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SUMMARY

This report compiles new data from six wells from the Canol Shale Play exploration area and two adjacent outcrop sections. New fossil identifications and conodont data from studied cores improve biostratigraphic constraints of the Kee Scarp/Canol and Canol/Imperial contacts. Lithofacies descriptions and core face photoplates are provided. Cored sections of Loon Creek O-06, Little Bear N-09, East McKay I-78, and Mirror Lake N-20 exploration wells (all drilled in 2013) intersect the upper Hume, Hare Indian, Canol formations, and the base of the Imperial Formation. Cores from two older wells Mackenzie River #4 (E-27) and Canyon Creek # 1 (G-51) are revisited to better understand the Kee Scarp / Canol contact and the Canol-Imperial transitional interval. The core from Loon Creek O-06 well has been sampled (380 samples) and analyzed for major oxides, trace elements, and total C and S (ICP-MS/ES and Leco methods). Same samples were run for Rock-Eval™ 6 pyrolysis. Selected rock structures were surveyed for chemical composition with ED-XRF. The measured outcrop sections are Prohibition Creek (upper Bluefish – upper Canol interval) and Francis Creek (Hume – Hare Indian interval). Spectral gamma log with 0.5 m vertical step allows for correlation of these outcrops with subsurface sections as exemplified by two cross sections. New data allow for improvement in local lithostratigraphic subdivision of the Horn River Group.

INTRODUCTION

The black shales of the Horn River Group, identified a decade ago to host the largest unconventional hydrocarbon resource in the region (Hamblin, 2006), have recently seen investment into the exploration in the central Mackenzie Plain (Hayes, 2011; Pyle et al., 2014) with over 1.2 million hectares to the south and northwest of Norman Wells covered by exploration licenses (AANDC, 2014). This prospect consists of the thickest (up to 180 m) Canol Formation with up to 16.9% TOC (Kabanov, 2015) and the Bluefish Member of the Hare Indian Formation that is thinner (up to 23 m) and has up to 10% TOC (Pyle et al., 2014). The two organic-rich units are divided by a gray to black shale interval of strongly variable thickness that was recently named the Bell Creek Member (Pyle et al., 2014). Where the Bell Creek member is thick, it is overbuilt by isolated carbonate banks and reef-like pinnacles of the Ramparts Formation. Available data indicate that the Horn River Group contains predominantly type I to II kerogen (offset towards type III in the Bell Creek Member and the newly defined Mirror Lake member) which, in the Mackenzie Plain, occurs within and locally beyond the oil window. The thermal maturity gradient generally increases to the west and south (Snowden et al., 1987; Gal and Pyle, 2012; Pyle et al., 2014).

The Husky wells Little Bear N-09 and Little Bear H-64 were the first two wells with representative cored sections, completed in 2012 and released to the public in 2014. Project results on Little Bear N-09 have been published by Kabanov et al. (2015). In 2013, exploration activity in the Central Mackenzie Valley included four new exploration wells, one geophysical field operation, and re-entering of five previously drilled wells (AANDC, 2014). This paper reports on Conoco Phillips Loon Creek O-06 and Mirror Lake N-20 and MGM Energy East Mackay I-78 wells, all completed in 2013 and released to the public in 2015. The last exploration well, Dodo Canyon E-76, was completed by Conoco Phillips in March 2014 and will be released to the public in March 2016.

Before this exploration campaign, the Horn River Group in the subsurface had very few and mostly short cores. The lithogeochemical, mineralogical, and organic-matter database for the Horn River Group has expanded dramatically in recent years due to the Mackenzie Plain Petroleum Project of the N.W.T. Geoscience Office (NTGO/NTGS). New data for this unconventional prospect were obtained from adjacent outcrops and drill cuttings (Gal et al., 2009; Gal and Pyle, 2011, 2012; Hayes, 2011; Pyle and Gal, 2012, 2013; Pyle et al., 2011, 2014). The Mountain River Tributary section (MR) has been proposed as a regional reference section for its stratigraphic completeness and short-distance helicopter accessibility from Norman Wells (Pyle et al., 2014). The North American Stratigraphic Code (2005, p. 1566) also supports the development of subsurface reference sections for lithostratigraphic units originally defined in outcrops.

New exploration wells from the Canol Shale Play with representative cores and up-to-date wirelog characterization offer an opportunity to study fine patterns that cannot be picked with cuttings resolution. Such sections are used to improve the surface-subsurface correlation and the stratigraphic framework for tight-reservoir resource evaluation and fundamental research. Study of these new wells is part of the Mackenzie Project of Geomapping for Energy and Minerals (GEM) Program of Natural Resources Canada.

METHODOLOGY

Cores from Devonian strata of the Mackenzie River Corridor were examined and sampled at the National Energy Board (NEB) Core and Sample Repository at the Geological Survey of Canada in Calgary (GSC-C). Core face has been usually sprayed with water for photographing to reduce light dispersion from rough surfaces and highlight fine structures. The cored section of the Loon Creek O-06 well has been selected for multiproxy sampling. A total of 380 samples, 7.0-8.0 gram each, were collected from core sides and loose chips. The core was sampled approximately every 50 cm in the Horn River Group and across the Hume/Bluefish contact and about 0.8 m in the underlying Hume Formation. Each sample represents an averaged material collected from a stratigraphic interval exceeding 1 cm (typically 2-5 cm) to ensure that none of the collected samples represented a single sedimentary lamina. Drilling mud from the core side was removed prior to collecting samples.

Bulk-element geochemistry

The samples were analyzed for bulk elemental concentration at Acme Analytical Laboratories in Vancouver, B.C. using the inductively coupled plasma-mass spectrometry (ICP-MS) instrumentation technique. Two sample preparation techniques were used before running through the ICP-MS in order to analyze for specific elements/compounds.

The first technique was the lithogeochemical whole rock fusion technique which involves mixing a 200 mg sample with a lithium metaborate ($LiBO_2$)/ lithium tetraborate ($Li_2B_4O_7$) flux in a crucible. The crucibles are then placed in a furnace and heated in order to fuse the sample. The bead that develops is cooled then dissolved in nitric acid and run for ICP-MS in order to analyze the concentrations of rare earth and refractory elements (11 compounds, 33 elements) (see Appendix 1). LOI is also measured by heating and then weighing an aliquot of the sample in order to determine weight loss. This is used as a rough approximation of organic matter (carbon) minus water and light hydrocarbons that were burned off.

The second technique was the geochemical aqua regia digestion whereby 500 mg of sample was digested in a 1:1:1 solution of hydrochloric acid (HCl), nitric acid (HNO_3) and de-ionized water while placed in a heated water bath for one hour. Dilute HCl is then added to the residue in order to top up the sample to the required analysis volume. Samples were split into 0.5 g subsamples and run through the ICP-MS instrument to determine the concentration of 14 elements that were not detected in the above technique, including Au and volatile elements, at the ppm level (see Appendix 1).

In addition, total carbon and total sulphur were measured using the LECO instrument. In this procedure, the induction flux is added to the crushed sample and ignited in an induction furnace. A carrier gas sweeps up the released carbon which is measured by adsorption in an infrared spectrometric cell. The results represent all forms of carbon and sulphur that are present in the sample. The detection limit for this procedure is 0.02%.

Rock-Eval™ 6 pyrolysis

The pyrolysis-combustion tests (Appendices 2 and 3) were conducted at the Organic Petrology and Geochemistry Laboratory in GSC (Calgary) using the Rock-Eval™ 6 instrument. Approximately 1g of the unwashed core sample was crushed to powder form using a mortar and pestle. A 70 mg aliquot of the sample was then inserted into a stainless steel crucible and heated in an open pyrolysis system. Initially, the samples are heated at 300°C for 3 minutes to volatilize any free hydrocarbons (HC), which are represented by the S1 peak on the pyrograms. The S1 value (mg HC/g of rock) corresponds to the amount of free and adsorbed hydrocarbons generated naturally over time in the rock (Behar et al., 2001).

The next step in the procedure is to heat the samples from 300 to 650 °C at a rate of 25°C/minute, which yields the S2 peak. The S2 value (mg HC/g of rock) represents the amount of hydrocarbon released due to thermal cracking of kerogen present in the sample. This is the remaining potential of the sample to generate hydrocarbons if conditions had allowed it. It is important to note that drilling mud contamination and hydrocarbon migration can affect both the S1 and S2 values (Issler et al., 2012), however, in collected core samples the possibility of drilling mud contamination is considered negligible because of pre-sampling surface cleaning and extremely low permeability of shales precluding mud cake formation.

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

The final step is the oxidation of the samples, which measures the total amount of organic carbon generated during this stage. Here, the samples are heated from 300°C to 850°C and the CO and CO_2 are detected by IR cells, producing the S4 curve which measures the residual organic carbon (RC). The S5 curve corresponds to the mineral carbon from CO and CO_2 generated during mineral oxidation (Behar et al., 2001), mainly calcination of carbonate salts.

The sum of the pyrolysable organic carbon (PC) and residual organic carbon (RC) is the total organic carbon (TOC; wt%) in the sample. Tmax is measured at the maximum of the S2 peak and indicates the maturity of the samples, which is dependent on the kerogen type (see Tissot et al., 1980). Other calculated parameters include: HI (S2*100/TOC), OI (S3*100/TOC) and PI (S1/S2+S3). These parameters aid in identifying the kerogen type (I-IV) and whether the organic matter in the sample is oil vs gas prone. All pyrograms can be found in Appendix 3.

ED-XRF geochemistry

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

On-core spectral gamma ray

The RS-230 BGO scintillometer of Radiation Solutions Inc. has been used to acquire spectral gamma-ray logs (SGR) of old cores and outcrop sections. These logs are used to correlate outcrop and well sections drilled in the exploration areas of Mackenzie Valley; on-core gamma logs are also used for core depth corrections against borehole gamma logs (Ellis and Singer, 2008).

Decomposition of gamma radiation into U, Th and K spectra is widely used to interpret lithology and depositional environments. Potassium and thorium are relatively stable and mostly bound in detrital siliciclastics, whereas uranium is more soluble and tends to be trapped by organic matter. Hence K and Th are usually better correlated to each other than K/U and Th/U, and are often used together as a uranium stripped K-Th gamma ray proxy for siliciclastic supply, also known as the computed gamma ray (CGR). Potassium is more involved in weathering mineral transformations than thorium and therefore tends to be bound in clays. Thorium is very stable near the Earth surface and preferentially resides in detrital mineral grains (Rider, 1999). The contribution of K, U, and Th series to the total gamma radiation (GR) is described by the empirical formula (Ellis and Singer, 2008):

$$GR[API] = 4Th[ppm] + 8U[ppm] + 16K[\%]$$

$$CGR[API] = 4Th[ppm] + 16K[\%]$$

The γ-ray (Gamma-ray) spectrometry is based on the fact that the natural radioactivity in ancient rocks mostly results from three isotopes, ^{232}Th, ^{40}K, and ^{238}U, having half-lives comparable to the age of the Earth crust. Other radioactive isotopes decay faster with diminutive significance back in the pre-Quaternary geological record. Thorium and uranium both decay through two different series of a dozen or more intermediate isotopes to a stable isotope of lead. These decays produce complicated gamma-ray spectra with energy emission lines characteristic for each series. Radioactive potassium ^{40}K decaying to stable ^{39}K has only one characteristic gamma energy of 1.46 meV (Ellis and Singer, 2008).

LITHOSTRATIGRAPHIC UNITS

The lithostratigraphy of the Horn River Group and basal Imperial Formation receive substantial upgrades based on core observations and log information (Figures 1, 5, 6, and 7; Appendices 5, 6, and 7). Expression of lithostratigraphic units in natural outcrops is described based on observations from 2015 field season at Prohibition and Francis creeks (Figures 1, 7, 8, and 9; Appendices 1 and 2). The correlation of these new off-bank sections with sections penetrating typical thick Hare Indian and Ramparts formations is given on cross-sections (Figures 10 and 11). More details on lithostratigraphic units, including new proposed members of Hare Indian, Canol, and basal Imperial formations, are given in (Kabanov et al., Submitted).

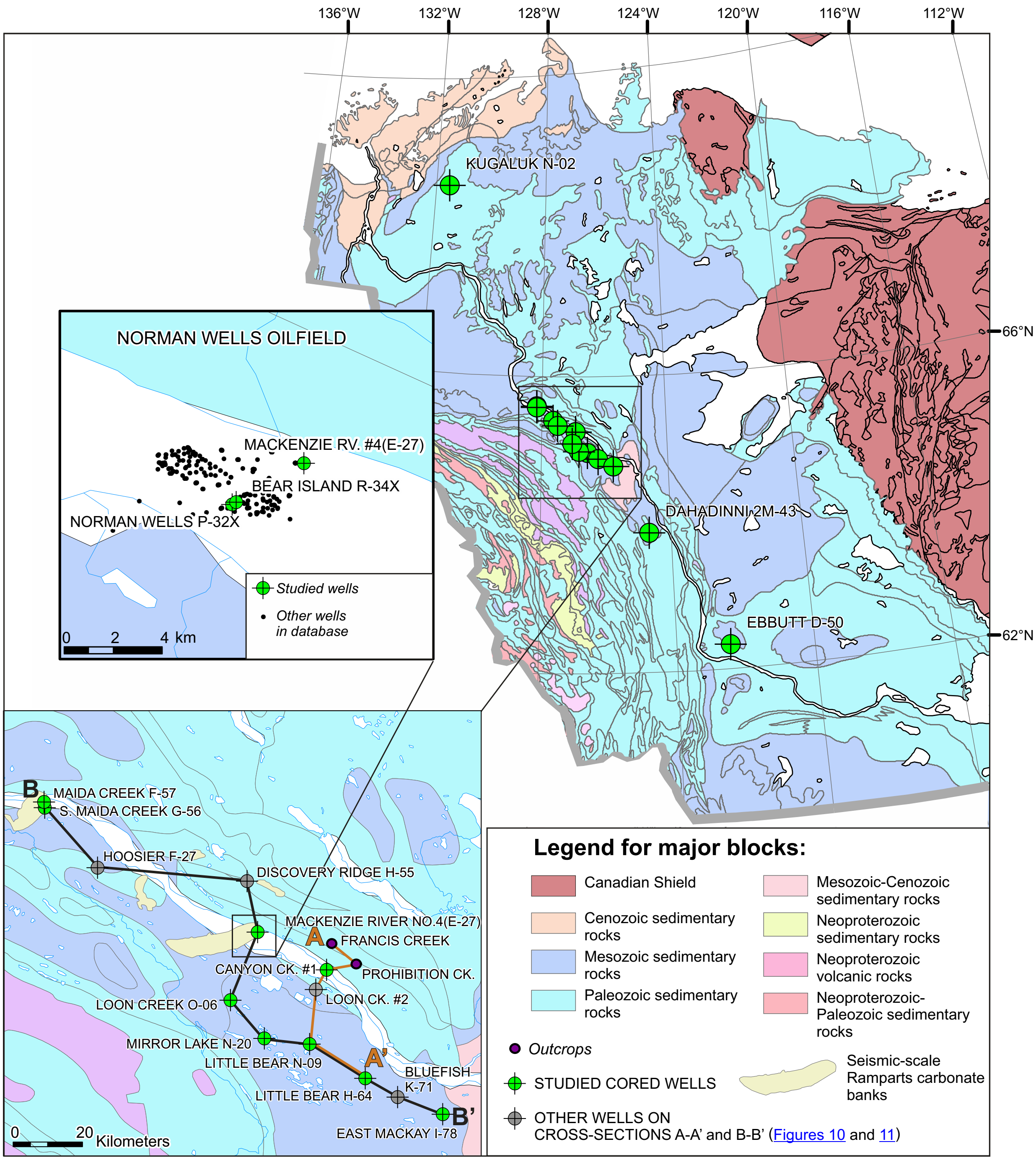


Figure 1. Location of studied wells (2013-2015) on Geological map of Northwestern Canada, based on Wheeler et al. (1997). Lines A-A' and B-B' on the inset show cross-sections on Figures 12 and 13, correspondingly. Seismic interpretation of Ramparts carbonate banks ('reefs') is courtesy of B.C. MacLean (slightly modified).

Bluefish Member of Hare Indian Formation

The Bluefish Member, defined by Bassett (1961) as the basal dark part of the Hare Indian Formation and named by Tassonyi (1969), has received comprehensive description in a number of works (Tassonyi, 1969; Pugh, 1983, 1993; most recently Gal et al., 2009; Pyle et al., 2014). In new cores, the Bluefish Member shows typical alternation of black calcareous shales (mudrocks) and muddy limestones with mass tentaculitids, in the upper one-half with pyritized sponge spicules and mass organic-walled acritarchs (*Leiosphaeridia*, *Tasmanites* s.l..; algocysts of Tassonyi, 1969 and Aitken et al., 1982).

A marker cone-in-cone fibrous diagenetic limestone (marker fibrous calcite bed; Mackenzie, 1972) is traced at very constant level above the Hume top: 2.7 m at Francis Creek, 2.6 m in Loon Creek O-06 well, and 2.5 m in Little Bear N-09 well. The East MacKay I-78 shows four levels of cone-in-cone limestone, the thickest one at 1941.95-1942.2 m (14.5 m above the Hume top), and the lower cone-in-cone limestone, only 10 cm thick, occurs at 1953.25 m MD, in 3.45 m above the Hume top.

Francis Creek and Prohibition Creek members

The newly proposed *Francis Creek* and *Prohibition Creek* members compose the Black-shale informal member of Pugh (1993) and the "atypical Bell Creek member" of Pyle et al. (2014) who correlated the typical thick gray-shale member of the Hare Indian Formation (type Bell Creek) to thinner, off-bank sections such as the section at Carcajou River. The latter has been designated as the type section for the "atypical" Bell Creek Member (Pyle et al., 2014). Here we propose to restrict the name *Bell Creek Member* to thick "typical" sections of greenish gray calcareous variously bioturbated and fossiliferous shales composing the "shale banks" (Muir et al., 1984; Muir, 1988), grading upwards and partly laterally into limestone-dominated "Platform member" of the Ramparts Formation and locally overbuilt by the Kee Scarp Member of the Ramparts Formation (Figure 2).

The rationale for restricting the usage of the Bell Creek Member lies in the difficulty to map the "black-shale member" separately from the overlying Canol Formation. Both are dominated by dark organic-rich shales and visually are very similar as repeatedly admitted (Pugh, 1993, Pyle et al., 2014); both historically were mostly mapped as Canol Formation (Pugh, 1983). However, the basal part of the "black-shale member" in studied new sections includes the thin although traceable gray-shale unit rich in terrigenous clays that we propose to name Francis Creek Member.

Francis Creek Member (after Francis Creek outcrop; Appendix 1 and 4) is a thin (7-14 m) K-Th rich unit with locally lowered uranium content (Figures 4, 7, 10, and 11). The Francis Creek member is composed of soft fissile non-calcareous shales, minor siltstones and rare very fine-grained muddy sandstones. The member is notably rich in expandable clays. Its prominent recessive character makes it distinct in the field (Figures 7 and 9). The top and the base of the unit are mostly gradational. In well-preserved core sections, silty shales and siltstones of this unit show mass pyritized tablets (acritarchs, *Tasmanites s.l.*; Figures 4 and 6). Pyrite encrustations on acritarchs are even and very finely crystalline. This taphonomic signature makes the Francis Creek unit distinct from the underlying upper part of the Bluefish Member where acritarchs are mostly devoid of pyrite crusts (Figure 6). Bioturbation is mostly lacking, and the rock retains sedimentary lamination; collapsed *Chondrites* burrows were encountered only once (Figure 6). From the typical Bell Creek member the newly defined Francis Creek member is different by lack of calcareous material, benthic shelly fossils and any significant bioturbation.

