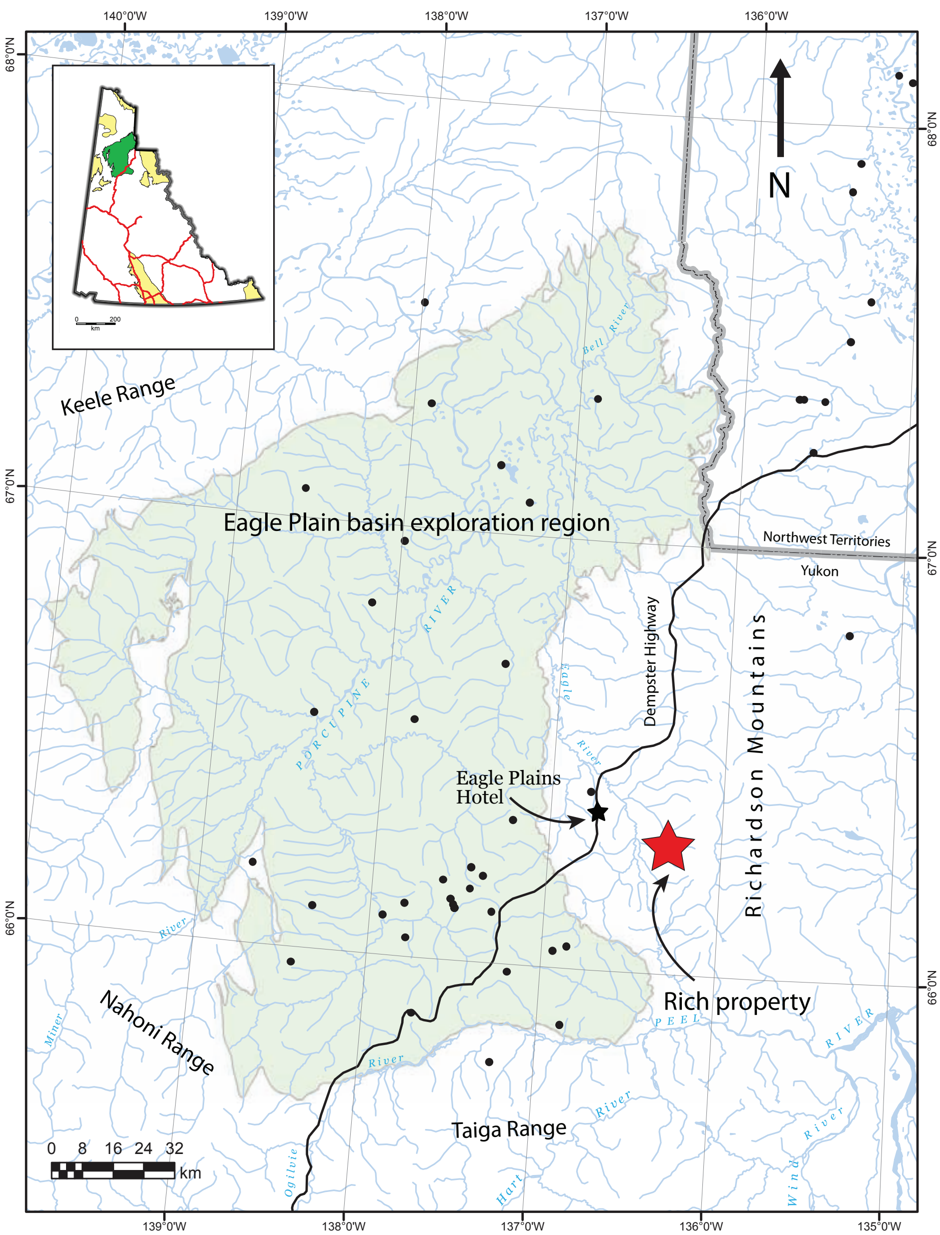

Figure 1. Map of Eagle Plain basin exploration region and the location of the Rich Property. Black dots represent oil and gas exploration well locations. Inset map of Yukon Territory with Eagle Plain exploration region in green and other oil and gas regions in yellow.

The Rich property, the location of this study, occupies part of the western limb of the north to northwest-trending Richardson anticlinorium, defining the southern Richardson Mountains. Rocks exposed in the anticlinorium are predominantly Cambrian to Devonian in age. At the Rich property, Road River Group, Canol and Imperial formations are exposed at surface (Figs. 2 and 3).

STRATIGRAPHY

Eagle Plain basin is underlain by an easterly tapering wedge of Phanerozoic sedimentary rock, locally up to 6 km-thick, that overlies Proterozoic strata (Osadetz *et al.*, 2005). The wedge consists of a Paleozoic succession unconformably overlain by a Mesozoic succession. Paleozoic strata generally include Cambrian to Middle Devonian carbonate platform strata deposited on the Yukon Stable Block in the west and associated basinal strata deposited in the Richardson trough to the east (Morrow, 1999; Fig. 3); Middle Devonian to Carboniferous siliciclastic rocks, including distal orogenic foredeep deposits; and mixed-carbonate siliciclastic deposits from Carboniferous to Permian time (Pugh 1983; Morrow, 1999). Mesozoic strata comprise locally preserved Jurassic and Early Cretaceous siliciclastic sediments overlain by widespread Albian shelf deposits up to 1500 m thick; and up to 2 km of Late Cretaceous foreland basin sediments (Dixon, 1992).

In Late Carboniferous and Early Permian time, development of the northeast-trending Ancestral Aklavik Arch (Morrow, 1999; Fig. 3) across the northern margin of the Yukon Stable Block removed a significant section of Carboniferous and uppermost Devonian strata in the central and northern areas of the basin (Dixon, 1998). Jurassic rocks and several Early Cretaceous units are preserved locally, especially on the northern and southern margins of the basin. Each remnant is separated by an unconformity, documenting successive cycles of marine inundation and subaerial exposures during this interval (Dixon, 1992).

This study concerns Middle Devonian to Carboniferous stratigraphy including the uppermost Road River

