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Qualitative petroleum resource assessment of eastern Hudson Bay and James Bay, Nunavut, Ontario, and Quebec

M.C. Hanna, H.M. King, and C.J. Lister

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EXECUTIVE SUMMARY

Natural Resources Canada (NRCan) has been tasked, under the Marine Conservation Targets[1] (MCT) initiative announced in Budget 2016, with evaluating the petroleum resource potential for areas identified for protection as part of the Government of Canada's commitment to conserve 10% of its marine areas by 2020. As part of this initiative, Parks Canada Agency (PCA) requested that NRCan conduct a qualitative petroleum resource assessment for an area of eastern Hudson Bay and James Bay, within which a National Marine Conservation Area (NMCA) may be evaluated.

This report provides the results of the qualitative petroleum resource assessment completed by NRCan's Geological Survey of Canada (GSC) for the study area of eastern Hudson Bay and James Bay. The GSC interpretation is visually represented by a qualitative petroleum potential map (Figure 1). Data were compiled and assessed for an area that is larger than what was requested by PCA based on practical geological considerations (Figure 2). This approach improves the detail and accuracy of GSC predictions. The GSC report will be used as part of PCA's decision-making process for any future NMCA in the study area.

The sedimentary basins that could contain petroleum potential in the study area are:

1. **Eastern Hudson Bay** (Belcher Basin). This region is comprised of thick Proterozoic sedimentary, low-grade metamorphic, and igneous rocks. The area is characterized by compressional deformation during the Trans-Hudsonian Orogeny.
2. **James Bay**. This region encompasses the eastern margins of the Moose River Basin, a Paleozoic carbonate basin with its depocentre located in onshore Northern Ontario. The Paleozoic sediments of the Moose River Basin are considered the most prospective sequence from a petroleum exploration perspective; however, petroleum potential is considered low.

   When considered from a national or global petroleum-basin perspective, both the Belcher and offshore Moose River basins are interpreted to have very low petroleum potential.

A secondary objective of this study was to summarize the potential for unconventional energy possibly including: gas hydrates, coal-bed methane, oil shale, and shale gas. Unconventional resource potential is considered very low in offshore parts of the study area. Oil shale and coal-bed methane may be prospective unconventional resources in onshore parts of the Moose River Basin (Appendix A). There is no evidence of gas hydrates in this study area.

A tertiary objective of the study is to identify areas with non-petroleum, resource potential (Appendix B). This was accomplished through literature review (Appendix C) and geologic interpretation over a regional scale. Mineral resources identified onshore, that may extend offshore include: limestone, lead, zinc, nickel, copper, iron, fluorite, barite, silver, gold, coal, chromite, lithium, gypsum, peat, granite carving stone, and micro-diamonds. Viability of offshore mineral resources requires that a regulatory framework is established allowing offshore mineral mining in Canada. Figure 3 provides information on mineral occurrences and mines near the study area.

[1] The Marine Conservation Targets (MCT) initiative provides targeted funding to Environment and Climate Change Canada (represented by the Parks Canada Agency), Fisheries and Oceans Canada (DFO), and Natural Resources Canada (NRCan) as part of the Government of Canada's commitment to conserve 10% of Canada's marine and coastal waters within the 200 nautical mile limit by 2020.

1. INTRODUCTION

The petroleum potential in the study area was evaluated by a team of GSC geoscientists from April 2017 to September 2017. Objectives were to: a) review, analyze, and integrate data from previous resource assessments, existing scientific literature, and available geoscience databases; b) interpret and map petroleum system elements and regional petroleum plays by applying sound geological principles; and c) provide a qualitative summary of the petroleum potential in the proposed study area. Data were compiled and assessed for an area that is larger than what was requested by PCA based on practical geological considerations. This approach improves the detail and accuracy of GSC predictions. Results of this qualitative assessment are shown in Figure 1.

2. GEOLOGIC SETTING

The geographic Hudson Bay and James Bay are composed of three geologic basins: Hudson Bay, Moose River, and the Belcher basins (Figure 2). The Hudson Bay and the Moose River basins contain Phanerozoic (primarily Paleozoic) carbonates while the Belcher Basin contains Proterozoic clastics. The Moose River Basin has a similar geological setting to the Hudson Bay Basin; it is located in onshore Ontario and marginally underlies James Bay. The Hudson Bay and Moose River basins are separated by the Cape Henrietta Maria Arch (Figure 3). Both the Proterozoic Belcher Basin and Paleozoic Moose River Basin (Figure 3) unconformably overlie Archean igneous and low-grade metamorphic basement rocks.

The Belcher Basin is part of the eastern Hudson Bay, an arcuate crustal collision zone created during the Paleo-Proterozoic Trans-Hudson orogeny. It is the oldest sedimentary basin in Hudson Bay containing several thousand metres of carbonate, clastic, low grade metamorphic, and igneous rocks. These sedimentary deposits have undergone episodes of burial, uplift, erosion, and structural deformation that may have caused not only petroleum generation and accumulation but also alteration, remigration, and leakage potentially reaching the seabed and sea surface. These natural geological processes may have led to present day petroleum indicators (e.g. slick-like features or oil seeps).

The Moose River Basin is part of the Paleozoic Hudson Platform that extends across Hudson Bay and adjacent onshore areas. Its depocentre is located in onshore Northern Ontario and the basin contains Ordovician to Devonian carbonate and clastic rocks. The basin is locally overlain by thin accumulations of upper Mesozoic and Cenozoic clastic strata. The eastern basin margin underlies James Bay.

Three distinct geologic mega-sequences were identified in the study area: Proterozoic, Paleozoic, and Mesozoic-Cenozoic (Figure 3). Mega-sequences, according to Schlumberger's on-line dictionary, "*The Oilfield Glossary*" (http://www.glossary.oilfield.slb.com), are defined as a large group of relatively conformable strata, normally from the same era, that represents cycles of deposition and is bounded by unconformities or correlative conformities (Appendix A and Appendix D). The presence of potential reservoirs, source, traps, and seals suggest there is potential for a petroleum system or systems within the three mega-sequences (Table 1). The less than 1.5 km of Paleozoic sedimentary thickness in the Moose River Basin is considered the most prospective sequence from a petroleum exploration perspective, although it is still interpreted as low potential. Source rock presence and maturity is of concern for this area (Appendix A). Proterozoic sedimentary mega-sequences in the Belcher and Moose River basins contain potential hydrocarbon reservoir rocks, traps, and seals, however source rock is considered to have the lowest chance of success. Mesozoic-Cenozoic strata in the Moose River Basin have limited or no source rock or reservoir potential. Petroleum system elements of the main mega-sequences are described in more detail in Appendix A.