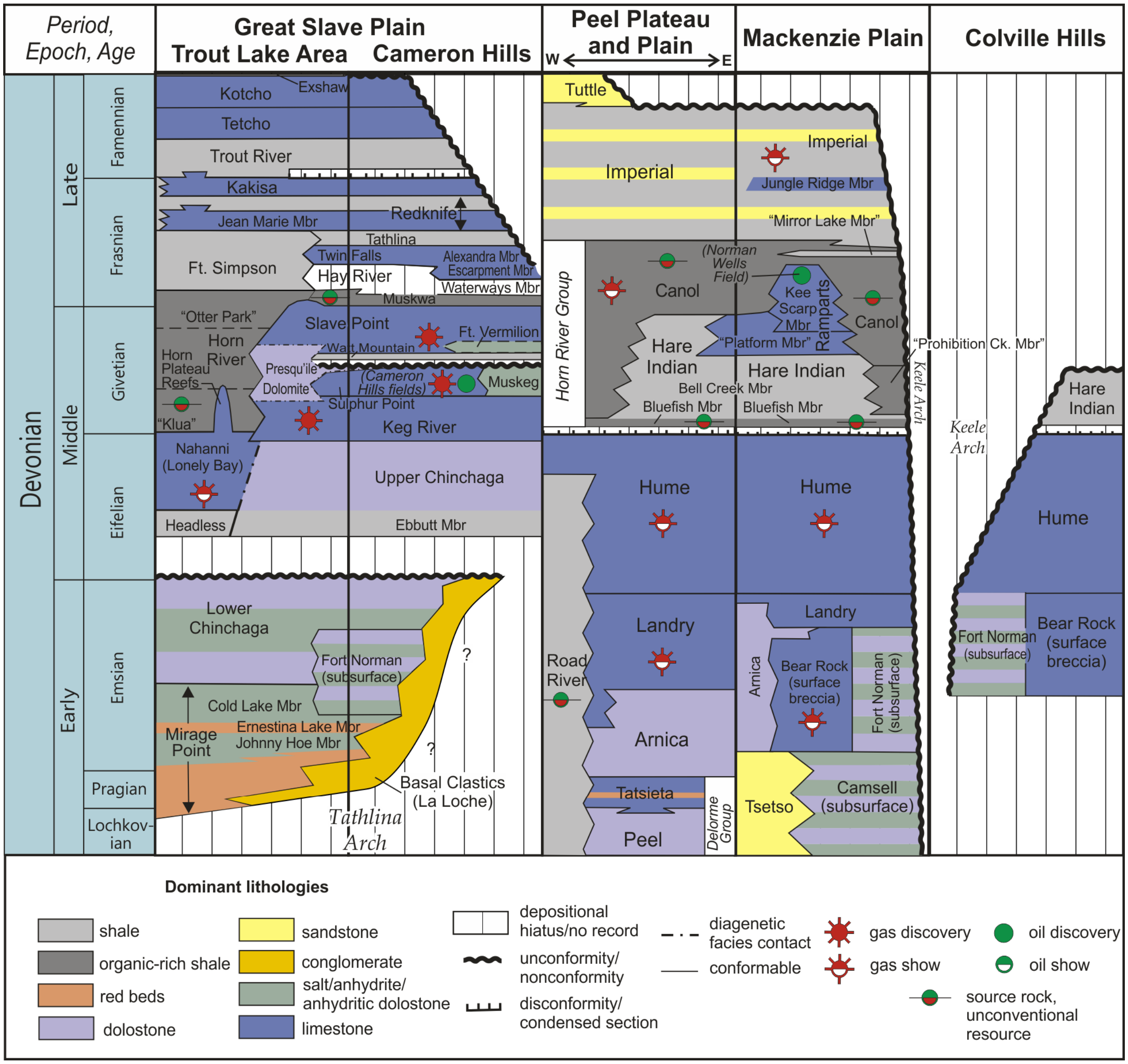


Figure 2. Table of Formations for the Devonian System of Northwest Territories. Note that northern and southern extremities of the study region (Beaufort-Mackenzie Basin and Liard Basin) are not included. The Horn River Group of Peel and Mackenzie Plain areas is updated comparing to Rocheleau and Fiess (2014).

Prohibition Creek Member (after Prohibition Creek exposures; Appendices 1 and 4) is composed of hard, dark-colored, variously calcareous to non-calcareous mudrocks with low K-Th values close to the values of the Basal Recessive (Vermillion Creek) member of the Canol Formation (Figures 10 and 11). The total gamma-ray values are in-between the Francis Creek and the Canol facies. The Prohibition Creek member is notably rich in pyritic-calcareous nodules (Appendix 1). As repeatedly admitted, the visual character of the proposed Prohibition Creek member is very similar to the "Basal recessive member" of the Canol Formation (here named the Vermillion Creek member; Kabanov et al., submitted) and therefore will likely be mapped as one Canol unit.

Canol Formation

The name "Canol Formation" has been introduced by Bassett (1961) for the black-shale unit directly overlying the Kee Scarp limestone. The new name, meant to replace the informal "bituminous member of the Fort Creek Formation" (Bassett, 1961), was taken from Camp Canol located across the Mackenzie River from Norman Wells. Its type section was designated along the northwest side of Powell Creek at 65.28°N, 128.77°W (Bassett, 1961; Pugh, 1993; Pyle et al., 2014).

Based on resistivity logs of then-available exploration wells, Tassonyi (1969) subdivided the Canol formation of our study area into lower, middle and upper members and demonstrated the likeliness of their traceability in the subsurface, including correlations between the thin Canol sections above Kee Scarp reefs and the thick Canol succession of the off-bank (basinal) areas. Pyle et al. (2011, 2014) and Pyle and Gal (2012) recognize in outcrops the basal (or lower) recessive, middle resistant, and upper recessive informal units of the Canol Formation. New surface-subsurface correlation between off-bank sections (Figure 10) indicates that the basal recessive and middle resistant units of Pyle and co-authors match the lower informal member of Tassonyi (1969). Correlation of the middle and upper units of Tassonyi (1969) will be discussed further below in the "Canol/Imperial contact" section. With conflicting sib-formational lithostratigraphy, it is not surprising that the usage of Canol subdivisions in the exploration geology has not been consistent ever since the formation was established (see well reports from drilling campaigns of 2012-2014, available at the Frontier Information Office of NEB, Calgary).

Here the Canol Formation is accepted as a hard siliceous mudrock package corresponding to the basal recessive and middle resistant members of Pyle and co-authors (2014). The surface-subsurface correlation based on SGR logs from the Prohibition Creek outcrops shows correspondence of these units to the lower member of Tassonyi (1969). The basal receive and middle resistant members can be correlated in the subsurface across the Mackenzie Plain between Norman Wells oilfield and the Keele Arch within NTS map sheets 96C-F, (Figure 10), and possibly even in the off-bank sections to the northwest of Norman Wells ol-producing carbonate bank (Figure 11).

Basal Recessive unit (Vermillion Creek member)

The Basal Recessive unit with the proposed name Vermillion Creek member (Kabanov et al., submitted) is defined by visual dominance of moderately recessive rocks in outcrops (Figures 7 and 8; Pyle et al., 2014). It contains less calcareous nodules than the Prohibition Creek member (Appendix 1). It is dominated by siliceous mudrocks with characteristically low K-Th. In studied cores it is variously calcareous, generally more pyritic than the Prohibition Creek member, and contains poorly preserved tentaculitids. Sponge spicules are absent (Figure 4; Kabanov et al., 2015).

The Vermillion Creek member directly overlies the Carcajou marker bed at the Mountain River Tributary (MR) section (the proposed type section for the Horn River Group; Pyle et al., 2014). The contact of the Vermilllion Creek and Dodo Canyon members is picked at a low-gamma 0.3-0.7 m thick calcareous mudrock that forms a traceable resistant rib in outcrops (unit 35 of Prohibition Creek; Figure 7). This low-gamma signature is also emphasized by sharp reversion to a very high-gamma spike immediately above the marker H. This marker bed is traced in the subsurface in all new wells (Figures 10 and 11) and was historically known as a "Canyon Creek marker" (Tassonyi, 1969; not to be confused with the Canyon Creek sandstone).

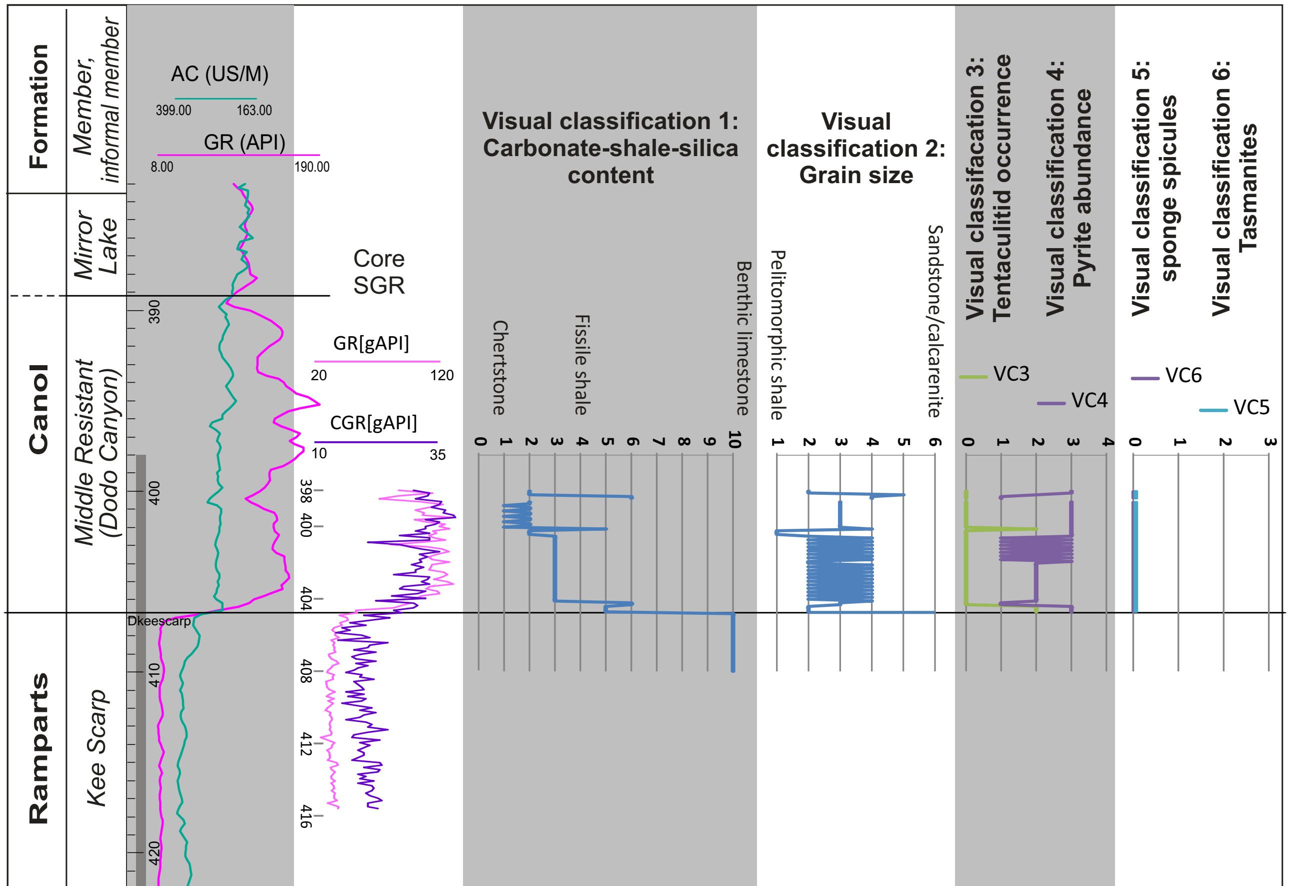
Middle Resistant unit (Dodo Canyon member)

This unit is wall-forming in outcrops (Figure 8) and is distinct by the lowest K-Th values for the whole Horn River Group, the highest pyrite and silica content in the rock matrix, and the rarity of calcareous beds. The proposed name originates from the Dodo Canyon outcrop section where this interval is substantially characterized by Pyle and Gal (2012) and Pyle et al. (2014), although the lower one-third of this member as defined at Dodo Canyon by L.J. Pyle has to be moved to the Basal Recessive (Vermillion Creek) member. The calcareous seams are scant and texturally different from the calcareous beds in the Prohibition Creek and Vermillion Creek members: they are dominated by authigenic "stellate calcite aggregates" submerged in hard non-calcareous matrix (Figure 6), whereas calcareous allochems (mostly tentaculitids) characteristic of the underlying units are rare and very poorly preserved. Dolomite is also present in the form of pre-compactional authigenic nodules and dolomitized siltstone beds (Pyle et al., 2014). Mudrocks of the Middle Resistant member are characteristically hard and brittle, laminated, grading to Radiolaria-rich chertstones. No bioturbation or benthic fossils are found. Sponge spicules are almost absent in both Vermillion Creek and Dodo Canyon members except for rare thin beds where they may be allochthonous. The Dodo Canyon member is interpreted as the most offshore unit (minimal K-Th and lithogeochemical proxies; Figures 14 and 15). Pyritic, non-calcareous, cherty mudrocks described from the base of Canol Formation above the top of the Kee Scarp limestone at Norman Wells oilfield (Figure 3; Kabanov, 2013) match the facies character of the Dodo Canyon member, which suggests correlation of the Kee Scarp carbonate pinnacles (reefs) mostly to the Vermillion Creek (Basal Recessive) member.

Canol/Imperial contact and basal beds of Imperial Formation

The Canol / Imperial contact is conformable and historically controversial. In the Canol Formation stratotype at Powell Creek, this contact was defined by Bassett (1961) as a thin (ca. 23 m) black-shale unit overlying the platform limestone member of the Ramparts Formation and composed of hard resistant mudstone in lower ¼ and grading to very fissile dark-colored shale in the upper ¾. These upper Canol shales are reportedly overlain by soft black shales of the basal Imperial Formation of controversial thickness, which in turn are overlain by more resistant and better exposed light-gray argillaceous siltstones (Bassett, 1961). In more recent measurements of the same section, the Canol Formation included the upper fissile dark-colored shales, but excluded the soft recessive mudrock that was very poorly exposed (Gal et al., 2009). In later interpretation of the same section (Pyle et al., 2011, 2014), the dark-colored fissile shale has been included in the Canol Formation as "the upper recessive member", and the total Canol thickness was measured in 18.2 m. However, L.J. Pyle and co-authors (*ibid.*) did not specify the existence of a soft mudrock different from the uppermost Canol facies and the basal Imperial siltstones.

The "upper recessive member" of the type Canol section has been correlated to a number of thicker off-bank sections including Prohibition Creek (Pyle et al., 2011, 2014; Pyle and Gal, 2012). The latter section was revisited by us in 2015 (Figures 7, 8, and 9). In these off-bank sections the "upper recessive member" refers to a prominently fissile interval exposed just above the wall-forming and siliceous mudrocks of the Middle Resistant member that are weathering characteristically yellow (Figure 8). However, the very recessive, clay-rich character of this unit makes it poorly exposed and mostly vegetated, not allowing to readily observe its upper part and the contact with the overlying unit.



Key to visual classifications (VC):

Visual classification 1 (Carbonate-shale-silica):

1. Chertstone
2. Hard siliceous shale and siltstone
3. Subfissile shale and siltstone with hard shale intervals
4. Fissile non-calcareous shale, siltstone or sandstone
5. Calcareous shale and siltstone
6. Argillaceous limestone to strongly calcareous shale or siltstone
7.Cone-in-cone limestone
8. Pelagic shaly to cherty limestone (calcarenite-calcisiltite)
9. Hemipelagic limestone (stylinolinid-dominated with admixture of benthic fossils)
10. Benthic limestone

Visual classification 2 (Grain size):

1. Pelitomorphic shale or chertstone
2. Shale with minor silt admixture or rare siltstone/calcisiltite laminae
3. shale with 10-30% of siltstone/calcisiltite laminae or silty shale
4. shale/siltstone alternation or homogeneous shaly siltstone; local minor admixture of sand-sized grains
5. siltstone with minor fine-grained sandstone / calcisiltite with minor calcarenite
6. Calcarenite or sandstone
7. Non-sorted sand-size grain fabrics (benthic limestones, loams)

Visual classification 3 (Tentaculitid occurrence):

0. No tentaculitids
1. Solitary tentaculitids
2. Tentaculitids rare or poorly preserved, in calcite seams only
3. Tentaculitids in calcite seams and on fissility planes in shales
4. Rock-forming tentaculitids

Visual classification 4 (Pyrite abundance in matrix):

0. No or little visual pyrite on core face
1. Only "pyrite dust"
2. Rare pyrite streaks, common "pyrite dust"
3. Pyrite streaks and "dust" common to abundant

Visual classification 5 (Sponge spicules):

0. No sponge spicules
1. Rare sponge spicules
2. Common sponge spicules (singular spicules common, rare bedding planes contain spicule meshes)
3. Abundant sponge spicules (common spicule meshes on bedding planes)

Visual classification 5 (Tasmanites):

0. No Tasmanites
1. Rare Tasmanites, as pyritized tablets
2. Common to abundant, as pyritized tablets
3. Common to abundant, non-pyritized (organic-walled)

Figure 3. Mackenzie River no. 4 (E-27). Lithofacies striplog with on-core SGR, borehole gamma and sonic logs; note 2 m discrepancy between borehole and core GR.