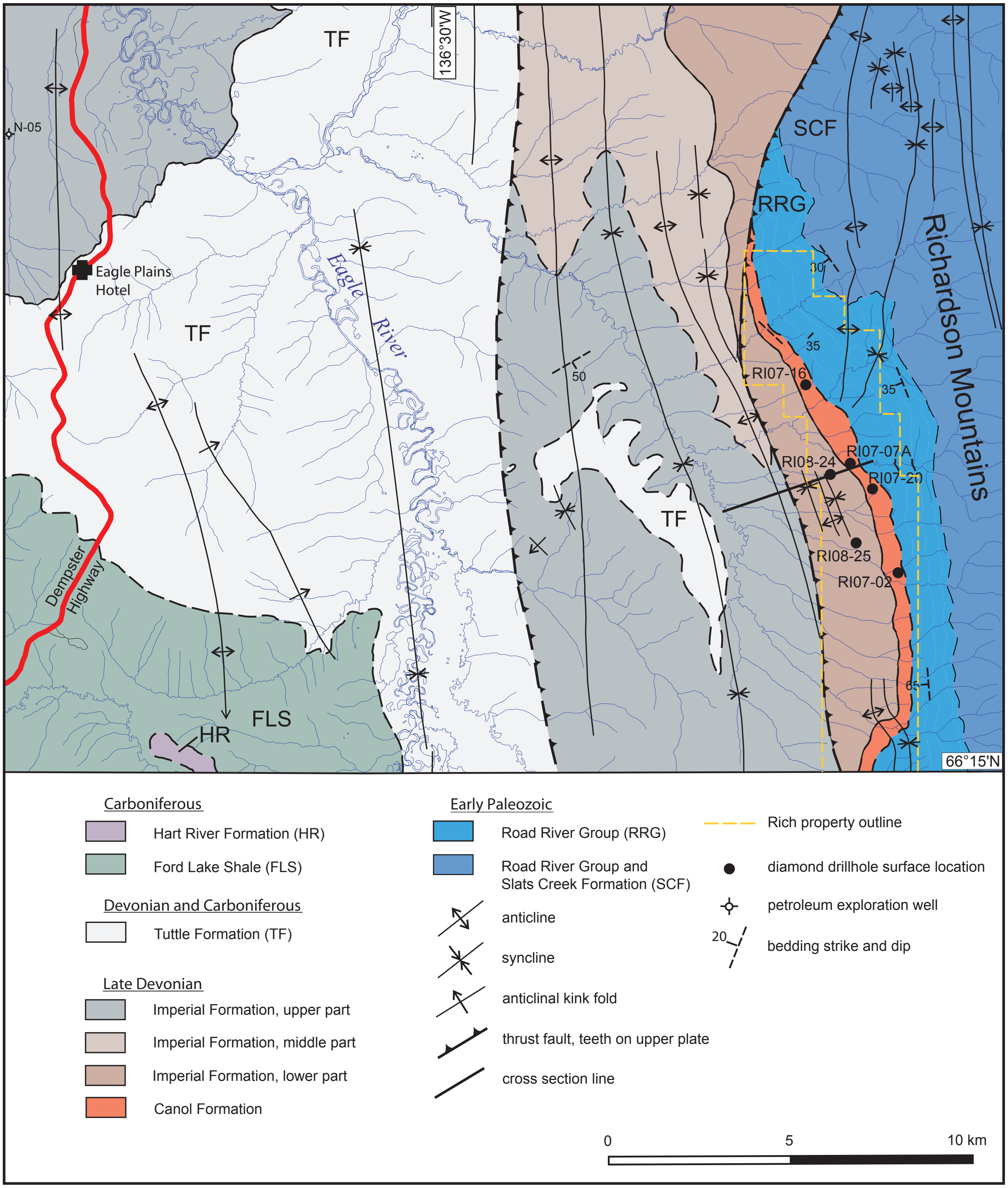

Figure 2. *Geological map of part of Mount Raymond (NTS 116I08), showing locations of the Rich property diamond drill holes from which core was recovered, in relation to the local stratigraphy and structure, as well as the Dempster Highway and Eagle Plains Hotel.*

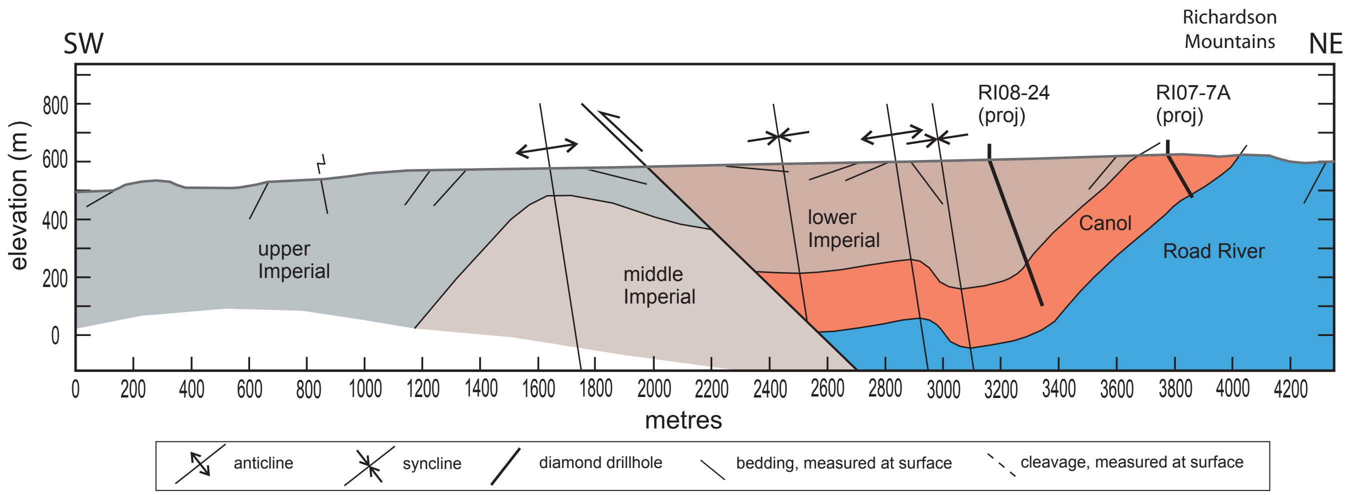

Figure 3. *Local structural cross section through the Rich property showing diamond drill holes RI07-7A (oriented -60° toward 070°) and RI08-24 (oriented -70° toward 090°) projected into the line of section.*

Group and Canol and Imperial formations. A stratigraphic column for the Silurian to Carboniferous is shown in Fig. 4, displaying the relationship and ages of the Road River Group, Canol and Imperial formations. Sedimentation in the study region was affected in the Middle Devonian by the Richardson trough and adjacent (present day west) Yukon Stable Block, and during the Late Devonian and Early Carboniferous by the Ellesmerian orogeny, which resulted in the deposition of a thick package of siliciclastic strata forming a progradational clastic wedge derived from a northern source (Pugh, 1983; Braman and Hills, 1992).

The Road River Group, originally defined by Jackson and Lenz (1962) and elevated to group status by Fritz (1985), was deposited in Late Cambrian to Middle Devonian time in the Richardson trough and on most of the Yukon Stable Block (Morrow, 1999). The upper part of the Road River Group, and that section of stratigraphy that relates to this study, includes the Upper Silurian and Lower to Middle Devonian Vittrekwa unit of Cecile *et al.* (1982). In outcrop, this unit is generally a graptolitic, black shale and shaly limestone, although the upper 50 m, and the stratigraphy pertinent to this study, is white weathering, siliceous shale, and chert. Road River Group strata are thickest, almost 3000 m, in the Richardson trough, however on the Yukon Stable Block it is less than that (Morrow, 1999). The nature of the contact of the Canol Formation with the Road River Group is contentious. Earlier work refers to a significant unconformity there, however more recent work favours the interpretation of the Canol as a condensed section possibly initiated by rapid sea level rise in Givetian time (Pugh, 1983; Morrow, 1999).