3. DATA

3.1 Literature

The geology of the Hudson Platform and surrounding areas have been the subject of many GSC, National Energy Board of Canada (NEB), provincial, and industry reports, as well as a wide range of academic publications. This GSC/NRCAN study consisted of interpretation and mapping of petroleum system elements and regional petroleum plays, based on reviews and analyses of previous publications and reports (Appendix C), and available geoscience data, including marine seismic profiles, bedrock geology, well data, Radarsat data and bathymetric data.

Poor data coverage and data density for any area leads to higher overall uncertainty when delineating petroleum systems elements. The petroleum potential map (Figure 1) shows a low petroleum potential in certain parts of the study area in part because the data coverage is too low to confirm the possible presence or absence of petroleum systems.

3.2 Geoscience data

GSC's qualitative assessment was based on limited available offshore two-dimensional single-channel marine seismic profiles (Figure 2) and their integration with onshore geology, surface slick-like features, bathymetric surveys, well data, surface geology, and potential field data (ship-, aero- and satellite-borne gravity and magnetic data). Two-dimensional marine multichannel reflection seismic data in the Hudson Bay region were acquired by the petroleum industry in the 1960s through the 1980s (Figure 2); however, most of this data is outside the study area.

Well data utilized for this study area are limited to existing offshore petroleum wells in the Hudson Bay due to the fact that no offshore petroleum exploration wells have been drilled in either James Bay or the eastern Hudson Bay. The closest offshore petroleum exploration wells (five wells) were drilled in the Hudson Bay Basin from 1969 to 1985 (Figure 3). None of these wells encountered significant quantities of producible petroleum. Although numerous wells have been drilled onshore of the Belcher Islands and in the Moose River Basin, their primary focus was mineral resource and development (Figure 3).

Geoscience mining data utilized for this study area included known mining activities, historical mining well data, provincial mining reports, mining company activity reports and presentations and previous mapping done on the onshore areas of this study area. Results of the mineral potential for this study area can be found in Appendix B.

3.3 Unpublished analytical data

The Geo-mapping for Energy and Minerals (GEM) program has been renewed until 2020 for its second phase of technical work to produce publically available regional geoscience knowledge of Canada's North. The GEM2 program collected various geological information collaboratively with stakeholders and partners during 2017. The GEM2 project is currently underway and collecting data, and therefore, not all data and analyses dependent on new information were available for this report. Available GEM2 data were reviewed.

4. METHODOLOGY

4.1. Scientific Reviews and Workshops

To ensure the sound integration of the geological data, workshops were held with GSC Calgary, GSC Québec, Manitoba and Ontario provincial experts. Developments of workflow, methodology, and mapping have been regularly reviewed by the team and advisors. The results of the team's work were presented in a draft version of this report to GSC advisors and reviewers for comment and internal technical review.

4.2. Play Mapping

The GSC approach for conventional petroleum resource assessment is currently under revision to align with petroleum industry practices, including the use of probabilistic assessment to generate qualitative petroleum potential maps. A petroleum potential map was created by combining probabilities of success at the play level for four petroleum systems elements (source, reservoir, trap, and seal). When determining the chance of success for each petroleum systems element, data caliber, density, and confirmation of physical data must be considered and incorporated into a value which reflects all information and confidence. Plays were weighted by a subjective global scale factor to rank their chance of success and globally competitiveness for exploration. Areas with limited data availability should be reassessed after more information has been collected. This iterative process creates more detailed maps with higher confidence. The sum of all plays' potential was calculated to create the overall petroleum potential map (Figure 1). A summary of identified plays within the study are can be found in Table 1.

5. RESULTS AND INTERPRETATION

The presence of potential petroleum systems in James Bay (northeast Moose River Basin) and in the eastern Hudson Bay (Belcher Basin) require two geologically separate assessments. The Moose River Basin contains Paleozoic carbonates similar to those in other producing intracratonic analogue basins within North America Paleozoic such as the Williston, Michigan, and Illinois basins (Figure 4). Within these Paleozoic rocks, in the Moose River Basin, lies the Upper Devonian Long Rapids Formation, an immature organic rich shale (for Hudson Bay; Zhang and Hu, 2013), that may be developable as an unconventional oil shale resource. However, it is likely that the source rocks of the Moose River Basin are too thin and were not buried deep enough to generate any economic accumulations of conventional petroleum. Historical well data supports this conclusion. However, no RADARSAT image analysis have been collected in James Bay that may indicate hydrocarbon seeps.

The Belcher Basin is composed of Proterozoic carbonates, clastic, low-grade metamorphic, and igneous rocks where burial happened soon before and/or during the Trans-Hudsonian Orogeny. The organic rich black shale of the Lower Omarolluk Formation may have been heated and charged the overlying Upper Omarolluk and Loaf formations. However, these rocks were buried over one billion years ago and any petroleum that might have been generated likely escaped during further tectonic movement and erosion of anticlines.

"*The presence of dark spots on RADARSAT images may imply (oil) slick-like features* [see Figure 3] *on the sea surface near the boundary between the Belcher Basin and the Hudson Basin. Within the Proterozoic eastern Hudson Bay, west and north of the Belcher Islands, a few dark targets are located near the Proterozoic-Paleozoic contact. These dark spots may be unrelated to a hydrocarbon origin (false-positive), however if they are related to hydrocarbon it would imply fluid escape along the basin margin or the presence of potential hydrocarbon source rock(s) in the Proterozoic succession of the*

Belcher Islands" (Decker et al., 2013). Since indirectly identified offshore petroleum accumulations have not been tested by drilling in the area of the RADARSAT dark spot images, interpretation and characterization was limited to offshore seismic where available, inference from single channel bathymetry data, and geologic outcrops extrapolated to the offshore.

Five plays were identified in the study area (Table 1). These were defined based on geologic trends extrapolated from previous mapping. Seismic data in the area are sparse and had shallow penetration and therefore provided limited value for play mapping. Following the approach outlined in 4.2, chance of success was generated for each play. In eastern Hudson Bay, the two Proterozoic plays show low to very low potential: there are poor reservoir intervals in the Belcher Island area and questionable traps and seals. In the Moose River Basin, the three Paleozoic plays are also low to very low potential: there is an immature source rock and a thin Paleozoic reservoir section within James Bay. The combined conventional petroleum potential in the study area is considered to be low to very low (Figure 1).

