Analytical Results from the Mirror Lake N-20 and Loon Creek O-06 Cores, Central Mackenzie Valley, Northwest Territories

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Introduction

In the Central Mackenzie Valley of the Northwest Territories, the Middle to Late Devonian Horn River Group (HRG) is a mixed carbonate and siliciclastic succession comprising mudstones of the Hare Indian and Canol Formations and carbonates of the Ramparts Formation. The HRG overlies the Hume Formation, and is overlain by the Imperial Formation. Interest in the development of unconventional reservoirs in the Northwest Territories during the late 2000s to mid 2010s sparked renewed research focus on the HRG of the Central Mackenzie Valley. In addition to its resource potential, the HRG presents an opportunity to study depositional processes associated with organic-rich mudstone units and local marine conditions in the Middle to Late Devonian of Earth's history.

Here, two mudstone cores (the ConocoPhillips Loon Creek O-06 core and the ConocoPhillips Mirror Lake N-20 core) were sampled by three graduate students at the University of Alberta (2 MSc and 1 PhD) in collaboration with the Northwest Territories Geological Survey (NTGS) with the objectives of 1) characterizing the reservoir potential of the Hare Indian and Canol Formations, and 2) developing a better understanding of the depositional setting for these formations. To meet these objectives, high resolution X-ray fluorescence data were collected, samples were taken for C and N stable isotope analysis, and samples were cut for petrographic analysis with the aim of assessing the sedimentology and ichnology.

Methods

X-ray Fluorescence

Energy dispersive X-ray fluorescence (ED-XRF) is a non-destructive method of collecting elemental composition data at high resolutions. The data were collected using a handheld Thermo Scientific Niton XL3t portable XRF analyser with helium purged analysis to decrease the detection limits of lighter elements (e.g., Al). The core was cleaned and was measured at 10 cm intervals and at selected depths of interest (Appendix 1, 2). Each depth was measured for 180 seconds. The analyser was calibrated by a proprietary algorithm owned by Thermo Scientific and certified reference materials (the United States Geological Survey Brush Creek Shale; 99.995% silica blank; Canadian Certified Reference Materials Project TILL-4) were analysed after every tenth measurement for accuracy.

C and N Stable Isotopes

At a 2 m spacing, samples were collected from the ConocoPhillips Mirror Lake N-20 core for carbon and nitrogen stable isotope analysis. An automated agate mortar and pestle was used to crush the samples into fine powder. Once powdered, samples were immersed in 1 M HCl, which dissolved the carbonate component over a period of 24 hours. Following immersion, the solution was centrifuged for 30 minutes with an acceleration of 29,000 xg and the resulting powder was washed three times with deionized water. This powder was then freeze dried and weighed into tin capsules. A Thermo Scientific Flash 2000 Organic Element Analyzer was used to produce CO_2 and N_2 by combustion and then these gases were separated by gas chromatography. A Thermo Scientific Delta V Isotope Ratio Mass Spectrometer was used to determine isotopic composition. $\delta^{13}C$ values are reported relative to Vienna Pee Dee Belemnite (V-PDB) and $\delta^{15}N$ relative to atmospheric N_2 (AIR). OAS High Organic Sediment Standard ($\delta^{13}C$ = –28.9‰ and $\delta^{15}N$ = 4.3‰) and OAS Low Organic Sediment Standard ($\delta^{13}C$ = –26.7‰ and $\delta^{15}N$ = 7.0) were used to calibrate isotopic measurements. Based on repeated measurements of the standards over time, analytical precision was within 0.2 ‰ for both nitrogen and carbon.