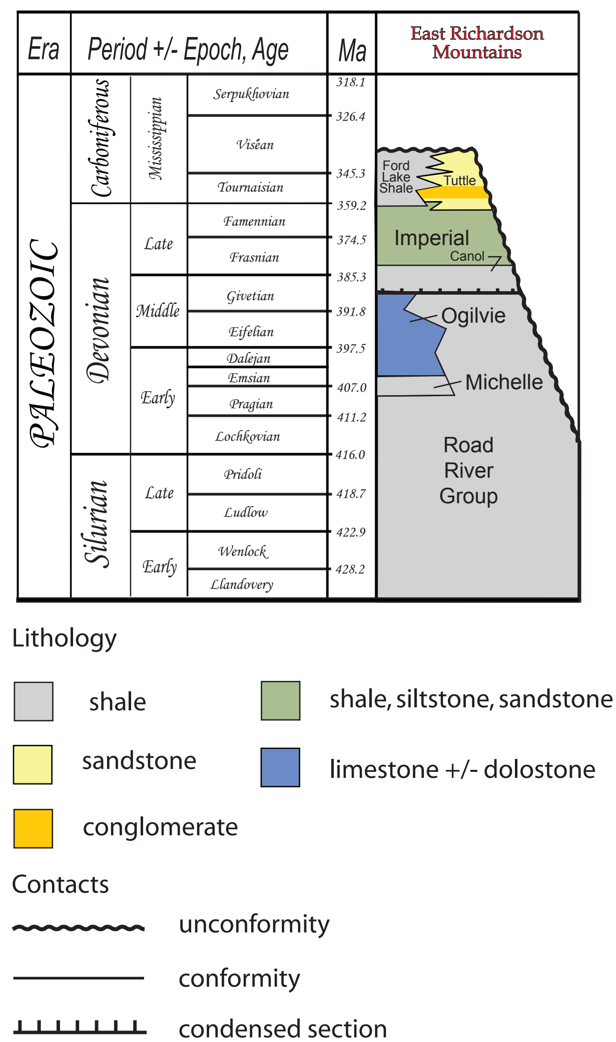

Figure 4. *Stratigraphic column of Silurian to Carboniferous geology of the Richardson Mountains (modified from Morrow, 1999).*

The Middle to Upper Devonian (late Givetian and early Frasnian) Canol Formation (Bassett, 1961) is a grey to black, siliceous thin-bedded, fissile and predominantly non-calcareous shale (Bassett, 1961; Norris, 1985). In the Eagle Plain basin, it ranges in thickness from approximately 4 to 80 m (based on well intersections; Fraser and Hogue, 2007). It is highly organic and is considered a hydrocarbon source rock in the region. In the Richardson Mountains, the Imperial Formation (A.W. Norris, 1997) conformably overlies the Canol Formation.

The Upper Devonian Imperial Formation, originally defined by Link (1921) and formalized by Hume and Link (1945), is a thick package of siliciclastic strata representing shelf, slope and basin deposits derived from the Ellesmerian orogeny (Pugh, 1983; Braman and Hills, 1992). In the western Richardson Mountains, the Imperial Formation consists of three lithologically different units: a lower rusty weathering, siliceous siltstone and shale with minor sandstone; a middle unit dominated by siliceous siltstone, turbiditic sandstone and shale; and an upper portion of light grey weathering, laminated shale and siltstone with thin orange weathering pyritic sandstone beds. The lower portion has been dated in this region as Frasnian to Famennian (Table 3; Braman and Hills, 1992; Dolby, 2010). In the subsurface of Eagle Plain, the Imperial Formation attains a maximum thickness of 1229 m in well intersections, and is overlain, depending on location, either conformably by the Ford Lake Shale or Tuttle Formation or unconformably by Permian or Cretaceous strata (Fraser and Hogue, 2007). Figure 3 displays a cross section of the geology through the Rich property, showing the projected localities of two of the drill holes examined in this study.

STRUCTURE

The Richardson Mountains and Eagle foldbelt comprise local elements of the northern Yukon fold complex that forms a 500 km-long deformed belt extending northward from the Ogilvie Mountains in the south to the Beaufort Sea in the north, and includes the structural salient of the northeastern Brooks Range. The latest Cretaceous and Tertiary deformation that produced this upland complex occurred in multiple pulses (Lane and Dietrich, 1995), with most of the shortening, uplift and cooling occurring in Paleocene to middle Eocene time, based on seismic stratigraphy, biostratigraphy and apatite fission track cooling ages (Lane, 1998). By Late Miocene time the regional tectonic setting had altered to produce broadly northward-directed displacements accommodated by right-lateral strike slip on faults in the Richardson Mountains and east-west trending folds in the offshore Beaufort Foldbelt (Lane and Dietrich, 1995; Mazzotti *et al.,* 2008).

PREVIOUS WORK

The majority of petroleum exploration wells in Eagle Plain were drilled in the 1960s and 1970s, where the Canol Formation, a principal petroleum source rock, is between 2000 and 3000 m deep. Drilling occurred where underlying lower Paleozoic carbonate was interpreted as a prospective conventional hydrocarbon objective, resulting in only eight of 34 wells intersecting the Canol Formation. The depth to the top of the Canol Formation ranges from 761.4 m below kelly bushing (KB) in borehole North Cathedral YT B-62 to 2775 m below KB in Alder YT C-33. The Canol Formation, ranges in thickness from 3.7 to 79 m, based on log responses interpreted in Eagle Plain exploration wells; the Imperial Formation, intersected in 13 wells, is up to 1228.6 m thick (Fraser and Hogue, 2007). However, no wells preserve a complete section of the Imperial Formation. In contrast, the Canol Formation typically varies between 150 and 250 m thick in outcrop along the western flank of the Richardson anticlinorium. Interpretations of limited seismic data from eastern Eagle Plain indicate preserved thickness for the Imperial Formation of up to 3000 m (*e.g.*, Lane, 1996, Fig. 9), but thinning westward, bevelled beneath the sub-Mesozoic unconformity.

The Canol Formation is considered to be the source rock in the Norman Wells oil field of Northwest Territories (Snowdon *et al.*, 1987). Other documented potential Paleozoic petroleum source rocks in Eagle Plain and Peel Plateau include shale of the Road River Group, Bluefish Member of the Hare Indian Formation, Imperial, Tuttle, Hart River, and Blackie formations and Ford Lake Shale (Link, 1988; D.K. Norris, 1997; Morrow, 1999; Allen and Fraser, 2008; Gal *et al.*, 2009). Recently, Rock-Eval and Oil Show Analyzer results obtained from core and well cutting samples were published for selected Eagle Plain wells (Lane *et al.*, 2010), five of which intersected both the Imperial and Canol formations.

Principal petroleum targets in the Eagle Plain basin include the Permian Jungle Creek Formation, Carboniferous Canoe River and Chance Sandstone members of the Hart River Formation (Osadetz *et al.*, 2005). In some wells, cores were cut in the Carboniferous and shallower Permian sections but few core intervals were cut in shale of the

Upper Devonian Imperial or Canol formations during oil and gas exploration in Eagle Plain. Canol Formation core exists for two wells, ranging from 30 cm to 2.74 m thick, while Imperial Formation core exists for five Eagle Plain wells, ranging in thickness from 30 cm to 8.23 m. All core collected from these oil and gas exploration wells are stored at the GSC Core Repository in Calgary, Alberta.

