Field descriptions of the Middle-Upper Devonian Canol Formation on Trail River, east Richardson Mountains, Yukon

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ABSTRACT

The Middle–Upper Devonian Canol Formation is the focus of a new study by the Yukon Geological Survey in north Yukon. Fieldwork in summer 2013 involved locating, measuring, and sampling Canol Formation strata in the Richardson and northern Ogilvie mountains. In June, 229 m of Canol Formation strata were measured on the Trail River, eastern Richardson Mountains (NTS 106L/6). The Canol Formation at this location is entirely exposed, except for ~2 m at its upper contact with the overlying Imperial Formation. On Trail River, the Canol Formation is a resistant, silica-rich unit that is characterized by rhythmically bedded siliceous shale and chert comprising four lithofacies: 1) siliceous shale; 2) chert; 3) siliceous shale (>50%) and chert (10-50%); and 4) chert (>70%) and siliceous shale (10-30%). Siliceous shale is fissile, finely laminated in beds up to 10 cm thick, and may be either soft and recessive or hard and resistant. Chert exhibits conchoidal fracture and occurs in beds up to 16 cm thick. Both shale and chert are black in color on fresh surfaces, and weather grey to black, olive grey, brown with a distinct yellowish orange, dark red, and/or very minor apple-green weathering residue. The lower contact of the Canol Formation with Road River Group calcareous shale is sharp, and marked by a concretionary bed overlain by a thin (<1 m) weathered mineralized zone. This mineralized zone may be in-part correlative with the Ni-Zn-PGE "Nick" horizon observed in the region. A marked lithology change occurs from the Canol to the Imperial formation which consists of weathered mudstones with a significantly lower silica content. Concretions up to 2.5 m long were observed in the Canol Formation but possible fossils were only observed at two locations where unidentified impressions on a bedding surface could be biological (or mineralogical). Fine-grained pyrite occurs throughout the formation, either as disseminated grains, in thin laminations (mm-scale), and rarely in concretionary horizons. The sampling program involved spectral gamma-radiation readings at one-metre intervals, and chip samples through two-metre intervals for Rock-Eval/total organic carbon (RE/TOC) and inductively coupled plasma-emissions/mass spectroscopy lithogeochemistry (ICP-ES/MS). Targeted samples for microfossil biostratigraphy, vitrinite reflectance, and XRD mineralogy were also collected. Laboratory results are anticipated in 2014.

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INTRODUCTION

The Canol Formation is a Middle-Upper Devonian shale and chert unit that is present in Northwest Territories (NWT and Yukon. Previous studies have identified it as a potential hydrocarbon source rock, but its lithology, geochemistry, age, stratigraphic relationships, and distribution in Yukon have not been systematically described. This paper presents descriptions of a near-complete stratigraphic section of the Canol Formation in the eastern Richardson Mountains, measured in summer 2013. The section is part of a larger project to characterize and correlate the Canol Formation within Yukon and to assess the formation's regional hydrocarbon potential, both as a source rock and a shale reservoir. This study is timely as the Canol Formation is currently being explored as an unconventional hydrocarbon resource in NWT's central Mackenzie Valley.

SECTION LOCATION AND REGIONAL GEOLOGY

The Canol Formation outcrop described in this paper is situated on the north bank of the Trail River, a tributary of the Peel River, on the eastern flank of the southern Richardson Mountains (NTS 106L/6; start of section at UTM 477796 E; 7366173 N; all UTM locations in this paper are NAD 83 Zone 8W; Fig. 1).

The Richardson Mountains coincide with the location of the former early to middle Paleozoic Richardson trough (Lenz, 1972). The trough was a north-south oriented deep water sedimentary basin flanked by carbonate shelves, Mackenzie Platform to the east (Lenz, 1972), and Porcupine Platform to the west (Jeletzky, 1962), that existed from Cambrian to Devonian time. Early Paleozoic deposition in the trough is recorded by the Road River