Petrography

Ninety-one thin sections were prepared from the N-20 (45 sections) and O-06 (46 sections) cores. Thin sections were cut extra-thin (approximately 20 µm thickness), to best show the sedimentary fabric of fine-grained organic-rich samples. Textural attributes of the thin sections at 20x, 100x, and 600x were described and photographed using a Nikon Eclipse 50i POL microscope and Nikon DS Fi1 camera. Sedimentological structures such as mineralogy, grain-size distribution, small-scale sedimentary features such as bedding and laminae, and early diagenetic features such as pyrite habit and carbonate character were noted. Percentage comparison tables were used to visually estimate the percentages of sand, silt, and clay. Biogenic features such as bioturbation intensities (measured as percentage of sediment that has been biogenically reworked, e.g. 0-100%) (Taylor & Goldring, 1993), ichnofossil morphotypes present (diversity), and burrow size (diameter), as well as microfossil elements including type, composition, and abundance were also noted. The microfacies present were described using the nomenclature scheme of Lazar et al. (2015). A Zeiss Sigma 300 VP-FESEM scanning electron microscope (SEM) was used on both polished and unpolished uncovered thin sections and core fragment 18 samples, to observe variations in microfacies microtextural elements and grain relationships (e.g. clay platelet arrangements).

Results and Interpretations

X-ray Fluorescence

The concentrations of Al, Ca, Fe, K, Mo, Si, Ti, V, and Zr at each analyzed depth are displayed in Appendix 1 for the N-20 core and Appendix 2 for the O-06 core. Additionally, the maximum, minimum, and average concentration of Al, Ca, Fe, K, Mo, Si, Ti, V, and Zr from each core are summarized in Table 1.

Table 1. X-ray fluorescence results from the N-20 and O-06 cores.

Core	Element	Maximum (ppm)	Minimum (ppm)	Average (ppm)
N-20	Al	1.76E+05	1.90E+03	6.84E+04
N-20	Ca	5.02E+05	2.66E+02	3.52E+04
N-20	Fe	2.50E+05	1.23E+02	2.43E+04
N-20	K	3.32E+04	1.73E+02	1.34E+04
N-20	Mo	1.68E+02	1.97E+00	3.35E+01
N-20	Si	6.83E+05	8.16E+03	3.91E+05
N-20	Ti	6.81E+03	1.23E+02	2.75E+03
N-20	V	1.74E+03	4.25E+01	3.78E+02
N-20	Zr	1.53E+02	3.58E+00	7.59E+01
O-06	Al	1.13E+05	1.07E+03	5.25E+04
O-06	Ca	6.31E+05	3.30E+02	6.42E+04
O-06	Fe	1.18E+05	1.44E+02	2.14E+04
O-06	K	2.67E+04	1.24E+02	2.14E+04
O-06	Mo	9.80E+01	1.57E+00	2.23E+01
O-06	Si	4.51E+05	3.81E+03	3.07E+05
O-06	Ti	6.49E+03	1.23E+02	1.36E+03
O-06	V	1.94E+03	2.50E+01	2.70E+02

O-06	Zr	1.03E+02	3.58E+00	3.85E+01

In mudstone lithologies, Al, Fe, K, Ti, and Zr are typically associated with terrestrially-derived sediment (e.g., Ratcliffe et al., 2012; Sano et al., 2013). In contrast, Si may be terrestrially-derived, hydrothermal, or biogenic. There are several depths in the N-20 core (most notably at 2086 m, 2055 m, 1994 m, and 1980 m) and O-06 cores (most notably at 1799 m, 1766 m, 1750 m, 1726 m, 1710 m, and 1693 m) where peaks in Si are present without accompanying peaks in Al, Fe, K, Ti, and Zr. These highs in Si relative to Al, Fe, K, Ti, and Zr likely reflect the presence of biogenic silica from radiolarian tests, which have been observed in the HRG (e.g., Biddle et al., 2021) and may be associated with times of lower terrigenous sediment supply or higher biological productivity.

