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Stratigraphy, age, and petroleum potential of Upper Devonian black shale (unit 'Cf'), east Richardson Mountains and Peel Plateau, Yukon

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Cover photo. Black shale of unit 'Cf', Aghoo Creek, Yukon.

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ABSTRACT

Peel Plateau and the contiguous east flank of the Richardson Mountains, northeastern Yukon, comprise a relatively unexplored but prospective petroleum basin. Within the Devonian succession of this basin, shale rocks of unit 'Cf' (Norris, 1981a) are little known, but may have the potential to form an important conventional source and/or unconventional reservoir target. Unit 'Cf' is dominated by thick intervals of dark grey to black, siliceous, organic-rich marine shale, together with intercalated siltstone and very fine grained sandstone beds. Although unit 'Cf' has been mapped at surface on the eastern flank of the Richardson Mountains, it is not known whether it occurs to the east in the Peel Plateau and Plain subsurface. A correlation of this unit to the Ford Lake Shale ('CF' map unit of Norris, 1981b,c), which occurs to the west in Eagle Plain and Kandik basins, has been implied by the nomenclature used by Norris (1981b, 1985a).

In this study, unit 'Cf' was assessed for lithology, mineralogy, age and hydrocarbon source and reservoir rock potential, including type and quantity of organic matter and thermal maturity. Common organic geochemical analytical techniques were utilized (including Rock-Eval pyrolysis and optical microscopy), together with X-ray diffraction (XRD) to determine shale mineralogy and age determination by palynology. Outcrop characteristics were then utilized to identify unit 'Cf' in four subsurface Yukon wells: H-37, N-25, I-21 and A-42.

Results have demonstrated the potential of unit 'Cf' shale as both source rocks and shale oil/gas reservoirs, and suggest that these strata have been overlooked as a hydrocarbon target in Yukon's Peel region. Rock-Eval results indicate that organic matter in unit 'Cf' consists of mixtures of type II and III kerogen (oil to gas-prone), and organic petrology confirms this in addition to the presence of type I kerogen (oil-prone). Organic matter is identified as mainly amorphous kerogen with alginite, vitrinite, and liptinite. The classification of unit 'Cf' as a good to very good source rock that has good to very good hydrocarbon generation potential is derived from: TOC contents ranging from 1.02-12.17 wt% (averaging 5.28 wt%), average S1 values of 1.61 mg HC/g rock and average S2 values of 12.91 mg HC/g rock. Thermal maturity indicators also place unit 'Cf' shale in the 'oil-window', or early stage of thermal diagenesis, including T_{max} values between 423° and 444°C, and vitrinite reflectance values between 0.5 and 0.95% Ro_R. Reddened shale (or clinker) units observed in the region attest to the high TOCs in these strata, and are evidence of historical and/or current burning. XRD results demonstrate the high silica (typically in excess of 90% quartz) and low clay mineral (<7%) contents of these strata, suggesting their ability to respond to artificial well stimulation techniques for unconventional hydrocarbon production.

A combination of palynological age (Fammenian-Late Devonian), TOC content (>1.02 wt%) and lithological composition data derived from outcrop results were utilized to successfully identify unit 'Cf' in the subsurface. Comparable strata were identified predominantly from within the Tuttle Formation, where their stratigraphic character changed from being present as two discrete, silt-rich, thin (95 m) intervals in the northwest (Caribou N-25) to one, shale-prone, thick (1118 m) interval in the southeast (Peel River I-21). Further work is planned to delineate the unit's regional extent in the subsurface, and to establish a correlative stratigraphic framework with the Ford Lake Shale in Eagle Plain and Kandik basins to the west.

INTRODUCTION

Mid-Paleozoic dark grey to black shale units of northern Yukon and Northwest Territories are thought to be important source/reservoir rocks for both conventional and unconventional petroleum systems in Eagle Plain and Peel Plateau and Plain basins. One such prospective shale interval that has been overlooked in the Peel region is map unit 'Cf' (Norris, 1981a), a succession of organic-rich, basinal marine shale. This shale unit occurs within the uppermost portion of the Paleozoic succession exposed in the eastern Richardson Mountains and the contiguous Peel Plateau and Plain (Fig. 1). Unit 'Cf' is also considered likely to extend eastwards into the subsurface of both Peel Plateau and Plain and westward throughout Eagle Plain. However, its geographic distribution is currently uncertain as it has not been identified in the subsurface and is potentially included as an intraformational shale unit within the Upper Devonian-Mississippian Tuttle and Imperial formations.

In this study, we examined stratigraphic sections and isolated outcrops of unit 'Cf' to document its lithology, mineralogy, sedimentology and age in this region; assessed its hydrocarbon source and reservoir rock potential, including quality, quantity and thermal maturity of organic matter within the strata; and used these new data to identify and characterize unit 'Cf' in the Peel subsurface. The data presented here are based on fieldwork conducted between 2006 and 2010 and subsequent analytical work.

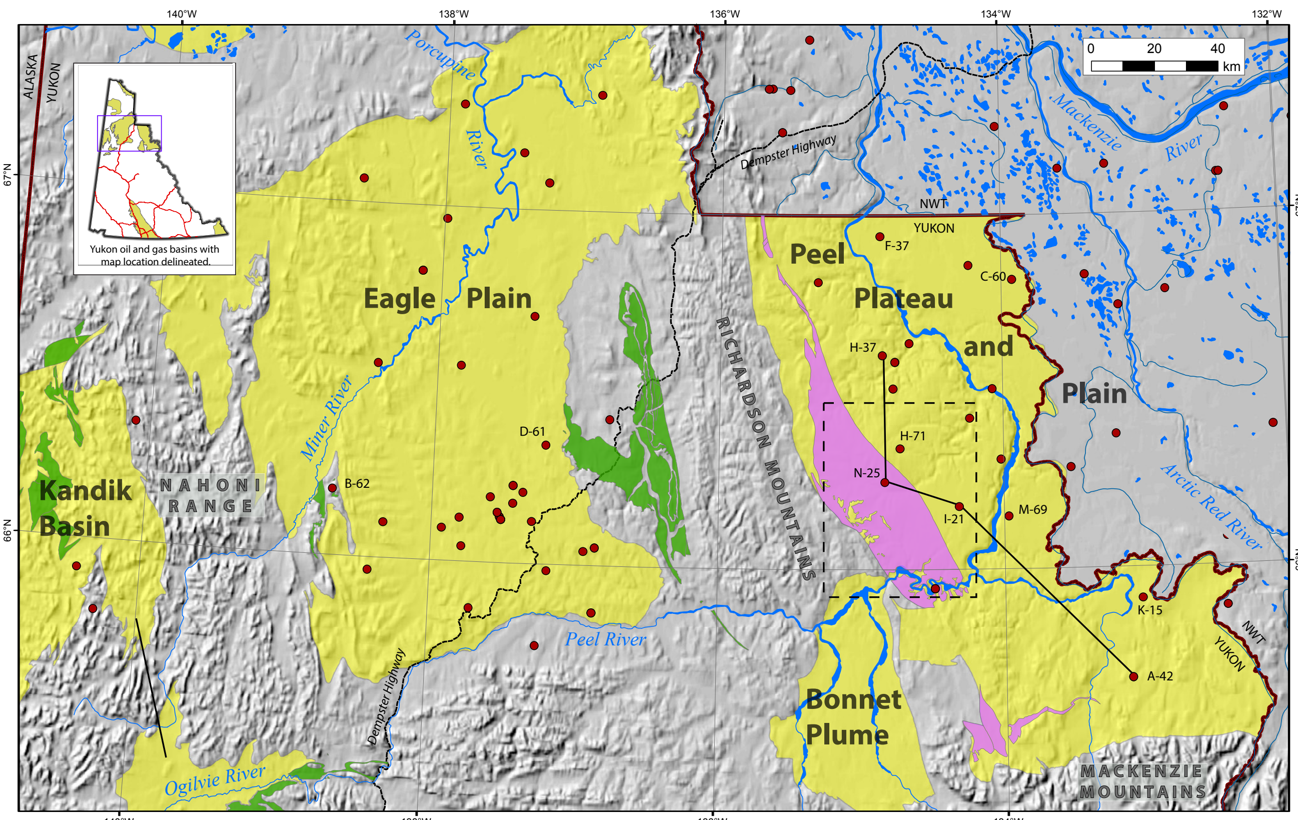
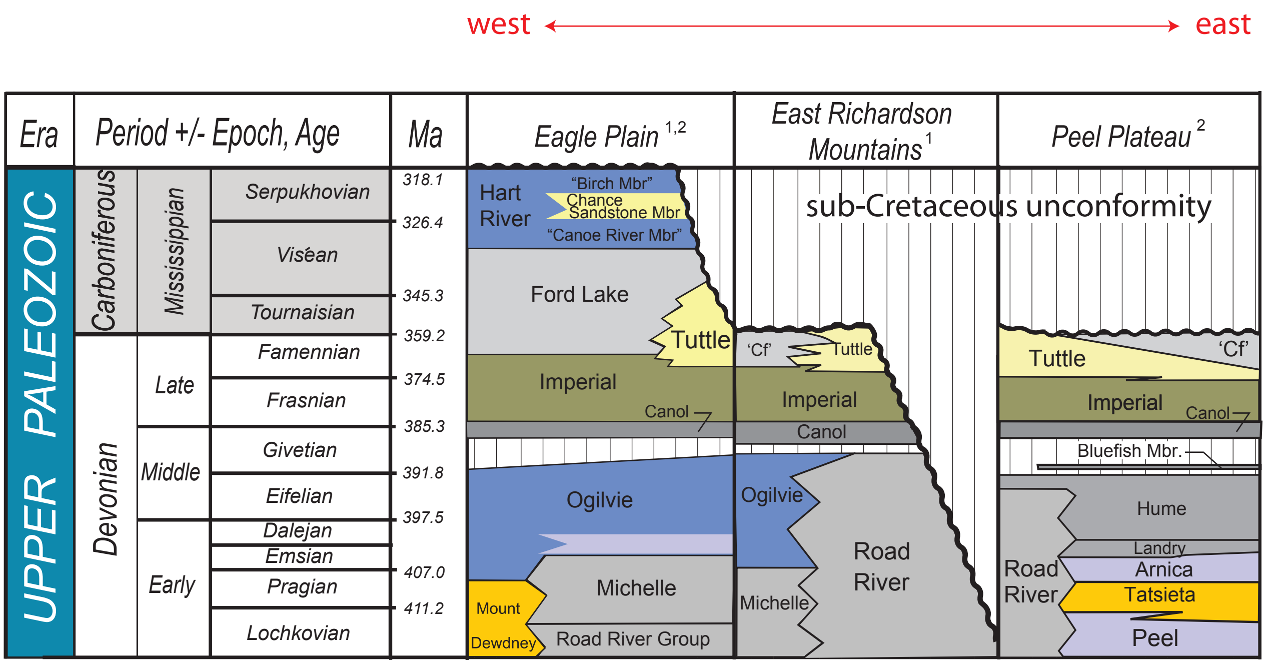


__Figure 1.__ Map of region including Richardson and Mackenzie mountains, Yukon's oil and gas basins (Peel Plateau, Eagle Plain, Kandik, Bonnet Plume), and oil and gas exploration wells referred to in this paper (see Table 1 for more details on the wells). Geologic units displayed include the 'Cf' map unit in pink, and the 'CF' or Ford Lake Shale in green. Geology by Norris (1985a) modified by Gordey and Makepeace (2003). The hatched box covers areas depicted in Figures 4 and 23. The well cross section line is shown in Figure 24.

Geological setting

The rocks in the Richardson Mountains and adjacent Peel Plateau and Plain were deposited on ancestral North America during its evolution following the breakup of the Rodinian supercontinent (Macdonald *et al.*, 2012). The Phanerozoic succession of the Peel Plateau and Plain forms an easterly tapering wedge of sedimentary rock that is locally greater than 4 km thick and unconformably overlies Proterozoic rocks (Fig. 2; A.W. Norris, 1997; Dixon, 1999; Morrow, 1999). During the early Paleozoic, the north to northwest-trending Richardson trough was a site of basinal shale deposition (Fig. 3; Pugh, 1983; Norris, 1985b; Morrow, 1999). The predominantly shale Cambrian to Devonian assemblage represents a phase of passive margin sedimentation that ended with deposition of black, bituminous shale of the Canol Formation in the Middle to Late Devonian (Gabrielse, 1967; Morrow and Geldsetzer, 1988). West and east of the trough, Cambrian to Devonian shallow water carbonate was deposited on the Yukon Stable Block and Mackenzie-Peel Shelf respectively (Morrow, 1999), but this was also eventually drowned by deposition of the Canol Formation.



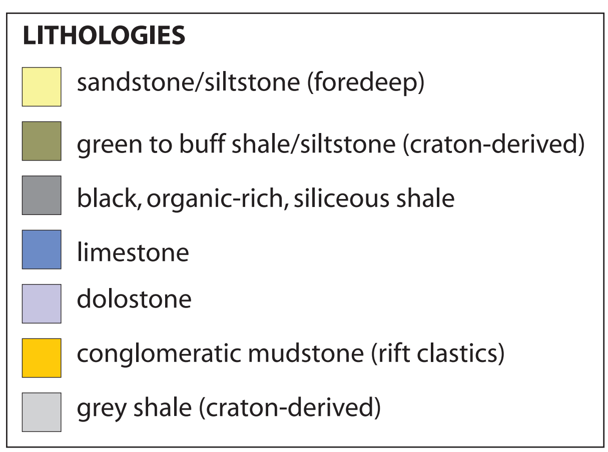


Figure 2. *Stratigraphic correlation chart of Upper Paleozoic strata illustrating the stratigraphic position of unit 'Cf' in the eastern Richardson Mountains and Peel Plateau in relation to Eagle Plain. The stratigraphic positions for the Imperial and Tuttle formations, unit 'Cf' and Ford Lake Shale have been modified from the original charts based on new palynological data (Utting, 2008a, 2009). [1]modified from Morrow et al. (2006), [2]modified from Pigage (2007). Ma=million years. Time scale after Gradstein et al. (2004).*

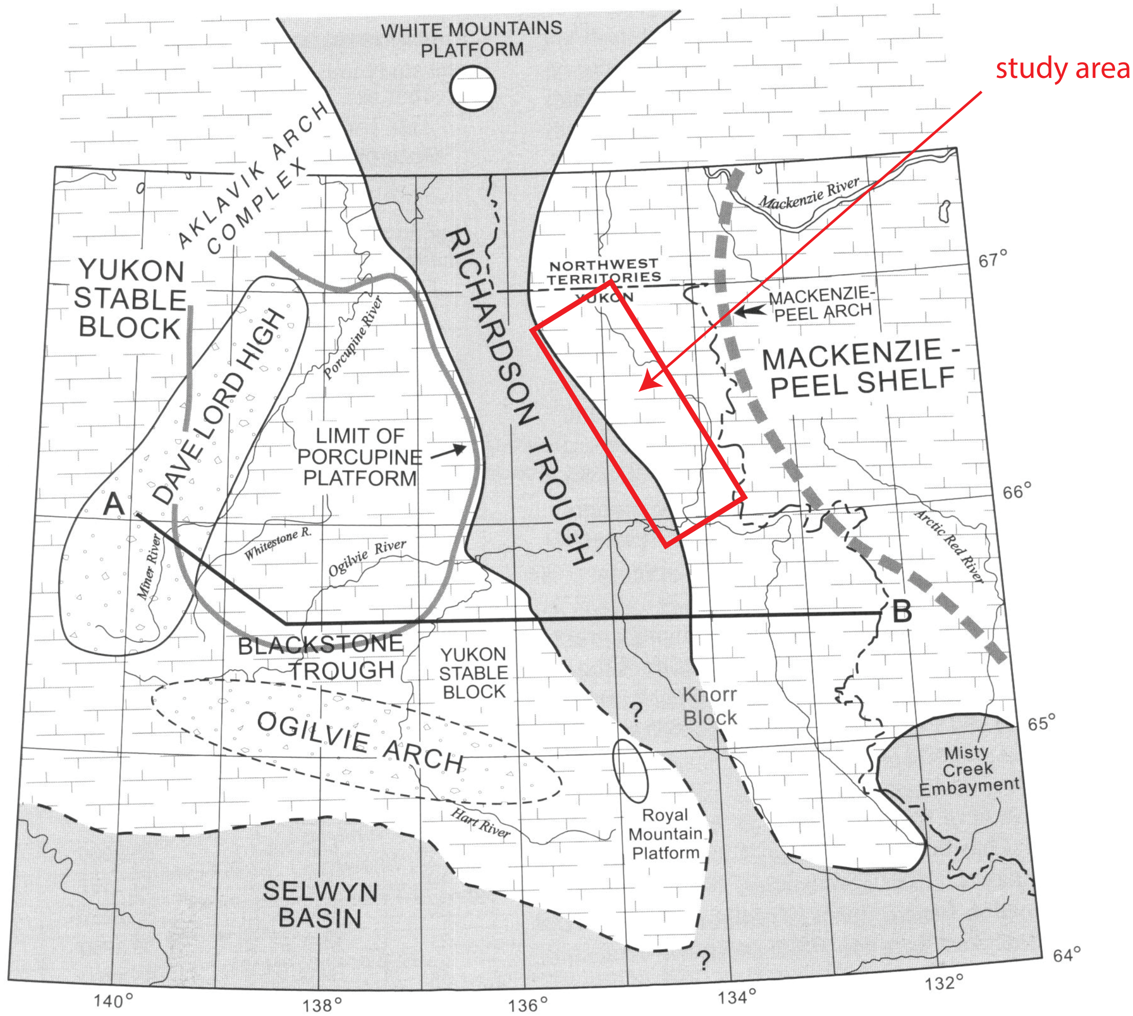


Figure 3. *Major paleogeographic elements that influenced sedimentation in early Paleozoic time. Areas of predominantly shallow-water carbonate deposition are filled with a brick pattern; shaded regions reflect areas of predominantly basinal shale deposition, including Richardson trough (from Morrow, 1999).*

A major change in tectonic regime precipitated by the Late Devonian to Early Carboniferous Ellesmerian orogeny affected sedimentation in the region (Morrow and Geldsetzer, 1988; Lane, 2007). Uplift created source lands to the east, west and north of the Peel region that shed clastic sediment into the adjacent basins (Gordey *et al.*, 1991). Upper Devonian to Lower Carboniferous clastic rocks of the Imperial and Tuttle formations (and presumably unit ‘Cf’) were deposited in a subsiding foreland basin setting at this time (Richards *et al.*, 1997). In the adjacent Eagle Plain, deposition of the Ford Lake Shale represented a major transgression over the underlying Imperial-Tuttle depositional system (Hamblin, 2006). During mid-Mississippian time sediment supply from the west and north waned, and marine clastic-carbonate deposition with clastic input from the craton was re-established (ibid).

Unconformably overlying the Paleozoic succession are Cretaceous clastic rocks on the order of 500 to 750 m thick in the study area (Hadlari *et al.*, 2009). These Aptian to Turonian foreland basin deposits comprise siltstone, shale and sandstone of the Martin House, Arctic Red and Trevor formations that were laid down during uplift of the Cordilleran orogen (Dixon, 1999). During the early to mid-Tertiary, the Richardson trough was inverted to form the Richardson Mountains anticlinorium (Gabrielse, 1957; Norris, 1985b; Lane, 1996; 1998). This uplift also resulted in the exposure of Proterozoic to Early Carboniferous strata (Viséan) in the Richardson Mountains (*e.g.*, Utting, 2006).

Previous work

During the 1960s, the Geological Survey of Canada (GSC) conducted Operation Porcupine, a reconnaissance-scale bedrock mapping project across northern Yukon. Operating north of latitude 65°N and west of longitude 132°W, the project established the regional geological framework for this region (Norris, 1981a-c, 1982a-d). Stratigraphic, structural and resource potential assessments followed the initial bedrock geological mapping component of Operation Porcupine (compiled in Norris, 1997). More recent detailed investigations (*e.g.*, Allen *et al.*, 2009; Rohr *et al.*, 2011) have further refined the geological understanding of the region.

During the 1960s and 1970s, oil and gas companies (*e.g.*, Shell, Amoco, Gulf Oil and Texaco) conducted exploration activities in the region. These activities included the acquisition of seismic data and exploratory well drilling, in addition to various surface field studies that comprised photogeological and geological mapping and section measuring. Gulf Oil documented a black, fetid pool formed by H_2S gas bubbling through outcrops of black siliceous shale on Caribou River (Capstick, 1968) - shale which they assigned to the Middle-Upper Devonian Canol Formation which was later included in the unit 'Cf' by Norris (1981a).

In the Yukon Peel Plateau and Plain, 19 wells were drilled during this early exploration phase by companies looking for oil (Oil and Gas Resources Branch, 2000; Fig.1; *see* Table 1 for wells referred to in this report). All wells were plugged and abandoned after being deemed dry, although well history reports from twelve wells describe 21 minor gas shows in drill stem tests from various stratigraphic intervals. Well cuttings and a small amount of drill core were retrieved and are stored at the GSC Calgary core and sample repository. In well history reports, Devonian to Carboniferous strata were named 'Mississippian' or 'M-D' without differentiating any separate dark shale units possibly correlative to unit 'Cf'. In the Yukon Peel Plateau, no new wells have been drilled or seismic data acquired since this initial phase of exploration.

A number of thematic studies were conducted in the region including Pugh's (1983) subsurface compilation of the Peel area which tied into surface geology. This study assigned all strata in the Peel area between the Upper Devonian Imperial Formation and the Mesozoic unconformity to the Tuttle Formation, including thick packages of fine-grained siliciclastic rocks.