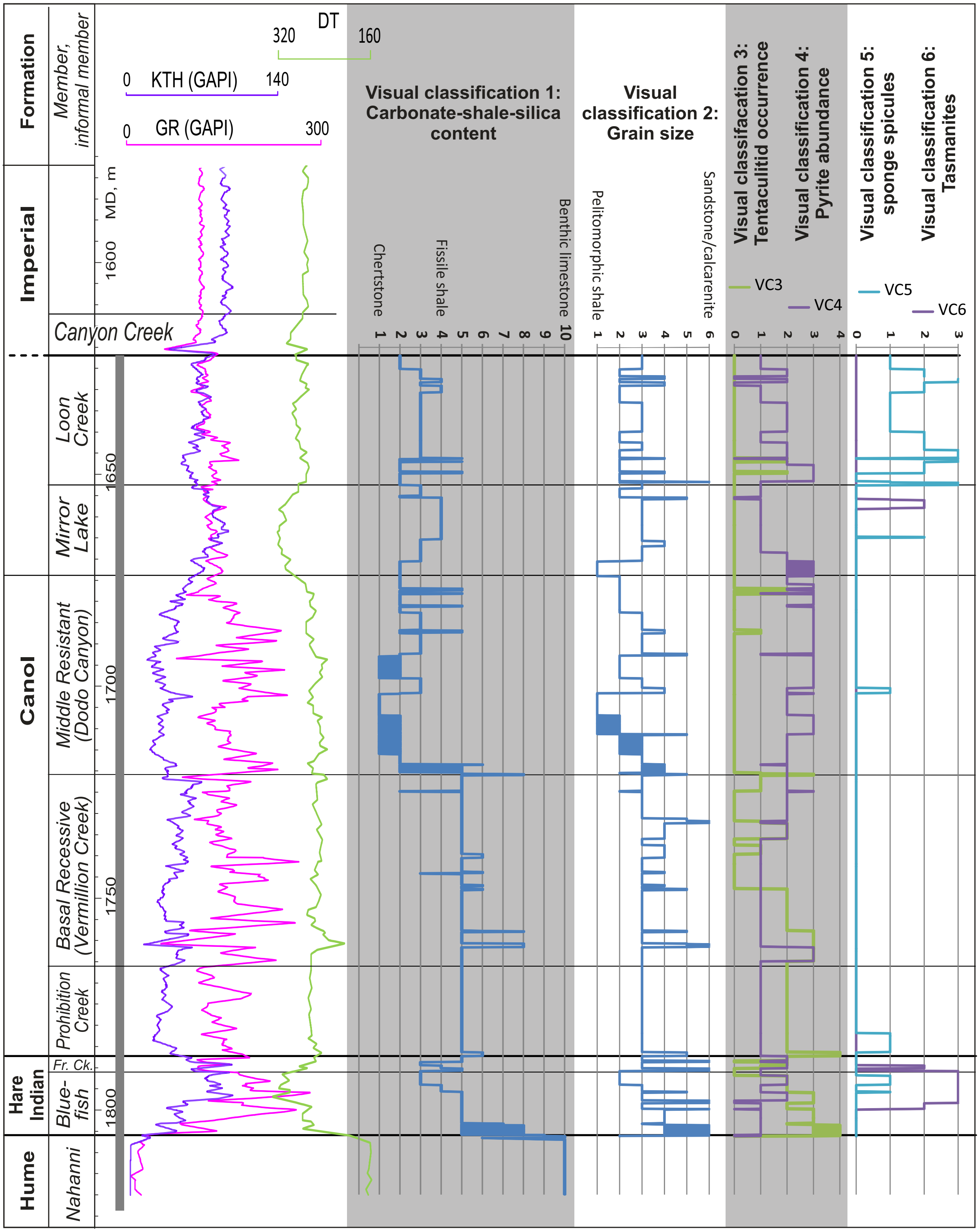


Figure 4. Loon Creek O-06. Lithofacies striplog with SGR and sonic geophysical logs. See Figure 3 for legend to visual classifications. Fr. Ck. is the Francis Creek informal member.

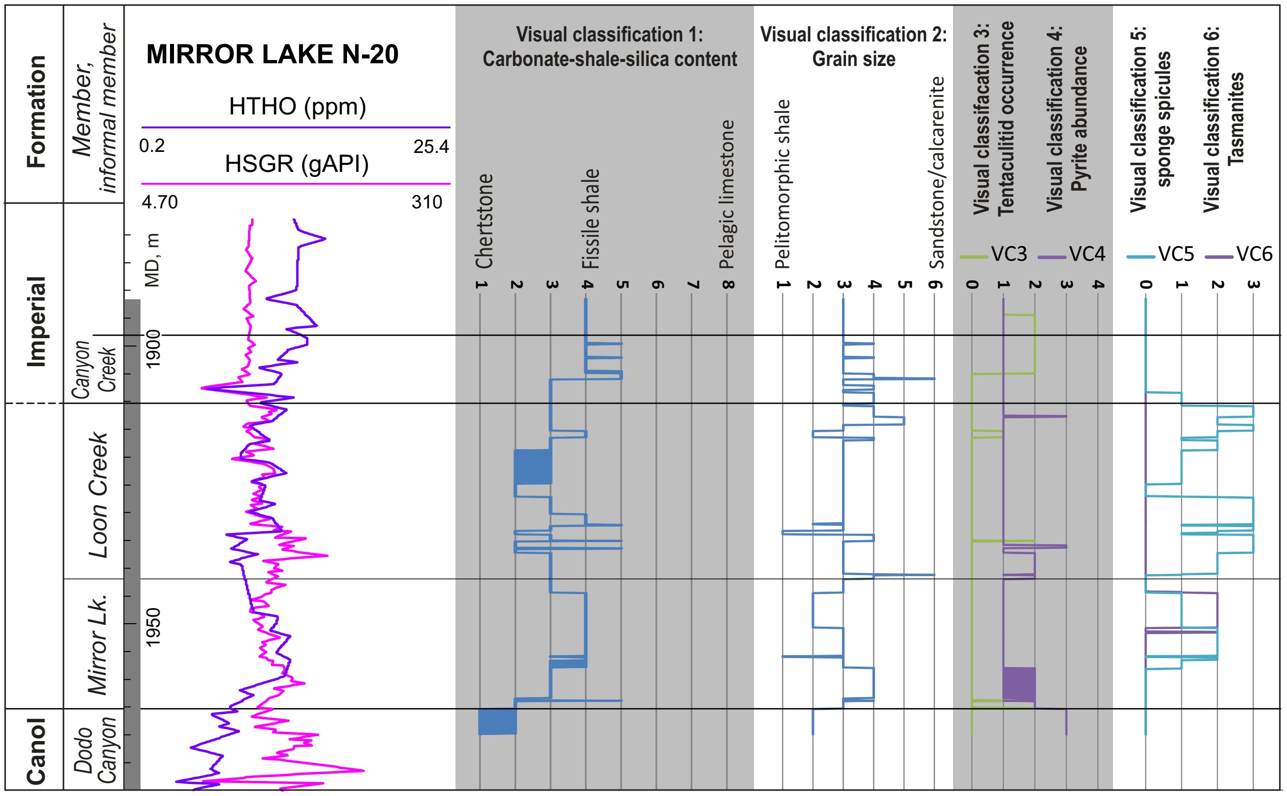


Figure 5. Mirror Lake N-20. Lithofacies striplog of the upper Canol – basal Imperial interval with SGR and sonic geophysical logs. See Figure 3 for legend to visual classifications.

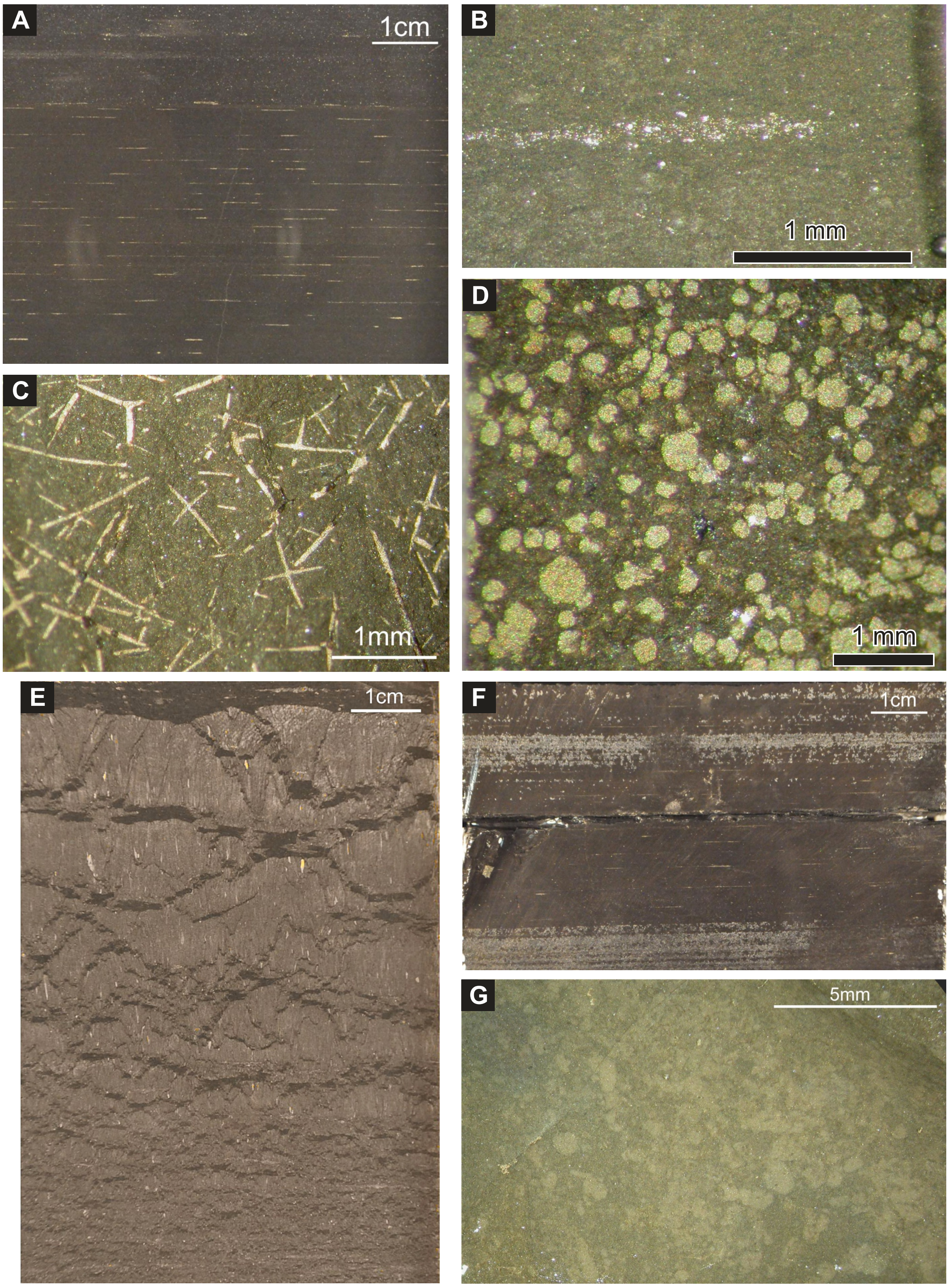


Figure 6. Textural signatures of Horn River Group mudrocks (except nodules): (A, B) Pyritic streaks and laminae characteristic of the Middle Resistant informal member of Canol Formation, (A) 1695.23 m MD and (B) close-up of a pyritic streak at 1709.4 m MD, both from Loon Creek O-06; (C) Hexactinic and triactinic(?) silicisponge spicules on bedding plane, Loon Creek Member, 1911.9 m MD, Mirror Lake N-20; (D) Pyritic tablets (pyritized acritarchs) on bedding plane, fissile gray shale of the Mirror Lake member, Loon Creek O-06, 1656.85 m MD; (E, F) Authigenic calcites: (E) upper surface of cone-in-cone limestone bed showing coarsening-upward fibrous calcite fans, 1826.3 m MD, Bluefish Member, Little Bear N-09; (F) laminar siliceous mudrock impregnated with tiny aggregates of "stellate calcite", darkened areas are etched with HCl, Middle Resistant member, 1714.4 m MD, Little Bear N-09; (G) Typical floccular texture of gray shales, fissility plane, Francis Creek member of Hare Indian Formation, 1789.6 m MD, Loon Creek O-06.

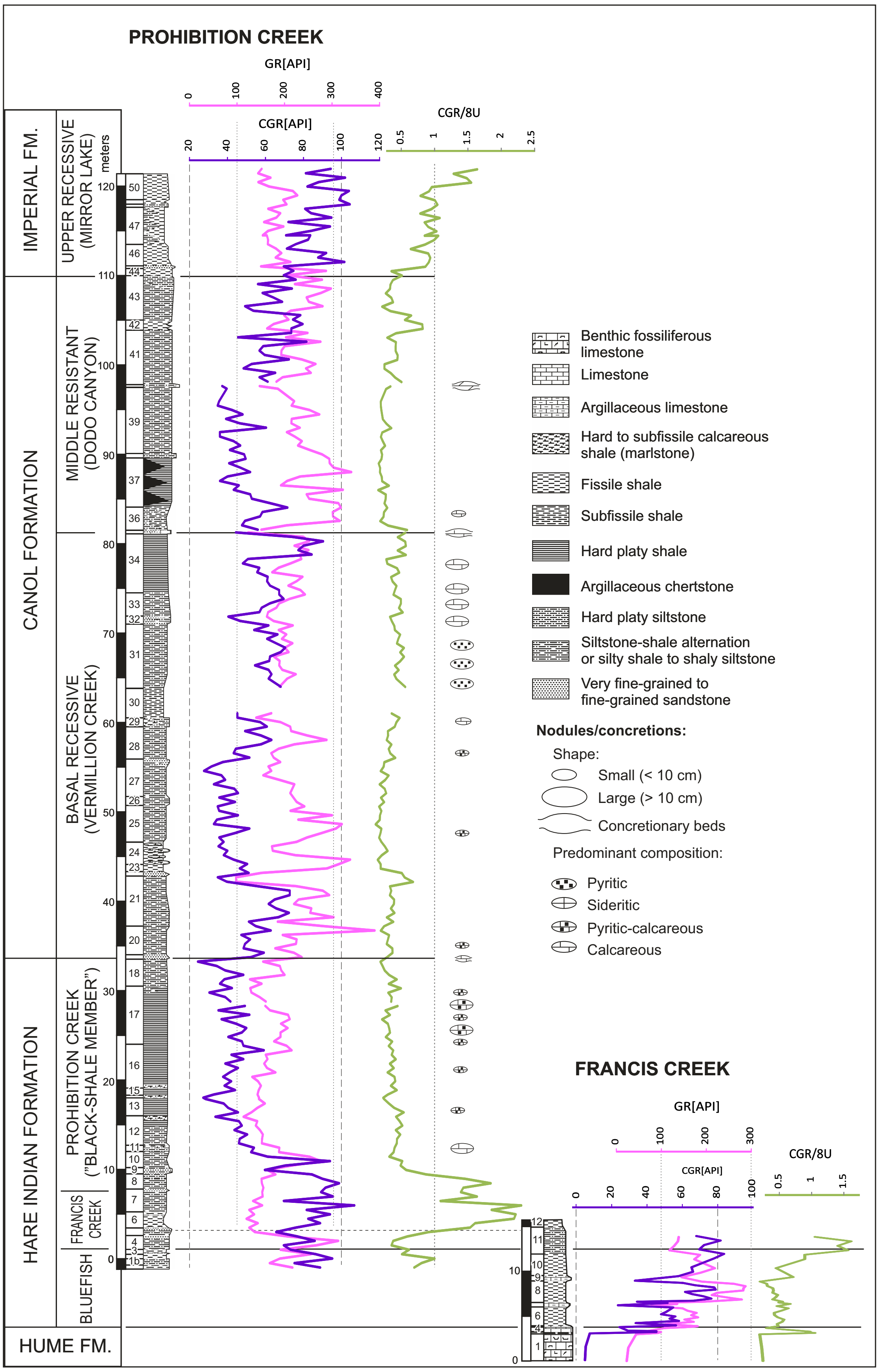


Figure 7. Prohibition and Francis Creek sections with SGR logs. See Appendix 1 for details and correlation of field stations.

Correlation of the Canol Formation in the subsurface was historically quite different. Based on resistivity logs, Tassonyi (1969) has subdivided the Canol Formation into lower, middle, and upper informal units seemingly traceable in then-available wells across central Mackenzie Plain. Although traceablility of these members in other mapping areas was not confirmed, the correlation of the Canol top proposed by Tassonyi (1969) has been followed in subsequent works on the subsurface stratigraphy (Pugh, 1983, 1993). New correlation involving two historical wells used by Tassonyi (1969) matches Tassonyi's Lower Canol member with the Basal Recessive and Middle Resistant outcrop members of L.J. Pyle and co-authors (Figure 10). The Middle Canol of Tassonyi (1969) with its distinct low resistivity and dominance of grey shales corresponds to the "Upper Recessive unit" of L.J. Pyle. This interval is recognized as a Mirror Lake member (Kabanov et al., Submitted). The Upper Canol member described by Tassonyi (1969) as "the interbedding of bituminous and grey shales" in the off-bank section of Loon Creek # 2 well has never been characterized in continuous cores and outcrops of the study area. This Upper Canol may partly correspond to the basal Imperial siltstone at Powell Creek type section and is characterized below under the new name Loon Creek member (Kabanov et al., Submitted).

Mirror Lake member

The informal Upper Recessive member of the Canol Formation and its contact with the Imperial Formation is notably poorly outcropped and the least known stratigraphically (Pyle et al., 2011, 2014), which escalates new continuously cored sections to absolutely critical value in this study (Figures 4, 5, 10, and 11). The Upper Recessive member is divided into two distinct parts that can be traced across the southern Mackenzie Plain, above the Norman Wells oil-producing bank (Figure 3), and likely at some distance to the north of Norman Wells (Figure 11). The Mirror Lake member (after Mirror Lake N-20 well) is a gray-shale prominently recessive unit with high K-Th values, lowered uranium content, and the moderate but persistent between sections acoustic slowdown (wirelogs on Figures 10 and 11). Top and base of the unit are gradational. The unit is dominated by silty subfissile to fissile shales enriched in expandable clays; it also contains minor siltstones and sandstones. The Mirror Lake member is generally pyrite-lean except for its basal transitional part. In core it is distinct by recurrence of pyritic tablets (pyritized acritarchs) and pyritized sponge spicules, which makes it similar to the Francis Creek member (Figures 4 and 5). Sponge spicules are likewise pyritized and unevenly present: numerous in Mirror Lake N-20 but rare to absent in Loon Creek O-06 (Figure 4) and Little Bear N-09 (Kabanov, 2015).

Loon Creek member

The Loon Creek member (after Loon Creek O-06 well) is dominated by dark gray subfissile mudrocks rich in silicisponge spicules (Figures 4 and 5). These mudrocks are harder than in the fissile shales of the Mirror Lake member, and sponge spicules are not pyritized. Recurrence to Canol pyritic facies is observed in the basal one-third of the unit marked by low K-TH and elevated total gamma (Figures 10 and 11). Above the basal one-third, the sections show gradual return to siliciclastics-rich and pyrite-lean mudrocks (elevated content of thorium and potassium on Figures 10 and 11). This member is generally non-calcareous with rare calcareous beds containing poorly preserved tentaculitids. Pre-compactional calcareous and dolomitic nodules are locally present.

Unlike underlying units of the off-bank Horn River Group, the thickness of the Loon Creek member is uneven and shows significant NW-SE facies change at the distance of tens of kilometers (Figures 10 and 11). The upper part of the Loon Creek member is dominated by dark colored shales in new wells, but in Bluefish K-73 it shows thick-bedded alternation of dark and light gray shales (controlled by cuttings), and in East MacKay I-78 it grades into a thick (1680-1731 m) shale-siltstone alternation with local dominance of siltstones as controlled by cuttings (Figure 11). Based on lithology this shale-siltstone unit is placed in the Canyon Member discussed further below. The thickness of the Loon Creek member between the top of the Mirror Lake shale and the base of the siltstone-dominated unit (Canyon Member) changes from 27 m in the type section to 77 m in Canyon Creek # 1 well (Figure 10) and 95 m in Bluefish K-73 well (Figure 11). The thickness in outcrops is difficult to assess because of poor exposures. This facies and thickness heterogeneity is thought to indicate transition from fondoformic strata of Canol depositional system to westward-accreting clinoforms characteristic of Imperial Formation (Hadlari, 2009).

Figure 8: Canol Formation at Prohibition Creek above fly cap site, between stations 15KOA007 (track on the right) and 15KOA009 (track on the left). Note burned shale patch resulted from natural lightning; yellow arrows point to rib-forming calcareous mudrocks and siltstones.