Unconventional petroleum potential could exist in the onshore Moose River Basin. However, Bezys and Risk (1989) question the economic viability of the Long Rapids Formation as an oil shale. Lignite-rich coal beds may have some potential for coal-bed methane in the Moose River Basin (Appendix A, and Telford and Verma, 1982). No evidence has been found for the presence of gas hydrates in the study area. This is not unexpected since conditions within the area are not within the hydrate stability zone.

6. CONCLUSIONS

The findings of this report are based on the interpretation of existing data, geologic maps, and reports. The major conclusions are:

1. Petroleum potential is low to very low throughout the entire study area (Figure 1).
2. Unconventional petroleum potential is low throughout the entire study area.
3. Mineral potential in the offshore is unknown; however, the onshore regions assessed all contain prospective mineral occurrences (Figure 3).

7. ACKNOWLEDGMENTS

The GSC Calgary MCT geoscience team sincerely thanks Tom Brent, Peter Hannigan, and Jim Dietrich for support and guidelines during duration of the study; Denis Lavoie, Nicolas Pinet, Derek Armstrong of the Ontario Geological Survey and Michelle Nicolas of the Manitoba Geological Survey for their expertise and consultation; Andy Mort and Keith Dewing for their geological insight; Lindsay Kung for GIS expertise and Yassir Jassim and Faizan Shahid for their technical support. Many other GSC colleagues are thanked for pointing to relevant literature, maps, and data resources as well as for sharing their stories and insights about regional geology. Without their generous help, it would have been impossible to complete this project on time.

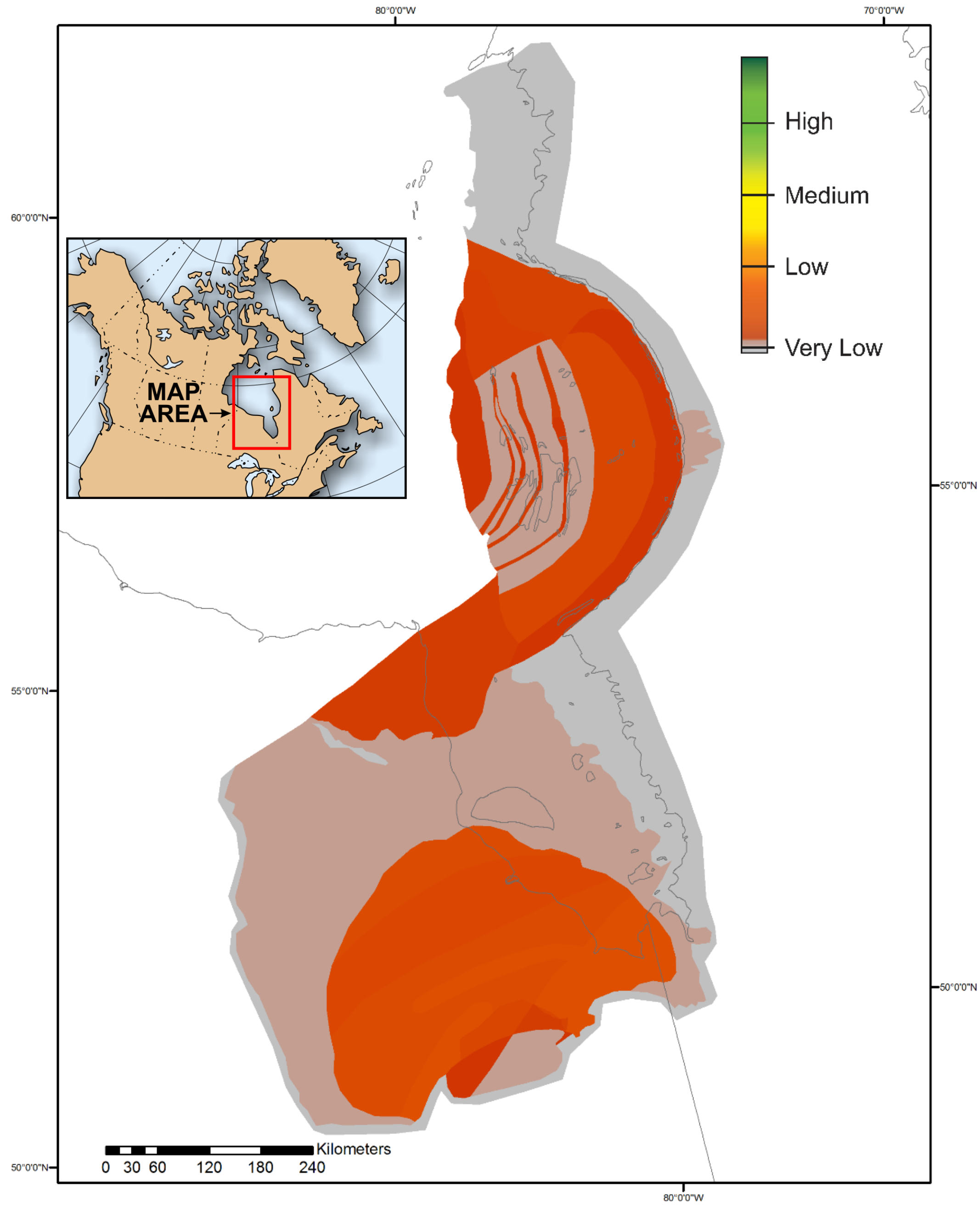

Figure 1. Eastern Hudson Bay and James Bay Petroleum Potential Map. Colour code - gradation bar ranges from little potential (red) to the highest potential (green, globally competitive for exploration) where grey indicates no petroleum potential. The study area contains only grey, red and orange, showing low to no potential. The Moose River Basin potential reflects a higher chance of success for the presence and maturity of Ordovician source rocks reflected in the orange polygon. Larger orange polygons, as in the northwest Belcher Basin, represent areas of high data uncertainty. The striped nature of the low petroleum potential reflects the limited structural trap potential within the Belcher Island area. More mapping, seismic, and potential field data would need to be collected to generate a more accurate representation of the petroleum potential.

