Preliminary Petroleum Potential and Organic Matter Characterization of the Mesoproterozoic Upper Arctic Bay Formation (Black Shale) at the Shale Valley Central, Northern Baffin Island, Nunavut, Canada

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Introduction

The Mesoproterozic Arctic Bay Formation of Borden Basin (Canadian Arctic) has been subject of several paleoenvironmental and inorganic geochemistry studies focused on reconstructing its geohistory and early life, and understanding genesis of mineral enrichments in polymetalic black shales (Turner and Kamber, 2012 and references there in). Although thick (>200m) organic-rich shale superbly exposed at Shale Valley (northern Baffin Island, Fig. 1A,B) has been documented, the nature of its organic matter, petroleum potential, and the fate of generated petroleum is poorly understood.

Methods

Organic matter characterization by Rock-Eval analysis (Fig. 1C), organic petrology and geochemistry, coupled with a depositional environment interpretation based on lithological descriptions and organic petrographic analysis, and the reconstructed tectono-stratigraphic post-depositional history, are used to refine the previous depositional environmental interpretation, reconstruct the ~1.1 billion year burial history, and evaluate the initial petroleum generation potential. Literature review forms the basis for understanding the petroleum migration and losses and provides inputs for ongoing petroleum system modeling.

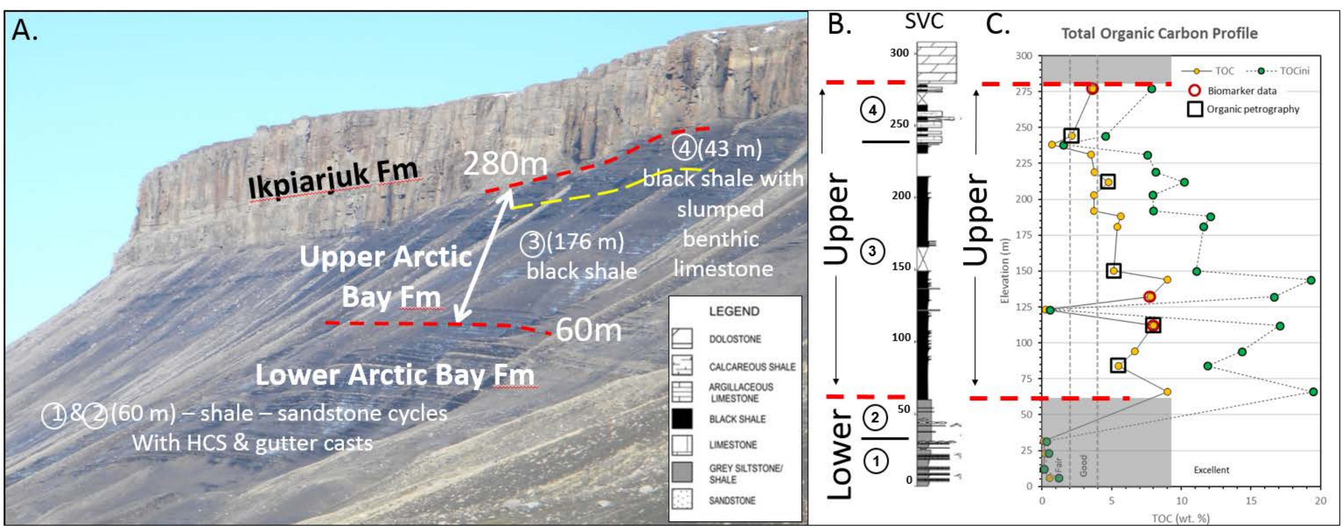

Figure 1. The Arctic Bay Formation at Shale Valley Central (SVC). **A.** Outcrop image **B.** Detailed sedimentological log (modified after Turner and Kamber, 2012). **C.** Measured and calculated initial Total Organic Carbon (TOC) values along ~280m thick exposure. **Key:** red dashed lines at 60 and 280m mark the base and top of the 220m thick upper Arctic Bay Formation. Circled numbers 1-4 are four identified lithostratigraphic units of Turner and Kamber (2012): (1) siltstone and sandstone of a northwest-deepening storm-dominated ramp; (2) sub-storm-wave-base siltstone with rare but conspicuous carbonate nodules; (3) black shale with subtle grain-size cycles; and (4) black shale with early diagenetic discoidal calcite concretions, sooty carbonate layers, and debrites of clasts of these lithofacies. Legend in A applies to B.; TOC – Total Organic Carbon; TOCini – initial Total Organic Carbon.