Table 1. *Summary of oil and gas exploration wells referred to in this paper. Total depth is measured below Kelly Bushing (KB).*

Unique Well Identifier (UWI)	Well Name	Region	KB Elev (m)	KB Elev (ft)	UTM Easting (NAD 83)	UTM Northing (NAD 83)	Total Depth (m)	Total Depth (ft)
300F376700134450	PEEL Y.T. F-37	Peel Plateau	54.6	179.1	505828	7424583	3368.0	11049.7
300C606650133450	ARCTIC RED Y.T. C-60	Peel Plateau	92.0	301.8	547342	7410967	2599.9	8529.8
300H376640134450	TRAIL RIVER Y.T. H-37	Peel Plateau	393.2	1290.0	506690	7387303	3721.6	12209.8
300H716630134300	PEEL Y.T. H-71	Peel Plateau	513.0	1683.1	512283	7357906	3419.6	11219.0
300N256620134450	CARIBOU Y.T. N-25	Peel Plateau	495.3	1625.0	507812	7347570	3600.3	11811.9
300I216620134150	PEEL R Y.T. I-21	Peel Plateau	381.2	1250.6	531244	7339738	2072.6	6799.8
300M696610133450	PEEL RIVER Y.T. M-69	Peel Plateau	291.7	957.0	546663	7336990	3272.6	10736.7
300K156600133000	TAYLOR LAKE Y.T. K-15	Peel Plateau	468.8	1538.0	588702	7311333	2378.7	7804.0
300A426550133001	CRANSWICK Y.T. A-42	Peel Plateau	620.1	2034.4	585010	7286314	4267.2	13999.8
300D616630137000	N. PARKIN Y.T. D-61	Eagle Plain	489.2	1605	400618	7359179	3352.8	10999.9
300B626620138300	N. CATH Y.T. B-62	Eagle Plain	540.1	1772	603584	7342641	2138.5	7016.0

A collaborative research project conducted between 2005 and 2009 included thematic studies based largely on field investigations. These studies are compiled in the 'Regional Geoscience Studies and Petroleum Potential, Peel Plateau and Plain, NWT and Yukon: Project Volume' (Pyle and Jones, 2009). The project spanned the Yukon-Northwest Territories border and included Cambrian to Cretaceous stratigraphic, structural and petroleum potential studies. Chapter 8 – Late Devonian to Carboniferous Strata II – Tuttle Formation Play includes a brief description of unit 'Cf' and its petroleum potential (Allen *et al.*, 2009). Research conducted as a part of this project includes documenting evidence of oil shows in surface exposures for this region (Allen *et al.*, 2008a). Another study includes analysis of a gas sample, collected in winter, at the surface of Turner Lake (Fig. 4; Allen and Osadetz, 2013).

A conventional reservoir petrophysical assessment of wireline geophysical logs from 17 wells in the Peel Plateau and Plain exploration region of Yukon was conducted to highlight specific geological formations with the potential to host economic quantities of conventional hydrocarbons (Fraser, 2011). This report identified the Tuttle Formation, with shale intercalations similar to and possibly correlative with unit 'Cf', as containing the best prospectivity for hosting hydrocarbons. Although the study did not assess unconventional reservoirs, it did recommend further study to assess hydrocarbon accumulations in 'intraformational' shale of the Tuttle and Ford Lake Shale formations, which may include unit 'Cf'.

Unconventional oil and gas potential in Yukon was assessed in a recent scoping study (Hayes and Archibald, 2012). This study was the first systematic attempt to characterize unconventional hydrocarbons in Yukon and evaluate Phanerozoic formations on a basin-by-basin basis. For Peel Plain and Plateau, the Ford Lake Shale is identified as a possible shale target in central to western Peel Plateau with good (?) prospectivity. Due to terminology inconsistencies (*see* section on Unit 'Cf' definition) it is interpreted that this report had been referring to the 'Cf' map unit, which on recent maps has been called Ford Lake Shale. Further mapping of its subsurface distribution and a better understanding of its characteristics were recommended in order to further quantify its potential.

Unit 'Cf': definition and nomenclature

Norris (1981a, 1982a,b) assigned "shale, dark grey, silty, concretionary; marine and nonmarine" rocks observed in outcrop along the eastern flank of the Richardson Mountains north of 66°N to unit 'Cf'. In contrast, Norris (1982b) assigned strata of the same lithological description on the eastern flank of the Richardson Mountains south of 66°N and those at Eagle Plain (on the western side of the Richardson Mountains) to map unit 'CF', which Norris correlated with Ford Lake Shale of the Kandik Basin of eastern Alaska and western Yukon (Brabb and Churkin, 1967; Brabb, 1969; Fig. 1). This 'Cf' versus 'CF' naming convention is consistently used on bedrock maps in the Operation Porcupine study area (65°N, 132°W to 67°N, 138°W; Norris, 1981a,b; 1982a,b,c). Subsequently, strata originally mapped as 'Cf' and 'CF' were later assigned to the Ford Lake Shale on a regional compilation map for the area (Norris, 1985a) and on the Yukon Digital Geology Map (Gordey and Makepeace, 2003).

The Ford Lake Shale, as defined by Brabb (1969) from exposures along the banks of the Yukon River, Alaska which were dated as Late Devonian to Late Mississippian, consists of "predominantly greyish-black siliceous shale and laminated greyish-black chert that splits with a slabby parting". Descriptions of the Ford Lake Shale are also recorded from river sections and road cuts along the Dempster Highway where it crosses Eagle Plain, as well as from 11 boreholes in Eagle Plain and two boreholes in the Kandik Basin (*e.g.*, Richards *et al.*, 1993; Pugh, 1983; Hamblin, 2006; Brabb, 1969; Brabb and Churkin, 1967). Recent palynological studies indicate that the Ford Lake Shale in Yukon ranges from early Famennian to as young as Viséan (Early Carboniferous; Utting, 2006; Dolby, 2010, 2011).

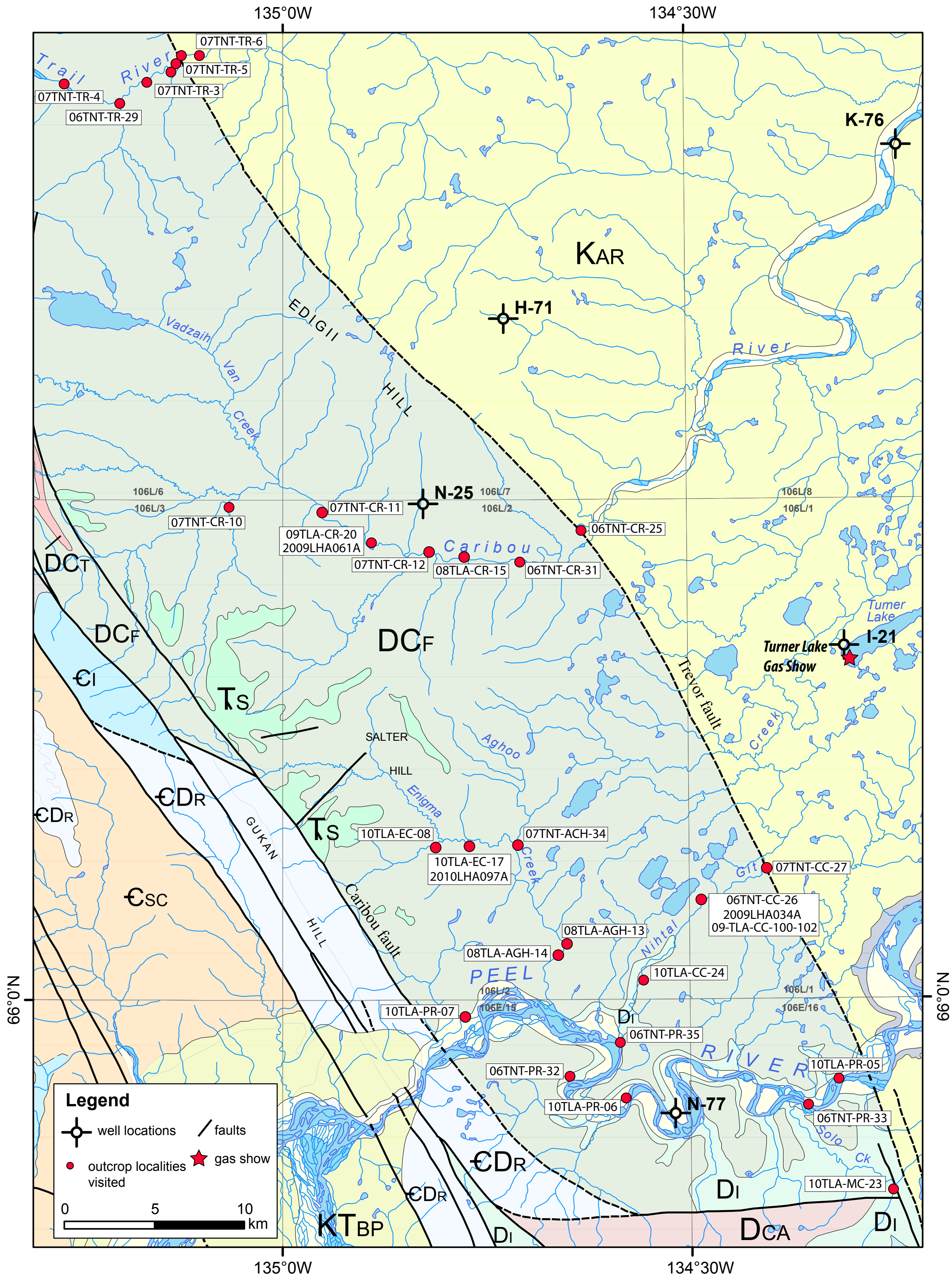


Figure 4. *Geological map of study area with section and sample locations (NTS map sheets 106E/15,16; 106L/1,2,3,6). Geology is from Norris (1985a) and Gordey and Makepeace (2003). KAr=Arctic Red Fm, KTBP=Bonnet Plume Fm, TS=Shublik Fm, DCF=unit 'Cf', DCT=Tuttle Fm, DI=Imperial Fm, DCA=Canol Fm, CDR=Road River Group, CSC=Slats Creek Fm.*

Other than the Operation Porcupine geology maps, little to no literature exists regarding unit 'Cf' in the eastern Richardson Mountains and Peel area (Allen *et al.*, 2009). No complete section of unit 'Cf' has been documented and its distribution in the subsurface is unknown. Hence, to rigorously evaluate Norris' (1985a) correlation of unit 'Cf' with the Ford Lake Shale and to determine both its surface and subsurface extent will require more information. As an aside, it should be noted that some Famennian and Strunian age determinations on unit 'Cf' had been available to Norris (1981a, 1982a,b) at the time, but the unit was designated as 'Cf' because, prior to 1983, the Strunian was included in the Tournaisian Stage of the Early Carboniferous, hence the 'C' in the designation 'Cf'. In 1983, however, the Strunian was placed at the top of the Famennian, the uppermost stage of the Devonian (Paproth *et al.*, 1983).

Objective, methods and study area

The objectives of this study are to describe unit 'Cf', and to acquire and interpret age, source/reservoir rock geochemical data from both reconnaissance and detailed sedimentological examination and sampling of unit 'Cf' in the Peel area, Yukon. These results are used to identify the hydrocarbon potential of the 'Cf' unit and to characterize the unit in the subsurface using existing well information. Outcrop measured sections revealed multiple lithofacies within unit 'Cf'. Samples of unit 'Cf' were examined using X-ray diffraction (XRD) to estimate quartz, clay and carbonate mineralogy. Palynology was used to constrain the age of strata and to better define stratigraphic relationships. Rock-Eval/ TOC pyrolysis was used to identify organic matter type and amount, depositional source and thermal maturity. Organic petrology and vitrinite reflectance provided additional information on organic matter type and thermal evolution. Source rock richness and maturity were characterized with organic solvent extract data. These new data were compared with data from exploration boreholes (*e.g.*, cuttings logs, TOC contents and biostratigraphic age determinations) to determine if unit 'Cf', currently not reported, is present in the subsurface having previously been included with other units, *e.g.*, the Tuttle Formation.

The study area lies between 65°45' and 67°00'N latitude and 134°00' and 135° 30'W longitude and is within the eastern Richardson Mountains and Peel Plateau physiographic regions of Matthews (1986; Figs. 1 and 4). Unit 'Cf' is exposed over an outcrop area of approximately 900 km2 extending from Caribou River (NTS map 106L/2; Fig. 4) east to Peel River where the Trevor fault separates Paleozoic from Cretaceous strata, as mapped by Norris (1981a, 1982b; NTS map 106E/16; Fig. 4). At the western extent of unit 'Cf', the northwest-trending Caribou fault separates the succession from the older Road River Group as is observed on Peel River (106E/15; Fig. 4; Norris, 1982b). The best exposures in the region occur in river cuts along the flanks of the Richardson Mountains where structural uplift has brought Paleozoic strata to the surface that are, in part, contiguous with strata of the Peel's subsurface.

LITHOSTRATIGRAPHIC CHARACTER

Outcrop exposures

Fieldwork for this project consisted of sedimentological description and sampling of measured sections and isolated outcrop localities. Locations examined and sampled for this study occur on Trail River (5 exposures), Caribou River (7), Enigma Creek (2), Aghoo Creek (3), Nihtal Git Creek (3), Peel River (6) and one exposure on Solo Creek (Fig. 4; Table 2). Drainages containing the best exposures of unit 'Cf' include Nihtal Git Creek, Aghoo Creek, Enigma Creek, Caribou River and Peel River (NTS map sheets 106L/1 and 2, and 106E/15) where up to 120 m of primarily dark grey to black siliceous shale, siltstone, and lesser intercalated sandstone and mudstone are semi-continuously exposed. These exposures are described below. Note that the same exposures sometimes have several section identification names, due to revisits over several years.

Table 2. *Outcrop locations visited for this study including UTM locations. These locations are plotted on Figure 4.*

Outcrop location name	UTM Easting (NAD 83)	UTM Northing (NAD 83)	Measured Section (M) or Spot Samples (S)
Trail River			
07TNT-TR-3	492374	7371087	S
07TNT-TR-4	487861	7371005	S
07TNT-TR-5	493679	7371673	S
07TNT-TR-6	494378	7372521	S
06TNT-TR-29	490861	7369955	S
Caribou River			
07TNT-CR-10	496904	7347179	S
07TNT-CR-11	501987	7347079	S
07TNT-CR-12	508013	7344901	S
08TLA-CR-15	509918	7344555	S
09TLA-CR-20	504747	7345353	S
06TNT-CR-25	516767	7345965	S
06TNT-CR-031	512994	7344407	S
2009LHA061A	504842	7345454	S
Enigma Creek			
10TLA-EC-08	508295	7328484	S
10TLA-EC-17	510172	7328515	M
10LHA097A	510183	7328517	M
Aghoo Creek			
08TLA-AGH-13	515667	7323109	S
08TLA-AGH-14	515172	7322454	S
07TNT-ACH-34	512804	7328585	S
Nihtal Git Creek			
06TNT-CC-026	523198	7325395	M
07TNT-CC-27	526761	7327329	S
10TLA-CC-24	519922	7321064	S
09TLA-CC-100	523211	7325558	S
09TLA-CC-101	523211	7325558	S
09TLA-CC-102	523211	7325558	S
2009LHA034A	523222	7325735	M
Peel River			
06TNT-PR-32	515914	7315451	S
06TNT-PR-33	529110	7314150	S
06TNT-PR-35	518634	7317560	S
10TLA-PR-05	530707	7315600	S
10TLA-PR-06	519227	7314347	S
10TLA-PR-07	509962	7319034	S
Solo Creek			
10TLA-MC-23	533860	7309439	S

A 120-m-thick continuous exposure of flat-lying, predominantly dark grey to black shale containing minor interbedded sandstone occurs on Nihtal Git Creek (06TNT-CC-26; 09TLA-CC-100 to 102; 2009LHA034A; Figs. 4 and 5a). The section is very steep and is capped with resistant, siliceous, burnt red shale (Fig. 5b). This section was described in historical reports by Stelck (1944) and Shell Canada Ltd. (1965), who informally named the creek "Calamites Creek".

The Aghoo Creek section (08TLA-AGH-13 and 14; Fig. 6), is approximately 20 m thick and flat-lying, resulting in laterally continuous exposures along a north-south distance of 10 km on both the west and east sides of the drainage. A portion of this section has been burnt and is locally actively burning today.

A continuously exposed section occurs on the south side of an unnamed tributary of Aghoo Creek (10TLA-EC-17; 10LHA097A; Fig. 4). This tributary was referred to as 'Enigma Creek' by Shell's 1964 field party who measured a stratigraphic section west of this locality (Shell Canada Ltd., 1965), currently covered by a slump. East of Shell's section, however, is this flat-lying section of predominantly dark grey to black shale in the lower half of the exposure (Fig. 7a). An interval of interbedded shale and coarse-grained sandstone that displays lithological similarity to the Upper Devonian to Lower Carboniferous Tuttle Formation caps this section (Fig. 7b). The exposure is greater than 130 m high, with the interbedded sandstone and shale interval starting approximately 100 m from the base of the section.

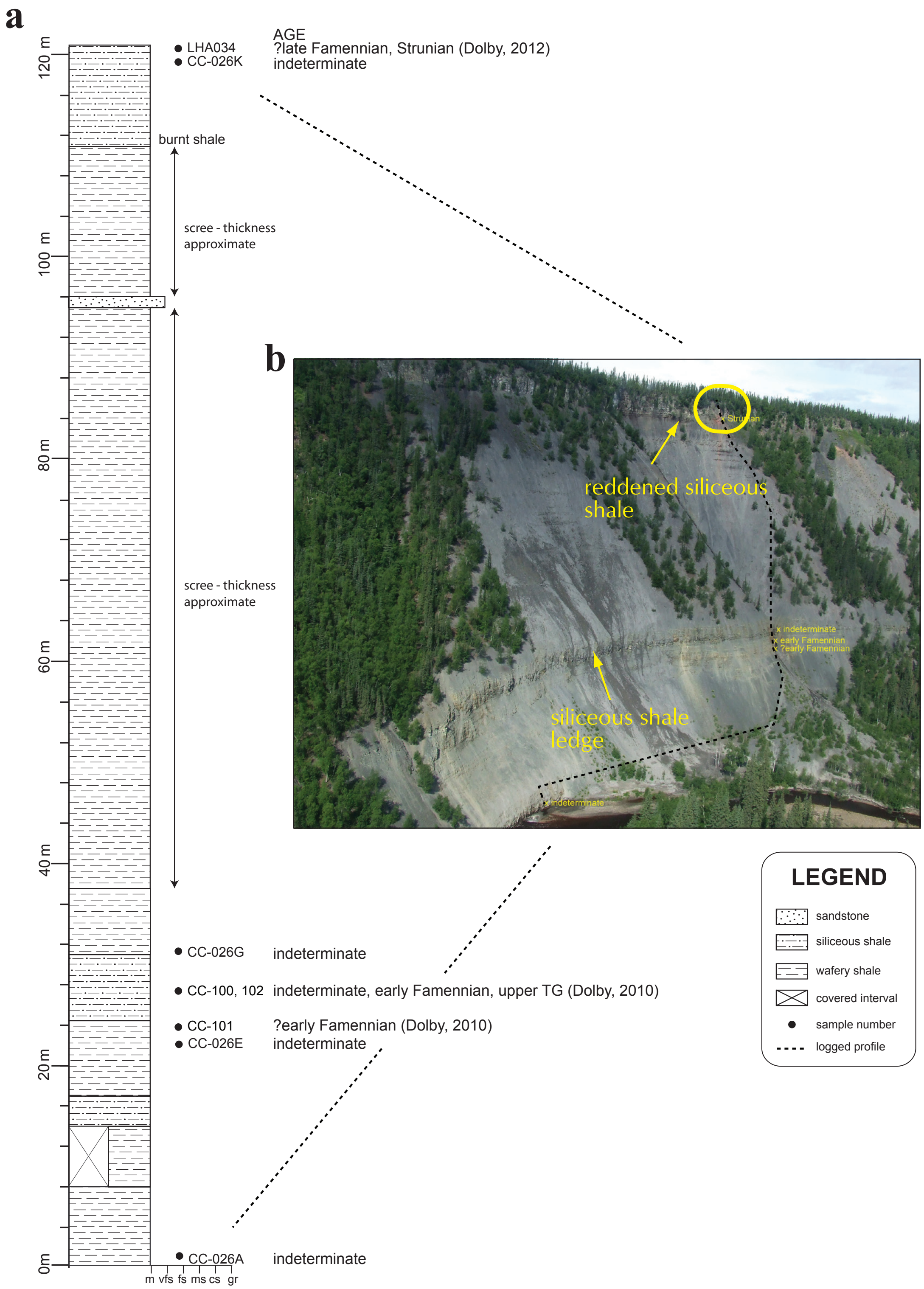


Figure 5. *a) Measured stratigraphic section (06TNT-CC-26) and b) outcrop photograph of black shale of the Upper Devonian unit 'Cf' of Norris (1981a) on Nihtal Git Creek (aka Calamites Creek). Bedding is horizontal at this location. The resistant light weathering bands are composed of siliceous shale. Outcrop exposure is approximately 120 m high. Note the red shale exposed at the top of the cliff that has previously been subjected to elevated temperatures.*

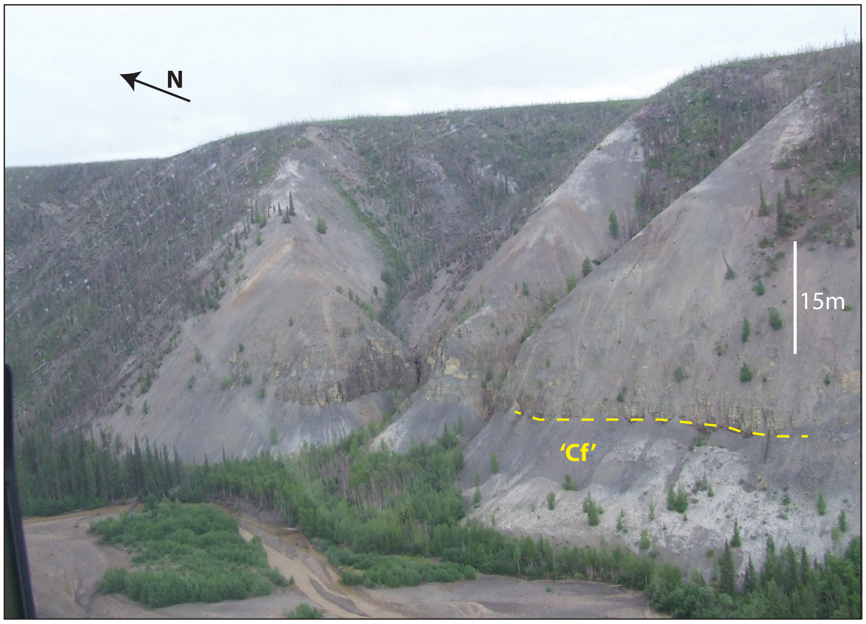


Figure 6. *Unit 'Cf' exposed on Aghoo Creek (08TLA-AGH-13).*

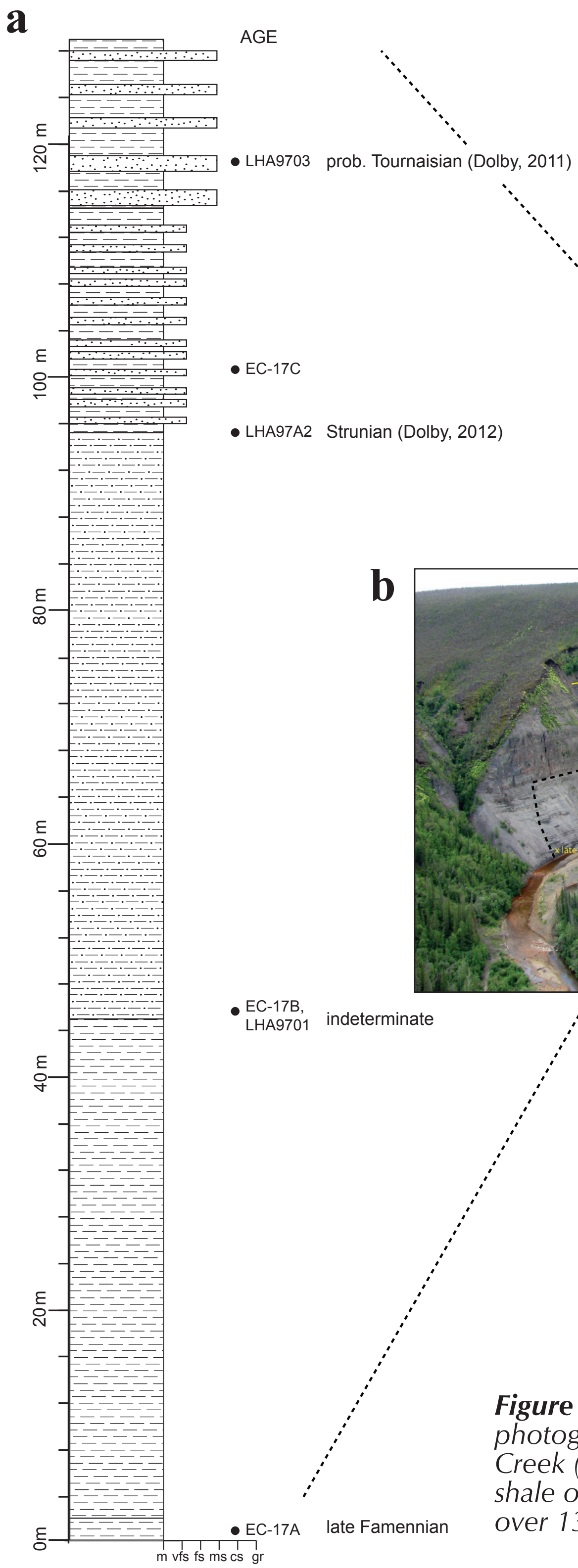
A series of outcrops occur on Caribou and Peel rivers, where the unit is semi-continuously exposed for approximately 8 km west to east (exposures 09TLA-CR-20, 2009LHA061A; 07TNT-CR-12, 08TLA-CR-15 and 06TNT-CR-31 on Caribou River; exposure 10TLA-PR-07 on Peel River; Fig. 4). Flat-lying exposures on Caribou River are generally 10 to 15 m high; however, where the river narrows, canyon-like exposures occur that are in contrast to the adjacent subdued topography with wider valleys.