In 2007 and 2008, at the eastern margin of the Eagle Plain basin, a mineral exploration company undertook a diamond drilling program targeting a stratabound nickel-molybdenum (NiMo) occurrence within the Canol Formation. Individual holes penetrated the lowermost Imperial Formation, Canol Formation, and uppermost Road River Group, recovering continuous core up to 565 m long. BTW (42 mm), NQ (47.6 mm), and HQ (63.5 mm) core from this exploration program were used in our analytical study.

METHODS

FIELD WORK

During September 2009, Yukon government and Northern Cross (Yukon) Limited personnel retrieved approximately 1400 m of the core drilled in 2007 and 2008 along the eastern margin of the Eagle Plain basin. This core program by Archer Cathro and Associates (1981) Limited was part of mineral assessment work performed on behalf of their client Southampton Ventures Inc. on the Rich property, an assemblage of mineral claims staked in 2006 by Archer, Cathro. The core was slung by helicopter to Eagle Plains Hotel and then transported by truck to the Geological Survey of Canada, Calgary office, for sample collection and analyses, including age determination, shale gas and petroleum source rock potential. Core salvaged from the sites were selected in order to collect a representative suite of continuous core along the 170 km-long north-south trend of Canol and Imperial formations, preserved at relatively shallow depth parallel to the structural uplift of the Richardson Mountains, allowing for both regional and local variation determination. Results presented here include six separate diamond drill holes all of which are from the Rich property (RI07-02, RI07-07A, RI07-16, RI07-20, RI08-24, and RI08-25). Location information for these holes is provided on Figure 2 and in Table 1.

ANALYTICAL WORK

Preliminary analytical work conducted on the core includes Rock-Eval/TOC, shale mineralogical and palynological determinations. All analyses were undertaken by GSC Calgary. Methods and results are presented here.

i) ROCK EVAL/TOC

Core samples from the Road River Group, Canol and Imperial formations were analysed for source rock determination using a Rock-Eval 6 Turbo pyrolysis apparatus in the Organic Geochemistry Laboratory of the Geological Survey of Canada, Calgary. These analyses provide information on organic matter quantity and quality, thermal maturity, and hydrocarbon potential. The sample spacing in the wells was typically every 10-18 m. As with all samples, the Rock-Eval/TOC samples were selected at a constant spacing measured perpendicular to local bedding, with minor adjustments to ensure suitable lithologies were sampled, and with selective additional sampling near contacts. A bitumen sample was also included in the sample set.

ii) SHALE MINERALOGY

XRD is a common method used to determine the mineral composition of shale, which is important in determining a formation's brittleness or 'fracability'

Table 1. *Summary of diamond drill holes used in this study.*

Diamond Drill Hole	Location (NAD83, Zone 8W)) Easting	Northing	Total Hole Depth (m)	Top - Canol (m)	Top - Road River (m)	Core Size	Azimuth	Dip
RI07-02	445508	7353769	176.79			BTW	090º	-50
RI07-07A	444283	7356805	170.69	24.83	158.67	BTW	070º	-60
RI07-16	443054	7359059	121.92	16.02	91.91	BTW	060º	-75
RI07-20	444880	7356092	189.28	51.30		BTW	060º	-75
RI08-24	443753	7356495	565.71	370		HQ and NQ	090º	-70
RI08-25	444390	7354600	343.50			HQ and NQ	090º	-70

(mechanically-induced fracture development). Sampling for semi-quantitative XRD analyses was carried out on shale samples from the Road River Group, Canol and Imperial formations at a typical spacing of 25 m measured perpendicular to bedding, with some additional samples collected in the vicinity of contacts. The XRD analyses were run on a Philips PW1700 powder diffraction system with cobalt x-ray source. All analyses were run on powder mounted samples, and executed by the PANalytical X'Pert Quantify software. Mineral determination was processed by PANalytical's X'pert Highscore program, and the quantification of minerals within samples was calculated from their mineral peak intensities (or peak area). Whole rock results are semi-quantitative and are expressed in mineral ratio percent. Total quartz (including chert), total carbonate, and total clay percentages were summed and recalculated out of 100% based on the XRD analyses, and plotted as ternary diagrams (Fig. 6).

iii) PALYNOLOGY

In addition to the organic geochemistry and mineralogy, additional samples were processed for biostratigraphy (palynology) at approximately 50 m intervals, measured perpendicular to local bedding. Thirteen core samples from the 66.9-565 m interval of diamond drill holeRI08-24 were analysed for palynology, spanning the Canol and Imperial formations. The Road River Group was not sampled for palynology.

PRELIMINARY RESULTS

i) ROCK EVAL/TOC

Table 2 summarizes the Rock-Eval/TOC results. Guidelines for interpreting these data are provided in several publications (Espitalié *et al*., 1985; Peters, 1986; Lafargue *et al*., 1998). In interpreting the results, it should be noted that Rock-Eval/TOC parameters have significance only above threshold S1, S2 and TOC values, otherwise all parameters have questionable meaning.

The Rock-Eval derived T_{max} values for all samples range between 271°C and 610°C. Of note are S1 and S2 yields approaching zero which indicate that all the available hydrocarbons have been produced (overmature) and that the T_{max} values are unreliable (Peters, 1986). These T_{max} values correspond to vitrinite Ro (random) values between 2.0 and 3.1% (Tissot and Welte, 1984). S2 pyrolysis yields of less than 0.2 mg HC/g rock render meaningless other hydrocarbon indicators such as Hydrogen Index (HI).

Nonetheless, TOC values in the Road River Group and Canol Formation are typically higher than those reported for the Imperial Formation. TOC values for the Road River Group and Canol Formation range from 0.31 to 7.31 wt%, but typically fall in the 2-5% range; whereas TOC values in the Imperial are typically below 1% and therefore suggest poor source rock potential (Fig. 5).

The high residual TOC values for the Road River Group and Canol Formation samples indicate that the initial TOC values were originally much higher. For Type II organic matter, hydrocarbon utilizes roughly half of the initial TOC (Tissot and Welte, 1984). Using this rule of thumb, the initial TOC of the Road River and Canol Formation in this area was typically in the 5-10% range, locally approaching 15%. These findings document that these units were excellent source rocks in the past, consistent with what is already well known for the formation beneath the Interior Platform to the southeast, where the Canol is identified as the principal source unit for the Norman Wells oil.

ii) MINERALOGY RESULTS

Each of the units studied has a distinct mineralogical composition (Fig. 6). XRD results suggest that shale in the Canol Formation is highly siliceous, typically exceeding 95% quartz, whereas the silty shale of the Imperial Formation shows a more varied lithology with up to 17% clay minerals (phyllosilicates) and less than 6% carbonate. Road River Group strata also have a more varied lithology, but are less clay-rich than the Imperial Formation with up to 36% carbonate. Two carbonate-rich samples from the Imperial Formation including one dolomite-rich sample (45% carbonate) and one siderite concretion (55% carbonate) are also presented in Figure 6. Results of XRD analyses are listed in Table 4. Caution should be used with these results as the amount of quartz tends to be overestimated and clay underestimated in many shale samples using standard XRD techniques (Spencer *et al*., 2010).