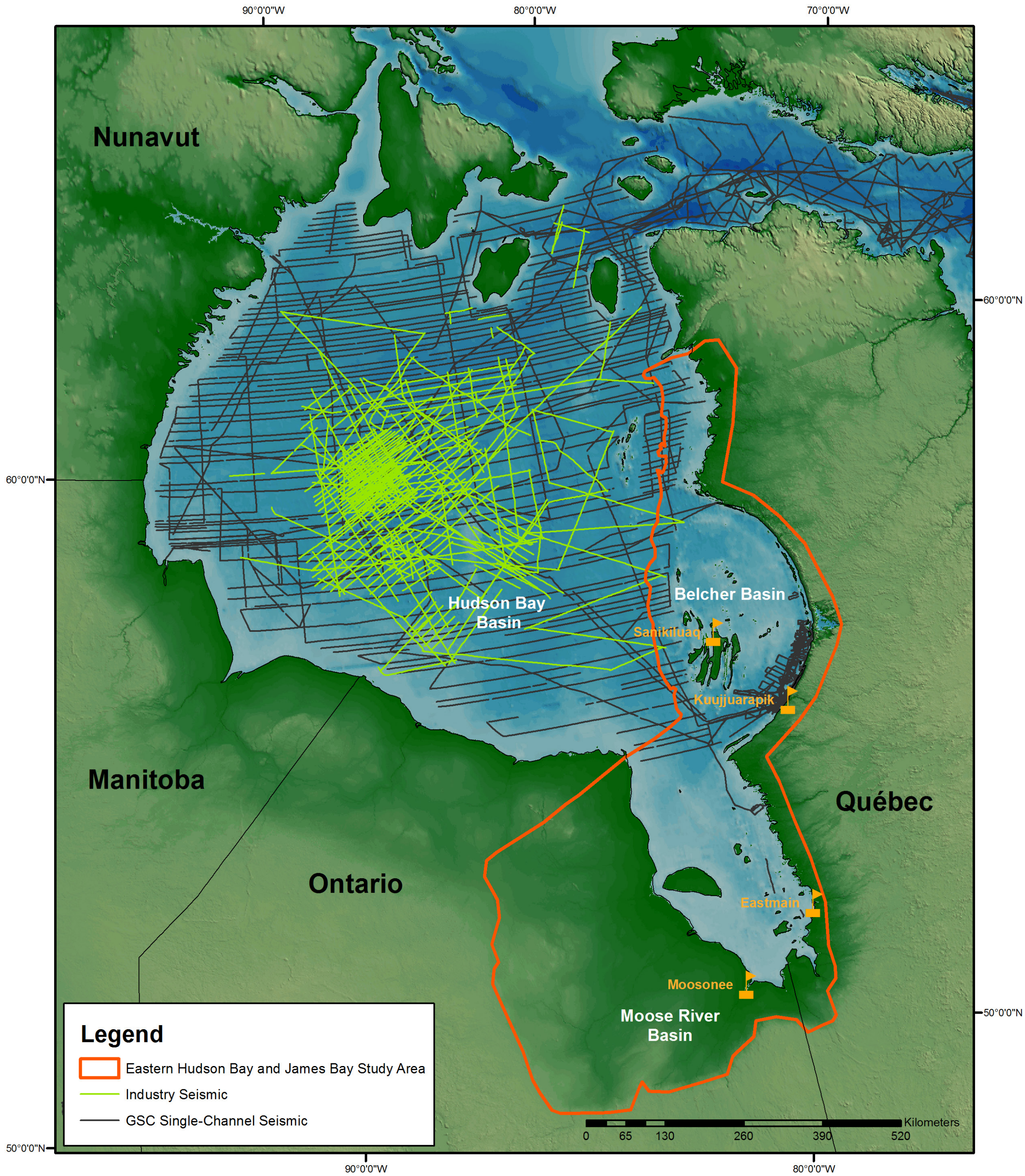

Figure 2. Location of two-dimensional seismic lines in Hudson Bay and James Bay.

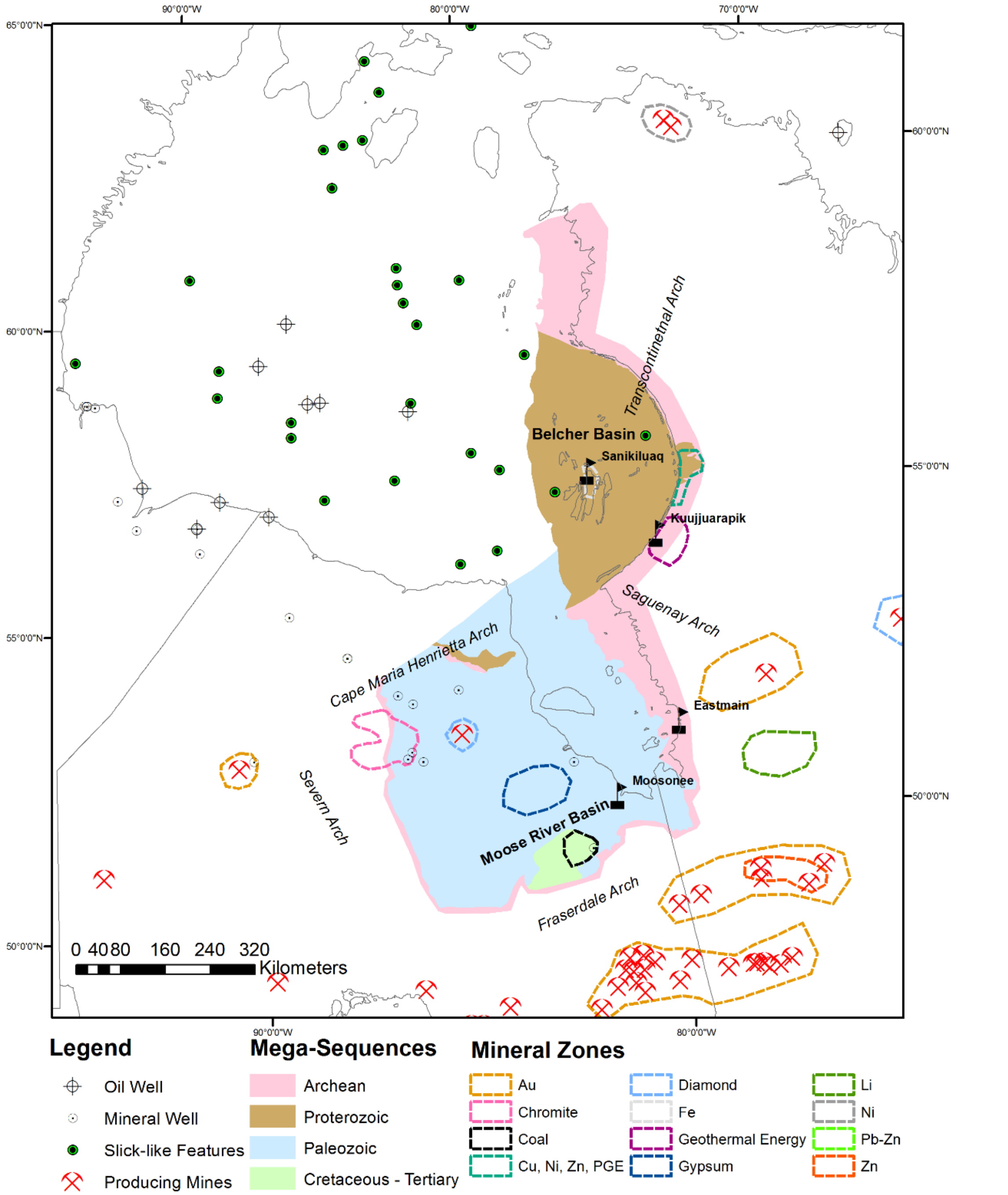

Figure 3. Eastern Hudson Bay and James Bay geologic mega sequences, select petroleum system indicators (sea surface, slick-like features) and well locations. Wells shown are both petroleum and mineral wells drilled in the Hudson Bay Basin, the Moose River Basin, and into the Canadian Shield. The abundance of mines in the SE corner of the map are located within the Abitibi Greenstone belt of Quebec and Ontario. Iron wells drilled on the Belcher Islands are not shown on the map, but are primarily within the Fe polygon of the mineral zone.