Biostratigraphy and contacts

Palynological studies were conducted on 29 samples from units mapped as 'Cf'. These studies were completed at the Palynology Laboratory, Geological Survey of Canada, Calgary (GSC,C), using techniques described in Wood *et al.* (1996; Table 3). The majority of these samples yielded Fammenian (Upper Devonian) dates (*see* Table 4 and Appendix A).

The contacts between unit 'Cf' and over and under-lying formations are generally obscured in the study area, with the unit's basal contact typically inferred from Norris' (1981a) map. The upper contact of unit 'Cf' was observed on Caribou River (09TLA-CR-020) and Enigma Creek (10-TLA-EC-17; Fig. 7). At both of these localities, sandstone intercalated with shale (interpreted as distal? Tuttle Formation) directly overlies black, siliceous shale of unit 'Cf'. At the Caribou River locality, this overlying intercalated sandstone is locally well-indurated, very fine grained, olive grey on fresh surfaces and weathers reddish to yellowish brown. Sandstone beds are 5-40 cm thick and exhibit flat to undulating erosive bases, parallel-laminated middles and rippled tops. On Enigma Creek, approximately 10 m of thinly bedded, very fine grained sandstone overlies unit 'Cf'. A single palynological sample from the base of this intercalated interval at this location (*see* Fig. 7a and Table 4, sample 10LHA097A02) yielded undifferentiated Fammenian to Strunian date estimates (Dolby, 2012).

This intercalated interval is in turn overlain by more thickly bedded, coarser-grained sandstones that display a more similar lithological character to the true Tuttle Formation (*i.e.*, they contain mud rip-up clasts, vari-coloured chert granules and small pebbles). These thicker bedded sandstones exhibit lateral thickness variability, and are interbedded with shale dated from one palynological sample as Tournaisian (Dolby, 2011; see Table 4, sample 10LHA097A03). These uppermost strata may represent the youngest rocks below the Mesozoic unconformity in the Peel area.



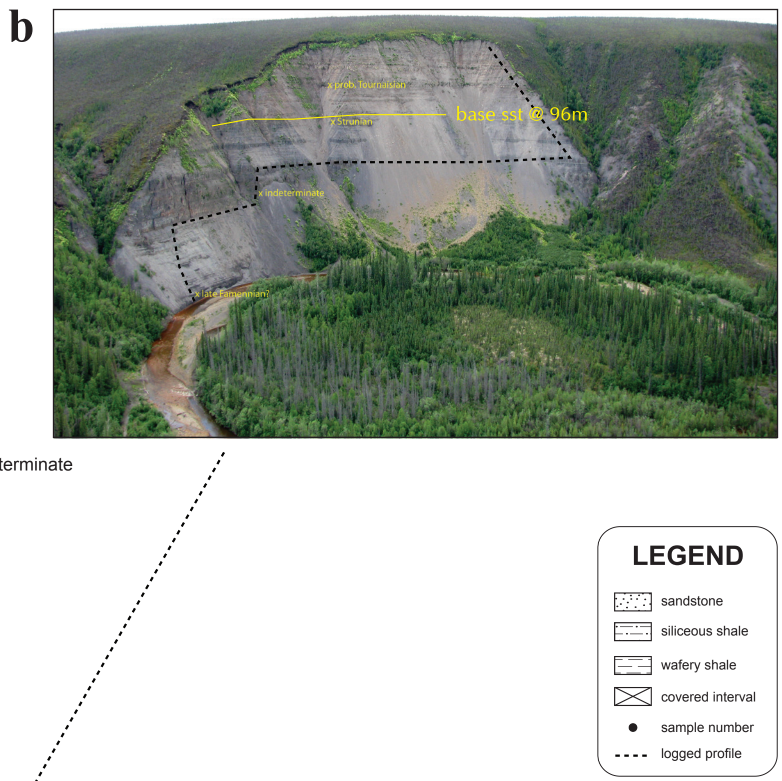


Figure 7. *a) Measured stratigraphic section and b) outcrop photograph of black shale of unit 'Cf' on south side of Enigma Creek (10TLA-EC-17). Note the succession of sandstone and shale observed overlying shale of unit 'Cf'. Outcrop exposure is over 130 m high.*

Table 3. *Summary of palynology results and corresponding thermal alteration indices (TAI) for samples of unit 'Cf'. Vitrinite reflectance data (%Ro$_R$) from Table 8 is offered for cross-referencing purposes. All UTM locations are NAD83, Zone 8. See Appendix A for more detailed information.*

Sample Name	GSC #	Location	UTM Easting	UTM Northing	Geological Unit	Probable Age	TAI	%Ro$_R$
Cf' map unit								
07TNT-ACH-34A	473147	Aghoo Creek	512804	7328585	Cf'	indeterminant[3]	2+?	0.85
07TNT-ACH-34B	473148	Aghoo Creek	512907	7328592	Cf'	Famennian?[3]	2+?	
07TNT-ACH-34C	473149	Aghoo Creek	512907	7328592	Cf'	Late Devonian[3]	2+?	
08TLA-AGH-13-03	532934	Aghoo Creek	515666	7323109	Cf'	indeterminant[2]	3/3+	
08TLA-AGH-13-04	532935	Aghoo Creek	515666	7323109	Cf'	indeterminant[2]	3/3+	0.72
08TLA-AGH-14-02	532936	Aghoo Creek	515172	7322454	Cf'	indeterminant[2]	3/3+	
06TNT-CR-031A/C	473070	Caribou River	512994	7344407	Cf'	Late Famennian (Strunian)[1]	2	0.67
07TNT-CR-010A	473171	Caribou River	496967	7347199	Tuttle or Cf	Famennian, Late Devonian[2]	2	
07TNT-CR-011A/B	473173	Caribou River	501997	7347100	Tuttle or Cf	Famennian, Late Devonian[2]	2	0.56
07TNT-CR-12A	473174	Caribou River	507992	7344887	Cf'	Famennian, Late Devonian[2]	2	0.50
2009LHA061A01	486335	Caribou River	504842	7345454	Cf'	Late Famennian (Strunian)[6]		0.85
08TLA-CR-15-02	532937	Caribou River	509918	7344555	Cf'	indeterminant	3/3+	
08TLA-CR-15-03	532938	Caribou River	509918	7344555	Cf'	Famennian[2]	3/3+	
10TLA-EC-08A	542069	Enigma Creek	507324	7328157	Cf'	?Devonian[5]	high	
10TLA-EC-17A	542102	Enigma Creek	510172	7328515	Cf'	Late Famennian[5]		0.75
10LHA097A01	491862	Enigma Creek	510183	7328517	Cf'	indeterminant[5]		0.81
10LHA097A02	491863	Enigma Creek	510183	7328517	Cf'	Late Famennian (Strunian)[6]		
10LHA097A03	491864	Enigma Creek	510183	7328517	Cf'	probably Tournaisian[5]		0.72
06TNT-CC-026A	473066	Nihtal Git Creek	523198	7355395	Cf'	indeterminant[1]	2	
06TNT-CC-026E	473074	Nihtal Git Creek	523225	7325515	Cf'	indeterminant[2]	3+(?)	
06TNT-CC-026G	473075	Nihtal Git Creek	523295	7325620	Cf'	indeterminant[2]	3+(?)	
06TNT-CC-026J/K	473067	Nihtal Git Creek	523167	7325671	Cf'	indeterminant[1]	2	0.65
07TNT-CC-27A	473143	Nihtal Git Creek	526761	7327329	Cf'	Late Devonian (late Famennian?)[3]	2	0.87
09TLA-CC-100-1	491978	Nihtal Git Creek	523211	7325558	Cf'	indeterminant[6]		0.95
09TLA-CC-101-1	536450	Nihtal Git Creek	523211	7325558	Cf'	?Early Famennian[4]		
09TLA-CC-102-1	536455	Nihtal Git Creek	523211	7325558	Cf'	Early Famennian[4]		
2009LHA034A01	486318	Nihtal Git Creek	523222	7325735	Cf'	?Late Famennian (Strunian)[6]		
10TLA-PR-07A	542067	Peel River	509962	7319034	Cf'	indeterminant[6]		
10TLA-PR-07B	542068	Peel River	509989	7319018	Cf'	indeterminant[6]		0.89

[1] Utting, 2007
[2] Utting, 2009
[3] Utting, 2008
[4] Dolby, 2010
[5] Dolby, 2011
[6] Dolby, 2012

Table 4. *Mineralogical compositions of unit 'Cf' samples from XRD semi-quantitative analyses (expressed in mineral weight percent). '*' refers to a sample of yellow efflorescence or sulphur precipitate commonly found on weathered surfaces of the shale. See Fig. 24 for results plotted on ternary diagrams. All UTM coordinates are NAD83, Zone 8.*

Sample Name	GSC-C#	Location	UTM Easting	UTM Northing	Mixed-Layer Clay (%)	Mica/Illite (%)	Kaolinite &/or Chlorite (%)
Cf' map unit							
08-TLA-AGH-14-2	C532936	Aghoo Creek	515172	7322454	1	2	
08-TLA-AGH-14-3	C485384	Aghoo Creek	515172	7322454	trace	2	trace
08-TLA-AGH-13-4	C532935	Aghoo Creek	515666	7323109	trace	2	trace
08-TLA-CR-15-1	C485385	Caribou River	509918	7344555	1	2	
08-TLA-CR-15-2	C532937	Caribou River	509918	7344555	1	3	trace
08-TLA-CR-15-4	C485386	Caribou River	509762	7344630	2	3	1
10-TLA-EC-08A	C542069	Enigma Creek	507324	7328157	trace	1	trace
06-TNT-CC-26B	C473073	Nithal Git Creek	523198	7325395	1	1	
06-TNT-CC-26D	C473115	Nithal Git Creek	523163	7325414	trace	2	trace
10TLA-PR-07A	C542067	Peel River	509989	7319018	1	1	
10-TLA-PR-07B	C542068	Peel River	509989	7319018	trace	1	
08-TLA-CR-15-5*	C481985A	Caribou River	509762	7344630	1	3	1

Table 4 continued

Sample Name	Total Clay (%)	Quartz (%)	Plagioclase (%)	Jarosite (%)	Pyrite (%)	Other minerals (%)	Lithofacies
Cf' map unit							
08-TLA-AGH-14-2	3	96		1			wafery shale
08-TLA-AGH-14-3	2	96		1		Anhydrite 1%	siltstone/siliceous shale
08-TLA-AGH-13-4	2	98		trace			siliceous shale
08-TLA-CR-15-1	3	96		trace		Anhydrite 1%	siliceous shale
08-TLA-CR-15-2	4	95		trace		Anhydrite 2%	wafery shale
08-TLA-CR-15-4	6	92		trace		Barite 2%	wafery shale
10-TLA-EC-08A	1	98				Anhydrite? 1%	siliceous shale
06-TNT-CC-26B	2	98		trace			siliceous shale
06-TNT-CC-26D	2	98			trace		siltstone/siliceous shale
10TLA-PR-07A	2	95	3	trace		Gypsum - trace	siliceous shale
10-TLA-PR-07B	1	98	1				wafery shale
08-TLA-CR-15-5*		94			1	Coquimbite 30%; Aluminocopiapite 59%; Halotrichite 11%	yellow effloresence on shale surface

Lithofacies of unit 'Cf'

Lithofacies interpretations are based on lithological descriptions from ten field stations on Peel and Caribou rivers, and Aghoo, Nihtal Git and Enigma creeks (Fig.4; Table 2). In this study, the term shale refers to fissile, or layered sedimentary rocks composed of clay-size particles, whereas mudstone refers to sedimentary rocks that lack fissility and are composed of clay and silt-sized particles.

Strata of unit 'Cf' can be divided into five lithofacies based on grain size, colour (fresh and weathered), mechanical properties and sedimentary features: 1) siliceous shale, 2) wafery shale, 3) siltstone, 4) sandstone, and 5) mudstone. These lithofacies are described below in order of abundance and summarized in Table 5. Differential weathering of the unit 'Cf' shale results in extensive exposure of siliceous, resistant units and the localized development of pillars of less resistant, wafery shale along river valleys.

Siliceous shale

Rocks assigned to the siliceous shale lithofacies consist of dark grey to black shale that weathers grey to bluish grey, greenish yellow, yellowish grey, yellowish orange and/or black. This lithofacies is characterized by fissile and brittle shale that breaks into sharp plates 2 mm to 2 cm thick (Figs. 8 and 9) and has a distinctive glass-like or porcelain-like sound when being broken. Siliceous shale is interbedded with wafery shale, (*see* section on wafery shale) in intervals 3-10 cm thick. Parallel laminae (mm-scale) are the only sedimentary structures observed. Dark grey concretions, generally less than 3 cm in diameter are common. The combination of its resistant, cliff-forming nature and common popcorn-like white to yellow chalky surface efflorescence (Fig. 10) makes this lithofacies difficult to distinguish

Table 5. *Lithofacies of unit 'Cf' as observed in eastern Richardson Mountains, with accompanying field descriptions.*

Lithofacies	Fresh colour	Weathering colour	Mechanical properties	Sedimentary Structures	Other	Figure No.
Siliceous shale	dark grey to black	black; bluish-grey; yellowish-grey; greenish yellow; yellowish-orange	fissile and brittle; breaks into sharp plates 2 mm to 2 cm thick; forms resistant cliffs which can weather to pillars	parallel laminations/ beds; laminae/beds 3 mm to 2 cm; in intervals 3-10 cm thick	compressed plant debris observed; petroliferous; smells sulphurous; nodular (mm to cm-scale); porcelain-like sound when broken; disseminated pyrite	8,9
Wafery shale	medium/dark grey to black	greyish yellow; pale yellowish orange; black	fissile; splits easily into paper or wafer-thin sheets; breaks easily by hand	parallel laminations; forms mm-scale partings; occurs in intervals 5-15 cm thick		13,14
Siltstone	greyish black; olive grey; grey	orange	resistant; well-indurated	parallel laminations; forms beds 3-15 cm thick; tabular and laterally continuous beds	petroliferous odour when struck with hammer; locally oil-stained	15
Sandstone	grey to olive grey	dark yellowish orange with white efflorescence	resistant to recessive; well-indurated	fine-grained sandstone; beds up to 55 cm thick are laterally continuous; parallel-laminae and ripple marks observed	vertical burrows and horizontal feeding traces attributed to *Cruziana* ichnofacies; ammonoid imprint in one location; plant debris; petroliferous odour when struck with hammer	16
Mudstone	light to dark grey	pale yellow	soft; breaks into small blocks <1 cm in diameter; non-fissile	structureless; occurs in intervals 4-12 cm thick		17

***Figure 8.** Dark grey to black siliceous shale characteristic of unit 'Cf' in the study area.*

***Figure 9.** Weathered shards of siliceous shale of unit 'Cf' as observed on Aghoo Creek. Hammer for scale is 30 cm long. (08TLA-AGH-13).*

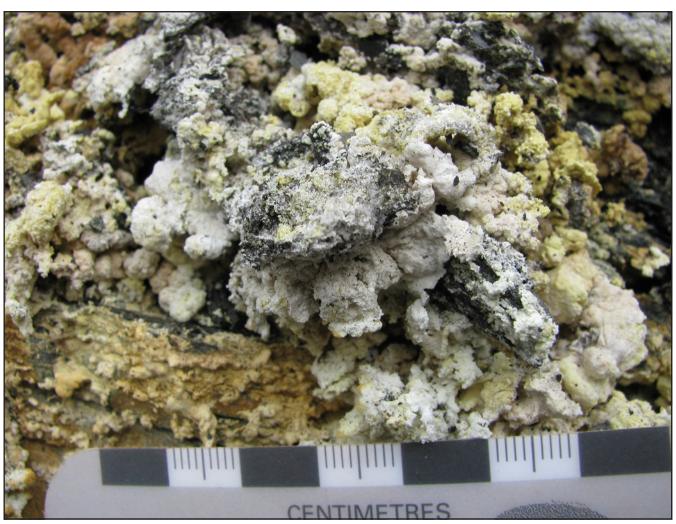


***Figure 10.** Close up of yellow efflorescent crust on shale as commonly observed on the weathered surfaces of unit 'Cf'. XRD results for this sample are reported in Table 3 and include rare aluminosilicate minerals such as coquimbite and aluminocopiapite.*

from sandstone at a distance (Fig. 5b). Other distinctive features of this lithofacies include the common presence of gypsum crystals on bedding planes, together with a sulphurous to petroliferous odour indicative of high organic content when the rock is broken.

A sample of the popcorn-like white to yellow chalky surface efflorescence was collected from the Caribou River section. XRD analysis showed it to be composed of the following metal-sulphate salts: 30% coquimbite, $Fe_2(SO_4)_3.9H_2O$; 59% aluminocopiapite $(Mg,Al)(Fe,Al)_4(SO_4)_6\ (OH)_2.20H_2O$; and 11% halotrichite $Al_2Fe(SO_4)_4.22H_2O$. Each of these is a secondary mineral typically formed by the oxidization of iron sulphide (pyrite) deposits in shale (Buckby *et al.*, 2003) and the presence of finely disseminated pyrite was noted in outcrop. XRD analyses also detected pyrite in a small number of shale samples, in addition to trace amounts of jarosite $KFe^{3+}{}_3(OH)_6(SO_4)_2$ in most samples of unit 'Cf' (Table 4), suggesting that the oxidization of pyrite is likely the process by which these sulphate salts were produced.

Along Aghoo and Nihtal Git creeks, siliceous black shale has been altered to a red colour at the top of the outcrop exposures. In these strata, fresh shale surfaces vary from black to very light grey and weathered surfaces vary from pink to reddish-brown (Figs. 11 and 12). The resulting pink to red outcrop distribution can be observed on coloured satellite imagery.

Wafery shale

The wafery shale is medium grey to black on fresh surfaces and weathers greyish-yellow, yellowish-orange and black. It is characterized by a tendency to split into paper or wafer-like sheets (laminae) on a millimeter-scale (Figs. 13 and 14), and it can easily be broken by hand. Its weathering character suggests a higher clay content than the siliceous shale, although XRD results from this study indicate little variation in composition (92-98% quartz versus 95-98% in the siliceous shale; Table 3). Intervals of this lithofacies are generally 5 to 15 cm thick.