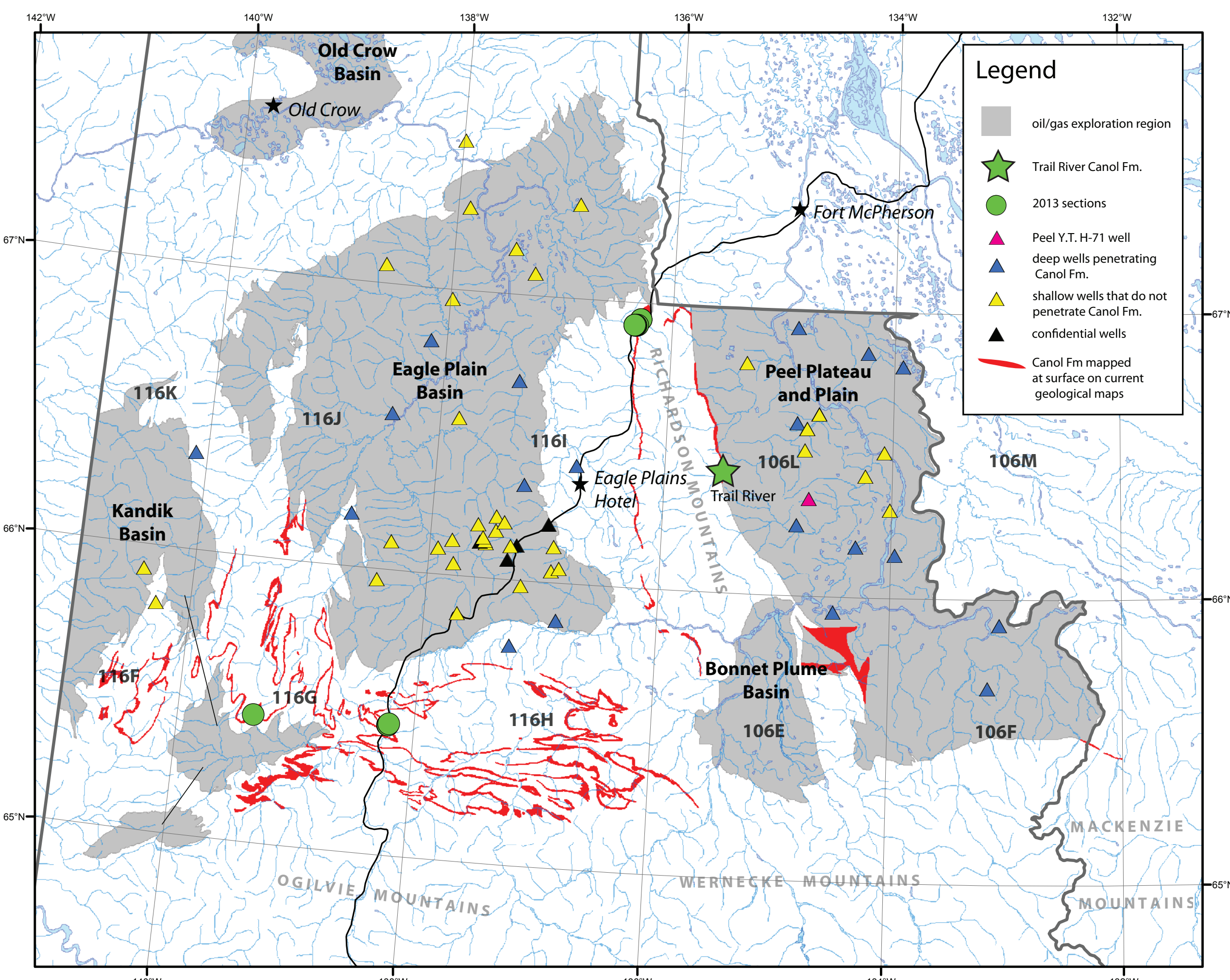


Figure 1. *Map of part of northern Yukon showing the location of 2013 measured sections with respect to the surface extent of Canol Formation (after Gordey and Makepeace, 2003), Yukon oil and gas exploration regions, and oil and gas exploration wells.*

Formation (Jackson and Lenz, 1962), a thick succession of graptolitic shale and argillaceous limestone. Post-Richardson trough deposits comprise the Middle-Upper Devonian Canol Formation basinal shale and chert, together with an overlying wedge of Upper Devonian–Mississippian, marine, siliciclastic strata of the Imperial, Tuttle, and Ford Lake Shale formations. Provenance for this succession was from a northern orogenic source area (Ellesmerian orogeny; Pugh 1983; Lane, 2007). The trough was inverted into a faulted, north-plunging anticlinorium by the reactivation of Paleozoic faults in Late Cretaceous and Tertiary time (Norris, D.K., 1997), resulting in the mountain range observed today.

THE CANOL FORMATION

TYPE SECTION

The Canol Formation was proposed by Bassett (1961) for black shale on the northeast flank of the Mackenzie Mountains in NWT that overlies either the Middle Devonian Ramparts or Hare Indian formations. The type section for the Canol Formation is at Powell Creek, NWT (65° 16′30″N; 128°46′30″W), where it comprises 23 m of grey to black, soft to hard, non-calcareous shale that is covered with a green and yellow weathering residue. The formation was named after Camp Canol, an abandoned military camp located on the shore of the Mackenzie River across from Norman Wells, which served as a supply camp for the construction of the Canol Road during World War II.

DISTRIBUTION AND THICKNESS

From the type section in NWT, the Canol Formation shale has been traced west-northwestwardly along the Mackenzie Mountain front to the Snake River area, along both flanks of the Richardson Mountains and westwardly along the northern Ogilvie Mountains to the Alaska border (Norris, A.W., 1997; Norris, 1981a,b; 1982a,b,c,d,e,f).

The Canol Formation has previously been mapped at surface in Yukon on NTS mapsheets 116 F, G, H, I, J, and 106 E, F, and L (Fig. 1); however, reconnaissance helicopter surveys as part of this study have determined that Canol surface exposures are rare. In the subsurface, Canol Formation strata were intersected in oil and gas exploration wells in and near Eagle Plain Basin, Peel Plateau and Plain, and northeast of Kandik Basin (Fraser and Hogue, 2007; Fig. 1). Subsurface interpretation of Yukon well logs suggests Canol strata range between 6 and 79 m thick in the Peel Plateau and Plain, and between 4 and 79 m thick in the subsurface of Eagle Plain. Canol Formation shale is inferred to be 271 m thick in one well northeast of Kandik Basin (Fraser and Hogue, 2007).

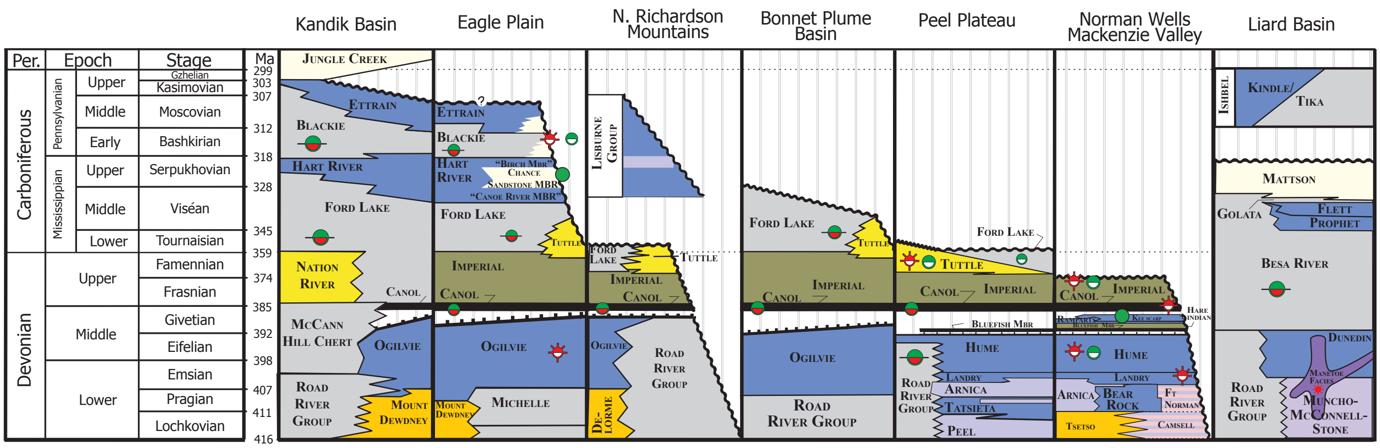
STRATIGRAPHY

In Yukon, the Canol Formation overlies either Middle Devonian carbonate of the Ogilvie and Hume formations (Norris, 1967; Norris, 1982a,b), or in the Richardson Mountains, by Road River Group limestone and shale (Cecile *et al.*, 1982; Morrow, 1999; Norris, 1982e; Fig. 2). The basal contact of the Canol Formation has been described as unconformable/disconformable (*e.g.*, Norris, 1985; Kunst, 1973; Bassett and Stout, 1967; Norris, 1968) or conformable (*e.g.*, Williams, 1983; Morrow, 1999). In Richardson Mountains, the contact between the Road River Group and Canol Formation is marked by metre-scale ironstone concretions and Ni-Zn-PGE mineralization called the “Nick” zone (Hulbert *et al.*, 1992). In north Yukon, Canol Formation is conformably overlain by clastic strata including the Imperial, Ford Lake Shale, and Nation River formations (Pugh, 1983; Churkin and Brabb, 1965; Norris, 1982a,b).