TABLE 1

Eastern Hudson Bay and James Bay study area petroleum potential chance of success summary

	Age (Ma)	Play	Reservoir	Trap	Source	Seal	Highest uncertainty	Global Scale factor (0-1)
		Hypothetical GREAT play						1
1	400	Paleozoic - in extension/inverted fault blocks	Carbonates, Clastics	Structural	Ordovician source, i.e. Boas River shale	Tight Carbonates, Shales	Source	0.450
2	420	Paleozoic Reef	Reefs	Stratigraphic	Ordovician source, i.e. Boas River shale	Tight Carbonates, Shales	Source	0.500
3	445	Paleozoic Hydrothermal Dolomite	Carbonates	Stratigraphic	Ordovician source, i.e. Boas River shale	Tight Carbonates	Source	0.450
4	999	Proterozoic Homocline	Clastics or Carbonates	Stratigraphic or Combination	Lwr. Omarolluk fm.	Tight Carbonates, Shales	Source/ Preservation	0.450
5	999	Proterozoic Structure	Clastics	Folds, Subcrop	Lwr. Omarolluk fm.	Tight Carbonates, Shales	Source/ Preservation	0.450

Eastern Hudson Bay and James Bay petroleum plays including petroleum systems elements, elements of highest uncertainty and a global scale factor (Section 4.2 of this report). Play ages are approximations of time of reservoir formation. Since this is a high level assessment of a low potential area, some plays (i.e. reefs) are lumped into one play type, although plays of Ordovician, Silurian, and Devonian ages would have different petroleum system inputs. Proterozoic plays are given the age '999' to ensure functionality and order in file structure. In the Belcher Basin, sediments are 1.8 Ga (billion years).

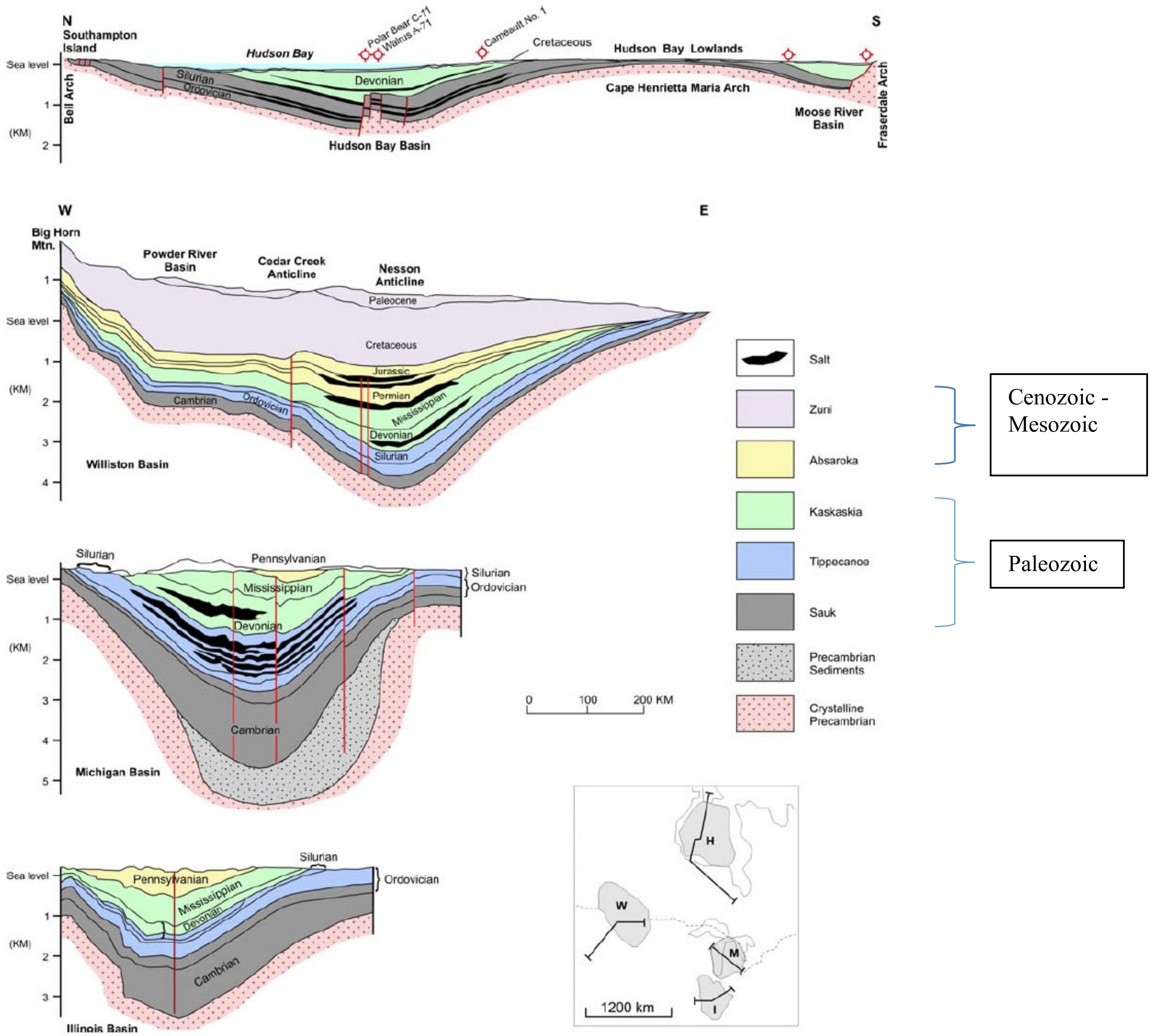

Figure 4. Schematic cross sections across the four intracratonic basins on the North American Craton. The Moose River Basin is the thinnest and smallest basin, located to the southern edge of the first cross section (from Zhang, S., 2010).