Sedimentology and petrology

Parallel-laminated organic-rich (kerogen and/or pyrobitumen) and organic-lean (silt) laminae (Fig. 2A), resembling varve-like lamina sets, suggest deposition in a stratified water column that experienced seasonal fluctuation in sediment supply and/or water chemistry. These diagnostic features apparent in multiple petrographic sections (Fig. 2) are consistent with the recently proposed alkaline lake environment for syndepositional deep-water dolostone seep mounds in the overlying Ikpiarjuk Formation (Fig. 1A; Hahn et al, 2015). Cross-lamination in silt (Fig. 2B) suggests periodic introduction of transported quartz, probably derived from shallow water during storm or wind events, and transported to the basin floor as density currents. Organic-rich laminae contain abundant (10 to 20 µm) euhedral dolomite crystals, typically clustered in micro-stringers as part of possible varve-like lamina sets or event couplets (Fig. 2C). The coexistence of dolomite and organic matter in a very thin lamina suggests formation of dolomite during thermochemical sulfate reduction (TSR) during burial diagensis. The predominant organic matter in the organic-rich shales of the Arctic Bay Formation is pyrobitumen with a morphological structure similar to lamalginite. Those lamalginites likely were formed in part by benthonic binding of a bottom cyanobacterial or bacterial community or derived by suspension settling of hemipelagic and pelagic organic matter into oxygen-depleted bottom waters (Crick, 1992). Eucaryotes and anerobic bacteria are common Type I-II Proterozoic source material. These have been recently documented in Archean and Proterozic lacustrine environments by Djokic et al, (2017). Burial reconstruction studies reveals deep burial (> 4000 m, Fig. 3) of the Arctic Bay Formation and consequent petroleum generation. Coarse crystalline nature of dolomite stringers suggest dolomite may have formed within the sediment due to alkalinity changes driven by sulphate-reducing bacteria (Turner and Kamber, 2012) as described by Mazzullo (2000) and Petrash et al (2017). The pyrobitumen lamellar structure and pore-filling nature suggest transformation of primary algae to bitumen. Migrabitumen that envelopes euhedral dolomite and other detrital grains and filled pores in coarser grain intervals suggests the migration of oil within the system and later transformation to pyrobitumen due to thermal maturity related to deep burial.