Canyon Member

The name Canyon Member (Canyon Creek sandstone) originates from the Canyon Creek # 1(G-51) borehole (Figure 10; Appendix 15) and historically refers to a thin (25-31 m) and discontinuous sandstone dominated unit; in some sections it is dominated by siltstones with minor or no sandstones (Tassonyi, 1969; Pugh, 1983). The Canyon Member was also referred to as "the basal Imperial sandstone" (Hadlari et al., 2009). The unit is relatively resistant, underlain and overlain by more recessive shales, and has been used as a mapping marker for the Canol/Imperial contact (e.g., Aitken et al., 1982). Because of laterally discontinuous nature of this unit, Pugh (1983) has called it "the Canyon Creek sandstone lentil". The unit was included in Table of formations as the Canyon Member (Hogue and Gal., 2008) and recognized by MGM Energy explorationists during the drilling campaign of 2012-2013 as an interval 1676-1735 m MD in East Mackay I-78 well (Figure 11).

The typical sections (Canyon Member type A) are composed of very fine-grained quartzose sandstones with minor siltstones and shales; the stratal pattern is organized in thick sandstone-dominated Bouma rhythms (Appendix 15). Offshore (southwestward) from type Canyon Creek # 1 and Loon Creek # 2 sections, the sandstone disappears, and this stratigraphic level is only marked by an interval with important siltstones and rare thin sandstone laminae that can be picked in most wells by its prominent low-gamma spike. This marker is here referred to as "the Canyon Member type B" (Figure 10). The full Canyon Type B section is cored in Mirror Lake N-20 (1904.9-1910.40 m MD). In Mirror Lake N-20 this low-gamma gamma marker is found at 1906.4-1908.8 m MD, in Loon Creek O-06 at 1632.0-1635.0 m MD (Figures 10 and 11). This gamma marker disappears southeastward towards East MacKay I-78 where a thick (1680-1731 m) interval of siltstone-shale alternation is placed in the Canyon Member. Similar shale-siltstone interval correlated as the Canyon Member (Hogue and Gal, 2008) is developed in wells Deh Cho-1 B-25 and Deh Cho-2 B-14 in 10 km to the SE of Norman Wells Oilfield. The small-fossil assemblages of the Canyon Member and the overlying Imperial shale are described from the Mirror Lake N-20 core in the section *Paleontological observations*.

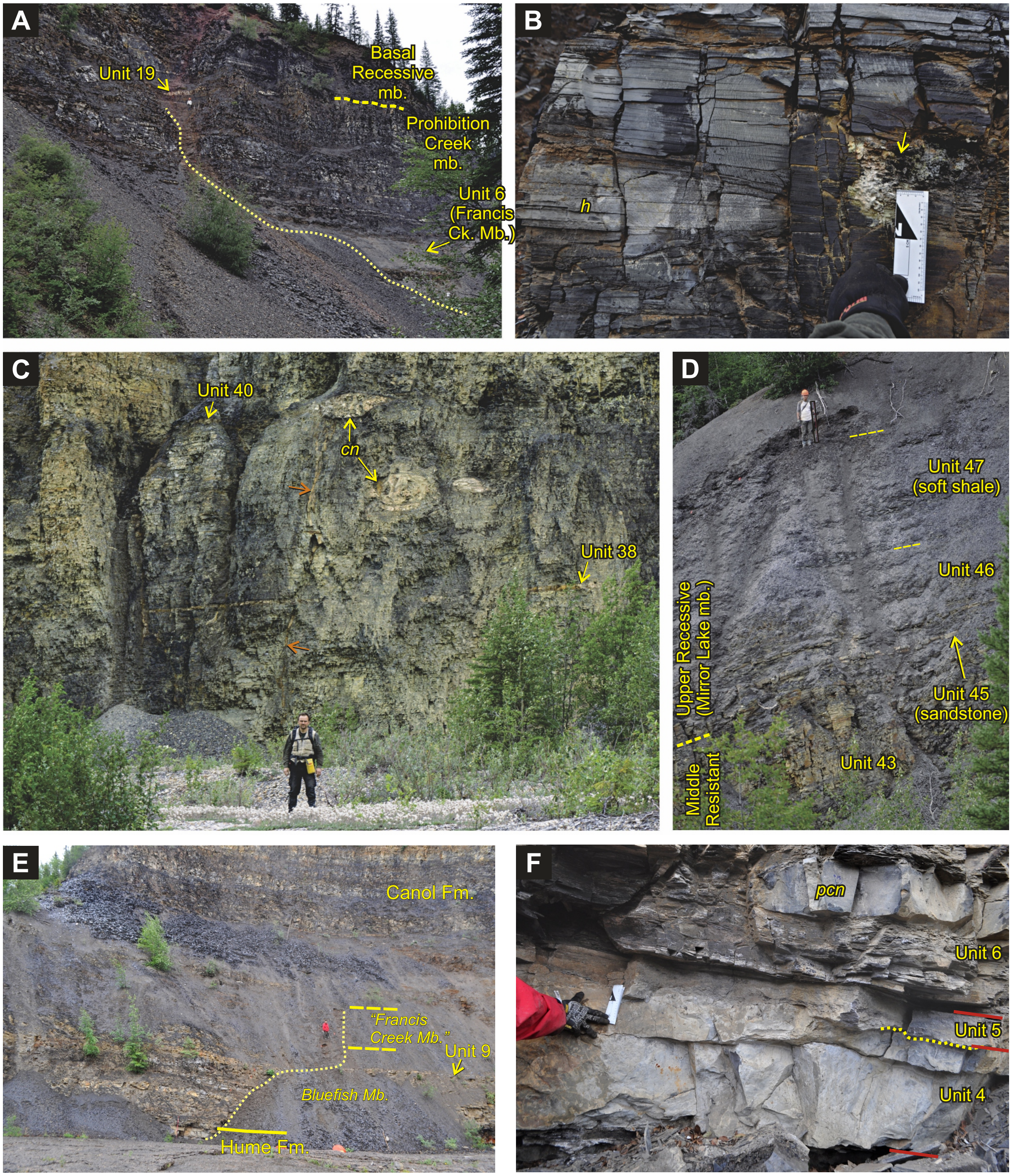


Figure 9. **Horn River Group outcrops of Prohibition and Francis creeks; measured traverses are traced with dotted lines: (A-D) Prohibition Creek: (A) Station 15KOA004 with the type section for the proposed Prohibition Creek member; note distinct recessive character of the Francis Creek member; (B) hummocky cross-lamination in Unit 16, station 15KOA004; (*h*) is siltstone core of a hummock; (C) A Middle Resistant member between stations 15KOA009 and 15KOA012 with large carbonate nodules (*cn*) nd marker resistant beds (units 38 and 40); (D) the contact of Middle Resistant and Mirror Lake members, station 15KOA012. (E and F) Francis Creek, station 15KOA006: (E) measured section and the gully bed formed by a rugged surface in Hume limestone; (F) Close-up of the Hume/Hare Indian contact. See Appendix 4 for station coordinates and bed-by-bed descriptions.**

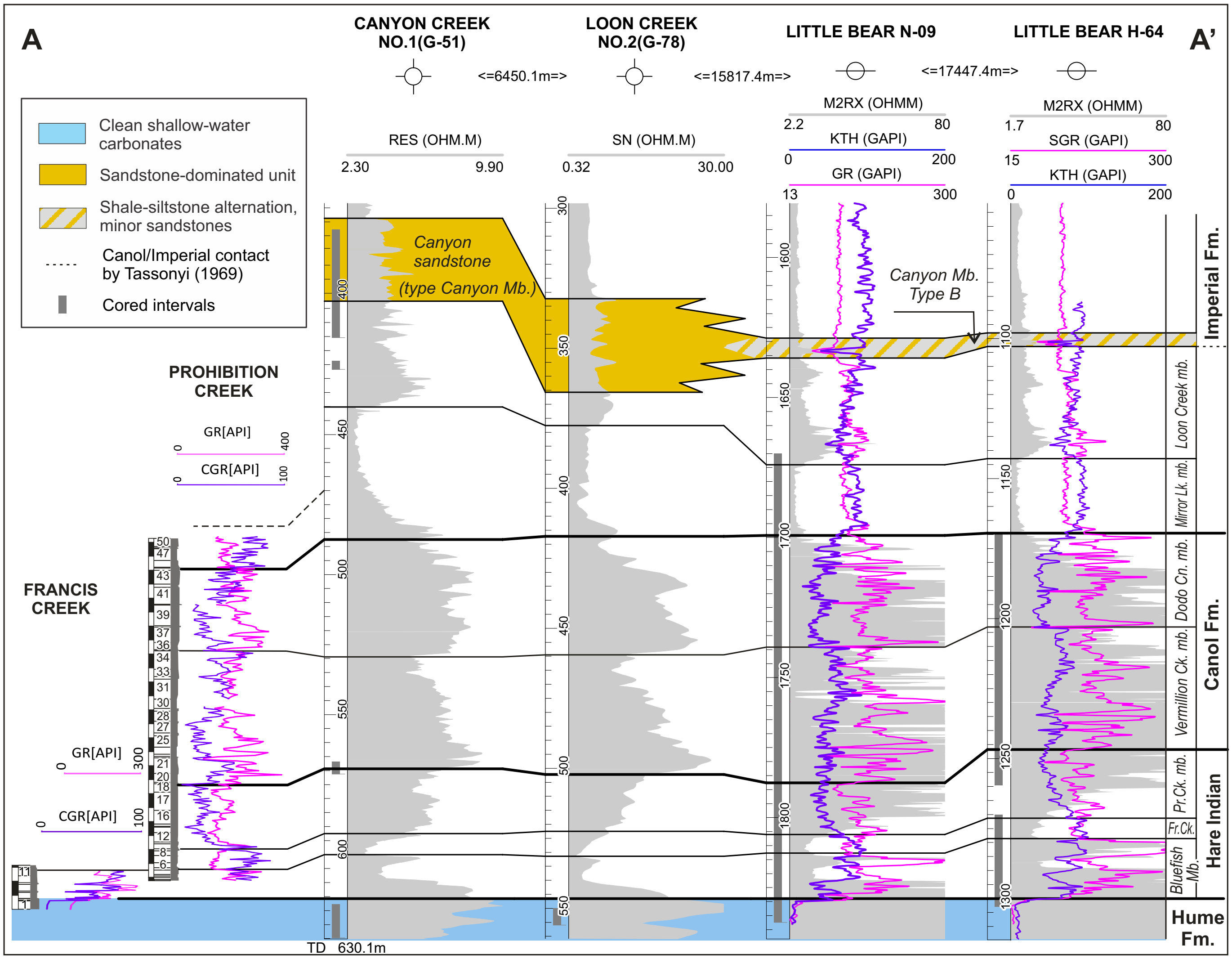


Figure 10. Cross-section A-A' (north to south): Wirelog correlation of new well sections Little Bear N-09 and H-64, historical sections Canyon Creek # 1 and Loon Creek # 2, and Prohibition Creek – Francis Creek outcrops. Historical sections are correlated based on resistivity tools, new sections based on SGR logs.

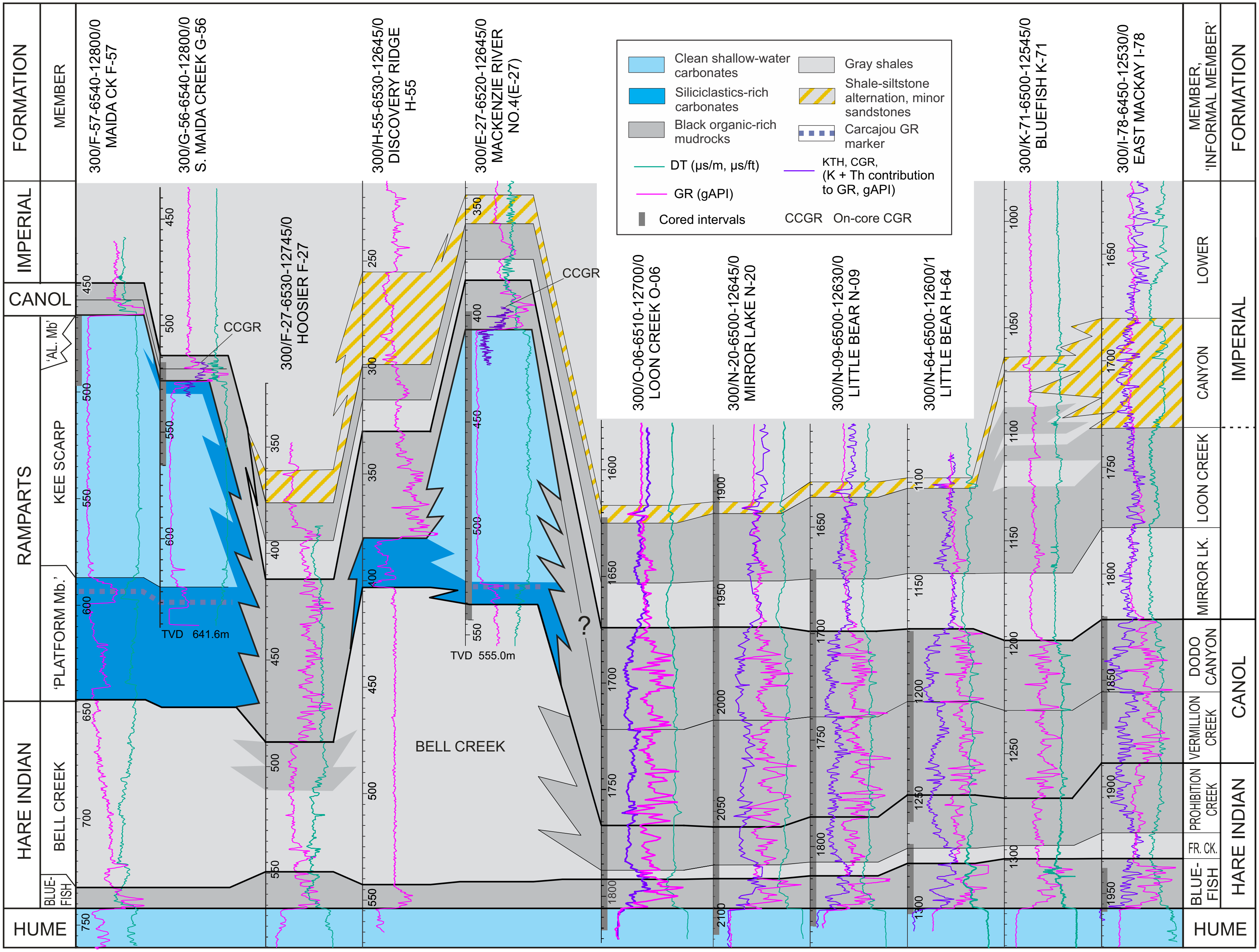


Figure 11. Cross-section B-B': Correlation of Horn River Group in the subsurface of Mackenzie Plain. Abbreviated lithological units: 'AL. Mb' = 'Allochthonous member', 'FR. CK.' = 'Francis Creek member'.

RED BENTHONITIC SHALE SEAMS

Measured core sections of Canol Formation (Appendices 5, 6, and 7) contain thin (first millimeters to first centimeter(s)) shale seams distinct on the background of dark mudrock by their bright brown (or brick red) color (Figures 12A-C). These seams contain higher amount of expandable clay than the host siliceous mudrock and tend to disintegrate into flakes even in fresh core, indicating their very low preservation potential in natural outcrops. Some of these shales appear micaceous under hand lens.

Brown shale seams show enhanced pyritization inside and in the ambient host mudrock (Figure 12C), and thicker seams contain authigenic anhydrite grains (Figures 12E-G). These anhydrite grains are usually interwoven with pyrite (Figure 12G). Examination under binocular of one thicker seam at 1930.25-1930.28 m of Mirror Lake N-20 core does not reveal confident detrital grains, and the granular appearance in thicker brown shales originates from authigenic granular pyrite and anhydrite (Figures 12E-G).

The ED-XRF scanning of brown shales (16 readings) vs. host siliceous mudrocks (21 readings) from different levels within the Canol Formation (Figure 13) shows persistent enrichment in alumina in brown shales (max. 44% and median 39% of Al_2O_3 with very low skewness of -2) against host mudrocks (max. 39% and median 16% of Al_2O_3 and higher skewness of 0.9). Skewness here is used as data departure criterion: the higher the skewness, the more scattered values are, and the negative skewness indicates high persistency of an element. Titanium shows almost double enrichment in brown shales but less persistent than Al_2O_3. Enrichment patterns of minor elements cannot be confirmed with the ED-XRF scanner resolution operated in non-vacuum mode.

Soaking fragments of the brown shales in a strong surfactant (Quaternary O detergent), allowed the study of the mineral crystals under the binocular microscope. No zircon or apatite crystals, both typically present in volcanic ash layers, were found in these brown shales.

Depositional environment of brown shale seams with anhydrites are not quite clear; options include event deposits of siliciclastic or volcanic ash fall nature.

LITHOGEOCHEMICAL DATA

In total, new high-accuracy lithogeochemical and Rock-Eval™ data were obtained from 706 samples collected from cores of recently drilled Loon Creek O-06 and Little Bear N-09 wells (Kabanov et al., 2015). This number includes 20 samples from the uppermost 6 meters of the Hume Formation, 59 samples from the Bluefish Member of the Hare Indian Formation, and 21 samples from the proposed Francis Creek member of the Hare Indian Formation. The Canol Formation is tested by 598 samples; the breakdown of Canol samples per informal members as correlated on Figures 10 and 11 is as follows: 85 from the Prohibition Creek, 181 from the Vermillion Creek (Basal Recessive) member, 175 from the Dodo Canyon (Middle Resistant) member, 92 from the Mirror Lake member, and 65 from the Loon Creek member. The basal part of the Canyon Member is tested by 7 samples from the Loon Creek O-06 well. These pyrolysis and lithogeochemical results are being used for high-resolution stratigraphic, tight-reservoir, and sedimentological studies (e.g., Kabanov et al., Submitted).

The ICP-MS/ES elemental data and Rock-Eval™ 6 data are reported here the same way as for Little Bear N-09 well (Figures 14, 15, 16, and 17; Appendices 10, 11, 12, and 13; Kabanov et al., 2015). The proxies shown on Figures 14, 15, and 16 include rock-forming elements (here expressed as SiO_2, CaO and Al_2O_3), degree of pyritization (Fe and S), siliciclastic vs. pelagic silica source (SiO_2/Zr), Enrichment factor for phosphorus (EFP) as a proxy to higher-metazoan (consumer) productivity, Ba (primary bioproductivity vs. early diagenesis), selected proxies for siliciclastic input (here K_2O, TiO_2, and Th/U), redox and anoxia trace-element proxies such as U, V, Mo, Mo/TOC, Ni/Co, and the Enrichment factors for Mo and V (EFMo and EFV, correspondingly, shown on logarithmic scale). Most of these proxies are widely used in black-shale sedimentology, stratigraphy, and hydrocarbon potential characterization (Tribovillard et al., 2006; Algeo and Rowe, 2012), some of them have been applied to the studied black-shale succession (Pyle et al., 2014). The lithogeochemical proxies used on Figures 14, 15, and 16 are discussed by Kabanov et al. (2015) and not repeated herewith. Lithogeochemical signatures of stratigraphic units based on ICP-MS/ES results from Loon Creek 0-06, Little Bear N-09, and previous data (Pyle et al., 2014, and references therewith) are discussed by Kabanov et al. (Submitted).

PYROLYSIS RESULTS

Rock-Eval™ pyrolysis/TOC results for 380 samples from Loon Creek O-06 cores are given in Appendices 11 and 12. Pyrolysis parameters for the Horn River Group of Loon Creek O-06 are consistent with those previously reported for Little Bear N-09 (Figures 17, 18, 19, and 20; Kabanov et al., 2015). Kerogens in both Hare Indian Formation and the "core Horn River interval" belong to one type I to II types with very low oxygen index (Figure 18). Here the "core Horn River interval" refers in both wells to the interval of Prohibition Creek – Dodo Canyon members dominated by typical Canol facies and showing similar hydrocarbon properties (Figure 18) except for hydrogen index (HI) which in the Prohibition Creek member shows elevated values similar to the underlying part of the Hare Indian Formation (Fiure 17).