APPENDIX A. MEGA-SEQUENCE PETROLEUM SYSTEM ANALYSIS

Mega-sequence 1 – Proterozoic Era

Proterozoic clastic, carbonate, sedimentary, low-grade metamorphic, and igneous rocks of the Belcher Basin, exposed on the Belcher Islands, in Northern Ontario (Sutton Inlier), and in the Richmond Gulf Graben (Chandler, 1988, Jackson 2013) suggests that they should have a significant presence offshore within eastern Hudson Bay. A review of the literature reveals limited information about Belcher Basin petroleum systems and potential; therefore, any petroleum assessment in this region is qualitative in nature and based on broad geologic trends. Literature on the Belcher Basin stratigraphy, tectonics (Jackson, 2013), and slick-like features (Decker et al., 2013) suggests that Belcher Basin may contain all necessary petroleum system elements and that it was and perhaps still has potential, albeit low, to contribute to petroleum resources within the Nastapoka region. Seismic data, or the lack thereof, were of limited use for mapping Belcher Basin internal stratigraphy.

Source Rock

Based on the work of Jackson (2013), the most prospective source interval in the Belcher Islands is the Omarolluk Formation: a 5-20 m thick basal black shale of Proterozoic age. This unit is seen on the Gilmour Peninsula and Young Point and is thought to represent turbidite deposition in a deep-water restricted basin. The authors have not found Rock Eval analyses or other testing the Total Organic Carbon (TOC) content of the Lower Omarolluk shale but it is equivocally considered to be the best candidate for a regional source rock. Anthraxolite has been mapped in seven locations on the Belcher Islands (Jackson, 2013) which is a high temperature residue of a previously existing hydrocarbon. Anthraxolite indicates the generation of at least some petroleum in the Belcher Basin. Circumstantial evidence of petroleum generation and migration comes from sea-surface slick-like features near the Belcher Islands (Decker et al., 2013) and from dark staining (potential oil staining) recorded in the Loaf sandstone (Jackson, 2013).

Reservoir

Potential reservoir units in the Belcher Islands and Richmond Gulf Graben include underlying (relative to source) sandstones of the McLeary (Belchers) and Pachi formations (Richmond Gulf, Chandler, 1988), and sandstones within the overlying Loaf and Omarolluk formations (Belcher Islands, Jackson, 2013). The authors have not encountered porosity measurements of these units, but it is thought that the formations may have low porosity due to greywacke lithology (Jackson, 2013) and mineralogical changes during diagenesis and subsequent metamorphism.

Trap

Deformation caused by the Trans-Hudsonian Orogeny (THO) buried, folded, and faulted the Belcher Basin sediments. Although the Loaf and Omarolluk sandstones have been eroded from the crests of anticlines, the McLeary Formation may exist in anticlines in the subsurface. Since the McLeary Formation underlies potential source rocks, it would require unusual, yet not impossible, geologic processes for hydrocarbon charge. The Loaf and Omarolluk sandstones are present in the synclines of the Belcher Islands, the arms of which have been folded to form smaller anticlinal features (Jackson, 2013). In these smaller anticlines, the trap and reservoir rocks are overlying potential source rocks. The striped nature of the low petroleum potential seen in Figure 1 reflects the limited structural trap potential within the Belcher Island area.

Seal

Regional seals would have been formed by shales and siltstones of the Upper Member of the Loaf Formation and a number of localized seals could exist within cemented zones of sandstone or carbonate.

Mega-sequence 2 – Paleozoic Era

Paleozoic carbonates and shales of the Moose River Basin (Telford and Verma, 1982) are located in northern Ontario and the western half of James Bay. Although similar Paleozoic carbonates and shales produce oil and gas throughout North America, the sediments in the Moose River Basin have low potential, mainly due to a lack of evidence of source rock thermal maturity. Figure A-1 illustrates the stratigraphy of Hudson Bay as compared to Moose River Basin.

Source

Source is the highest uncertainty element in mega-sequence 2. In the Moose River Basin, the Long Rapids Formation has low potential as an Upper Devonian oil shale (i.e. not thermally mature enough to generate conventional hydrocarbons, Bezys, 1991). The equivalent to the Long Rapids formation can be correlated to hydrocarbon producing shale deposits in the Michigan, Appalachian, and Illinois Basins, and the Kettle Point Shales of Southern Ontario (Bezys, 1991). These source rocks are not noted in the offshore study area. In the onshore Moose River Basin, historical wells did not encounter mature source rock.

Although there is some evidence for an Ordovician source in the Moose River Basin, adjacent Paleozoic basins contain upper Middle Ordovician source rocks (Lavoie et al., 2013). The Upper Ordovician Red Head Rapids Formation (Nicolas and Lavoie, 2012) and Boas River Formation are likely the most important source rocks for the greater Hudson Bay Platform (Zhang and Lavoie, 2012, Lavoie et al., 2013), but have been only reported in two locations in the Moose River Basin. The prospectivity map (Figure 1) was generated using an Ordovician source stratigraphically aligned with the other basins and below the other mapped petroleum system elements. Maturity of these potential source rocks is a contentious issue as compared to other analog intracratonic basins in North America (Nicolas and Lavoie, 2012, Reyes et al., 2016).

Reservoir

Regionally, reservoir units in mega-sequence 2 are primarily Ordovician to Devonian carbonates which exist in the Moose River Basin. Carbonate reservoir distribution is highly variable and affected by numerous lithologic and diagenetic influences (Ahr, 2008). The two major reservoir facies identified are Paleozoic reefs and hydrothermal dolomite. Paleozoic reefs have been mapped in the Moose River Basin (onshore, Norris A.W. in Stott and Aitken, 1993, Figure 8.15) as well as within the Hudson Bay Basin (Hu and Dietrich, 2012). Hydrothermal dolomite occurs when hot fluids intrude a carbonate facies and alter pre-existing minerals. This type of reservoir is a prolific hydrocarbon producer in North America (Davies and Smith, 2006). These reefs and hydrothermal dolomite features have been seismically imaged and mapped in the subsurface and in surface outcrops of the Hudson Bay Basin (Hu and Dietrich, 2012, Lavoie et al., 2011, Castagner et al., 2016). The Long Rapids and Red Head Rapids formations may have some unconventional reservoir potential.