CORRELATIVE AND COEVAL STRATA

In Mackenzie Plains region, NWT, the Canol Formation is the uppermost formation of the Horn River Group, which also includes the older Ramparts Formation (Kee Scarp member) and the Hare Indian Formation with its basal Bluefish Member (Pugh, 1983). West of Richardson trough, the Canol Formation may be equivalent to, or form a part of, the ‘unnamed shale unit’ of Norris (1968) and the upper part of the McCann Hill Chert (Churkin and Brabb, 1965; Clough and Blodgett, 1984) of east-central Alaska (Fig. 2). The ‘unnamed shale unit’ does not appear on geological maps of north Yukon; it is mapped as Canol Formation, suggesting the term is no longer in use.

Coeval shale strata occur on Banks Island (Nanuk and Ibbett Bay Formations; Miall, 1976), in Selwyn Basin in central Yukon (Earn Group *e.g.*, Portrait Lake Formation (Gordey and Anderson, 1993) and Misfortune Formation (Cecile, 2000), Liard Basin (Besa River Formation; Pigage, 2009), and Horn River Basin, northeastern British Columbia (Muskwa Member, Horn River Formation; Pugh, 1983; Fig. 2).



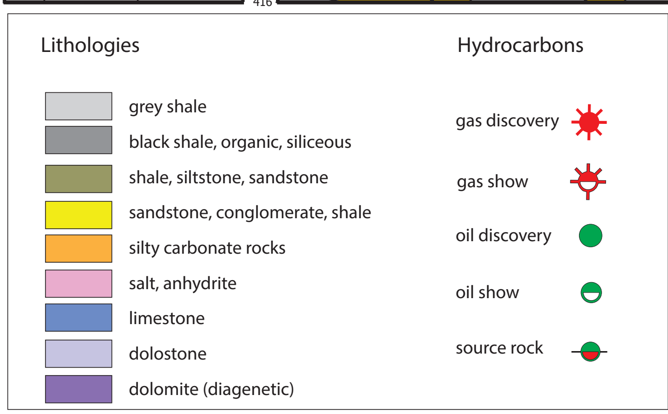


Figure 2. *Devonian-Carboniferous strata in northern Yukon, Mackenzie Plain, and Liard Basin. Modified from Pigage (2009) and Morrow et al. (2006).*

AGE

Fossils are rare in the Canol Formation; however, conodont, ostracod, and/or palynomorph identifications suggest that the Canol Formation is Middle–Upper Devonian in age (Givetian, Norris, 1985; late(?) Givetian to early Frasnian, Gal *et al.*, 2009). Palynomorphs collected from the Trail River section in Yukon described in this paper provide late Givetian or early Frasnian dates (Norris, 1985).

LITHOLOGY AND DEPOSITIONAL ENVIRONMENT

Near the type section in NWT, the Canol Formation is described as dark grey to black, soft to very hard, non-calcareous black shale and mudstone that weathers greenish, yellowish, and rusty brown (Bassett, 1961). It is organic-rich, siliceous, and may contain chert, mudstone with carbonate concretions, calcisiltite, and crinoidal grainstones (Muir and Dixon, 1984). Further west along the Mackenzie Mountains, between Arctic Red and Snake rivers, the Canol Formation is described as very dark grey to jet black mudstone, with a bright yellow, orange, and apple green weathering patina on the surface, and local orange-brown clay ironstone and pyrite nodules (Norris, 1968; 1985). In the subsurface of the Peel Plateau and Plain region, the Canol Formation is readily identified on gamma-ray logs by its high radioactivity and is observed in drill cuttings as dark grey to black, bituminous shale that is commonly siliceous and pyritic (Pugh, 1983). In the east Richardson Mountains, the Canol Formation has been described as a cliff-forming black, organic-rich, siliceous shale interbedded with black chert, covered with a distinctive apple-green to yellow patina (Allen and Fraser, 2008). The measured section described in this paper will expand on this definition.

The correlative 'unnamed shale unit' in the northern Ogilvie Mountains west of the Blackstone River (delineated as Canol Formation on bedrock geology maps) is described as a recessive unit comprising a variety of types of shale that overlie the Ogilvie Formation (Norris, 1967; 1968). Near the Blackstone and Hart rivers, it is a black, fissile, non-calcareous shale that may be burnt to a brick red or pink color. In Nahoni Range, southwest of Eagle Plain, it is a hard, highly fissile siliceous shale interbedded with soft, black shale which weathers to bluish grey or silvery grey. West of Miner River, the unit is composed of black, hard, non-calcareous, and, in part, silty and ferruginous shale, including minor interbeds of sandstone. Outcrops near the Yukon-Alaska border consist of medium brownish-grey shale in part burnt to a brick red colour.

Studies of organic matter carbon isotopes ($\delta^{13}C$), total organic content, and iron content in pyrite in Canol Formation shale in the Mackenzie Mountains, NWT, suggest that the sediments were deposited in anoxic, low energy conditions that persisted over relatively long, uninterrupted periods (Al-Aasm *et al.*, 1996).

HYDROCARBON POTENTIAL

The Canol Formation has been proven to be the source of oil for the Kee Scarp Formation reservoir in Norman Wells, NWT (Snowdon *et al*., 1987). It has also been identified as a potential source rock in northern Yukon and northwestern Northwest Territories, with variable thermal maturity (e.g., Pugh, 1983; Snowdon *et al*., 1987; Link *et al*., 1989; Gal *et al*., 2009; Fraser *et al.* 2012).

Current exploration in the central Mackenzie Valley, NWT (Shell Canada Limited, MGM Energy Corporation, Husky Energy Incorporated, Imperial Oil Limited, and ConocoPhillips Canada Resources Corporation) is focussed on unconventional oil targets in the Canol Formation and the Middle Devonian Bluefish Member of the Hare Indian Formation. Since 2011, the play has resulted in work proposal bids totalling $645 million (Aboriginal Affairs and Northern Development Canada, 2013). Results from one well (East MacKay I-78) have been released: 140 barrels of fluid consisting of a mixture of frack fluid and formation hydrocarbons consisting of light, sweet crude and natural gas (Campbell, 2013).

TRAIL RIVER FIELD STUDIES 2013

A near-complete section of Canol Formation is exposed on the north side of Trail River, eastern Richardson Mountains (Fig. 3). This outcrop was measured over a five-day period in June, 2013. Access to the outcrop was by helicopter contracted from Dawson City via Eagle Plains Hotel. Flight distance to the outcrop from the hotel is approximately 55 km east.