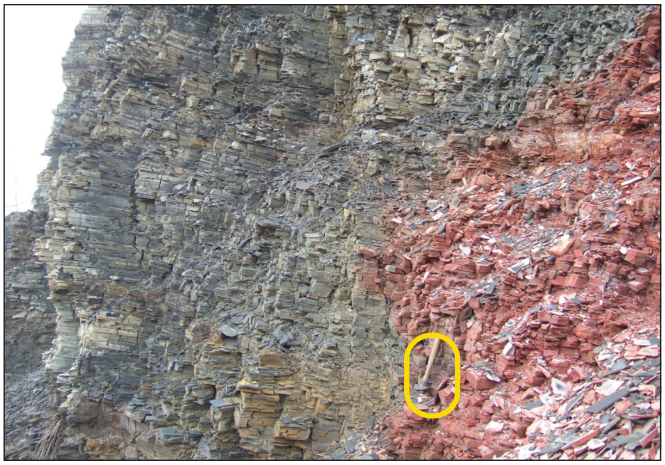


Figure 11. *Shale at section 08TLA-AGH-14, typical of unit 'Cf' as observed in the Peel area, is oxidized from dark grey or black to pale or moderate reddish-brown as a result of burning of the rock. Hammer is 30 cm long.*

Figure 12. *Close up of oxidized shale in Fig. 11.*

Figure 13. *Medium to dark grey wafery, fissile shale. Note centimetre-scale on top of scale card. (08TLA-CR-15).*

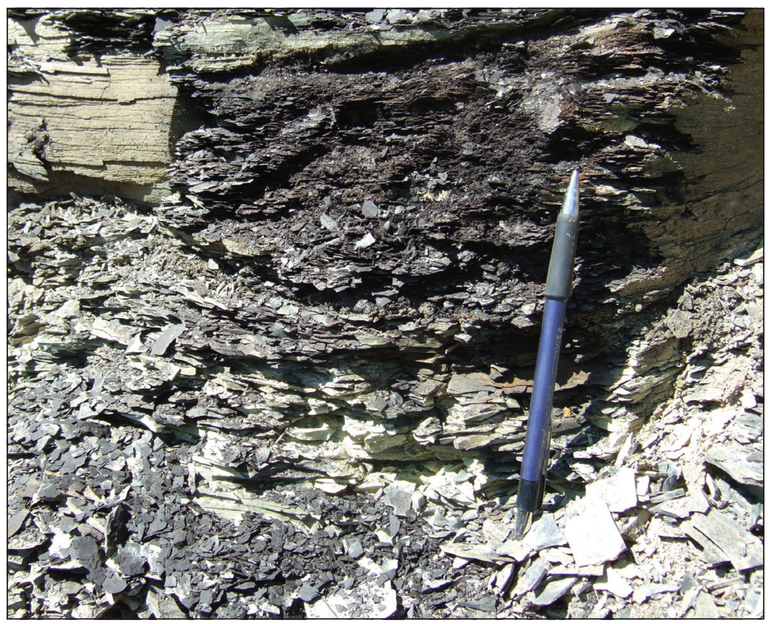


Figure 14. *Wafery shale of unit 'Cf' as observed on Nihtal Git Creek (06TNT-CC-26). Pencil for scale.*

Siltstone

This lithofacies is less common than either shale facies. On fresh surfaces, the siltstone is greyish- black, grey and olive grey (Fig. 15), and weathers orange. Siltstone beds are between 3 and 15 cm thick, tabular and laterally continuous along the length of outcrops (tens of metres). The siltstone is resistant and well-indurated with parallel laminae. A petroliferous odour is given off when struck with a hammer, and oil-staining was confirmed in siltstone at the GSC Organic Geochemistry Lab, Calgary, Alberta (Allen *et al.*, 2008a, 2009).

Figure 15. *Siltstone of unit 'Cf' from Aghoo Creek (07TNT-ACH-34). This sample was submitted for organic solvent extraction analyses and tested positive for a hydrocarbon show (see Allen et al., 2008a, 2009).*

Sandstone

Sandstone beds are not common in unit 'Cf', comprising less than 10% of section. This lithofacies consists of very fine grained sandstone. It is grey to olive grey on fresh surfaces and weathers yellowish-orange with a white efflorescence. Bedding thickness ranges from less than 1 cm to 55 cm, and beds are laterally continuous over the extent of the outcrop exposures. Sedimentary structures noted within the sandstone include parallel-laminae (locally calcareous) and ripple marks. This lithofacies exhibited a petroliferous odour when hammered.

Mudstone

The mudstone lithofacies is the least commonly observed lithofacies in the 'Cf' unit, however, it may be underrepresented in outcrop due to its recessive nature and its likelihood of being covered. This lithofacies is light to dark grey on fresh surfaces. It commonly weathers to pale yellow, small blocks (<1 cm diameter). The mudstone is structureless, lacks fissility, and occurs in intervals 4-12 cm thick (Fig. 16).

Figure 16. *Mudstone lithofacies of 'Cf' map unit as noted on Caribou River (08TLA-CR-15).*

FOSSILS

Overall, the ‘Cf’ unit contains a low diversity and abundance of fossils, both at macro and micro scales. Fossil impressions observed on the bedding planes in shale include dendroid graptolites (Norford, 2009; Fig. 17), and inferred maxillipeds, or toothed paired appendages, of the probable eumalacostracan Angustidontus (identified using Rolfe and Dzik, 2006; Fig. 18). Fossil antenna of these organisms, similar to crinoid stems, may also be present. Angustidontus sp. is a predatory pelagic crustacean common in Upper Devonian to Mississippian strata in North America and Europe (Rolfe and Dzik, 2006). Hand specimens of the sandstone lithofacies revealed trace fossils that include vertical burrows and horizontal feeding traces attributed to the Cruziana ichnofacies (after Benton and Harper 1997). A single ammonoid imprint was also observed in this lithofacies (Fig. 19). Centimetre-scale, comminuted plant debris is common.

Palynological samples revealed a palynofacies rich in amorphous (shapeless) fragments and finely dispersed organic debris. Identifiable material includes wood and coal fragments (over half the samples), a lower relative abundance of sphaeromorphs, as well as rare acritarchs and scolecodonts (Utting, 2007, 2008a, 2009; Dolby, 2010, 2011; Appendix A). Organic petrology identified macerals including alginite (mainly prasinophyte, Tasmanites, Leiosphaeridia), terrestrial plant derived liptinite (*i.e.*, sporinite, cutinite and resinite) as well as minor calcareous and siliceous microfossils and rare spiny acanthomorphic acritarchs (Appendix B).

Figure 17. *Dendroid graptolites (Norford, 2009) collected from Nihtal Git Creek (09TLA-CC-100). Photo courtesy of Larry Lane.*

Figure 18. *Close up of fossil imprint of pelagic crustacean, Angustidontus (Norford, 2009) at section 09TLA-CC-100. These fragments are most likely of a maxilliped pair. Scale=cm divisions.*

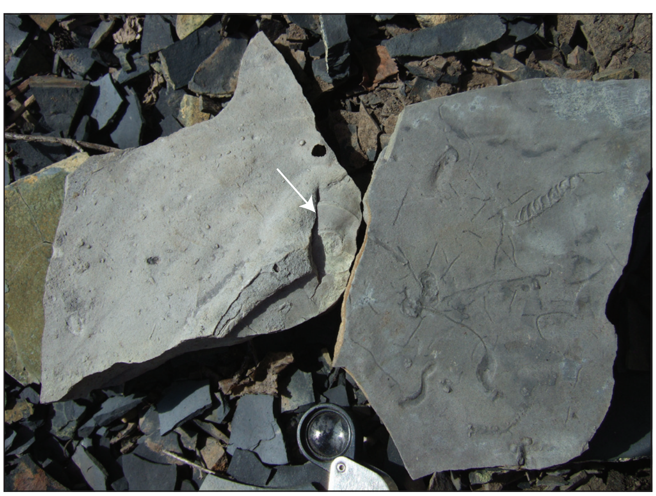


Figure 19. *Sandstone bedding-plane from unit ‘Cf’ from Nihtal Git Creek (06TNT-CC-26) with vertical burrows and horizontal feeding traces attributed to the Cruziana ichnofacies (after Benton and Harper, 1997). Note ammonoid imprint (arrowed). Hand lens for scale.*

SOURCE ROCK CHARACTERISTICS

The sedimentological characteristics of the siliceous and wafery shale lithofacies of unit Cf', specifically the thin laminations, dark colour, plant debris and petroliferous odour suggest that it is a prospective hydrocarbon conventional source and unconventional reservoir rock. This intimation was examined further by assessment of source rock character, including quantity and type of organic matter as well as its thermal maturity.

Twenty-nine surface samples of unit 'Cf' were analyzed in order to characterize organic richness (quantity), type of organic matter and organic matter thermal maturity (Table 6; 14 of these samples were previously published by Allen *et al.*, 2009). A Delsi Rock-Eval 6 Turbo pyrolysis apparatus equipped with a total organic carbon (TOC) analysis module was utilized at the Organic Geochemistry Laboratories at the Geological Survey of Canada, Calgary. TOC was derived from summing the carbon in the pyrolosis residue with the carbon obtained by oxidizing the residual organic matter at 600°C (Peters and Cassa, 1994). Analyzed samples were taken from the siliceous shale (n = 16), wafery shale (n = 10), mudstone (n = 2) and sandstone (n = 1) lithofacies. Three of the siliceous shale samples contained some siltstone, and one wafery shale sample contained some mudstone. One extra sample of burnt red siltstone (clinker) was included to investigate the effect of combustion on the shale's organic geochemistry (*see* Table 6). Additional thermal maturity analyses were conducted on selected unit 'Cf' samples, including vitrinite reflectance (n = 12), thermal alteration indices (n=13), and organic solvent extraction/gas chromatography (n = 3).

Quantity & type of organic matter

Parameters

Measured parameters derived from Rock-Eval/TOC analyses include TOC, S1, S2, S3 and T_{max}. TOC describes the quantity of organic carbon in a sample and includes both kerogen and bitumen (Peters and Cassa, 1994). S1 represents free or adsorbed hydrocarbons that were already present in the rock before pyrolysis that can be thermally distilled (given in units of mg HC/g rock). S2 represents hydrocarbons in the rock that have the potential to generate oil and/or gas if burial and maturation continues to completion, and provides an indirect measure of the organic matter's hydrogen content (also given in mg HC/g rock). S3 represents carbon dioxide generated during pyrolysis and is an indication of the amount of oxygen in the kerogen (given in mg CO_2/g rock; Peters, 1986; Peters *et al.*, 2005; Dembicki, 2009). T_{max} is the oven temperature (°C) at which the maximum rate of pyrolysis occurs or when the maximum amount of S2 hydrocarbon is generated (Peters, 1986; Jarvie *et al.*, 2007) and represents the temperature at the top of the S2 peak. Values of TOC, S1 and S2 and how they are used to describe the richness of source rocks are given in Table 7.

Parameters calculated from S2, S3 and TOC values include the hydrogen index (HI: S2/TOCx100) and oxygen index (OI: S3/TOCx100). These parameters are used to characterize the type of kerogen (*e.g.*, type I, II or III) within the rock when cross-plotted on a pseudo Van Krevelen diagram (as kerogen types vary in terms of their H/C and O/C atomic ratios; Peters, 1986). HI is a proxy for determining the H/C atomic ratio in a sample, and expresses the pyrolysable or "useable" fraction of organic content in a sample (*i.e.*, the amount of organic content that is available for producing hydrocarbons; Allen and Allen, 2005). HI values of <50 imply a predominance of inert kerogen, while values of >200 suggest the presence of significant amounts of hydrogen-rich (oil-prone) kerogen (Allen and Allen, 2005). HI values of 0-150, 150-300 and >300 mgHC/g Corg suggest that gas, gas and oil, and oil will be generated respectively, at thermal maturations equivalent to R_o = 0.6% (Peters, 1986). OI is a proxy for the O/H atomic ratio in a sample and corresponds to the quantity of carbon dioxide relative to the TOC (Peters *et al.*, 2005). High OI values are a negative indicator of source rock potential and are attributed to oxidation and a level of thermal maturity reached which tends to remove hydrogen and adds oxygen to the kerogen (Waples, 1985; Durand and Monin, 1980).

Table 6. *Summary of Rock-Eval/TOC data for samples of unit 'Cf'. Parameters measured or derived from Rock-Eval 6 pyrolysis include TOC (total organic carbon expressed as percent weight of whole rock); S1 (mg HC/g rock); S2 (mg HC/g rock); S3 (mg CO2/g rock); PI (production index=S1/S1+S2); HI (hydrogen index=100x(S2/TOC), expressed as mg HC/g C_{org}); OI (oxygen index=100x(S3/TOC), expressed as mg CO2/g C_{org}); T_{max} (temperature in °C at which the maximum amount of S2 hydrocarbons are generated during Rock-Eval pyrolysis). Vitrinite reflectance (% Ro_R) from Table 8 and thermal alteration index (TAI) from Table 4 are shown for cross-referencing purposes. '+' represents burnt, red siltstone. '*' represents analyses published in Allen and Fraser, 2008. All UTM locations are NAD83, Zone 8.*

Sample	Location	UTM Easting	UTM Northing	TOC	S1	S2	S3	S1+S2	PI	HI	OI	T_{max}	TAI	%Ro_R	Lithofacies
Cf' map unit															
07TNT-ACH-34A*	Aghoo Creek	483017	7370843	4.46	2.51	12.79	0.12	15.30	0.16	287	3	441	2+?	0.85	siliceous shale
07TNT-ACH-34B*	Aghoo Creek	512907	7328592	3.29	5.07	10.74	0.13	15.81	0.32	326	4	444	2+?		siliceous shale
07TNT-ACH-34C*	Aghoo Creek	512907	7328592	3.11	1.12	8.13	0.14	9.25	0.12	261	5	437	2+?		wafery shale / mudstone
08TLA-AGH-13-3	Aghoo Creek	515666	7323109	3.13	1.67	8.20	0.15	9.87	0.17	262	5	440	3/3+		wafery shale
08TLA-AGH-13-4	Aghoo Creek	515666	7323109	3.95	1.81	9.52	0.34	11.33	0.16	241	9	436	3/3+	0.72	siliceous shale
08TLA-AGH-14-2	Aghoo Creek	515172	7322454	4.96	2.20	13.11	0.42	15.31	0.14	264	8	434	3/3+		wafery shale
08TLA-AGH-14-3	Aghoo Creek	515172	7322454	3.02	1.46	8.04	0.25	9.50	0.15	266	8	437			siliceous shale / siltstone
07TNT-CR-12A*	Caribou River	507992	7344887	3.51	0.79	8.87	0.13	9.66	0.08	253	4	439	2	0.5	wafery shale
08TLA-CR-15-1	Caribou River	509918	7344555	8.32	2.62	23.44	0.50	26.06	0.10	282	6	437			siliceous shale
08TLA-CR-15-2	Caribou River	509918	7344555	5.98	0.75	15.15	0.56	15.90	0.05	253	9	436	3/3+		wafery shale
08TLA-CR-15-4	Caribou River	509762	7344630	6.97	1.75	20.89	0.19	22.64	0.08	300	3	437			wafery shale
2009LHA061A01	Caribou River	504842	7345454	5.88	0.56	7.00	0.49	7.56	0.07	119	8	434		0.85	wafery shale
2009LHA061A02	Caribou River	504842	7345454	9.19	0.68	21.29	0.25	21.97	0.03	232	3	437		0.67	siliceous shale
10TLA-EC-08A	Enigma Creek	508295	7328484	7.30	2.02	17.97	0.37	19.99	0.10	246	5	442	high		siliceous shale
10TLA-EC-17A	Enigma Creek	510172	7328515	1.02	0.19	0.59	0.20	0.78	0.24	58	20	437		0.75	mudstone
10TLA-EC-17C	Enigma Creek	510112	7328368	1.60	0.05	1.49	0.42	1.54	0.04	93	26	432			mudstone
10LHA097A01	Enigma Creek	510183	7328517	10.21	2.12	24.61	1.05	26.73	0.08	241	10	436		0.81	siliceous shale
10LHA097A03	Enigma Creek	510183	7328517	1.61	0.05	1.40	1.13	1.45	0.03	87	70	436		0.72	sandstone
06TNT-CC-026B*	Nihtal Git Ck	523198	7325395	2.54	0.48	5.30	0.08	5.78	0.08	209	3	443			siliceous shale, petroliferous
06TNT-CC-026C*	Nihtal Git Ck	523163	7325414	4.04	2.37	11.37	0.19	13.74	0.17	281	5	444			siliceous shale, petroliferous
06TNT-CC-026D*	Nihtal Git Ck	523163	7325414	3.47	2.18	9.87	0.12	12.05	0.18	284	3	441			siliceous shale/ siltstone, petroliferous
06TNT-CC-026E*	Nihtal Git Ck	523225	7325515	3.10	2.27	8.08	0.13	10.35	0.22	261	4	441	3+?		siliceous shale
06TNT-CC-026G*	Nihtal Git Ck	523295	7325620	12.17	1.42	31.45	0.64	32.87	0.04	258	5	436	3+?		wafery shale
06TNT-CC-026J*	Nihtal Git Ck	523167	7325671	9.24	1.47	21.18	0.64	22.65	0.06	229	7	440	2	0.65	siliceous shale / siltstone
06TNT-CC-026K*	Nihtal Git Ck	523167	7325671	8.64	1.59	21.03	0.36	22.62	0.07	243	4	443			siliceous shale
07TNT-CC-27A*	Nihtal Git Ck	526761	7327329	6.10	0.46	10.27	0.36	10.73	0.04	168	6	438	2	0.87	wafery shale
2009LHA034A01*	Nihtal Git Ck	523222	7325735	8.69	1.40	20.62	0.33	22.02	0.06	237	4	444			siliceous shale
10TLA-PR-07A	Peel River	509962	7319034	4.15	2.38	10.87	0.24	13.25	0.18	262	6	438			siliceous shale
10TLA-PR-07B	Peel River	509989	7319018	3.41	3.38	11.12	0.24	14.50	0.23	326	7	440		0.89	wafery shale
06TNT-CC-026I+*	Nihtal Git Ck	523167	7325671	0.07	0.01	0.05	0.24	0.06	0.17	71	343	437			burnt red siltstone

Table 7. *Source rock richness defined by TOC, S1 and S1 derived from Rock-Eval/TOC analyses (after Peters, 1986).*

Source rock richness	TOC (wt %)	S1 (mg HC/g rock)	S2 (mg HC/g rock)
Poor	0.0-0.5	0.0-0.5	0.0-2.5
Fair	0.5-1.0	0.5-1.0	2.5-5.0
Good	1.0-2.0	1.0-2.0	5.0-10.0
Very Good	>2.0	>2.0	>10.0

Unit 'Cf' Results

Strata of unit 'Cf' yielded TOCs ranging from 1.02 to 12.17 wt%, and averaging of 5.28 wt% (Table 6 and Fig. 20), suggesting that these strata have the potential to be very good source rocks (Table 7; Peters, 1986) and unconventional shale reservoirs (Zou *et al.*, 2013). All samples containing less than 2 wt% TOC are mudstone or sandstone, while the siliceous and wafery shale lithofacies samples all contained greater than 2.5 wt% TOC.

Other Rock-Eval-measured and derived parameters also indicate that unit 'Cf' has good source rock characteristics. Almost 70% of samples (n=20) had S1 yields between 1.12 and 5.07 mg HC/g rock and an average of 1.61 mg HC/g rock (Table 6). Ninety percent of samples (n=26), assessed in this study had S2 yields between 7.00 and 31.45 mg HC/g rock, and an average of 12.91 mg HC/g rock. These data are indicative of good to very good source rock potential (Table 7 and Fig. 21). A representative sample of unit 'Cf' from Aghoo Creek (07TNT-ACH-34B) having an S1 value of 5.07 mg HC/g rock and a S2 value of 10.74 mg HC/g rock was confirmed by organic solvent extract analyses to be oil-stained as reported in Allen *et al.* (2008a, 2009).

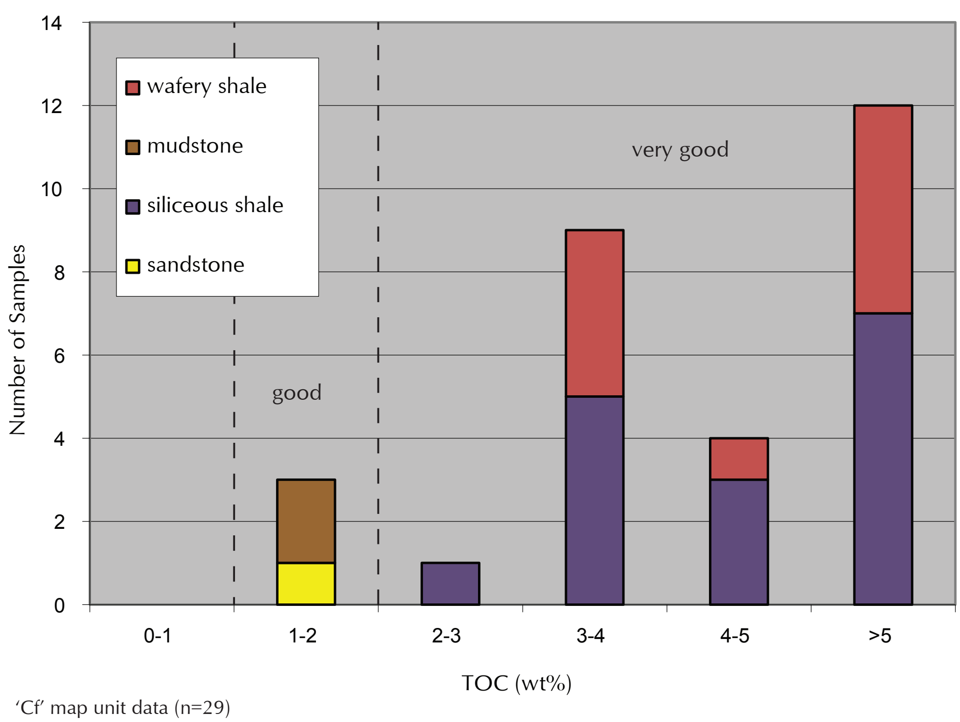


Figure 20. *Histogram summarizing total organic carbon (TOC), expressed in weight percent (wt%), from samples collected during this study of unit 'Cf'. The TOC categories (good and very good) correspond with source rock generative potential (Peters et al., 2005). See Table 6 for corresponding dataset.*

Rock-Eval derived HI values for the 'Cf' strata range from 58-326 mg HC/g Corg, and average 235 mg HC/g C_{org} (Table 6), suggesting hydrocarbons in the form of gas and oil are most likely to be generated (Peters, 1986). OI values for the shale samples range from 3 to 9 mg HC/g C_{org} (Table 6), and higher values are recorded for the two mudstone samples (20 and 30 mg HC/g C_{org}), and sandstone sample (70 mg HC/g C_{org}).