Two redox-sensitive trace metals are considered (Mo and V) and their enrichment factors relative to Al are calculated following Equation 1, where X is the element of interest (e.g., Tribovillard et al., 2006). We used the Post-Archean Average Shale (PAAS) values of 84,000 ppm Al, 1 ppm Mo, and 140 ppm V (Taylor and McLennan, 1985). Calculated enrichment factors (EF) for Mo and V are included in Appendix 1 for the N-20 core and Appendix 2 for the O-06 core.

$$EF_X = (X/Al)_{sample}/(X/Al)_{average\ shale} \qquad (1)$$

In both the N-20 and O-06 cores, enrichment factors for V and Mo show peaks that correspond to the highs in Si relative to Al, Fe, K, Ti, and Zr, suggesting a common control.

C and N Stable Isotopes

In the N-20 core, $\delta^{15}N$ ratios range from –3.8‰ to +1.9‰, with an average of –2.3‰. $\delta^{13}C$ results are between –31.0‰ and –24.3‰, with an average of –29.1‰ (Appendix 3). Although the $\delta^{13}C$ ratios present in this interval plot in the range associated with many different types of primary producers (e.g., bacteria, marine algae, freshwater algae; Lamb et al., 2006), these $\delta^{15}N$ signatures are characteristic of N sourced from N_2-fixing organisms (e.g., Minagawa and Wada, 1986).

Petrography

Petrographic analysis allowed the identification of subtle differences in sedimentologic and compositional changes throughout the otherwise homogeneous-appearing dark mudstone cores. Microscale bioturbation intensities (BI - the amount of sediment being reworked by infaunal organisms) varied throughout the core. Overall, eight distinct microfacies were identified. Microfacies include: (1) homogeneous-looking radiolarian-rich siliceous fine mudstone, (2) homogeneous dolomitized argillaceous fine mudstone, (3) discontinuous wavy-parallel laminated to homogeneous- looking argillaceous fine mudstone, (4) rarely bioturbated discontinuous wavy-parallel laminated silt-bearing fine mudstone, (5) bioturbated discontinuous wavy-parallel laminated to homogeneous-looking silt-bearing fine mudstone, (6) bioturbated discontinuous planar parallel laminated to continuous wavy non-parallel laminated argillaceous-siliceous medium mudstone, (7) fossiliferous discontinuous to continuous wavy-parallel laminated argillaceous fine mudstone, and (8) intraclast-rich discontinuous planar parallel laminated argillaceous fine mudstone. Individual characteristics and resulting interpretations for each microfacies are outlined in Table 2. An expanded discussion can be found in Biddle et al. (2021), and individual thin section descriptions and abbreviations can be found in Appendix 4 and 5. The microfacies naming scheme was developed from the terminology and classification nomenclature outlined by Lazar et al. (2015), with a continuum classification ranging from fine mudstone (fMs), through medium mudstone (mMs), to coarse mudstone (cMs). Terms “dominated” refers to sediments composed of > 90% of a constituent, “rich” refers to sediments containing 50–90% of a constituent, “bearing” refers to sediments having 10–50% of a constituent, and “poor” refers to < 10% of a constituent (following Macquaker and Adams, 2003).

In summary, petrographic analysis was pivotal in identifying different sediment delivery mechanisms acting over the depositional locations of these two cores. This included small scale sediment gravity flows, wave-enhanced sediment gravity flows, high density plug like flows, and storm-derived winnowing of sea floor sediments resulting in bioclastic (shelly) lags. Identification of these sediment delivery mechanisms, along with petrographically identified compositional intricacies, further allowed us to place these cores in relative proximal-distal relationships with the other cores examined in this study (N-09, H-64, I-78).