Figure 3. *Aerial view of the near-complete exposure of Canol Formation on Trail River, east Richardson Mountains. The stratigraphic thickness of the Canol formation at this locality is 229 m. View is towards the northeast.*

At the Trail River location, the Canol Formation is 229.3 m thick and forms resistant, steep exposures and canyons. Strata generally strike north (000°) and dip 35-50° east. The basal contact with strata of the Road River Group is exposed (UTM 477805E; 7366765N) and the upper contact with the Imperial Formation underlies a ~2 metre covered interval (UTM 478181E; 7366563N). This section is the most complete Canol Formation section observed during reconnaissance studies in the region over the past eight years and thus presented a good opportunity for detailed sampling and description.

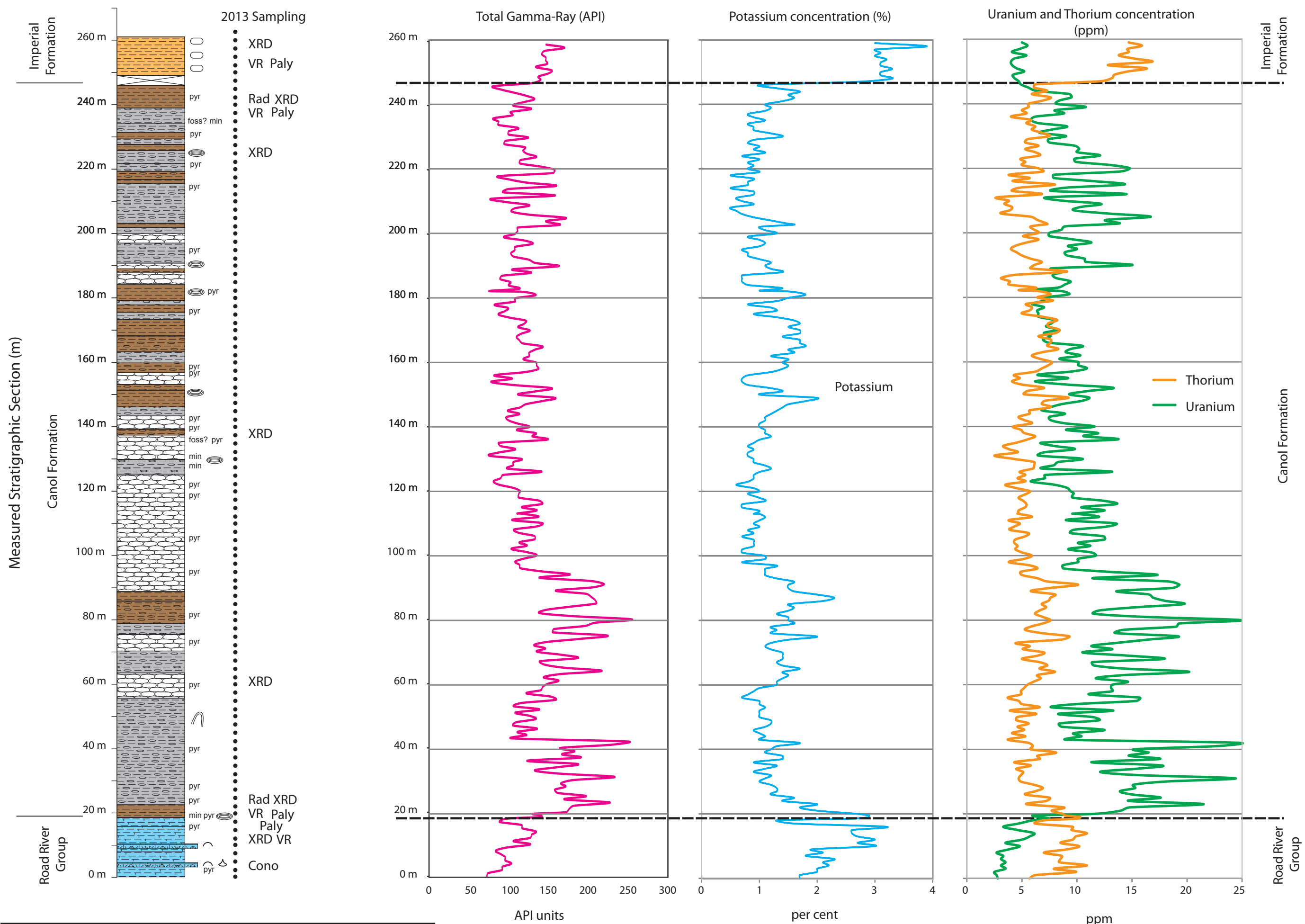
Four geologists measured, described, and sampled 261 m of section, including the underlying upper Road River Group (19.7 m), Canol Formation (229.3 m) and overlying Imperial Formation (12.0 m). Detailed lithological descriptions were made of the section and spectral gamma-radiation counts (SGR) of uranium, thorium, and potassium were measured with a handheld spectrometer at one-metre intervals. Shale/chert chip samples were collected through two-metre intervals for Rock-Eval/total organic carbon (RE/TOC) and inductively coupled plasma-emission/mass spectroscopy lithogeochemistry (ICP-ES/MS). Targeted samples for microfossil biostratigraphy (conodonts, radiolarians, pollen) and vitrinite reflectance (VR) were collected near formation contacts. All rock types were sampled for XRD mineralogy.

FIELD OBSERVATIONS

Presented here are the lithological descriptions and spectral gamma ray data from the Canol Formation outcrop on Trail River. Figure 4 displays a lithological log of the section, with sample locations indicated, and corresponding potassium, uranium, and thorium elemental concentrations and total API (derived using Schlumberger equation in Rider, 1996).

ROAD RIVER GROUP

The upper 19.7 m of the Road River Group observed at Trail River consists of recessive calcareous shale and mudstone, with ~10% resistant beds of bioclastic packstone (Fig. 5). Calcareous shale and mudstone are dark grey on fresh surfaces, weather grayish brown to brownish grey, are laminated, and occur in beds ~2–10 cm thick (Fig. 6). Fine-grained pyrite, both disseminated and laminated, is present. Bioclastic packstone beds are medium grey on fresh surfaces and weather medium to light grey, yellowish grey, and white (Fig. 7). Beds are up to 28 cm thick and have scoured lower and sharp upper contacts. Fossil debris includes crinoids, brachiopods, and