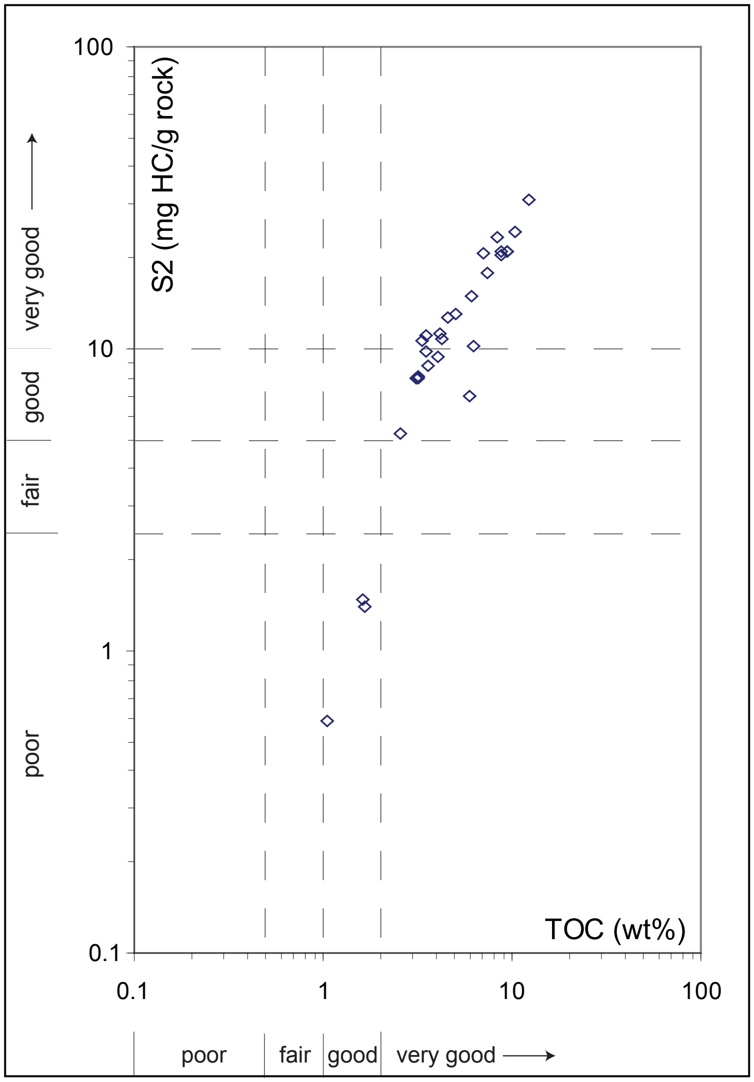


Figure 21. *Hydrocarbon generation potential of unit 'Cf'. This S2 versus TOC plot indicates that most unit 'Cf' samples have very good to excellent hydrocarbon generative potential. Categories based on Peters et al. (2005).*

The types of organic matter were determined using geochemical, organic petrological and palynological methods. Geochemically, cross-plots of Rock-Eval-derived parameters including HI versus OI (or pseudo-Van Krevelen diagram), HI versus T_{max} and S2 versus TOC (Fig. 22) suggest that the organic matter within the unit is a mixture of type II (algal and bacterial) and type III (terrestrial land plant) kerogen which are typically oil-prone and gas-prone respectively. Organic petrology and palynological analyses identified mainly amorphous kerogen having variable amounts of alginite (type I - mainly prasinophytes including Tasmanites and Leiospaeridia), vitrinite (type II), and terrestrial plant derived liptinite (type III - *i.e.*, sporinite, cutinite and resinite) macerals (Appendices A and B). Organic petrology further revealed hydrocarbon fluid inclusions (hcfi) in three samples of unit 'Cf' from Caribou River and Aghoo Creek, together with orange and red fluorescing solid bitumen/hydrocarbons and bitumenite in samples from Caribou River, Nihtal Git and Aghoo creeks (Appendix B). Samples from Enigma and Nihtal Git creeks and Peel River are described as containing sapropelic (type I) kerogen and debris (Dolby, 2010, 2012).

Burnt red siltstone sample results

Rock-Eval/TOC results of the burnt red siltstone sample show that the combustion process caused significant organic geochemical changes to the strata, characterized by lower TOC values of 0.07 wt%, low S1 and S2 values (0.01 and 0.05 mg HC/g rock, respectively), and elevated OI values (343 mg HC/g C_{org}). Because of the low S1 and S2 values and the high OI value, the T_{max} and HI values for this sample are deemed to be unreliable (Peters, 1986).

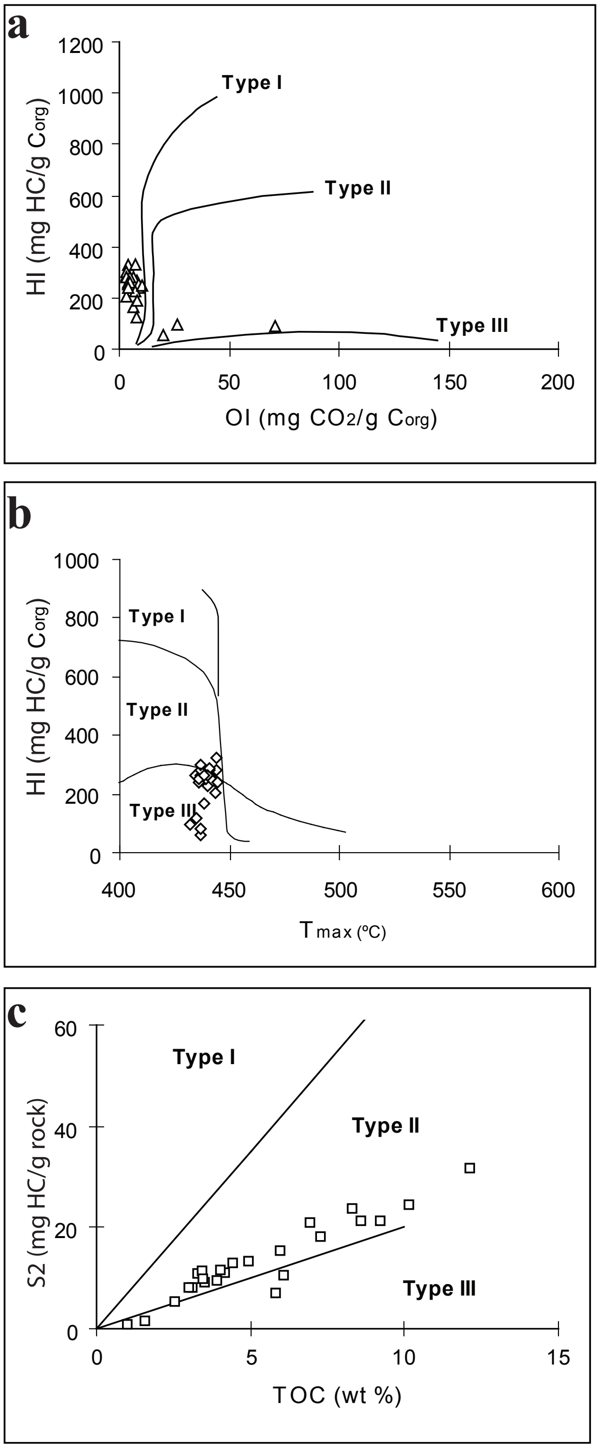


Figure 22. *a) Hydrogen index (HI) versus oxygen index (OI) cross-plot; b) HI versus T_{max} cross-plot and c) TOC versus S2 cross-plot. All plots indicate that the kerogen within unit 'Cf' samples contain mixtures of types II and III kerogen. Most samples fall within the Type II kerogen categories on these cross-plots suggesting that the organic matter is most likely derived from dominantly marine with mixed terrestrial source material that can generate oil. Categories based on Peters et al. (2005).*

Thermal maturity

Thermal maturity provides an indication of the maximum paleotemperature reached by a source rock (Jarvie *et al.*, 2007). For hydrocarbons to be generated, kerogen must be subjected to thermal stress either via temperature and/or pressure (burial). Temperature and duration of exposure to various heat intensities are the most important factors controlling thermal maturation of organic matter (Kalkreuth and McMechan, 1988). Determining the thermal maturity of organic matter is important for establishing the petroleum generation window of strata. During thermal maturation of organic matter, hydrogen and oxygen are lost more rapidly than carbon, resulting in a progressive increase in the concentration of carbon and darkening of kerogen with increased temperature (Waples, 1985; England and Bustin, 1986). This known colour change in organic matter forms the basis of visual thermal maturity assessment techniques, including vitrinite reflectance and thermal alteration index (TAI). Due to pitfalls in visual techniques, geochemical assessments (*e.g.*, T_{max}) should also be employed to assess thermal maturity (Jarvie *et al.*, 2007). Thermal maturity indicators used in this assessment include vitrinite reflectance, TAI, Rock-Eval-derived T_{max} values, and organic solvent extraction and gas chromatography.

T_{max}

As previously stated, T_{max} derived from Rock-Eval pyrolysis, is the oven temperature (°C) of peak evolution of S2 hydrocarbons (Jarvie *et al.*, 2007). T_{max} is used as a relative thermal maturity indicator under the assumption that T_{max} increases as maturity increases; it is not meant to represent the actual burial temperature of the rock. The term "oil window" is used to represent the stage of organic maturation when kerogen is cracked into oil, usually between T_{max} values of 435° and 470°C (Peters, 1986).

T_{max} values for unit 'Cf' outcrop samples range from 432° to 444°C, averaging 439°C (Table 6), and are therefore considered to be within the "early oil window" (Peters and Cassa, 1994).

Vitrinite reflectance

Vitrinite reflectance analysis is a well-established and commonly used technique for assessing thermal maturity of sediments (Dembicki, 2009; Hunt, 1979; Peters, 1986; Tissot and Welte, 1984; Teichmüller, 1982; Jarvie *et al.*, 2007. It is a measure of thermal maturity based on increases in the level of reflectivity of macerals (recognizable remains of organic matter that show distinct petrographic properties such as different grey levels of reflectivity and morphology; *e.g.*, Teichmüller, 1982; Peters and Moldowan, 1993). Potential source rocks with vitrinite reflectance values of 0.5 to 1.35% Ro (reflectance in oil) are considered mature with respect to hydrocarbon (oil) generation, with peak maturity in the 0.65-0.9% Ro range (Peters and Cassa, 1994). Vitrinite reflectance results are also fundamental for thermal modeling and estimating paleotemperatures of sediment burial.

Vitrinite reflectance and organic petrology were completed on 12 samples at the Organic Geochemistry Laboratory, Geological Survey of Canada, Calgary, where standard procedures for organic petrology, based on Mackowsky (1982), were followed. All vitrinite reflectance values (one sample has two results) fall between 0.5 and 0.95% Ro_R (random reflectance in oil) indicating that sample maturity falls within the early to peak maturity stage for oil (*i.e.*, falls within the “oil window”; Table 8). These findings are consistent with the T_{max} values obtained from both outcrop and borehole unit ‘Cf’ samples.

Thermal alteration index (TAI)

TAI values are useful maturity indicators obtained from palynological preparations. The values are based on colour changes of pollen and spores as a result of increased thermal maturity, with an increase in TAI corresponding to an increase in thermal maturity (Utting *et al.*, 1989; Utting and Hamblin, 1991). A disadvantage in using this technique to is the subjectivity of the colour determination, although the use of standards can reduce the severity of this problem (Peters and Cassa, 1994. The TAI scale used for these samples is based on the scale proposed by Utting *et al.* (1989) for the Upper Paleozoic of the Sverdrup Basin.

Table 8. *Summary of vitrinite reflectance data for ‘Cf’ samples. Vitrinite reflectance is expressed as random percent reflectance in oil (%Ro_R). Key for organic type: 2=vitrinite; 4=bitumen. All UTM locations are NAD83, Zone 8. See Appendix B for more detailed information.*

Sample Name	GSC- C #	Location	UTM Easting	UTM Northing	Organic Type	%Ro_R
07TNT-ACH-34A	473147	Aghoo Creek	483017	7370843	2	0.85
08TLA-AGH-013-04	532935	Aghoo Creek	515666	7323109	2	0.72
06TNT-CR-031A/C	473070	Caribou River	512994	7344407	2	0.67
07TNT-CR-11A/B	473172	Caribou River	501997	7347100	2	0.56
07TNT-CR-012A	473174	Caribou River	507992	7344887	2	0.50
2009LHA061A01	486335	Caribou River	504842	7345454	2	0.85
2009LHA061A02	486336	Caribou River	504842	7345454	4	0.67
10LHA097A01	491862	Enigma Creek	510183	7328517	4	0.81
10LHA097A03	491864	Enigma Creek	510183	7328517	2	0.72
10TLA-EC-17A	542102	Enigma Creek	510172	7328515	2	0.75
07TNT-CC-27A	473143	Nihtal Git Creek	526761	7327329	2	0.87
06TNT-CC-026J/K	473117	Nihtal Git Creek	523167	7325671	2	0.65
2009-TNT-CC-100-1	491978	Nihtal Git Creek	523211	7325558	2	0.95
10TLA-PR-07B	542068	Peel River	509962	7319034	2	0.89

TAI values were obtained for 18 unit 'Cf' samples (Utting, 2007, 2008a, 2009; Dolby, 2011; Table 3. Ten samples were assigned values ranging from 2 to 2+(?), equivalent to 0.55-0.9 Ro% or within the early to peak oil generation window. Seven samples were assigned values of 3/3+ or 3+(?), equivalent to 1.4-1.6 Ro% or within the wet and/or dry gas generation zone. One sample was identified as "high" TAI, suggesting overmature conditions with respect to oil generation or within the dry gas generation zone. Forty-four percent of the TAI values obtained in this study suggest 'Cf' strata are postmature with respect to oil generation and therefore are not consistent with the other thermal maturity indicators acquired in this study (e.g., vitrinite reflectance (Table 8) and T_{max} (Table 6)). Due to the subjective nature of TAI, these results are used with caution.

Organic solvent extraction and gas chromatography

Bitumen extraction is another method used to estimate the level of thermal maturity of a sample, and the fractionation of extracted bitumen using gas chromatography is important in determining source rock potential (Fowler *et al.*, 2005). The Soxhlet technique (Fowler *et al.*, 2005) was used to extract bitumen from three organic carbon-rich samples of unit 'Cf'; samples were analyzed at the Organic Geochemistry Laboratory, Geological Survey of Canada, Calgary (A. Mort, pers. comm., 2014; Table 9). Total bitumen extract weight is expressed as mg of extract (or hydrocarbons) normalized to the grams of organic carbon in the rock, known as hydrocarbon yield (Fowler *et al.*, 2005) Samples with normalized solvent extract hydrocarbon yields containing more than 30 mg HC/g C_{org} of extractable hydrocarbons are considered source rocks, while those over 80 mg HC/g C_{org} are considered to have excellent source rock potential or are stained (Fowler *et al.*, 2005). The bitumen extract samples were fractionated using packed column chromatography into hydrocarbon (saturates and aromatics) and non-hydrocarbon components (nitrogen, sulphur and oxygen containing compounds and asphaltenes). The saturated fraction provides information on biomarker classes such as pristine/phytane (Pr/Ph) ratios.

Table 9. *Summary of gross composition data from organic solvent extraction (extract yield and hydrocarbon yield) and results from gas chromatography saturate fractionation of total extract into hydrocarbon (saturates and aromatics) and non-hydrocarbon (nitrogen, sulphur and oxygen) contents. Total organic carbon (wt%) is derived from RE/TOC analyses. Extract yield is the quantity of extract expressed as mg of extract normalized to the total organic carbon content (mg extract/g of organic carbon in the rock). HC yield is quantity of hydrocarbons expressed as mg of hydrocarbons normalized to the total organic carbon content (mg HC/g of organic carbon in the rock). %R+A is the percentage of extract that comprises resins and asphaltenes (non-hydrocarbons). Sat/Aro is the ratio of saturate to aromatic hydrocarbons in the extract. %Sat is the percentage of extract that are saturate hydrocarbons. %Aro is the percentage of extract that are aromatic hydrocarbons. Pr/Ph is the pristine/phytane ratio. Extract ppm is the extractable hydrocarbons normalized to the weight of the rock sample. HC ppm is the sum of the saturate and aromatic hydrocarbon fractions normalized to the weight of the rock sample. Sample highlighted in grey was published in Allen et al., 2009. All UTM locations are NAD83, Zone 8.*

Sample Name	GSC #	UTM Easting	UTM Northing	TOC	Extract Yield	HC Yield	%HC	%R+A
08TLA-CR-15-1	C-485385	509918	7344555	8.32	78.28	40.01	51.11	47.56
08TLA-AGH-14-2	C-532936	515172	7322454	4.96	206.77	114.46	55.35	37.79
07TNT-ACH-34B	C-473148	512907	7328592	3.29	318.2	255.1	80.16	19.65

Table 9 continued

Sample Name	Sat/ Aro	%Sat	%Aro	Pr/ Ph	Extract ppm	HC ppm
08TLA-CR-15-1	1.4	29.39	21.72	1.83	6511	3328
08TLA-AGH-14-2	1.7	34.63	20.72	1.18	10252	5675
07TNT-ACH-34B	1.5	47.83	32.32			

Two samples with the appearance of oil-staining have hydrocarbon yields of 40.01 and 114.46 mg HC/g C_{org} (08TLA-CR-15-1 and 08TLA-AGH-14-2, respectively). Results previously published for a siltstone sample from Aghoo Creek had a hydrocarbon yield of 255.1 mg HC/g C_{org} (Allen *et al.*, 2008a). The percentage of hydrocarbons (also derived from organic solvent extraction) for the two aforementioned samples measure 51.11 and 55.35%HC respectively, and are within the main phase of oil generation (50-60%HC). A third sample (07TNT-ACH-34B) with over 80%HC (Allen *et al.*, 2008a, 2009), is suspected of being oil-stained (Fowler *et al.*, 2005). Corresponding TOC values for these three samples ranged from 3.29 to 8.32 wt%, therefore also indicating very good source rock potential.

Pr/Ph ratios obtained for two unit 'Cf' samples (Table 9) are less than 2.0. Pr/Ph ratios can be used as palaeoenvironmental indicators for the setting in which sedimentary organic matter was deposited, with ratios of less than two indicative of crude oils sourced from marine organic matter (Peters and Moldowan, 1993). The ratios obtained in this study are therefore suggestive of marine-sourced organic matter deposited within a reducing environment (Powell and McKirdy, 1973).

SHALE MINERALOGY

X-ray diffraction mineralogy (XRD) is a common method used to estimate shale mineral composition in order to evaluate its mechanical properties and characterize its brittleness or 'frac-ability'. The higher the silica (quartz) and carbonate content, the more brittle the rock and therefore the more likely it is to respond to stimulation practices required for hydrocarbon extraction (*e.g.*, hydraulic fracturing). In contrast, a high clay mineral percentage imparts a plastic character to the shale that significantly reduces its ability to respond to current well stimulation techniques. Data collated from the principal global shale gas reservoirs suggest that brittle mineral contents of greater than 40-50% and clay mineral contents of 30-50% are indicative of excellent shale prospectivity (Zou *et al.*, 2013; Passey *et al.*, 2010). Fracturing in shale (whether natural or induced) is therefore a critical factor in assessing shale gas reservoir potential.

Semi-quantitative XRD analyses were conducted on eleven shale samples and one weathered residue sample of unit 'Cf' using a Philips PW1700 powder diffraction system with cobalt X-ray source at the Inorganic Geochemistry Laboratory at GSC, Calgary. XRD results, expressed in mineral ratio percent (Table 4 and Fig. 23), indicate unit 'Cf' is predominantly quartz (90 to 98%, average 95.7%) with lesser mica, illite, mixed layer clay and anhydrite (trace amounts up to 3%). Other minerals present in only trace amounts include jarosite, pyrite and barite. All shale lithofacies samples analyzed have at least 92% quartz, with siliceous shale ranging from 95 to 98% quartz and wafery shale ranging from 92 to 98% quartz. The XRD results indicate that all strata examined in this study of unit 'Cf' are highly siliceous, containing <7% clay mineral content. This first pass mineralogical analysis therefore suggests that the rock is brittle and would respond effectively to induced fracturing.

UNIT 'CF' IN THE PEEL SUBSURFACE

Despite the occurrence of dark grey to black organic-rich shale, up to 555 m thick in outcrop, unit 'Cf' has not been recognized in the Peel subsurface. However, wells that penetrate the Imperial and Tuttle formations have been noted to contain thick, shale-prone sections of similar lithological and organic character that may be possible lithostratigraphic equivalents of this unit. In this section, we use the sedimentological and geochemical knowledge gained from surface exposures of unit 'Cf' to attempt to identify its presence in the Peel subsurface.

The following paragraphs describe intervals of selected wells in the Peel area that may contain unit 'Cf' strata based on well history reports and examination of washed wellbore cuttings. Four wells (Trail River YT H-37, Caribou YT N-25, Peel River YT I-21 and Cranswick YT A-42) are presented as a single northwest-southeast panel, with the top Imperial Formation used as a correlation marker (Fig. 24). Reported depths are in metres below Kelly bushing (KB).

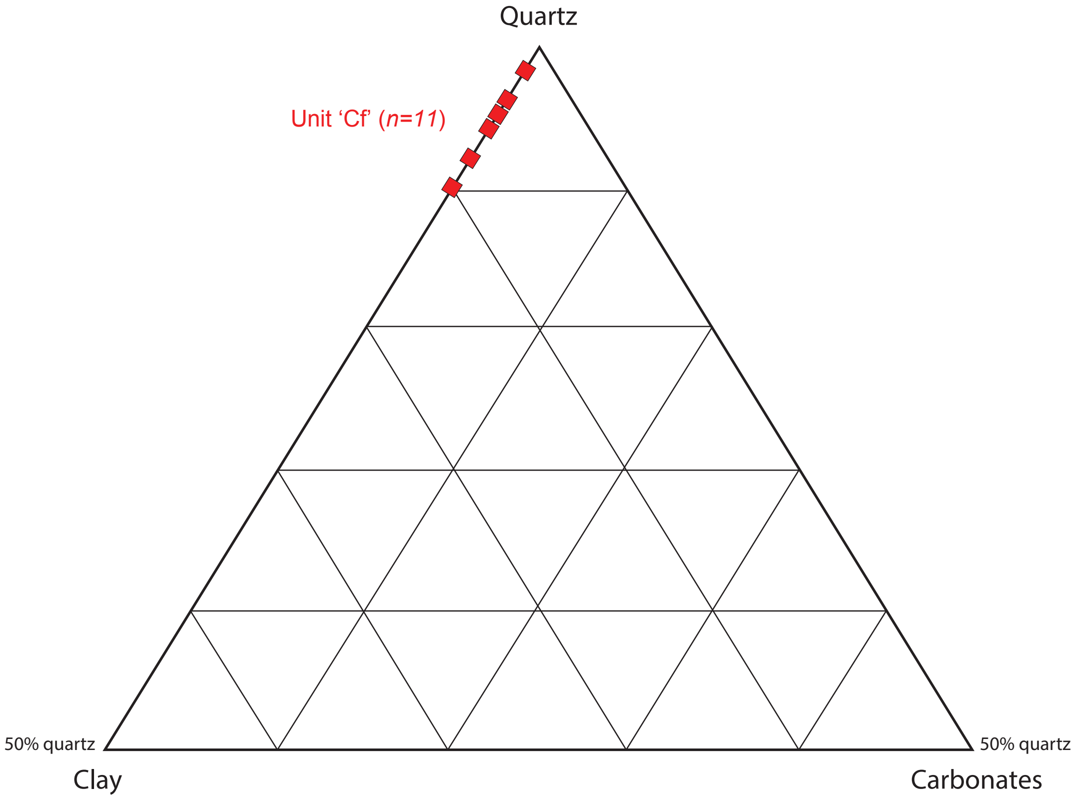


Figure 23. *Ternary diagram displaying the relative mineralogical composition of unit 'Cf. The corresponding data are in Table 3.*

The following principal characteristics were used to identify possible 'Cf' equivalents in these wells: the presence of dark grey to black, siliceous and pyritic shale; TOCs typically equal to or greater than the minimum TOC percentage obtained from outcrop analysis (1.02 wt%); and palynology-derived age estimates of Fammenian to early Tournaisian age. In overview, these characteristics suggest that unit 'Cf' strata are present:

- in both the Imperial and Tuttle formations as defined by Pugh (1983) and Fraser and Hogue (2007), with a dominant occurrence in the Tuttle Formation;
- as two discrete, silt-rich intervals in the N-25 well and as one thicker interval in the H-37, I-21 and A-42 wells; and
- in thicknesses that range from approximately 95m in N-25 to approximately 1118 m of continuous section in I-21.