Trap

There are a variety of trap types within the Paleozoic carbonate plays in the Moose River Basin. Paleozoic reefs and hydrothermal dolomite (considered both a reservoir and a stratigraphic trap) have been mapped in both in the Moose River Basin and in Hudson Bay (Dietrich et al., 2013). Fault block traps may be present as the southern margins of the Moose River Basin contain large basement faults (Norris A.W., 1993). These three identified traps styles have also been mapped in the Appalachian Basin of Southern Ontario (Lazorek and Carter, 2008) but have not been mapped in James Bay.

Seal

Seals in the study area are varied. Evaporites offer the greatest chance for hydrocarbon preservation as they are ductile and may have survived multiple deformation episodes (Norris A.W., 1993). Hydrothermal dolomites may be sealed by overlying carbonates; however, carbonates are brittle and may have fractured during post hydrocarbon generation deformation. Seal is considered the highest uncertainty element within the study area.

Note: Paleozoic carbonates in the Canadian Arctic and Southern Ontario are proven hydrocarbon systems (e.g. Bent Horn Field, Canadian Arctic; Lake Erie – Maitland Pool, Appalachian Basin). In the study area there is weak supporting evidence of all major components for a working petroleum system. Source rocks of Ordovician age are present (Zhang and Lavoie, 2012) with evidence of oil staining and bitumen/pyro-bitumen. However, no exploration wells in the Moose River Basin area show evidence for hydrocarbon generation. Prospective reservoir, trap, and seal combinations in the study area have not conclusively shown strong evidence of a working petroleum system.

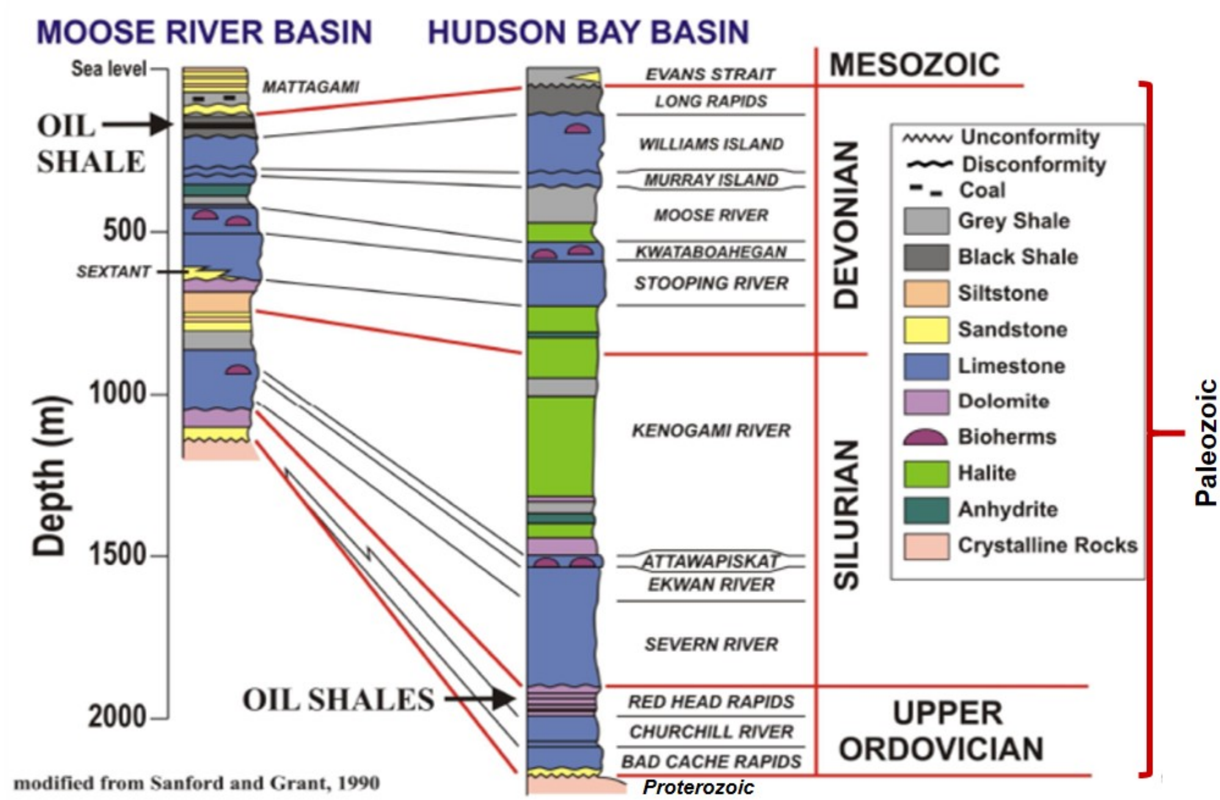

Figure A-1. Schematic cross section of Moose River Basin stratigraphy as compared to Hudson Bay stratigraphy, modified from Lavoie et al., 2011.

Mega-Sequence 3 – Mesozoic and Cenozoic Eras

Terrigenous Mesozoic and Cenozoic clastic sediments (~300 m thickness) are aerially restricted to the onshore portion of Moose River Basin in Northern Ontario (Telford and Verma, 1982). The lack of Mesozoic and Cenozoic sediments in the study area is associated with basement uplift and unconformable overlap of sediments on the edges of Paleozoic aged rocks that rest directly on the Precambrian (Sanford et al., 1967, p. 37). The lignite-rich Mattagami Formation (120 m maximum thickness) is the most prevalent formation representing the Mesozoic to Cenozoic sedimentation in the onshore, northern Ontario Moose River Basin (Telford and Verma, 1982,). Mega-sequence 3 is the least prospective sedimentary package for conventional petroleum within the study area.

Source Rocks

No potential conventional source rocks have been mapped within this mega-sequence. The lignite-rich (coal) beds of the Mattagami formation imply terrigenous input (Telford and Verma, 1982). These lignite beds may have some potential for coal-bed methane.

Reservoir

Limited potential as the Mesozoic to Cenozoic deposition has been eroded due to basement uplift. The Mattagami Fm. consists of quartz sand and clays (Telford and Verma, 1982); these mixed lithologies would at best make moderate reservoirs. Cenozoic sandstones are also potential reservoir units (Telford and Verma, 1982), although they are poorly sorted therefore a low quality reservoir.

Trap

None identified.

Seal

Interbedded clays of the Mattagami Formation have variable thickness (up to 37 m, Telford and Verma, 1982). However, these units are primarily unconsolidated, making their seal capacity questionable.

APPENDIX B. MINING ACTIVITY AND MINERAL POTENTIAL SUMMARY

Mineral resources were identified through scientific papers, industry press releases, and interpretation on geologic maps. The following summary is a snapshot of some of the mineral potential near the study area.