Table 2: Microfacies descriptions and interpretations

PRIMARY SEDIMENTATION MECHANISM	MICROFACIES	NAME	TOC%	DESCRIPTION	INTERPRETATION
(S1) **Pelagic suspension settling**	**MF1**	**Homogenous-looking radiolarian-rich siliceous fMs**	No Data	>70% siliceous radiolarian tests and spines Commonly intercalated with thin microbial mats and argillaceous fMs beds (MF3) BI: 0% Can be recrystalized to carbonate or partially pyritized	Pelagic suspension settling in quiescent oxygen starved bottom waters during proliferation pulses
(S2) **Plug-like flow dominated**	**MF2**	**Homogenous-looking dolomitized argillaceous fMs**	Range: 2.2 – 4.7 **Median: 2.43**	>20% early diagenetic dolomite, most commonly ferroan rhombic dolomite <5% detrital silt Sedimentary structures and bioturbation cannot be identified due to pervasive dolomitization Rare tentaculitid fossils	Rare laminar plug-like sediment gravity flows with long residence times, associated with poorly oxygenated sediment pore waters
	MF3	**Discontinuous wavy parallel to homogenous-looking argillaceous fMs**	1.4 – 5.7 **4.20**	<5% detrital silt Wavy-crenulated fabric Rare intraclasts BI: 0-40% Body fossils: radiolarians, conodonts, tentaculitids Diagenetic dolomite and rare euhedral pyrite	Sedimentation is dominated by plug-like flows with some low density surge and surge-like turbidity flows, associated with poorly oxygenated pore waters
	MF4	**Rarely bioturbated discontinuous wavy parallel silt-bearing fMs**	2.9 – 6.8 **4.10**	5 – 30% detrital silt Unlaminated to weakly plane parallel laminated Absent to common intraclasts rare microbial mats BI: <10% Body fossils: conodonts, agglutinated foraminifers, radiolarians, tentaculitids Common diagenetic dolomite and calcite	A mix of plug-like flows and low density turbidity flows with poorly oxygenated sediment pore waters
(S3) **Combined surge/surge-like turbidity currents, plug-like flows, and debrites**	**MF5**	**Bioturbated discontinuous wavy parallel silt-bearing fMs**	3.8 – 8.7 **5.42**	5 - 30% detrital silt Rare to common intraclasts Planar to wavy laminated BI: 10-100% Body fossils: conodonts, radiolarians Diagenetic dolomite	A mix of plug-like flows and low density turbidity flows with increased carrying capacity, associated with partially oxygenated pore waters
	MF6	**Bioturbated discontinuous planar parallel to continuous wavy non-parallel argillaceous—siliceous mMs**	4.8 – 7.7 **5.48**	>30% detrital silt grains Common intraclasts Detrital clay deposited as silt-sized clay aggregates Primary sedimentary features: undulatory scour surfaces, detrital silt and intraclast lags, normally graded silt-to-clay beds, low amplitude current ripples BI: 20-100% Body fossils: conodonts, radiolarians, agglutinated foraminifers, tentaculitids	Sedimentation dominated by surge and surge-like low density turbidity flows, with intermittent plug-like flows, and partially oxygenated pore waters
	MF7	**Fossiliferous discontinuous to continuous wavy parallel argillaceous fMs**	5.3 – 7.7 **5.50**	10 - 100% tentaculitid fossil shells Shells are generally intact, some are fragmented Fossils are sporadic throughout (matrix supported) and/or concentrated along isolated bedding planes (grain supported) Contains bioclastic graded bedding (coarse fossil beds fining upwards to detrital clay beds) BI: 0-20% Diagenetic dolomitization and pyritization	Sedimentation represented by a mixture of debrites, plug-like flows, and surge-like turbidity currents, with an oxygenated overlying water column, and subject to intense storm reworking
(S4) **Proximal plug-like flows**	**MF8**	**Intraclast-rich discontinuous planar parallel argillaceous fMs**	3.3 – 4.2 **4.10**	>30% Intraclasts 0 – 30% detrital silt Graded bedding, thin distal low density turbidites, and rare soft sediment deformation BI: 0-20% Body fossils: conodonts, radiolarians	Persistent plug-like flows occurring in a proximal setting where intraclasts are continuously generated

Appendices

1. X-ray fluorescence results from the N-20 core, listed by depth.
2. X-ray fluorescence results from the O-06 core, listed by depth.
3. C and N stable isotope results from the N-20 core, listed by depth.
4. Terminology/abbreviation list for thin section data tables
5. Thin section data tables, listed by depth.

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