The "core Horn River interval" shows TOC values 4.5% (median) and 9.1% (maximum) in both wells. The Bluefish Member shows variable TOC with 5.0% (median) and the greatest value of 8.9%. Considering these rocks are in post peak oil generation, the initial TOC could have been substantially higher. Twenty samples from the thin (5-7 m) Francis Creek member retrieve 4.9% maximum and 2.6% median values of TOC.

The Mirror Lake and Loon Creek members of the Canol-Imperial transitional interval are distinct from the underlying part of the Horn River Group by low TOC (3.8% max, 2.1% median), lowered Tmax, and the elevated HI (Figure 17). The Mirror Lake member (1674.2-1699.3 m in Little Bear N-09 and 1653.25-1674.2 m in Loon Creek O-06) was previously referred as the "Imperial-type gray-shale facies (Kabanov et al., 2015). This unit is distinct by the spike of oxygen index offsetting its kerogen towards Type III (Figure 18D). This OI spike suggests significant change in kerogen type that is most likely attributed to the influx of coaly detritus along with terrigenous clays (high alumina on Figure 14).

The hydrocarbon is of high quality with very high S2 vs. TOC, which is characteristic of Canol play kerogens and offsets them towards Type I (Figure 19). The production index (PI) in Loon Creek O-06 spans post-peak oil generation and gas condensate zones (Figure 20A) indicating slightly higher kerogen maturity than in Little Bear N-09 where it mostly occurs in the oil window (Figure 20B; Kabanov et al., 2015).

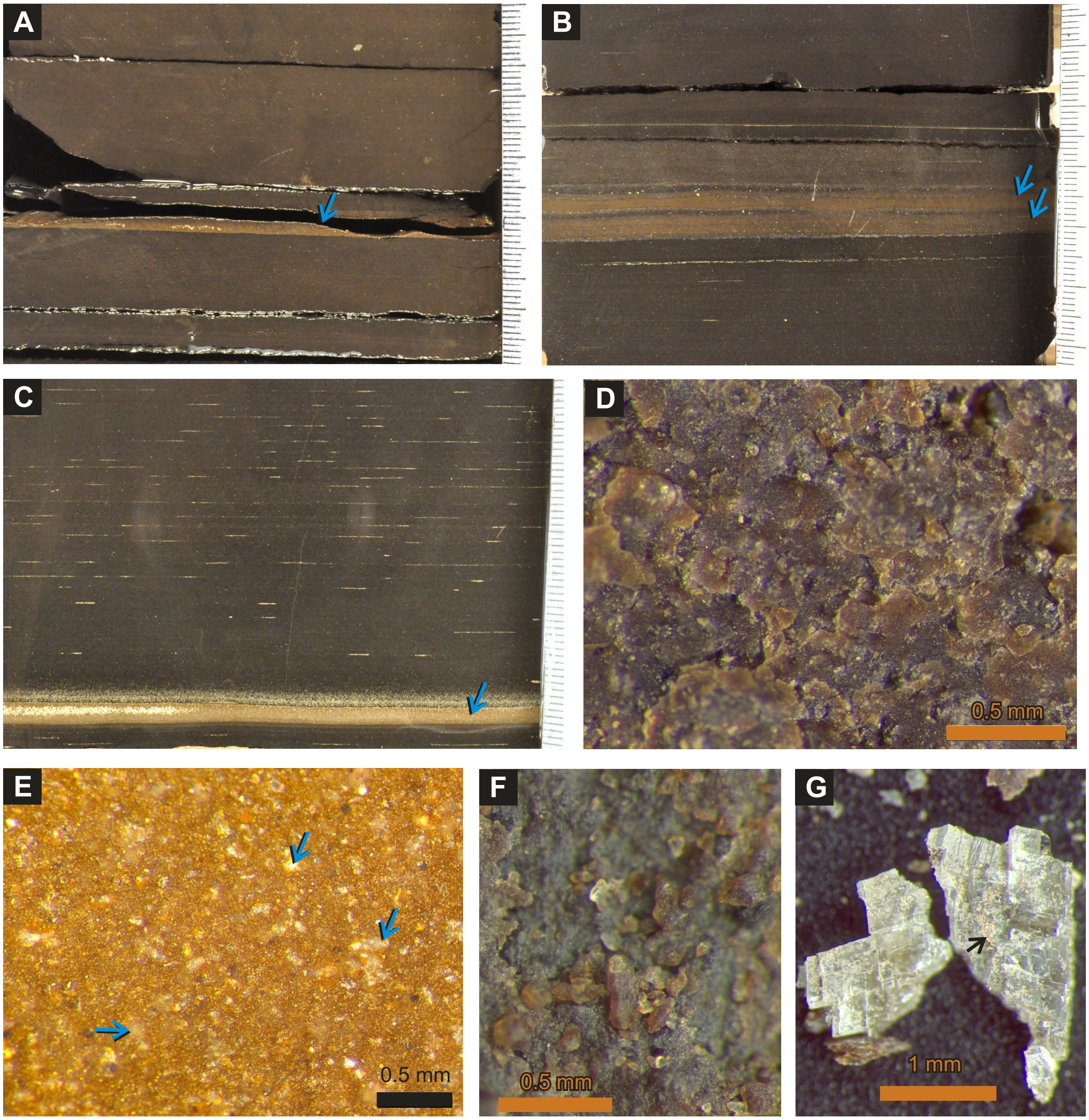


Figure 12. Brown benthonitic shale seams (arrowed on A-C), Canol Formation: (A) 1681.21 m MD, (B) 1694.58 m MD, (C) 1695.23 m MD, all core face photos from Loon Creek O-06; note enhanced pyritization associated with the shale seam on (C). (D-G) Photomicrographs of a thick brown shale at 1930.25-1930.28 m MD, Mirror Lake N-20 well: (D) dry flake surface; (E) glycerol wet flake surface with grains composed of intergrown anhydrite-pyrite (arrows); (F) dry surface of a shale flake rich in anhydrite crystals; (G) coarse anhydrite crystals extracted close to shale seam base; minor intergrown pyrite is arrowed.

PALEONTOLOGICAL OBSERVATIONS

Examination of the fissility/bedding planes of selected intervals of Loon Creek O-06, Mirror Lake N-20, Norman Wells P32X and Mackenzie River 4 cores has revealed small-fossil assemblages. The core from Mackenzie River # 4 was checked for the presence of conodonts in the Canol shale immediately above the Kee Scarp top. Conodonts were detected on five levels. The majority of the conodonts found are ramiform elements with no stratigraphic value; several conodont elements are platforms (*Palmatolepis*, *Mesotaxis* and *Polygnathus*). The former two showed only a lower view, whereas the characteristic ornamentation of the upper view was not accessible in a hard non-dissolvable siliceous mudrock. The *Polygnathus* platform elements are exposed in lateral view, inhibiting identification on species level. Detaching the conodont elements from the sediment only lead to fragmenting of the specimens. An interval of 6.20 m to 6.70 m above the base of the Canol Formation has yielded, *Palmatolepis punctata* (Figures 25A, C, D, E, and M), *Mesotaxis falsiovalis/Klapperina ovalis* (Figures 25B and J) , transitional forms between *Pa. transitans* and *Pa. punctata* (Figures 25F, G, I, and H), *Polygnathus* sp. and ramiform elements (Figure 25O) have been identified. The co-occurrence of *Pa. punctata* and *Klapperina ovalis/Mesotaxis falsiovalis* restricts the stratigraphic position of those levels to the MN zones 5-6 (Klapper, 1997), or the *punctata* Zone in the Standard Zonation (Klapper and Becker, 1998).

In the Noman Wells P32X, the contact between the Ramparts and Canol formations and the basal part of the Canol shale were inspected for microfossils. Ramiform and platform conodont elements were found on nine levels, all partially embedded in host mudrock. At the Kee Scarp / Canol contact, two specimens of *Klapperina ovalis/Mesotaxis falsiovalis* were identified (Figures 25K and L). *Icriodus symmetricus* (Figures 24A1 and A2) was found at 90 cm above the base of the Canol Formation. This taxon ranges from within the Upper *falsiovalis* Zone all the way up to within the *linguiformis* Zone (Bultynck, 2003) and is no aid in restricting the stratigraphic interval. Combining these observations with two conodont samples taken by A. Hedinger in 1997 (pers. comm. to Tom Uyeno) at the same contact in the Norman Wells Quarry and showing a rich fauna (a.o. *Klapperina ovalis/Mesotaxis falsiovalis* and *Pa. transitans*), restricts the stratigraphic position of the contact within the MN4-6 zones interval (*transitans* and *punctata* zones) (Klapper 1997).

In Mirror Lake N-20 well, the lower shale of the Imperial Formation above the Canyon Member was rich in small fossils. The fossils preserve as imprints with no shells left. The top 10m of the core is very rich in these fossil imprints. The assemblage includes bivalves (*Glyptohallicardia palmata*, Figures 21A and B), cephalopods (mostly juvenile goniatites of which a few might be identified on genus level (Figures 21D and E), orthocone cephalopods (Figures 22D, F, and G), anaptici that may belong to bactritids [Figures 22H and I]), as well as tentaculitids and pelagic ostracodes. The preservation of the tentaculitids is insufficient for the formal identification at the species level (Figures 21I, 22A, and 22B). The ostracods show a remarkable fingerprint-like ornamentation and are tentatively identified as entomozoacean ostracods (Figures 22C and E). Although the interval is rich in fossils, only one bivalve species *Glyptohallicardia palmata* with a long range (Frasnian-Famennian; Grimm 1998) has been identified. This fossil assemblage does not add new information to constrain the chronostratigraphic position for the Canol/Imperial contact.

The core from Loon Creek O-06 well was inspected for microfossils in the lower part of the Hare Indian Formation (Bluefish Member and basal part of the "Francis Creek member", Figures 12 and 13). The interval is characteristically rich in tentaculitids and has yielded several bedding planes with well-preserved sculptured forms. Conodonts were found on four levels in the basal part of the "Francis Creek member" and the uppermost part of the Bluefish Member. Most elements are ramiforms, one is platform (Figure 23L) and is identified as *Polygnathus* ex. gr. *varcus,* which places this stratigraphic level in the *rhenanus* Zone (middle Givetian) or younger. Tentaculitids are rather well preserved and some specimens could be identified to the species level. The co-occurrence of *Nowakia otomari* (Figures 23B and H) and *Nowakia* cf. *postotomari* (Figures 23J and K) in the Bluefish Member in 20 cm above the Hume top (1805.8 m MD) would indicate a lower Givetian position (*hemiansatus* Zone based on Alberti (1993) or the lower *varcus* Zone based on Gradstein et al. (2012)).

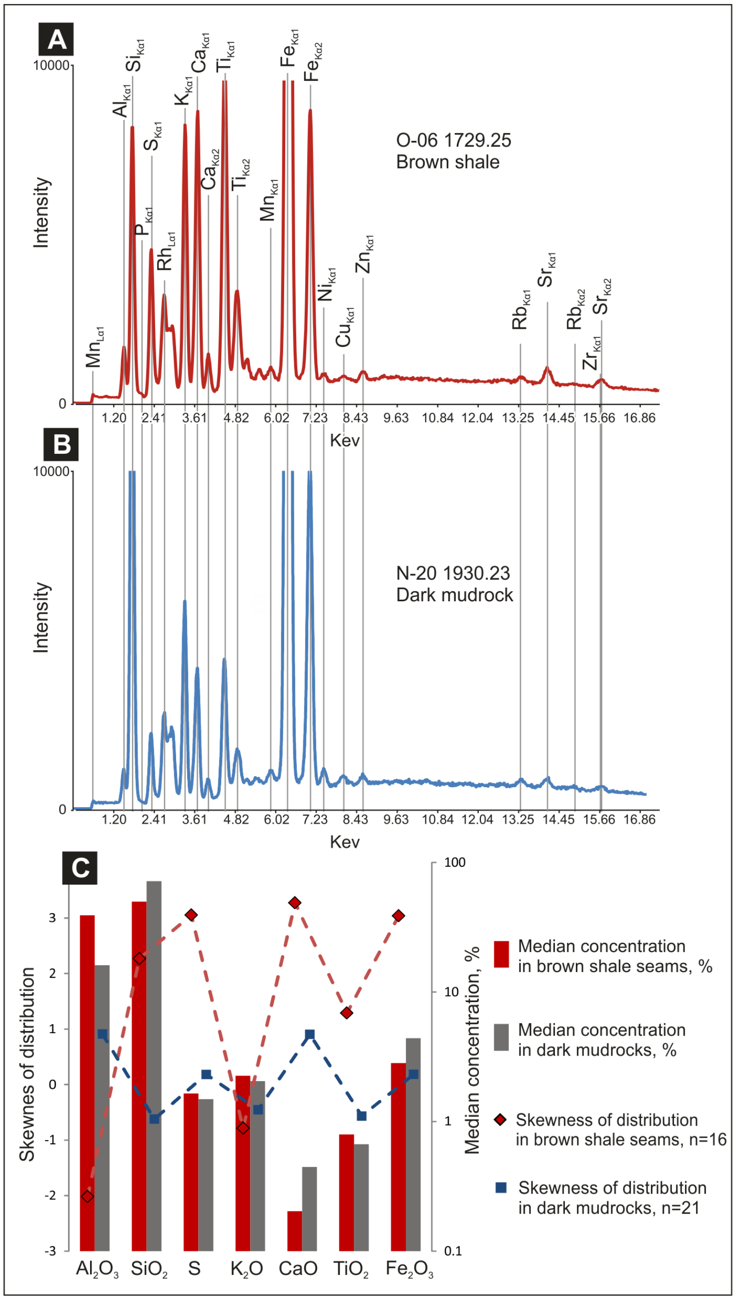


Figure 13. ED-XRF signatures of brown benthonitic shale seams, Canol Formation, Mirror Lake N-20 and: (A) Interpreted ED-XRF spectrum of a brown shale at 1729.25 m MD, Loon Creek O-06 well; (B) Interpreted ED-XRF spectrum of a dark mudrock (background Canol facies), 1930.23 m MD, Mirror Lake N-20; (C) Comparison of median concentration of main oxides (with maximum concentrations exceeding 1%) in brown shales (n=16) and dark mudrocks (n=21); note logarithmic scale for median concentrations.

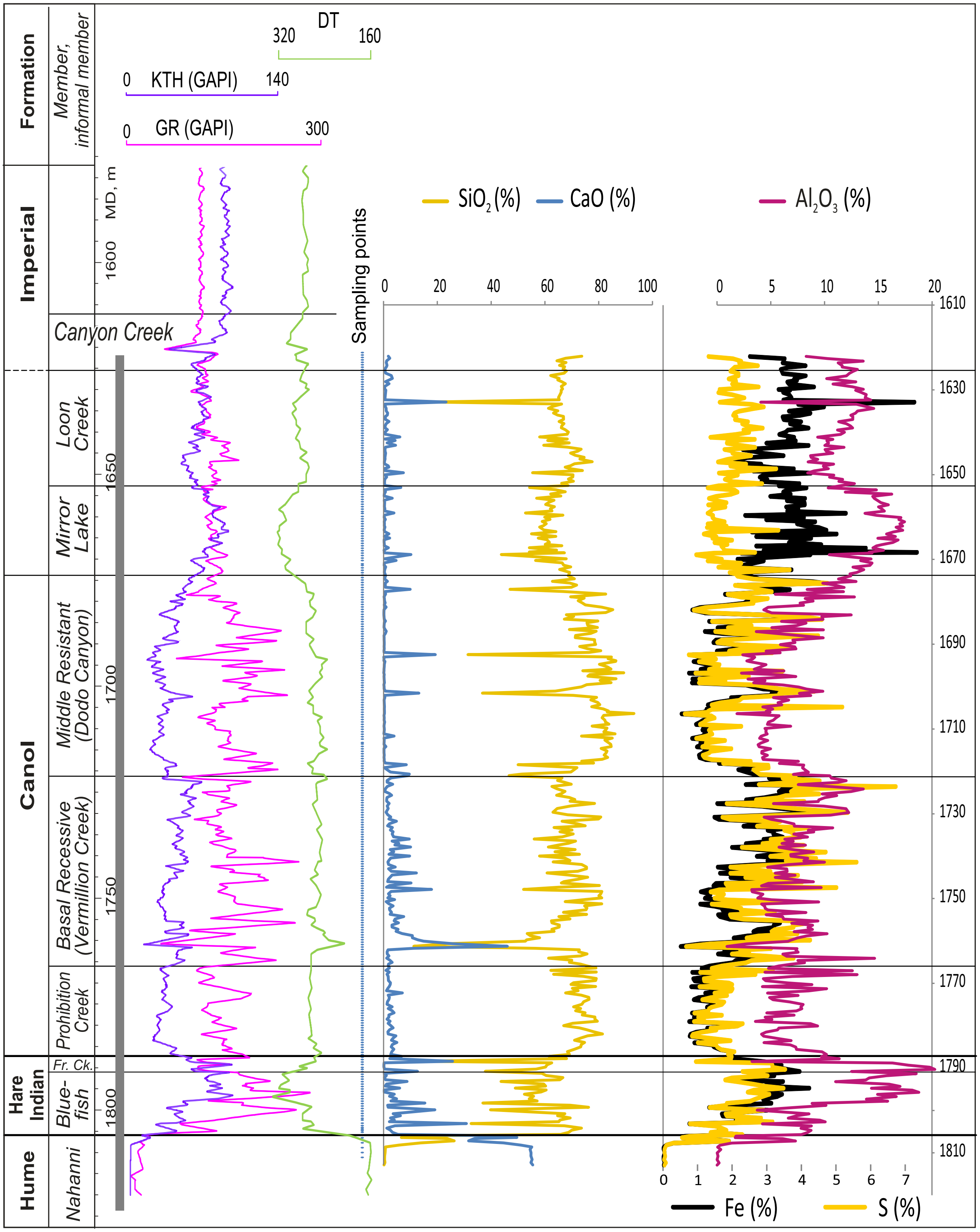


Figure 14. **Lithogeochemical logs for the cored section of Loon Creek O-06 well compared against geophysical logs: main rock-forming elements (Si, Ca, and Al) in oxide notation, iron and sulphur as proxies for pyrite abundance. Sulphur refers to Total S in the LECO combustion method.**