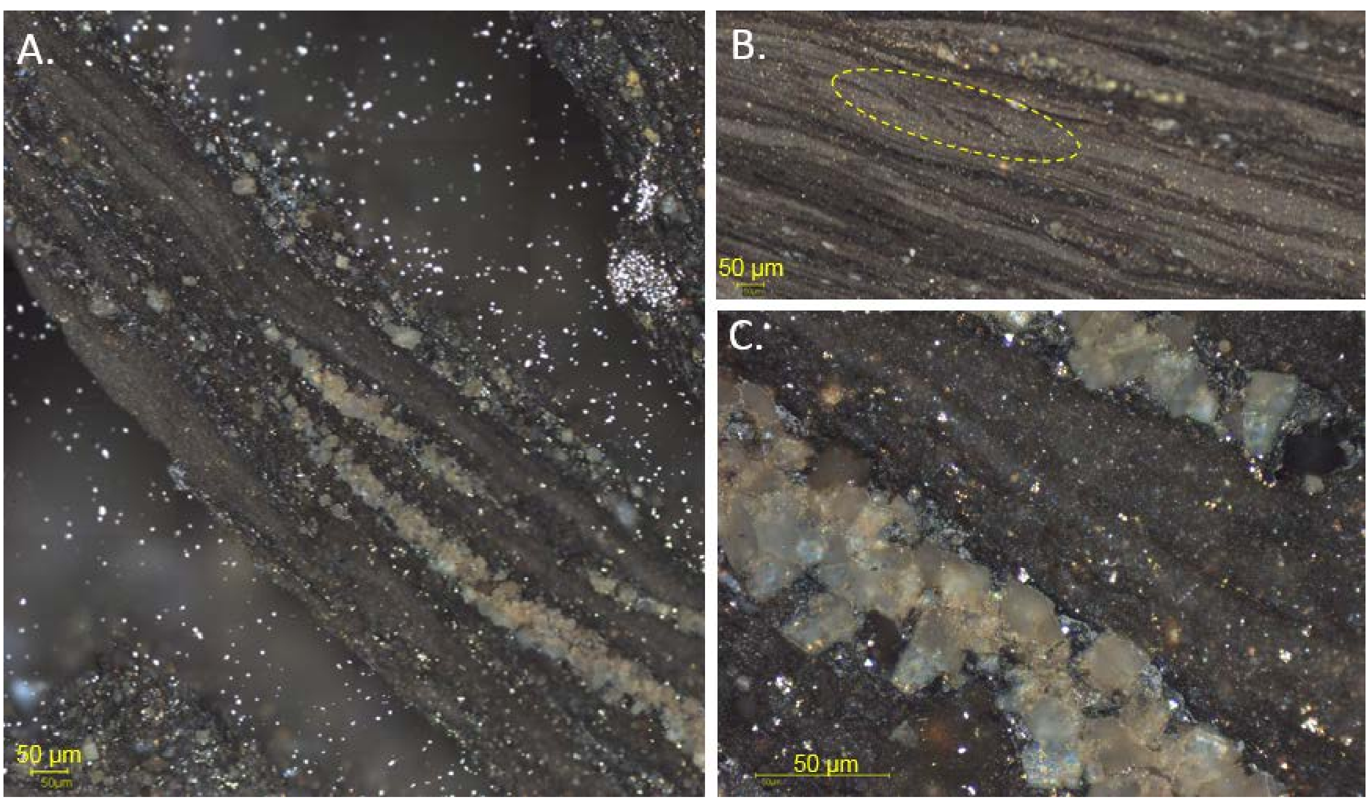

Figure 2. petrographic sections. **A.** Varve-like lamina sets, **B.** Cross-laminated silt; **C.** Euhedral dolomite.

Organic matter characterization

Rock-Eval: The results of Rock-Eval 6 analysis indicates that, the outcrop black shale samples from Shale Valley have a mean total organic carbon (TOC) content of 4.91 ± 2.7 wt. % (n = 18), mean hydrogen index (HI) of 21, and mean Tmax value of 556 ± 39°C. The residual carbon (RC) over TOC ratio of 96 ± 3% (average = 97%) suggests that the Arctic Bay Formation is in the dry gas window, and has very limited remaining hydrocarbon-generating potential. The TOC restoration methods proposed by Peters et al (2005), Justwand and Dahl (2005), Modica and Lapierre (2012) and Chen and Jiang (2016) are used to estimate the original TOC contents for the studied samples:

$$C^{o}_{toc} = \frac{C_{toc}}{1 - \alpha T_R}$$

where α is the ratio of convertible carbon to total carbon (α= H_I^o / 1200), and T_R the kerogen transformation ratio that is defined as:

$$T_R = \frac{1200}{H_I^o}\frac{(H_I^o - H_I)}{(1200 - H_I)},$$

HI is the present-day hydrogen index obtained from Rock-Eval analysis and Ho I is the initial hydrogen index before thermal degradation.

Assuming an original HI of 650 for the organic matter, which is typical for sediment with lacustrine aquatic phytoplankton as the main source of organic input, the average original TOC content is estimated to have been 10.53 ± 5.79%.

Petrography: The mean random bitumen reflectance (%BRo) of three studied samples is 1.5 ± 0.1% (n = 289). The equivalent vitrinite reflectance (VRo_{eqv}) using Landis & Castano (1995) equation is 1.8 ± 0.1%. This further supports the overmature interpretation for the samples studied.

Organic Geochemistry: Although most of biomarkers are absent or in low concentrations due to high thermal maturity, the abundance of methylphenathrenes allowed for the calculation of Methylphenanthrene Index (MPI) and methylphenathrene ratio (MPR) to be 1.62 to 1.64 and 0.72 to 0.74 respectively. These values indicate a thermal maturity of 1.37 to 1.49 Ro% and support the high thermal maturity estimated by vitrinite reflectance and Rock-Eval Tmax values. Although little pyrite was observed from petrographic analysis, the presence of elemental sulfur was detected in the solvent extracts from the three outcrop samples (Fig. 1C) submitted for geochemical analysis.

Depositional Environment Interpretation - Synthesis

The results of previous studies on paleo-depositional environment of the Arctic Bay Formation based on high TOC and the presence of sulfur coupled with elevated concentration of molybdenum (Turner and Kamber, 2012) support the interpretation of a strongly stratified, saline and/or brackish, oxygen-deficient water column, indicative of euxinic depositional environment characteristic of middle and late Proterozoic oceans (Canfield, 1998). Alternative modern analogues include East African Rift lakes such as Lake Tanganyika and/or semi-restricted basins such as Black and/or Baltic seas.

The rift lake interpretation is preferred, considering: (i) described evidence of varve-like lamina sets; (ii) recent interpretation of alkaline lake environment for syndepositional deep-water dolostone seep mounds in the overlying Ikpiarjuk Formation, and (iii) a thick (>200m) interval of continuous black shale which is more common in rift lakes than marine settings.