Determination of shale mineralogy can be used as a first approximation in determining whether shale is 'fracable', however, other shale characteristics such as fabric may be even more important than mineralogy in determining the mechanical and flow properties of shale (Spencer *et al*., 2010). This study assessed only the mineralogy of the shale sampled, with the premise that 'fracable' shale contains higher proportions of brittle minerals such as quartz, and lesser proportions of more ductile minerals such as phyllosilicates. An initial observation is that shales of the

Table 2. *Summary of Rock-Eval/TOC data from six diamond drill holes. Parameters measured and derived from Rock-Eval pyrolysis include TOC = total organic carbon as percent weight of whole rock; S1 = mg hydrocarbons/g rock; S2 = mg hydrocarbons/g rock; S3 = mg CO2/g rock; PI = Production Index (S1/S1+S2); HI = Hydrogen Index (100x(S2/TOC)); OI = Oxygen Index (100x(S3/TOC)); Tmax = maximum temperature (°C) at top of S2 peak. Note where S2 values are less than 0.2 mg HC/g rock, the PI and Tmax values are unreliable. Bitumen sample is highlighted.*

Sample	GSC Curation #	Downhole Depth (m)	Formation	S1	S2	PI	S3	Tmax	TOC	HI	OI
R107-02-1	C-491561	105.60	Road River	0.01	**0.10**	0.10	0.24	608	**6.06**	2	4
R107-02-2	C-491562	90.00	Road River	0.01	**0.07**	0.17	0.24	428	**2.40**	3	10
R107-02-3	C-491563	75.80	Road River	0.02	**0.10**	0.16	0.35	343	**2.68**	4	13
R107-02-4	C-491564	58.70	Road River	0.02	**0.12**	0.15	0.21	534	**3.43**	3	6
R107-02-5	C-491565	44.70	Road River	0.02	**0.08**	0.19	0.78	606	**2.53**	3	31
R107-02-6	C-491566	34.00	Road River	0.02	**0.08**	0.19	0.43	607	**2.27**	4	19
R107-07A-1	C-491515	166.50	Road River	0.01	**0.02**	0.25	0.10	316	**2.44**	1	4
R107-07A-2	C-491516	140.21	Canol	0.01	**0.05**	0.12	0.08	610	**3.73**	1	2
R107-07A-3	C-491517	127.50	Canol	0.01	**0.04**	0.23	0.09	611	**3.60**	1	3
R107-07A-4	C-491518	114.80	Canol	0.01	**0.03**	0.21	0.07	357	**2.43**	1	3
R107-07A-5	C-491519	102.30	Canol	0.00	**0.01**	0.26	0.07	343	**2.42**	0	3
R107-07A-6	C-491520	91.00	Canol	0.00	**0.02**	0.20	0.09	611	**3.61**	1	2
R107-07A-7	C-491521	78.10	Canol	0.01	**0.02**	0.20	0.15	340	**4.71**	0	3
R107-07A-10	C-491524	63.20	Canol	0.00	**0.02**	0.19	0.10	513	**5.65**	0	2
R107-07A-11	C-491525	50.60	Canol	0.01	**0.03**	0.19	0.13	421	**3.66**	1	4
R107-07A-12	C-491526	37.80	Canol	0.01	**0.02**	0.26	0.18	389	**5.12**	0	4
R107-16-1	C-491554	121.92	Road River	0.01	**0.04**	0.19	0.14	607	**1.57**	3	9
R107-16-2	C-491555	103.10	Road River	0.02	**0.03**	0.32	0.17	607	**1.60**	2	11
R107-16-3	C-491556	86.00	Canol	0.01	**0.02**	0.29	0.11	606	**2.53**	1	4
R107-16-4	C-491557	72.90	Canol	0.01	**0.05**	0.16	0.10	606	**3.51**	1	3
R107-16-5	C-491558	58.50	Canol	0.01	**0.04**	0.20	0.13	607	**4.83**	1	3
R107-16-6	C-491559	42.00	Canol	0.01	**0.05**	0.19	0.13	606	**3.76**	1	3
R107-16-7	C-491560	25.50	Canol	0.01	**0.04**	0.20	0.09	522	**2.11**	2	4
R107-20-1	C-491567	185.93	Canol?	0.02	**0.07**	0.21	0.23	604	**2.92**	2	8
R107-20-2	C-491568	169.26	Canol?	0.02	**0.08**	0.23	0.21	606	**1.74**	5	12
R107-20-3	C-491569	152.59	Canol	0.04	**0.10**	0.29	0.30	607	**3.64**	3	8
R107-20-4	C-491570	135.92	Canol	0.02	**0.11**	0.13	0.24	606	**3.32**	3	7
R107-20-5	C-491571	119.25	Canol	0.01	**0.04**	0.14	0.11	607	**3.72**	1	3
R107-20-6	C-491572	102.58	Canol	0.01	**0.03**	0.18	0.20	607	**3.60**	1	6
R107-20-7	C-491573	85.91	Canol	0.00	**0.02**	0.16	0.12	489	**2.40**	1	5
R108-24-1	C-486467	565.00	Canol	0.01	**0.03**	0.17	0.04	420	**1.64**	2	2
R108-24-3	C-486469	546.50	Canol	0.01	**0.06**	0.13	0.47	606	**2.69**	2	17
R108-24-4	C-486470	531.30	Canol	0.01	**0.02**	0.17	0.11	608	**7.31**	0	2
R108-24-5	C-486471	521.30	Canol	0.01	**0.04**	0.16	0.27	371	**4.61**	1	6
R108-24-6	C-486472	511.70	Canol	0.01	**0.04**	0.17	0.49	383	**3.69**	1	13
R108-24-7	C-486473	507.70	Canol	0.01	**0.03**	0.16	0.06	386	**4.17**	1	1
R108-24-8	C-486474	494.50	Canol	0.00	**0.00**	0.28	0.17	541	**5.01**	0	3
R108-24-9	C-486475	483.25	Canol	0.00	**0.04**	0.08	0.15	609	**0.31**	13	48
R108-24-10	C-486476	477.50	Canol	0.01	**0.03**	0.17	0.04	357	**2.81**	1	1
R108-24-12	C-486479	458.80	Canol	0.00	**0.02**	0.10	0.00	609	**3.08**	1	0
R108-24-13	C-486480	441.00	Canol	0.01	**0.05**	0.12	0.00	446	**3.42**	1	0
R108-24-14	C-486481	425.00	Canol	0.01	**0.03**	0.15	0.00	606	**2.76**	1	0
R108-24-15	C-486482	408.75	Canol	0.01	**0.04**	0.13	0.11	394	**2.61**	2	4
R108-24-16	C-486483	401.70	Canol	0.01	**0.03**	0.17	0.25	609	**6.45**	0	4
R108-24-17	C-486484	393.00	Canol	0.01	**0.03**	0.16	0.06	610	**3.42**	1	2
R108-24-18	C-486485	384.30	Canol	0.00	**0.02**	0.15	0.21	609	**3.70**	1	6