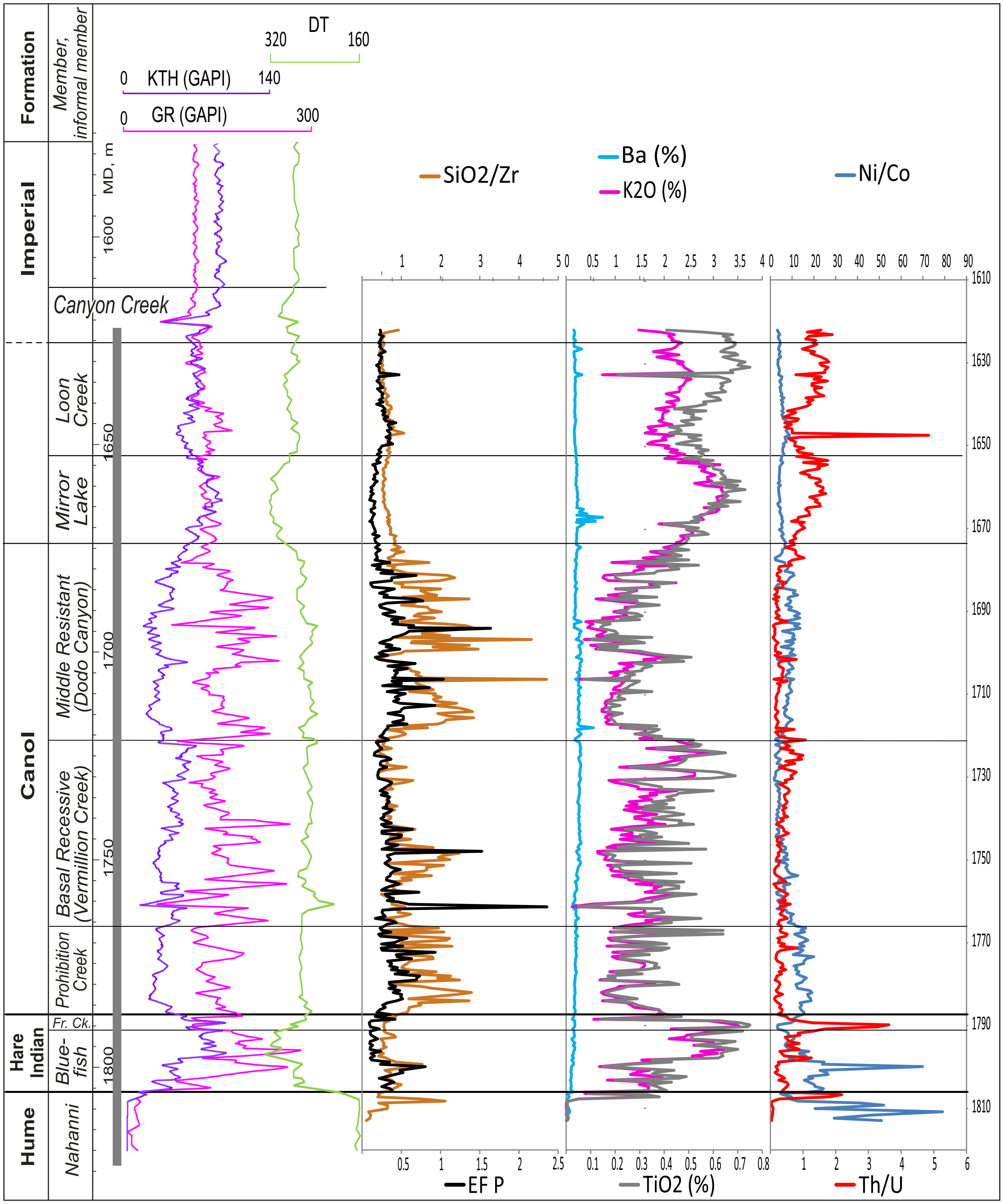


Figure 15. Lithogeochemical logs for the cored section of Loon Creek O-06 well compared against geophysical logs. Proxies for depositional environments: SiO_2/Zr (siliciclastic vs. basinal biogenic silica, SiO_2 in % and Zr in ppm), Enrichment factor for phosphorus (EFP, proxy for consumer bioproductivity), Ba (primary bioproductivity vs. early diagenesis), K_2O, TiO_2, and Th/U (siliciclastic input), and Ni/Co (redox proxy).

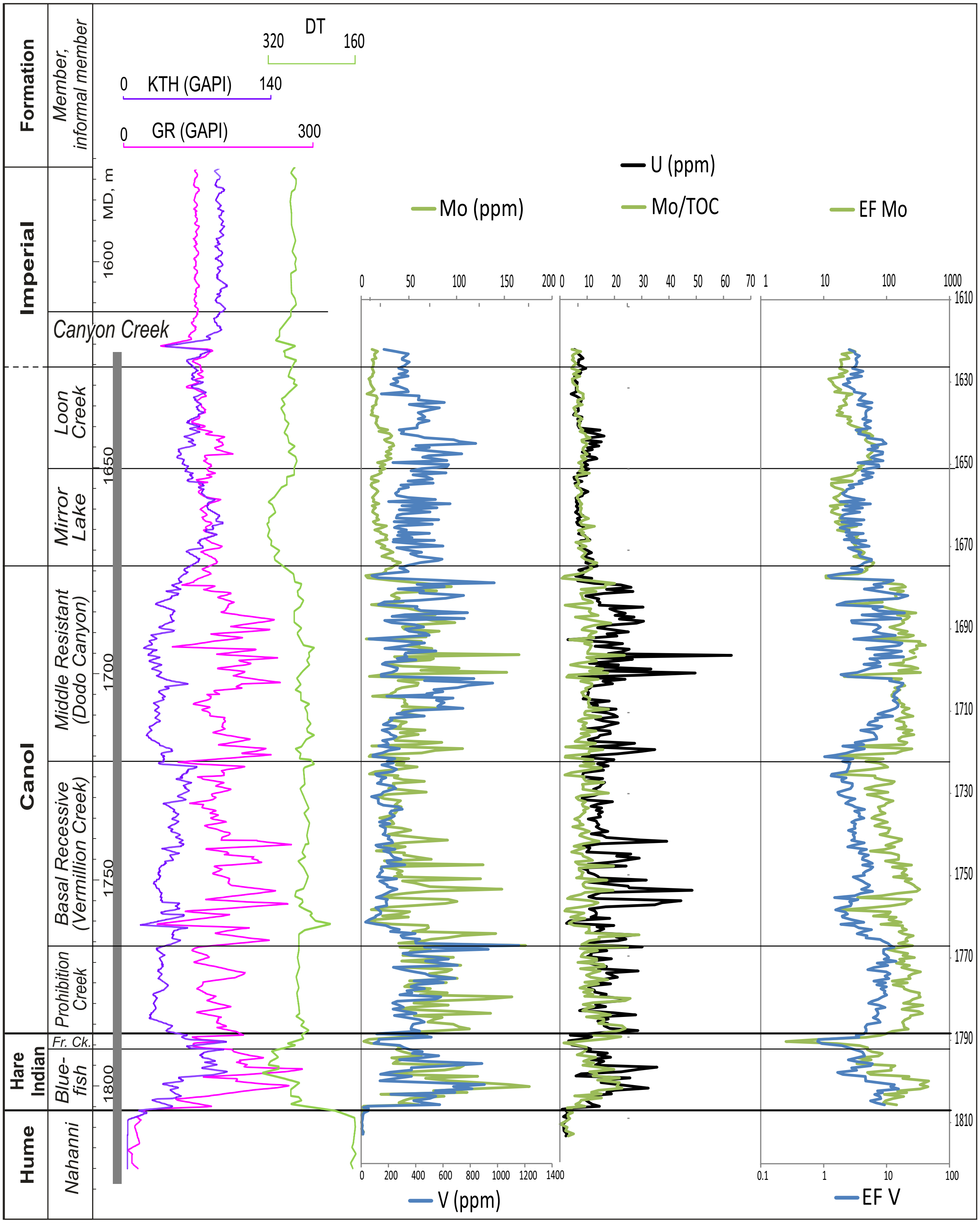


Figure 16. Lithogeochemical logs for the cored section of Loon Creek O-06 well. Seafloor anoxia proxies: U, V, Mo, Mo/TOC, and the Enrichment factors for Mo and V (EFMo and EFV, correspondingly, on logarithmic scale).

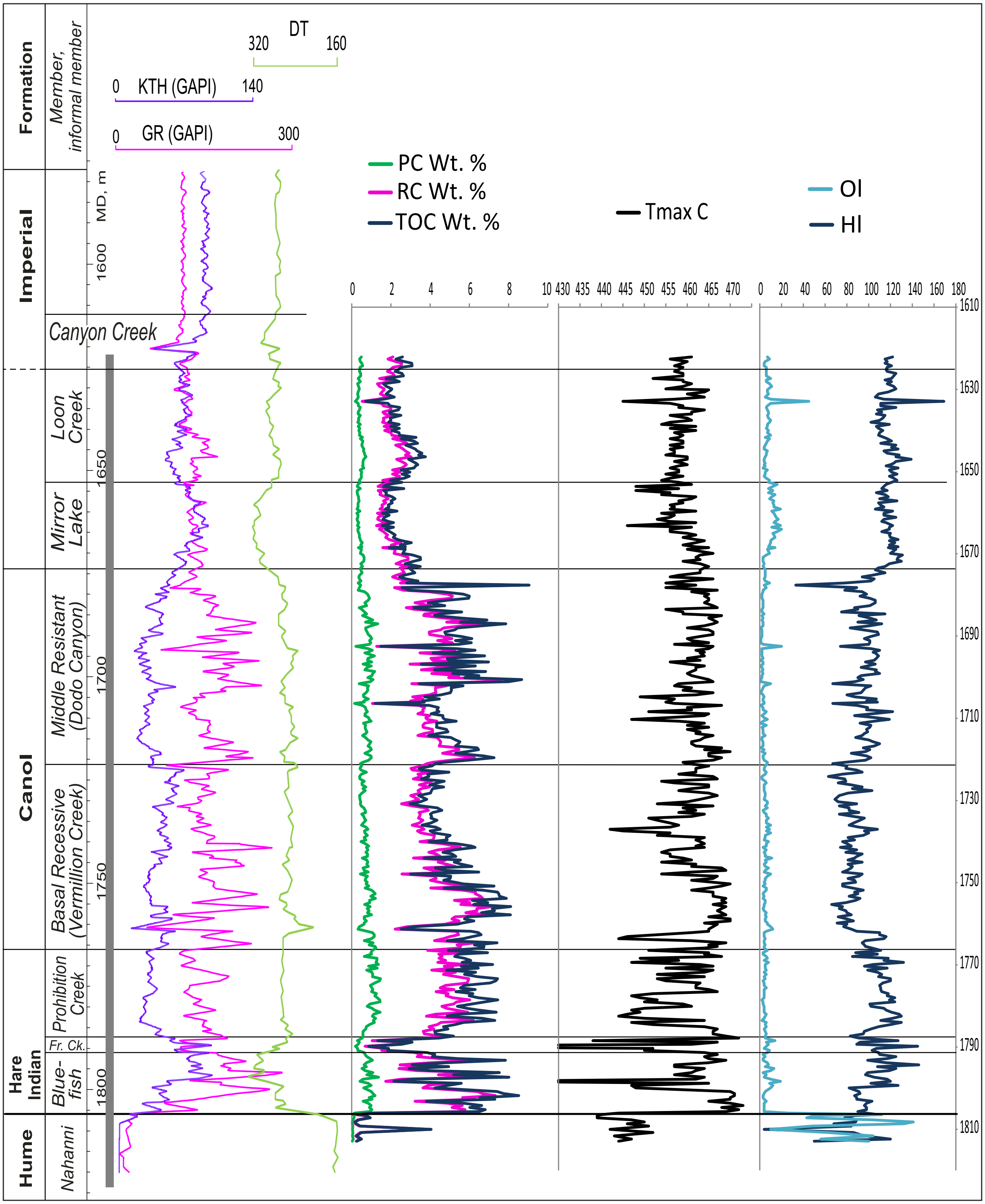


Figure 17. Rock-Eval™ 6 parameter logs for the cored section of Loon Creek O-06 well.

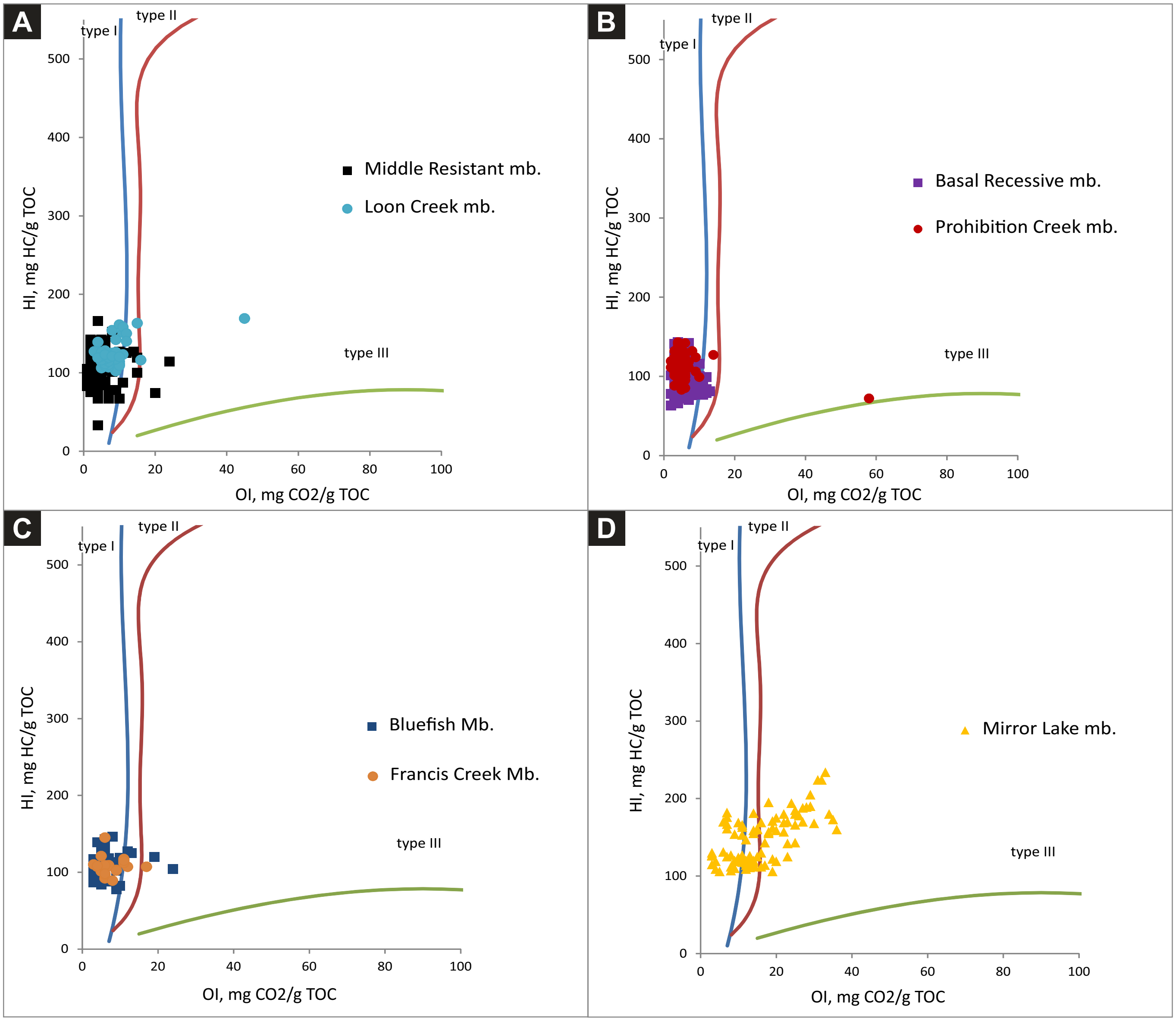


Figure 18. Pseudo van Krevelen diagrams (HI vs. OI) of Rock-Eval™ data from Little Bear N-09 and Loon Creek O-06 wells.

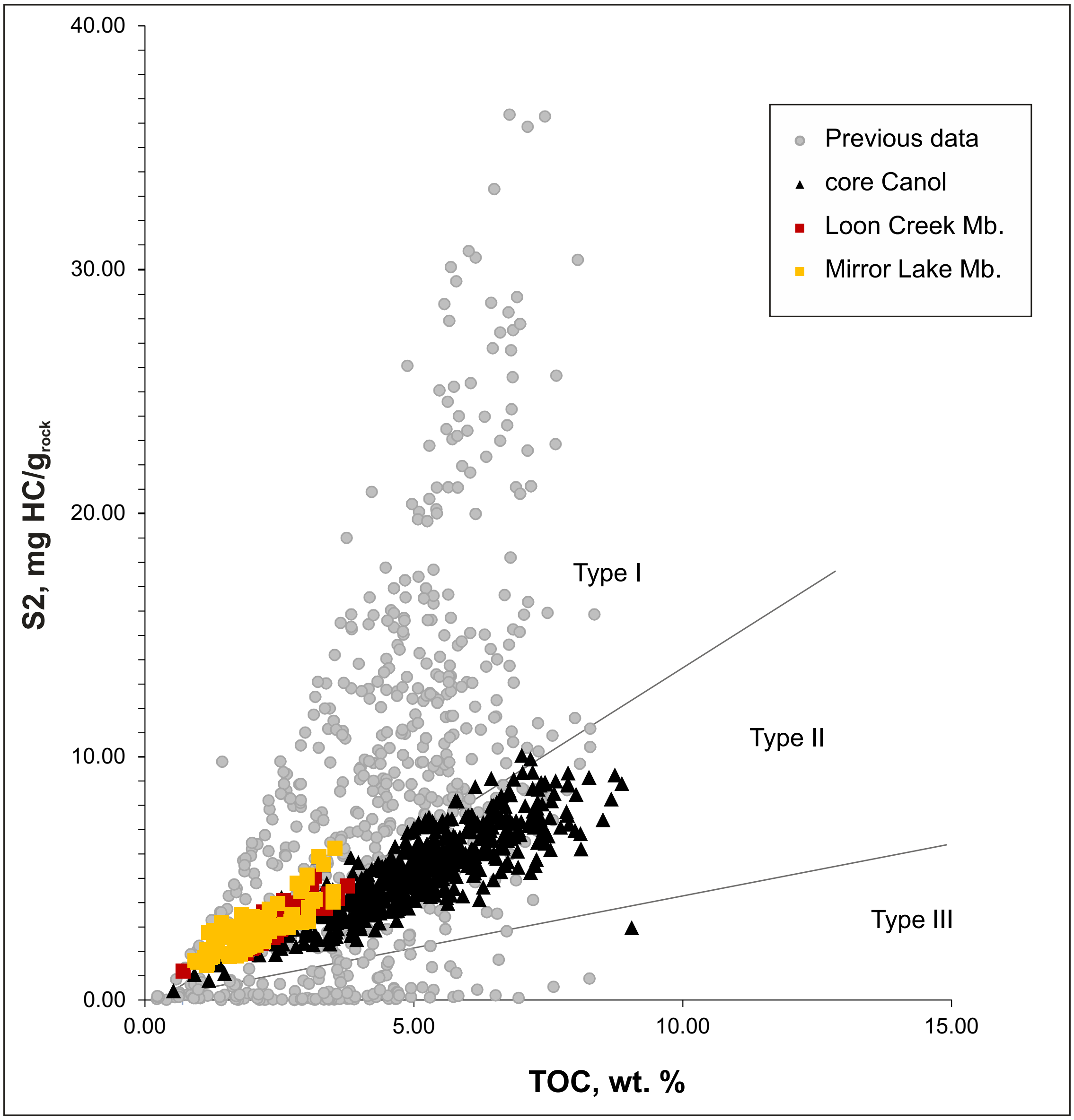


Figure 19. **S2 vs. TOC for Canol Formation, 658 samples from Canol Formation of Loon Creek O-06 and Little Bear N-09 wells plotted against previous data for Canol Formation (Pyle et al., 2011; Pyle and Gal, 2012, 2013; Gal and Pyle, 2012; unpublished data in SAMS GSC database). In previous data, six outlier samples with extremely high TOC >14% and S2 > 80 mg HC/g_{rock} are excluded. The "core Canol" here refers to joint Prohibition Creek, Basal recessive, and Middle resistant informal members.**