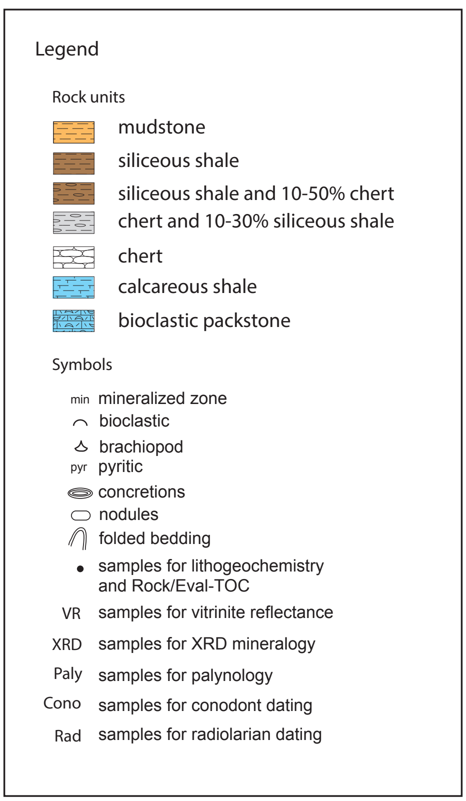


Figure 4. *Measured stratigraphic section and field-collected spectral gamma radiation logs of the Canol Formation on Trail River. Gamma-ray data were collected at one-metre intervals.*

Figure 5. *Upper 15 m of the Road River Group on Trail River. Strata of the Road River Group at this location consist of recessive calcareous shale and mudstone with minor resistant beds of bioclastic packstone. These resistant beds can be seen as continuous light grey horizons in the photograph. Orange flagging is placed at one-metre stratigraphic thicknesses.*

unidentified bivalves. Rare pyrite occurs as fine-grained disseminations or in fossil replacements. A ~10 cm thick channel-form bed made up of chert rip-up clasts in a limestone matrix was also observed (Fig. 8).

The uppermost Road River Group is characterized by concretions and highly weathered and mineralized shale/mudstone. A resistant, continuous, bed of concretions up to 30 cm thick occurs 2-3 m below the contact (Fig. 9). Concretions in this bed are light grey on fresh surfaces and weather beige, yellow, or powdery white. They are microcrystalline, slightly calcareous, and very dense, suggesting the presence of dolomite or barite. An iron-stained, highly weathered, elongate mudstone concretion at least 4.5 m long and up to 1 m thick was observed 1-2 m below the contact. The concretionary horizon is reminiscent of the "limestone ball" member immediately below the Ni-Zn-PGE mineralization identified at the Nick Property, approximately 190 km south of the Trail River location (Hulbert *et al.*, 1992). Geochemical samples to evaluate this correlation are currently being analysed.

The contact with the Canol Formation was placed at the first competent, bedded, siliceous shale bed above mineralized, weathered, recessive mudstone (Fig. 9). However, it has been suggested that the onset of Canol sedimentation may have occurred at the top of the last concretionary bed, immediately below the mineralized zone, approximately 1 m below the current placement (Rob Carnes, pers. comm). The placement of this contact will be reviewed when geochemical data are available.

Figure 6. *Calcareous shale/mudstone of the upper Road River Group. These rocks are laminated and occur in beds ~2–10 cm thick.*

Figure 7. *Bioclastic packstone of the upper Road River Group. These beds are commonly 5–10 cm thick, but were observed up to 28 cm thick.*

Figure 8. *Individual bed of chert rip-up clasts fining up to laminated limestone in the upper Road River Group.*

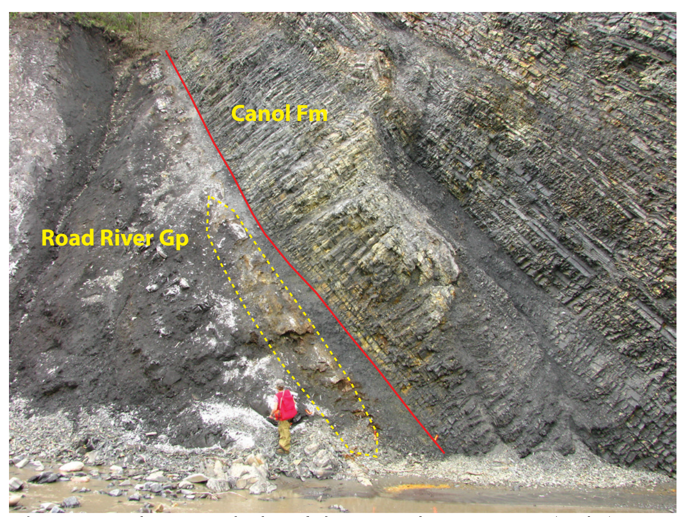


Figure 9. *Siliceous shale of the Canol Formation (right) overlying calcareous shale of the upper Road River Group. Note the large, rusty-colored ironstone concretion immediately to the right of the geologist (circled).*

CANOL FORMATION

Lithology

Overall, the Canol Formation is a resistant, silica-rich unit that is characterized by rhythmically bedded siliceous shale and chert (Fig. 10). Fifty-three separate lithological units were described in the field, based on the relative proportion of each of the rock types and changes in bedding thicknesses. These units were then grouped into the following lithofacies: siliceous shale; chert; siliceous shale (>50%) and chert (10-50%); and chert (>70%) and siliceous shale (10-30%).

Siliceous shale is black on fresh surfaces and weathers dark grey to black and olive grey, often with a distinctive pale and dark yellowish orange, dark red, light yellow, yellowish grey and/or very minor apple-green weathering residue (Fig. 11). A distinguishing characteristic about this lithofacies is the fissility of the shale that cleaves into wafers, sheets, or plates, depending on lamination/bed thickness (Fig. 12). Walking on the scree beneath an exposure of siliceous shale is akin to walking on broken glass, attesting to the high silica content of this formation. Bedding is planar and contacts are sharp. Two variants of this lithofacies are: 1) thin to medium bedded units, up to 10 cm thick, which require a hammer to break; and 2) recessive, finely laminated units, composed of beds up to 3 cm thick that are softer and easy to break by hand, and locally weathering to a soft clay-consistency. The siliceous shale lithofacies may include up to 10% chert beds.

Chert is black on fresh surfaces and weathers dark/medium grey to black, olive brown, light brown, and may have a distinctive pale and dark yellowish orange, dark red, and/or very minor apple-green weathering residue. Unlike the fissility of the shale, the chert exhibits conchoidal fracture and is very difficult to break with a hammer (Fig. 13). The chert weathers to irregular blocks.