Table 2 continued

Sample	GSC Curation #	Downhole Depth (m)	Formation	S1	S2	PI	S3	Tmax	TOC	HI	OI
R108-24-19	C-486486	376.20	Canol	0.01	**0.04**	0.15	0.11	608	**2.69**	1	4
R108-24-20	C-486487	366.80	Imperial?	0.01	**0.03**	0.13	0.00	537	**1.12**	3	0
R108-24-21	C-486488	360.00	Imperial	0.00	**0.03**	0.10	0.34	568	**0.72**	4	47
R108-24-22	C-486489	345.70	Imperial	0.00	**0.03**	0.12	0.01	359	**0.83**	4	1
R108-24-23	C-486490	330.85	Imperial	0.00	**0.03**	0.10	0.09	609	**0.91**	3	10
R108-24-24	C-486491	316.00	Imperial	0.00	**0.03**	0.09	0.12	608	**0.94**	3	13
R108-24-26	C-486493	302.80	Imperial	0.01	**0.03**	0.13	0.09	609	**0.89**	3	10
R108-24-27	C-486494	287.30	Imperial	0.00	**0.03**	0.11	0.00	607	**0.76**	4	0
R108-24-28	C-486495	273.20	Imperial	0.00	**0.02**	0.10	0.06	607	**0.79**	3	8
R108-24-29	C-486496	258.90	Imperial	0.01	**0.06**	0.10	0.21	499	**0.73**	8	29
R108-24-30	C-486497	244.10	Imperial	0.00	**0.02**	0.10	0.07	605	**0.88**	2	8
R108-24-31	*C-486498*	*236.20*	*Imperial*	*0.09*	***3.04***	*0.03*	*0.94*	*608*	***97.96***	*3*	*1*
R108-24-33	C-486500	230.00	Imperial	0.00	**0.03**	0.11	0.06	609	**0.85**	4	7
R108-24-34	C-491501	214.30	Imperial	0.00	**0.03**	0.12	0.04	609	**0.76**	4	5
R108-24-36	C-491503	199.00	Imperial	0.01	**0.03**	0.17	0.18	385	**3.09**	1	6
R108-24-37	C-491504	184.50	Imperial	0.01	**0.04**	0.12	0.33	609	**0.83**	5	40
R108-24-38	C-491505	170.50	Imperial	0.00	**0.03**	0.10	0.06	608	**0.79**	4	8
R108-24-39	C-491506	155.00	Imperial	0.00	**0.02**	0.11	0.09	609	**0.77**	3	12
R108-24-40	C-491507	141.50	Imperial	0.01	**0.03**	0.15	0.01	607	**0.79**	4	1
R108-24-41	C-491508	129.60	Imperial	0.01	**0.18**	0.04	0.10	436	**0.81**	22	12
R108-24-42	C-491509	111.40	Imperial	0.01	**0.05**	0.22	0.05	334	**0.87**	6	6
R108-24-43	C-491510	96.32	Imperial	0.00	**0.03**	0.14	0.05	609	**0.82**	4	6
R108-24-44	C-491511	86.20	Imperial	0.01	**0.04**	0.17	0.00	601	**1.21**	3	0
R108-24-45	C-491512	66.90	Imperial	0.00	**0.03**	0.13	0.00	609	**0.79**	4	0
R108-24-46	C-491513	52.00	Imperial	0.00	**0.02**	0.15	0.03	610	**0.66**	3	5
R108-24-47	C-491514	39.30	Imperial	0.00	**0.01**	0.15	0.11	609	**0.73**	1	15
R108-25-1	C-491574	343.51	Imperial	0.01	**0.04**	0.23	0.09	605	**0.76**	5	12
R108-25-2	C-491575	329.10	Imperial	0.02	**0.04**	0.35	0.10	292	**0.82**	5	12
R108-25-3	C-491576	314.70	Imperial	0.01	**0.04**	0.15	0.06	606	**0.71**	6	8
R108-25-4	C-491577	300.60	Imperial	0.01	**0.03**	0.26	0.08	607	**0.90**	3	9
R108-25-5	C-491578	286.50	Imperial	0.02	**0.04**	0.33	0.08	607	**0.80**	5	10
R108-25-7	C-491580	271.00	Imperial	0.01	**0.05**	0.21	0.11	607	**2.13**	2	5
R108-25-8	C-491581	255.70	Imperial	0.01	**0.04**	0.26	0.07	605	**0.71**	6	10
R108-25-9	C-491582	240.40	Imperial	0.02	**0.04**	0.35	0.09	605	**0.78**	5	12
R108-25-10	C-491583	225.10	Imperial	0.01	**0.03**	0.25	0.14	422	**0.85**	4	16
R108-25-11	C-491584	209.70	Imperial	0.01	**0.02**	0.27	0.09	607	**0.76**	3	12
R108-25-12	C-491585	194.40	Imperial	0.01	**0.04**	0.17	0.08	606	**2.16**	2	4
R108-25-13	C-491586	179.10	Imperial	0.01	**0.04**	0.23	0.12	434	**0.76**	5	16
R108-25-14	C-491587	163.80	Imperial	0.01	**0.03**	0.14	0.06	607	**0.76**	4	8
R108-25-15	C-491588	148.50	Imperial	0.01	**0.06**	0.15	0.16	607	**0.74**	8	22
R108-25-16	C-491589	134.50	Imperial	0.02	**0.03**	0.37	0.11	473	**0.74**	4	15
R108-25-17	C-491590	120.50	Imperial	0.01	**0.05**	0.21	0.11	605	**0.75**	7	15
R108-25-18	C-491591	105.50	Imperial	0.11	**0.08**	0.59	0.10	334	**0.71**	11	14
R108-25-19	C-491592	91.50	Imperial	0.06	**0.09**	0.41	0.14	271	**0.72**	12	19
R108-25-20	C-491593	77.50	Imperial	0.01	**0.02**	0.43	0.16	607	**0.57**	4	28
R108-25-21	C-491594	63.50	Imperial	0.01	**0.02**	0.23	0.08	606	**0.60**	3	13
R108-25-22	C-491595	49.50	Imperial	0.01	**0.03**	0.30	0.06	607	**0.67**	4	9