Burial History

The Proterozoic burial history has been reconstructed from extensive field observations (Turner and Kamber 2012; Turner et al., 2016), and the Paleozoic burial history is extrapolated from Yong Bay F-62 well drilled on Prince of Wales Island (Mayr et al., 2004). Despite its significant distance from Shale Valley graben, paleo-geographic maps suggests that Paleozoic successions dominated by carbonate platforms were similar at two localities, allowing for the use of Young Bay F-62 for modeling Paleozoic burial (Fig. 3). The main tectonic controls on the burial/denudation history were two short-lived periods of denudation during the Proterozoic (at 1050 and 1000 Ma), maximum burial at about 650 and 370 Ma (Fig. 3), and events related to Franklinian orogenesis (723 Ma) and Boothia uplift (420 Ma).

Maximum denudation occurred at ~180-200 Ma. Denudation is related to rifting and subsequent increased slope gradients for sediment transport towards the Sverdrup Basin. Present-day geothermal data are missing, but extrapolation from nearby localities (Grasby et al., 2012), and previous studies in the area (i.e. Brent et al., 2013) suggests that 25°C is a reasonable approximation. Considering the significant burial, the impact of rifting (1050 Ma) and the Franklin igneous event (723 Ma), are considered relatively neglegiable.

The burial history chart suggests that oil window conditions were reached twice in the unit's geological history (Fig. 3). Oil generation occurred about 1Ga (Fig. 3). Consequently, 1.1 Ga old paleo-gas accumulations in the overlying Nanisivik Formation (Hnatyshin et al., 2016) interpreted in the context of formation of lead-zinc mineralization (Turner, 2011) cannot be thermogenic. Presumably this would have been microbially generated gas that migrated, or locally generated thermogenic gas related to migration of hot fluids that locally matured the shale in the immediate vicinity of the deposit. Petroleum generated about 1Ga (Fig. 3) would have migrated through the overlying Precambrian rocks and charged a range of traps (Atkinson et al., 2017). Subsequent tectonic events, including significant denudation, would have allowed for oil remigration and seepage, the subject of an ongoing study. The second major burial at about 370 Ma (Fig. 3) would have limited petroleum generation potential since source rock already matured in the Proterozoic.