In the James Bay Lowlands, there is a planned chromite mining and smelting development named the Ring of Fire. If developed, the more than 30,000 existing claims could potentially add chromium-iron, vanadium and platinum to the mix of minerals with chromite and nickel having the most significant development opportunities. The Moose River Basin was also extensively drilled for coal in the mid-20th century, although results determined that development was uneconomic (Telford and Verma, 1982).

Onshore of the eastern Hudson Bay, are mineral claims for copper and silver (Cu-Ag); lead, zinc and gold (Pb-Zn-Au), and lead and zinc (Pb-Zn). These minerals occur in the rocks of the Canadian Shield, which are overlain by the Proterozoic sediments of the Belcher Basin in Hudson Bay. The Belcher Islands contain a marble quarry that supplies over 50 tonnes of quality stone to local carvers (Nunavut Mineral Exploration, Mining and Geoscience publication, 2016) and active iron exploration leases (Haig Inlet Iron Project) that covers over 230 km^2 of the Belcher Islands. The Haig Inlet Iron Project has an indicated resource of 230 million tonnes of iron ore (at a cut off grade of 35.17%, Canadian Ore Bodies, 2017). There is low potential for geothermal energy development in the offshore area near the Belcher Islands. However, there may be some future potential for the onshore area of this report's study area to supply geothermal energy utilizing abandoned mines near Kuujjuarapik. The greatest potential for geothermal energy in Canada exists in Alberta, Yukon and British Columbia (Grasby et al., 2012).

APPENDIX C. REVIEWED DOCUMENTS

BOLD: Key Reference Documents

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APPENDIX D. GLOSSARY OF TERMS

(* from or modified from The Oilfield Glossary: http://www.glossary.oilfield.slb.com)

***Carbonate**: A class of sedimentary rock whose chief mineral constituents (95% or more) are calcite and aragonite (both $CaCo_3$) and dolomite [$CaMg(CO_3)_2$]. Limestone and chalk are carbonate rocks.

Cenozoic: Geological Era approximately 66 million years ago to present.

***Clastic:** Sediment consisting of broken fragments derived from pre-existing rocks and transported elsewhere and redeposited before forming another rock. Examples of common clastic sedimentary rocks include siliciclastic rocks such as conglomerate, sandstone, siltstone and shale. Carbonate rocks can also be broken and reworked to form clastic sedimentary rocks.

***Formation**: A body of rock that is sufficiently distinctive and continuous, and can be mapped.

***Hydrate:** An unusual occurrence of hydrocarbon in which molecules of natural gas, typically methane, are trapped in ice molecules. More generally, hydrates are compounds in which gas molecules are trapped within a crystal structure. Hydrates form in cold climates, such as permafrost zones and in deep water. To date, economic liberation of hydrocarbon gases from hydrates has not occurred, but hydrates contain quantities of hydrocarbons that could be of great economic significance. Hydrates can affect seismic data by creating a reflection or multiple.

***Maturation**: The process of a source rock becoming capable of generating oil or gas when exposed to appropriate pressures and temperatures.

***Mega-sequence:** A large group of relatively conformable strata, normally from the same era, that represents cycles of deposition and is bounded by unconformities or correlative conformities.

Mesozoic: Geological Era approximately 145 to 252 million years ago.

***Migration:** The movement of hydrocarbons from their source into reservoir rocks.

***Mineral:** A crystalline substance that is naturally occurring, inorganic, and has a unique or limited range of chemical compositions. Minerals are homogeneous, having a definite atomic structure. Rocks are composed of minerals, except for rare exceptions like coal, which is a rock but not a mineral because of its organic origin. Minerals are distinguished from one another by careful observation or measurement of physical properties such as density, crystal form, cleavage (tendency to break along specific surfaces because of atomic structure), fracture (appearance of broken surfaces), hardness, luster and color. Magnetism, taste and smell are useful ways to identify only a few minerals.

Paleozoic: Geological Era approximately 252 to 541 million years ago.

***Petroleum System:** Geologic components and processes necessary to generate and store hydrocarbons, including a mature source rock, migration pathway, reservoir rock, trap and seal. Appropriate relative timing of formation of these elements and the processes of generation, migration and accumulation are necessary for hydrocarbons to accumulate and be preserved.

***Play:** An area in which hydrocarbon accumulations or prospects of a given type occur.

***Pool:** A subsurface oil accumulation. An oil field can consist of one or more oil pools or distinct reservoirs within a single large trap. The term "*pool*" can create the erroneous impression that oil fields are immense caverns filled with oil, instead of rock filled with small oil-filled pores.

Proterozoic: Geologic eon encompassing ages of 2500 – 541 million years ago. This eon represents the youngest portion of the Precambrian and is sub-divided into three geologic eras: Paleoproterozoic (oldest), Mesoproterozoic and Neoproterozoic (youngest).

***Reservoir:** A subsurface body of rock having sufficient porosity and permeability to store and transmit fluids. Sedimentary rocks are the most common reservoir rocks as they have more porosity than most igneous and metamorphic rocks and form under temperature conditions at which hydrocarbons can be preserved. A reservoir is a critical component of a complete petroleum system.

***Seal:** A relatively impermeable rock, commonly shale, anhydrite or salt that forms a barrier or cap above and around reservoir rock such that fluids cannot migrate beyond the reservoir. A seal is a critical component of a complete petroleum system.

***Sequence:** A group of relatively conformable strata that represents a cycle of deposition and is bounded by unconformities or correlative conformities.

***Source rock:** A rock rich in organic matter which, if heated sufficiently, will generate oil or gas. Typical source rocks, usually shales or limestones, contain about 1% organic matter and at least 0.5% total organic carbon (TOC), although a rich source rock might have as much as 10% organic matter.

***Trap:** A configuration of rocks suitable for containing hydrocarbons and sealed by a relatively impermeable formation through which hydrocarbons will not migrate. Traps are described as structural traps (in deformed strata such as folds and faults) or stratigraphic traps (in areas where rock types change, such as unconformities, pinch-outs and reefs). A trap is an essential component of a petroleum system.

***Unconventional resource**: An umbrella term for oil and natural gas that is produced by means that do not meet the criteria for conventional production. What has qualified as unconventional at any particular time is a complex function of resource characteristics, the available exploration and production technologies, the economic environment, and the scale, frequency and duration of production from the resource. Perceptions of these factors inevitably change over time and often differ among users of the term. At present, the term is used in reference to oil and gas resources whose porosity, permeability, fluid trapping mechanism, or other characteristics differ from conventional sandstone and carbonate reservoirs. Coalbed methane, gas hydrates, shale gas, fractured reservoirs, and tight gas sands are considered unconventional resources.