Figure 10. *Typical outcrop of the Canol Formation on Trail River, showing consistent, rhythmic bedding of chert and siliceous shale.*

Figure 11. *Typical weathering colors of the Canol Formation on Trail River.*

Figure 12. *Fissile siliceous shale of the Canol Formation, 5.3 m above the basal contact (25 m stratigraphic level).*

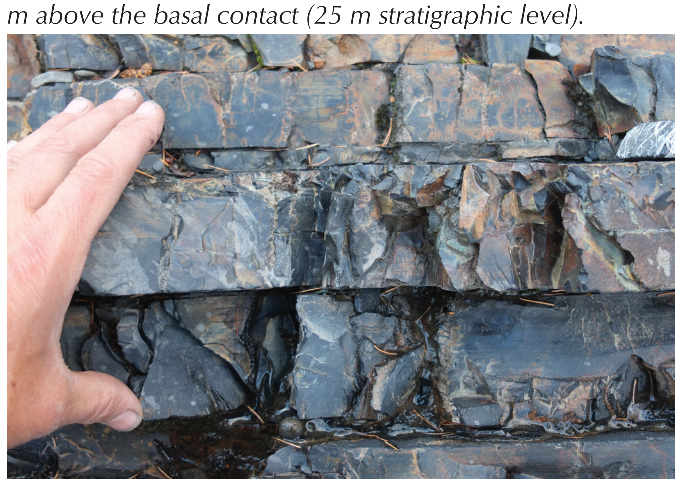


Figure 13. *Conchoidally fractured chert of the Canol Formation, 90.3 m above the basal contact (110 m stratigraphic level).*

Laminations (mm-scale) can be observed on weathered surfaces; however, the rocks do not split along these surfaces, but will separate along certain bedding planes. Bed thicknesses are commonly 1–10 cm, but may be as thick as 16 cm. This unit may include up to 10% siliceous shale partings in intervals <5 cm thick.

Two additional lithofacies were identified in intervals where chert and siliceous shale were interbedded (Fig. 14). *Siliceous shale and chert* is characterized by ≥50% siliceous shale interbedded with 10-50% chert. Shale is more dominant overall and is more recessive than the chert-dominated lithofacies. *Chert and siliceous shale* is characterized by a ≥70% chert beds interbedded with 10-30% siliceous shale. For this lithofacies, the shale generally forms thinner partings between thicker chert beds.

In addition to stratigraphic variations in lithology, it can also vary along strike. For example, it is commonly observed that chert grades laterally into siliceous shale and vice versa. As well, the difference between chert and siliceous shale is sometimes difficult to determine in the field, as there were some beds that exhibited both conchoidal fracture and some fissility. Further refinement of what constitutes chert and siliceous shale and gradations thereof in the Canol Formation will be addressed in a future publication.

Concretions

Concretions (or nodules) of various sizes occur locally in the measured section. The term concretion is used in this study as many of these features were inaccessible, and as such it was difficult to determine with certainly whether they formed around an obvious nucleus. At 130 m and 151 m stratigraphic levels (Fig. 4), flat and elongate, orange and yellow-weathered concretions up to 2 m long and up to 0.15 m wide occur in continuous discrete iron-rich horizons.

More notable are the large concretions at 182 m, 190 m, and 227 m stratigraphic levels (Fig. 4). At 182 m, several non-calcareous mudstone concretions measuring 2.5 m-long and 0.75 m-wide occur in a discrete horizon. One located at river level is flat and elongate, internally planar laminated, dark grey on fresh surfaces, and weathers dark grey and reddish brown with a white chalky residue. This concretion occurs within beds of thin, fissile shale that appear to have been deformed by its growth, or compaction around it (Fig. 15). This is the only large concretion that was accessible for sampling and will be submitted for XRD mineralogy.

Isolated concretions occur at 190 m (1.5 m long and 0.90 m wide) and at 227 m stratigraphic levels (1.5 m long and 0.90 m wide; Fig. 4). These concretions have flat bases and appear mound-like (Fig. 16). These concretions were inaccessible for sampling or close inspection, but they weather reddish brown (190 m) or light grey (227 m) with a white chalky residue and appear to be composed of mudstone. Overlying strata are either deformed around these features due to compaction, or may be draped around what may have been a positive feature on the seafloor. The flat bases of these concretions suggest that they may have formed during deposition of the shale/chert, rather than post-deposition.

Figure 14. *Interbedded chert and siliceous shale of the Canol Formation, 20.7 m above the basal contact (40 m stratigraphic level).*

Figure 15. *Mudstone concretion in Canol Formation, 162.3 m above the basal contact (182 m stratigraphic level). The concretion is 2.5 m long, 0.75 m wide, and has planar laminations. Note the white chalky residue on the weathering surface.*

Fossils

With two possible exceptions, no macrofossils or trace fossils were observed in the Canol Formation at this section. At ~134 m and 236 m stratigraphic levels (Fig. 4), bedding surfaces were marked with small, semi-rounded, positive features <1 cm long that could be biological remnants (Fig. 17); however, they may also be interpreted as mineral casts.

Pyrite

Fine-grained pyrite is common in the Canol Formation and was found in the Trail River section concentrated along bedding planes or disseminated within shale. Coarse-grained pyrite was observed in a 35 cm long and 3 cm wide pyrite nodule (concretion?) at the 25 m stratigraphic level (Fig. 18). Continuous or semi-continuous horizons of red weathering, iron-rich concretionary or nodular horizons (up to 20 cm thick) occur but they are not a common feature.

Figure 16. *Isolated concretion (or mound?) in the Canol Formation; 207.3 m above the basal contact (227 m stratigraphic level). Note the flat base and the thinning of bedding around the top of the feature, suggesting it may have been a positive feature on the seafloor, having formed during the deposition of the shale/chert, rather than being a post-depositional feature. Like other concretions in the section, it has a white chalky residue on the weathering surface.*

Structure

The entire section is relatively undeformed, except for an area of ~14 m thick at the 43-57 m stratigraphic horizon where beds are tightly folded and locally fractured. This structure could result in the thickening of the section by ~7 m.

IMPERIAL FORMATION

Twelve metres of the lower Imperial Formation was measured. The Canol-Imperial contact is covered at this section, but its location is estimated to within ~2 m. Imperial strata at this location comprise weathered mudstone with continuous iron-rich nodular horizons

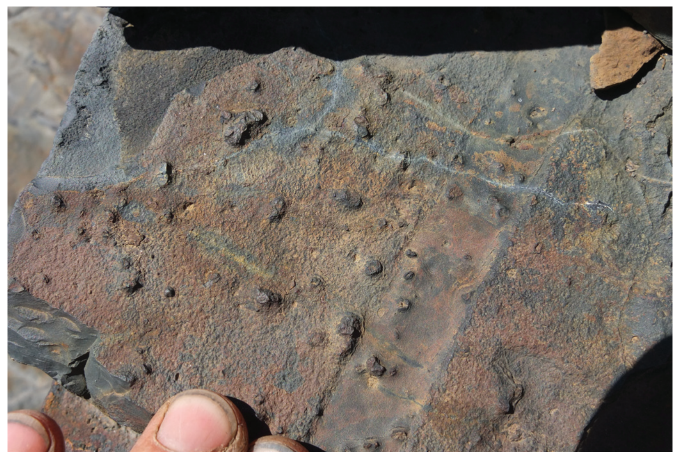


Figure 17. *Small, semi-rounded features on the bedding surface of Canol Formation siliceous shale at 236 m stratigraphic level (216.3 m above the basal contact). These may be biological remnants; alternatively, they may be casts of minerals.*