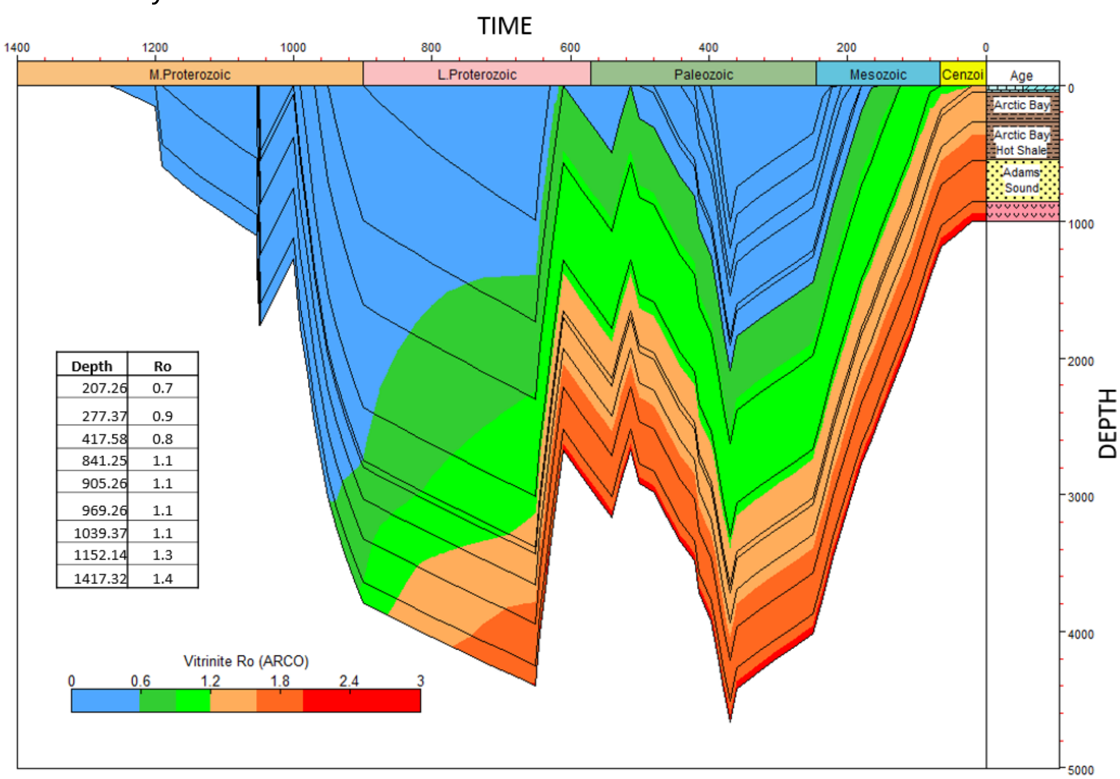

Figure 3. Burial history of Arctic Bay Formation exposed at Shale Valley (generated in Genesis, product of Zetaware). Inset Table: Vitrinite Reflectance (Ro) from Young Bay F-62.

Petroleum Generation Potential

Basin analysis based on the Rock-Eval data on outcrop samples from Shale Valley coupled with suggested Type I (lacustrine) organic facies suggests that the ultimate petroleum expulsion potential is ~246,000 million barrels of oil per square kilometer (Fig. 4), which is about five times higher than well-known high-quality source rocks in Gulf of Mexico and West Africa.

Conclusions

Rock-Eval analysis coupled with organic petrography, geochemistry, and sedimentology interpretation suggests that the Arctic Bay Formation is characterized by an excellent Type I lacustrine source rock. Based on thickness of 220 m and initial TOC of 11 % of Type I source rock we estimate the ultimate expulsion potential of ~246,000 barrels per square kilometer, which is about five times higher than well known source rocks in Gulf of Mexico, and West Africa. The geographic extent of organic-rich shale and the fate of expelled oil is a subject of an ongoing research.

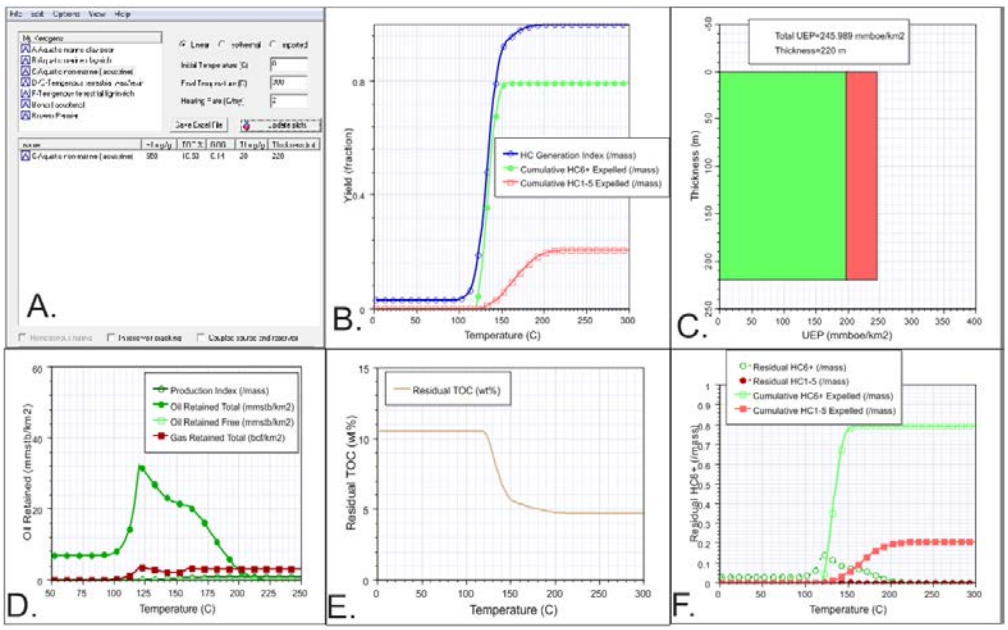

Figure 4. Shale Valley kinetic modeling results (data generated in Kinex, product of ZetaWare).

A. Input parameters
B. HC generation index and cumulative expelled oil
C. Ultimate Expulsion Eficiency
D. Production index and retained oil
E. Residual TOC
F. Cumulative and residual oil and gas

Future Work

Source-rock interpretation provides input for ongoing three-dimensional petroleum migration studies, which should allow for a better understanding of the fate of expelled petroleum, including its potential impact on geological events in the area. An ongoing microfossil (acritarch) study is expected to shed more light on paleoecology and paleoenvironmental conditions, including water depths (Butterfield and Chandler, 1992). This may allow for further advancements in understanding the origin of organic matter. Isotopic and elemental composition (scanning electron microscopy) may provide further insights about depositional setting and diagenetic processes.

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