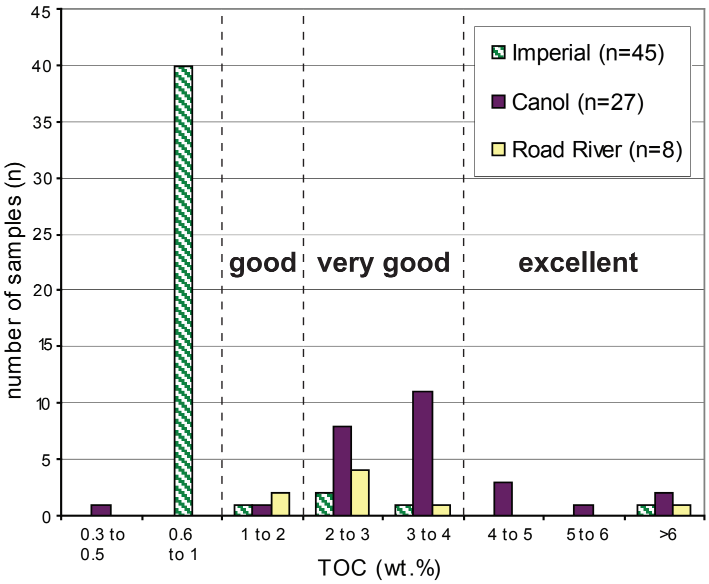

Figure 5. *Histogram summarizing total organic carbon (TOC), expressed in weight percent (wt%), from samples collected during this study of the Road River Group, Canol and Imperial formations. The TOC categories (good to excellent) correspond with source rock generative potential (Peters, 1986). See Table 2 for corresponding dataset.*

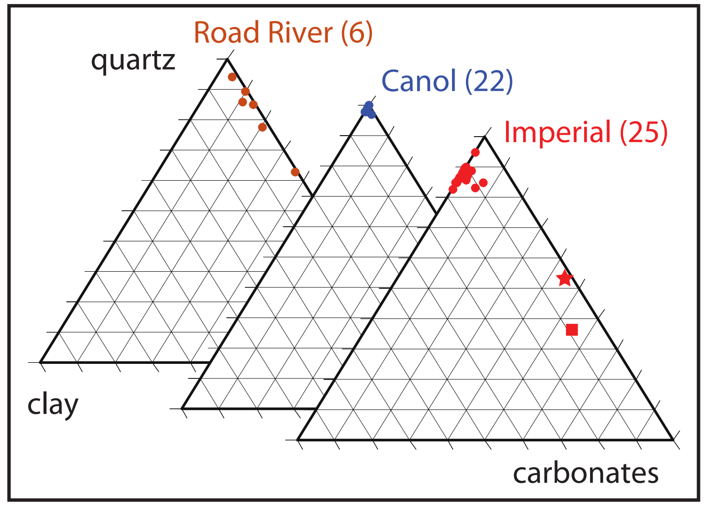

Figure 6. *Ternary diagram displaying the relative mineralogical composition of Road River Group, Canol and Imperial formations shale. The square represents the iron carbonate concretion sample; the star represents a dolomite-rich sample from the Imperial Formation. The corresponding data are in Table 4.*

Canol Formation have the best prospects for fracability when compared to the Imperial Formation and Road River Group. Enhancing this study with thin section examination utilizing a scanning electron microscope (SEM) would provide a more comprehensive understanding of the mechanical properties of the shale.

iii) PALYNOLOGY

Due to very high thermal maturities throughout the section, very few palynomorphs could be identified from the Canol and Imperial formations. Spores were abundant in some samples, however most of them are opaque and unidentifiable (Dolby, 2010). Palynomorphs and chitinozoa fragments suggest the Canol Formation is Middle to Late Devonian in age. Spores identified in Imperial strata are characteristic of undifferentiated Frasian to mid Famennian species (Dolby, 2010). Results are summarized in Table 3.

SUMMARY AND DISCUSSION

Retrieval of diamond drill core from the Road River Group, Imperial and Canol formations on the western flank of the Richardson Mountains has provided an opportunity to examine relatively 'fresh' rock for the purpose of assessing shale gas potential in the region.

The Canol Formation sampled in the Rich property diamond drill holes is highly siliceous, organic-rich, and contains Middle to Late Devonian palynomorphs. The overlying lowermost Imperial Formation is siltier, less organic-rich, and less siliceous than the Canol, and is dated as Frasnian to mid Famennian in age based on palynology. Road River Group shale is organic-rich and the least siliceous of all strata examined. The thermal maturity of all strata studied is very high, with corresponding vitrinite reflectance values in the range of 2-3%. Thermal maturity data indicate that the hydrocarbon generative potential of these rocks has been exhausted and the remaining organic carbon is inert.

The influence of Laramide orogenesis and associated heat flow along the western margin of the Richardson uplift is likely greater than occurs in the more stable setting of the Eagle Plain basin further to the west, where thermal maturities have been established as much lower or even immature for hydrocarbon generation. Somewhere between these extremes, shale gas potential seems likely to be present. Previous studies of Canol and Imperial strata have indicated that the thermal maturity is less extreme

Table 3. *Summary of palynological data from diamond drill hole RI08-24 for the Canol and Imperial formations. Dolby (2010) completed the identifications and assignments.*

Sample ID	GSC Curation #	Unit	Downhole Depth (m)	Probable ages based on palynology
RI08-24-1	C486467	Canol	565.00	Middle Devonian (chitinozoans)
RI08-24-8	C486474	Canol	494.50	Middle Devonian (chitinozoans)
RI08-24-16	C486483	Canol ?	401.70	Middle to Late Devonian undifferentiated
RI08-24-18	C486485	Canol ?	384.30	Middle to Late Devonian undifferentiated
RI08-24-19	C486486	Canol ?	376.20	Middle to Late Devonian undifferentiated
RI08-24-20	C486487	Imperial	366.80	Late Devonian - Frasnian to mid Famennian
RI08-24-21	C486488	Imperial	360.00	Late Devonian - Frasnian to mid Famennian
RI08-24-26	C486493	Imperial	302.80	Late Devonian - Frasnian to mid Famennian
RI08-24-30	C486497	Imperial	244.10	Late Devonian - Frasnian to mid Famennian
RI08-24-37	C491504	Imperial	184.50	Late Devonian - Frasnian to mid Famennian
RI08-24-41	C491508	Imperial	129.60	Late Devonian - Frasnian to mid Famennian
RI08-24-45	C491512	Imperial	66.90	Late Devonian - Frasnian to mid Famennian

to the west in Eagle Plain, where cuttings samples have yielded Ro (random) and equivalent values varying about 1% in several petroleum exploration wells, suggesting the strata are within the oil window at the basal Imperial and Canol stratigraphic level (Link, 1988; Link and Bustin, 1989; Lane *et al*., 2010). In the Link and Bustin (1989) study, the apparent lack of a maturity discontinuity at the sub-Cretaceous unconformity indicates that the thermal peak was achieved in post-Cretaceous time. However, a lesser, earlier thermal peak is not precluded by the data. The occurrence of immobile pyrobitumen in fractures indicates that hydrocarbons were previously produced and mobilized into the fractures prior to the thermal peak, thus supporting the possibility of an earlier thermal event.