Figure 18. *Thirty-five cm-long pyrite concretion observed ~5 m above the basal contact of the Canol Formation, at the 25 m stratigraphic level. These concretions are rare in the section. Fine-grain disseminated or laminated pyrite is more common.*

(Fig. 19). The mudstone is dark grey on fresh surfaces, and weathers moderate brown, reddish brown, and minor yellowish brown. From a distance, the outcrop appears reddish brown or burgundy, which is diagnostic of the Imperial Formation in north Yukon. The mudstone is friable, weathering to small 1 cm angular shards (Fig. 20). Due to the degree of weathering, no sedimentary structures other than the continuous nodular horizons are apparent. Dense, microcrystalline and iron-rich nodules occur in continuous beds, 2-8 cm thick, every 2-50 cm throughout the unit; they are olive grey on fresh surfaces, weather reddish orange and smell sulphurous on fresh surfaces. In east Richardson Mountains, the nodules are comprised of 55% siderite (Allen *et al.*, 2011).

No macrofossils or trace fossils were observed in the Imperial Formation.

SPECTRAL GAMMA RADIATION (SGR)

Spectral gamma radiation data were collected using a Radiation Solutions RS-230 BGO gamma-ray spectrometer (Fig. 4). Potassium (K) was collected as a percentage (%), and uranium (U) and thorium (Th) as parts per million (ppm). The total gamma-ray, incorporating the gamma-radiation from U, Th, and K, is displayed as API units (American Petroleum Institute) which is the industry standard for the presentation of the gamma-ray curve and is useful for correlating to subsurface well logs (see next section). API was calculated using the following multiplier: 1ppm U = 8 API units; 1 ppm Th = 4 API units; and 1% K = 16 API units (Schlumberger NGT-A log in Rider, 1996).

A full analysis of the SGR data is not presented in this paper, but will be provided in future publications where geochemical and petroleum potential data can be incorporated for a more robust interpretation. General trends and statements about the relevance of the data are presented here.

GENERAL TRENDS

The total gamma-ray curve in Figure 4 shows that the upper Road River Group is less radioactive than the Canol and Imperial Formations, averaging 107 API. A marked increase in overall radioactivity appears at the Road River–Canol contact. The Canol Formation becomes less radioactive from the base to the top of the section. The most radioactive part of the exposure is the lower ~75 m of the Canol section, between the Canol-Road River contact and the 95 m stratigraphic level. A noticeable shift occurs at ~95 m, from an average of 165 API between 19.7 m and 95 m to an average of 115 API between 95 m and 247 m. The transition from the Canol to the Imperial formation results in a slight increase in average radioactivity to 145 API and the actual contact is marked by a sudden, sharp increase of over 50 API between the two formations.

URANIUM

The occurrence of uranium in sediments can result from chemical precipitation in acidic, reducing environments, by adsorption by organic matter or living plants and animals, or by chemical reactions in phosphate rich rocks (Rider, 1996). Because uranium is highly soluble, the most likely

Figure 19. *Typical exposure of Imperial Formation on Trail River. Here it consists of friable mudstone with continuous horizons of iron concretions spaced every 2–50 cm apart. The section has a reddish brown to burgundy weathering colour, distinctive of this formation in north Yukon.*

Figure 20. *Close-up of weathered mudstone and ironstone concretions of the Imperial Formation. Concretions in the Imperial Formation in west Richardson Mountains are comprised of 55% siderite.*

way it is incorporated into sediments is in association with organic matter, where loose bonds are formed between the uranyle ion ($U0_2$) and organic material. In hydrocarbon source rock studies, higher levels of uranium often correlate to higher levels of total organic content (TOC), and as a result, uranium concentration log curves are often used to predict the presence of potential source rock intervals from wireline data.

Uranium concentrations in the Road River Group and Imperial Formation are lower than in the Canol Formation, averaging 4.5 and 4.6 ppm respectively (Fig. 4). In the Canol Formation, uranium concentration decreases towards the top of the section from an average of 14.8 ppm between the lower contact and 95 m stratigraphic level, to an average of 9.4 ppm between 95 m and the upper contact. Notable are marked changes in uranium radiation at both the upper and lower contacts of the Canol Formation. Correlating organic content to uranium would suggest that the lower one-third of the Canol Formation is likely to contain the highest TOC values of the section and hence show the best source rock or shale gas prospectivity, with possibly slightly higher values between 190 m and 220 m stratigraphic levels. The Road River Group and the Imperial Formation are likely to be organically lean.

POTASSIUM AND THORIUM

Potassium readily forms chemical bonds and is common in rocks (Rider, 1996). It occurs variably in clay minerals and micas (*e.g.*, illite), feldspars, and in evaporites. The average shale has a potassium content of 2-3.5% (Rider, 1996 and references therein). Thorium is generally transported to sites of sediment deposition as clay fraction detrital grains and is chemically stable (Rider, 1996). Both potassium and thorium may be used as proxies for detrital clay influx.

Potassium concentration in the Road River Group and Imperial Formation are higher than in the Canol Formation, at 2.3% and 3.1% respectively (Fig. 4), falling within the average shale category. Potassium concentration in the Canol Formation varies from 0.5% to 2.0%, averaging 1.2%, which is lower than an average shale. Potassium concentrations in the Canol are cyclic, occurring in ~40–50 m thick cycles of either ~1% or 1.5% concentrations. Both upper and lower contacts of the Canol Formation are marked by strong shifts in potassium concentrations: a decrease from 3.2% in the Road River Group to 1.3% in the Canol at the lower contact, and an increase from 1.0% in the Canol to 2.7% in the Imperial at the upper contact.

Average thorium concentrations are highest in the Imperial Formation (14.5 ppm) followed by Road River Group (8.8 ppm), and the Canol Formation (5.8 ppm). There is a gradual decrease in thorium radiation from the Road River Group to the Canol Formation, and a marked increase from the Canol Formation to the Imperial Formation. Thorium levels within the Canol Formation are consistent, averaging 5.8 ppm, and do not show any significant trends.

Potassium and thorium concentration data suggest the Road River Group and Imperial Formations received more detrital input than the Canol Formation. There is evidence of very minor fluctuations in detrital input in the Canol Formation as shown in the potassium curve, but detrital input is interpreted as insignificant. This interpretation could also suggest that the silica and organic material in these sediments may be biogenic, sourced from local organisms, as opposed to detrital.