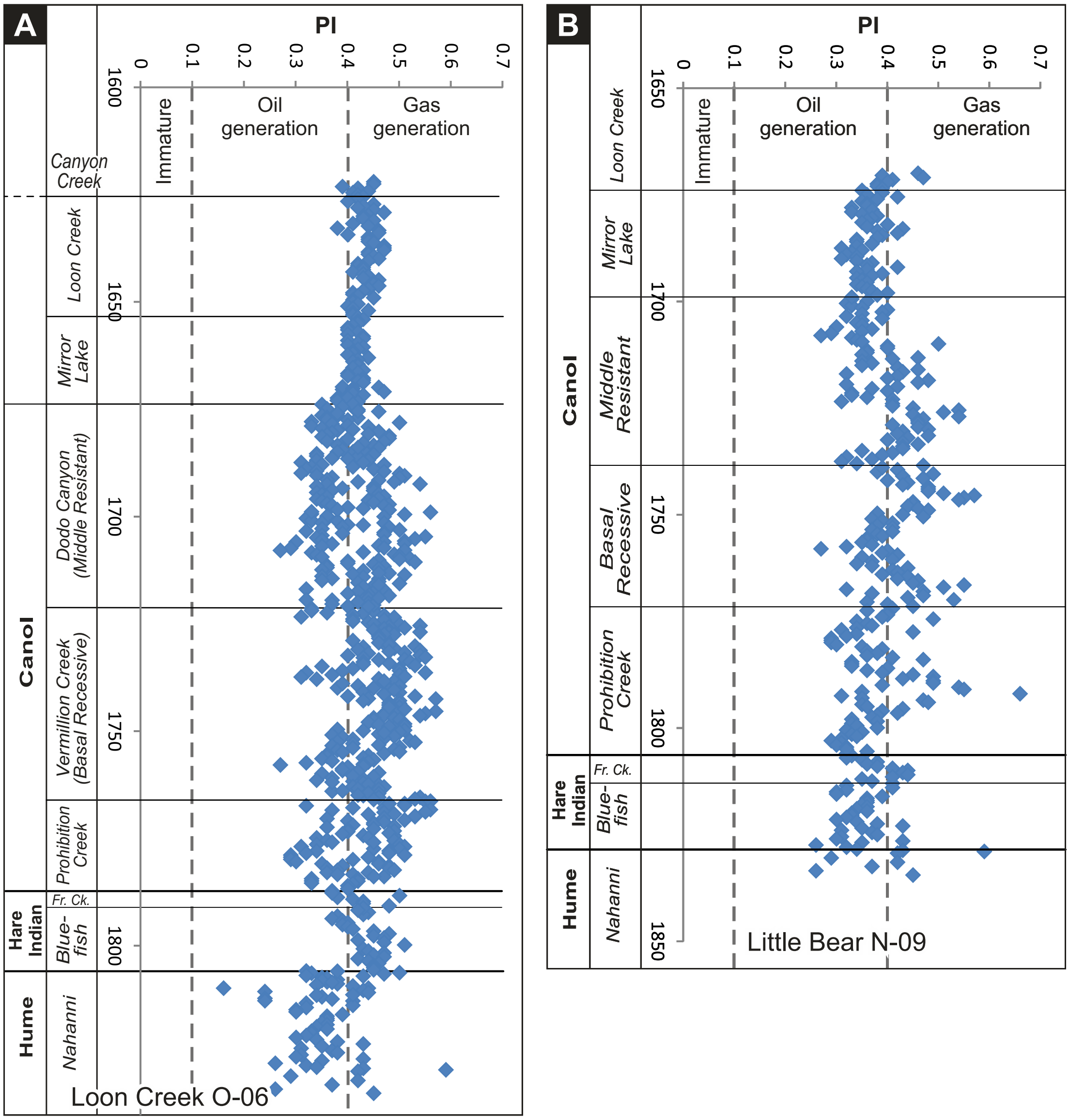


Figure 20. Production index (PI) vs. measured depth, (A) Loon Creek O-06, (B) Little Bear N-09.

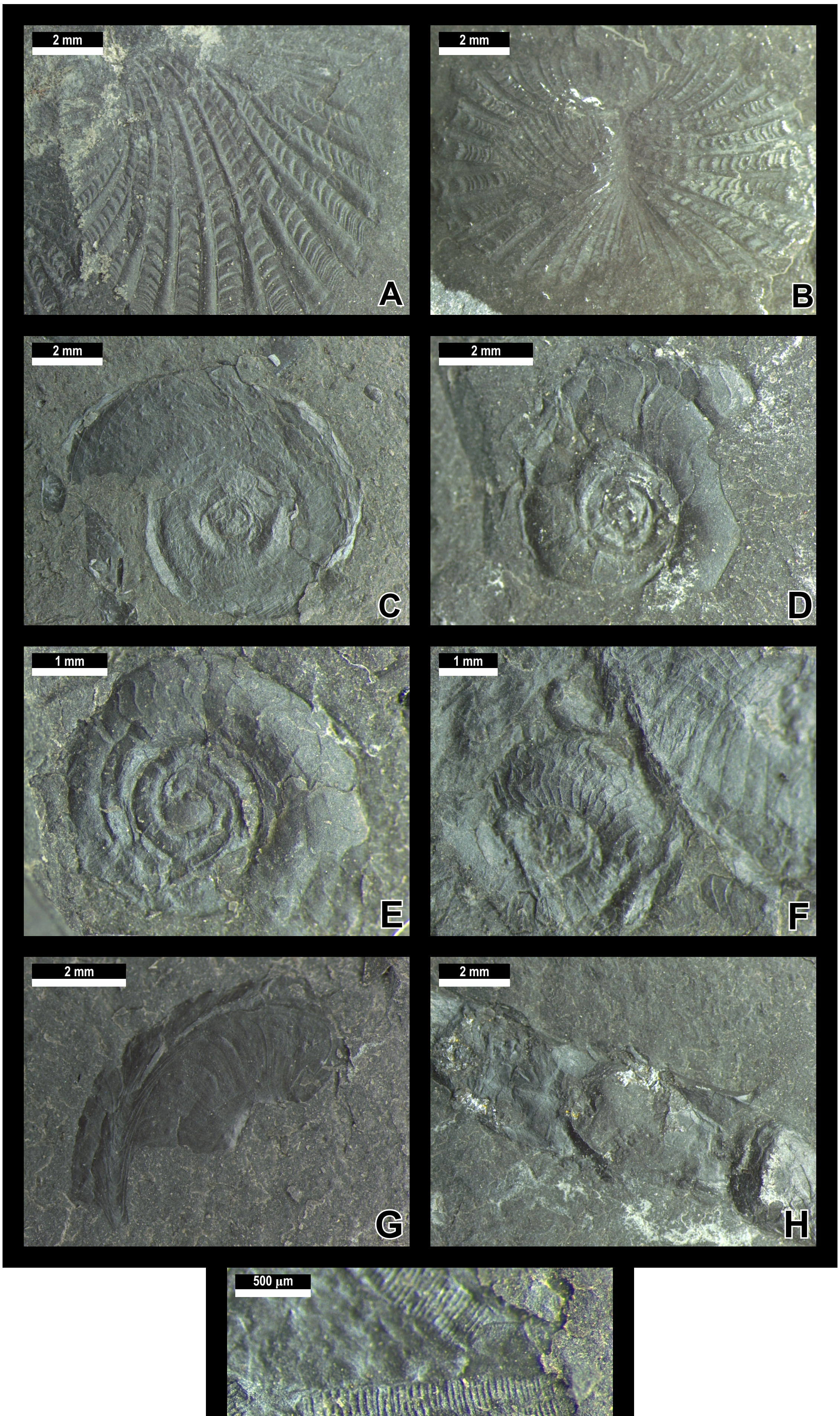


Figure 21. Fossil assemblage from the lower part of the Imperial Formation, Mirror Lake Core N-20: (A) *Glyptohallicardia palmata* (Goldfuss, 1837), 1898.3 m; (B) *Glyptohallicardia palmata* (Goldfuss, 1837), double shells, 1898.3 m. C-G, juvenile evolute goniatite shell imprints. (C) 1904.59 m; (D) Gephuroceratoidea (possibly *Manticoreras* specimen) 1898.29 m; (E) Gephuroceratoidea (possibly *Manticoceras* specimen) 1899.55 m; (F) 1904.61 m; (G) Aulatornoceratinae Becker 1993, 1898.18 m; (H) orthocone cephalopod, 1898.82 m; and (I) tentaculitid, 1904.62 m. Photographs by S. Gouwy.

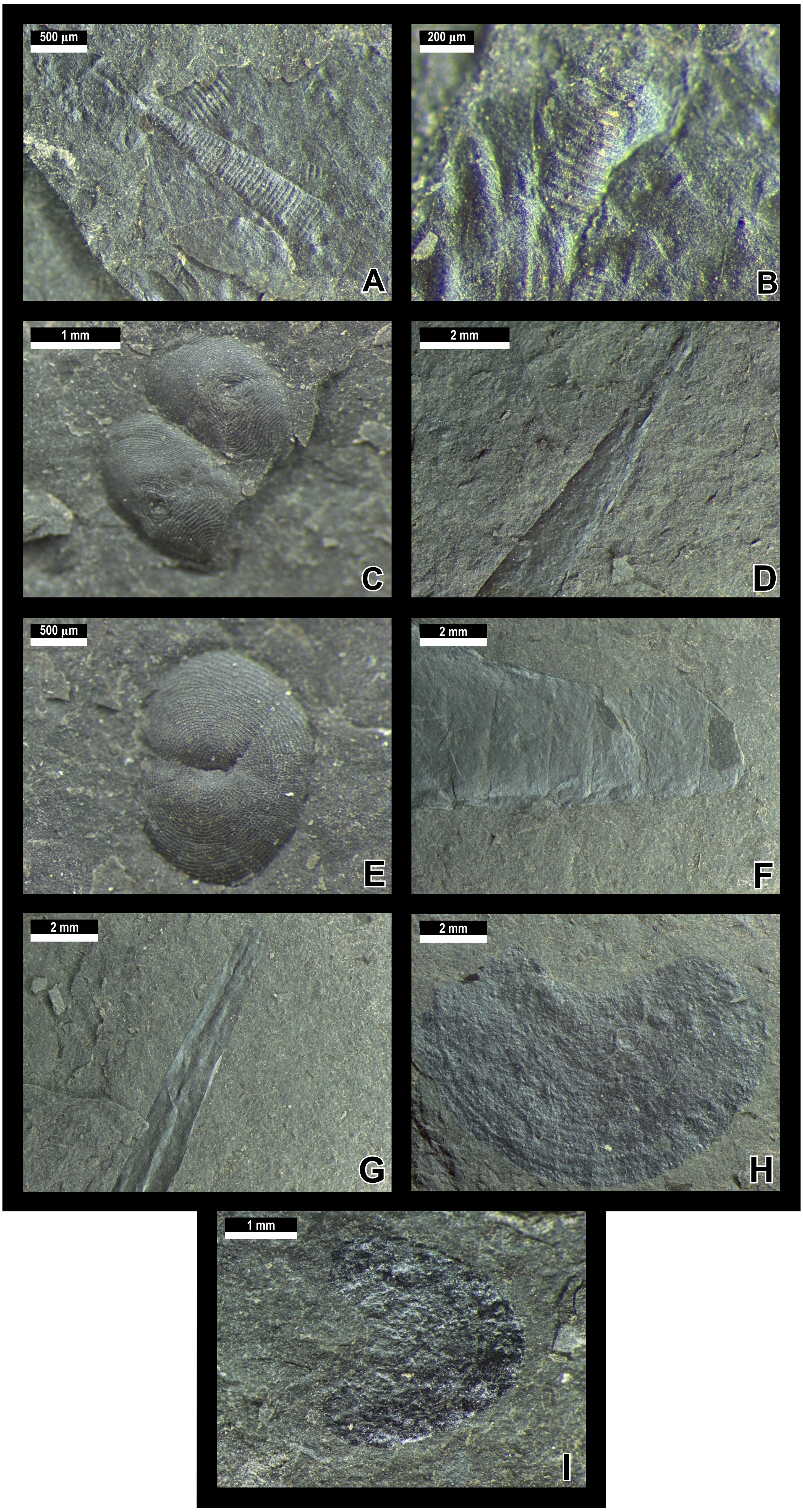


Figure 22. Microfossil assemblage from the lower part of the Imperial Formation, Mirror Lake Core N-20: (A) Tentaculitid, 1904.62 m; (B) ?Nowakia sp., 1904.62 m; (C) Pelagic ostracod imprint, 1892.6 m; (D) Collapsed ortocone cephalopod, 1899.55 m; (E) Pelagic ostracod imprint, 1893.0 m; (F) Ortocone cephalopod, 1900.83 m; (G) Collapsed ortocone cephalopod, 1900.83 m; (H) anapticus (organic shadow) possibly from bactritid specimen, 1900.50m; (I) anapticus (organic shadow) possibly from bactritid specimen, 1902.99 m. Photographs by S. Gouwy.

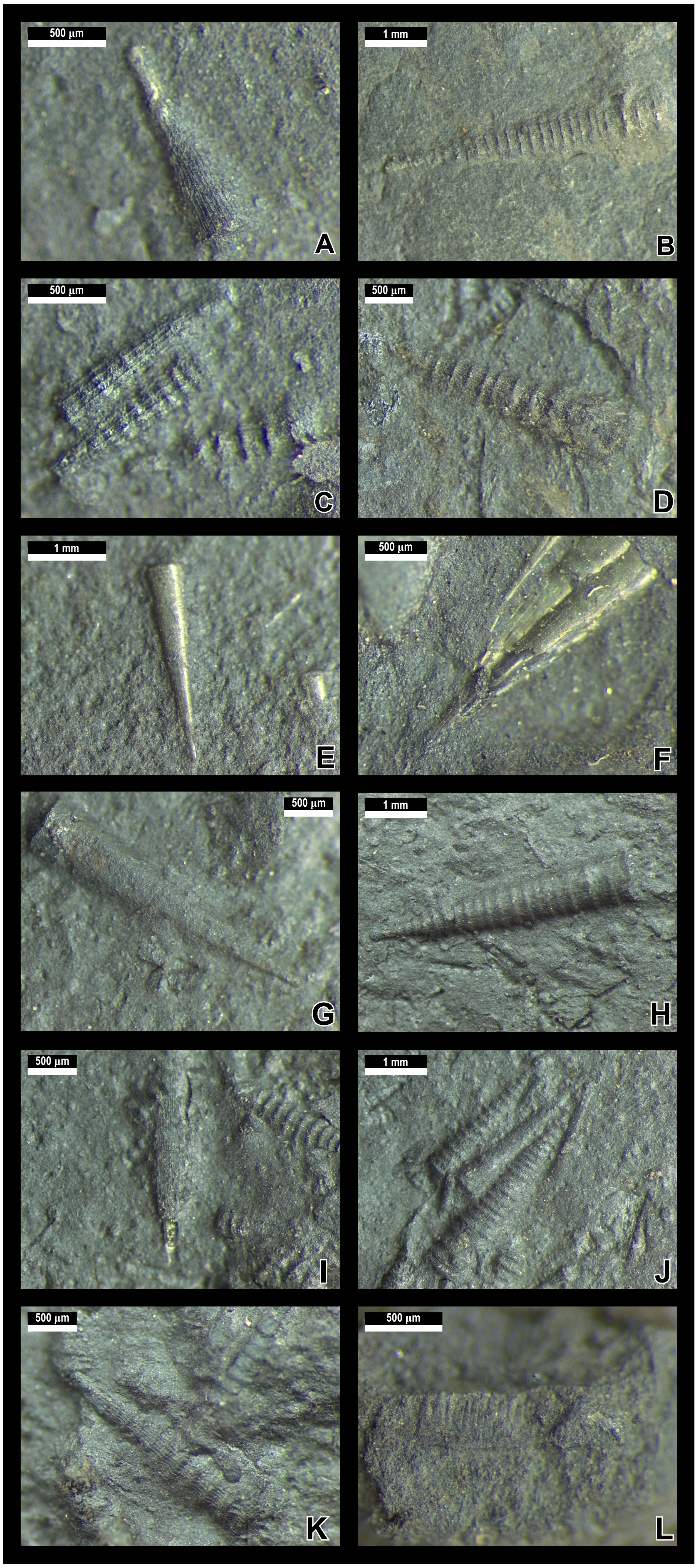


Figure 23. Microfossil assemblage (Tentaculites and conodonts) from the Bluefish Member, Hare Indian Formation in the Loon Creek Core (O-06): (A) *Costulatostyliolina* sp., 1801.25 m; (B) *Nowakia otomari*, 1803.95 m; (C) *Viriatellina* sp. 1804.37 m; (D) *Nowakia* sp. 1804.40 m; (E) *Costulatostyliolina* sp., 1804.83 m; (F) *Costulatostyliolina* sp., 1804.95 m; (G) *Costulatostyliolina* sp., 1805.80 m; (H) *Nowakia otomari*, 1805.80 m; (I) *Viriatellina* sp., 1805.80 m; (J) *Viriatellina* (right), *Nowakia* cf. *postotomari* (left), 1805.80 m; (K) *Nowakia* cf. *postotomari*, 1805.80 m; (L) *Polygnathus* ex. gr. *varcus*, lateral view, 1796.78 m. Photographs by S. Gouwy.