Trail River H-37

Intervals of characteristic hard, light to dark grey shale were logged below the Late Devonian-Early Cretaceous unconformity between 676.6 and 1508.8 m (Shell Canada, 1974), with red oxidized shale intersected between 765 and 823 m. Sidewall sample descriptions highlight that dark grey shale in the uppermost Devonian succession in this well (*i.e.*, between 677 and 841 m) also contain appreciably high percentages (up to 80%) of very fine grained, silica-cemented sandstone. Underlying this, shale containing up to a maximum of 80% siltstone (averaging 38% siltstone) occurs between 841 and 1113 m; this shale exhibits TOC contents similar to or higher than outcrop samples from unit 'Cf' (up to 1.07 wt%). This interval is also dated as Fammenian (Utting, 2009), although an age of Strunian or younger is inferred due to the presence of underlying Strunian-aged palynomorphs (Utting 2008b). The potential unit 'Cf' has a thickness of 272 m (892 ft).

Caribou N-25

The uppermost 204.8 m of this well is described as predominantly quartzose, very fine grained sandstone with intercalated grey-brown, black and red shale (Gulf Oil Canada, 1974), and includes an approximately 25-m-thick black, silty, pyritic and potentially bituminous shale unit at the base of this interval (Pugh, 1983). Strunian-aged palynomorphs were recovered between 137.2 m and 245 m in this well (Utting, 2008b). Examination of washed cuttings from this well suggests, however, that only the uppermost 82 m of the well can be confidently assigned to the Tuttle Formation based on the presence of tripolitic chert granules. Below this, two potential unit 'Cf' equivalents have been identified: a 125-m-thick section between 205 and 330 m, and a 95-m-thick section between 445 and 540 m. The shallower section includes palynomorph and conodont recoveries dated to Strunian (Utting, 2008b) and Late Devonian/Fammenian (Uyeno, 1974) respectively. The deeper, shale-dominated section is approximately 95 m thick, occurs between 445 and 540 m depth, and is of uncertain age (here assigned to the Imperial Formation; Pugh, 1983; Fraser and Hogue, 2007). TOC and Rock-Eval-derived S2 and HI values in the upper 457 m of this well are also typically greater than observed within the Imperial Formation (Allen *et al.*, 2008b; Allen, 2010), ranging from 1.35-5.42 wt%, 2.5 mg HC/g rock, and 186 mg HC/g C_{org} respectively (Allen *et al.*, 2008b).

Peel River I-21

The Peel River I-21 well is located 20 km northeast of the easternmost surface exposure of unit 'Cf', and intersects a succession dominated by medium to dark grey pyritic shale (Shell Canada, 1966). In the uppermost 192.1 m, red fragments of shale and siltstone occur in well cuttings, and between 536.5 and 777 m thin intercalations of Tuttle-Formation-like pebbly quartz and chert-bearing sandstone occur within the shale. Palynological data suggest strata above 731.5 m are of probable early Tournaisian (Early Mississippian) age (McGregor, 1968; Utting, 2008b), thereby conflicting with the assignment of a Cretaceous age for strata at the surface on bedrock maps by Norris (1981a), unless the pollen have been recycled. Shale strata between 762 and 975.4 m are dated as Strunian or possible Strunian (McGregor, 1968), and Rock-Eval-derived TOC, S2 and HI values also compare favourably to unit 'Cf' to a depth of at least 1036.3 m (1.01-3.82 wt%, >1.3 mg HC/g rock, and >149 mg HC/g C_{org} respectively). Below 1138 m and above the Canol Formation at 1408 m, TOC values less than 1 wt% are considered more typical of the Imperial Formation (Allen *et al.*, 2008b; Allen, 2010; Fraser *et al.*, 2012). Examination of washed cuttings for this well suggests that atypical Late Devonian strata incorporated into the Tuttle Formation are lithologically more similar to unit 'Cf'. Overall, unit 'Cf' shale may extend from near surface to as deep as 1138 m, with tongues of Tuttle-character clastic rocks occurring between 536.5 and 777 m.

Cranswick A-42

Cranswick A-42 occurs southeast of unit 'Cf' outcrop exposure, and contains a 540-m-thick succession of Late Devonian (late Fammenian: Utting, 2008b) shale between the Cretaceous Martin House Formation at 1170.4 m (Fraser and Hogue, 2007) and 1710 m (last siltstone interval up-section (Terriff, 1973)). Well report descriptions indicate the presence of 'carbonaceous stringers' (organic-rich horizons), abundant brown concretions, pyrite and gypsum (Terriff, 1973) similar to that found in road-cuts along the Dempster Highway and mapped as Ford Lake Shale (Norris, 1981b). Although coarse-grained units typical of the Tuttle Formation were not observed, it is here suggested that the current stratigraphic assignment of the shale (between 1170.4 and 1710 m) to the Tuttle Formation should be revised to unit 'Cf' equivalence based on organic character and late Fammenian age.

Subsurface thermal maturity

T_{max} values have been reported from subsurface samples of possible unit ‘Cf’ collected from wellbores. Values range from 430° to 452°C in borehole I-21 to a depth of 1146 m, gradually increasing down hole; 438° to 447°C in borehole N-25 between 192 and 457 m; from 431° to 441°C in borehole H-37 between 744 and 1509 m; and 472° to 576°C in borehole A-42 between 1146 and 1725 m (Allen *et al.*, 2008b). Strata in boreholes N-25, I-21 and H-37 are within the “oil window” and consistent with values obtained from surface exposures of ‘Cf’ strata (Allen *et al.*, 2008b). In borehole A-42, strata below the Cretaceous Arctic Red Formation have very high thermal maturities and are postmature with respect to oil generation (Peters and Cassa, 1994).

Conclusion

In conclusion, intervals of organic-rich, Fammenian to Tournaisian aged, dark grey to black shale are observed to occur in the Peel wells studied for this report. These intervals are considered to represent the correlative subsurface equivalent of unit ‘Cf’, but have previously been assigned to the Imperial or Tuttle formations. The recognition of unit ‘Cf’’ in these wells has also increased the known lateral extent of the unit to the east (at least as far as Snake River). It is of note from an exploration perspective that unit ‘Cf’ becomes thicker and less sand-prone towards the southeast of the Peel region (*see* Fig. 24). In addition, ‘Cf’ strata in the subsurface of Peel Plateau are within the “oil window”, becoming overmature in the south towards the Mackenzie Mountains.

DIRECT OBSERVATIONS OF HYDROCARBONS

Fumes of hot gases were noticed on June 29, 2009 from a shale outcrop that is marked by reddening of grey and black shale on Aghoo Creek (08TLA-ACH-14; Fig. 25). The rocks are altered and range in colour from reddened (moderate reddish-brown) to bleached (light grey; *see* Figs. 11 and 12). Trees around the fumes are dead, vegetation is absent within the immediate vicinity, and existing tree roots are charred. Immediately underlying the colluvium, the ground is hot and flames emerge when the ground is disturbed. The fumes have a strong noxious odour unlike H2S. A dark brownish-grey tarry residue appears to be a byproduct of the fumes, deposited along fissures in the colluvium. Analysis of this residue (sample GL-0940A), conducted at GSC Calgary, determined that the residue is 23% hydrocarbons (K. Osadetz, pers. comm., 2013).

Heating hand specimens from this and other localities with a propane torch resulted in the black shale initially glowing red then changing colour to light grey and reddening around the outermost edges. The rock also splits parallel and perpendicular to bedding, expels small splintery fragments, and produces a noxious odour and flames along the fractures which burn. A small hand sample will burn for about four seconds once the direct heat is removed from the rock and then continue to smolder. In regards to the degree of thermal alteration, the shale observed in outcrop is slightly baked and appears to have resulted only in a change of colour and composition. The rocks are not fused, welded, or converted to paralava. Matthews and Bustin (1984) observed that heating mudstone by only a few hundred degrees (~300°C) causes discolouration and expulsion of combustible gases. Shale becomes baked red as the reduced iron, present as pyrite, is oxidized to hematite (West, 2006). Other areas marked by similarly brightly coloured rocks of unit ‘Cf’, without smoke, were noted on the top of steep exposures on Nihtal Git Creek and at numerous other locations along Aghoo Creek and its tributaries.

In the subsurface, bitumen or solid hydrocarbons were reported in the Tuttle Formation in borehole Peel River YT M-69 at 960.7 m (3152 ft) and 1586.2 m (5204 ft) depths (Shell Canada Ltd., 1975). Recent organic petrology (unpublished vitrinite reflectance report, J. Potter, 2011) revealed the presence of minor brown staining, indigenous bitumen, bitumen inclusions, bitumenite (oil-prone

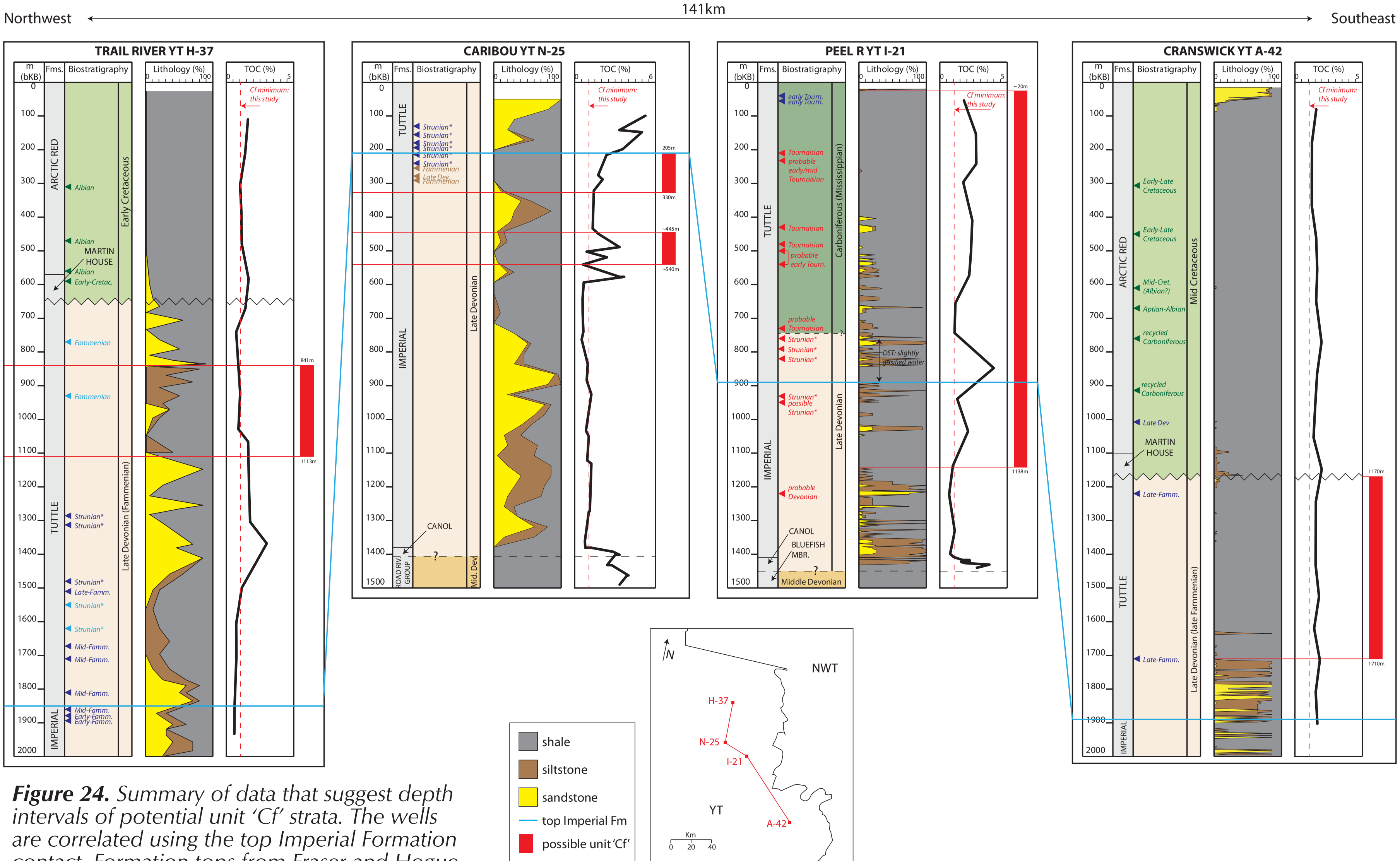


Figure 24. *Summary of data that suggest depth intervals of potential unit 'Cf' strata. The wells are correlated using the top Imperial Formation contact. Formation tops from Fraser and Hogue (2007), depths in metres below Kelly Bushing, TOC data from Allen et al. (2008b), biostratigraphic ages from White and Boyce (2009); Utting (2008b); Uyeno (1974); and McGregor (1968) – note that Strunian* indicates latest Fammenian. Lithology data are presented in cumulative percentages, and were sourced from: Shell Canada (1966, 1974) for wells I-21 and H-37 respectively; Terriff (1973) for well A-42; and Canadian Stratigraphic Services (2000) Ltd. (1974) for well N-25. For well H-37, lithological percentages were provided from sidewall samples across depth ranges of up to approximately 500 ft. For well N-25, percentages were visually estimated from the downhole lithological cuttings log. For wells A-42 and I-21, percentages were obtained from ditch cuttings logs, and were assigned specific and consistent values based on sample descriptors.*

Figure 25. Smoldering colluvium noted just above an outcrop of burnt red shale on Aghoo Creek (08TLA-AGH-14).

maceral type) and hydrocarbon fluid inclusions in various formations including Martin House, Arctic Red, Tuttle, Imperial, Canol, Road River, Hume, and Landry in wells: Peel YT F-37, Taylor Lake YT K-15, Peel River YT M-69, Peel YT H-71, Cranswick A-42 and Arctic Red YT C-60. Although unit 'Cf' is not currently documented in the subsurface, it is conceivable that in the subsurface this unit would also contain hydrocarbon fluid inclusions.

DISCUSSION

This study of unit 'Cf' has documented its lithology, mineralogy, sedimentology, age and hydrocarbon source rock and reservoir characteristics. Although this study is largely outcrop-based, well data was also examined to complement surface findings and evaluate the extent of unit 'Cf' in the Peel subsurface. Direct observations of hydrocarbons in the Peel surface and subsurface are also presented. These new data have implications for the depositional environment, basin architecture and petroleum system prospectivity of unit 'Cf' as both a conventional source rock and unconventional shale gas reservoir.

Environment of deposition

In summary, the lithological, sedimentological and mineralogical character of unit 'Cf', combined with paleontological and organic geochemical/petrological results supports a quiescent, basinal marine depositional environment for this succession, punctuated by rare, higher energy conditions. The fine-grained nature, fine-scale of lamination and typical grey/black colouration of the dominant shale facies are suggestive of deposition in a low-energy, poorly-oxygenated water body. Potentially anoxic bottom-waters are indicated by the absence of bioturbation in the laminated shale, visible organic-rich intervals, the elevated TOC's and the presence of pyrite and jarosite. Pyrite typically forms in heavily reducing conditions, with jarosite formed due to later pyrite oxidation.

The presence of algal prasinophytes Tasmanites and Leiosphaeridia attest to a marine depositional setting (Hutton, 1987), as do the presence of acritarchs (Caribou River, Nihtal Git and Aghoo creeks), graptolites, one ammonoid (Nihtal Git Creek), and scolecodonts (Enigma Creek). The presence of Angustidontus, indicates a low-diversity, open-sea pelagic environment (Rolfe and Dzik, 2006). In addition, as previously noted, Pr/Ph ratios in this study range from 1.0 to 3.0 which is commonly associated with marine organic matter deposited into a reducing environment (Powell and McKirdy, 1973; Peters and Moldowan, 1993).

In contrast, rare intercalated sandstone units within the thick shale (*e.g.*, in the Nihtal Git Creek section) required higher energy conditions for deposition, and their presence is suggestive of either shallowing due to sea-level fall and shoreline progradation, or of distal submarine fan deposition. Vertical burrows and feeding traces within these sandstone units are, however, indicative of a return to more quiescent conditions (sediment stability) and oxygenated bottom-waters following sand deposition that promoted the colonization of the substrate. The assignment of this trace fossil assemblage to the Cruziana ichnofacies (after Benton and Harper, 1997) attests to a mid to distal continental shelf setting with typical water depths of below normal wave base. Associated rippling in these very fine sandstones may be attributed to wave action during storms.

Correlation, regional extent and stratigraphic architecture

Ford Lake Formation

New data from outcrop studies and inferences from subsurface information show that the organic shale-dominated unit 'Cf' ranges in age from Famennian to Tournaisian. These data demonstrate that unit 'Cf' is coeval with the Ford Lake Shale which ranges in age from early Famennian to as young as Viséan, early Carboniferous (Utting, 2006; Dolby, 2010, 2011). These preliminary results suggest support for Norris' (1985) assignment and amalgamation of map units 'CF', and 'Cf' with the Ford Lake Shale in north Yukon. As rock units in the Eagle Plain and Kandik Basin subsurface originally named 'Mississippian-Devonian Shale', 'Unit 1 Shale', 'Unnamed shale', 'Lower Member', 'Mississippian Parkin Creek Formation', 'Upper Mississippian' or 'Mississippian Shale' in well history reports have been reassigned to the Ford Lake Shale (Pugh, 1983; Fraser and Hogue, 2007), they would also be coeval with unit 'Cf'. Based on this, regional basinal organic-rich shale deposition is considered to have occurred from eastern Alaska to at least as far east as Peel Basin and Plateau from at least the early Famennian to at least the Tournaisian, and possibly into the Viséan.

Imperial & Tuttle formations

The outcrop occurrence of fine-grained, thinly bedded sandstones (similar in character to either the distal Tuttle Formation or Imperial Formation) within thick intervals of dark grey to black, organic-rich, siliceous shale of unit 'Cf' suggest that regionally this Upper Devonian to Lower Mississippian clastic succession may best be interpreted as locally interfingering lithostratigraphic equivalents of each other (Fig. 26). Biostratigraphic ages presented here compare favourably to those of Pugh (1983) in that Fammenian to Viséan organic-rich shale is in part coeval with sandstone and conglomerate assigned to the Tuttle, and possibly Imperial formations (*see also* Fig. 24).

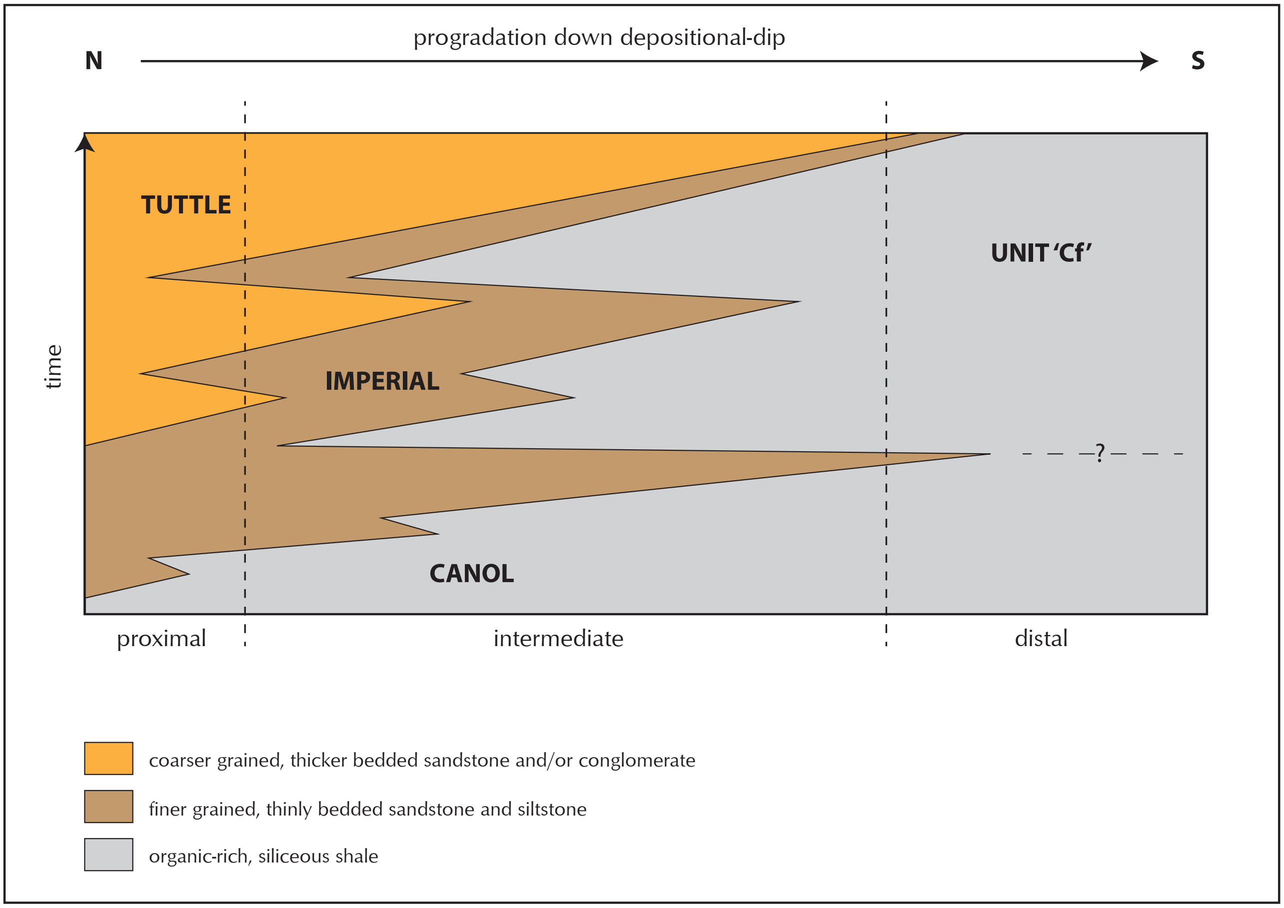


Figure 26. *Schematic diagram to illustrate the formational interfingering down depositional-dip within the Devonian-Mississippian clastic sequence of Peel Plateau. Note that lithological heterogeneity is greatest at intermediate positions within the basin, and that unconventional reservoir potential is considered to increase towards the south.*

Farther to the north, the Tuttle Formation is typically much coarser grained, and in its type section (well F-37, UWI 300F376700134450) consists of sandstone and/or conglomerate-dominated intervals ranging between 55 and 144 m (Fraser and Allen, 2007; Pugh, 1983). However, intercalated shale and siltstone intervals, between 23 and 54 m thick, are also noted in this section, where more mud-prone Tuttle Formation appears similar in character to both the aforementioned coarser grained intervals of unit 'Cf' in outcrop, and to finer grained siliciclastic rocks that occur as interbedded strata within the upper Imperial Formation.