CORRELATION

The total gamma ray curve (API) is correlated to the closest well that penetrates the Canol Formation, Peel Y.T. H-71 (300G716630134300), drilled 35 km southeast of the outcrop section (Fig. 21). In older well logs, such as this one drilled in 1977, spectral gamma-radiation data is not available. The Canol section in the well is 79 m thick, compared with the outcrop section where it is 229 m thick. Despite the variation in thickness, the overall trend in gamma-radiation is comparable between the sections. The Road River Group shows the least radioactivity of all strata. At both locations, the Canol Formation is more radioactive in its lower part, although this accounts for two-thirds of the well section (between 1840 m and 1887 m below Kelly Bushing) and only one-third of the outcrop section (between 19.7 m and 95 m stratigraphic levels). The change from Canol to Imperial formation strata is marked at both locations by a sharp increase in gamma API.

SUMMARY AND FUTURE WORK

A near-complete stratigraphic section of Middle-Upper Devonian Canol Formation was measured on Trail River, east Richardson Mountains, in June, 2013. The section description is part of a larger study aimed at characterizing and correlating the Canol Formation within the Yukon, and assessing the formation's regional hydrocarbon potential, both as a source rock and an unconventional shale reservoir. The Canol Formation at this location

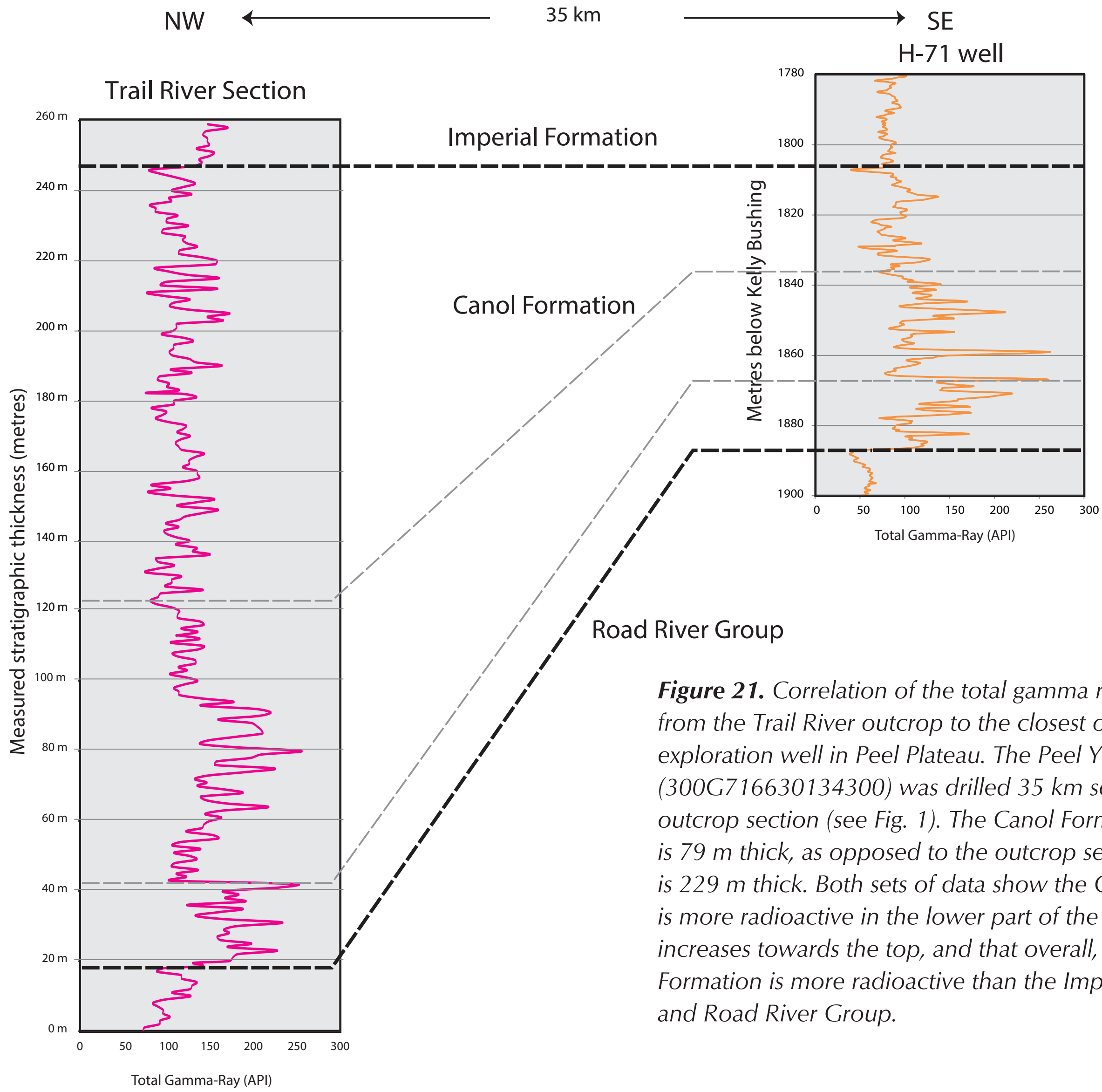


Figure 21. *Correlation of the total gamma ray curve (API) from the Trail River outcrop to the closest oil and gas exploration well in Peel Plateau. The Peel Y.T. H-71 well (300G716630134300) was drilled 35 km southeast of the outcrop section (see Fig. 1). The Canol Formation in the well is 79 m thick, as opposed to the outcrop section where it is 229 m thick. Both sets of data show the Canol Formation is more radioactive in the lower part of the section and increases towards the top, and that overall, the Canol Formation is more radioactive than the Imperial Formation and Road River Group.*

overlies the upper part of the Road River Group, and underlies the Devonian–Carboniferous Imperial Formation. In total, 261 m of section were measured and sampled for spectral gamma-radiation (U, K, Th), Rock-Eval/TOC, lithogeochemistry (ICP-ES/MS), XRD, VR, and microfossil biostratigraphy. A key part of this study is to collect data to assist in regional correlations in an attempt to differentiate shale packages in frontier areas. The spectral gamma-ray data collected in this study shows the effectiveness of this tool for surface to subsurface correlations.

This description of the Trail River section of the Canol Formation will be supplemented by lithogeochemical, RE/TOC, VR, XRD data and microfossil biostratigraphy. These data will provide further insight into questions about the Canol Formation, e.g., the source of the silica in the shales and chert (biogenic or detrital); the formation's internal geochemical variability and its utility in correlating within and beyond the basin; the stratigraphic position of the "Nick" horizon and evaluating its extent in the Yukon; the extent, age, and variability of the Canol Formation throughout the Yukon; and ultimately, the hydrocarbon potential of Devonian shale, both as a source rock and a shale reservoir.

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