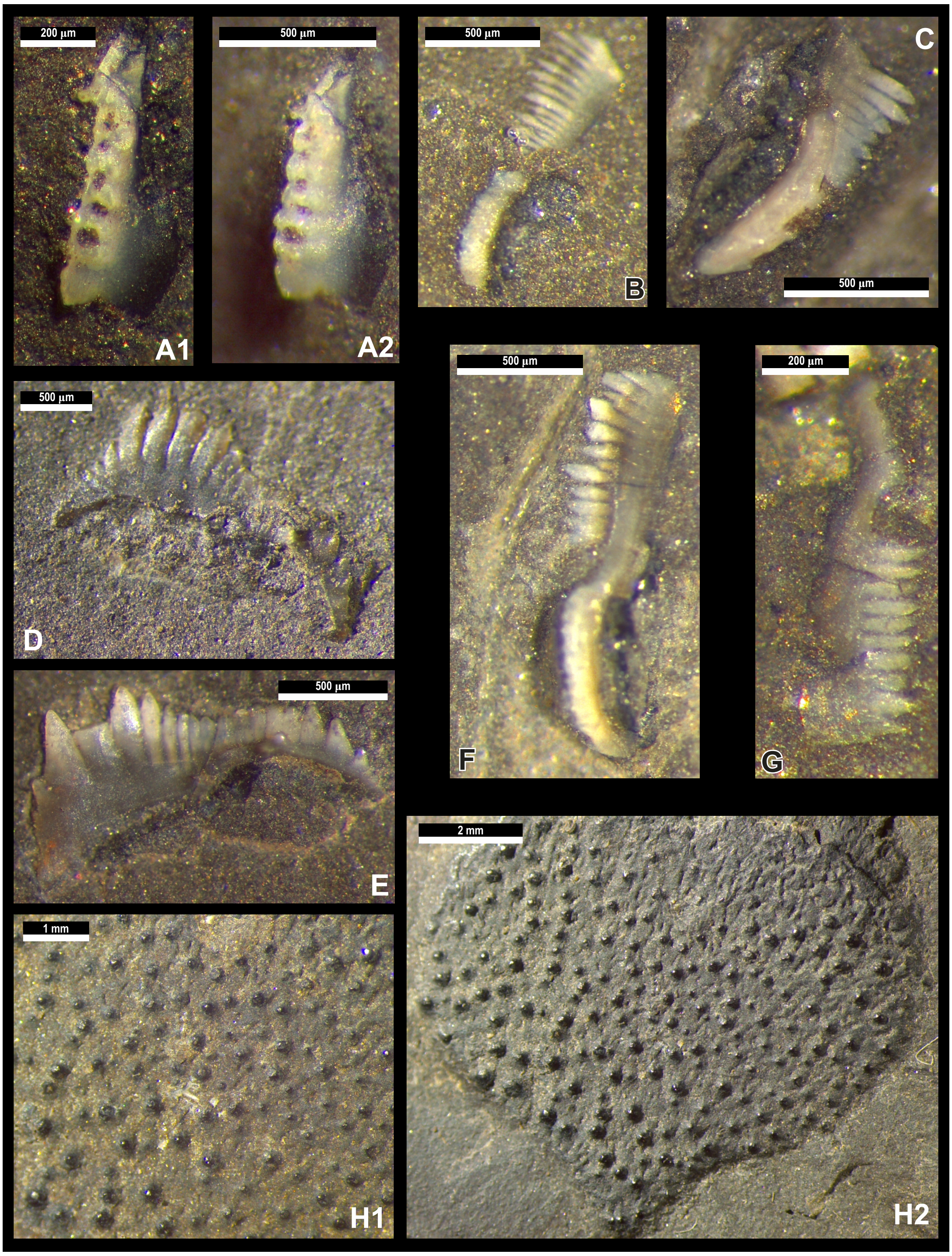


Figure 24. **Conodonts from the lower part of the Canol Formation, Norman wells Core (P32X):**
(A1-2) ***Icriodus*** **cf.** ***symmetricus*****, upper-lateral and lateral views, 754.90 m;**
(B) ***Polygnathus*** **sp., lateral view, partially embedded, 755.63 m;**
(C) ***Polygnathus*** **sp., lateral view, partially embedded, 754.75 m;**
(D-E) ***Polygnathus*** **sp. (2 specimens), lateral view, partially embedded, 754.65 m;**
(F) ***Polygnathus*** **sp., lateral view, partially embedded, 752.98m;**
(G) ***Polygnathus*** **sp., lateral view, partially embedded, 752.90m;**
(H1-2) Fish plate fragment, 752.90 m.
Photographs by S. Gouwy.

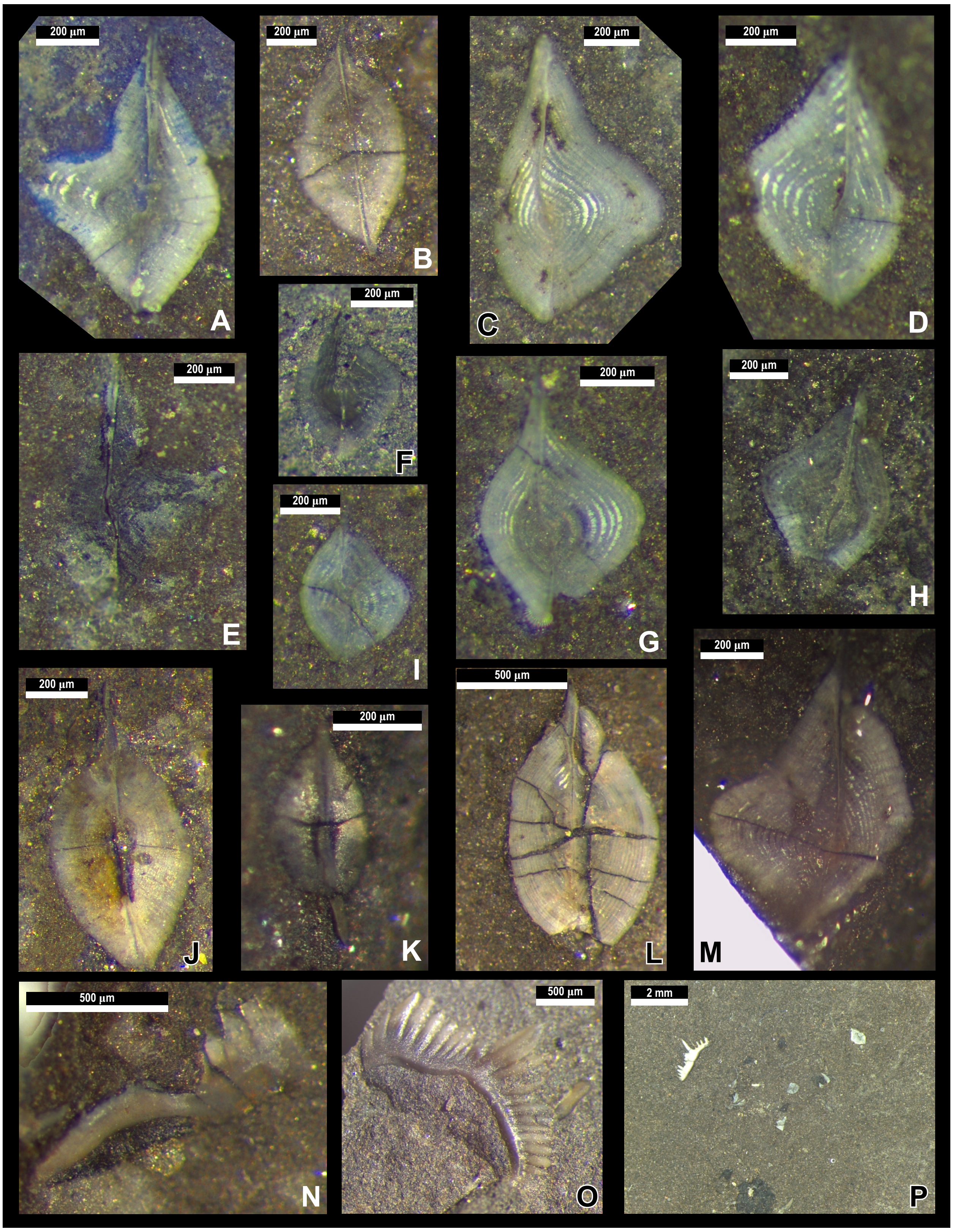


Figure 25. **Conodonts from the lower part of the Canol Formation, Mackenzie River Core no. 4 (E-27) and the Norman Wells Core (P32X): (A) *Palmatolepis punctata*, lower view, Mackenzie River core, 398.25 m; (B) *Klapperina ovalis/Mesotaxis falsiovalis*, lower view, Mackenzie River core, 398.25m; (C) *Palmatolepis punctata*, lower view, Mackenzie River core, 398.60 m; (D) *Palmatolepis punctata* early form, lower view, Mackenzie River core, 398.60 m; (E) *Palmatolepis punctata*, lower view, organic "ghost" of the conodont element, Mackenzie River core, 398.10 m; (F, G, and I) transitional forms between *Palmatolepis transitans* and *Palmatolepis punctata*, lower view, Mackenzie River core, 398.60 m; (H) Transitional form between *Palmatolepis transitans* and *Palmatolepis punctata*, lower view, Mackenzie River core, 398.25 m; (J) *Klapperina ovalis/Mesotaxis falsiovalis*, lower view, Mackenzie River core, 398.12 m; (K) *Klapperina ovalis/Mesotaxis falsiovalis*, lower view, Norman Wells core, 755.81 m; (L) *Klapperina ovalis/Mesotaxis falsiovalis*, lower view, lowermost part of the Canol Formation, Norman Wells core, 755.81 m; (M) *Palmatolepis punctata*, lower view, Mackenzie River core, 398.12 m; (N) *Polygnathus* sp. lateral view, Norman Wells core, 755.81 m; (O) ramiform element, lateral view, Mackenzie River core, 398.60 m; (P) View on a bedding plane with conodonts, Mackenzie river core, 398.60 m. Photographs by S. Gouwy.**

CONSTRAINTS ON TIMING OF RAMPARTS CARBONATE DEPOSITION

The Ramparts carbonate banks with their upper reefal Kee Scarp member are spatially restricted seismic-scale features (map inset on Figure 1) developed on top of bank-like swellings of the upper Hare Indian Formation (Figure 11). These thick Hare Indian sections are composed of calcareous fossiliferous shales and siltstones with known lateral gradations into the limestone-dominated “Platform member” of the Ramparts Formation (Figure 2; Muir, 1988). Historically these thick Hare Indian sections with typical Bell Creek facies are referred to as *shale banks* (Muir et al., 1984). Pyle et al. (2014) proposes the name Bell Creek Member for the gray-shale member of the Hare Indian Formation and its equivalents in the off-bank basinal sections recognized herewith as a separate “Prohibition Creek member” (Figure 11).

A stratigraphic gap between the deposition of the Hare Indian and Ramparts formations, on one hand, and the Canol Formation, on another, has been postulated from observations of the first half of XX century leading to recognition of a “Late Middle Devonian unconformity” (Hume and Link, 1945). Since then, the existence of this unconformity (“sub-Canol unconformity”) has remained a controversy (Pugh, 1983), however, this hiatus was favored by many researchers (e.g., Norris, 1997) and survived in successive formation charts including most recent ones (Morrow, 2012; Rocheleau and Fiess, 2014).

Biostratigraphic constraints

Most data available from the upper part of typical sections of the Bell Creek member (Hare Indian Formation) suggest an *ansatus* Zone (Middle *varcus* Zone, middle Givetian) assignment (Uyeno, 1979, 1991). Conodonts from the lower part of the (atypical) Bell Creek member at Dodo Canyon indicate a stratigraphic position within the *timorensis* Zone (lower Givetian) based on the combined ranges of *Polygnathus ensensis*, *P. pseudoeiflius* and *P. linguiformis weddigei* (revised conodont sample 11DC-007A from McCracken, 2012; Figure 16 in Pyle and Gal., 2012).

Conodonts collected from the uppermost part of the Ramparts Formation (Kee Scarp Member) suggest a stratigraphic position within the *norrisi* to MN4 zones interval (uppermost Givetian to lower Frasnian) (Powell Creek, Uyeno in Muir, 1988). The lower part of the Canol Formation contains conodonts indicating a stratigraphic position within the MN4 Zone (Powell Creek, Uyeno in Muir, 1988), or locally on a lower stratigraphic level within the *norrisi* Zone (Gayna River, Uyeno in Muir, 1988). It needs to be mentioned that the uppermost 10 m of the Ramparts Formation and the lowermost 10 m of the Canol Formation in Powell Creek, did so far not provide any short-ranged conodont taxa that would allow the accurate positioning of the Givetian-Frasnian boundary. More recent conodont findings from the top of the Kee Scarp Member in the Norman Wells Quarry (pers. comm. A. Hedinger) place the top of the Member within the MN4-6 zones interval. Combining these data with the conodont results from the initial layers of the Canol Formation in the Norman Wells Core and the Mackenzie River Core (MN5-6 zones), suggests that at these localities so far there is no reason (based on conodont data) to assume there is a stratigraphic gap between the Ramparts and Canol Formations.

Textural observations

The Kee Scarp - Canol contact in Norman Wells P32X well of the Norman Wells Oilfield (Kabanov, 2013) shows a sharp surface with the pressure solution aspect (Figure 26A). The uppermost 10 cm in top of the Kee Scarp limestone (755.8-755.9 m MD) is composed of strongly chalkified limestone with occasionally preserved wackestone to packstone sedimentary texture (Figures 26B and D). This uppermost bed contains *Amphipora* in life position, but in difference to the underlying reefal part of the section, no large stromatoporates or pachyporid tabulate corals are present (Kabanov et al., 2013). The chalkification refers to a characteristic fabric-destructive transformation of the original limestone that occurred during burial (Kaldi, 1989; Al Aasm and Azmy, 1996). The facies in the uppermost 10 cm is bioturbated. Marine isopachous cements are rare and thin (Figure 26D) indicating deposition leeward of or below the high-energy zone. The limestone in the Kee Scarp top does not bear signatures of synsedimentary – early diagenetic dissolution, hardground development (Figures 26B and D) or deposition in the intertidal zone. The fenestral facies with lamination aspect that might have been deposited in the intertidal zone occurs in 10 cm below the top (755.9-756.0 m MD), and the typical coral-stromatoporoid facies regarded as reefal is developed from 756.0 m downward. The $\delta^{13}C$-$\delta^{18}O$ signatures of the uppermost several centimetres of the Kee Scarp Member in this well (Kabanov, 2015) are in line with other values from Ramparts Formation (Al Aasm and Azmy, 1996) indicating no weathering offset. The presence of a conodont-rich thin packstone-wackestone bed in top of Kee Scarp limestone was also reported from the Norman Wells quarry bank by A.C. Hedinger (pers. comm. to T. Uyeno, 1997).

CONCLUSIONS

New materials from recently drilled exploration wells of central Mackenzie Valley allow for significant upgrade in the lithostratigraphic subdivision of the Horn River Group. The stratigraphic results are augmented by representative (706 samples) lithogeochemical and Rock-Eval™ pyrolysis data obtained from continuous cores of Little Bear N-09 and Loon Creek O-06 wells. These data provide new resolution for identifying stratigraphically controlled sweet spots and selective fracking strategies in the Canol shale hydrocarbon play.

Upgrades in lithostratigraphy of the Horn River Group include several new units that appear to be traceable within central Mackenzie Valley (NTS 96C-F map sheets). These units, characterized by Kabanov et al. (Submitted), include the Francis Creek and Prohibition Creek members replacing the Black-shale member of the upper Hare Indian formation, the Vermillion Creek and Dodo Canyon members comprising the Canol Formation, and the Mirror Lake and Loon Creek members that historically were partly or completely attributed to the basal Imperial Formation in outcrops but included into the Canol Formation in the subsurface. Above the Loon Creek member, the Canyon Member that has been previously used as a Canol/Imperial contact marker is expanded by inclusion of a thin offshore siltstone unit with a traceable low-gamma marker.

The available conodont data, including new data, place both the upper Ramparts and the lower Canol (as it occurs above the Kee Scarp member in Norman Wells) within the MN4-6 conodont zones interval (*transitans*-*punctata* zones, lower part of the Frasnian). Textural observations from the top of the Kee Scarp member at the Norman Wells oilfield do not support shoaling, subaerial exposure, nor development of a long-lasting sediment-bypass submarine surface (hardground) before the deposition of the Canol anoxic shale, which is also supported by $\delta^{13}C$-$\delta^{18}O$ data. These observations discredit the "sub-Canol unconformity" (Figure 2), which is consistent with earlier arguments for the essentially conformable nature of stratigraphic surfaces inside the Horn River Group (Muir, 1988). The short-living (ephemeral) disconformities capping sedimentary cycles/parasequences are only recorded in the shallow-water Kee Scarp bank of Norman Wells Oilfield (Muir et al., 1984; Yose et al., 2001).

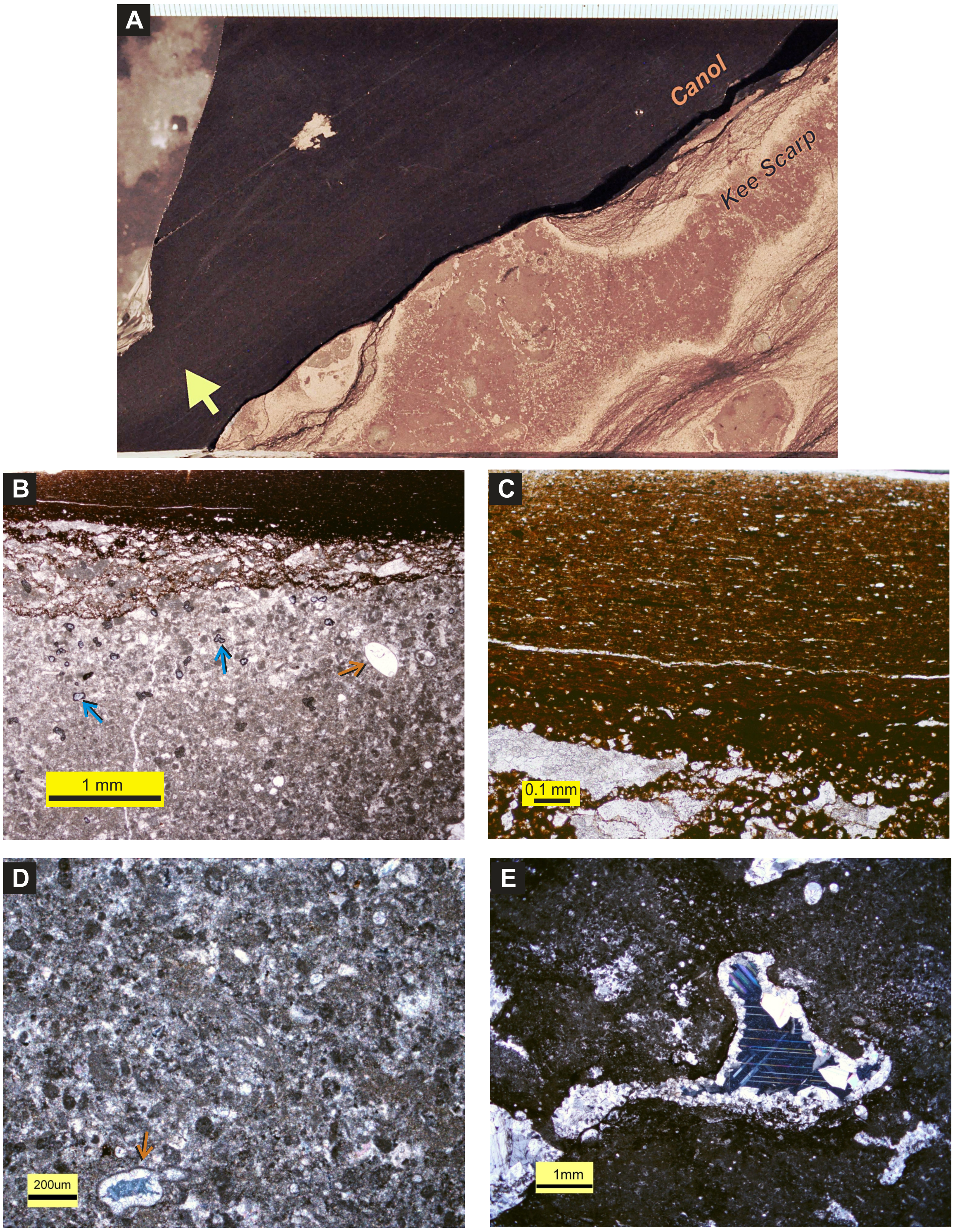


Figure 26. The contact of Kee Scarp Member and Canol Formation, 755.8 m MD, deviated section of Norman Wells P32X production well: (A) core face photo showing nodular diagenetically chalkified Kee Scarp limestone overlain by Canol black shale; arrow shows stratigraphic up; the scale ruler is graduated in millimetres. (B-E) Thin sections: (B and C) plane polarized light, (D and E) crossed polarized light. (B) Kee Scarp/Canol contact with pressure solution features and partly preserved packstone texture beneath; note well preserved ostracod (orange arrow) and bubbles (artifacts, blue arrows); (C) Close-up of the pressure-solution contact with details of Canol base; note absence of transitional facies; (D) a patch of well-preserved bioclastic packstone just beneath the top with a parathuramminid foraminifer bearing internal isopachous cement and blocky sparite cement; (E) a fenestra-like structure with the same cement sequence; note smooth walls indicating absence of sediment dissolution.

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limestone; (**F**) Close-up of the Hume/Hare Indian contact. See Appendix 4 for station coordinates and bed-by-bed descriptions.

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