The nature of this lithostratigraphic facies interfingering has generalized implications for understanding the regional stratigraphic architecture of this upper Paleozoic succession and its effect on hydrocarbon systems (see list below), however it should be noted that a higher-resolution, regional interpretation is outside the scope and data capacity of this study:

- the prediction of source/reservoir distribution and quality – Fig. 24 suggests that source rock and unconventional reservoir thickness increases to the south in association with a decrease in sand and siltstone content. Conventional reservoir facies (e.g., in the Tuttle Formation) are therefore more likely to be of higher quality and thickness to the north of the basin; however seal presence and effectiveness carries an increased associated risk.
- the prediction of multiple source/reservoir intervals – Tuttle and Imperial formation strata may likely include both source rock/unconventional reservoir and conventional reservoir (sandstone)

targets, especially in intermediate positions (*i.e.*, not proximal or distal) down depositional-dip. This lithological heterogeneity may also result in the increased presence of intra-reservoir barriers/baffles that impede vertical fluid flow in conventional reservoirs, or impair artificial fracture propagation in unconventional reservoirs.

Implications on regional geological mapping

Other observations collected during the course of this study can be used to refine the regional reconnaissance-scale geological map for the area. Some areas shown as unit 'Cf' on earlier maps are lithologically more like the Tuttle or Canol formations. In one locality on Trail River (07TNT-TR-05), in the area assigned to unit 'Cf' (Norris, 1981a), bedrock consists of thick-bedded, medium to coarse-grained, poorly sorted sandstone and intercalated fine-grained sedimentary rocks that are better assigned to the Tuttle Formation (Allen and Fraser, 2008; Braman and Hills, 1992).

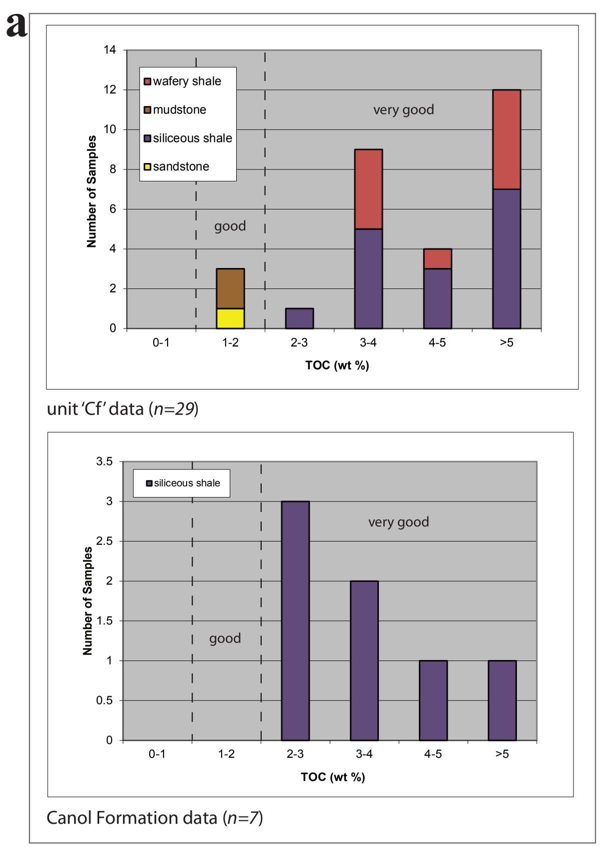
Likewise, shale outcrops mapped as unit 'Cf' (Norris, 1981a,b; 1982a,b,c) or Ford Lake Shale (Norris, 1985a) in the extreme southeast of the study area along the Peel River and Solo Creek (*see* Fig. 4) have thermal maturities, organic matter types and palynological age dates more consistent with them belonging to the Givetian? – Frasnian? (Dolby, 2011; Pugh, 1983; A.W. Norris, 1985; Gal *et al.*, 2009) Canol Formation (Fig. 27b,c; Appendix C, Tables 1 to 3). It should be noted, however, that total organic carbon content and XRD mineralogy are indistinguishable between the Canol and 'Cf' samples analyzed as part of this study (Fig. 27a,d; Appendix C, Table 4). Secondary characteristics that are suggestive of a Canol Formation affiliation are the presence of numerous metre-scale, spherical to lozenge-shaped carbonate(?) concretions (Fig. 28) that occur at the base of the Peel River exposures that have been noted in earlier publications (*e.g.*, Fraser, 2014; Allen and Fraser, 2008; Gal *et al.*, 2009; Morrow, 1999; Héon, 2006).

The Canol Formation and unit 'Cf' have often been confused. Black siliceous shale of unit 'Cf' on Caribou River was formerly assigned to the Canol Formation by Capstick (1968), and later mapped as unit 'Cf' by Norris (1981a). These strata were assigned a Famennian age by McGregor (1968), but were subsequently re-examined by G. Dolby (pers. comm. 2013) who constrained the date as latest Famennian (Strunian) and therefore not of Canol Formation origin.

Summary of the hydrocarbon potential of map unit 'Cf'

Our data demonstrate that unit 'Cf', its correlatives in the Peel region subsurface, and its probable western correlative in the coeval Ford Lake Shale represent a laterally extensive petroleum system component that exhibits both potential conventional source rock and unconventional shale reservoir properties. Collectively, our new data, well information and observations of hydrocarbon shows reveal that the 'Cf' unit has produced hydrocarbons in the past.

In regards to source rock potential, unit 'Cf' is a very good candidate. The total amount of organic carbon classifies the shale as having very good source rock generative potential with all samples over 2.5 wt% TOC (Peters *et al.*, 2005). Rock-Eval pyrolysis derived parameters (HI and OI) suggest that the organic matter within samples in this study consists largely of types II and III kerogen. This conclusion is consistent with organic petrology results indicative of types I, II and III kerogen. Alginite, such as Tasmanites, which has been identified in the shale, is frequently a major contributor to type I kerogen (Peters *et al.*, 2005). Sapropelic kerogen and debris, also identified as being present in the strata, is also classified as type I or oil-prone (North, 1990). The presence of vitrinite macerals identified through organic petrology and abundant woody and coal fragments in palynology studies confirm these geochemically-based findings.



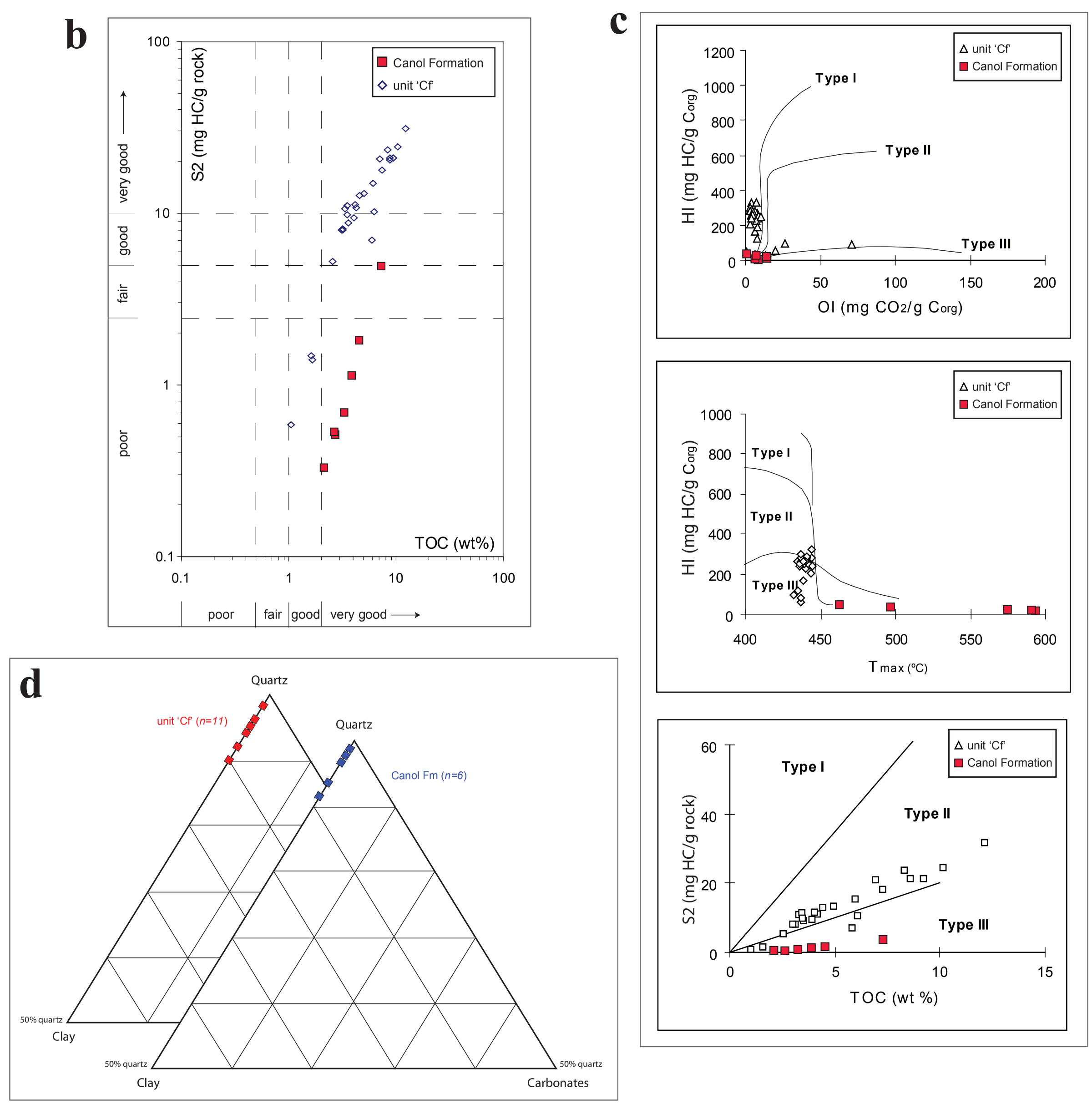


Figure 27. *Comparison of Rock-Eval and shale mineralogy results between unit 'Cf' strata mapped in the Peel River/Solo Creek area (here assigned to the Canol Formation - see Appendix C for data tables) and the rest of the study area. a) Histogram summarizing total organic carbon (TOC), expressed in weight percent (wt%); b) hydrocarbon generation potential (S2 vs TOC) plot, with data from the re-assigned Canol Formation showing comparable TOC but typically lower S2 contents than unit 'Cf' to the north and east; c) hydrocarbon quality and maturation plots, with samples from the re-assigned Canol Formation having very low HI and OI values (making it impossible to determine the kerogen type) and elevated T_{max} thermal maturities; and d) mineralogical composition ternary diagrams as determined by XRD analysis (note the diagrams only show quartz percentages >50%).*

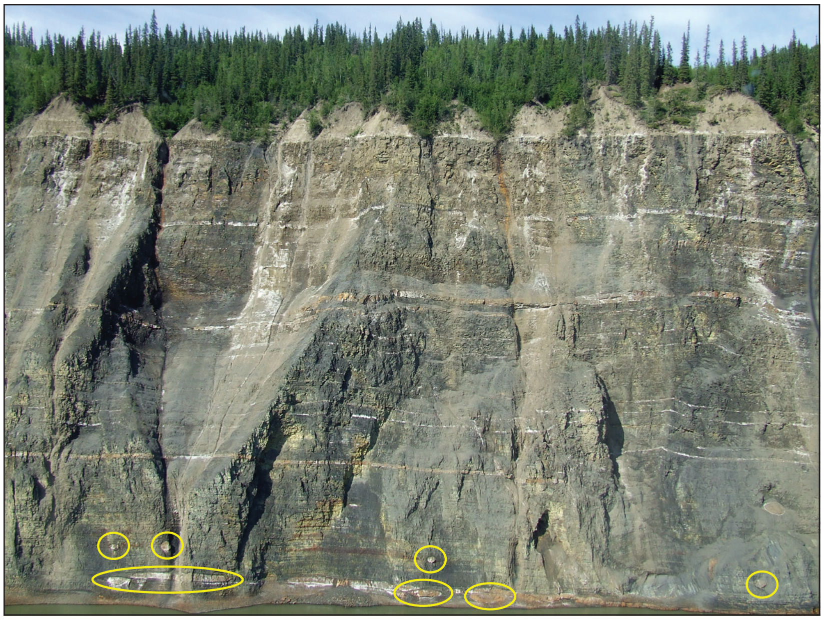


Figure 28. *Outcrop of flat-lying Canol Formation mapped as 'Cf' by Norris (1982b) on north side of Peel River. The height of the exposure is approximately 70 m. Note the large metre-scale spherical and elongate nodules at the base of the exposure circled in yellow. (10TLA-PR-07).*

Collectively, thermal maturity data, including T_{max} values ranging from 432° to 444°C, vitrinite reflectance values ranging from 0.5 to 0.95%Ro_R, and TAI values ranging from 2 to 3+, suggest that surface exposures of unit 'Cf' are within the "oil window" in the east Richardson Mountains and are likely to generate hydrocarbons.

Oil-stained rocks are direct evidence of a hydrocarbon system in a region. A sample of unit 'Cf' siltstone, collected from Aghoo Creek and suspected of being oil-stained, was confirmed by organic solvent extraction; the total extract contains over 80% hydrocarbons potentially derived from an Upper Paleozoic marine source rock (Allen *et al.*, 2008a, 2009) such as the Canol or Imperial formations, unit 'Cf' or the Tuttle Formation. Direct evidence of the presence of hydrocarbons is also observed in the local occurrence of reddened, burnt shale. In addition to the occurrences in unit 'Cf' on Nihtal Git Creek, burnt shale was observed within the Canol Formation (Peel River, Dempster Highway) and Carboniferous Hart River Formation (tributary of the Eagle River) of Eagle Plain. This phenomena is also documented at a number of localities outside Yukon including in the Monterey Formation of California (Bentor *et al.*, 1981), on southern Ellesmere Island (Estrada *et al.*, 2009), in the Smoking Hills of the Arctic Coast, NWT (Matthews and Bustin, 1984), the Burning Cliffs of Dorset, south England (West, 2006) and from within the Upper Jurassic Kimmeridge Clay Formation, in or near 17 oil and gas fields, in the UK (Cisowski and Fuller, 1987). The cause of ignition of the shale is uncertain, however, a number of natural processes can generate high enough temperatures to cause spontaneous combustion of rocks including spontaneous oxidation of fine-grained sulphide, combustion metamorphism associated with oil fields, ignited natural gas seeps and wildfires (Matthews and Bustin, 1984; Sokol and Volkova, 2007; Mariner *et al.*, 2008). Matthews and Bustin (1984) concluded that spontaneous combustion of pyrite-rich, organic mudstone following a landslide was responsible for igniting the Smoking Hills Formation on the Arctic coast of Northwest Territories. This formation contains enough fuel (*e.g.*, organic matter, coal) to sustain a continual burn, whilst also producing smoke and reddened, baked rocks. The 'Cf' unit observed in the Peel region appears to contain an ignition source (pyrite) and fuel (organic matter) required to produce the reddened shale. Minor pyrite was identified in black shale using XRD analyses, organic petrology, and during examination of hand specimens. In addition, a yellow efflorescence commonly noted on weathered surfaces of the black shale was identified by XRD as containing hydrated ferric sulphate minerals. The 'Cf' shale also has high TOC content (2.54-12.17 wt%) which is interpreted as the fuel source to sustain continual burning after ignition.

SUMMARY AND CONCLUSIONS

Strata recognized as unit 'Cf' in Yukon's Peel area are dominated by organic-rich, dark grey to black siliceous shale deposited in a basinal, marine setting. Lithological character and sedimentological characteristics, combined with various analytical data that include Pr/Ph ratios, hydrogen and oxygen indices, sulphur content, and maceral, palynomorph and other fossil identifications, all support this depositional setting. Five lithofacies were identified from outcrop within unit 'Cf', and include siliceous shale, wafery shale, siltstone, mudstone and subordinate sandstone. The most prevalent lithofacies of this unit is the resistant siliceous shale, and this forms ledges and, in some instances, is reddened on the top of steeply inclined slopes. XRD analyses of siliceous and wafery shale assessed in this study highlighted quartz contents of greater than 92%, together with minor amounts of mica, expanded clay, gypsum, pyrite and its derivative jarosite.

Low faunal diversity and limited numbers of spores and pollen have made age determination challenging. Despite low numbers of palynomorphs, unit 'Cf' in the study region has been assigned a Famennian (Late Devonian) age ranging from early Famennian to latest Famennian (Strunian), while coarser grained strata overlying unit 'Cf' (generally assigned to the Tuttle Formation) have been dated as latest Famennian to Tournaisian (early Carboniferous).

Total organic carbon contents for unit 'Cf' (average of 5.28 wt%), S1 (average 1.61 mg hydrocarbons/g rock) and S2 values (average 12.91 mg hydrocarbons/g rock) indicate that the unit has favourable source rock generative potential. High organic carbon content is also suggested by the presence of burning or burnt, reddened shale associated with rising fumes of gas that have a noxious smell. Organic petrology has identified the type of organic matter within the unit as consisting mainly of amorphous kerogen with alginite, sporonite and liptinite (types I, II and III). Geochemical determination of kerogen by Rock-Eval pyrolysis suggests the organic matter consists of a mixture of types II and III, and as such is typically oil to gas-prone. The presence of oil staining in unit 'Cf' was confirmed by solvent extraction techniques. HC yield derived from Soxhlet extraction, coupled with TOC content and organic matter type and maturity data, suggest that unit 'Cf' samples have very good source rock potential.

Analyses assessing a range of thermal maturity indicators (T_{max}, vitrinite reflectance, thermal alteration index) were employed for this study. T_{max} values, derived from Rock-Eval pyrolysis, are consistently between 423° and 444°C for most of the study area and correspond to vitrinite reflectance values that range from 0.5 to 0.95%Ro_R. These values suggest that organic matter within unit 'Cf' is within the "early oil window", indicating that the rock has the potential to generate oil.

Shale, lithologically identical to and coeval to that of unit 'Cf', occurs within sandstone-dominated strata that are assignable to the Tuttle Formation (Pugh, 1983), suggesting that unit 'Cf' is actually a fine-grained facies equivalent of Pugh's (1983) Tuttle Formation. Our work also supports the regional correlation between unit 'Cf' and the Ford Lake Shale proposed by Norris (1985). On this basis, the hydrocarbon-prospective (Hamblin, 2006) Ford Lake Shale, found mainly west of the Richardson Mountains, can be here extended into the eastern Richardson Mountains and eastward into the subsurface of the Peel Plateau.

RECOMMENDED STUDIES

In light of these conclusions regarding the character and correlation of unit 'Cf', a large volume of work is still required to gain a comprehensive understanding of the unit, including its extent, relationship to other units and to petroleum systems in the region. The following are some suggestions for future research:

- a re-examination of Famennian to Tournaisian stratigraphy using a sequence stratigraphic framework is recommended throughout the Richardson Mountains and adjoining Peel region, using both borehole data and surface outcrops. As the Imperial and Tuttle formations and map units 'Cf' and 'M0' were defined based on their lithology (lithostratigraphy), the current usage of the terms is confusing, and hinders the ability to assess the entire rock package as part of a regional depositional system with varying ratios of shale to sandstone.

- detailed bedrock mapping is also suggested for parts of NTS map sheet 106L (Trail River), namely 1:50 000 map sheets 1, 2, 6, 7, 11 and 13 and NTS map sheet 106E (Wind River), namely map sheets 15 and 16 to determine the areal extent of the unit at surface, its relationships with neighbouring units and variability within the unit. There are a number of discrepancies in the distribution of unit 'Cf' versus Tuttle Formation on the bedrock maps, notably on NTS map sheet 106L (Trail River) of Norris (1981a) that need to be resolved to better understand the distribution of these units. In addition to bedrock mapping, a more detailed, systematic study of the sections identified (*e.g.*, Enigma Creek) is recommended, including increased frequency of sampling to gain a better constraint on the age of the strata and lithological heterogeneity of the shale. Logging the shale to sand ratios and collection of whole-rock geochemistry data, spectral gamma-radiation readings and isotope concentrations (*e.g.*, C, S) at a fine scale will help enhance stratigraphic resolution, facilitate chemostratigraphic correlations, and decipher depositional environments.
- although the source rock potential of unit 'Cf' has been demonstrated in this study, further work is required to characterize the interval for unconventional (shale gas) reservoir potential. These follow-up studies should include using SEM to identify rock fabric, porosity and permeability, identification of natural fracture patterns, and identifying biogenic versus detrital silica contents. Resultant data would be useful to further assess the mechanical and flow property response of this formation during artificial well stimulation.