Stratigraphic evidence in Eagle Plain as well as fission track cooling ages from widespread localities across the region (Lane, 1998; O'Sullivan and Lane, 1997) indicate that the dominant uplift/cooling event in the region was latest Cretaceous to Eocene in age, and that inversion of the Richardson trough and uplift of the Richardson anticlinorium was accommodated on outward-directed thrust faults (Lane, 1996). Thermal maturation levels are distinctly higher on the upthrown sides of those faults, which juxtaposed older strata from deeper crustal levels against younger, cooler strata at that time. A candidate mechanism for possible earlier burial and thermal maturation lies in the Late Devonian and Early Carboniferous deposition of some 2-4 km of Ellesmerian foredeep clastic rocks across the Eagle Plain – Richardson trough – Peel Plateau region (Lane, 2010).

Due to the very high thermal maturity (T_{max}) of the cored section, the mineralogy data are the most valuable for shale gas evaluation purposes. High quartz percentages and total organic carbon contents in the Canol Formation suggest that this formation may be the most prospective in terms of shale gas potential, although further studies are required to assess its full potential. The high silica content of these shales is more favourable for fracing the rock than more clay-rich rocks of the Imperial Formation.

Further results are anticipated regarding thermal maturity based on vitrinite reflectance data. These data combined with data from other mineral exploration properties extending over a 170 km length will be presented in supplementary publications.

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Table 4. *XRD semi-quantitative analysis (expressed in mineral ratio percent) of black shale core samples. One sample is an iron carbonate concretion (highlighted in grey) (see Fig. 6).*

Sample ID	GSC Curation #	M.L.C.*	Mica / Illite	Clinochlore	Gypsum	Quartz	Feldspars	Calcite	Dolomite	Pyrite	Siderite	Others	Total Carbonate	Total Clays	Unit	Depth (m)
RI07-02-1	C491561		1			81	1	14		1		Sphalerite?-2	14	1	Road River	105.60
RI07-02-3	C491563		2			75		19	1	3			20	2	Road River	75.80
RI07-02-5	C491565		3		3	81		11		2			11	3	Road River	44.70
RI07-07A-1	C491515		2			92		4		2			4	2	Road River	166.50
RI07-07A-2	C491516		1			96	1(K)	1		1			1	1	Canol	140.21
RI07-07A-4	C491518		2			95				3			0	2	Canol	114.80
RI07-07A-5	C491519	trace	1			94				5			0	1	Canol	102.30
RI07-07A-6	C491520		1		trace	96		trace	1	2			1	1	Canol	91.00
RI07-07A-10	C491524		2		2	88				8			0	2	Canol	63.20
RI07-07A-12	C491526		1		1	90				8			0	1	Canol	37.80
RI07-16-1	C491554		1			88		10		1			10	1	Road River	121.92
RI07-16-2	C491555		1			61		34	2	2			36	1	Road River	103.10
RI07-16-3	C491556		1			98	trace			1			0	1	Canol	86.00
RI07-16-5	C491558		2			92	2(K)			4			0	2	Canol	58.50
RI07-16-7	C491560		2			95	trace			3			0	2	Canol	25.50
RI07-20-1	C491567		2			96				2			0	2	Canol?	185.93
RI07-20-3	C491569		1			96				2	1	Siderite?-1%	1	1	Canol	152.59
RI07-20-5	C491571		1		trace	98				1			0	1	Canol	119.25
RI07-20-7	C491573		1		1	95				3			0	1	Canol	85.91
RI08-24-1	C486467		trace			99				1			0	0	Canol	565.00
RI08-24-4	C486470		1			93				5		Rutile?-1%	0	1	Canol	531.30
RI08-24-7	C486473		1			93				6			0	1	Canol	507.70
RI08-24-8	C486474		1			95				4			0	1	Canol	494.50
RI08-24-12	C486479		trace			95				4		Hercynite?-1%	0	0	Canol	458.80
RI08-24-14	C486481		1			93				5		Gahnite(ferroan)?-1%	0	1	Canol	425.00
RI08-24-16	C486483		2			91				6		Anhydrite-1%	0	2	Canol ?	401.70
RI08-24-17	C486484		2			96				2			0	2	Canol ?	393.00
RI08-24-18	C486485		2		trace	95				3		Hercynite?-trace	0	2	Canol ?	384.30
RI08-24-19	C486486		1			95			2	2			2	1	Canol ?	376.20
RI08-24-20	C486487	trace	5			88	trace			7			0	5	Imperial	366.80
RI08-24-21	C486488		2			45		2	36	15			38	2	Imperial	360.00
RI08-24-23	C486490	3	3	2		81	2(Na)		4	2	3	Siderite-3%	7	8	Imperial	330.85
RI08-24-25	*C486492*	*2*	*2*	*5*		*36*					*55*	*Siderite-55%*	*55*	*9*	*Imperial*	315.20
RI08-24-26	C486493	3	4	4		85				2	2	Siderite-2%	2	11	Imperial	302.80
RI08-24-28	C486495	3	5	7		83				2			0	15	Imperial	273.20
RI08-24-30	C486497	3	4	7		84				2			0	14	Imperial	244.10
RI08-24-34	C491501	3	4	4		87				2			0	11	Imperial	214.30
RI08-24-37	C491504	3	4	10		81				2			0	17	Imperial	184.50
RI08-24-39	C491506	3	4	5		86				2			0	12	Imperial	155.00
RI08-24-41	C491508	3	4	8		82				3			0	15	Imperial	129.60
RI08-24-43	C491510	2	2	5		85	2(Na)		2	2			2	9	Imperial	96.32
RI08-24-45	C491512	2	3	6		84	3(Na)		1	1			1	11	Imperial	66.90

Table 4 continued.

Sample ID	GSC Curation #	M.L.C.*	Mica / Illite	Clinochlore	Gypsum	Quartz	Feldspars	Calcite	Dolomite	Pyrite	Siderite	Others	Total Carbonate	Total Clays	Unit	Depth (m)
RI08-24-47	C491514	2	3	5	trace	84	4(Na)			2			0	10	Imperial	39.30
RI08-25-1	C491574	3	4	6		85				2			0	13	Imperial	343.51
RI08-25-3	C491576	3	3	7		83	2(Na)			2			0	13	Imperial	314.70
RI08-25-5	C491578	3	4	6		85	trace			2			0	13	Imperial	286.50
RI08-25-8	C491581	3	4	7		84	trace			2			0	14	Imperial	255.70
RI08-25-10	C491583	2	3	6		86				3			0	11	Imperial	225.10
RI08-25-12	C491585	3	3	3		84			2	5		Fe-dolomite	2	9	Imperial	194.40
RI08-25-14	C491587	2	3	7		82	2(Na)		2	2		Fe-dolomite	2	12	Imperial	163.80
RI08-25-16	C491589	2	3	5		87				3			0	10	Imperial	134.50
RI08-25-18	C491591	2	3	5		85	3(Na)			2			0	10	Imperial	105.50
RI08-25-20	C491593	2	3	6		81	trace			2	6	Siderite-6%	6	11	Imperial	77.50
RI08-25-22	C491595	2	3	9		82	2(Na)			2			0	14	Imperial	49.50

* M.L.C means Mixed Layer Clays

Iron carbonate concretion

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