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Appendix A. 'Cf' palynological data including organic material descriptions.

Expanded palynology results and corresponding thermal alteration indices (TAI) for unit 'Cf', Yukon's Peel area, including organic material descriptions. Vitrinite reflectance data from this paper (%Ro_R) is offered for cross-referencing purposes. All UTM locations are NAD83, Zone 8.

Sample Name	GSC #	Location	UTM Easting	UTM Northing	Geological Unit	Probable Age	TAI	%Ro_R	Comments	Reference	Report
Cf' map unit											
07TNT-ACH-34A	473147	Aghoo Creek	512804	7328585	Cf'	indeterminant	2+?	0.85	Abundant amorphous material; rare woody and coaly fragments.	Utting, 2008	JU-2008-04
07TNT-ACH-34B	473148	Aghoo Creek	512907	7328592	Cf'	Famennian?	2+?		Abundant amorphous material; rare woody and coaly fragments. A single specimen of the acritarch *Veryhachium sp*. was recorded, indicating a possible near-shore marine environment of deposition.	Utting, 2008	JU-2008-04
07TNT-ACH-34C	473149	Aghoo Creek	512907	7328592	Cf'	Late Devonian	2+?		Abundant amorphous material; rare woody and coaly fragments.	Utting, 2008	JU-2008-04
08TLA-AGH-13-03	532934	Aghoo Creek	515666	7323109	Cf'	indeterminant	3/3+		Abundant amorphous fragments; rare woody and coaly fragments; finely dispersed organic debris.	Utting, 2009	JU-2009-04
08TLA-AGH-13-04	532935	Aghoo Creek	515666	7323109	Cf'	indeterminant	3/3+	0.72	Abundant amorphous fragments; exinous fragments rare; common woody and coaly fragments. Rare large unidentified Sphaeromorphs (70-75 microns).	Utting, 2009	JU-2009-04
08TLA-AGH-14-02	532936	Aghoo Creek	515172	7322454	Cf'	indeterminant	3/3+		Abundant amorphous fragments; common woody and coaly fragments. Rare unidentified small spores.	Utting, 2009	JU-2009-04
06TNT-CR-031A/C	473070	Caribou River	512994	7344407	Cf'	Late Famennian (Strunian)	2	0.67	Common finely dispersed organic debris; common exinous fragments; abundant woody and coaly fragments.	Utting, 2007	JU-2007-02
07TNT-CR-010A	473171	Caribou River	496967	7347199	Tuttle or Cf	Famennian, Late Devonian	2		Abundant amorphous fragments; abundant finely dispersed organic debris; common exinous material; abundant woody and coaly fragments.	Utting, 2009	JU-2009-04
07TNT-CR-011A/B	473173	Caribou River	501997	7347100	Tuttle or Cf	Famennian, Late Devonian	2	0.56	Abundant finely dispersed organic debris; amorphous fragments; common exinous material; abundant woody and coaly fragments.	Utting, 2009	JU-2009-04
07TNT-CR-12A	473174	Caribou River	507992	7344887	Cf'	Famennian, Late Devonian	2	0.50	Abundant amorphous fragments; common finely dispersed organic debris; common exinous material; abundant woody and coaly fragments. Large Sphaeromorphs abundant.	Utting, 2009	JU-2009-04
08TLA-CR-15-02	532937	Caribou River	509918	7344555	Cf'	indeterminant	3/3+		Abundant amorphous fragments; common woody and coaly fragments. *Hystricosporites delectabilis*and Sphaeromorphs.	Utting, 2009	JU-2009-04
08TLA-CR-15-03	532938	Caribou River	509918	7344555	Cf'	Famennian	3/3+		Abundant amorphous fragments; finely dispersed organic debris; exinous material; abundant woody and coaly fragments.	Utting, 2009	JU-2009-04

Appendix A continued

Sample Name	GSC #	Location	UTM Easting	UTM Northing	Geological Unit	Probable Age	TAI	$\%Ro_R$	Comments	Reference	Report
Cf' map unit											
2009LHA061A01	486335	Caribou River	504842	7345454	Cf'	Late Famennian (Strunian)		0.85	The age is based on numerous specimens of *Retispora lepidophyta*.Leiospheres are abundant in the coarse fraction.	Dolby, 2012	Dolby, 2012.8
10TLA-EC-08A	542069	Enigma Creek	507324	7328157	Cf'	?Devonian	high		The TAI is high in this sample and the residue consists of amorphous debris. The coarse fraction contains numerous large leiosphaeres that resemble *Protoleiosphaeridium major*.	Dolby, 2011	Dolby, 2011.6
10TLA-EC-17A	542102	Enigma Creek	510172	7328515	Cf'	Late Famennian		0.75	Heavy bacterial corrosion and pyrite damage. Scolecodont identified.	Dolby, 2011	Dolby 2011.6
10LHA097A01	491862	Enigma Creek	510183	7328517	Cf'	indeterminant		0.81	The residue consists of amorphous kerogen with numerous small, simple, unidentifiable sporomorphs.	Dolby, 2011	Dolby 2011.6
10LHA097A02	491863	Enigma Creek	510183	7328517	Cf'	Late Famennian (Strunian)			The kerogen is predominantly sapropelic debris and many of the spores are corroded. The assemblage is of very limited composition and is dominated by super-abundant specimens of *Retispora lepidophyta*.	Dolby, 2012	Dolby, 2012.8
10LHA09703	491864	Enigma Creek	510183	7328517	Cf'	probably Tournaisian		0.72	There are rare spores that resemble *Tumulispora rarituberculata* and *T. malevkensis* as well simple spores. This group, in the absence of *Retispora lepidophyta,* favors a Tournaisian age. Bacterial corrosion hinders identification. A noticeable feature of this sample is the super-abundance of *Cyrtospora cristifera*. This species can occur in the Early Tournaisian but not in such numbers. These are considered to have been reworked from the Famennian and this is confirmed by the presence of *Hystricosporites spp*. in the coarse fraction.	Dolby, 2011	Dolby,2011.6
06TNT-CC-026A	473066	Nihtal Git Creek	523198	7355395	Cf'	indeterminant	2		Abundant amorphous particles; common exinous material; rare woody and coaly fragments. Abundant well preserved sphaeromorphs of unknown affinity; rare biodegraded trilete spores.	Utting, 2007	JU-2007-02
06TNT-CC-026E	473074	Nihtal Git Creek	523225	7325515	Cf'	indeterminant	3+(?)		Abundant amorphous fragments; common finely dispersed organic debris, woody and coaly fragments.	Utting, 2009	JU-2009-04
06TNT-CC-026G	473075	Nihtal Git Creek	523295	7325620	Cf'	indeterminant	3+(?)		Abundant amorphous fragments; finely dispersed organic debris; common exinous material; abundant woody and coaly fragments.	Utting, 2009	JU-2009-04
06TNT-CC-026K	473067	Nihtal Git Creek	523167	7325671	Cf'	indeterminant	2	0.65	Abundant well preserved sphaeromorphs of unknown affinity; rare biodegraded trilete spores. A single specimen of acanthomorph acritarch (*Baltisphaeridium sp.*) suggests a marine environment of deposition.	Utting, 2007	JU-2007-02

Appendix A continued

Sample Name	GSC #	Location	UTM Easting	UTM Northing	Geological Unit	Probable Age	TAI	$\%Ro_R$	Comments	Reference	Report
Cf′ map unit											
07TNT-CC-27A	473143	Nihtal Git Creek	526761	7327329	Cf′	Late Devonian (late Famennian?)	2	0.87	Abundant amorphous debris; abundant coaly fragments. Rare finely dispersed organic debris; abundant woody and coaly fragments.	Utting, 2008	JU-2008-04
09TLA-CC-100-1	491978	Nihtal Git Creek	523211	7325558	Cf′	indeterminant		0.95	The residue consists of amorphous sapropelic debris. The few palynomorphs are unidentifiable due to bacterial corrosion.	Dolby, 2012	Dolby, 2012.8
09TLA-CC-101-1	536450	Nihtal Git Creek	523211	7325558	Cf′	?Early Famennian			Amorphous, sapropelic kerogen and very rare spores, most of them degraded and unidentifiable. The coarse fraction contains numerous large leiospheres.	Dolby, 2010	Dolby 2010-03-11
09TLA-CC-102-1	536455	Nihtal Git Creek	523211	7325558	Cf′	Early Famennian, upper TG			This is a typical Early Famennian assemblage in which *Cyrtospora cristifera* and *Cornispora varicornata* are prominent. There is evidence of reworking of Frasnian rocks.	Dolby, 2010	Dolby 2010-03-11
2009LHA034A01	486318	Nihtal Git Creek	523222	7325735	Cf′	?Late Famennian (Strunian)			The residue consists predominantly of oxidized amorphous sapropel. There are numerous small sporomorphs and leiospheres that are unidentifiable due to the bacterial corrosion. The tentative age is based on two questionable specimens of *Retispora lepidophyta* the ornament of which might be an artifact of bacterial attack. The coarse fraction is similar with a modest number of large leiospheres.	Dolby, 2012	Dolby, 2012.8
10TLA-PR-07A	542067	Peel River	509962	7319034	Cf′	indeterminant			Residues consist of amorphous, sapropelic debris with extremely rare palynomorphs, most of which are unidentifiable due to bacterial corrosion. Contains a questionable *Tumulispora rarituberculatus (malevkensis* type) that, if correct, would indicate a Tournaisian age.	Dolby, 2012	Dolby, 2012.8
10TLA-PR-07B	542068	Peel River	509989	7319018	Cf′	indeterminant		0.89	Residues consist of amorphous, sapropelic debris with extremely rare palynomorphs, most of which are unidentifiable due to bacterial corrosion.	Dolby, 2012	Dolby, 2012.8

Appendix B. 'Cf' vitrinite reflectance and organic petrological data.

Summary of vitrinite reflectance data in random percent reflectance in oil (%Ro_R). Key for organic type: 2=vitrinite; 4=bitumen. Organic material descriptions derived from organic petrology are shown in the comments column. All UTM coordinates are NAD83, Zone 8.

Sample Name	GSC- C #	Location	UTM Easting	UTM Northing	Organic Type	%Ro_R	Comments
07TNT-ACH-34A	473147	Aghoo Creek	483017	7370843	2	0.85	Organic and pyrite rich silty shale consisting mainly thin interconnected network of amorphous kerogen with minor amount of yellow orange to reddish fluorescing and non fluorescing alginite macerals (mainly prasinophyte, *Tasmanites* with rare siliceous microfossil), and rare amount of orange fluorescing bitumen. Measurements are taken from mostly granular solid bitumen. Trace amount of vitrinite and inertinite macerals.
08TLA-AGH-13-4	532935	Aghoo Creek	515666	7323109	2	0.72	Organic rich shaly mudstone of mostly interconnected network of dark brown amorphous kerogen with minor amount of fluorescing bitumen and trace amount of yellow fluorescing alginite macerals (large *Tasmanites* and *Leiosphaeridia*) and inclusions. Rare amount of calcareous and siliceous microfossils were also observed. Note: yellow fluorescing hydrocarbon fluid inclusion annealed in carbonate fractures and pores were observed proximal to fluorescing solid hydrocarbon.
06TNT-CR-031A/C	473070	Caribou River	512994	7344407	2	0.67	Pyrite rich black shale with high amount oxidized amorphous kerogen lenses (some kerogen have high amount of micrinitic particles). Intense yellow to orange yellow fluorescing liptinite (mostly sporinite some alginite) most of which are indigenous but some are recycled (i.e. weak fluorescing fragments of sporinite). Sporinite were observed parallel to and perpendicular to the bedding.
07TNT-CR-011A/B	473172	Caribou River			2	0.56	Mostly alginite (golden yellow fluorescing) rich mudstone with rare yellow orange fluorescing sporinite and bitumen, and some allocthonous vitrinite and inertinite inclusion. Rare hcfi annealed with quartz and calcite minerals. Mainly thin and thick walled yellow fluorescing prasinophyte and rare spiny acanthomorphic acritarchs.
07TNT-CR-012A	473174	Caribou River	507992	7344887	2	0.50	Contains mainly continuous network of brown granular amorphous kerogen and hebamorphinite within pyrite rich marl-matrix with high allochthonous vitrinite and inertinite inclusion. There are mainly thin and thick walled yellow fluorescing prasinophyte, rare spiny acanthomorphic acritarchs, yellow orange fluorescing sporinite and bitumen. Rare hydrocarbon fluid inclusions annealed within quartz and calcite minerals.
2009LHA061A01	486335	Caribou River	504842	7345454	2	0.85	Organic and framboidal pyrite rich silty shale with mostly brown granular amorphous kerogen showing major amount of yellow to orange fluorescing thick walled *Leiosphaeridi* like alginite inclusions. Some orange to reddish fluorescing bituminite and isotropic solid bitumen. Trace amount of inertodetrinite macerals.
2009LHA061A02	486336	Caribou River	504842	7345454	4	0.67	Similar to above sample with the exception of the highly oxidized nature of the matrices, presence of solid hydrocarbon in some pores and microfractures, and hydrocarbon fluid inclusions. Organic and framboidal pyrite rich silty shale with mostly greyish to creamy white granular amorphous kerogen (due to oxidation) but still showing minor amount of dull yellow to orange fluorescing thick walled *Leiosphaeridi and Tasmanites*alginite inclusions. Some weak fluorescing bituminite and isotropic solid bitumen. Rare amount of inertodetrinite macerals. %Ro may be suppressed due to oxidation.

Appendix B continued

Sample Name	GSC- C #	Location	UTM Easting	UTM Northing	Organic Type	$\%Ro_R$	Comments
10LHA097A01	491862	Enigma Creek	510183	7328517	4	0.81	Silty shale with minor amount of long thin lenses of amorphous kerogen some showing rare amount of orange fluorescing *Tasmanites sp*.and trace amount of orange to brown fluorescing macro and micro sporinite macerals. Minor amount of calcareous and siliceous microfossils were also observed. Measured are mostly small migrabitumen macerals.
10LHA097A03	491864	Enigma Creek	510183	7328517	2	0.72	Siltstone matrix with minor amount of brownish orange to non fluorescing, cutinite (from originating from leaves and roots) macro and microsporinite macerals some showing detailed ornamentations. Trace amount of inertinite and measurable vitrinite and bitumen macerals.
10TLA-EC-17A	542102	Enigma Creek	510172	7328515	2	0.75	Highly reworked siltstone-mudstone matrix with mostly terrestrial plant derived liptinite and inertinite macerals, i.e. yellow to orange fluorescing sporinite, cutinite, and trace amount of resinite. Rare amount of yellow fluorescing alginite and orange fluorescing bitumen macerals were also observed in most sandstone microlithotype. Most sporinite macerals shows pyrite inclusion due to bacterial sulphate reduction and possible oxidation.
07TNT-CC-27A	473143	Nihtal Git Creek	526761	7327329	2	0.87	Organic rich silty shale with major amount of interconnected network of amorphous kerogen (oxidation post uplift) with yellow orange to reddish fluorescing alginite (prasinophyte, *Tasmanites*, *Leiosphaeridia*) maceral inclusion. Rare amount of allochthonous inertinite macerals and trace amount of reddish brown fluorescing sporinite maceral.
06TNT-CC-026J/K	473117	Nihtal Git Creek	523167	7325671	2	0.65	Black shale with highly degraded amorphous kerogen due to weathering. Some kerogen with high amounts of micrinitic particles showing signs of oxidation. There are rare particles of oxidation and weak orange fluorescing sporinite (macrosporinite).
2009-TNT-CC-100-01	491978	Nihtal Git Creek	523211	7325558	2	0.95	Organic and framboidal pyrite rich shale showing high percentage of both granular and isotropic primary solid hydrocarbon/bitumen. Secondary low reflecting, weak reddish brown fluorescing bituminite and non fluorescing secondary bitumen observed micro and macro pores and fractures. Yellow fluorescing soluble organic brecciated between solid bitumen and mineral matrices including reddish orange alginite macerals are also observed. Soluble or %Ro may be suppressed to the presence of soluble organics in the matrices. Minor surface oxidation may also be factor. Trace amount reworked fusinite and inertodetrinite are also present.
10TLA-PR-07B	542068	Peel River	509962	7319034	2	0.89	Organic rich shale consisting mostly of network amorphous kerogen with rare inclusions of solid bitumen, yellow to orange fluorescing prasinophyte and *Tasmanites* alginite, and trace amount of orange to reddish fluorescing sporinite macerals. Rare amount of inertinite macerals were also observed.

Appendix C. Canol Formation analyses: XRD, palynology, vitrinite reflectance, RockEval/TOC.

Table 1. *Palynological determinations of Canol Formation samples in the Peel region. Summary of palynology results and corresponding thermal alteration indices (TAI) for Canol Formation samples, Yukon's Peel area. Vitrinite reflectance data (%Ro) is offered for cross-referencing purposes. All UTM locations are NAD83, Zone 8.*

Sample Name	GSC #	Location	UTM Easting	UTM Northing	Geological Unit	Probable Age	TAI	$\%Ro_R$	Comments	Reference
Canol Formation										
06TNT-PR-033A/B	473071	Peel River	529110	7314150	Canol	indeterminant	3+/4-	0.78	Common amorphous particles; common finely dispersed organic debris; abundant spores and exinous fragments with numerous sulphide pseudomorphs; common woody and coaly fragments.	Utting, 2007
10TLA-PR-05C		Peel River	530707	7315600	Canol	?Frasnian			TAI is very high and the residue consists of inertinite with numerous small, black, indeterminate sporomorphs.	Dolby, 2011
10TLA-MC-23A	542112	Solo Creek	533860	7309439	Canol	probably Middle Devonian (Givetian?)	very high	1.63	The TAI is high in this sample and small spores are numerous but too poorly preserved to identify with confidence. The coarse fraction contains scolecodonts and chitinozoans.	Dolby, 2011

Table 2. *Rock-Eval/TOC analyses of Canol Formation samples in the Peel region. Summary of Rock-Eval/TOC data for Canol Formation samples measured in the Peel region. Parameters measured or derived from Rock-Eval 6 pyrolysis include TOC (total organic carbon expressed as percent weight of whole rock); S1 (mg HC/g rock); S2 (mg HC/g rock); S3 (mg CO2/g rock); PI (production index=S1/S1+S2); HI (hydrogen index=100x(S2/TOC), expressed as mg HC/g Corg); OI (oxygen index=100x(S3/TOC), expressed as mg CO2/g Corg);* T_{max} *(temperature in °C at which the maximum amount of S2 hydrocarbons are generated during Rock-Eval pyrolysis). Vitrinite reflectance (%* Ro_R*) and thermal alteration index (TAI; Utting, 2007; Dolby, 2011) are shown for cross-referencing purposes. '+' represents burnt, red siltstone. '*' represents analyses published in Allen and Fraser, 2008. All UTM locations are NAD83, Zone 8.*

Sample	Location	UTM Easting	UTM Northing	TOC	S1	S2	S3	S1+S2	PI	HI	OI	Tmax	TAI	%Ro_R	Lithology
Canol Formation															
06TNT-PR-033A*	Peel River	529110	7314150	4.54	0.27	1.56	0.28	1.83	0.15	34	6	497	3+/4-		siliceous shale
06TNT-PR-033B*	Peel River	529110	7314150	3.89	0.10	1.03	0.50	1.13	0.09	26	13	574		0.78	siliceous shale
10TLA-PR-05A	Peel River	530707	7315600	3.25	0.16	0.53	0.21	0.69	0.24	16	6	593			siliceous shale with greasy coating
10TLA-PR-05C	Peel River	530807	7315637	2.63	0.20	0.34	0.21	0.54	0.37	13	8	605	high		siliceous shale
10TLA-PR-05D	Peel River	530807	7315637	7.31	1.32	3.58	0.10	4.90	0.27	49	1	462			siliceous shale
10TLA-PR-05F	Peel River	530807	7315637	2.13	0.06	0.27	0.16	0.33	0.17	13	8	605			siliceous shale / siltstone
10TLA-MC-23A	Solo Creek	533860	7309439	2.63	0.04	0.47	0.36	0.51	0.07	18	14	591	very high	1.63	siliceous shale
06TNT-PR-033C+*	Peel River	529110	7314150	0.03	0.01	0.05	0.15	0.06	0.18	167	500	354			burnt red shale / siltstone

Appendix C continued

Table 3. *Vitrinite reflectance analyses for Canol Formation samples in the Peel region. Summary of vitrinite reflectance data for Canol Formation samples. Vitrinite reflectance is expressed as random percent reflectance in oil (%Ro_R). Key for organic type: 2=vitrinite; 4=bitumen. All UTM locations are NAD83, Zone 8.*

Sample Name	GSC- C #	Location	UTM Easting	UTM Northing	Organic Type	%Ro_R	Comments
06TNT-PR-033B	473122	Peel River	529110	7314150	2	0.78	Black shale with mostly oxidized amorphous kerogen lenses. Most of the amorphous kerogen and vitrinite measured contain some micrinitic particles which may affect the average %Ro (higher %Ro).
10TLA-MC-23A	542112	Solo Creek	533860	7309439	4	1.63	Organic rich shale consisting mostly of interconnected network of amorphous kerogen with rare inclusions of solid and granular pyrobitumen showing effects of oxidation. Trace amount of inertinite macerals were also observed.

Table 4. *XRD analyses for Canol Formation samples in the Peel region. Mineralogical compositions of Canol Formation samples from XRD semi-quantitative analyses (expressed in mineral weight percent). '*' refers to a sample of yellow efflorescence or sulphur precipitate commonly found on the weathered surfaces of the shale. All UTM coordinates are NAD83, Zone 8.*

Sample Name	GSC C-#	Location	UTM Easting	UTM Easting	Mixed-Layer Clay (%)	Mica/ Illite (%)	Kaolinite &/or Chlorite (%)	Total Clay (%)	Quartz (%)	Jarosite (%)	Pyrite (%)	Other minerals (%)
Canol Formation												
10-TLA-MC-23A	C542112	Solo Creek	533860	533860		1		1	99			Anhydrite - trace
10-TLA-PR-05C	C542063	Peel River	530707	530707		1		1	98	trace		Gypsum 1%
10-TLA-PR-05F	C542065	Peel River	530807	530807		1	trace	1	99	trace		
10-TLA-PR-05G	C543970A	Peel River	530807	7315637	2	4		6	92		1	trace gypsum
10-TLA-PR-05G*	C543970	Peel River	530807	7315637							37	Rozenite 24%; Pickeringite 35%; Copiapite? 4%